Communications Research Centre

PROPAGATION MEASUREMENTS FOR LAND-MOBILE SATELLITE SYSTEMS AT 1542 MHz

by

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Directorate of Space Systems

Government of Canada
Department of Communications

Gouvernement du Canada
Ministère des Communications

CRC TECHNICAL NOTE NO. 723

OTTAWA, AUGUST 1984

Canada

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ABSTRACT

A measurement program was undertaken with the objective of providing engineering design data on excess path-loss for potential land-mobile satellite systems operating in the 1500 MHz band. In the suburban and rural areas which could be served by such a system, fading due to multipath propagation and shadowing by terrain obstacles were the two phenomena characterized. Using an omni-azimuth vehicle antenna to receive a signal at 20 degrees elevation from the MARECS A satellite, the diffuse multipath signals were found to be 10 dB less than the direct component. The percentage of shadowed locations on the test routes varied from 5% in open farmland to 33% in suburban locations. The corresponding signal margins required to provide 99% coverage over the various test routes ranged from 12 dB to 21 dB.

1. INTRODUCTION

1.1 SUBJECT

The Department of Communications, in co-operation with NASA in the United States, is developing the concept of a regional mobile satellite system. Initially, it is proposed to provide service in the 806 - 890 MHz band, with some interest in future systems expanding into the 1545 - 1660.5 MHz band (part of L-Band). Internationally, parts of L-Band serve maritime mobiles through the INMARSAT (International Maritime Satellite Organization) system. INMARSAT and its signatories have shown interest in investigating the expansion of services to include, for example, service to trans-oceanic aircraft. With the recent developments in voice-coding and modulation methods, the provision of satellite services to lower-cost, low G/T mobile stations is becoming practical. For this reason, the Department of Communications has funded a program to develop and evaluate technology for such mobile stations. So far this program has included the development of advanced voice coding and modulation techniques and of several types of mobile antennas. With such equipment, the signal power required at the mobile is reduced substantially compared with standard FM systems.

In considering the use of such equipment for aeronautical or land-mobile applications, the question of appropriate propagation margins must be addressed. While both application areas are subject to the effects of multipath propagation, the land-mobile application is further complicated by the shadowing effects of terrain obstacles such as roadside trees and buildings. To characterize these excess path-loss effects for land-mobile, a measurement program was conducted as the first phase of an extensive field-trial of newly-developed equipment.

1.2 PURPOSE AND SCOPE

The purpose of this report is to describe the measurement methods used to characterize the path-loss statistics of an unmodulated 1542 MHz satellite source as received by a land-mobile vehicle and to present and discuss the results obtained. Similar measurements made at 870 MHz are the subject of a companion report (Butterworth, 1984).

1.3 PARTICIPATING ORGANIZATIONS

With the launch of the MARECS A satellite in December 1981, INMARSAT was able to pursue their policy of encouraging research and development of new services and new equipment by offering signatories an opportunity to conduct satellite communications experiments. In co-operation with the Department of Communications, the Canadian INMARSAT signatory, Teleglobe Canada, submitted a comprehensive experiment proposal including, as a first phase, the characterization of excess path-loss for land-mobile applications. After negotiations to define satisfactory safety procedures for the Canadian transmitting station which would provide the uplink to the satellite, the experiment proposal was accepted. A downlink EIRP of 28 dBW at 1542.5 MHz was authorized. This was equivalent to 25% of the total spacecraft output power capability.

2. SATELLITE CHARACTERISTICS

The MARECS A satellite, launched on the 20th December 1981, is situated in synchronous orbit at 26°W longitude. It is a three-axis stabilized spacecraft with East-West stationkeeping. From the Ottawa area its elevation angle is about 20 degrees. Its general communications characteristics in the shore station-to-mobile direction are:

Uplink frequency band :	6420.25 - 6425.0 MHz
Uplink polarization :	RHCP
Uplink EIRP required :	60 dBW/standard communications channel
Downlink frequency band :	1537.75 - 1542.5 MHz
Downlink polarization :	RHCP
Maximum Total EIRP :	34 dBW
Maximum traffic capacity:	40 channels (SCPC/NBFM)

The authorized operating levels and frequencies for our experimental use were:

Nominal uplink frequency	:	6425 MHz
Nominal uplink EIRP	:	70 dBW
Stabilized downlink frequency	:	1542.5 MHz
Downlink EIRP	:	28 dBW
Frequency channel number	:	300

3. SATELLITE LINK CONFIGURATION

In order to make useful measurements of received signal strength with a mobile laboratory equipped with an omnidirectional antenna, it was necessary to use an unmodulated source signal and a very narrow receive bandwidth to maximize the signal-to-noise ratio. To make this feasible, the downlink signal from the satellite was frequency-stabilized to eliminate any drift due to spacecraft motion or translation oscillator instability. An 8.5m L-Band earth station received both the test signal and the MARECS pilot signal. The pilot signal is uplinked at a precise frequency by the INMARSAT Coastal earth station at Southbury (U.S.A.) and is used for frequency control purposes. Its nominal downlink frequency is 1537.525 MHz. Any difference of the received pilot from this frequency is used as a correction for the uplink test signal frequency.

In addition to supplying the received pilot signal to the 8m C-Band uplink station, the L-Band station was also used to accurately monitor the line-of-sight level of the received test signal. As the MARECS transponder has automatic level control for the total output signal power, some variation of the test signal output was anticipated due to fluctuations in the operational traffic volume. In practice, the variations turned out to be no more than 1 dB and so were essentially negligible. Figure 1 provides a useful overview of the system configuration.

3.1 DETAILS OF AFC AND FAULT DETECTION SYSTEMS

Figure 2 shows further details of the earth station equipment. Signals received by the L-Band station were down-converted so that the nominal centre frequency of the pilot signal was 250 MHz. The down-converted signals were transmitted over coaxial cable to the C-Band station (located nearby) which was used as the operations control centre. There, a double-conversion telemetry receiver, phase-locked to the pilot signal, was used to derive a correction frequency for the uplink signal. The receiver VCO output, exactly 60 MHz when the pilot was on its nominal frequency, would track up or down as the pilot varied down or up in frequency, causing the uplink frequency to vary in the opposite sense from the received pilot. This stabilized the test signal downlink on its assigned frequency of 1542.5 MHz with excellent accuracy despite satellite range-rates of up to 40 km/h.

Figure 2 also shows the fault detection system requested by INMARSAT to avoid any accidental interference with operational traffic. The fault detector automatically removed the drive from the HPA in the event of an overpower fault causing the transmitter output to rise more than 1 dB above nominal. The out-of-lock signal outputs from all phase-locked frequency sources were also fed into the fault detector to prevent sweeping of the uplink frequency in the event of an out-of-lock failure mode. The received L-Band test signal was monitored in level and frequency. A microprocessor-controlled digital voltmeter provided an alarm in the event of the received signal level being outside a certain tolerance band. The received frequency was similarly monitored by a counter and desktop computer to provide an alarm if the frequency varied more than 1 kHz from nominal.

3.2 LINK ANALYSIS TO MOBILE STATION

The authorized satellite EIRP for this experiment was 28 dBW. The average range of the satellite from Ottawa was 39650 km. To accommodate the full spectrum of the Doppler-spread multipath signal, a bandwidth of 300 Hz was usually required at the mobile receiver. The received signal-to-noise ratio was calculated from:

$$C/N = EIRP - LD - P + G/T - B + 228.6$$

C/N = received signal/noise ratio in dB
EIRP = satellite EIRP (28 dBW)
LD = downlink $1/d^2$ loss (188.2 dB)
P = polarization coupling loss, assuming both antennas have 4 dB axial ratio and are in worst-case orientation (0.9 dB)
G/T = gain-to-noise-temperature ratio of mobile receiver (-24 dB/K)
B = receiver noise bandwidth expressed as 10 log b, where b is the bandwidth in Hz
228.6 = Boltzman's constant in dBW/K/Hz

Consequently:

$$C/N = 28 - 188.2 - 0.9 - 24 - 25 + 228.6$$
$$= 18.5 \text{ dB}$$

Although lower than desirable, this value of signal-to-noise ratio was considered adequate for the purpose. Where conditions permitted the mobile laboratory to be driven slowly, 100 Hz bandwidth was used, giving an unfaded signal/noise ratio of 23.5 dB.

4. FACTORS INFLUENCING EXPERIMENTAL PROCEDURES

In making mobile measurements of signal strength by taking samples at discrete increments of distance, consideration must be given to the effects of Doppler shift of the direct signal, Doppler spreading of the multipath signals and the choice of the sampling interval.

4.1 PRE-DETECTION RECEIVER BANDWIDTH REQUIRED

In communications with a mobile vehicle, the received line-of-sight signal frequency is influenced by the motion of the vehicle and, in the general case, of the source. Here, the effects of source motion were eliminated by a closed-loop frequency control system. The received direct component was therefore only influenced by the vehicle motion and was Doppler-shifted by an amount:

$$f_d = \frac{\pm V \cos\theta \cos\alpha}{\lambda}$$

V = mobile speed
θ = source elevation angle (20°)
α = angle of vehicle heading from source azimuth
λ = source wavelength (0.194 m)

The worst-case Doppler shift of the direct component corresponding to a vehicle speed of 80 km/h along the source azimuth is 107 Hz.

Assuming an omni-azimuth antenna, if the vehicle is traversing a uniformly-scattering plane, the received multipath components will arrive uniformly from all directions and will have Doppler shifts depending on their angle of arrival relative to the vehicle heading. The maximum Doppler shift of the multipath components will be $f_m = \pm V/\lambda$ by scattering from terrain directly ahead of or behind the vehicle. The energy spectral density will be (Clarke, 1968, Eq. 27):

$$S(f) = 1/(\pi f_m (1 - f^2/f_m^2)^{1/2})$$

where f is the received frequency difference from the source frequency. Fig. 3 shows the shape of the multipath spectrum. The receiver bandwidth required to accommodate a multipath bandwidth of 2 f_m and a direct component shift of f_d at 80 km/h vehicle speed is about 230 Hz. The next-higher selectable bandwidth of 300 Hz was used for most of the measurements.

