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UNDERWATER SOUND PROPAGATION IN THE STRAITS OF FLORIDA
THE MIMI LUNAR-CYCLE RECEPTIONS

by

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ABSTRACT

This study is part of a continuing program of underwater sound propagation research called project MIMI. The report covers reception and processing and a limited number of analytic comments. Data acquisition started on 13 December 1966 and ended 10 January 1967. The test timing and duration were chosen to allow closer examination of propagation anomalies previously observed during the early winter and to obtain continuous data on an entire lunar-tide cycle (approximately 28 days). The major objectives were to provide data for the design of more extensive experiments and to test the programs and techniques associated with the LINC-8 computer. The transmitted signal was a 63 bit pseudo-random sequence having a period of 1.2 seconds. The sequence amplitude modulated a 420 Hz carrier. The data samples were each six minutes long and were taken at two hour intervals. Signal processing was designed to yield both multipath information and data on anomalous path conditions. The principal success of the study has been in the improvement of processing programs and experiment design.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions made by the several institutions and individuals involved.

The stimulating support by the Sponsor, Acoustics Programs, Code 468 of the Office of Naval Research, made possible the present development in the MIMI Project.

The enthusiastic and skillful work by members of the Acoustics Group of the Institute of Marine Sciences (IMS), The University of Miami, and in particular by J. Loewenstein and T. Crabtree, on transmission and reception, implemented the success of the experiment.

In the organization of the Stochastic Signal Processing Program, Cooley Electronics Laboratory (CEL), The University of Michigan, the outline for the experiment and data processing were given by the project director, Dr. T. G. Birdsall; R. Veenkant and E. Tury designed the computer program; E. Tury wrote the programs and set up the equipment for photographic recording; P. Wood processed a portion of the data; R. Baker wrote Appendix C and made the final photographic runs. The IMS members mentioned above, performed the actual experiment and recorded the analog data.

The authors would like to express their special gratitude to B. Lastinger and the personnel in the CEL Reports Office for the careful processing and assemblage of the large amount of photographic results and for the drawing of the illustrations. Several drafts of the manuscript were typed by Mrs. A. Fulmer.

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1. INTRODUCTION

A study of underwater sound propagation in the Straits of Florida and its relation to environmental circumstances, project "MIMI," is a joint effort by the Acoustics Group, Institute of Marine Sciences (IMS), The University of Miami, and the Stochastic Signal Processing Program, Cooley Electronics Laboratory (CEL), The University of Michigan. Experimental results are reported in publications of IMS and CEL, and in articles in the Journal of the Acoustical Society of America (Ref. 1), and at U. S. Navy Symposia on Underwater Acoustics (Ref. 2).

Most of the experiments use a 420-Hz continuous wave transmission (CW) from a sound source off Miami (MIMI-A), and phase-coherent on-line demodulation (PCD) of the signals received by deep and shallow hydrophones off Bimini, Bahamas (MIMI-B). Environmental measurements are correlated with the amplitude and phase of the demodulated signal. The CW transmission power is approximately 95 dbμb referenced to one meter. The expanse of the Straits is 43 nautical miles; the maximum depth is 800 meters.

The long term CW experiments are occasionally combined with transmission of a maximal pseudo-random sequence (SEQ) modulating the 420-Hz carrier to resolve the multipath propagation. While the instrumentation of all tests and the processing of the long

term CW experiments are done by the IMS Acoustics Group, the signal design and data processing of combined CW/SEQ tests are done by CEL (MIMI-C), using correlation techniques on a digital computer. Two previous reports describe the MIMI experiments of 3 and 4 February 1965 (Ref. 3) and of 11, 12, and 13 August 1966 (Ref. 4).

The LUNAR experiment of December 1966 covered a whole month, using periodic amplitude modulated sequence (AMSEQ) transmission.[1] The AMSEQ signal allows the simultaneous analysis of carrier power and phase, and multipath. The experiment covered the four weeks 13 December 1966 to 10 January 1967 during which 6 minute intervals of reception were recorded every 2 hours.

This month was chosen for several reasons. A full month of transmission would encompass an entire lunar cycle. It is known that the tide affects the propagation. Hence, the results of this transmission would enable a better study of this phenomenon. Also, the dynamic weather conditions in December are quite interesting. The winter's first storms and cold fronts change the structure of the channel, thereby altering the propagation paths.

MIMI-A has two LINC-8 digital computers built by Digital

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[1] Appendix A discusses AMSEQ.

Equipment Corporation to be used as on-line processors. CEL has a similar computer and the responsibility of developing on-line processing techniques. This report describes the first complete processing system of the standard Bimini sequence reception on the LINC-8 digital computer. The algorithm used in this system is basically the same as the one described in Refs. 3 and 4. The purpose of this report is twofold. First, it is a presentation of data from December '66. Second, it is a demonstration of the feasibility of a rather complex processing system on this small computer. The system described in this report is not intended to be used at the receiving site. However, it demonstrates feasibility, sets some guidelines, and demonstrates some of the difficulties inherent in an automatic receiver.

2. LUNAR PROCESSING HARDWARE

The organization of the equipment used in processing the lunar data is shown in Fig. 1.

The analog tape unit, the phase-locked oscillator, and the LINC-8 computer are the heart of the processing system. One channel of the analog tape contains the 1680 Hz reference signal which is used as the input to the phase-locked oscillator. This oscillator then generates a coherent 1680 Hz square wave which the computer uses as a sampling clock for one of its A/D converter channels. The phase-locked oscillator output, rather than the signal directly from the tape, is used for the sampling clock because it is noise free, coherent, and present even when tape dropouts cause the taped signal to disappear. The A/D channel samples the data at the coherent 1680 Hz rate, which is four times the 420 Hz carrier frequency of the data.

The peripheral hardware functions are:

Bandpass filter: Removes noise that the tape recorder has introduced into the data channel. f = 420 ± 100 Hz.

Phaselock Monitor: Provides a visual picture of the phase locking process by adding the

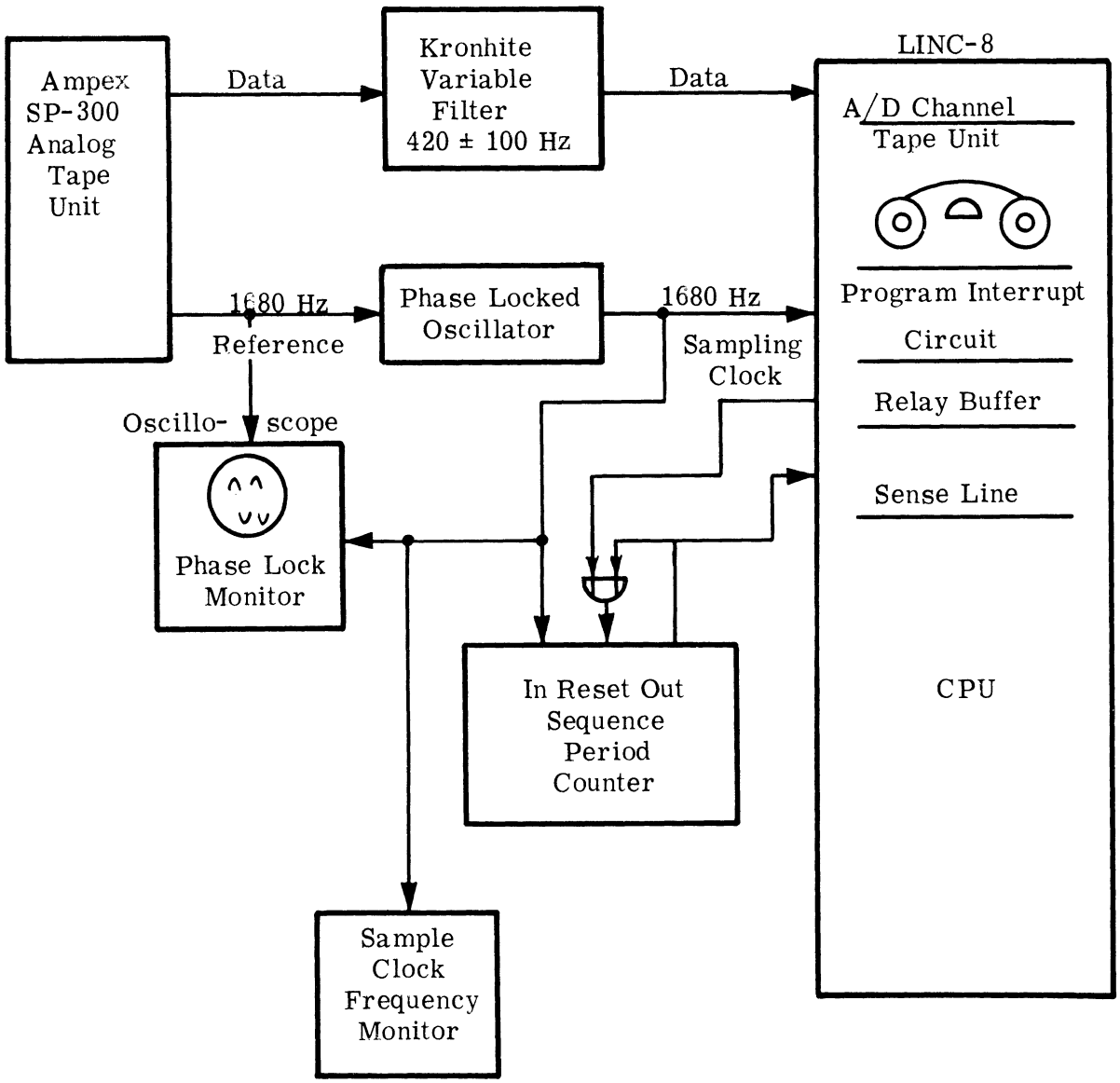


Fig. 1. Off-line processing equipment configuration

	phase-locked oscillator's input to its output and displaying this waveform on an oscilloscope.
Frequency Counter:	Provides a check on reference signal frequency (i.e., the tape speed) and also the free-running output of the phase-locked oscillator.
Sequence Period Counter:	Maintains processing coherency during tape writing by delivering sense pulses to the LINC once each period. The program waits for this pulse after each tape writing operation before it resumes processing.
Program Interrupt Circuitry (PI):	A pulse to this LINC circuit interrupts the computing and results in an immediate sampling of the analog signal (within 3 μsec).

3. GENERAL DESCRIPTION OF THE LUNAR PROCESSOR

The original discussion of the lunar processing scheme is contained in Refs. 3 and 4. Therefore, only a diagram of the present algorithm and a brief outline of its subprograms is presented here (Fig. 2).

DISPATCH loads the two programs needed for the real time processing (CALTONE and PROCESSO), and controls the operating sequence of the various programs.

The six minute intervals of analog recording are called files. Each file begins with a precisely timed calibration tone. CALTONE maintains processing coherency between files by using magnitude and phase information of the calibration signal. Coherency is achieved by starting PROCESSO at the same time (relative to the calibration tone) in each file. CALTONE determines the necessary information by computing the average amplitude values of the sine and cosine components of the signal. These values, called X_{AV} and Y_{AV}, are saved and later recorded. The received signal is described by

$$\begin{aligned} r(t) &= R(t) \cos (\omega_0 t - \theta(t)) \\ &= x(t) \cos \omega_0 t + y(t) \sin \omega_0 t \end{aligned}$$

CMPRESS samples the data once every 90^o of the carrier

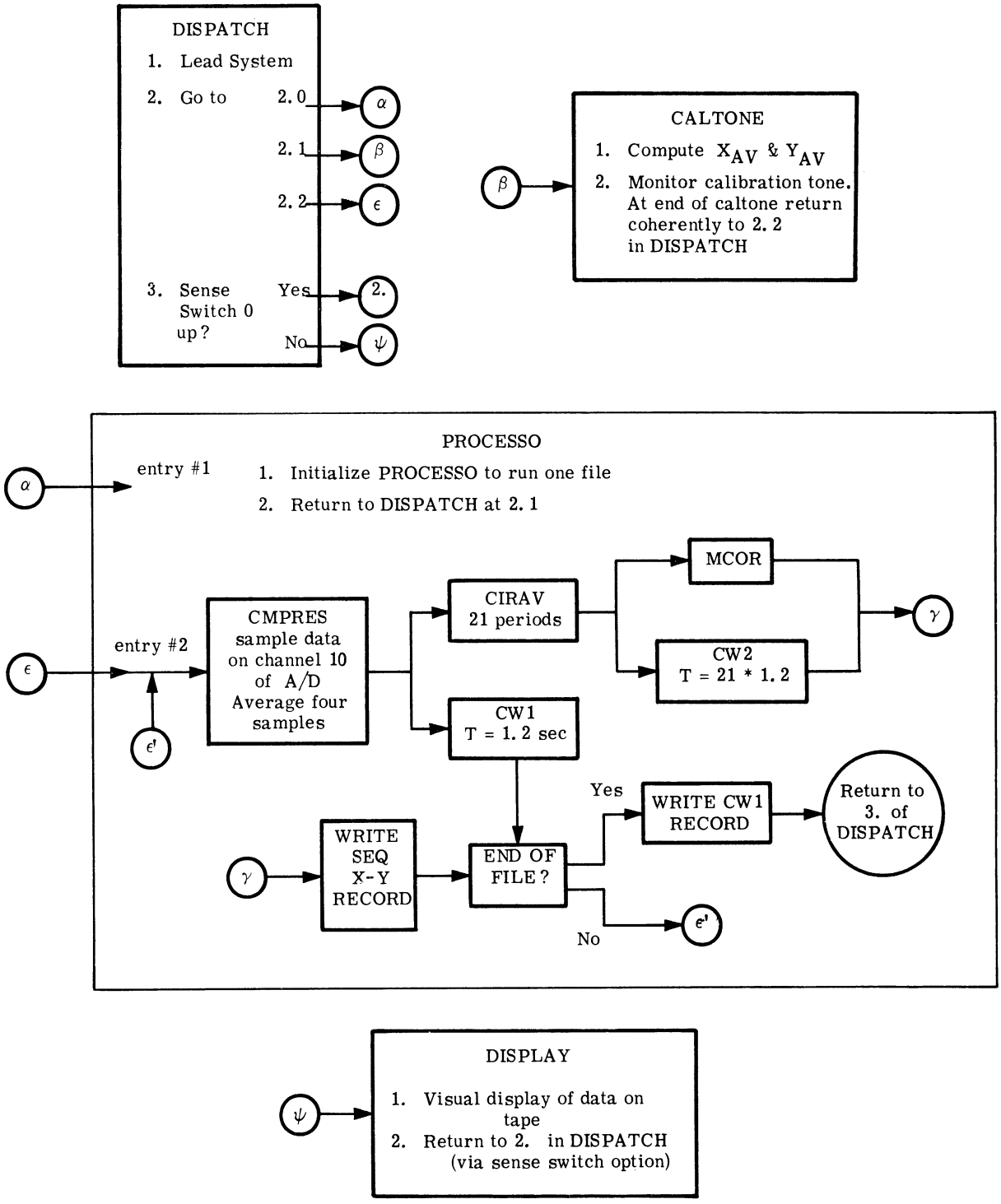


Fig. 2. Program system of lunar processor

and averages four samples to obtain one value. This process is a phase-coherent digital demodulation of r(t) into the low pass Cartesian components x(t) and y(t). For simplicity one pair of values [x(t), y(t)] is called a single "complex" value, z. In addition to demodulating, CMPRESS reduces the quantity of data by a factor of four. (For a more complete explanation, see Ref. 3.)

Two CW analyses are performed. The first, CW1, is a 1.2 second integrate and dump, or, equivalently, a 1.2 second filter matched to CW. The process is described by

$$X_{CW_1}(n) = \int_{1.2n}^{1.2(n+1)} x(t)\, dt$$

and

$$n = 0, 1, \ldots, N$$

$$Y_{CW_1}(n) = \int_{1.2n}^{1.2(n+1)} y(t)\, dt$$

Since the process is digital, the integral is a sum over the 252 samples in the 1.2 second time interval. This summation returns one complex value per sequence period.

The second CW analysis, CW2 (which uses CIRAV), is the same as CW1 except for the averaging time. CW2 averages over 25.2 seconds rather than 1.2 seconds and returns one complex value per 21 sequence periods.

The sequence analysis is performed by CIRAV and MCOR. CIRAV is a circulating average process which returns one "representative" period from twenty-one actual periods of sequence. This process is described by

$$z'(I) = \sum_{n=0}^{20} z(I + n252) \qquad I = 1, 2, \ldots, 252$$

MCOR performs a 1.2 second cross-correlation of the "representative" period with a stored reference (called BMSEQ), to obtain the multipath analysis. A complete discussion can be found in Ref. 3.

DISPLAY is an operator-called display program which is used to view the output of the processing. This program may be called at the end of each file, but if it is, the analog tape must be restarted at the correct place to resume the processing. This routine is not normally used since it requires operator control.

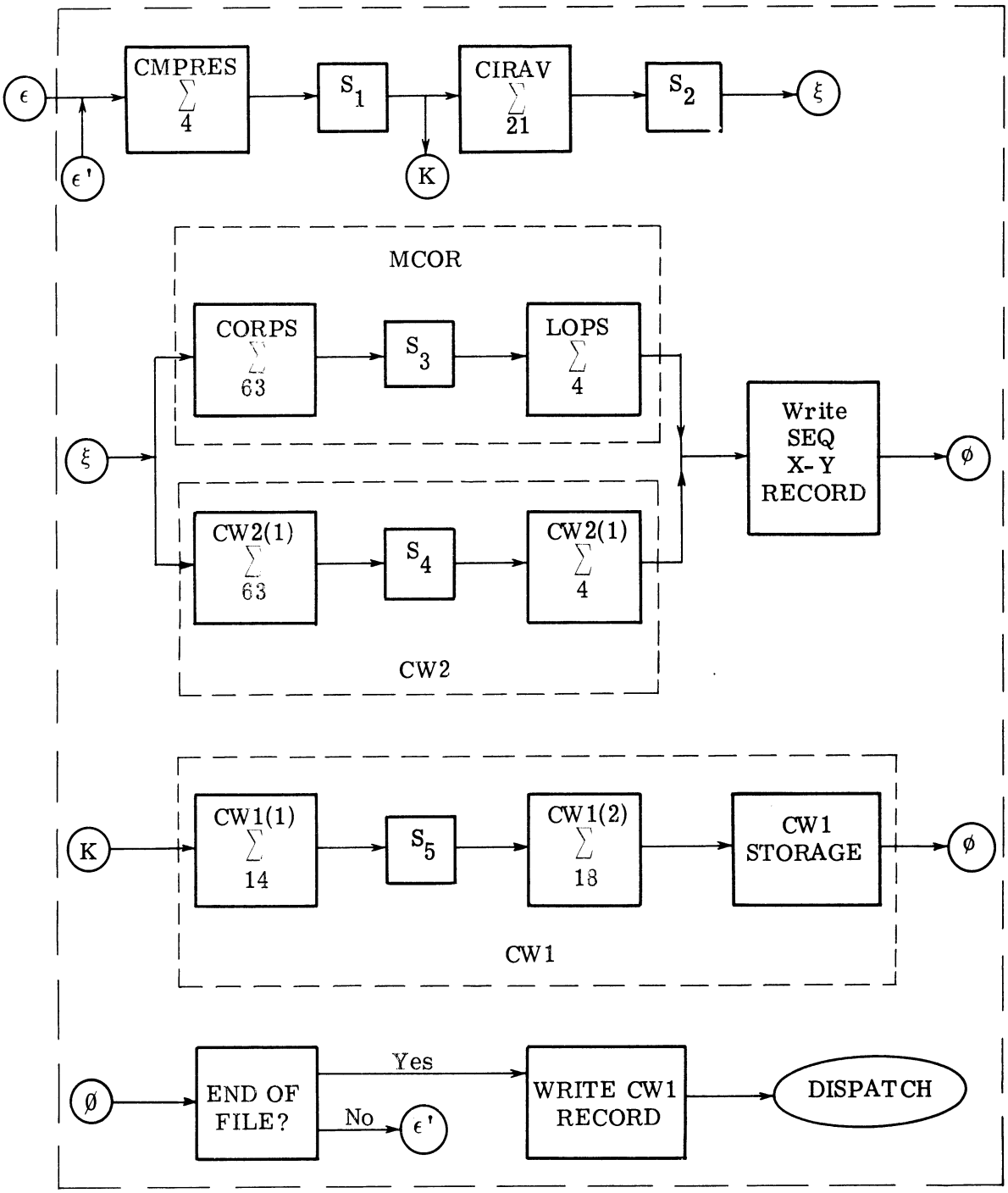
3.1 Scaling

Since the arithmetic in the processing is performed in twelve bit integer mode, special care is taken to prevent overflow. Overflow is prevented by scaling the data at convenient points in the processor. Floating point arithmetic would also solve this problem. However, it is not feasible due to storage and execution time considerations. The scaling is always done by powers of two so that it

may be achieved by simply shifting the binary data to the right. The box, $x \longrightarrow \boxed{S_i} \longrightarrow x'$, in the diagram denotes the scaling operation; e.g., suppose the scale factor is $k = 2^{-S_i}$, then $x' = x \cdot 2^{-S_i}$; x is actually shifted right S_i binary positions. Any bits shifted out of the least significant position are lost. The diagram indicates those scale factors which are variable (computed) and the values of the predetermined scale factors.

Since shifting obviously affects accuracy, it is performed only when absolutely necessary, and then, just enough to prevent overflow before the next scaling point. S_2 , the shifting parameter on the output of CIRAV is computed in the program because of the large fluctuation in the output of CORPS over long periods of time. S_3 and S_4 are both chosen equal to $6 - S_2$ to maintain constant open loop scaling. This choice compensates for the actual value of S_2 , which may change from record to record, simplifying interpretation of the output amplitude over many records.

Each of the routines, MCOR, CW2, and CW1, has been decomposed into a pair of subroutines. Before further discussion the notation, $\sum_n$, in the boxes of Fig. 3 will be defined. $\sum_n$ signifies that n input values will be added to obtain an output number. The scaling operator can be looked at as a normalizing constant on the input of each summation. The value of S_i is usually closely related to the value of n on the summation associated with S_i . However,



$S_1 = 4$

$0 \leq S_2 \leq 6$

$S_3 = S_4 = 6 - S_2$

$S_5 = 3$

These are the ranges or values which the scale factors in PROCESSO can have.

Fig. 3. Detailed breakdown of the PROCESSO portion of the complete processing program

nothing is implied about how the input or output values are indexed. The reasons for the choice of separation of the functions at the particular points differs from the different functions. The locations of S_4 and S_5 in CW2 and CW1, although somewhat arbitrary, were controlled by the necessity of scaling. The decomposition of MCOR was controlled by the fact that MCOR can be interpreted nicely as a two step process, (1) correlation, and (2) low pass filtering. The first part, CORPS, performs a wideband correlation; the ouput numbers are called CORrelation Partial Sums. The second part averages the partial sums and is called LOPS for LOw Pass Summation.

A detailed discussion of the tape output and format is in the section titled Output from PROCESSO (Section 3.3).

3.2 Description of CALTONE

The analog tape contains data in 6 minute intervals, called file. Each file consists of approximately 39 seconds of calibration signal followed by 5 minutes and 21 seconds of AMSEQ data.

The program CALTONE uses the calibration signal to perform two operations. It computes a magnitude reference for the CW data, and it maintains time and phase coherency between files.

The average value of the two orthogonal signal components are computed and are called X_{AV} and Y_{AV}. It is assumed that the input signal at this time is the calibration tone, and, thus, X_{AV} and

Y_{AV} represent this signal. These two numbers are recorded in all of the output records, both SEQ and CW , of this file. The end of the calibration signal is precisely timed at recording and is followed by approximately 40 milliseconds of silence. The end of the signal is detected by monitoring magnitude and comparing it to $R_{AV} = [X^2_{AV} + Y^2_{AV}]^{1/2}$. Specifically, CALTONE computes R_{inst} (instantaneous) until four successive values of R_{inst} are less than $R_{AV}/2$. When this inequality has been satisfied ($R_{inst} < R/2$) coherency has been attained to within 0, 1, 2, or 3 sample values. This remaining error is due to the fact that R_{inst} required four samples. By using the phase information available in X_{AV} and Y_{AV} , CALTONE computes the necessary delay (0, 1, 2, or 3 samples) to achieve full coherency. After the delay CALTONE has completed its work for one file, and data processing begins. Processing continues for six minutes. At this point a new file begins and CALTONE runs again. Hereafter, the two numbers from CALTONE will be referred to as X_{AV} and Y_{AV} .

3.3 Output from PROCESSO

The major portion of the output from PROCESSO is the X;Y record from MCOR and CW2. This output represents the analysis of 21 sequence periods or 25.2 seconds of data. The X data and the Y data are written onto tape in consecutive blocks. Each block of data is formatted as shown in Fig. 4.

x_1	- - -	x_i	- - -	x_{252}	0	x_{CW2}	0	x_{AV}

X Block (256 values)

y_1	- - -	y_i	- - -	y_{252}	0	y_{CW2}	0	y_{AV}

Y Block (256 values)

Fig. 4. X-Y record from MCOR

Following the 12 X-Y records from MCOR and CW2, is an X-Y record from CW1. Each data point, (X, Y), represents one sequence period or 1.2 seconds. The CW1 data is processed concurrently with the MCOR data. However, the CW1 output is delayed until all the data is available. The CW1 data block is pictured in Fig. 5.

X_1 word 1	- - -	X_{246} word	X_{AV} word 247	- - -	X_{AV} word 256

X - CW1 represents
4.92 minutes

Fig. 5. CW1 X block format

The last 10 samples are filled with the X_{AV} value from CALTONE. The CW1 Y block has the same format as the X block. The last 7.2 second portion of CW1 data is ignored.

A summary and a few added details complete the discussions. One output file--given one file of input--is shown in Fig. 6.

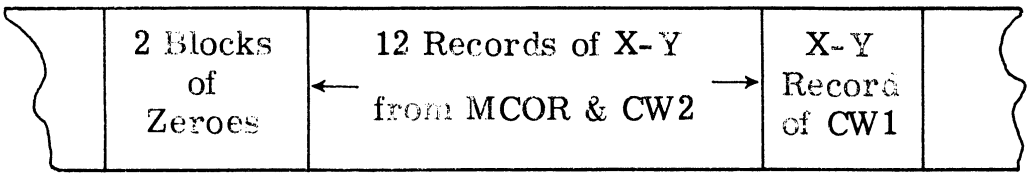


Fig. 6. Output file format

The two zero blocks each serve a purpose. The first identifies the beginning of an output file, while the second contains alphanumeric information pertinent to the file. Eighteen such files are contained on a LINC tape. This represents one hour and forty-eight minutes of processing. Since a six-minute input file was recorded every two hours, the tape represents a thirty-six hour real time interval.

4. DESCRIPTION OF RICKY POST-PROCESSOR

RICKY performs the following computations and operations on the output tape of PROCESSOR:

1. Search the current file (12 records) of MCOR data for the maximum value of $R = x^2 + y^2$. Call this value RMAX.

2. Compute $K = 250.0/RMAX$

3. For each MCOR record in this file

   3.1 Read the current record and multiply the data by K.

   3.2 Compute and save the values of

$$BBPWR = \sqrt{\sum_{1}^{252} (x_i^2 + y_i^2)}$$

$$CW2 = \sqrt{X^2_{CW2} + Y^2_{CW2}}$$

   3.3 Write the scaled record back onto tape replacing the input data.

4. After step 3 is performed for all MCOR records, print the file number, FN = " ", the scale factor, K = " ", and the calibration signal magnitude, CAL = " ".

5. Normalize the CW1 record so that the magnitude of the calibration tone equals 250.

6. If an entire tape has been processed, halt. Otherwise return to step 1 and repeat.

Each block of data from RICKY has the format shown in Fig. 7.

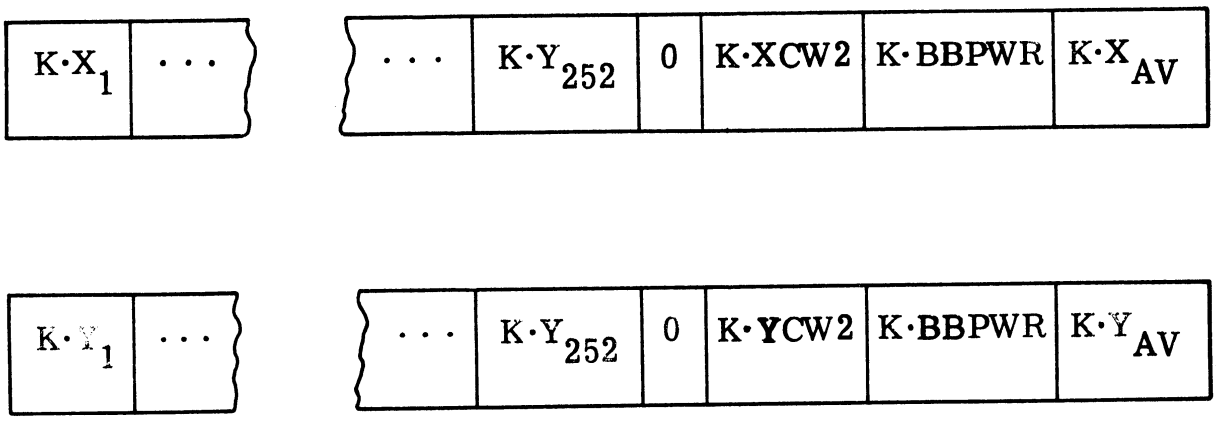


Fig. 7. RICKY output format

The variables BBPWR and CW in step 3.2 are the square root of the power in the broadband and narrowband about the carrier.