4.2 POST-DETECTION BANDWIDTH AND SAMPLING RATE

The spectrum of the linearly envelope-detected baseband signal extends in frequency to 2 f_m and may include two peaks, depending on vehicle heading relative to the source azimuth (Clarke, 1968, Fig. 7b). Fig. 4 shows a typical case. In order to sample, digitize and store the baseband signal, the sampling rate should be at least 4 f_m and preferably higher to avoid aliasing errors. In spatial terms, this is equivalent to at least four samples per wavelength travelled. In practice, samples were taken every 2.5 cm, which is equivalent to about eight samples per wavelength.

5. DESCRIPTION OF THE MOBILE LABORATORY

The mobile laboratory was designed for real-time recording of digitized samples of received signal strength, as well as for making tape recordings of received signal amplitude and phase ("stored-channel" recordings). Figure 5 shows a block diagram of the equipment. A spectrum analyser was chosen as the receiver instead of a general-purpose receiver or field-strength meter. The advantages of the spectrum analyser were the ability to operate the instrument under computer control through the IEEE 488

GPIB, the wide range of IF and video bandwidths available and the centre-frequency stability necessary to make measurements in 300 Hz bandwidth at frequencies up to 1600 MHz.

5.1 "STORED CHANNEL" RECORDING SYSTEM

The spectrum analyser, used in zero-scan mode during measurements, provided a 21.4 MHz IF output to a quadrature demodulator. The in-phase and quadrature outputs were recorded separately on two tracks of an instrumentation tape-recorder. This method of producing "stored channel" recordings was developed at DFVLR in Germany (Hagenauer, 1982). Other tracks of the same tape recorded a commentary channel, the demodulated output of the receiver and distance markers from the odometer.

5.2 DIGITIZED DATA RECORDING SYSTEM

The linearly envelope-demodulated output (video output) from the spectrum analyser was also used as input to a chart recorder and to a high-speed three-and-a-half digit digital voltmeter. This voltmeter, used on its one-volt range, where its resolution was one millivolt, provided a 60 dB dynamic range in the digitized data. Used under control of a desktop computer, the apparatus was capable of digitizing and recording up to a thousand readings per second. Readings were triggered by pulses produced by the odometer subsystem for every 2.5 cm travelled by the mobile laboratory. Readings were transferred from the voltmeter to the computer, via the GPIB, for storage on floppy discs. About 130,000 readings could be stored on each disc, corresponding to 3.25 km distance travelled by the vehicle. Trigger pulses were also supplied to the chart recorder to advance the paper in proportion to the distance travelled by the vehicle.

5.3 ANTENNA SYSTEM

The antenna used for data collection was the drooping crossed-dipole shown in Fig. 6. Fig. 7 shows the elevation-plane pattern of the antenna, as mounted on the vehicle roof. This pattern was obtained by making a mock-up of the vehicle roof, mounting the antenna on it and measuring the pattern in a large anechoic chamber.

5.4 ODOMETER AND POWER SUBSYSTEMS

The original odometer drive cable was disconnected from the dashboard instrument and a special gearbox was interposed between the two to give a second odometer drive output. This extra output rotated an optical-type shaft angle encoder providing 2500 pulses per revolution. By driving a measured distance it was ascertained that 1536 pulses were produced for each metre travelled by the vehicle. The pulse train was applied to a selectable-ratio divider. A division ratio of 38 resulted in one pulse for every 2.5 cm travelled by the vehicle.

The power subsystem consisted of two components. The first was an engine-driven high-output alternator with integral 12 volt regulator, capable of providing 100A at idle speed and 145A at full speed. The second component was a static inverter, used to convert the 12V input to 115V/60 Hz AC regulated output, with a maximum capability of 1000 VA. The installed equipment required about 700 VA.

6. DESCRIPTION OF TEST ROUTES

Three test routes representative of different classes of terrain were chosen for the measurements. These were:

- an older suburban residential area consisting mainly of one and two-storey single-family dwellings.
- a rural/forested area consisting of hilly terrain covered with immature timber of mixed species, interspersed with occasional cleared areas. The route followed a series of paved provincial highways with one lane for each traffic direction and with gravel shoulders.
- a rural/farmland area consisting almost entirely of flat, open fields. About 5% of this route ran through occasional wooded areas. The roads were paved county roads with one lane for each traffic direction and with gravel shoulders.

In the suburban area, about 12 km of the route was characterized. In the rural areas this extended to about 30 km for each case.

7. DESCRIPTION OF PROCEDURES

For each route, starting locations were chosen which had clear line-of-sight in the satellite direction for at least a short distance along the route. A data sample of 1000 readings was then taken in this area. The median value of this sample provided a good estimate of the unfaded, unshadowed received signal level. For convenience, this reference level will be referred to as the "line-of-sight" signal level. After this, the mobile laboratory proceeded along the route. Digitized readings of received signal strength were recorded in files of up to 130,000 readings on double-sided 13.3 cm diskettes of 260 k bytes capacity. At the same time, analog tape-recordings were made on half-inch tape of the I and Q outputs of the quadrature demodulator. Because of this latter requirement, the receiver (spectrum analyser) was used in linear mode rather than the more customary logarithmic mode, so that the tape-recordings could be used directly as control signal sources for "stored-channel" simulation purposes. A more detailed description of the data acquisition methodology and software is given in Appendix 1.

8. PRESENTATION OF DATA

The individual data points were converted into dB levels relative to the average line-of-sight reference level for the particular route in question. The data were then grouped into class intervals of 1 dB in received signal strength and a relative-frequency histogram was computed. Next a frequency polygon was tabulated by conceptually joining the centre-points of the top of the column in each class-interval of the histogram. The frequency polygon was then integrated using the trapezoidal rule to obtain an ogive (cumulative percentile curve). The graphically-smoothed ogives were used to obtain an estimate of the distribution function of the relative received signal level. The level-crossing rate (LCR) was also calculated from the data and, using a method described by Lee (Lee, 1982, Sec. 2.8) the average fade duration was derived from a knowledge of the distribution function and the LCR. A more detailed description of the methodology and software used for data analysis is provided in Appendix 2.

The first measurements were made in November 1982 when the deciduous trees were without leaves. Fig. 8 shows the distribution functions obtained for the three test areas. Fig. 9 shows the corresponding level-crossing rates and Fig. 10 the average fade durations.

A second series of measurements were made over the same routes in June 1983. Fig. 11 shows the distribution functions. Much as would be expected, the suburban and rural/farmland curves are very similar to the November 1982 results, but the rural/forested curve shows larger attenuation values due to the presence of foliage on the deciduous trees.

9. INTERPRETATION OF DATA

9.1 GENERAL OBSERVATIONS

The distribution functions (Figs. 8 and 11) can be divided into three areas. The part to the left of the "knee" (i.e. at higher signal levels) has a Rician shape which is relatively insensitive to the percentage of the data recorded in shadowed locations. The "straight-line" (log-normal) part to the right has an intercept point with the Rician part which moves to the left with an increasing percentage of shadowed data. The third part, the right-hand tails of the distributions, is no longer "straight-line" except in the case of the suburban data shown in Fig. 8. In this case a bandwidth of only 100 Hz was used, providing a 5 dB increase in dynamic range compared with the other data sets. It is hypothesized that the deviation from "straight-line" in the other data sets is due to the limited dynamic range of the receiver before the distribution function becomes that of the receiver noise itself, i.e. Gaussian rather than log-normal. Similar data taken at 870 MHz with the same equipment but much higher signal-to-noise ratio did not show this deviation from log-normal (Butterworth, 1984).

9.2 COMPARISON WITH SIMULATION RESULTS

A greater insight into the nature of the physical processes producing these results can be obtained by the use of a suitable channel simulator. Individual simulator parameters can be varied to observe their effect and to approximate the experimental data. A suitable simulator is shown in Fig. 12. The signal input is split into two paths: a "direct" path and a "fading" path. The signal following the fading path is modulated in amplitude and phase by a Rayleigh-fading generator (quadrature modulator) controlled by two pseudo-random Gaussian sequences. The fading signal so generated can be added to the direct signal at various selectable levels, so producing a Rice-distributed output signal with a selectable parameter "K" (K is the simulated multipath-to-direct component power ratio).

To simulate shadowing effects, the direct signal level is controlled by a voltage-controlled attenuator (VCA) before combination with the simulated multipath signal. The VCA is controlled by a third Gaussian sequence which varies at a slower rate than those used for fading control. The direct signal at the output of the VCA is thus log-normally distributed in amplitude. The mean attenuation of the VCA is set to 2.5 times the standard deviation chosen for the log-normal variations.

The "suburban" data of Fig. 8 were simulated by choosing a multipath-to-direct signal ratio (K) of -10 dB, a shadowing standard deviation of 3 dB and by combining fading-only and fading-plus-shadowing data in a two-to-one ratio. This is illustrated in Fig. 13. The upper curve shows the distribution function under fading-only conditions, the lower curve under fading-plus-shadowing conditions and the third curve shows the combined result for 33% shadowed data. This latter curve matches closely the "suburban" curve of Fig. 8 and so one can conclude that the percentage of shadowing on this route was similar. Note that the "lognormal" part of the combined curve of Fig. 13 results from the concatenation of the two data sets, but is not present in either data set individually.

The simulated level-crossing rate and average fade-duration curves corresponding to Fig. 13 are shown in Figs. 14 and 15. These results are also very similar to the "suburban" data of Figs. 9 and 10.

Figure 16 shows the effect of changing the percentage of fading-plus-shadowing data in the simulated data set. Comparing this with Figs. 8 and 11, it can be inferred that the rural/farmland data set included about 5% of fading-plus-shadowing data. This agrees very well with the value estimated from a land-use map. Obviously, this type of correlation would not hold at higher elevation angles where the line-of-sight signal would pass over a larger percentage of shadowing obstacles. Fig. 16 is however a useful tool to evaluate the effects of shadowing. For example, if 99% area coverage is required, even 5% shadowing calls for 5 dB more signal margin than the fading-only curve.

10. CONCLUSIONS

The tests were all performed with a source at an elevation angle of about 20 degrees. The percentage of the data sets recorded under shadowed conditions has been shown to range from about 5% for the rural/farmland case to about 33% for the suburban case. The corresponding signal margins required to provide service to, for example, 99% of the test areas varies from 12 dB to 21 dB.

The data can be simulated closely by assuming the multipath signals to be Rayleigh-distributed, having a mean power 10 dB below the unattenuated direct signal. Shadowing effects can be simulated by assuming a log-normal attenuating effect for the direct signal, with a standard deviation of 3 dB and mean value of 7.5 dB.

11. ACKNOWLEDGEMENTS

The results described in this report could not have been achieved without the dedicated and unstinting efforts of M. Dufour, E. Matt and R. Yank at CRC. Colleagues in the other participating organizations also provided invaluable help: in particular J. Feneley of Teleglobe Canada and L.J. Cohen of INMARSAT.

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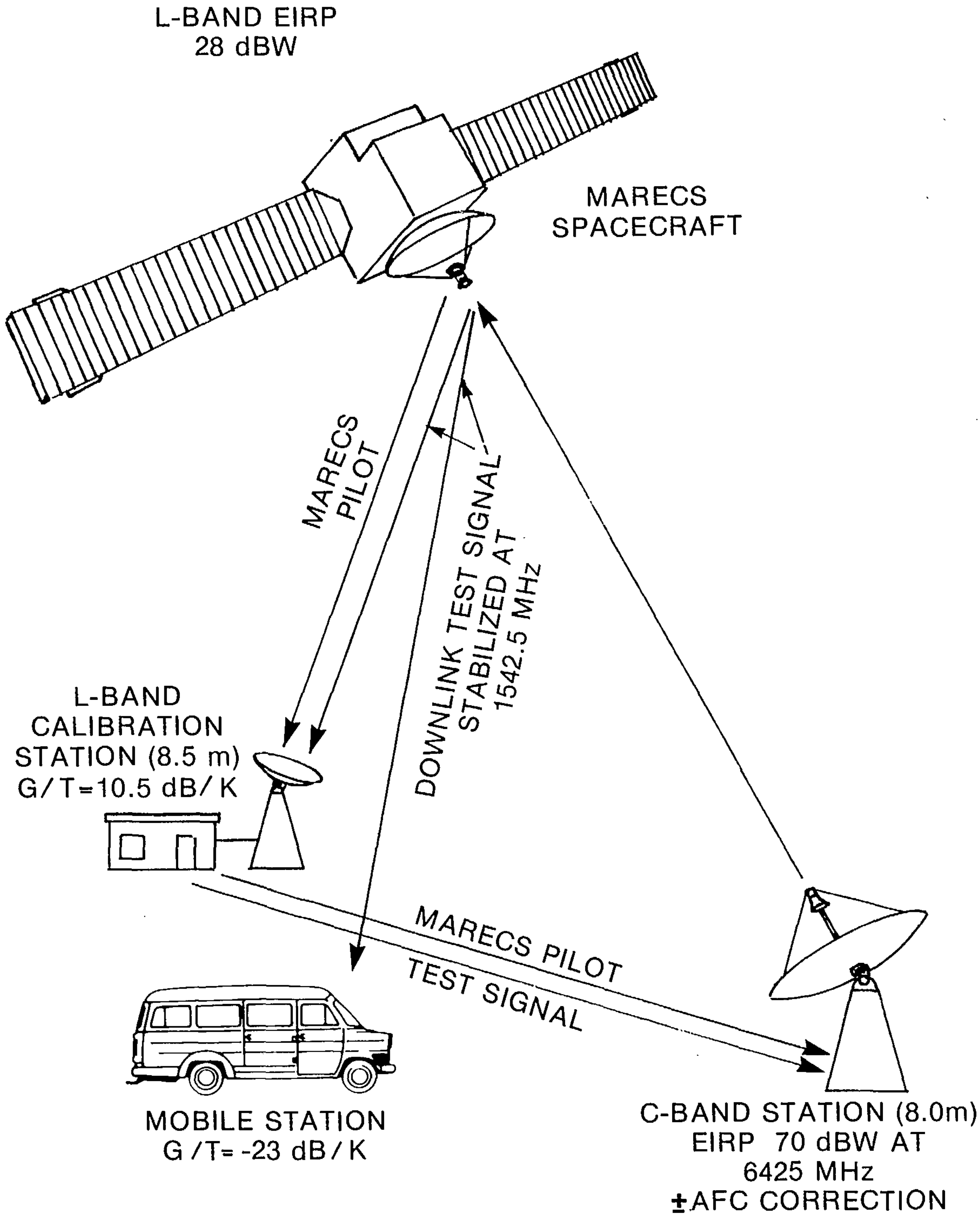


Fig. 1 System configuration for experimental measurements

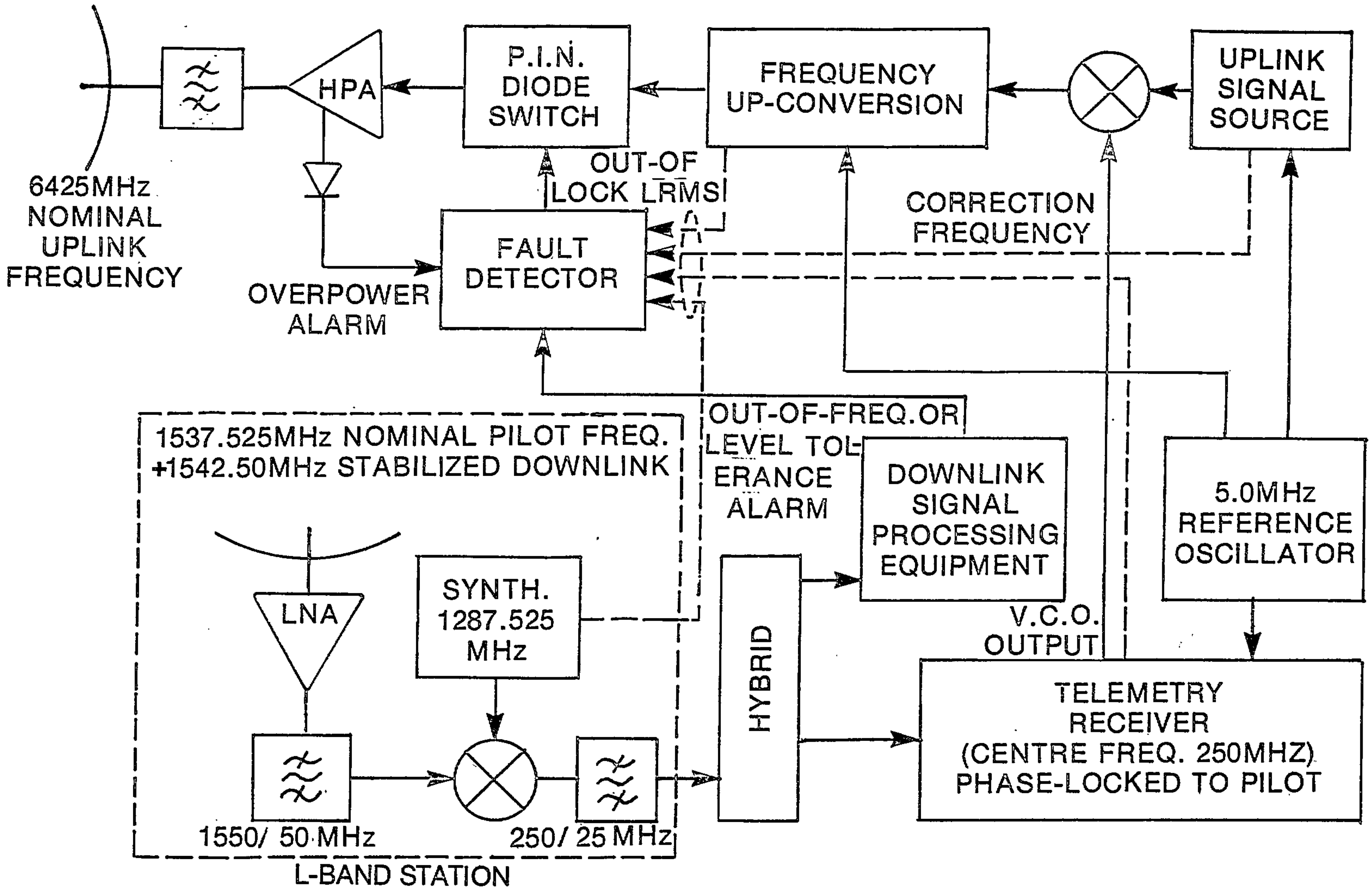


Fig. 2 Frequency stabilization and fault detection system

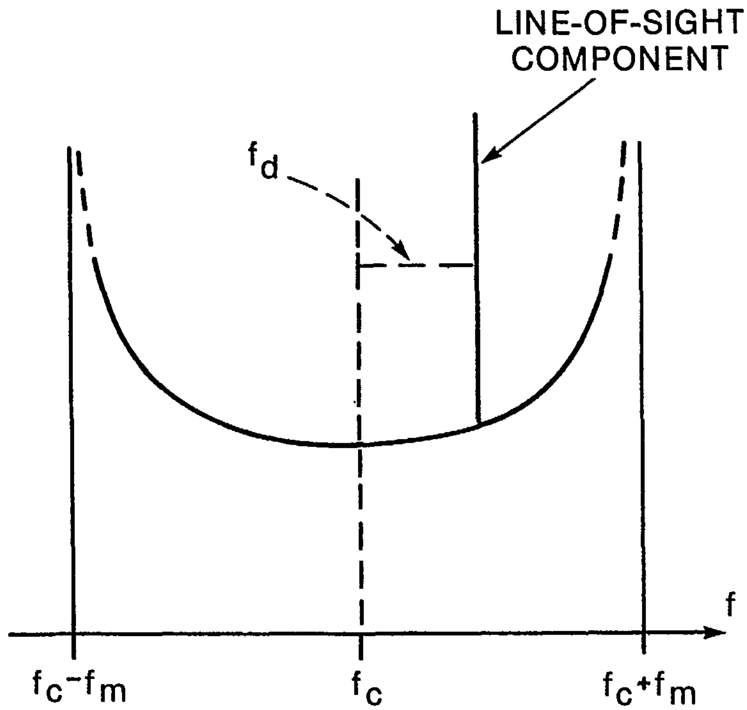


Fig. 3 Theoretical power spectrum of the multipath signals received by an omnidirectional antenna