The purpose of scaling the data and performing the slight reorganization of the output is for ease of viewing and to make optimal use of the scope display in photography.

5. PHOTOGRAPHIC RECORDING OF THE RESULTS

The results of the CW1 and sequence analyses were photographed using an automatic system. Each file of data was summarized by a code frame, by two multiple exposure sequence pictures and by a CW1 pictures. The code frame contains file identification, the scale factor used in RICKY, and the magnitude of the calibration signal. The data are presented in polar coordinates (R,θ). The conversion from Cartesian, X, Y coordinates to polar coordinates was performed by an algorithm called POLAR (Ref. 3).

The file was split into two 3-minute sequence displays. An overlay of six correlation output periods comprise each sequence picture. Frequent transient shifting in the source sequence generator prevented 12-shot multiple exposures of the sequence results. A similar shifting problem with lower recurrence rates was present in past experiments. Usually one of the two sequence pictures contained a peak shift resulting in a bad picture. However, due to the highly redundant nature of the data in a file, little information is lost. Pictures with detected peak shifts have been omitted from the data shown in Appendix B.

6. DISCUSSION OF SEQUENCE RESULTS

In previous experiments signal stability has been the most prominent feature of the broadband reception, particularly the signal phase. Correlation outputs within a six-minute sampling interval have been very similar in signal arrival regions. Multiple exposure photographs of the data would not have been useful without this stability. Since noise reception has random (uniform) phase, any stable structure in the phase of a multiple exposure indicates signal reception. Such phase detection of the signal is possible in very low signal-to-noise ratio regions, where amplitude detection is questionable. However, phase detection is not limited to poor SNR situations. Signal arrival durations measured using phase detection were 300 to 500 milliseconds in February 1965 and 120 to 500 milliseconds in August 1966. The current experiment showed that under certain anomalous conditions arrivals at least 1.2 seconds in length occur. Some examples are shown in data for 1843 hours 22 December 1966 and 2043 and 2243 hours 28 December 1966 (see Appendix B). Phase stability again allowed multiple exposure photography over six minute intervals and detection in low SNR arrivals. (Three minute pictures were required for reasons already explained.) Signal arrival durations varied from 50 msec to a full period (but usually between 80 and 600 msec). Although there

were general similarities, the current experiment displayed a high quality of transmission which was previously observed only on analog processing equipment. Not too surprisingly the quality of reception varied considerably during the month. However, in general, there were definite multipath phenomena with time resolution several times better than either February 1965 or August 1966. The improved resolution was a result of natural changes in propagation rather than in processing. A large percentage of the correlation peaks were nearly or completely non-overlapping while overlapped signals were prevalent in past experiments. Although the sequence processing is linear, the output is difficult to interpret when there are overlapping peaks. When the peaks are non-overlapping,each one can be studied separately without ambiguity. Outstanding features of the phase were the 90 degree and 180 degree jumps in successive path arrivals and the constant slope of several arrivals within a period. The slope of a linear phase sweep can be interpreted as the center frequency of a dominant band of energy reception. The invariant slope of successive arrivals indicates a strong physical relation between seemingly independent transmission paths. These arrivals probably traveled similar physical paths. For example, the arrivals may have been a refraction-bottom bounce type, where a refraction results in a 90 degree phase shift.

Multipath reception has been difficult to interpret in the past because of poor time resolution. However, the general phase characteristics of December 1966 data and February 1965 and August 1966 results were similar, indicating a strong possibility of the same dominant transmission mode. The phase of signal in August 1966 and February 1965 contained several discrete sections of phase data resembling the multipath reception. Most importantly there were many instances of invariant linear slope. Therefore, past reception probably consisted of many (5 or 6) simple but interfering multipath arrivals which traveled similar physical paths. The possibility of a single dominant mode of transmission was not apparent before because interference, caused by overlapping arrivals, created very complex phase and amplitude structures.

Some important detailed features of the December data must also be pointed out. The energy was often equally distributed throughout the signal arrival rather than concentrated in the first 200 milliseconds as in August and February. The correlation peak widths varied from 40 to 80 msec, where the ideal peak is about 40 msec. Six or more such peaks frequently occur in a sequence period. A linear flat wideband media would pass the ideal signal, but narrowband and non-flat filters, such as MCOR, widen these peaks. The phase commonly contains linear sweeps equivalent to center frequencies of about 6 Hz and 12 Hz below carrier. The same pheno-

menon observed in August 1966 and February 1965 indicated energy bands centered at frequencies ranging from 4 to 20 Hz below carrier (the most common value was 16 Hz). Occasionally the December data contained linear phase sweeps which indicate dominant energy in the reception at frequencies above carrier. This has not been observed in past receptions at Bimini.

In conclusion the sequence results of the December 1966 experiment show that although large variations in acoustic propagation quality occur, there seems to be a single dominant mode of transmission in the Straits of Florida. Hopefully this will allow general conclusions based upon the simpler current data. More experiments must be performed before propagation qualities (e.g., high time resolution of path arrivals) can be predicted. The December 1966 experiment obtained the best data in this respect. It may be more than coincidental that the data were obtained shortly after the first winter cold front moved into the Straits of Florida.

As in previous experiments signal stability allowed phase detection and multiple exposure photography throughout the six minute files. However, the reception should be sampled much more frequently than every two hours because reception quality changed too widely between files. A better scheme would require one or two minute samples every ten or fifteen minutes. This fact was apparent in the August 1966 experiment; however, the equipment changes

could not be made before December.

In previous experiments measurement of the correlation peak widths, except for possibly one major arrival, could not be made. Therefore, the fact that the December 1966 data approximated the ideal correlation peak so well was new and unexpected information. An investigation of filtering effects upon the shape and width of the correlation function should be valuable.

Quite obviously, signal modeling, physical interpretation, and propagation prediction are wide open topics. Long term, on-line sampled experiments are planned for the future in addition to experiments to study the transmitter's filter characteristics, to accurately measure transit times and to study the first seven miles (shallow water) of the sound channel. Only experience from these tests and much work can produce answers and solutions for these questions.

7. A PROPOSED ON-LINE PROCESSOR

An on-line receiver similar to the one in this report will eliminate all of the problems with analog tape recording, such as, phase locking and other time coherency problems.

The present system would not make an effective on-line receiver because of its dependence upon the external counting circuitry, the processing in RICKY, and a limited program interrupt routine. The interrupt routine will not service LINC-8 console interrupts. Thus it does without the benefit of the many LINC-8 operator control features during development of most programs. Similarly the routine could not service the external clock during computer tape unit operations. Therefore, an external counting circuit was needed to maintain coherency when data were written onto tape. The necessary modification of PROGOFOP and its tape routine should be relatively easy. Therefore, the limitations pointed out can be removed with reprogramming of PROGOFOP and the interrupt routine.

The variable scaling performed in PROCESSO is a form of automatic gain control. However, if interpretation of data is to be simple, the scaling must be compensated before visual output. The scheme used in PROCESSO was satisfactory, but could certainly be improved.

Judging from experience, post-processing such as that performed by RICKY is extremely cumbersome. The value of any function which cannot be incorporated into the on-line receiver (or programmed in FORTRAN) should be questioned.

Before an efficient routine can exist, a means of reducing the quantity of output data must be found. This problem is currently of major interest to the entire MIMI project.

There is room for improvement in several areas of the processing system. However, there can be no doubt that a useful and workable system is at our disposal.

Appendix A

TRANSMISSION AND RECEPTION OF AMSEQ

Transmission at MIMI-A: AMSEQ

The amplitude modulated pseudo-random sequence transmission is described by the signal

$$s_a(t) = \frac{1}{2}[1 + m(t)] \cos \omega_0 t \qquad \text{(A. 1)}$$

where

$s_a(t)$ = transmitted signal in AMSEQ transmission

$m(t)$ = biphase pseudo-random sequence (BMSEQ)

$\omega_0 = 2\pi f_0$

f_0 = 420-Hz carrier frequency

$\frac{1}{2}[1 + m(t)]$ = amplitude modulation of the carrier (AMSEQ)

The biphase pseudo-random sequence (Refs. 3 and 4) is a periodic pulse pattern, each period consisting of 63 digits, 32 "plus ones" and 31 "minus ones." One period of sequence is 1.2 sec; each digit has a duration of eight carrier cycles, i.e., $\frac{1}{52.5}$ sec = $19\frac{1}{21}$ msec. The 420-Hz sine wave and the 52.5-Hz clock frequency are coherently derived from the MIMI-A 1680-Hz precision oscillator.

From Eq. A. 1 it follows that AMSEQ, $\frac{1}{2}[1 + m(t)]$, consists

of 63 digits, 32 ones and 31 zeros. Where BMSEQ transmission

$$s_b(t) = m(t) \cos \omega_0 t , \qquad m(t) = \pm 1 \tag{A.2}$$

contains approximately the same power as CW transmission,

$$s_c(t) = \cos \omega_0 t \tag{A.3}$$

the AMSEQ modulation causes a loss of approximately 3 db transmission power, since 31 out of the 63 sequence digits turn the carrier signal off.

Writing Eq. A. 1 as

$$s_a(t) = \underbrace{\frac{1}{2} \cos \omega_0 t}_{\text{CW}} + \underbrace{\frac{1}{2} m(t) \cos \omega_0 t}_{\text{BMSEQ}} \tag{A.4}$$

it may be seen that the AMSEQ transmission power is equally distributed over the signals CW and BMSEQ. Thus, by applying CW analysis and SEQ analysis as described in Ref. 3 it is possible to obtain simultaneously information about the low frequency modulation of carrier by the ocean and about the multipath sound propagation. Since in AMSEQ both signals CW and BMSEQ appear with one-half the amplitude, the processing results are 6 db less compared with processing either CW, or BMSEQ signals as in the February 1965 experiment. Furthermore, the sound source has

deteriorated, now transmitting at a level of only 95 dbμb instead of the original 103 dbμb. Thus, in comparing the signal strength of processed data in the August 1966 with that of the February 1965 experiment, a total loss of 14 db has to be taken into account.

Reception at MIMI-B

The reception techniques used in this experiment are the same as described in Ref. 4. Summarizing, the received signal is amplified, filtered in a fixed filter with a passband of 370 Hz to 470 Hz, and recorded onto analog tape by means of an SP300 4-track analog tape recorder, in this experiment, at a speed of $1\frac{7}{8}$ ips. The signals were received by one shallow hydrophone. The reference signal from the 1680-Hz precision oscillator at MIMI-B was recorded on channel 1, and the signal from the D-2 hydrophone on channel 3 (Fig. 8). Also, the signal was phase coherently demodulated and the resulting amplitude R(t) and phase angle θ(t), together with the filtered, non-demodulated signal, were recorded on a Sanborn graphic recorder. In this recorder the "raw" signal is rectified, low-pass filtered, and scaled logarithmically, the recording giving an impression of the power level of the received noise in the 370-Hz to 470-Hz band. The signal R(t) is also scaled logarithmically. Both the phase coherent demodulator (PCD) at MIMI-B, and the processing at MIMI-C use the 1680-Hz reference signal from the MIMI-B precision oscillator. Phases and delays thus find their reference at

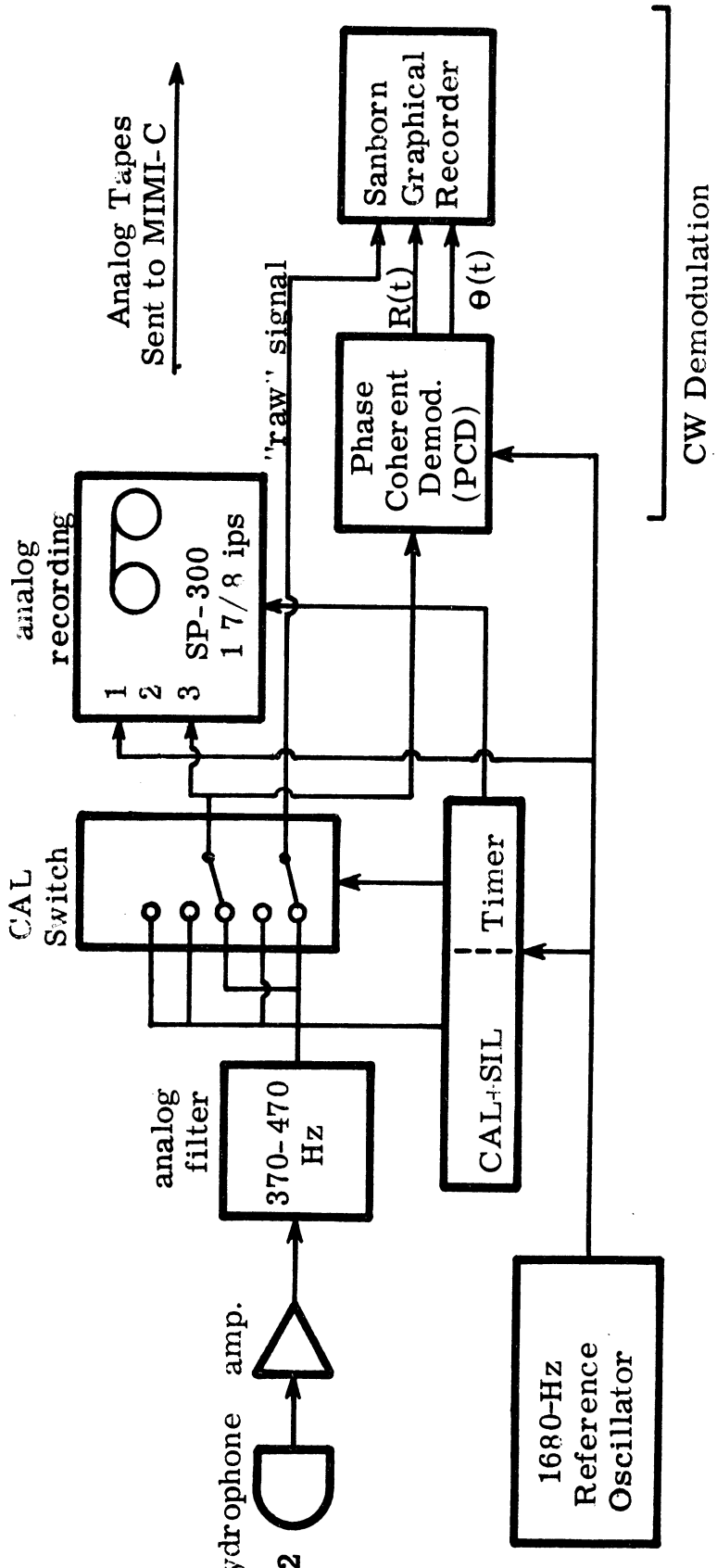


Fig. 8. Reception at MIMI-B

reception rather than at transmission. The reference oscillators at transmission and at reception have a stability of about one part in 10^{10}.

To provide for coherent processing at MIMI-C, calibration tones (CAL) were inserted periodically in the analog recordings. CAL is a 420-Hz noise free sine wave, the amplitude for the present experiment usually corresponding to a -44 dbμb hydrophone reception, and has a duration of $39\frac{1}{105}$ sec. CAL is followed by a period of zero signal or "silence" (SIL) of $19\frac{1}{21}$ msec, the duration of one sequence digit.

The analog recording was started every two hours, beginning with the CAL + SIL format, and stopped after 6 minutes.

The derivation of the 420-Hz CAL tone, the durations of CAL and of SIL, and all timing involved in programming the SP300 recorder were coherently derived from the 1680-Hz reference oscillator by means of logic countdown circuitry.

Appendix B

PHOTOGRAPHS OF RESULTS

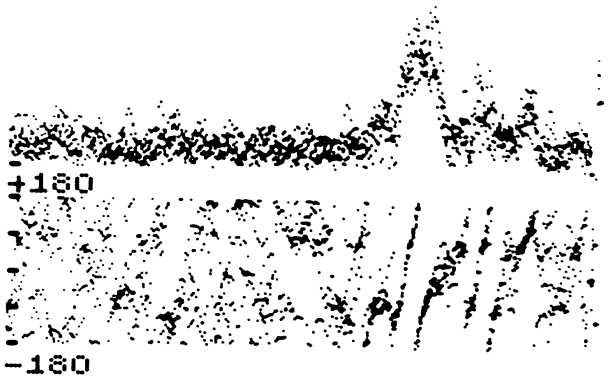
The following photographs show a significant portion of the results obtained from the experimental data. For each six minute reception, twelve records of processed sequence data were obtained. The twelve records were divided into two groups of six each and the data were overlayed photographically by a multiple exposure process. The resulting photographs contain amplitude vs. time data on an arbitrary scale in the top half and phase data (-180^{o} to $+180^{o}$) in the bottom half. A third photograph summarizes the behavior of the 420 Hz carrier during the entire six minute reception. Again, the top half is amplitude vs. time, the bottom half is phase vs. time.

The following notes apply to photographs missing from the normal sequence.

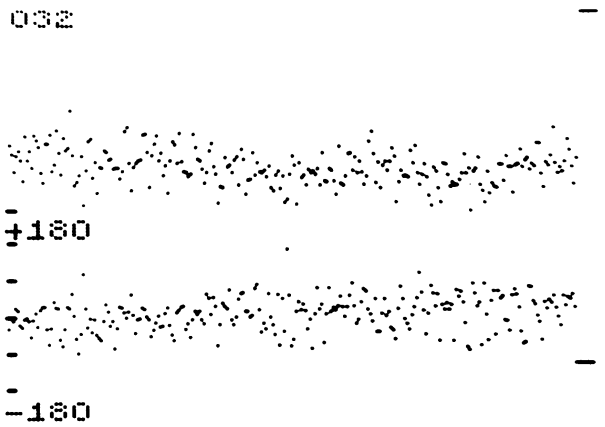
Note 1. A processing error has invalidated the data making this photograph unuseable.

Note 2. A * interposed between sets of photographs indicates that a set or sets of photographs have been omitted because high noise levels completely obscured the data.

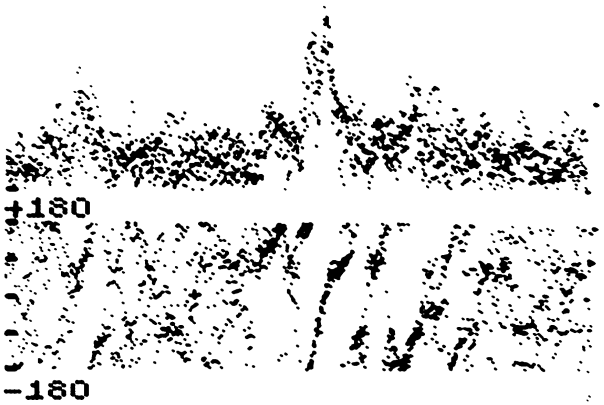
Additionally, on 28 December 1966 an equipment malfunction prevented recording of valid data from 0001 to 1800 hours. No photographs were made corresponding to this period.



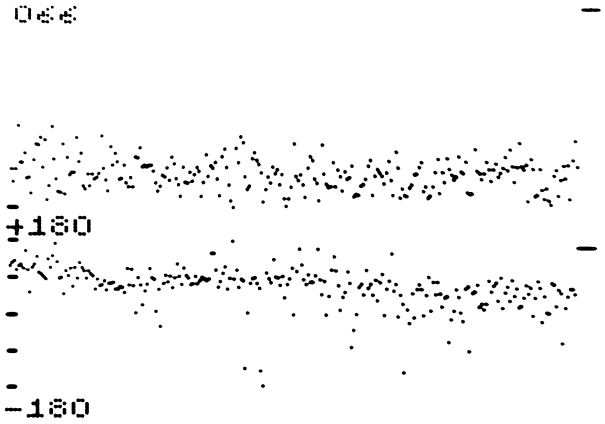
See Note 1



13 December 1966 2243 - 2249



See Note 1

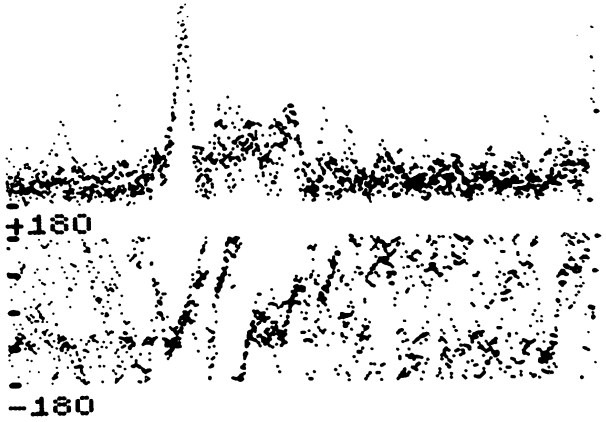


14 December 1966 0043 - 0049

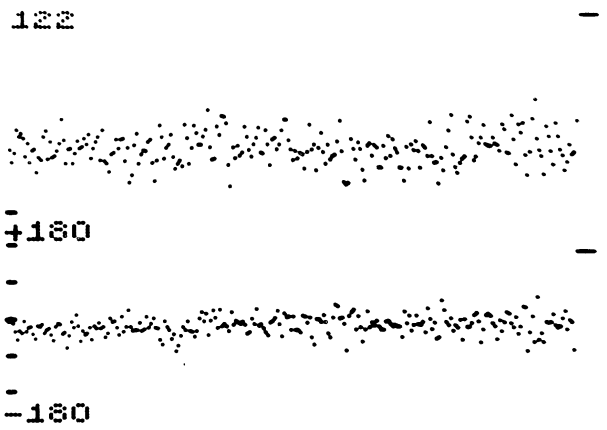
First 3 minutes

Second 3 minutes

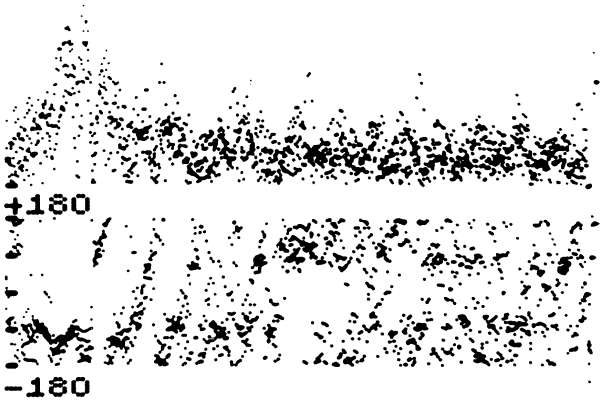
Carrier (entire 6 minutes)



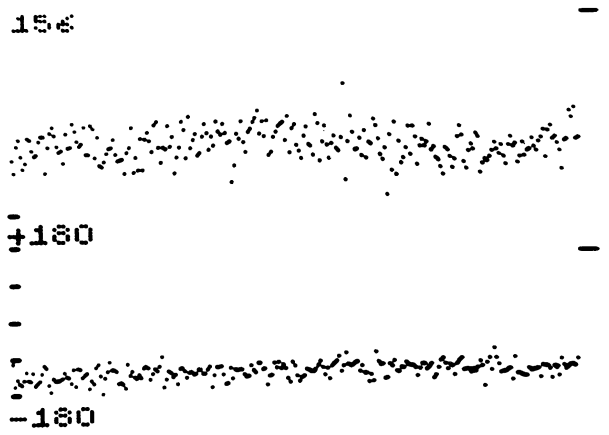
See Note 1



14 December 1966 0243 - 0249



See Note 1

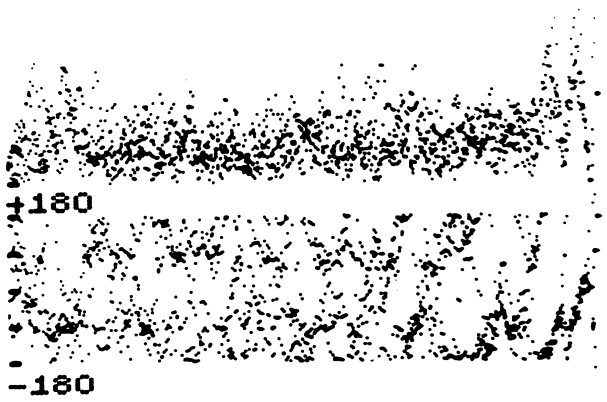


14 December 1966 0443 - 0449

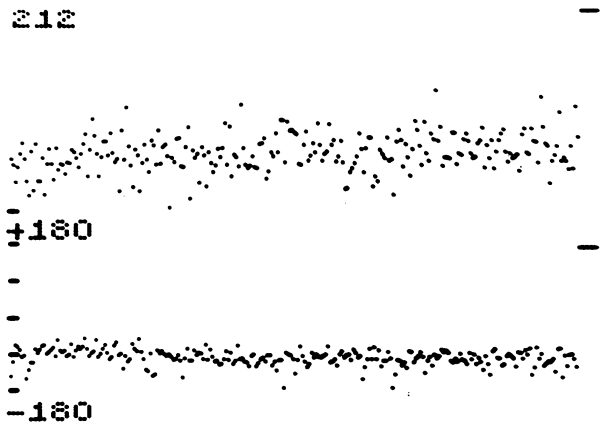
First 3 minutes

Second 3 minutes

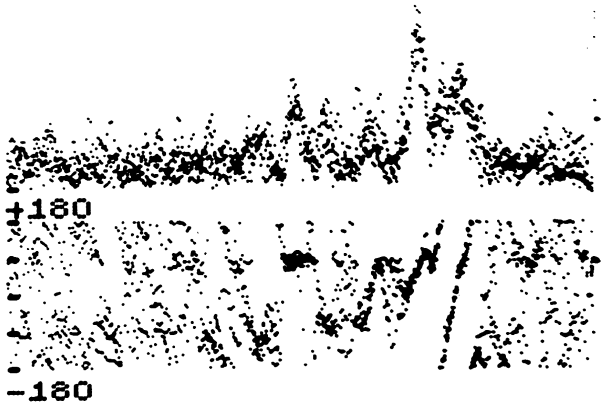
Carrier (entire 6 minutes)



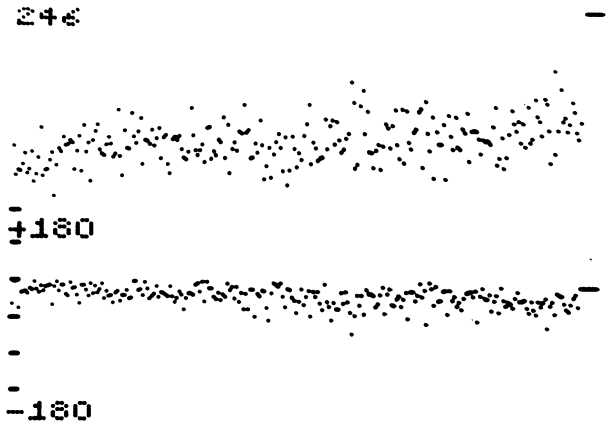
See Note 1



14 December 1966 0643 - 0649



See Note 1



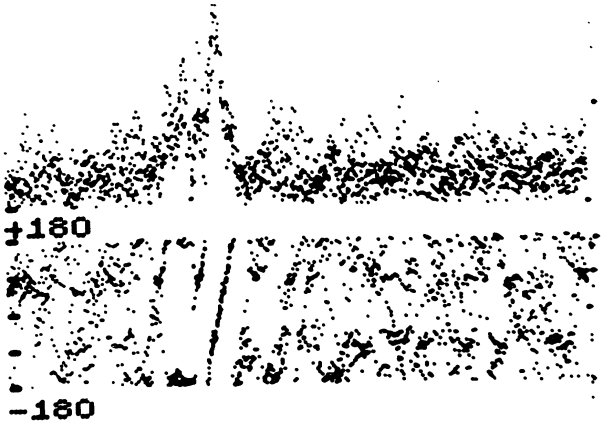
14 December 1966 0843 - 0849

First 3 minutes

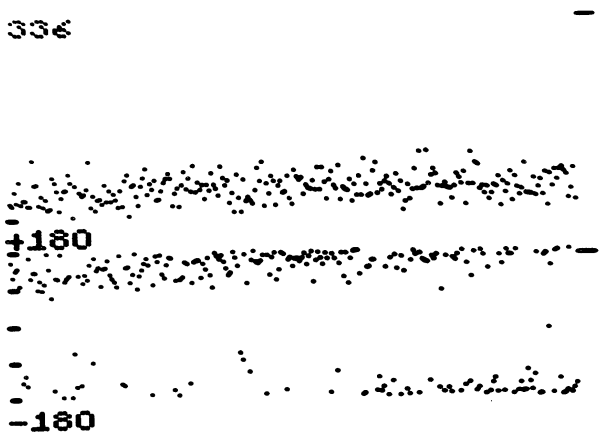
Second 3 minutes

Carrier (entire 6 minutes)