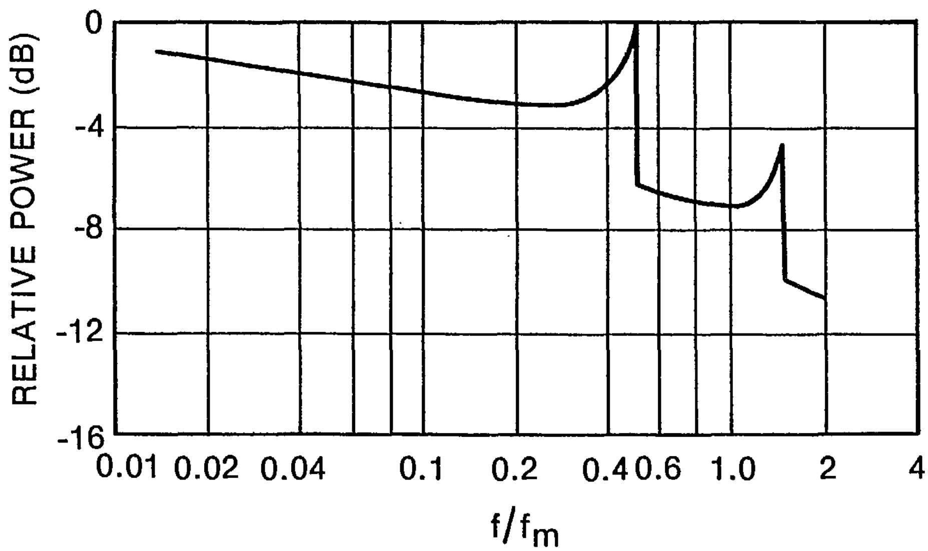


Fig. 4 Spectrum of the envelope-detected baseband signal corresponding to the RF spectrum of Fig. 3

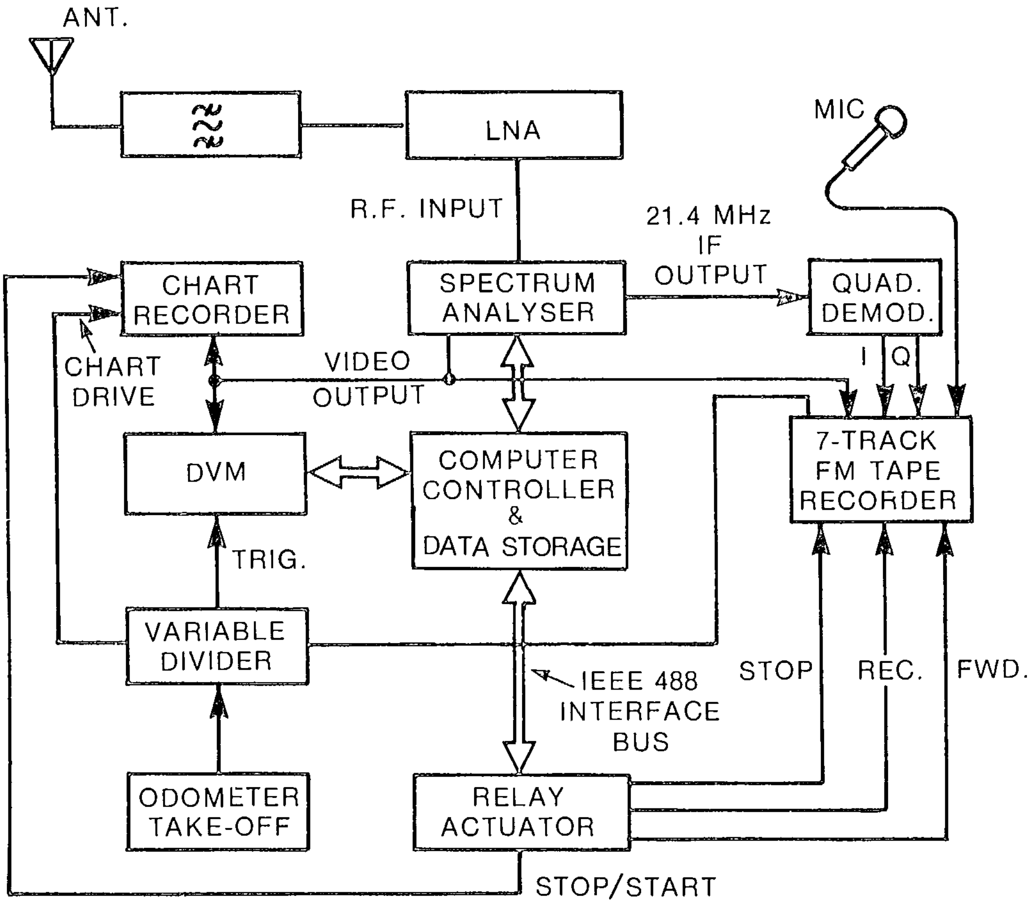


Fig. 5 Block diagram of the mobile laboratory equipment

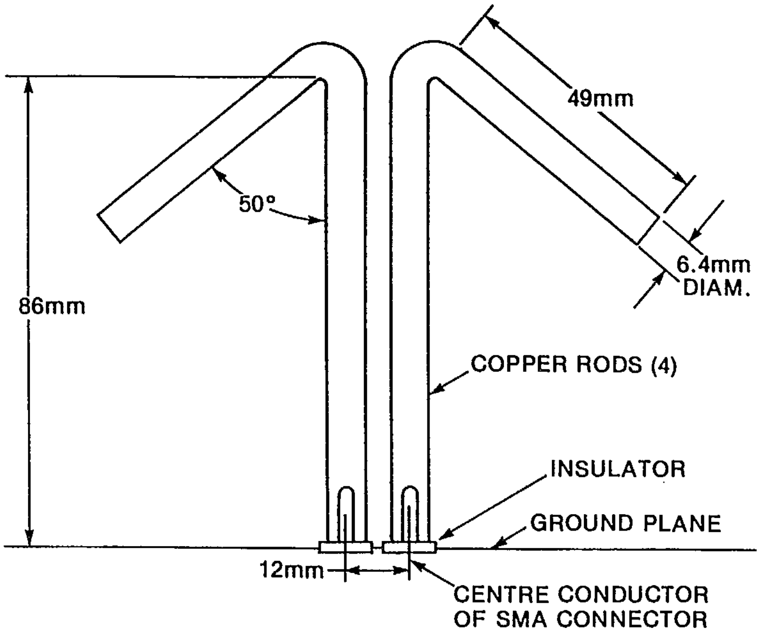


Fig. 6 Crossed-drooping-dipole antenna used for data collection (for clarity only two of the four elements are shown)

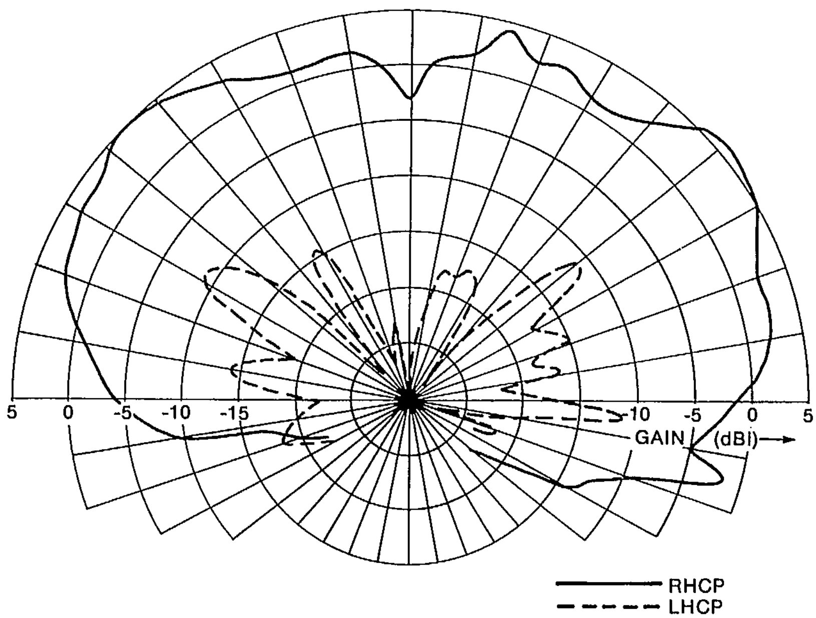


Fig. 7 Broadside elevation-plane pattern of the antenna as-mounted on the vehicle roof