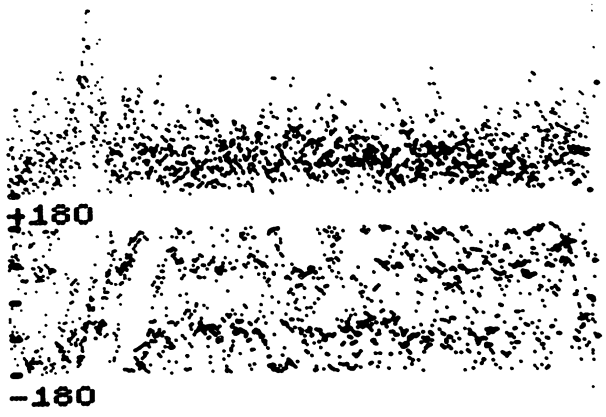
★



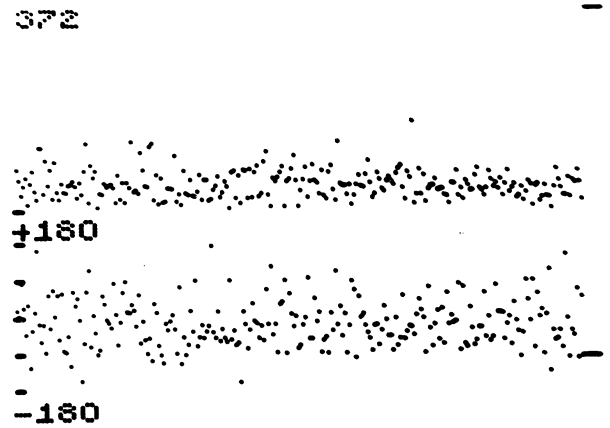
See Note 1



14 December 1966 1243 - 1249



See Note 1



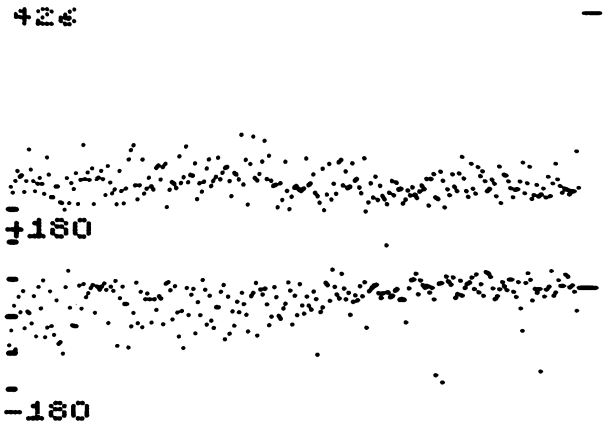
14 December 1966 1443 - 1449

First 3 minutes

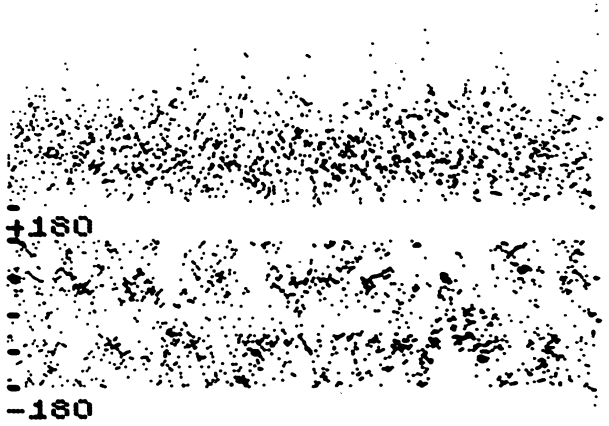
Second 3 minutes

Carrier (entire 6 minutes)

See Note 1



14 December 1966 1643 - 1649



See Note 1

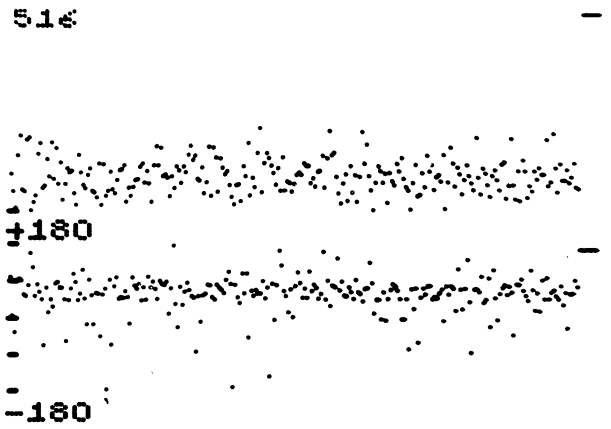
14 December 1966 1843 - 1849

First 3 minutes

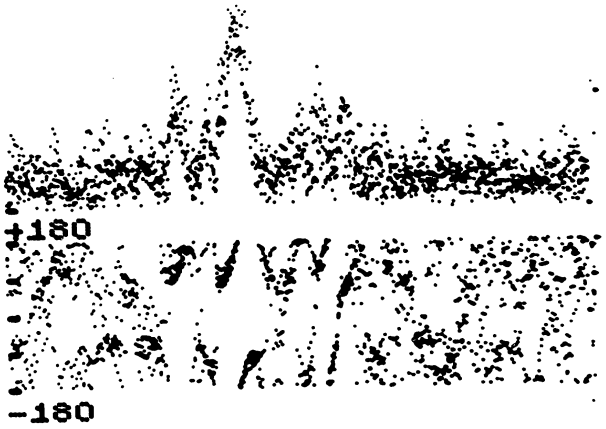
Second 3 minutes

Carrier (entire 6 minutes)

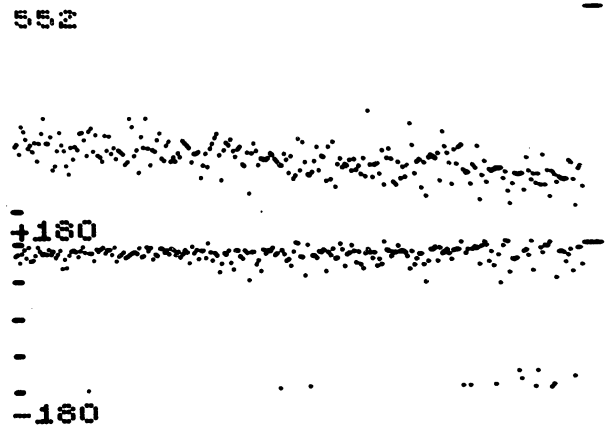
See Note 1



14 December 1966 2043 - 2049



See Note 1

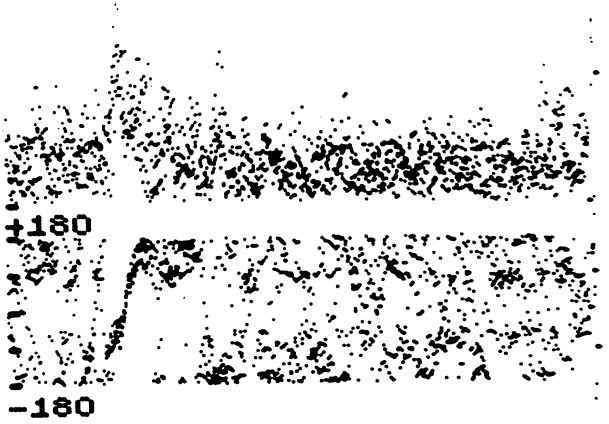


14 December 1966 2243 - 2249

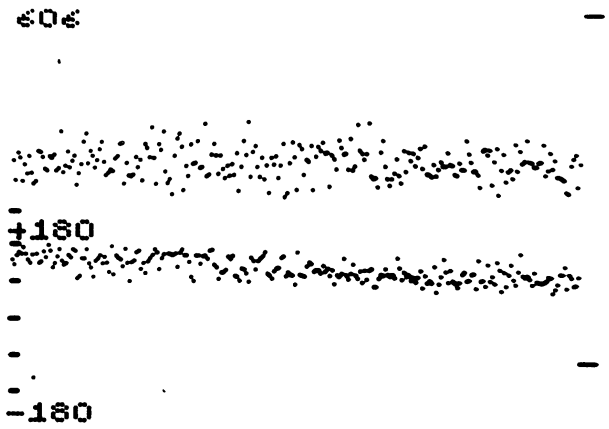
First 3 minutes

Second 3 minutes

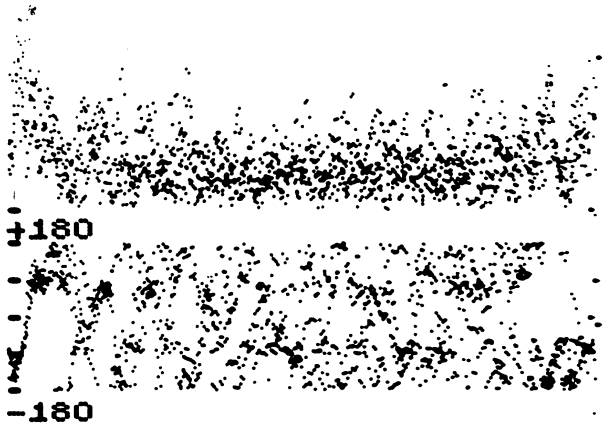
Carrier (entire 6 minutes)



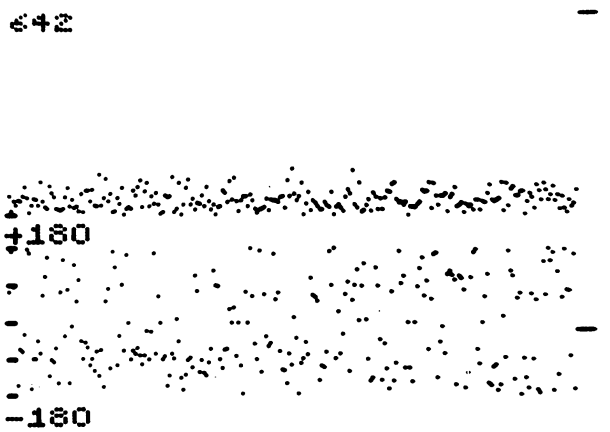
See Note 1



15 December 1966 0043 - 0049



See Note 1

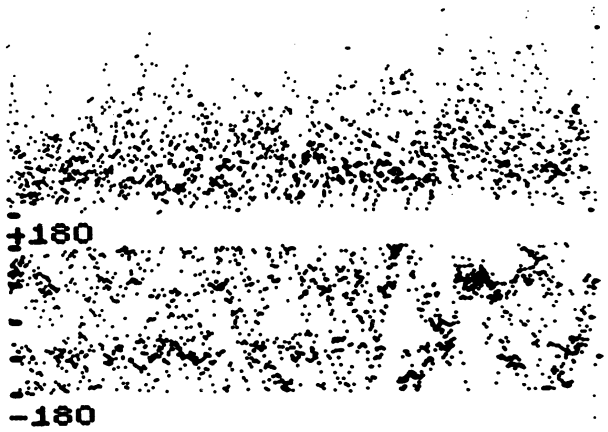


15 December 1966 0243 - 0249

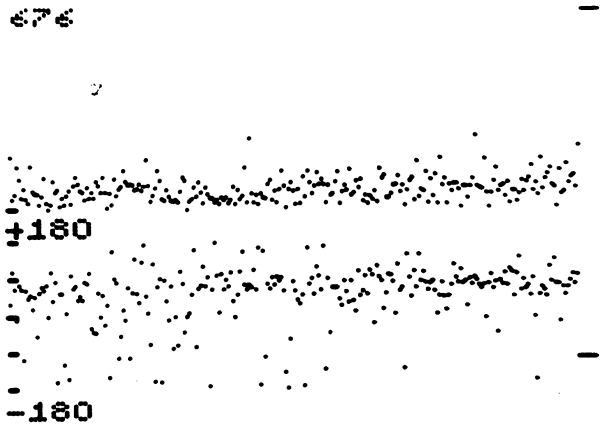
First 3 minutes

Second 3 minutes

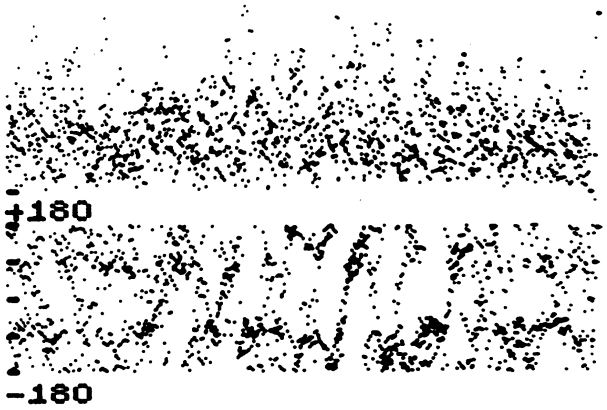
Carrier (entire 6 minutes)



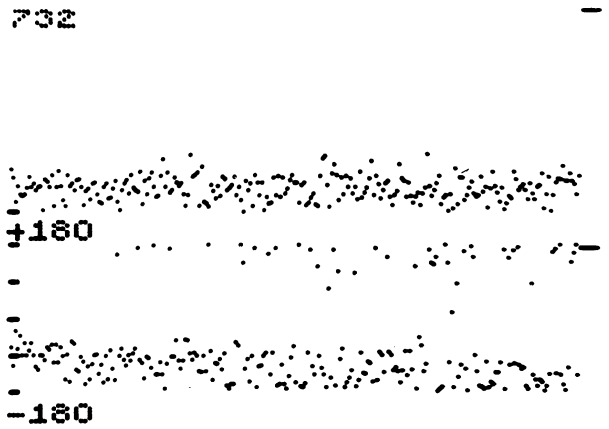
See Note 1



15 December 1966 0443 - 0449



See Note 1

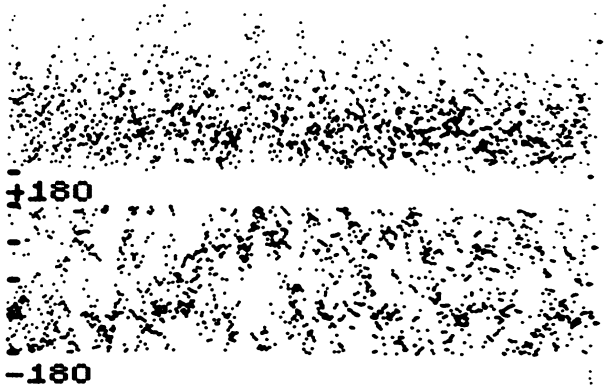


15 December 1966 0643 - 0649

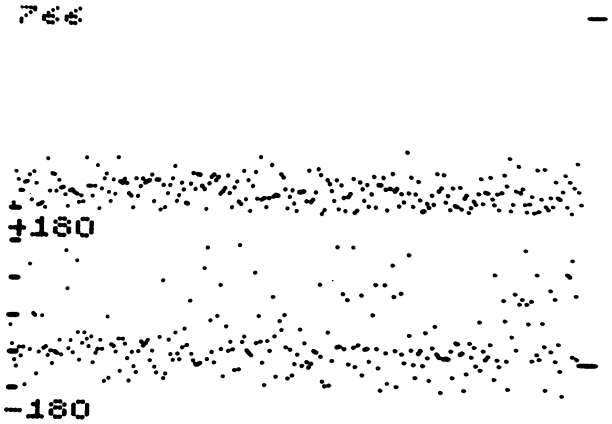
First 3 minutes

Second 3 minutes

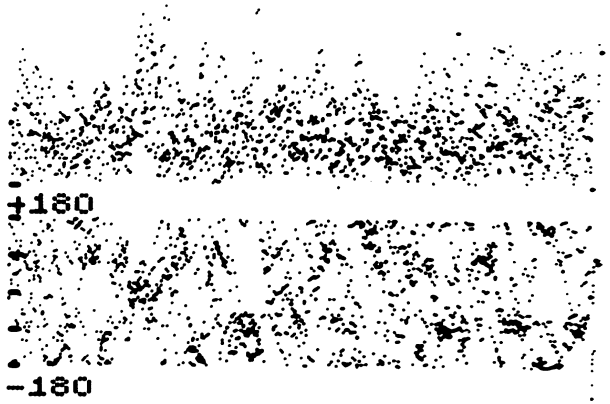
Carrier (entire 6 minutes)



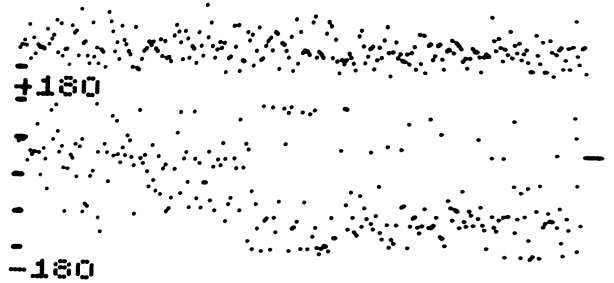
See Note 1



15 December 1966 0843 - 0849



See Note 1

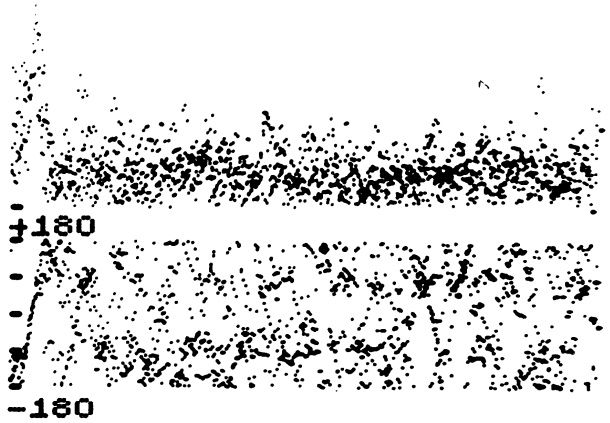


15 December 1966 1043 - 1049

First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



See Note 1

15 December 1966 1243 - 1249

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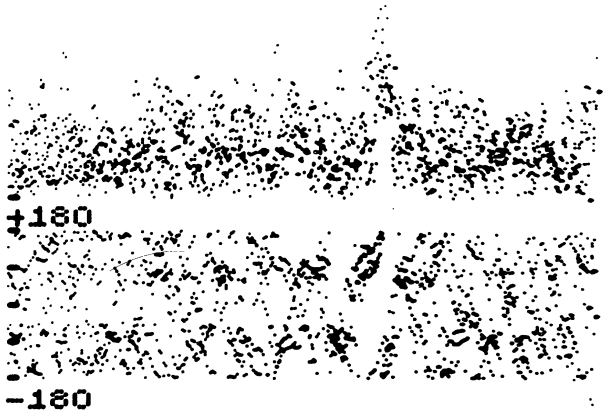
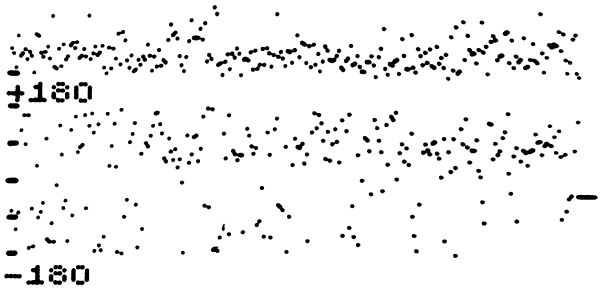


See Note 1



15 December 1966 1643 - 1649

First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

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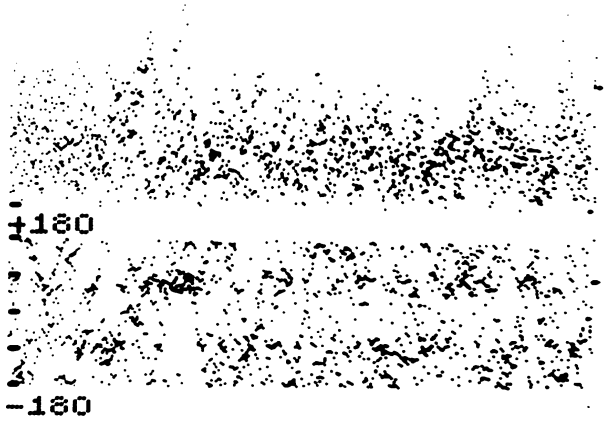
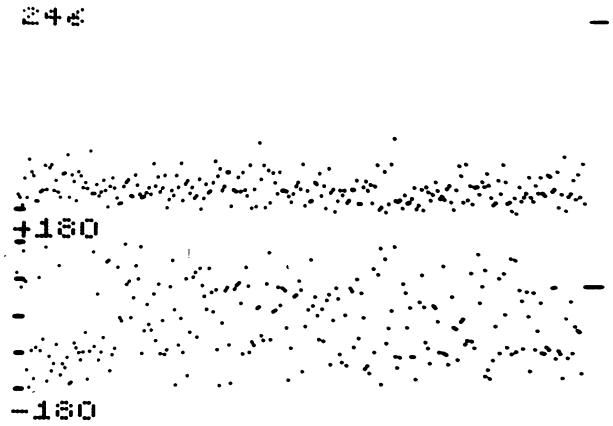
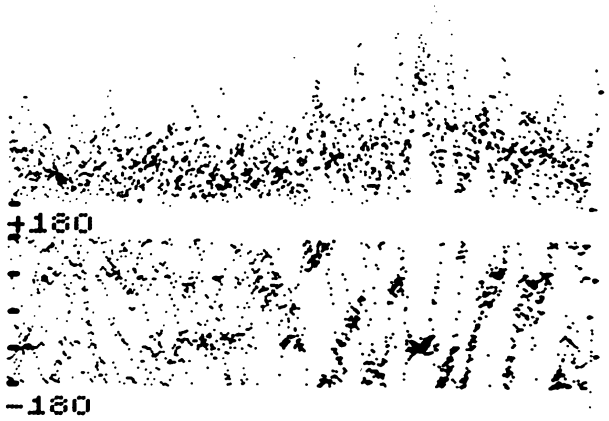
See Note 1





15 December 1966 2043 - 2049



See Note 1

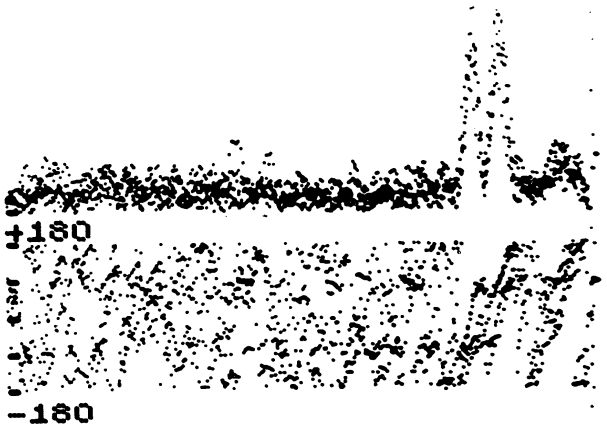
15 December 1966 2243 - 2249

First 3 minutes

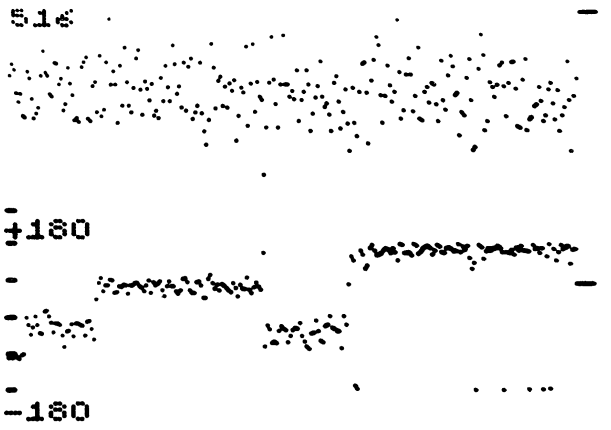
Second 3 minutes

Carrier (entire 6 minutes)

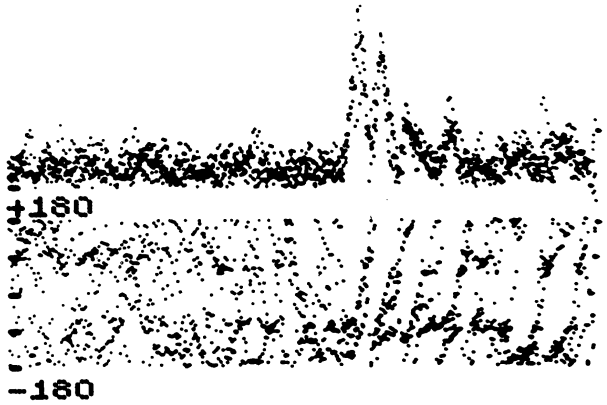
★



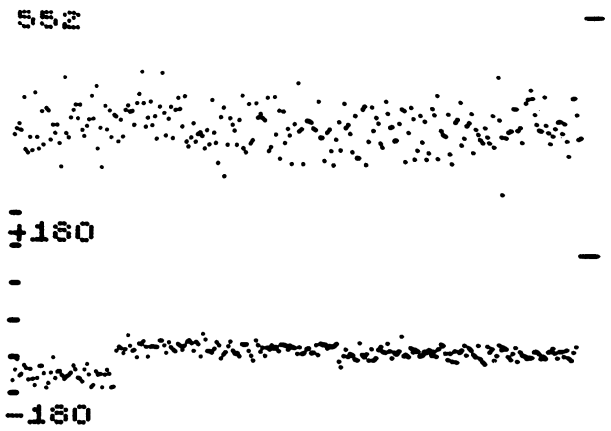
See Note 1



16 December 1966 0843 - 0849



See Note 1



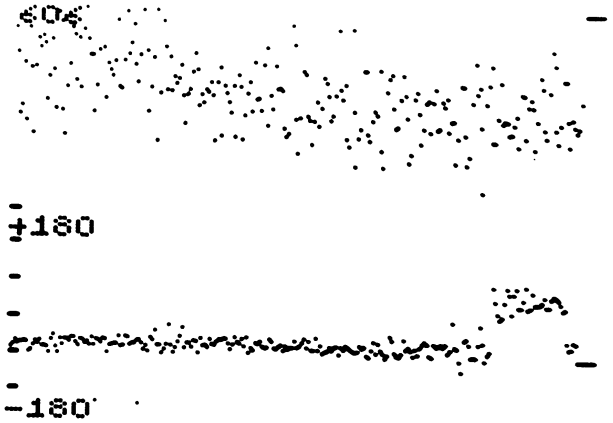
16 December 1966 1043 - 1049

First 3 minutes

Second 3 minutes

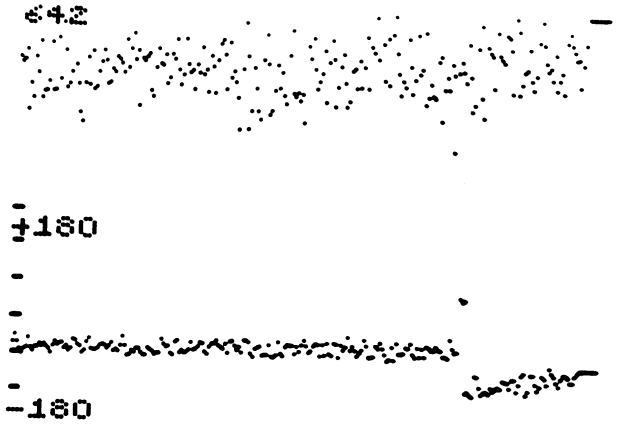
Carrier (entire 6 minutes)

See Note 1



16 December 1966 1243 - 1249

See Note 1



16 December 1966 1443 - 1449

First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

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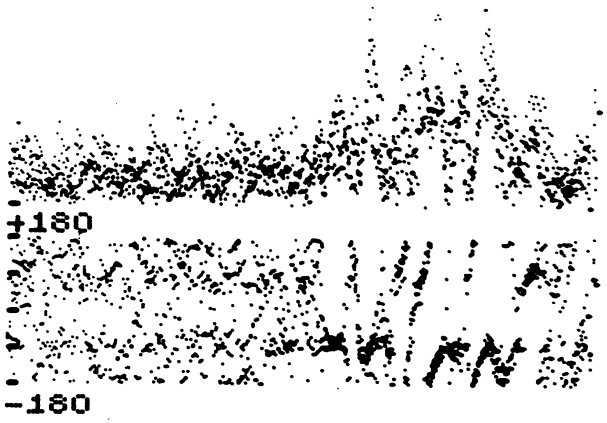
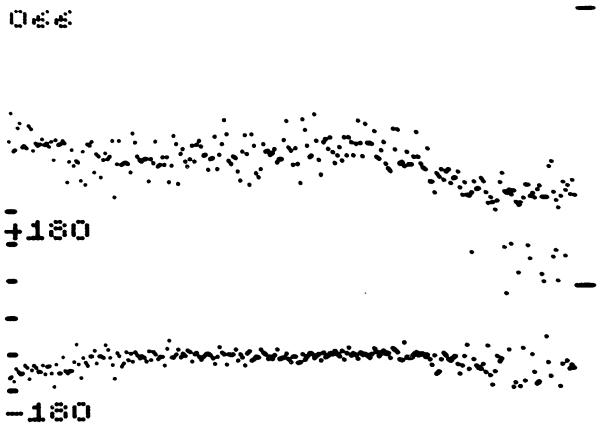
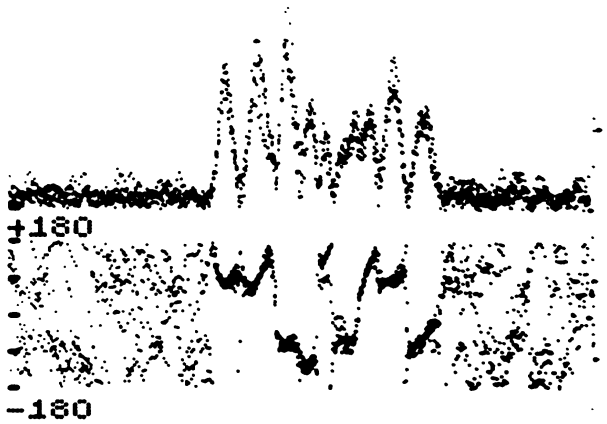