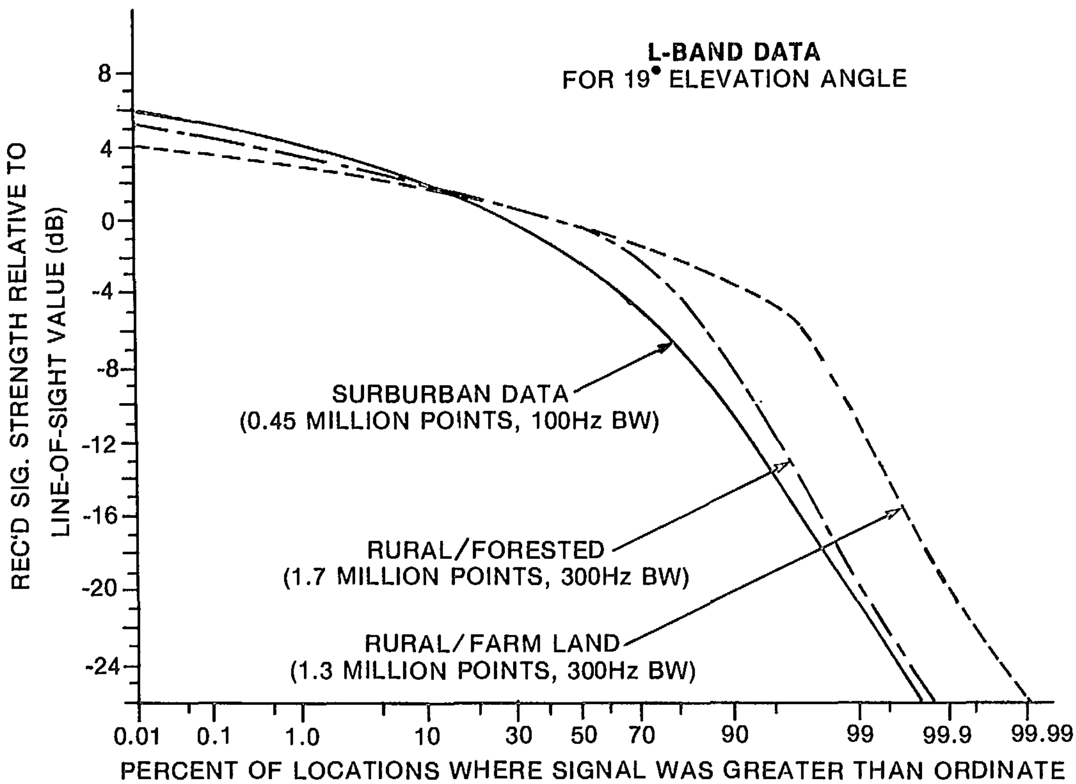


Fig. 8 Distribution functions of data recorded in November 1982

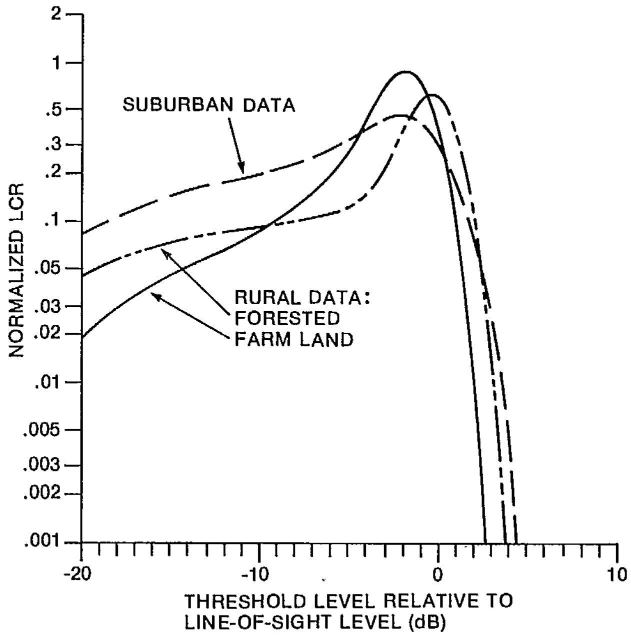


Fig. 9 Normalized level-crossing rate (number of positive crossings per wavelength travelled) for November 1982 data

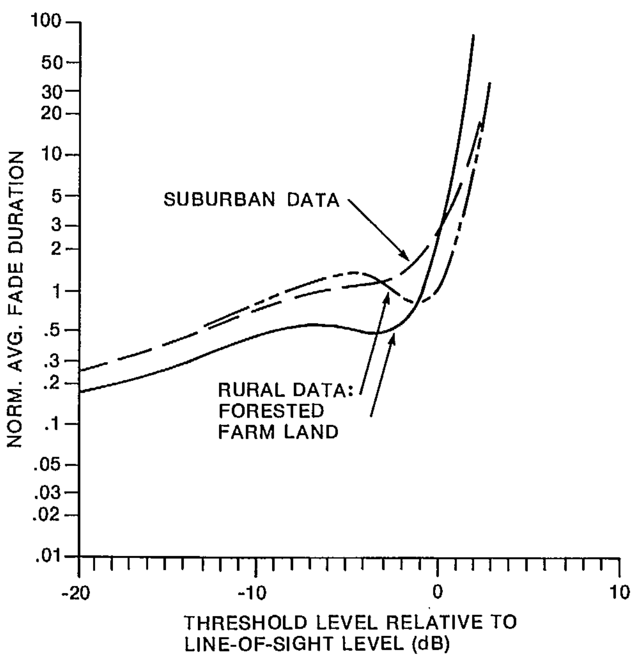


Fig. 10 Normalized average fade duration (in multiples of a wavelength travelled) for November 1982 data

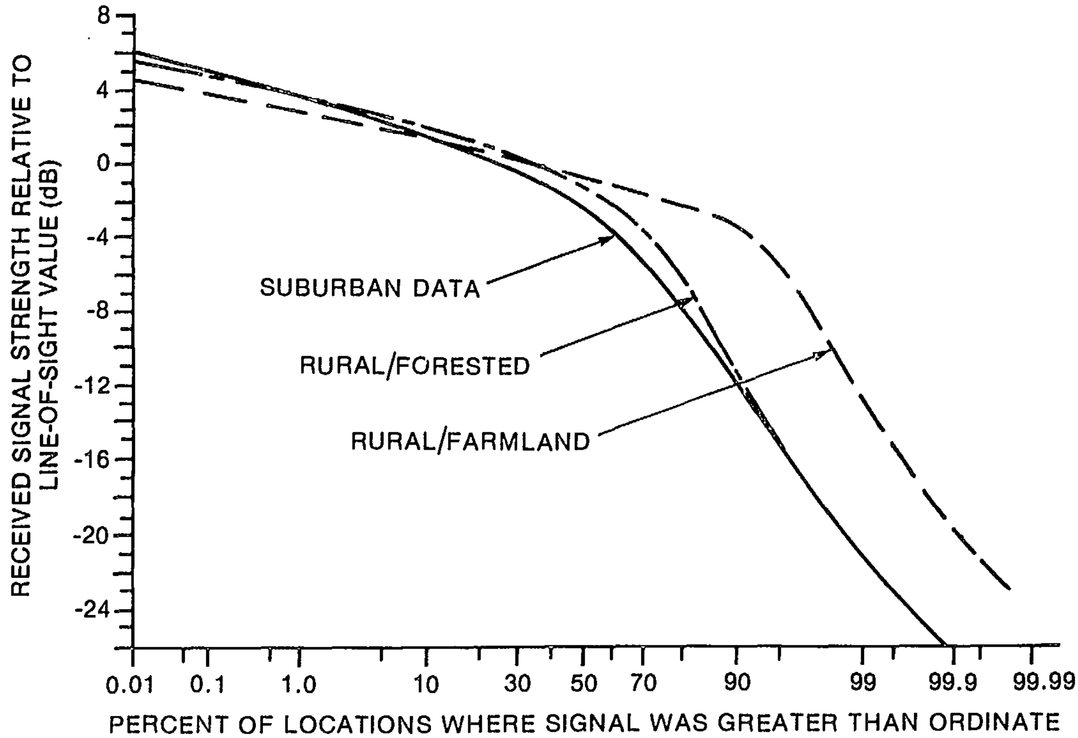


Fig. 11 Distribution functions for data recorded in June 1983

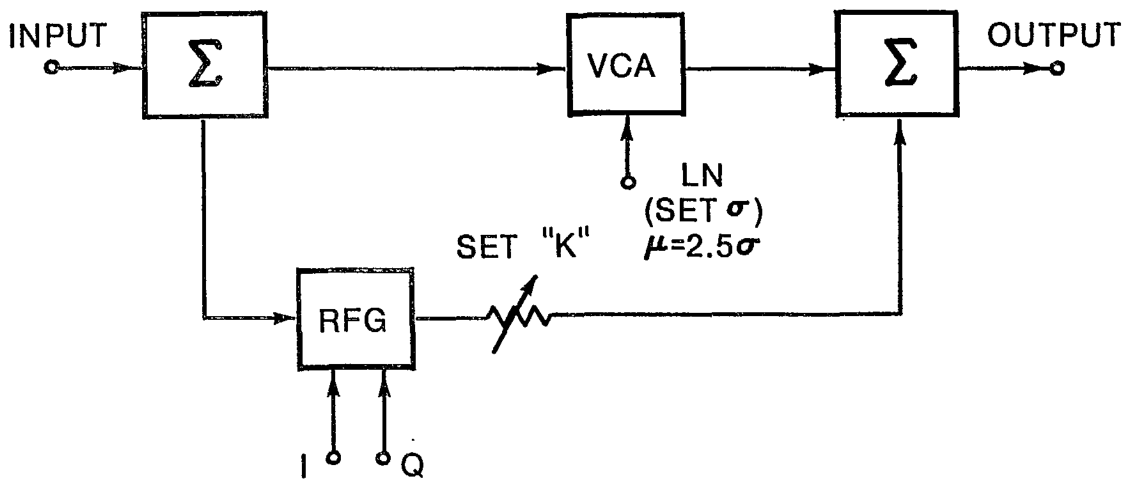


Fig. 12 Block diagram of channel simulator
RFG = Rayleigh fading generator
VCA = Voltage-controlled attenuator