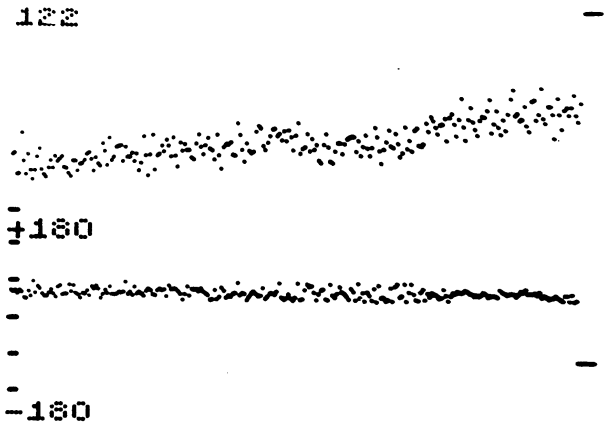
See Note 1



17 December 1966 1843 - 1849



See Note 1

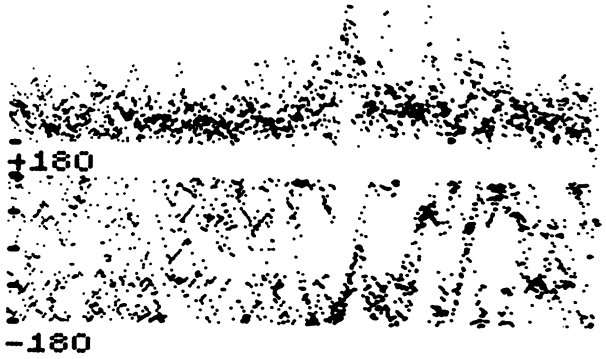


17 December 1966 2043 - 2049

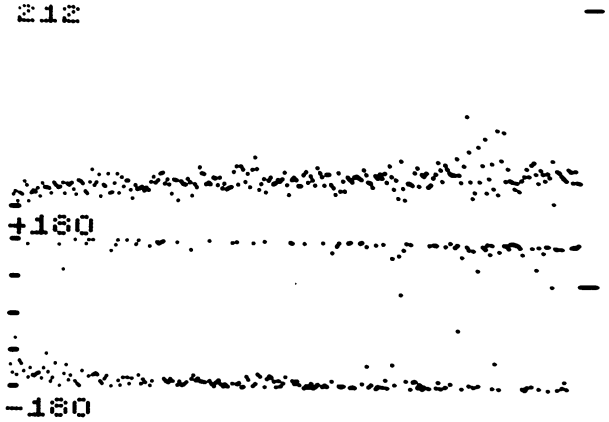
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

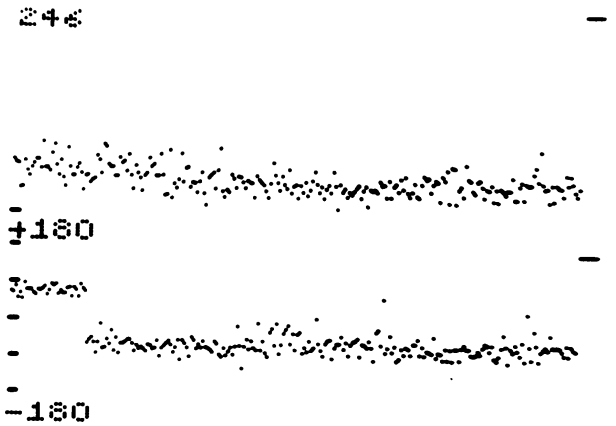


See Note 1



17 December 1966 0643 - 0649

See Note 1

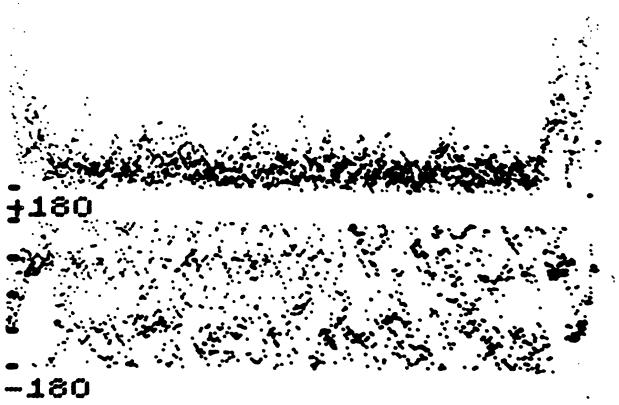


17 December 1966 0843 - 0849

First 3 minutes

Second 3 minutes

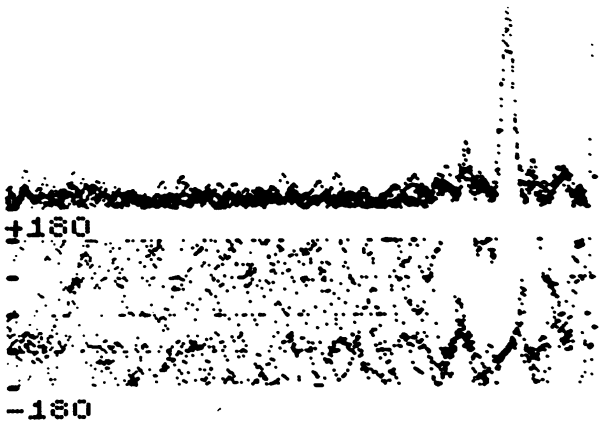
Carrier (entire 6 minutes)



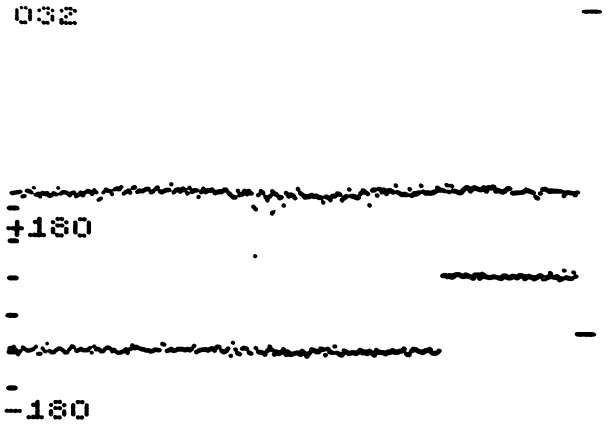
See Note 1

See Note 1

17 December 1966 1443 - 1449



See Note 1

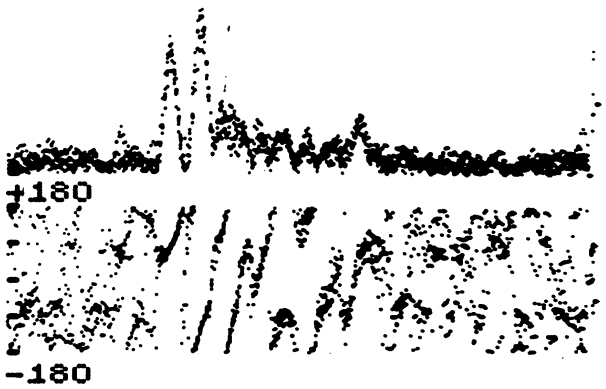


17 December 1966 1643 - 1649

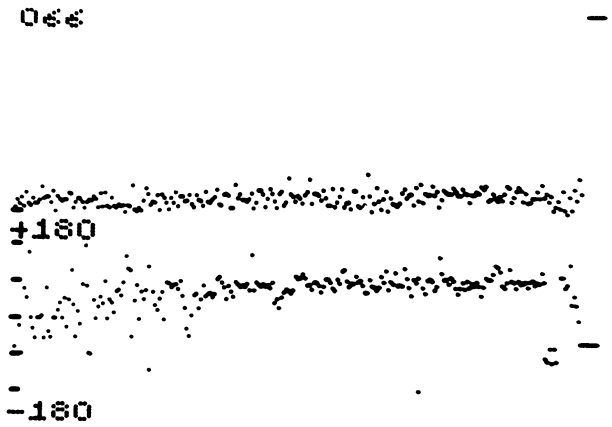
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

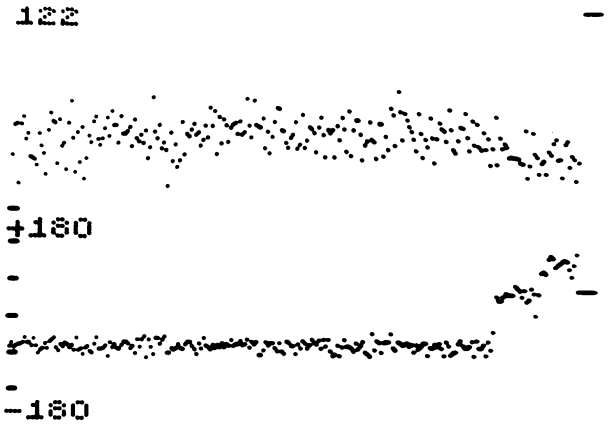


See Note 1



17 December 1966 0043 - 0049

See Note 1

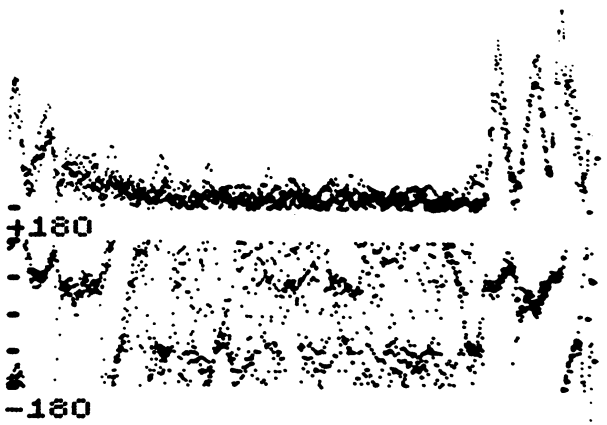


17 December 1966 0243 - 0249

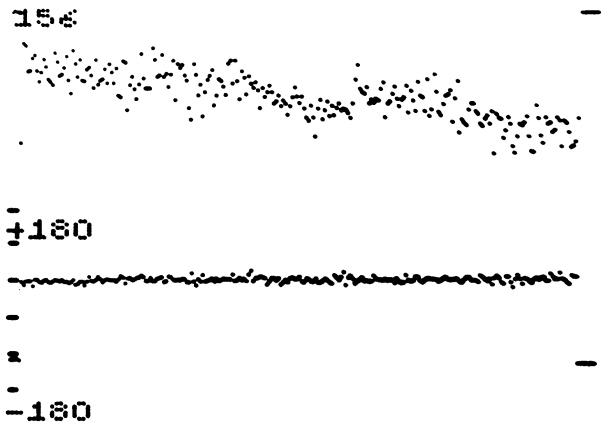
First 3 minutes

Second 3 minutes

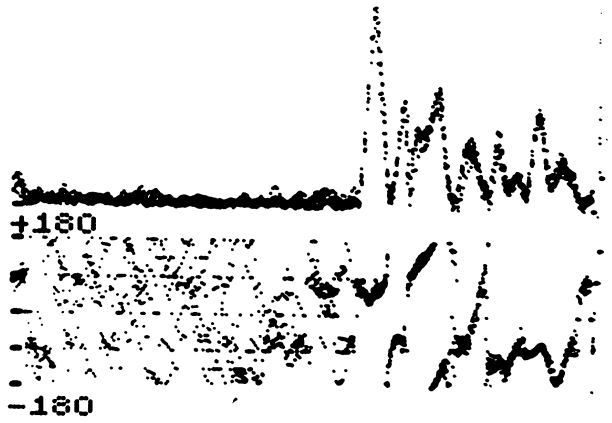
Carrier (entire 6 minutes)



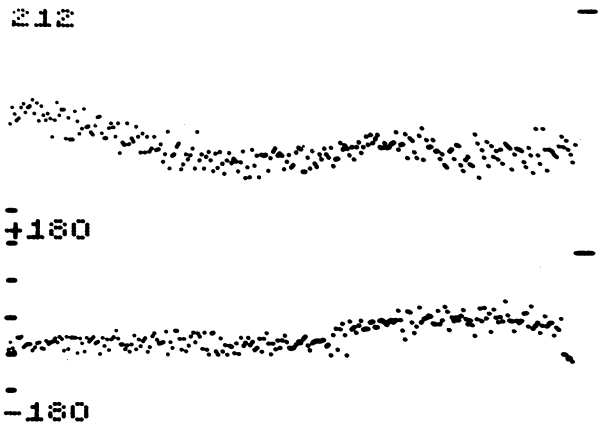
See Note 1



17 December 1966 2243 - 2249



See Note 1

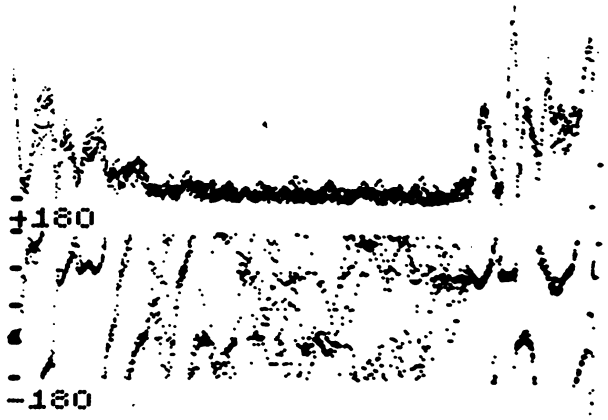


18 December 1966 0043 - 0049

First 3 minutes

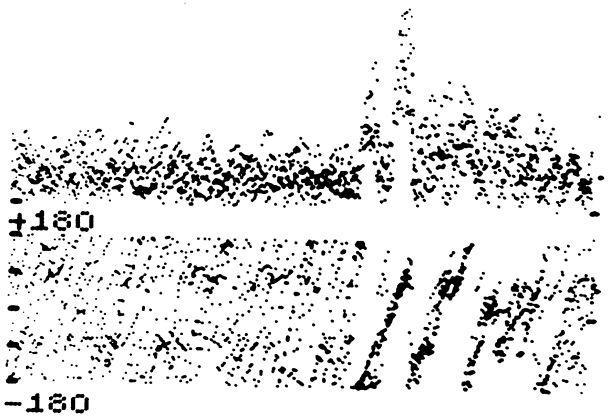
Second 3 minutes

Carrier (entire 6 minutes)

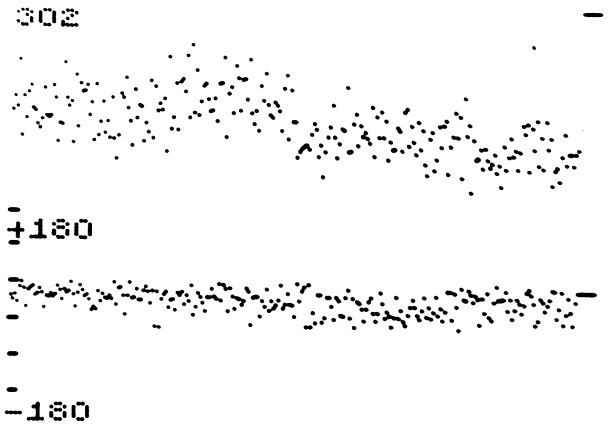


See Note 1

18 December 1966 0243 - 0249



See Note 1

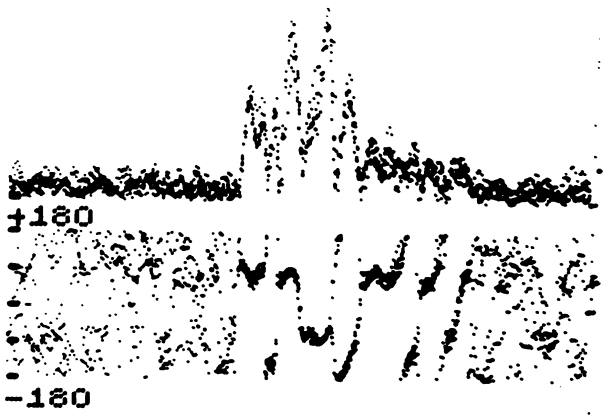


18 December 1966 0443 - 0449

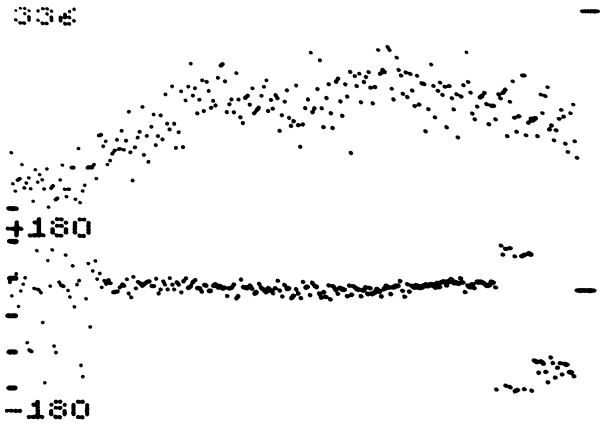
First 3 minutes

Second 3 minutes

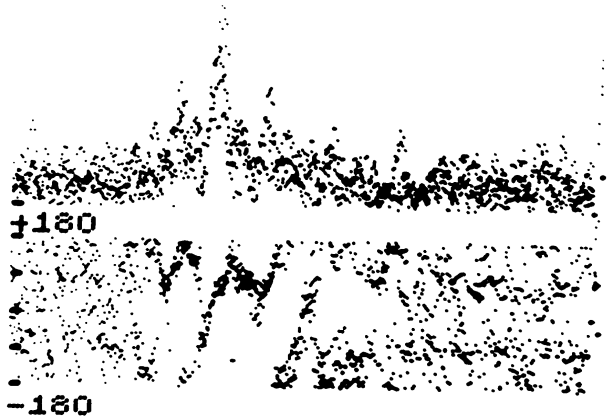
Carrier (entire 6 minutes)



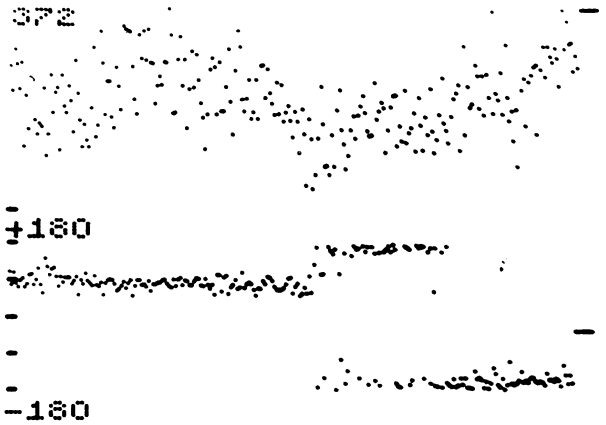
See Note 1



18 December 1966 0643 - 0649



See Note 1

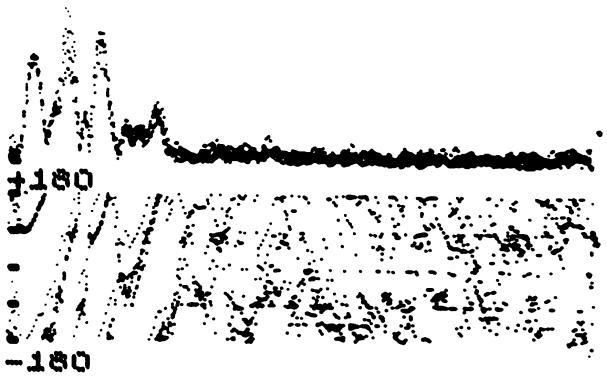


18 December 1966 0843 - 0849

First 3 minutes

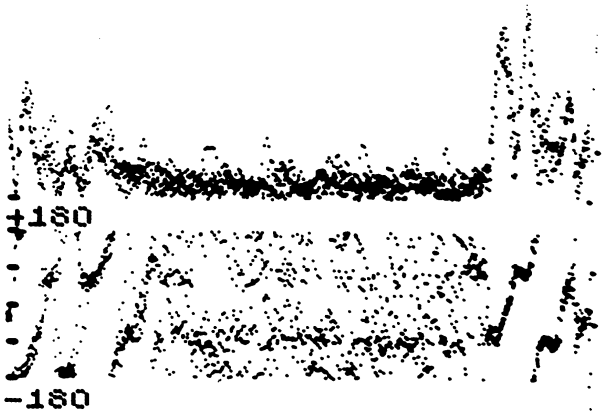
Second 3 minutes

Carrier (entire 6 minutes)



See Note 1

18 December 1966 1043 - 1049



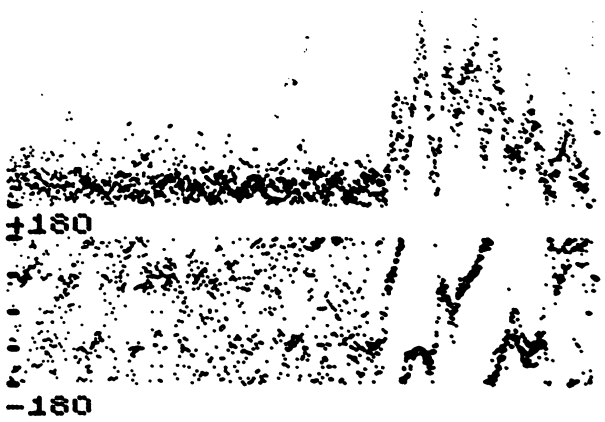
See Note 1

18 December 1966 1243 - 1249

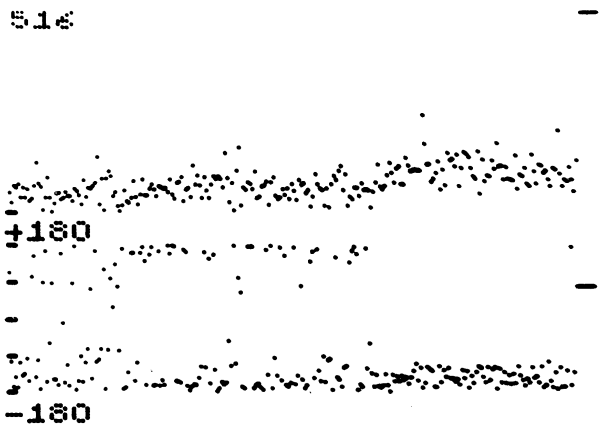
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

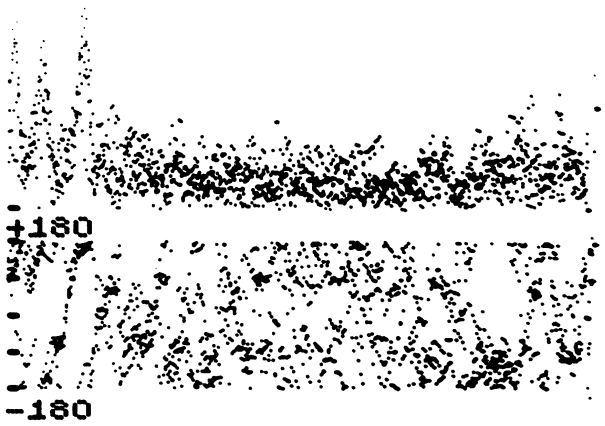


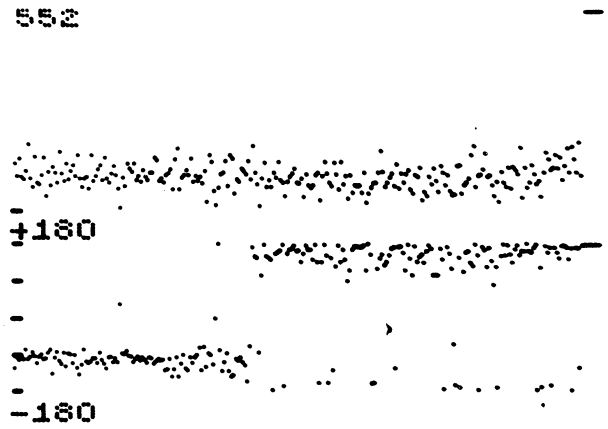
See Note 1



18 December 1966 1443 - 1449

See Note 1



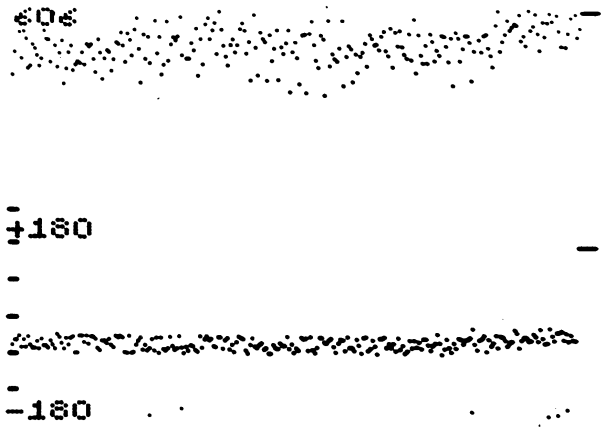


18 December 1966 1643 - 1649

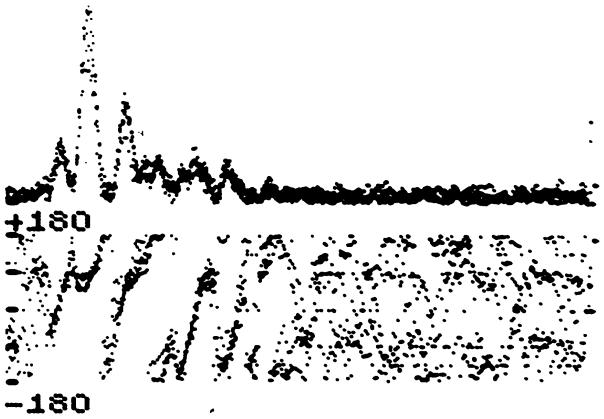
First 3 minutes

Second 3 minutes

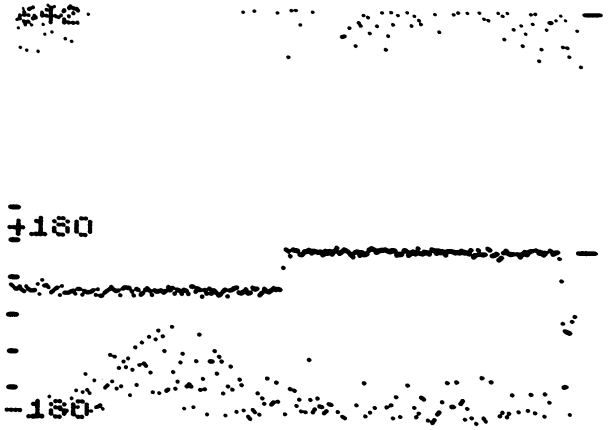
Carrier (entire 6 minutes)



18 December 1966 1843 - 1849



See Note 1

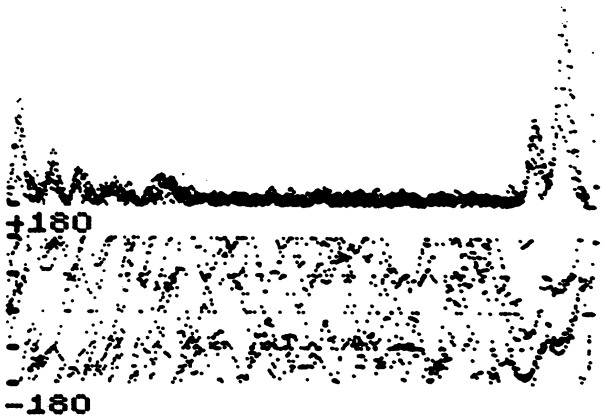


18 December 1966 2043 - 2049

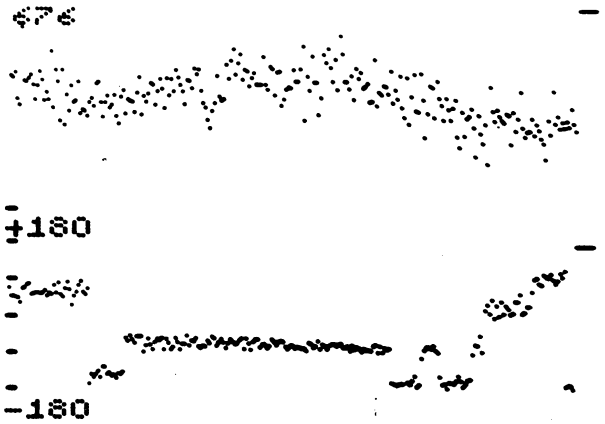
First 3 minutes

Second 3 minutes

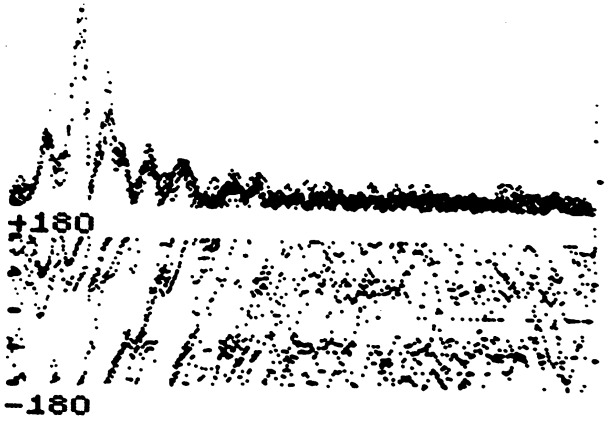
Carrier (entire 6 minutes)



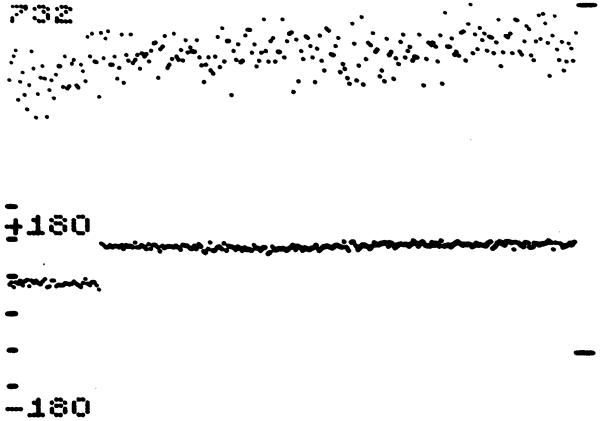
See Note 1



18 December 1966 2243 - 2249



See Note 1



19 December 1966 0043 - 0049

First 3 minutes

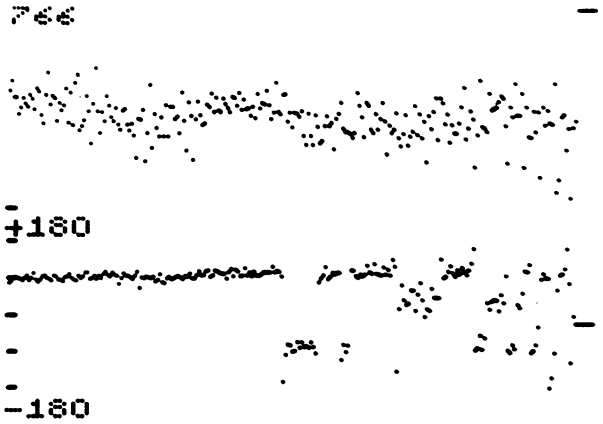
Second 3 minutes

Carrier (entire 6 minutes)

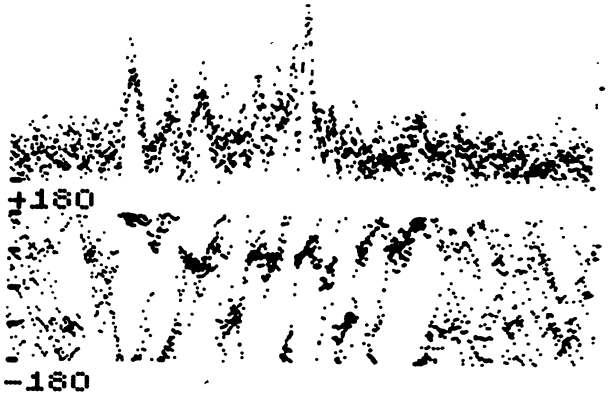
First 3 minutes

See Note 1

19 December 1966 0243 - 0249



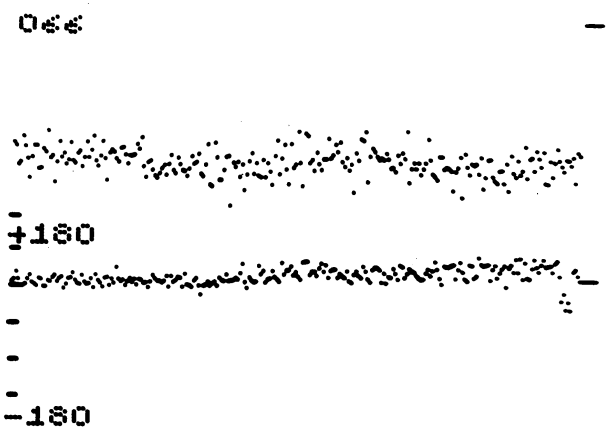
Carrier (entire 6 minutes)



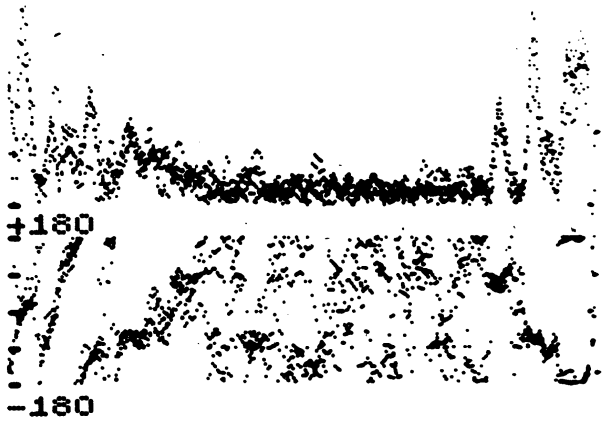
Second 3 minutes

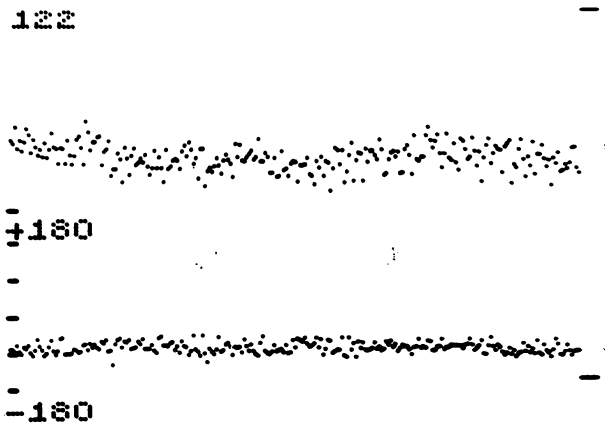
See Note 1

19 December 1966 0643 - 0649



See Note 1





19 December 1966 0843 - 0849

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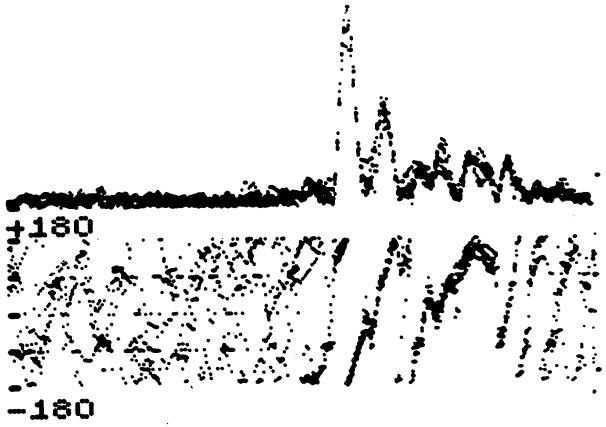
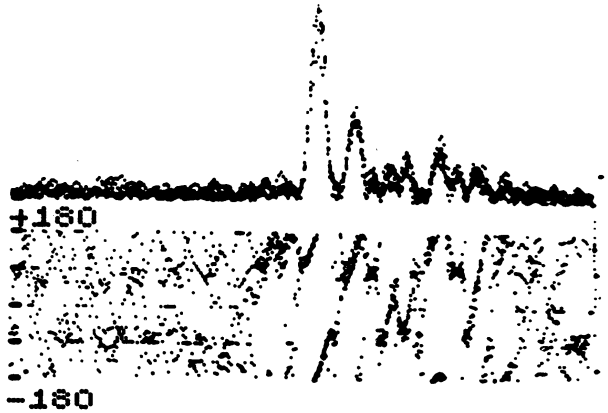
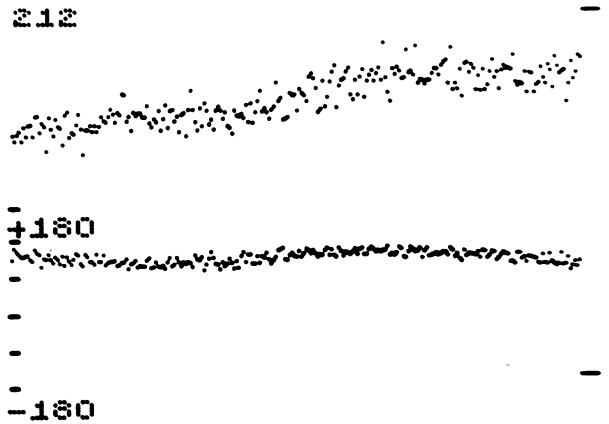




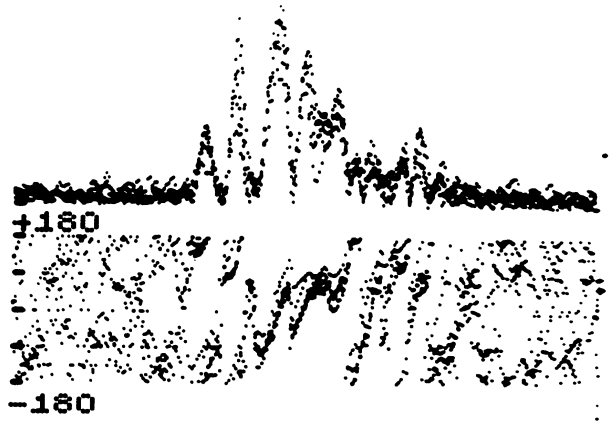


19 December 1966 1243 - 1249

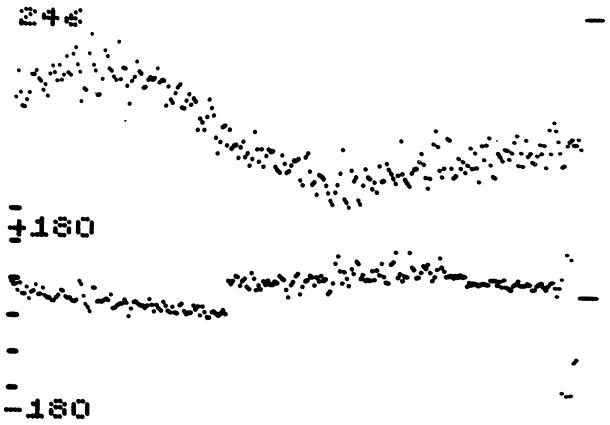
First 3 minutes

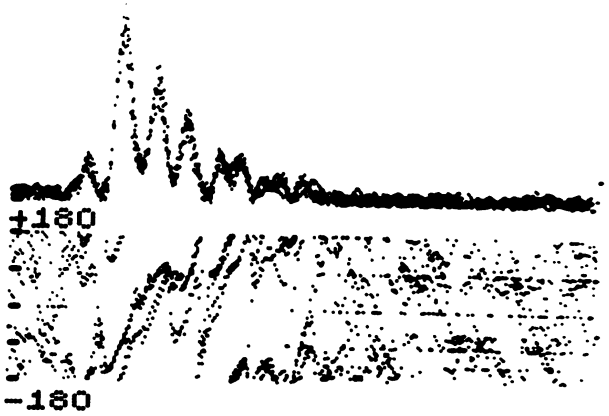
Second 3 minutes

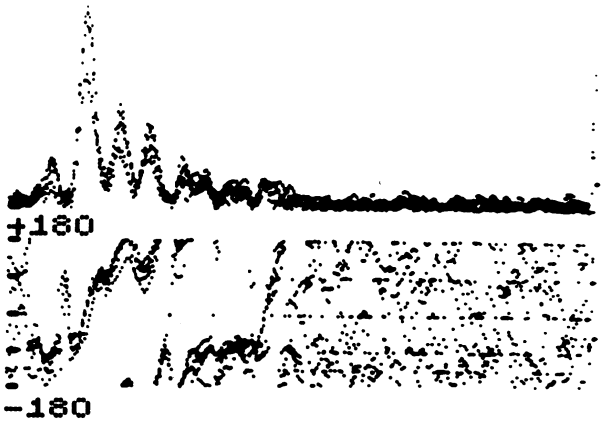
Carrier (entire 6 minutes)



19 December 1966 1443 - 1449







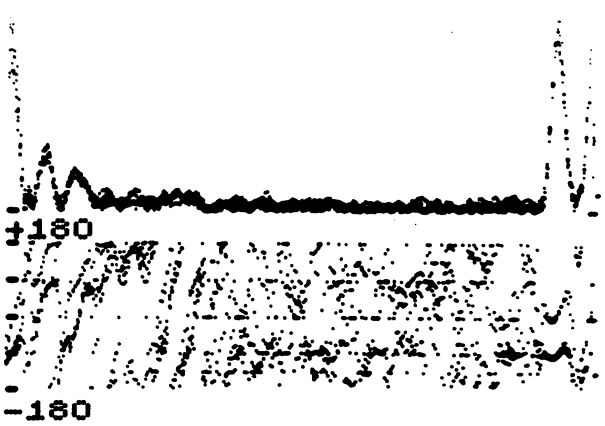
19 December 1966 1643 - 1649

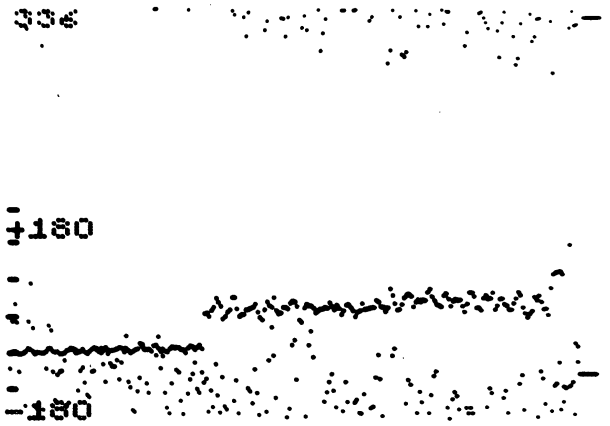
First 3 minutes

Second 3 minutes

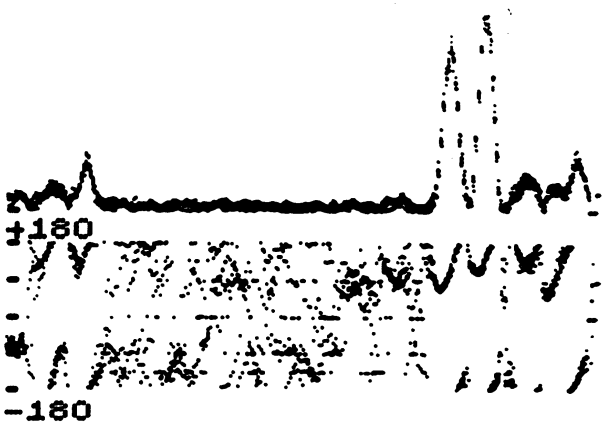
Carrier (entire 6 minutes)

See Note 1

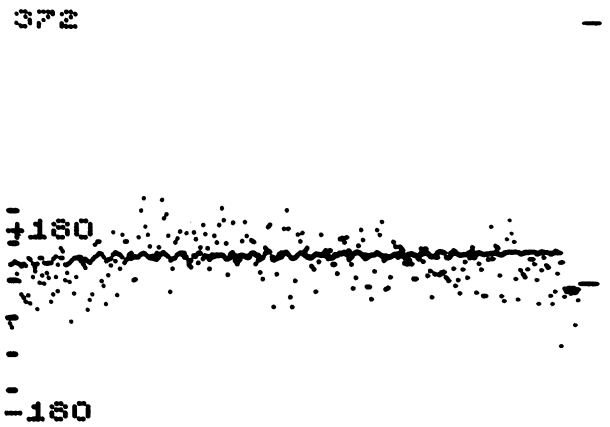




19 December 1966 1843 - 1849



See Note 1



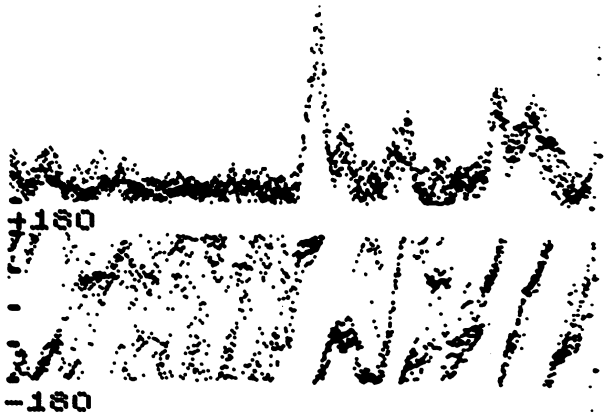
19 December 1966 2043 - 2049

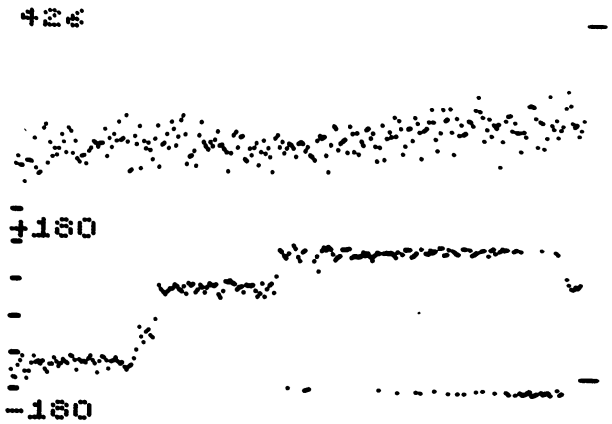
First 3 minutes

Second 3 minutes

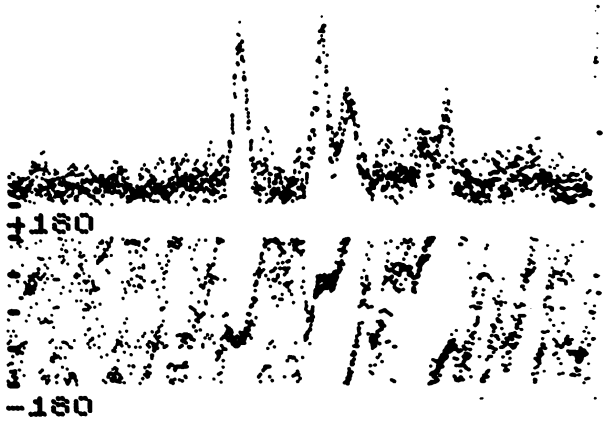
Carrier (entire 6 minutes)

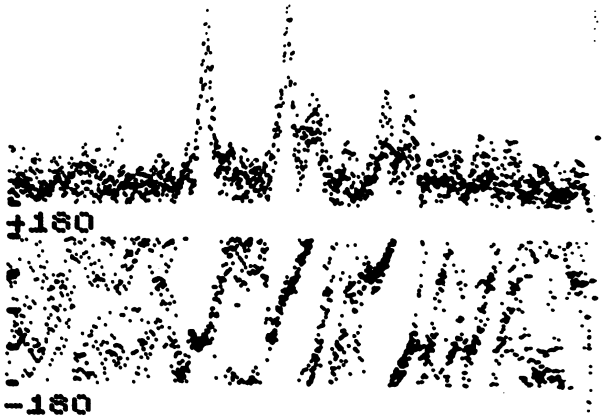
See Note 1

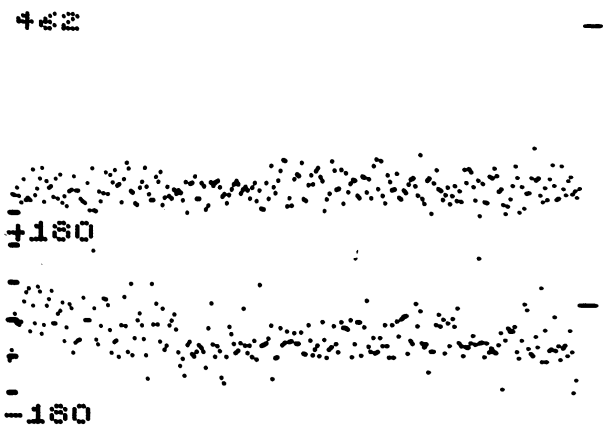




19 December 1966 2243 - 2249





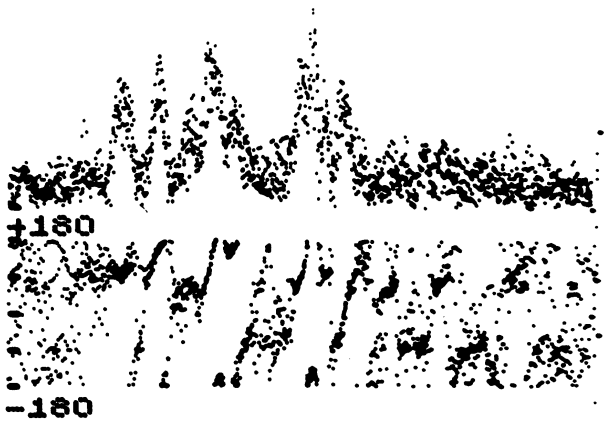


20 December 1966 0043 - 0049

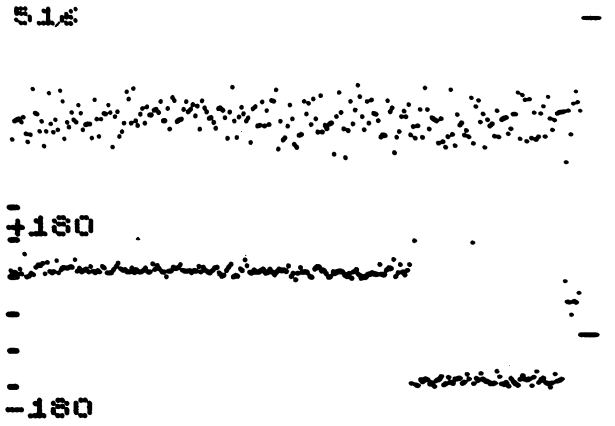
First 3 minutes

Second 3 minutes

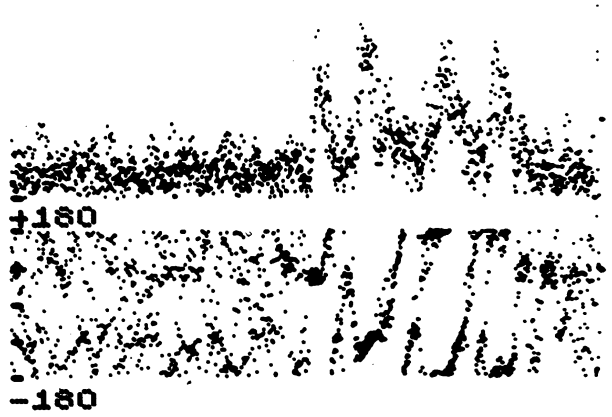
Carrier (entire 6 minutes)



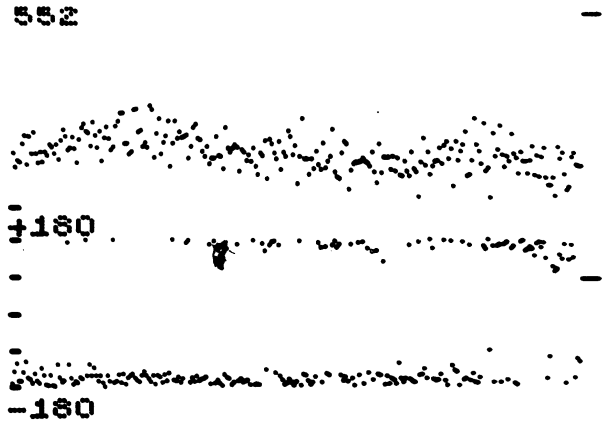
See Note 1



20 December 1966 0243 - 0249



See Note 1



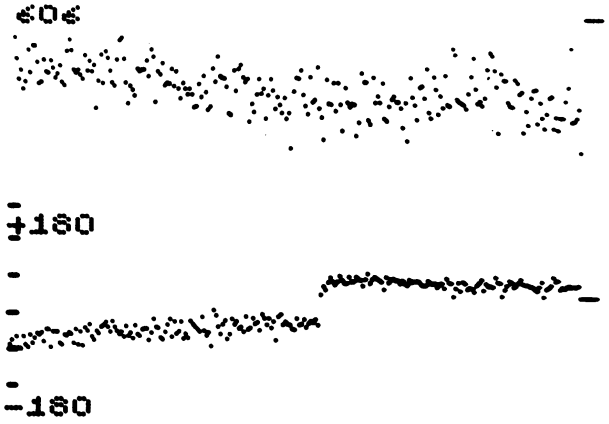
20 December 1966 0443 - 0449

First 3 minutes

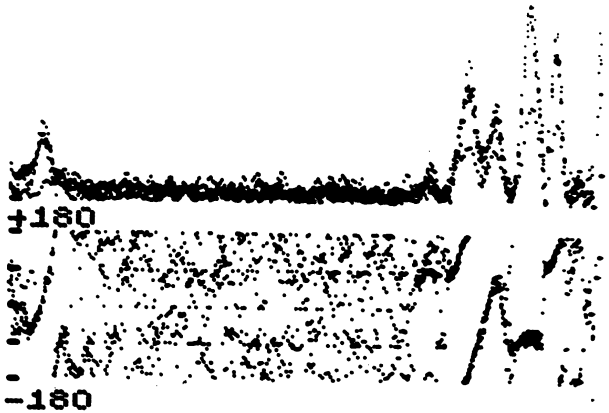
Second 3 minutes

Carrier (entire 6 minutes)

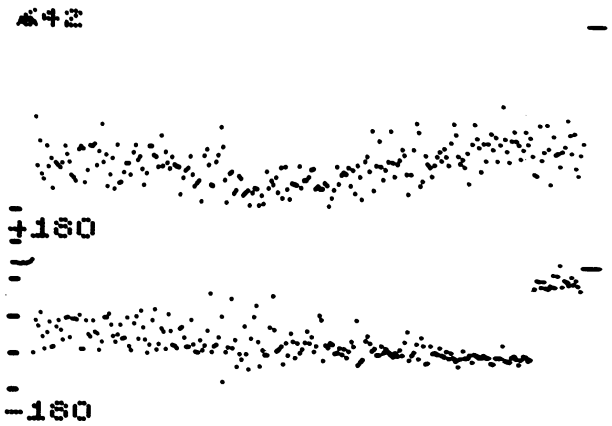
See Note 1



20 December 1966 0643 - 0649



See Note 1

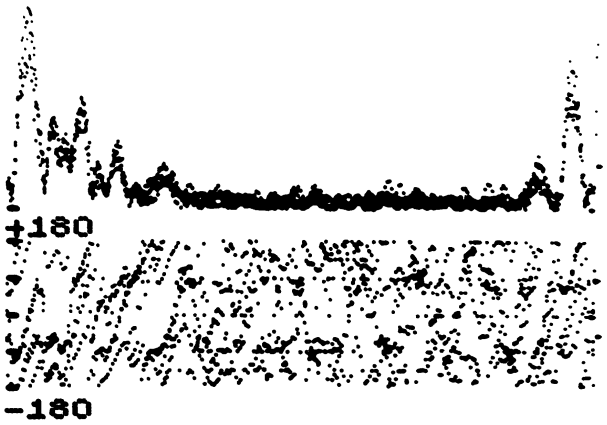


20 December 1966 0843 - 0849

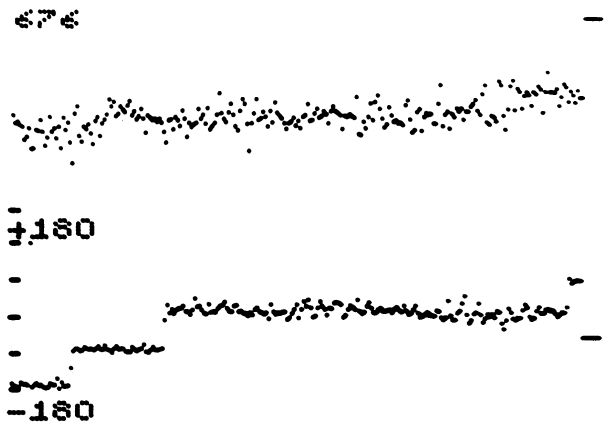
First 3 minutes

Second 3 minutes

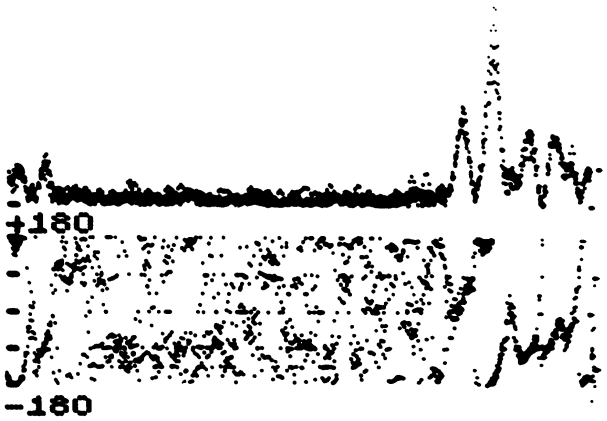
Carrier (entire 6 minutes)



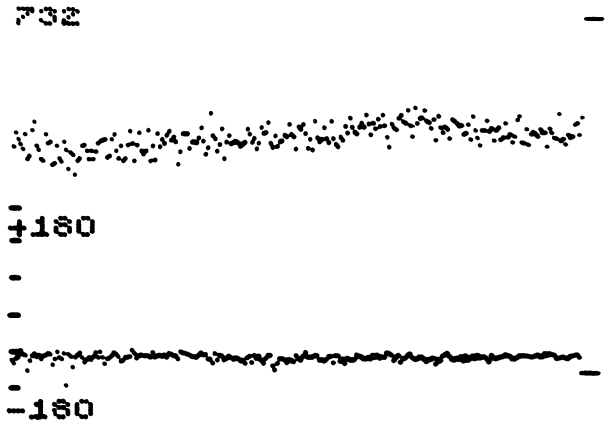
See Note 1



20 December 1966 1043 - 1049



See Note 1

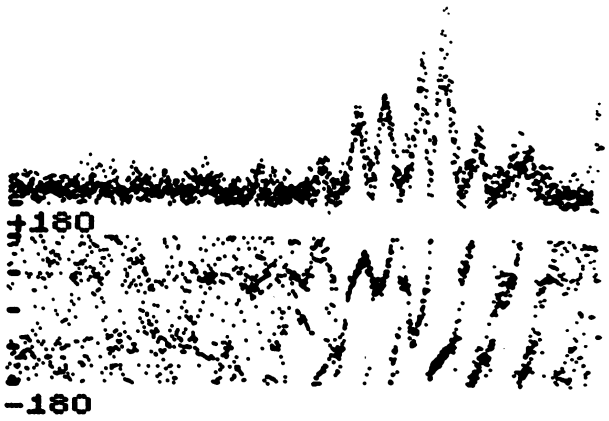


20 December 1966 1243 - 1249

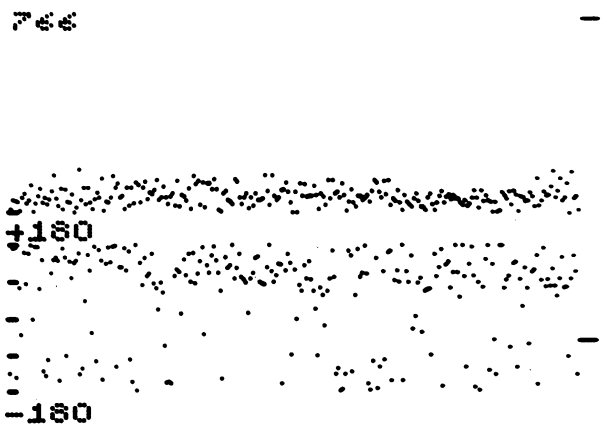
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