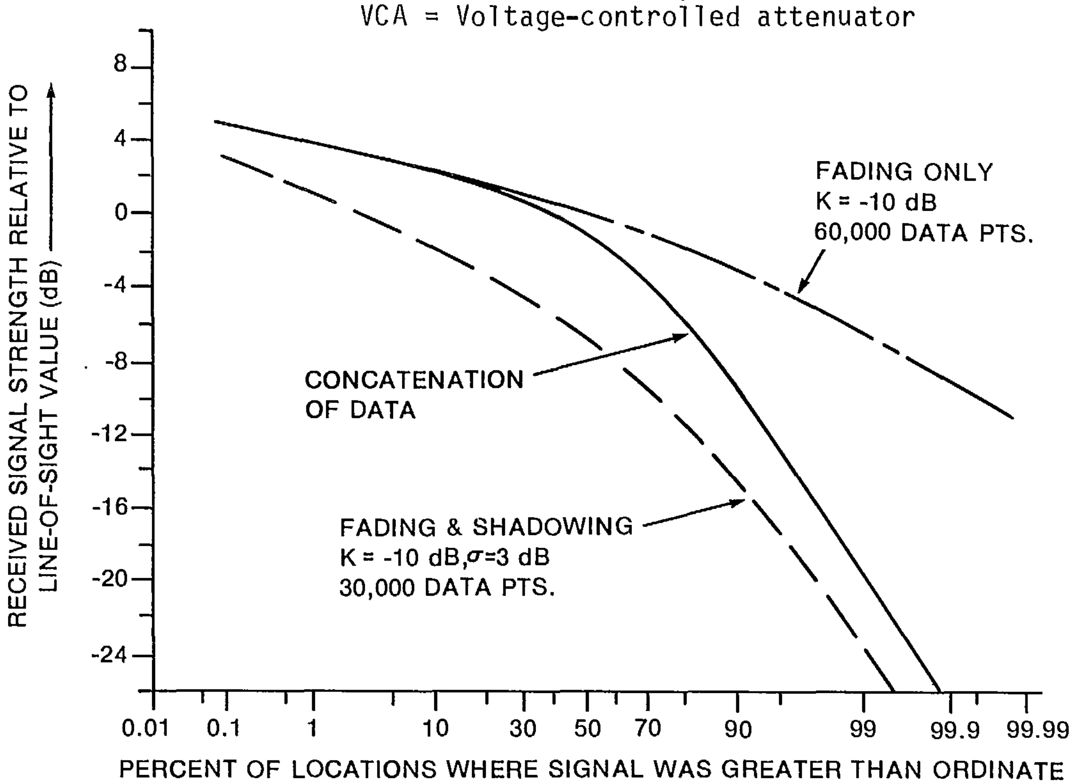


Fig. 13 Distribution functions of simulator data

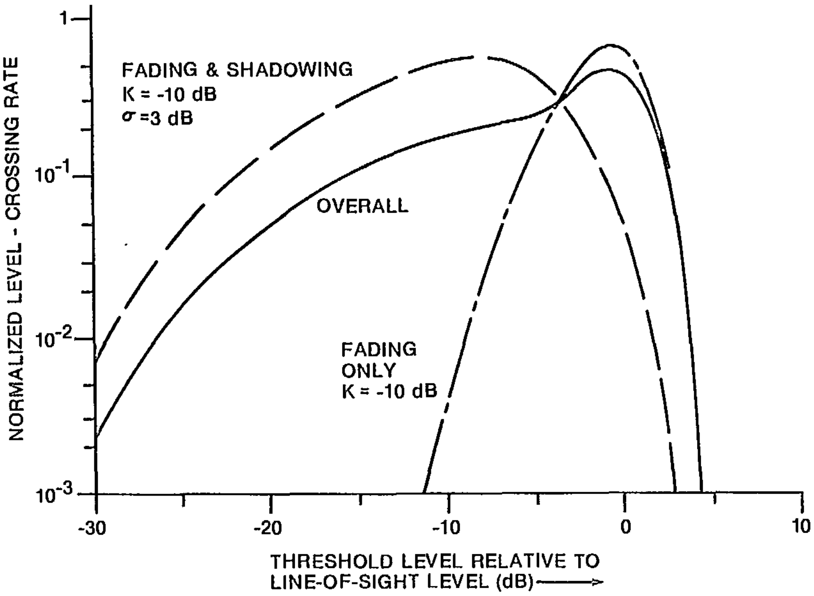


Fig. 14 Level-crossing rate of simulator data

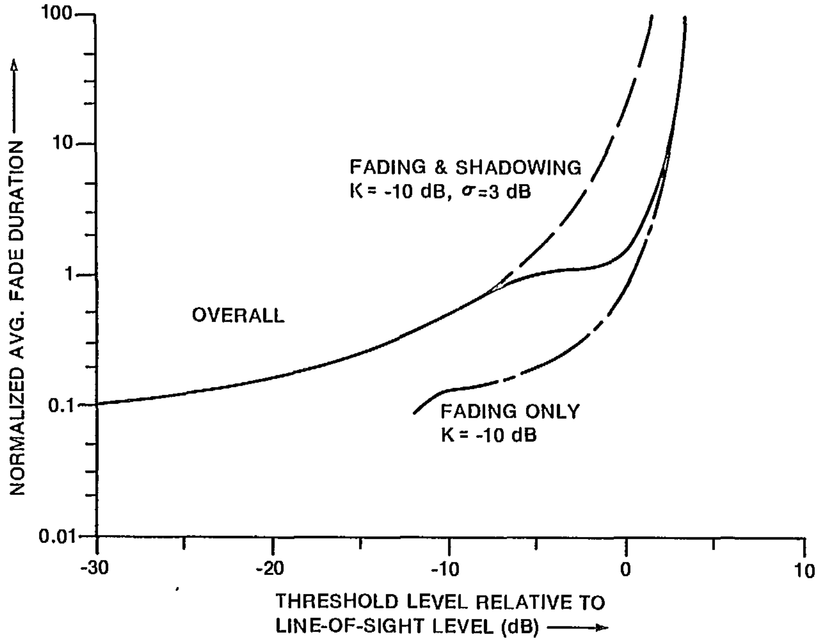


Fig. 15 Average fade duration of simulator data

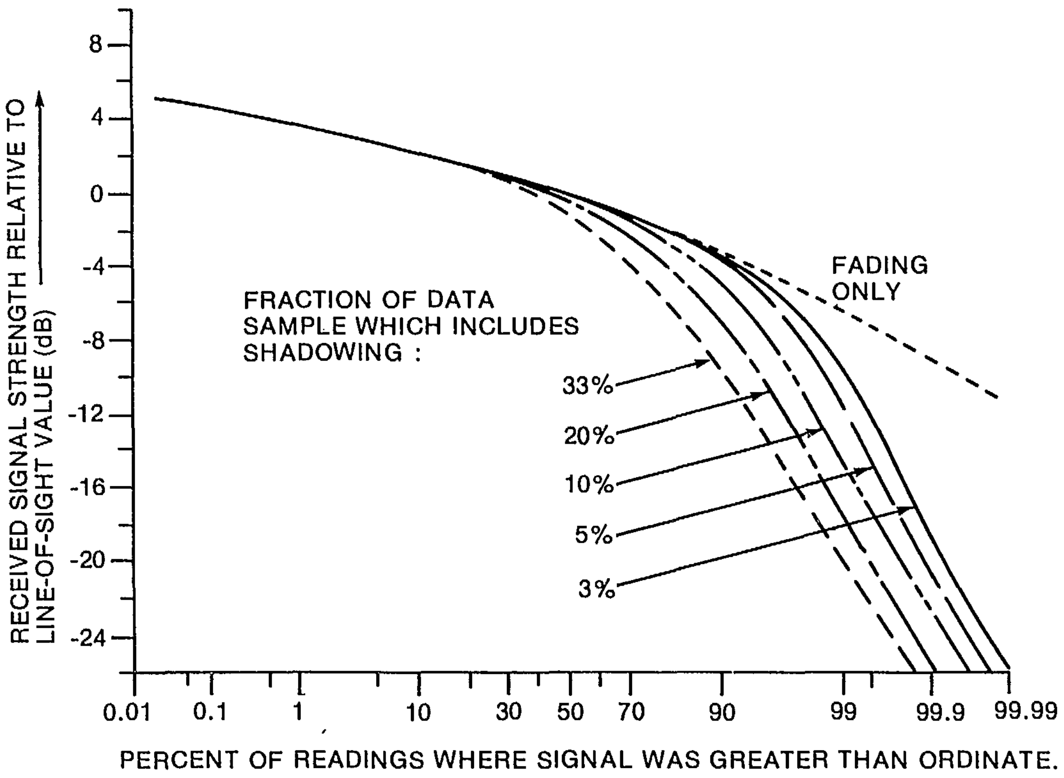


Fig. 16 Distribution functions of simulator data containing various percentages of shadowing

APPENDIX A

Description of the Data Acquisition Program

The program "SATELLITE", written in BASIC, is designed to acquire real-time digitized data from the high-speed DVM connected to the receiver video output. Data are transferred from the DVM to the computer via the IEE 488 interface bus (GPIB) for storage on a floppy disc. A GPIB-controllable relay actuator is also used to enable computer control of the instrumentation tape-recorder used for making "stored-channel" recordings.

Figure A1.1 shows a flow-chart of "SATELLITE". The program starts with the definition of variables, the assignment of input and output addresses for external equipment, a reset to zero for external equipment and a pause permitting the operator to insert an initialized floppy disc. The following steps calibrate the spectrum analyser. Generally, it has been the operator's choice to perform this calibration once only for each test period (usually about 3 hours). The calibration routine is built into the spectrum analyser and takes 1-2 minutes to complete. The necessary calibration factors are retained by the analyser and applied automatically to the measurements.

When the calibration is completed, the program passes to controland verification of the measurement equipment. The state of the spectrum analyser is set to certain default values, namely 1542.5 MHz centre-frequency, 300 Hz resolution bandwidth, 10 KHz video bandwidth and -20 dBm reference level. The file name and the amount of storage space available on the disc are verified next, then the initial information for the impending test is displayed on the computer screen. At the same time several "soft-keys" are defined which permit changes to any of the default values.

There are ten "soft-keys" which provide the operator with a great deal of flexibility in determining the flow of the program. Briefly, these functions are:

Key 0. RETURN/CONTINUE: permits a return to the analyser calibration, if desired.

Key 1. LINE-OF-SIGHT = YES/NO?: when pressed, this key permits the taking a data sample of 1000 points under unshadowed conditions.

Key 2. N-SAMPLE: permits specification of the sample size for the test. Each sample uses two bytes of storage capacity. The discs have a total capacity of 260 k bytes. It is also possible to specify sample size in terms of distance travelled, in which case the maximum distance is 3.25 km.

Key 3. ON/OFF T: permits the operator to enable or disable operation of the instrumentation tape-recorder.

Key 4. S/N : permits evaluation of the received signal-to-noise power density ratio. Moves marker to read peak signal power, then moves marker off signal to read noise power.

Key 5. FI NAME: this key can be used to set the file name.

Key 6. SETDATE: permits entry of experiment date.

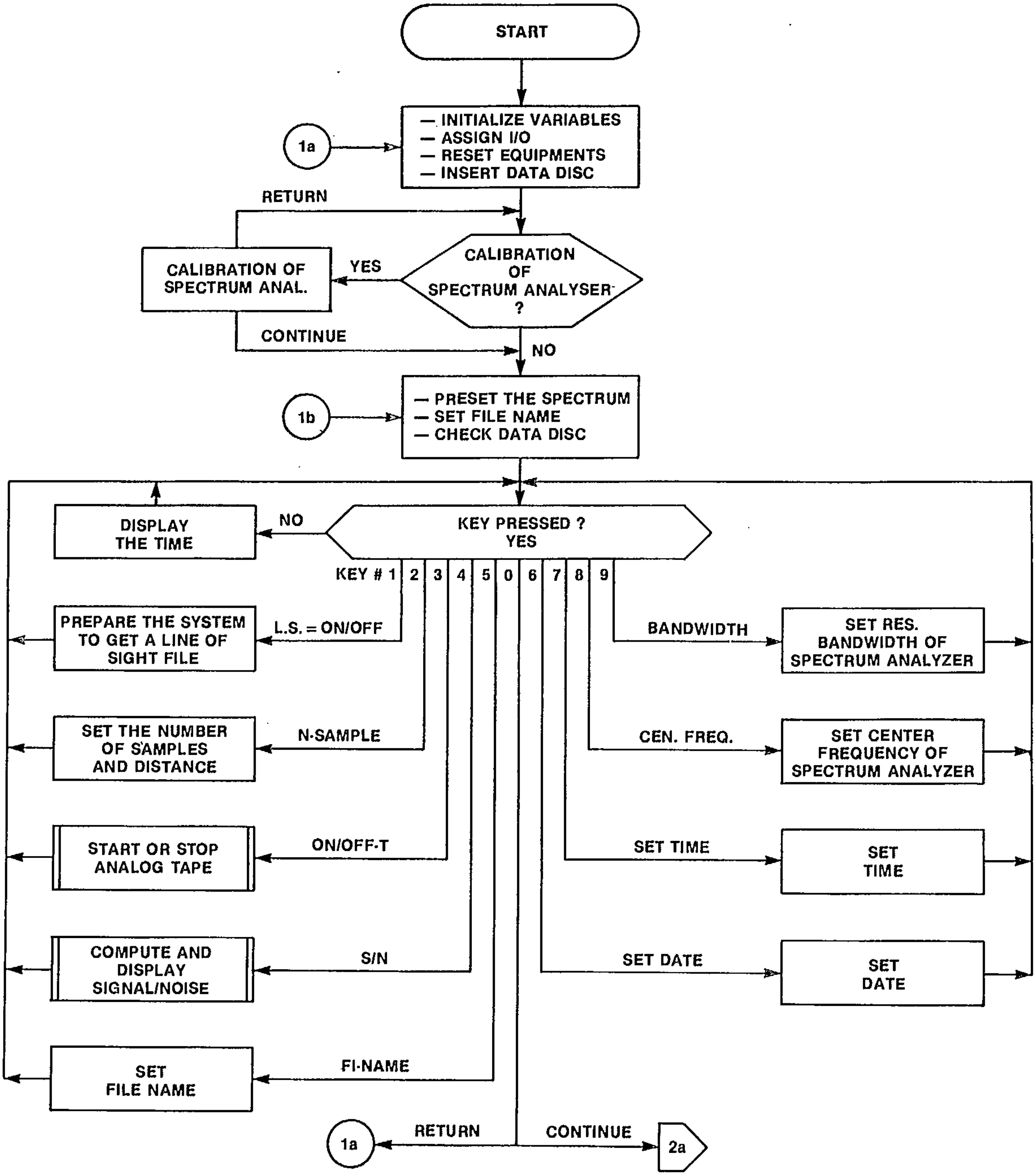
Key 7. SETTIME: permits entry of standard time (UTC).

Key 8. CEN.FREQ: permits entry of spectrum analyser centre frequency, with a default value of 1542.5 MHz.

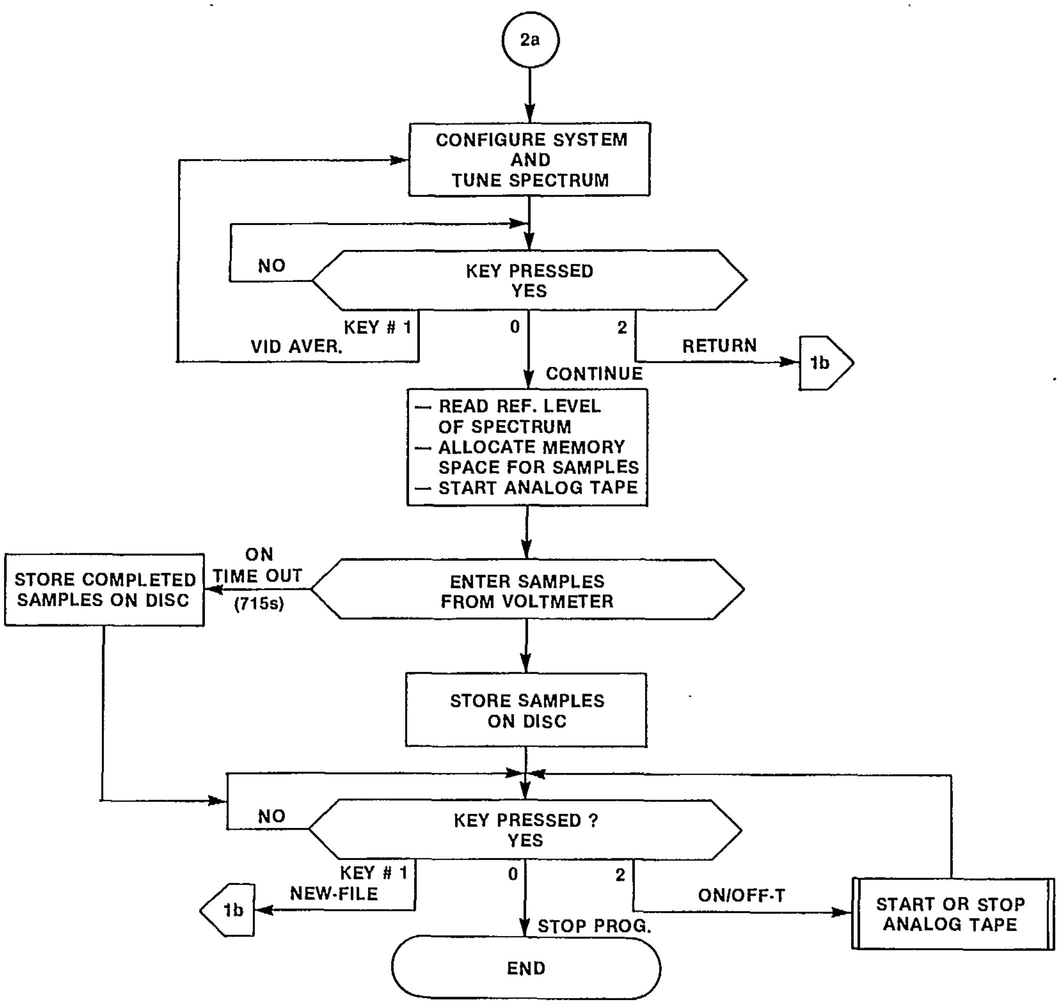
Key 9. BANDWIDTH: permits selection of spectrum analyser resolution bandwidth from the discrete values of 30,100, 300 and 1000 Hz, with a default vaue of 300 Hz.

Having selected "CONTINUE" with Key 0, the program prepares the measurement system for taking data. This consists of creating a data file to receive the sample points and of setting the equipment into the correct mode of operation. This setting includes the programming of the digital voltmeter (1 volt scale, external or internal clock, etc.) and, of particular importance, the tuning of the spectrum analyser to the precise frequency of the source signal. The video output of the spectrum analyser varies between 0 and 1.5 volts, where 1 volt corresponds to the chosen "reference level" of the analyser. The reference level is determined automatically by the program to be twice the amplitude of the mean signal level under line-of-sight conditions. The analyser is used in linear mode rather than logarithmic, because of the requirement to record the quadrature-demodulated IF output for "stored-channel" use.

Signal sampling starts by reading the selected analyser reference level, starting the instrumentation tape-recorder and reserving memory space for the data points. The maximum size of each file is 130,000 points and the data acquisition rate may vary up to a maximum of 1000 samples/second. Data transfer to disc takes place in successive blocks. There is a pause of five seconds in data acquisition each time this transfer is made. When the file is completed, the program gives access to three "soft-keys" called "STOP PRG", "NEW FILE" and "ON/OFF_T". These keys enable the operator to start a new test, terminate the session or to turn the tape-recorder on or off.



A1.1 Flow-Chart for "SATELLITE"
(continued on next page)



A1.1 (continued)

APPENDIX B

Description of the Data Analysis Program

Figure A2.1 shows a flow-chart of the program "SATPLOT". The program begins by a definition of variables and verification of the presence or absence of an external printer. In the absence of a printer, results are shown only on the internal CRT display. Pertinent information such as a list of file names on the disc in use is shown on the screen at the same time as the definition of a number of "soft-keys" which give the operator control over the flow of the program. The functions of these eight keys are:

Key 0. CONTINUE: used to start the analysis

Key 1. L SIGHT: used to calculate the median value of a signal sample taken in an unshadowed area

Key 2. SET NAME: allows operator to set file name

Key 3. PRINT: displays information on the screen

Key 4. DUMP: prints the analysis results on the external printer

Key 7. SUM: data analysis is performed file-by-file. The results are accumulated for all files when the "SUM" key is activated. Accumulation is performed after analysis of each file and the cumulated totals are stored in a file called "SUM" which includes the following data:
- median level of line-of-sight signal sample (V_R)
- total number of data points
- distribution of cumulated signal amplitudes ($P_{xt}(X)$) (grouped into class intervals of 1 dB)
- distribution of cumulated normalized level-crossing rate ($LCR_{n,xt}(X)$) (grouped into class intervals of 1 dB).

Key 8. CLR SUM: resets to zero the active memory registers containing the cumulated totals.

Key 9. RCL SUM: recalls cumulated totals etc. into the active memory registers.

When the appropriate operating conditions have been selected with the aid of these keys, the analysis is started. The data is read and the amplitude distribution of the signal sample, $P_x(X)$, the normalized level-crossing rate, $LCR_n(X)$, and the normalized average fade duration, $FD_n(X)$, are calculated. The amplitude distribution of the signal is calculated on a logarithmic (dB) scale. The scale range extends from -45 to +10 dB, where 0 dB corresponds to the median level of the signal sample taken under unshadowed conditions. The scale is divided into 56 class intervals with centres corresponding to the integers +10, +9, ...-44, -45. The 54 central classes are consequently of width 1 dB and the two extreme classes are "open" at their extreme ends. The decoded amplitude data are thus stored as vectors which are cumulated for each of the 56 class intervals.