See Note 1



20 December 1966 1443 - 1449

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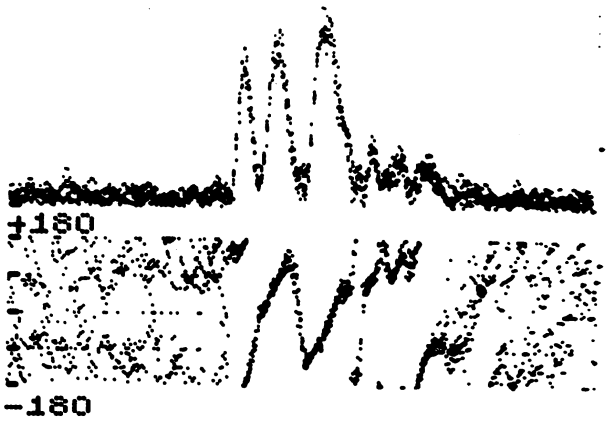
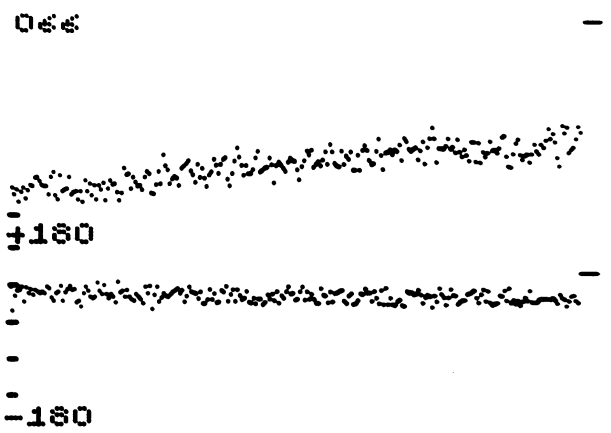


See Note 1

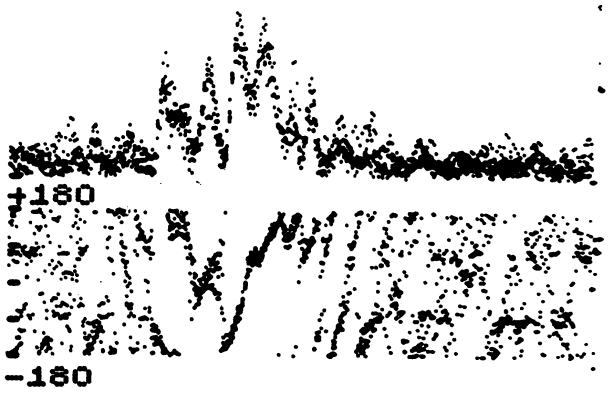


20 December 1966 1843 - 1849

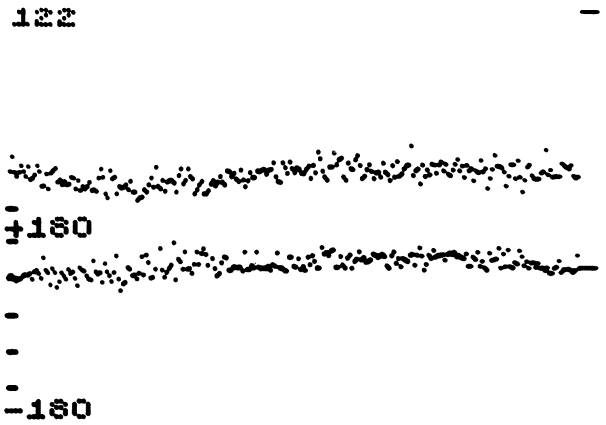
First 3 minutes

Second 3 minutes

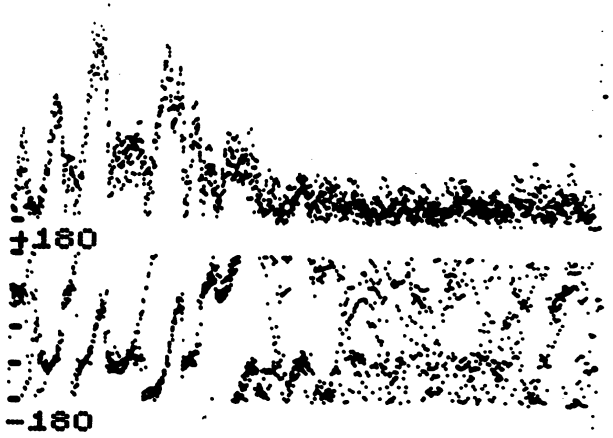
Carrier (entire 6 minutes)



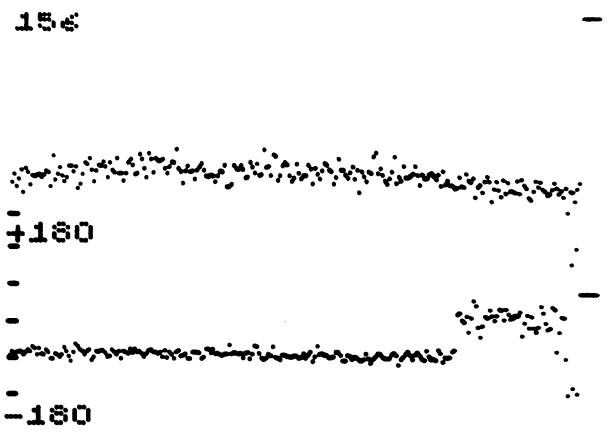
See Note 1



20 December 1966 2043 - 2049



See Note 1

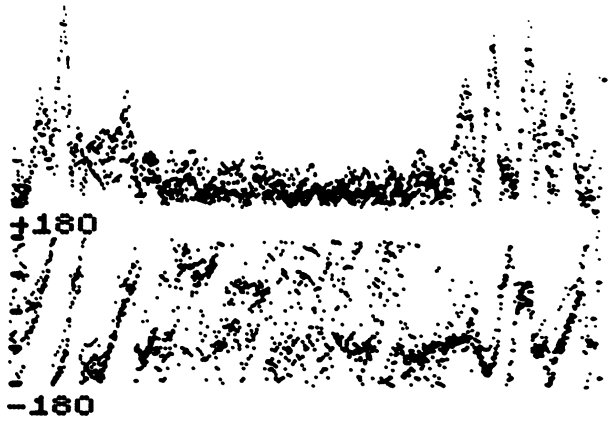


20 December 1966 2243 - 2249

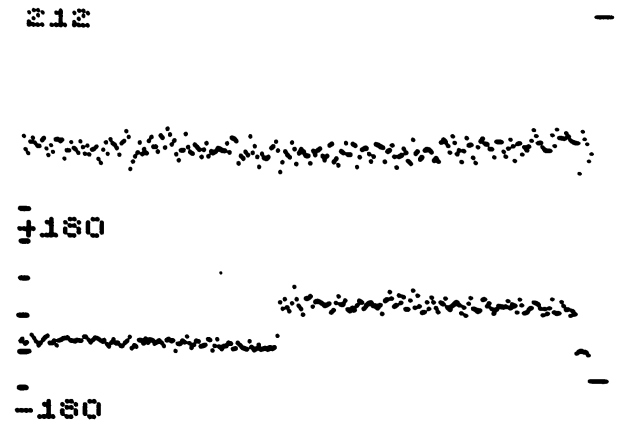
First 3 minutes

Second 3 minutes

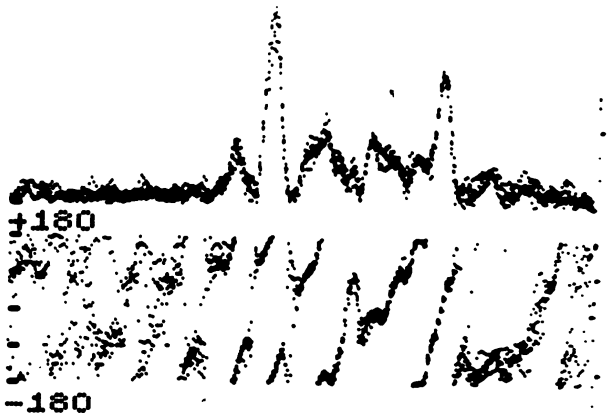
Carrier (entire 6 minutes)



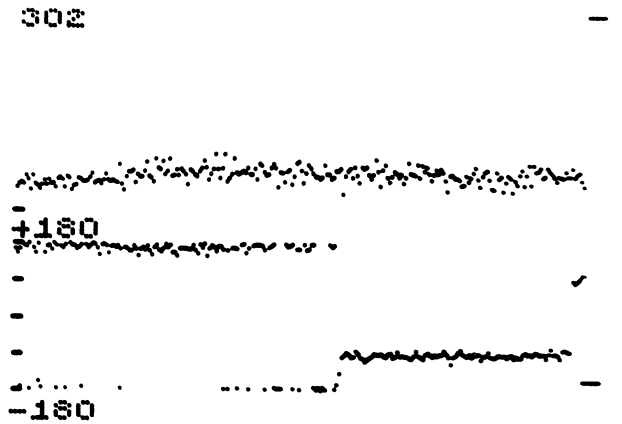
See Note 1



21 December 1966 0043 - 0049



See Note 1

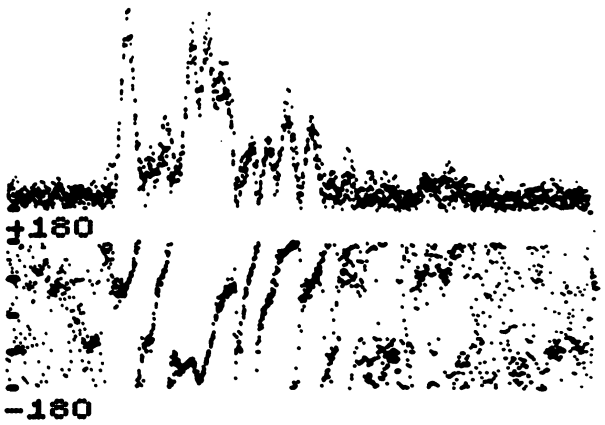


21 December 1966 0443 - 0449

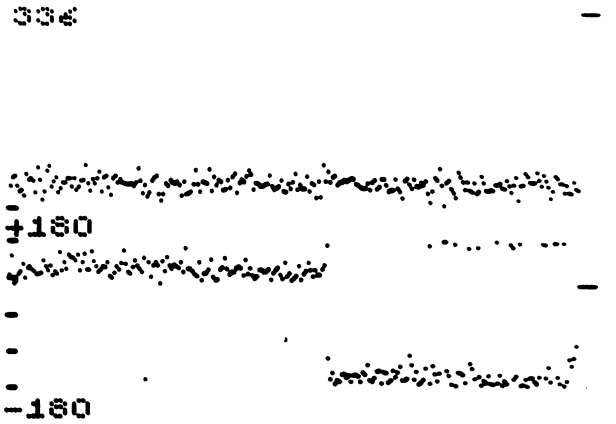
First 3 minutes

Second 3 minutes

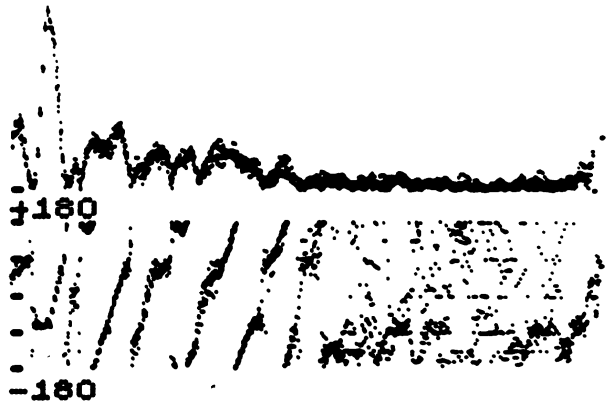
Carrier (entire 6 minutes)



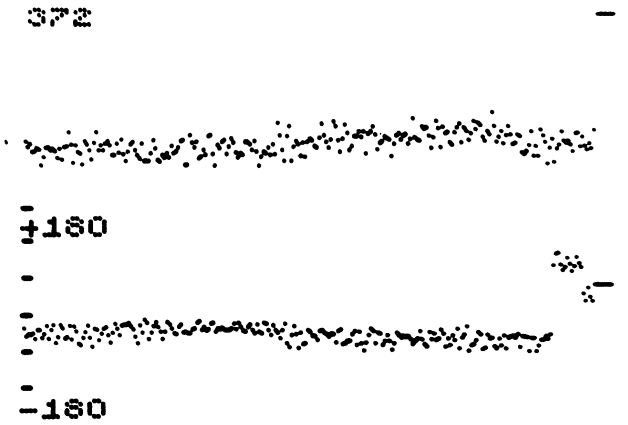
See Note 1



21 December 1966 0643 - 0649



See Note 1

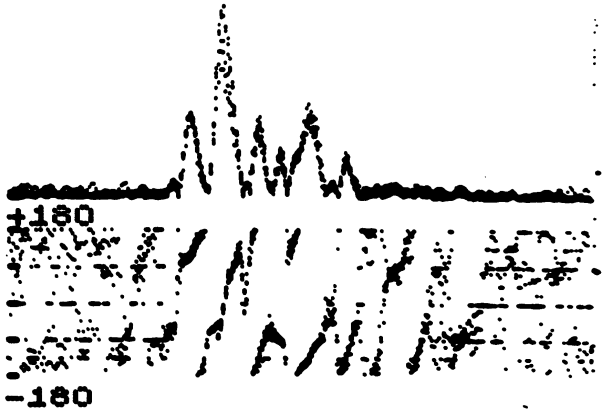


21 December 1966 0843 - 0849

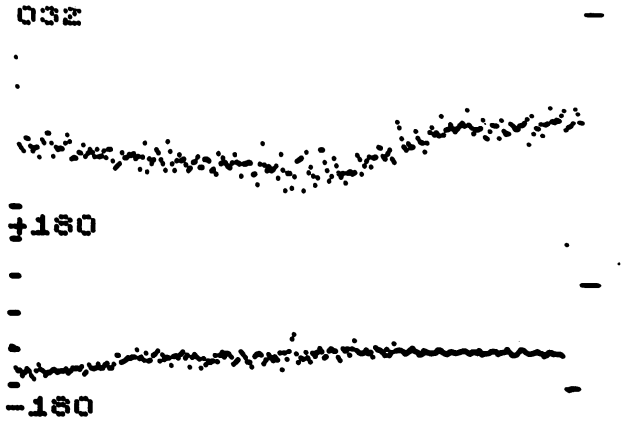
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

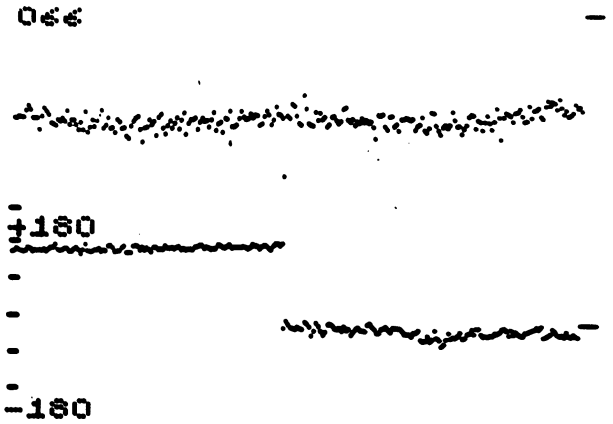


See Note 1



21 December 1966 1043 - 1049

See Note 1



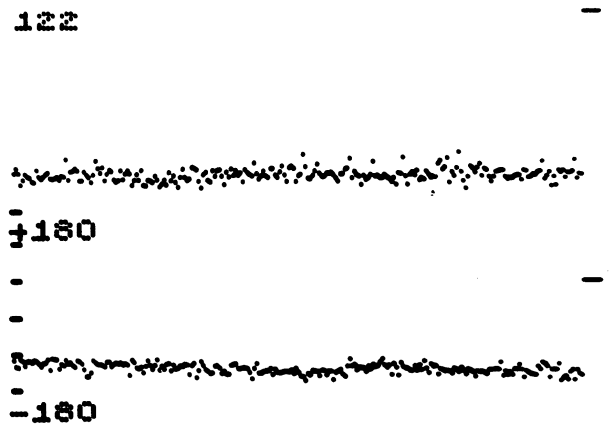
21 December 1966 1243 - 1249

First 3 minutes

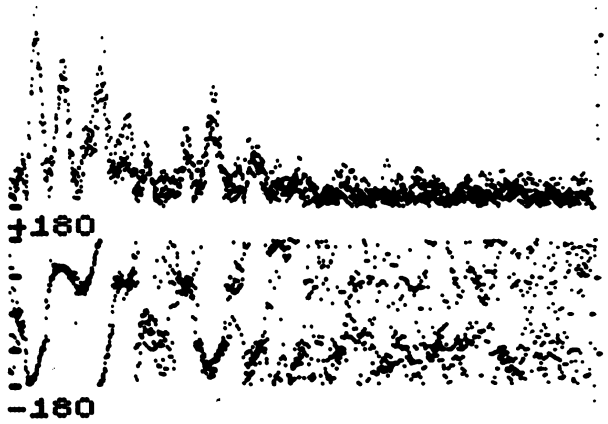
Second 3 minutes

Carrier (entire 6 minutes)

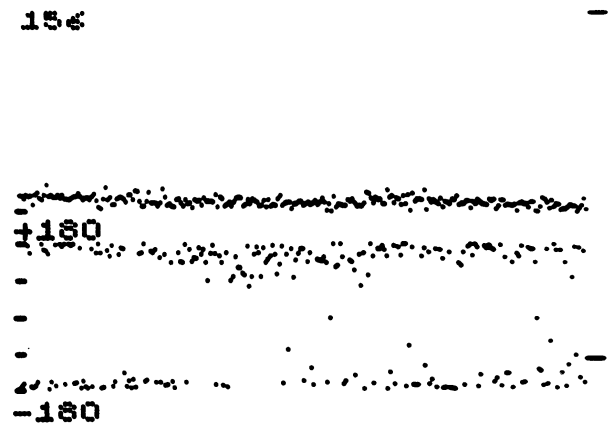
See Note 1



21 December 1966 1443 - 1449



See Note 1

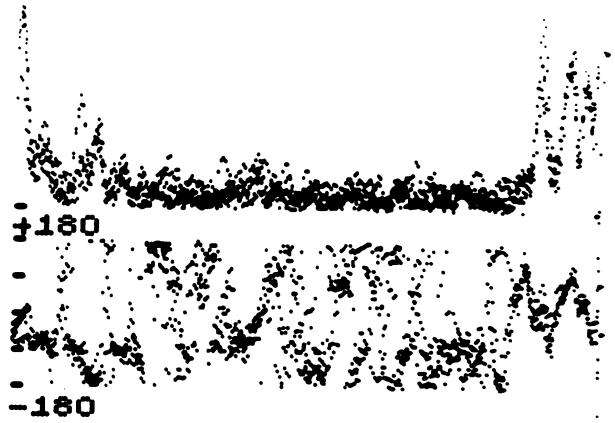


21 December 1966 1643 - 1649

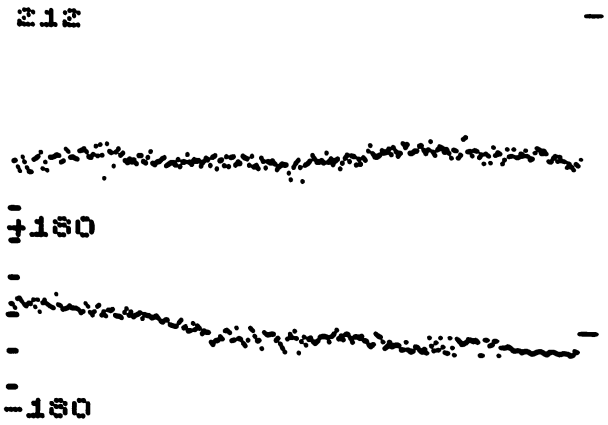
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



See Note 1



21 December 1966 1843 - 1849

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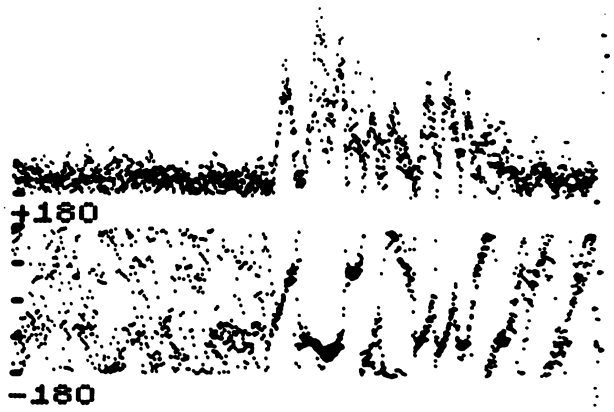
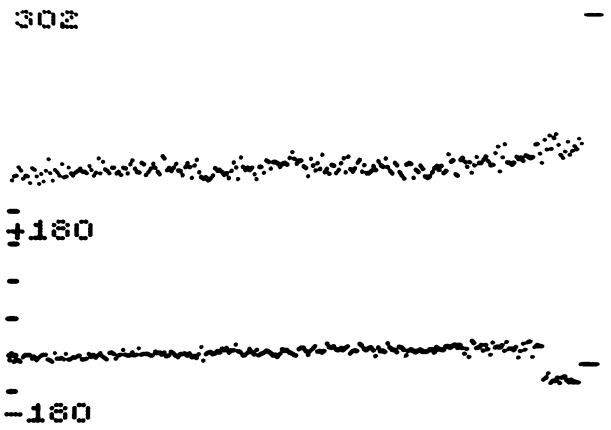


See Note 1

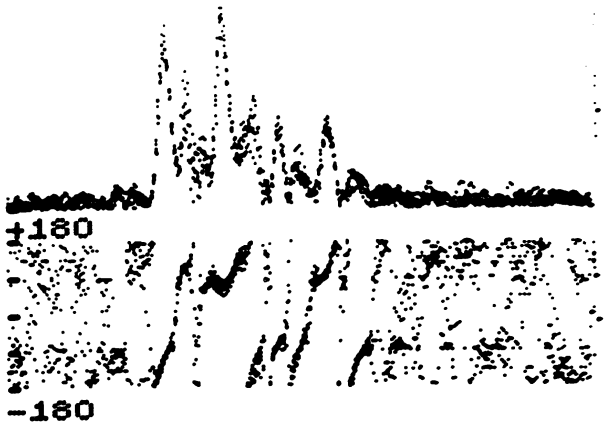


21 December 1966 2243 - 2249

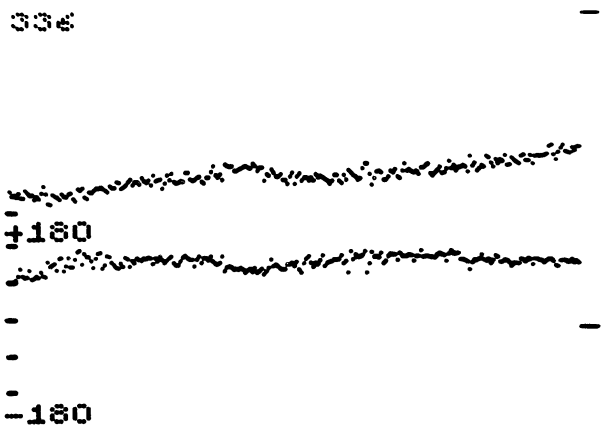
First 3 minutes

Second 3 minutes

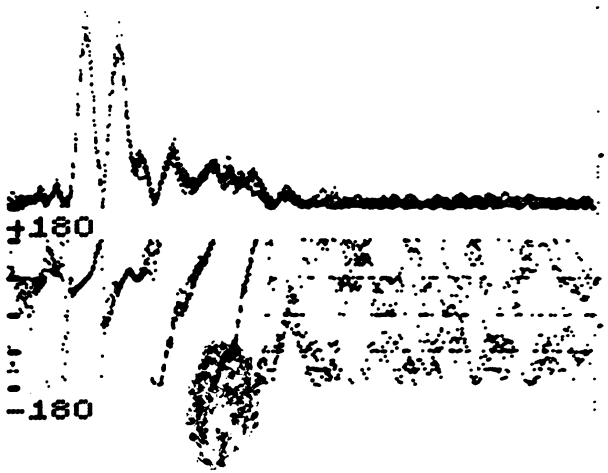
Carrier (entire 6 minutes)



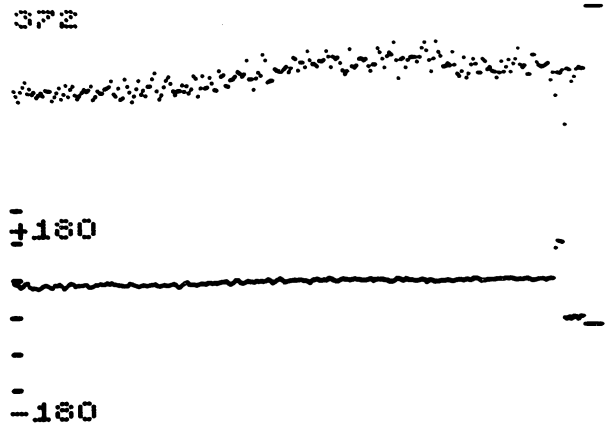
See Note 1



22 December 1966 0043 - 0049



See Note 1

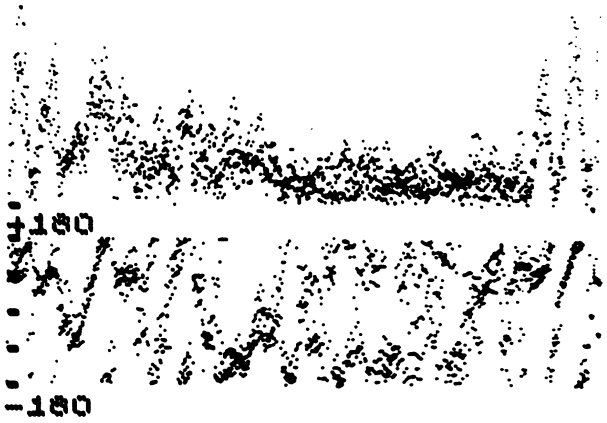


22 December 1966 0243 - 0249

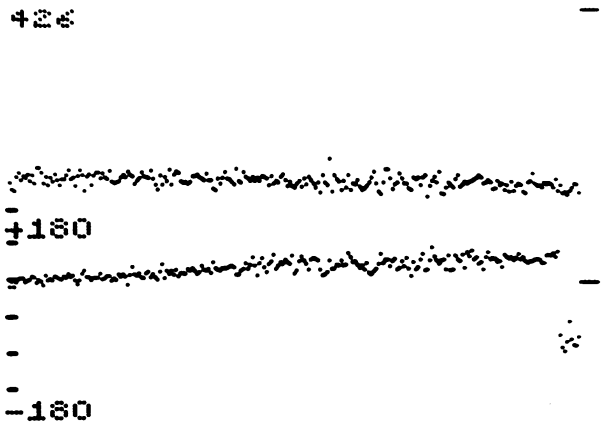
First 3 minutes

Second 3 minutes

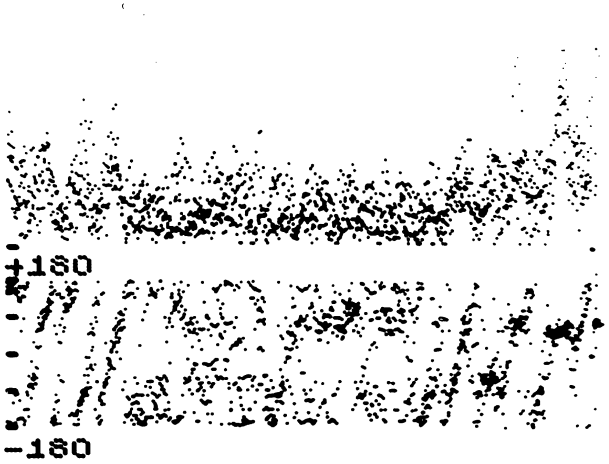
Carrier (entire 6 minutes)