At the same time, the program calculates the level-crossing rate for the various signal levels. To do this, each sample point is compared with its predecessor. When the difference in level is found to increase from the predecessor to the sample point under consideration, a positive level crossing has occurred for each of the class intervals between the levels of the two data points. The vectors representing each of these class intervals are then incremented by one. At the end of the analysis one thus obtains a set of vectors (one for each class interval) giving the number of positive crossings, $P_+(X)$. From this, the normalized level-crossing rate is calculated:

$$LCR_n(X) = \lambda \frac{P_+(X)}{Nd}$$

λ = signal source wavelength
N = number of data points in the sample
d = distance between data points (2.5 cm)

The normalized average fade duration can be obtained directly from the two preceding functions, $P_X(X)$ and $LCR_n(X)$. It is calculated from the relationship*:

$$FD_n(X) = \frac{F_X(X)}{LCR_n(X)} \qquad -45 < X < 10 \text{ dB}$$

Here $F_X(X)$ is the cumulative distribution function of the data, calculated by numerical integration of the density function $P_X(X)$. To perform this integration, the centre-points of the top of each bar of the relative frequency histogram are conceptually joined to form a frequency polygon. The distribution function is then obtained by numerical integration of the frequency polygon using the trapezoidal rule.

The cumulation of results from several files is relatively simple. As an example, consider two files f_1 and f_2 with statistics $P_{X1}(X)$, $P_{X2}(X)$, $LCR_{n\ X1}(X)$, $LCR_{n\ X2}(X)$, from which it is desired to calculate the statistics of a third file, f_t, formed from the union of f_1 and f_2. As already discussed, for the amplitude distribution it is only necessary to cumulate the vectors for each class-interval. For the level-crossing rate, a weighted mean must be calculated. From the definitions:

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*Lee, W.C.Y., 1982, "Mobile Communications Engineering", New York, McGraw-Hill, Section 2.8

$$LCR_n\ x_1(X) = \frac{\lambda}{d}\ \frac{P_+\ x_1(X)}{N_1}$$

$$LCR_n\ x_2(X) = \frac{\lambda}{d}\ \frac{P_{+2}\ x_2(X)}{N_2}$$

it follows that:

$$LCR_n\ xt(X) = \frac{\lambda}{d}\ \frac{P_{+,}x_1(X) + P_+\ x_2(X)}{N_1 + N_2}$$

By re-arrangement of terms, the following expression is obtained:

$$LCR_n\ xt(X) = \frac{N_1\ LCR_n\ x_1(X) + N_2\ \ LCR_n\ x_2(X)}{N_1 + N_2}$$

This last equation (extended to an indeterminate number of files) is used to obtain the level-crossing rate for the concatenated data.

Finally, the average fade duration for the union of several files is obtained from:

$$FD_n\ xt(X) = \frac{F_{xt}(X)}{LCR_{n,xt}(X)}$$

Having completed the analysis and displayed the results, the program returns control to the operator. By the use of "soft-keys" the operator can choose to end the program or continue with the analysis of new data.

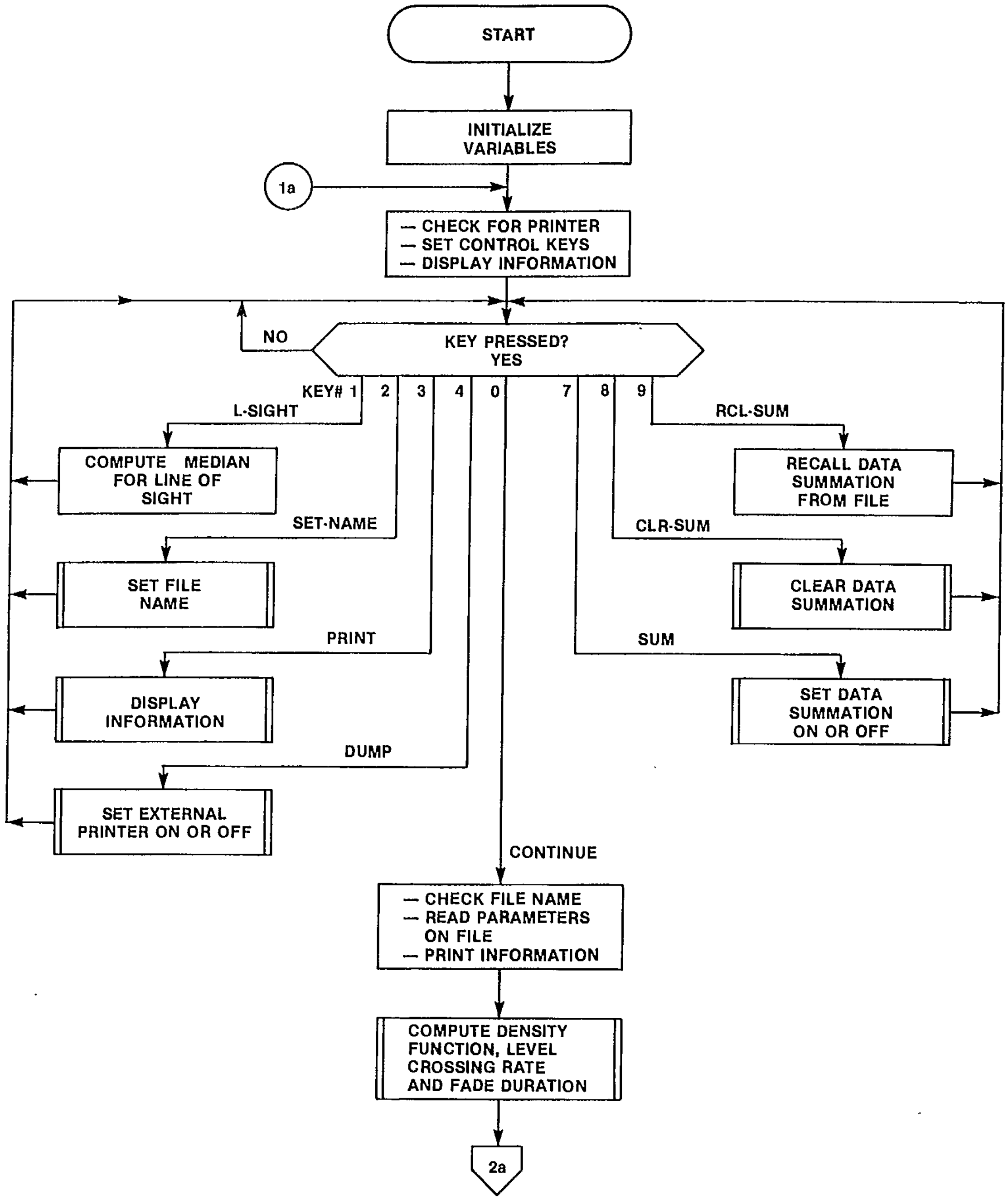

Fig. A2.1 Flow-Chart for "SATPLOT"
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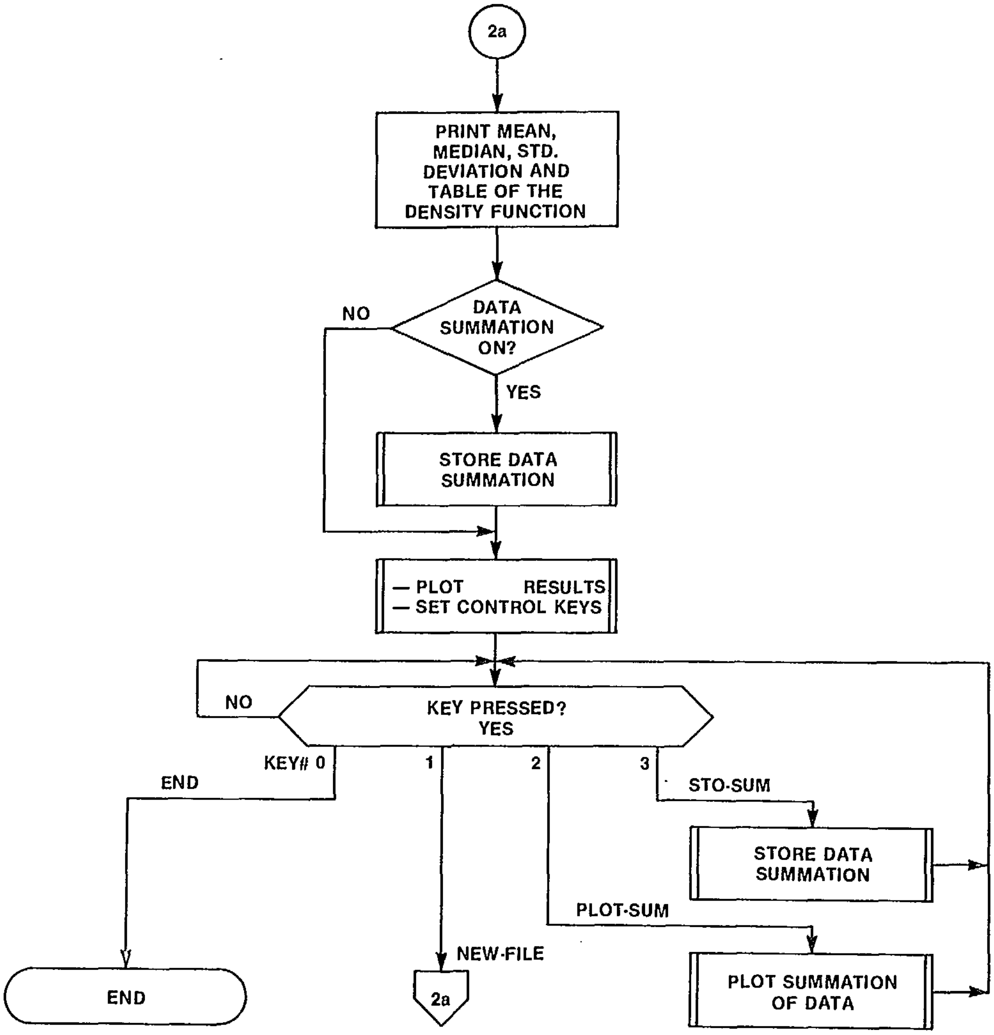

Fig. A2.1 (continued)