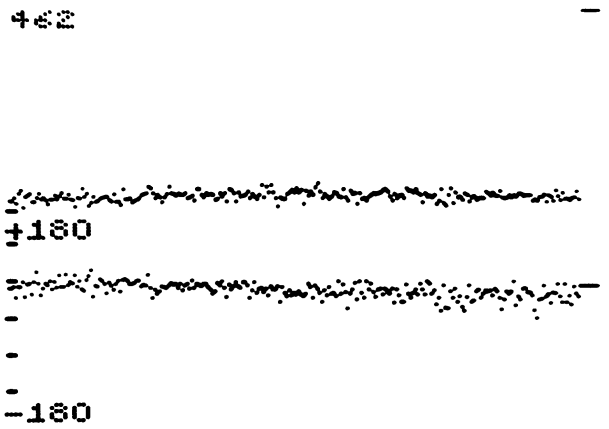
See Note 1



22 December 1966 0443 - 0449



See Note 1

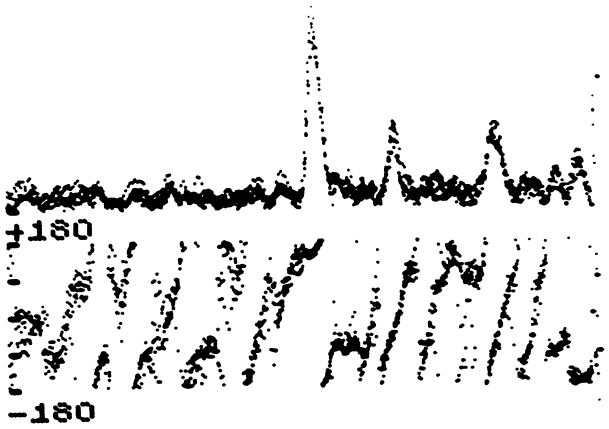


22 December 1966 0643 - 0649

First 3 minutes

Second 3 minutes

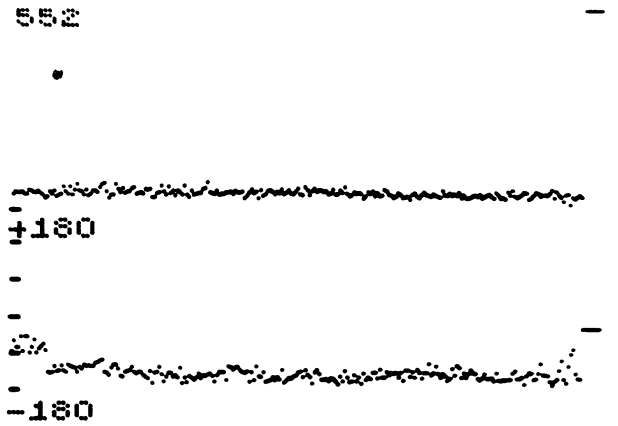
Carrier (entire 6 minutes)



See Note 1

22 December 1966 0843 - 0849

See Note 1

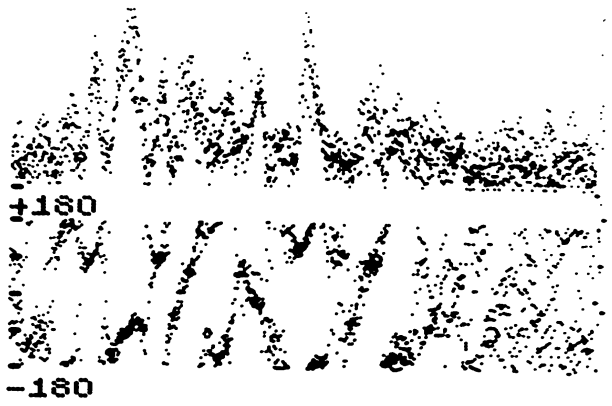


22 December 1966 1043 - 1049

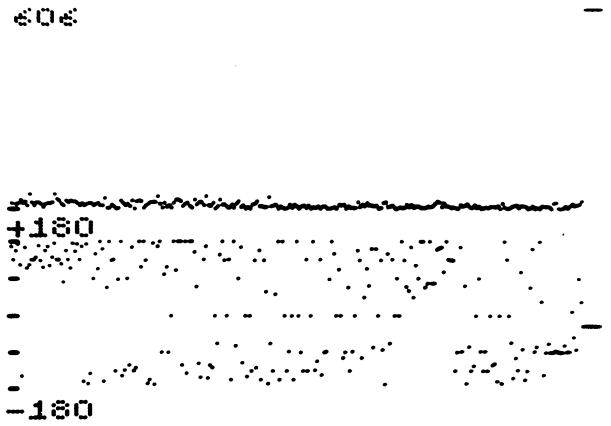
First 3 minutes

Second 3 minutes

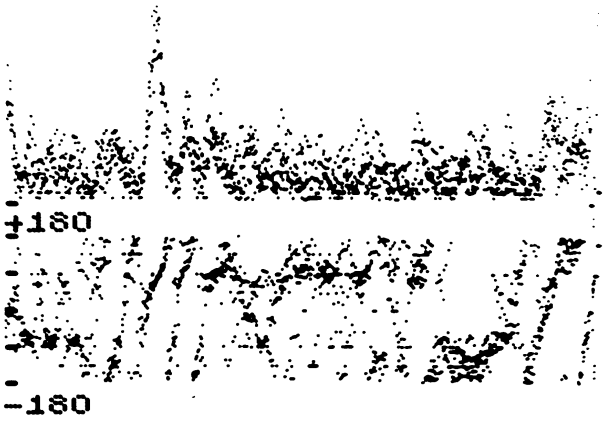
Carrier (entire 6 minutes)



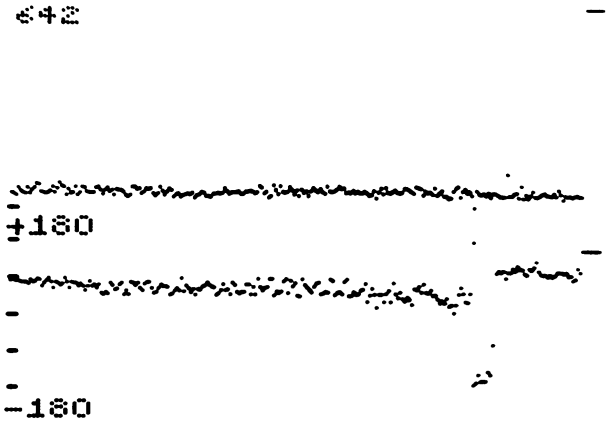
See Note 1



22 December 1966 1243 - 1249



See Note 1

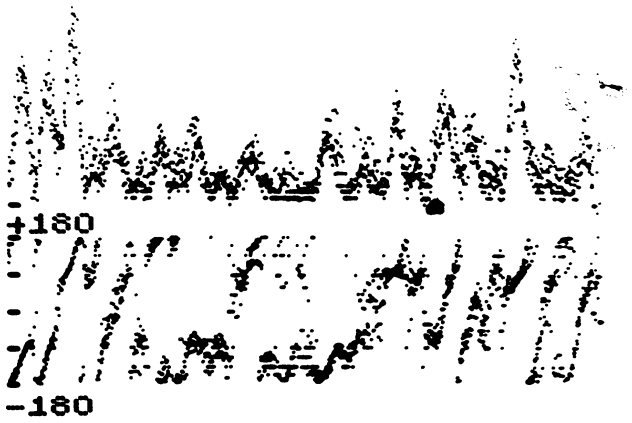


22 December 1966 1443 - 1449

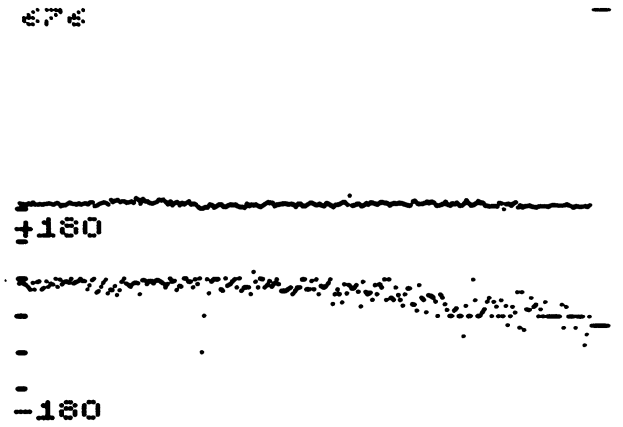
First 3 minutes

Second 3 minutes

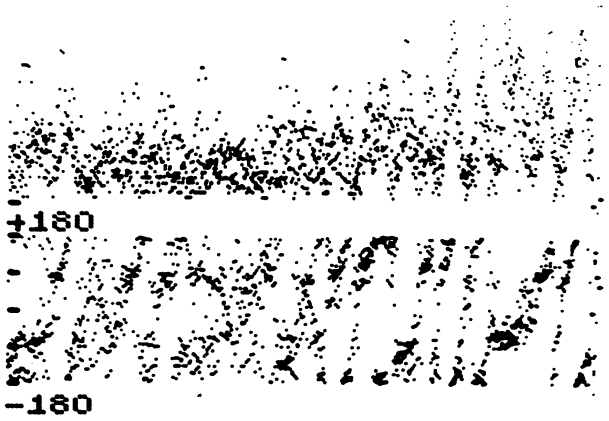
Carrier (entire 6 minutes)



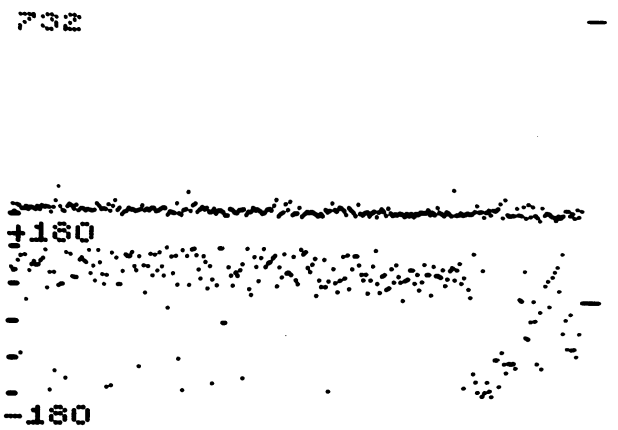
See Note 1



22 December 1966 1643 - 1649



See Note 1

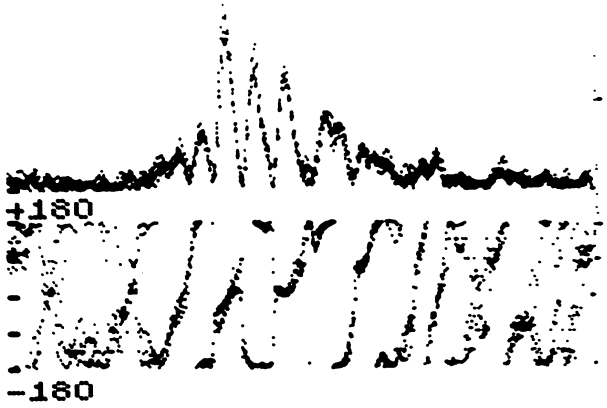


22 December 1966 1843 - 1849

First 3 minutes

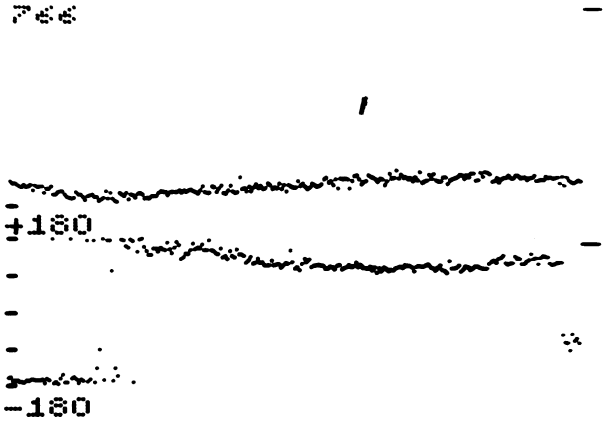
Second 3 minutes

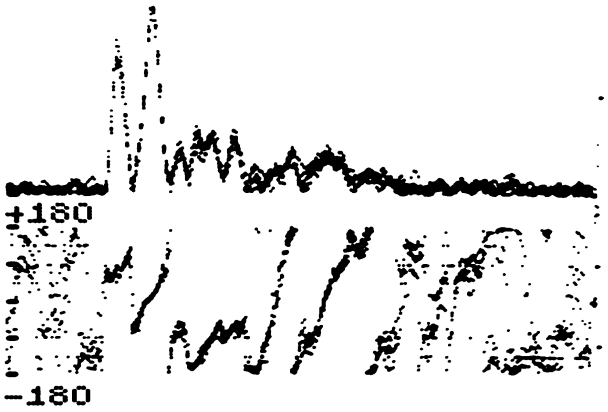
Carrier (entire 6 minutes)



See Note 1

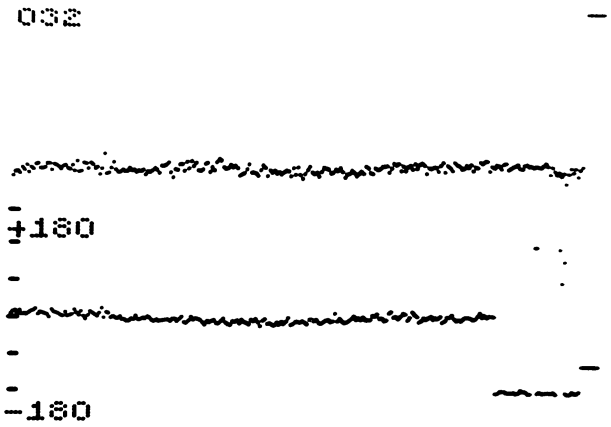
22 December 1966 2043 - 2049





See Note 1

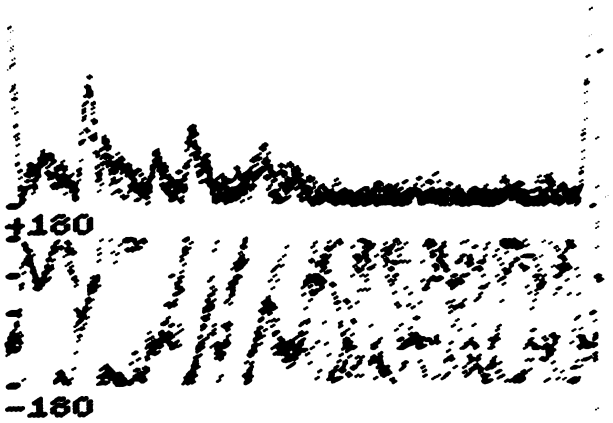
22 December 1966 2243 - 2249



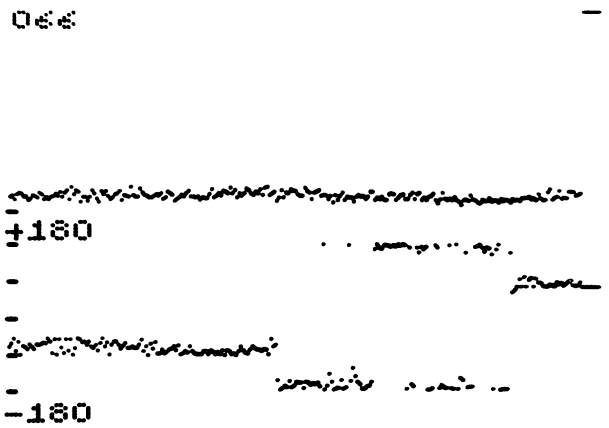
First 3 minutes

Second 3 minutes

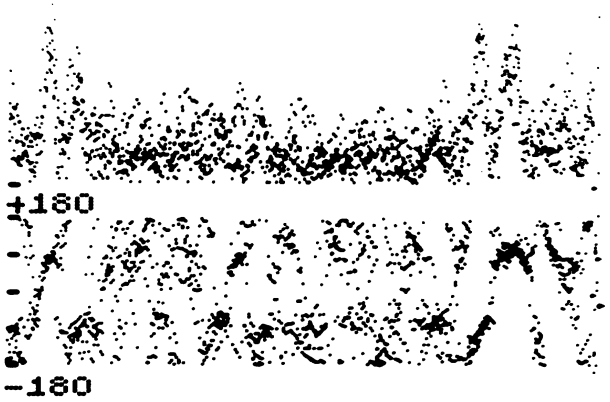
Carrier (entire 6 minutes)



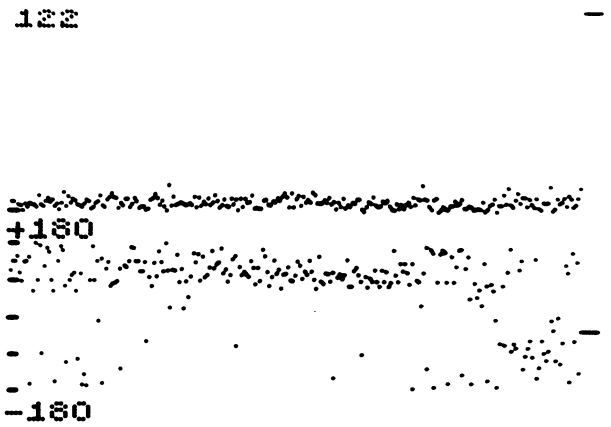
See Note 1



23 December 1966 0043 - 0049



See Note 1

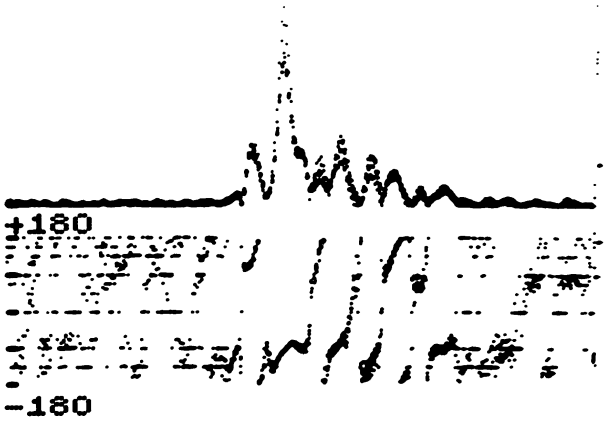


23 December 1966 0243 - 0249

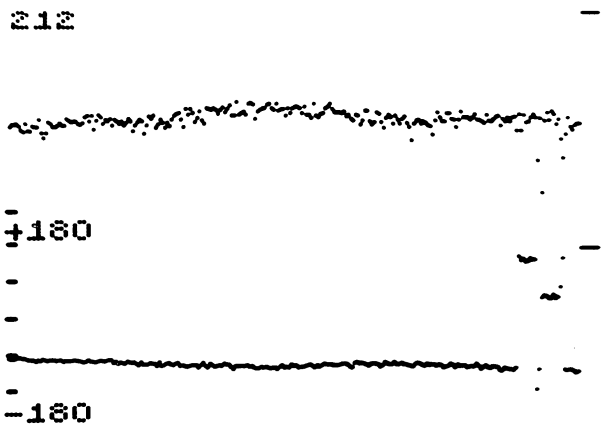
First 3 minutes

Second 3 minutes

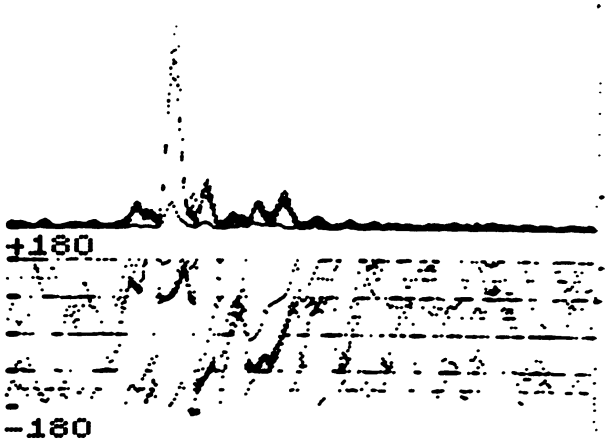
Carrier (entire 6 minutes)



See Note 1



23 December 1966 0643 - 0649



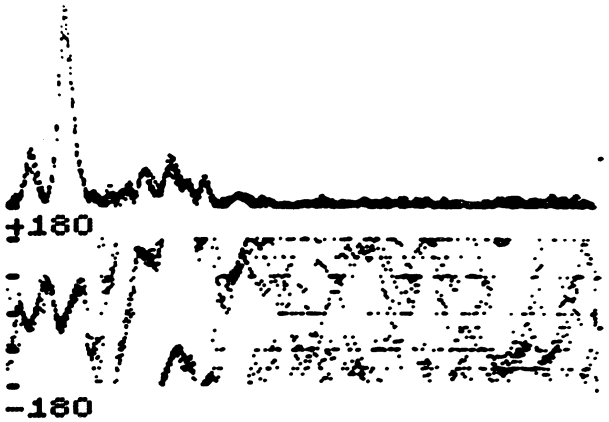
See Note 1

23 December 1966 0843 - 0849

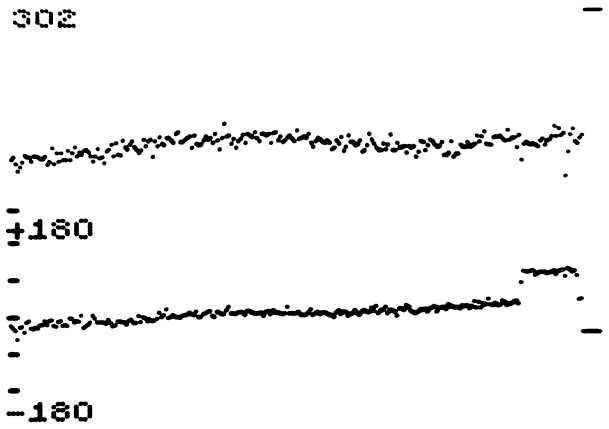
First 3 minutes

Second 3 minutes

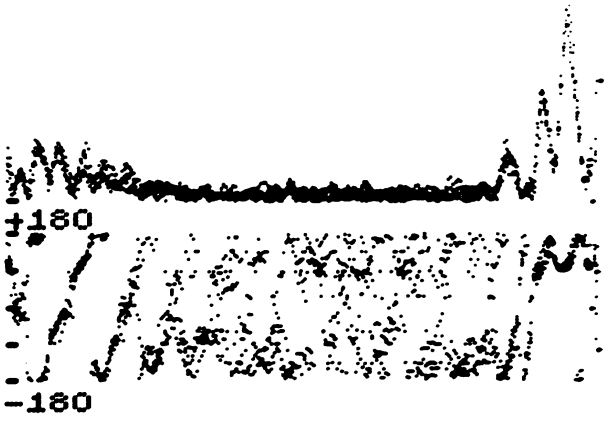
Carrier (entire 6 minutes)



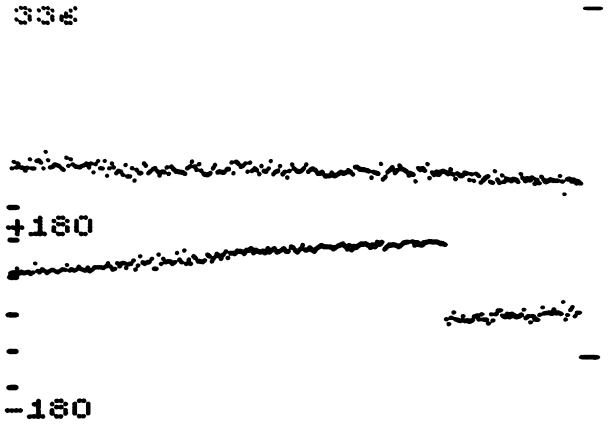
See Note 1



23 December 1966 1043 - 1049



See Note 1

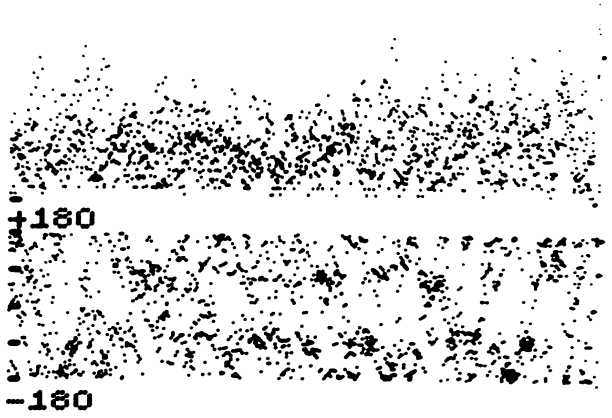


23 December 1966 1243 - 1249

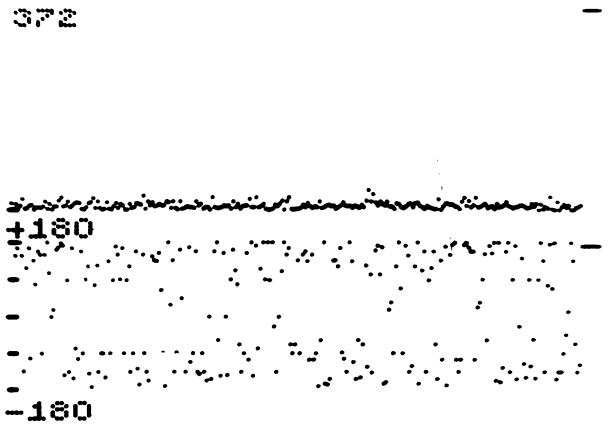
First 3 minutes

Second 3 minutes

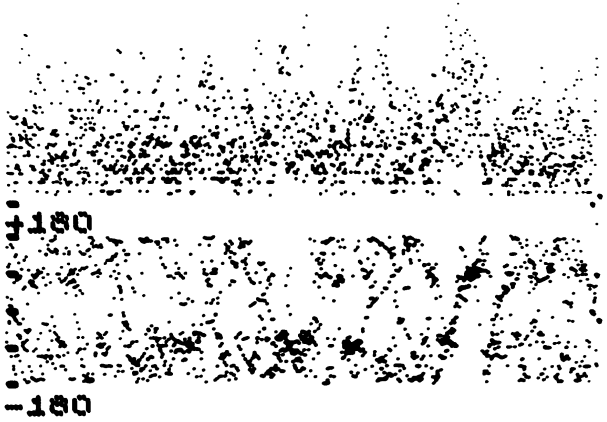
Carrier (entire 6 minutes)



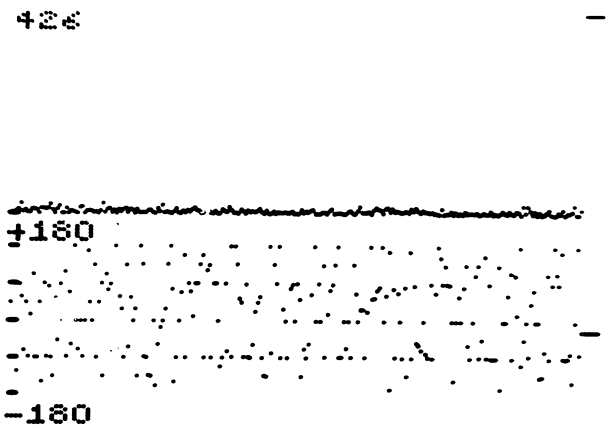
See Note 1



23 December 1966 1443 - 1449



See Note 1

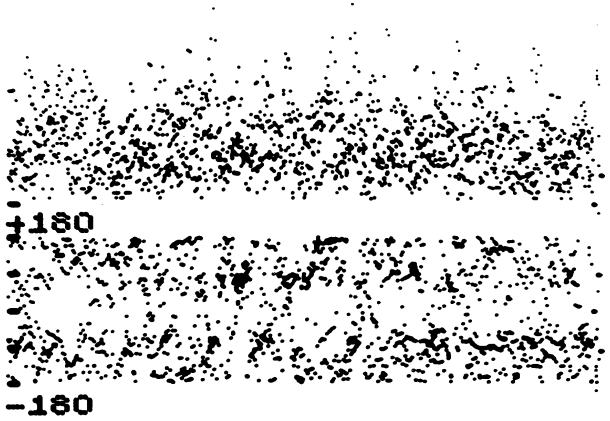


23 December 1966 1643 - 1649

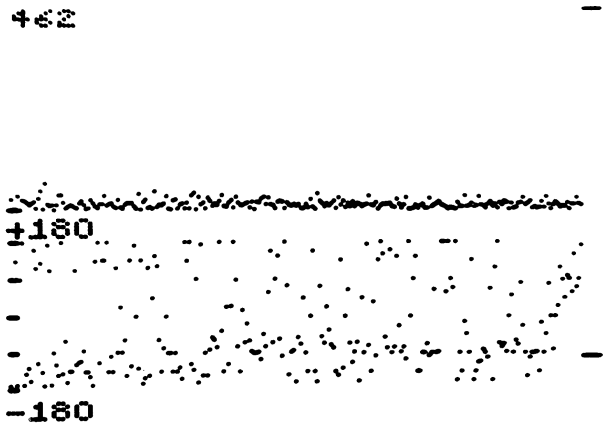
First 3 minutes

Second 3 minutes

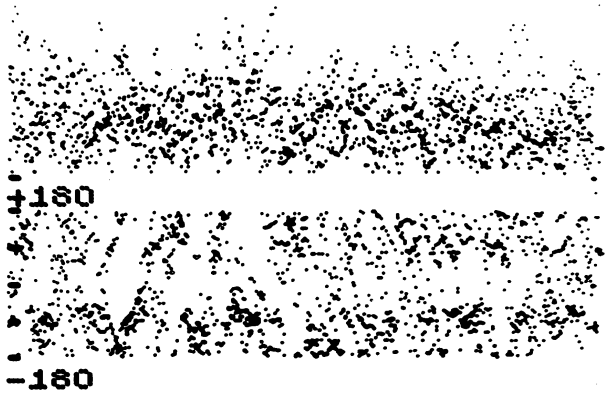
Carrier (entire 6 minutes)



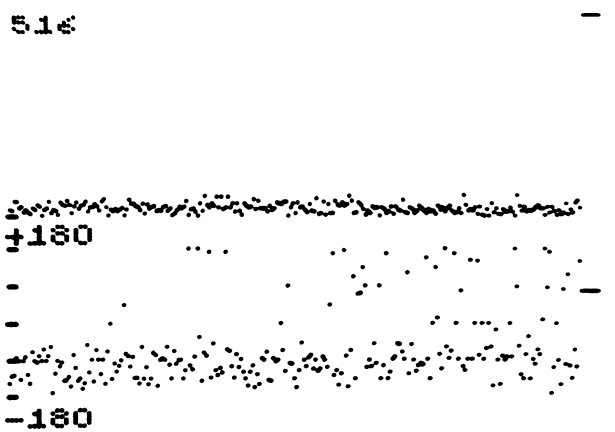
See Note 1



23 December 1966 1843 - 1849



See Note 1

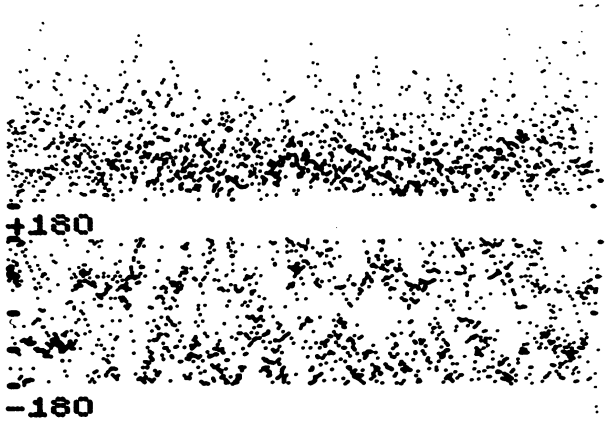


23 December 1966 2043 - 2049

First 3 minutes

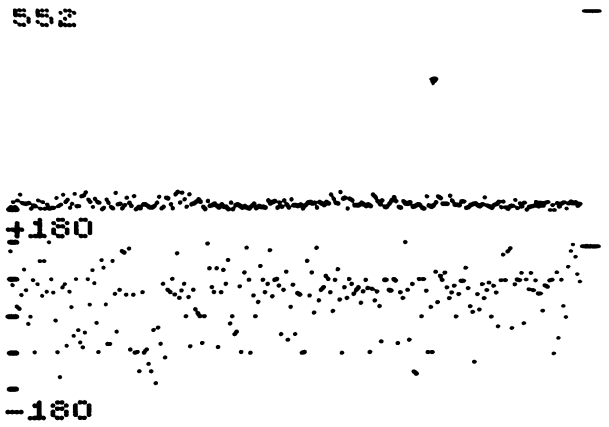
Second 3 minutes

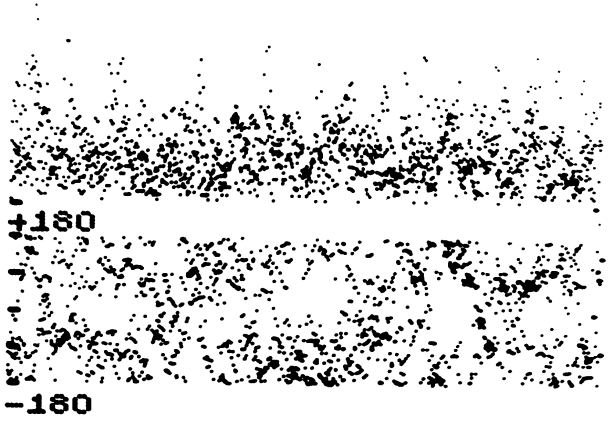
Carrier (entire 6 minutes)



See Note 1

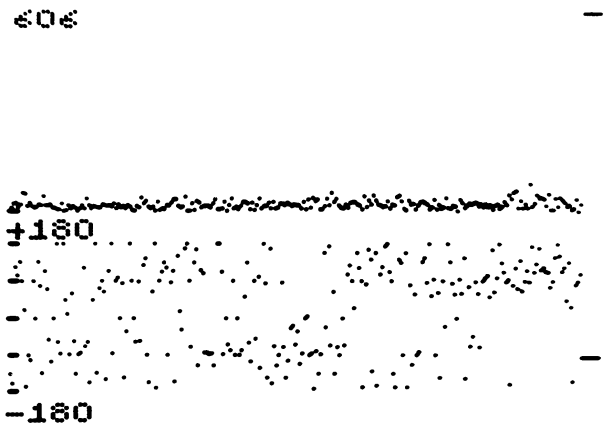
23 December 1966 2243 - 2249





See Note 1

24 December 1966 0043 - 0049

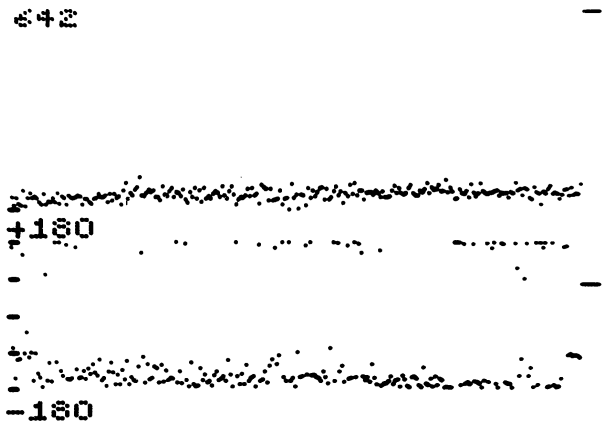


First 3 minutes

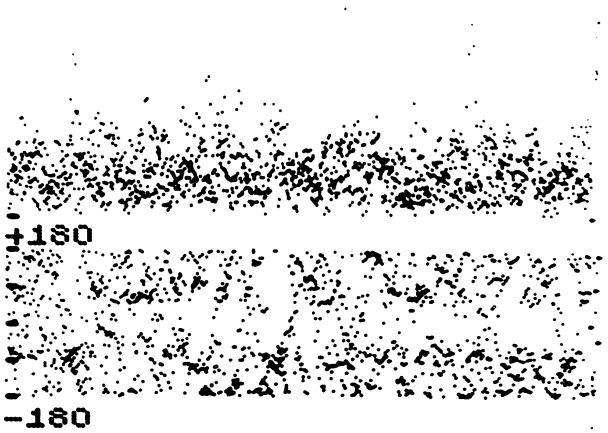
Second 3 minutes

Carrier (entire 6 minutes)

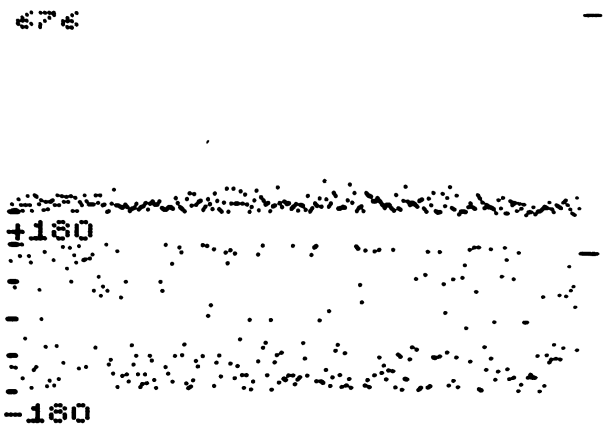
See Note 1



24 December 1966 0243 - 0249



See Note 1



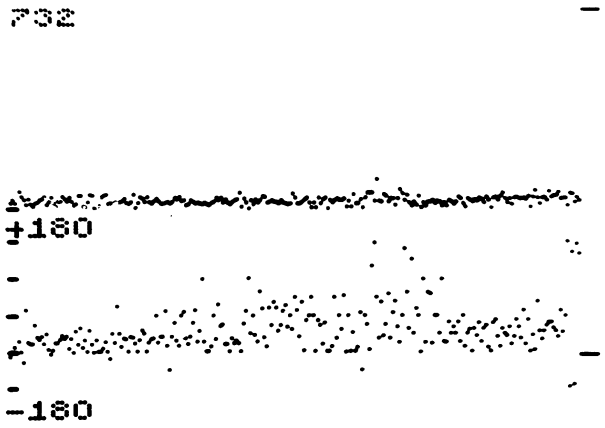
24 December 1966 0443 - 0449

First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

See Note 1



24 December 1966 0643 - 0649

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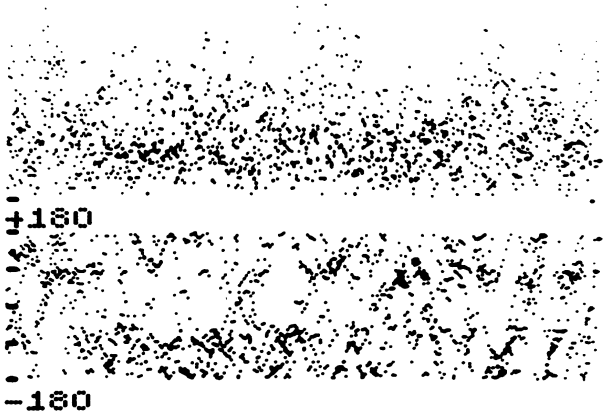
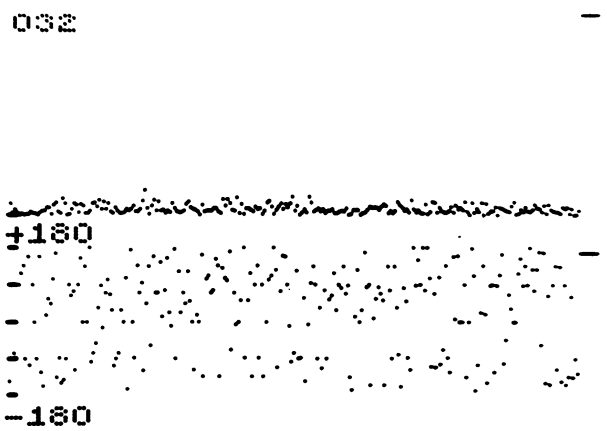


See Note 1

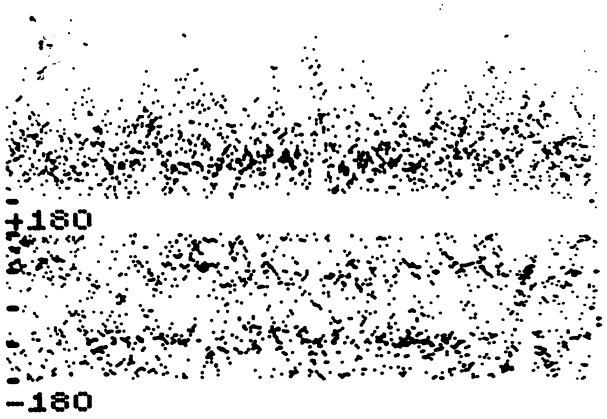


24 December 1966 1043 - 1049

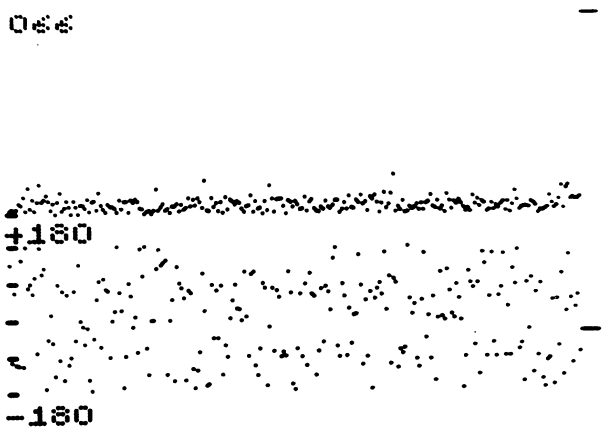
First 3 minutes

Second 3 minutes

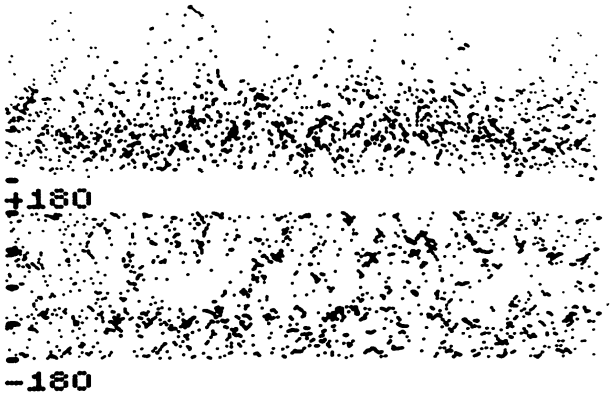
Carrier (entire 6 minutes)



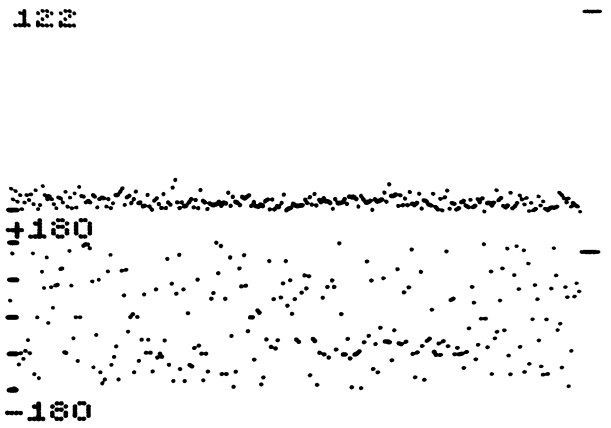
See Note 1



24 December 1966 1243 - 1249



See Note 1

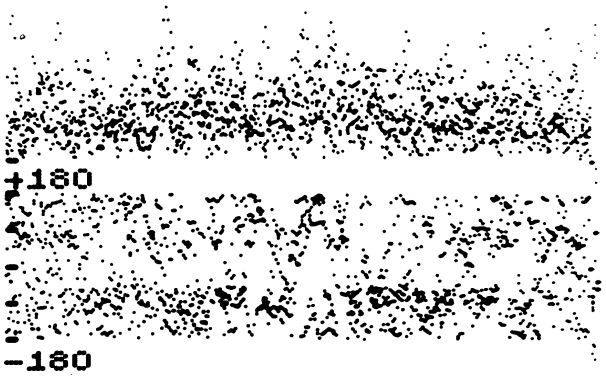


24 December 1966 1443 - 1449

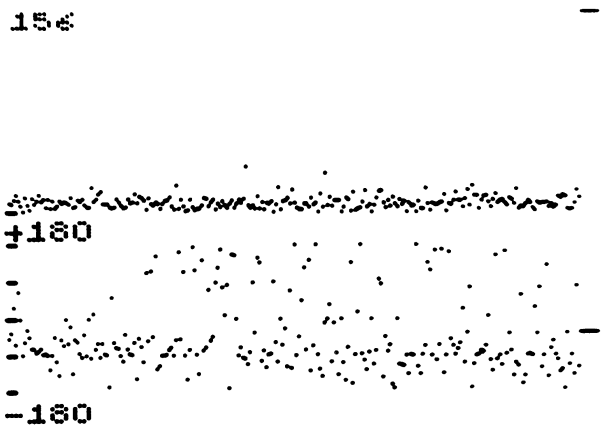
First 3 minutes

Second 3 minutes

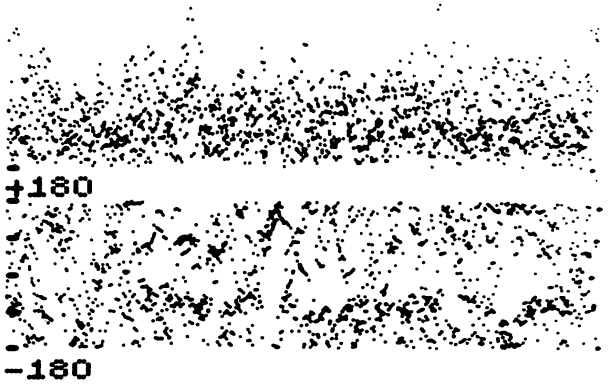
Carrier (entire 6 minutes)



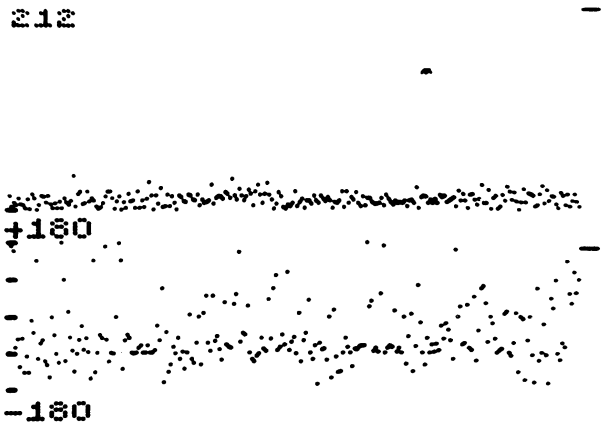
See Note 1



24 December 1966 1643 - 1649



See Note 1

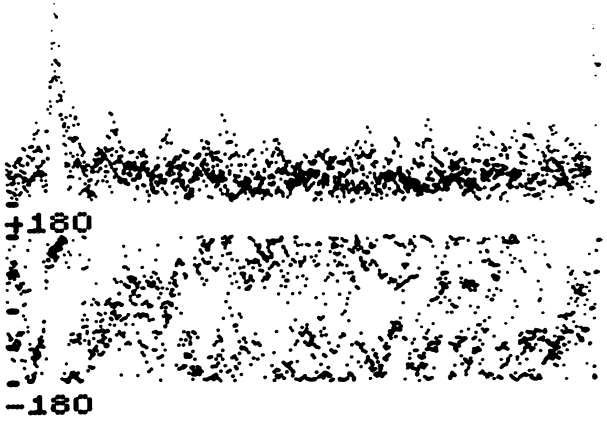


24 December 1966 1843 - 1849

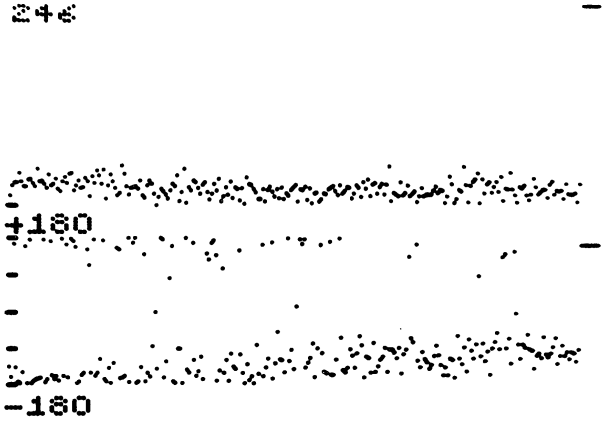
First 3 minutes

Second 3 minutes

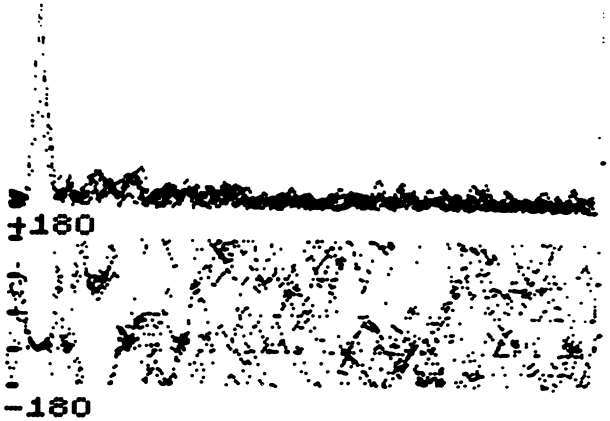
Carrier (entire 6 minutes)



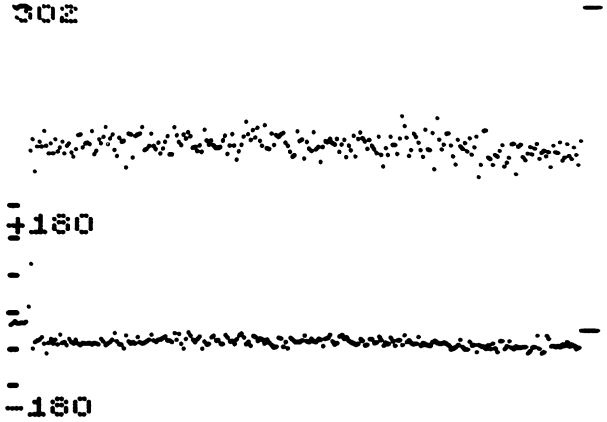
See Note 1



24 December 1966 2043 - 2049



See Note 1

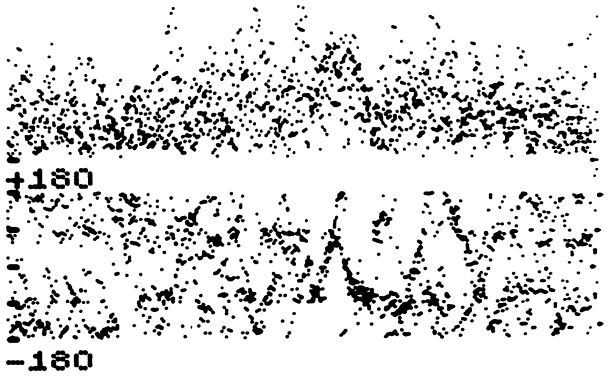


24 December 1966 2243 - 2249

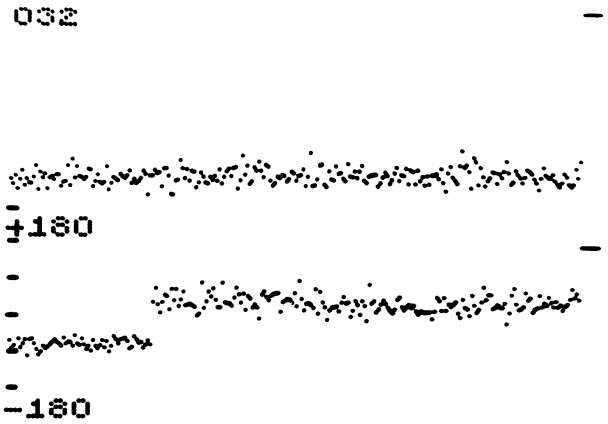
First 3 minutes

Second 3 minutes

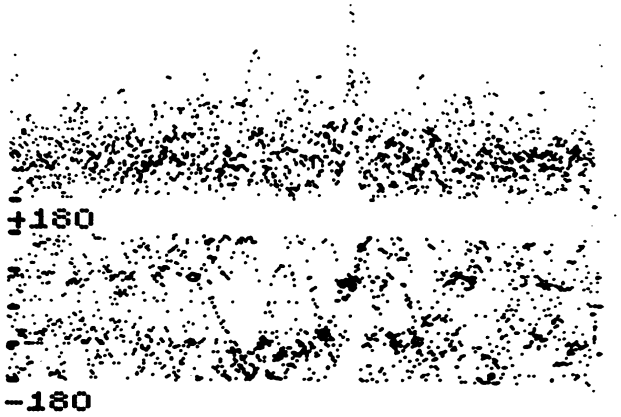
Carrier (entire 6 minutes)



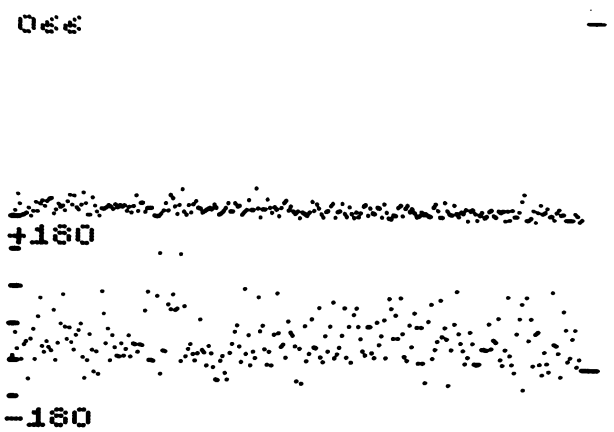
See Note 1



25 December 1966 0043 - 0049



See Note 1

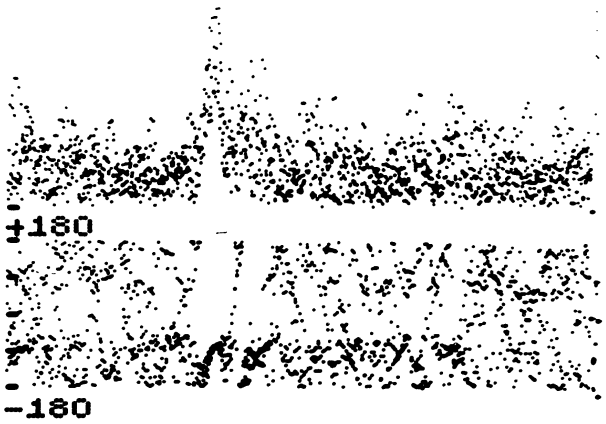


25 December 1966 0243 - 0249

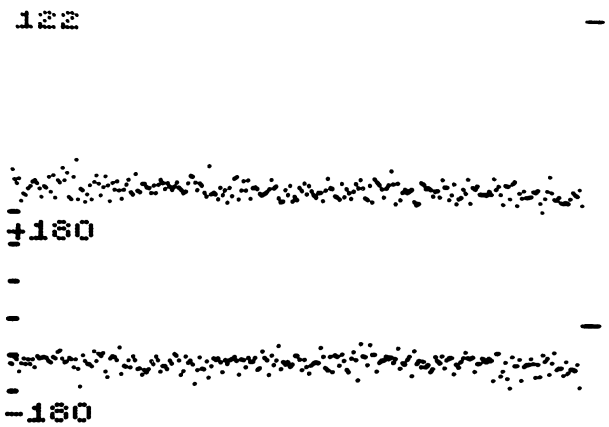
First 3 minutes

Second 3 minutes

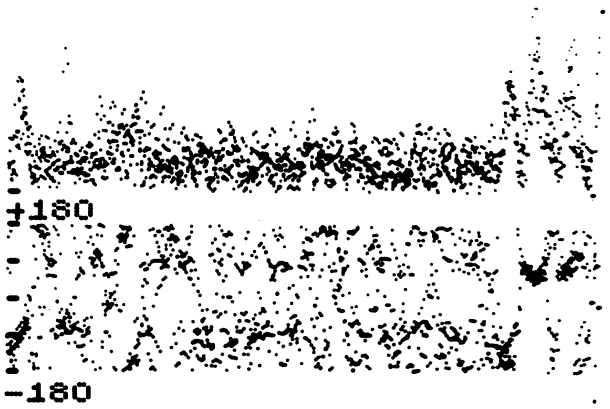
Carrier (entire 6 minutes)



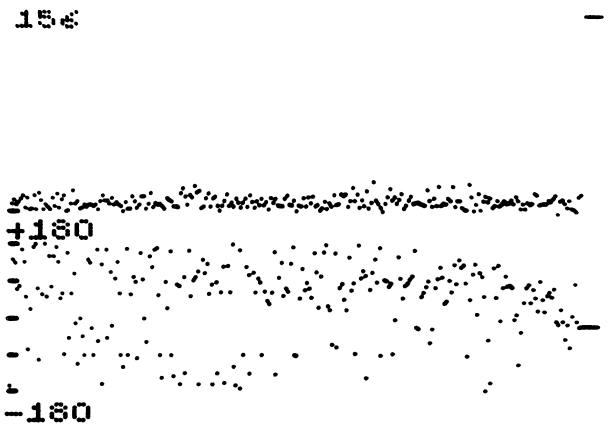
See Note 1



25 December 1966 0443 - 0449



See Note 1

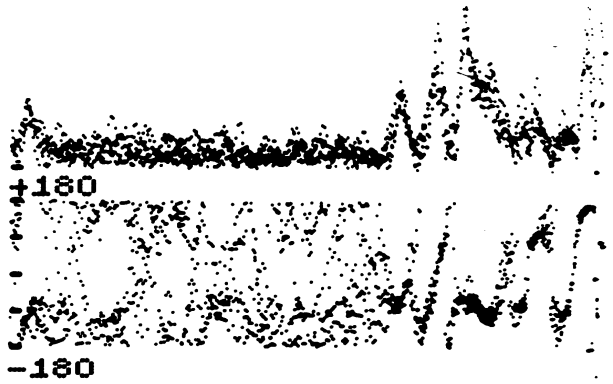


25 December 1966 0643 - 0649

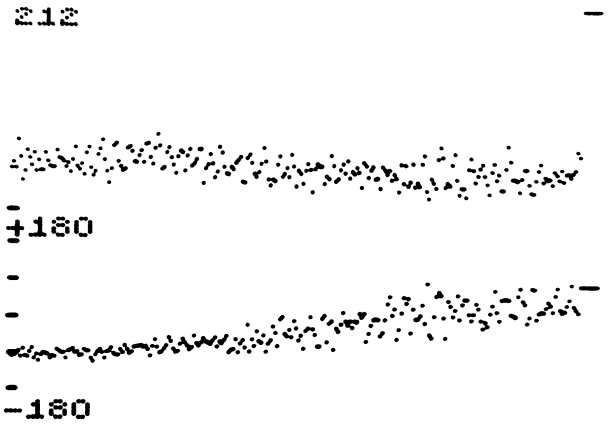
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



See Note 1



25 December 1966 0843 - 0849

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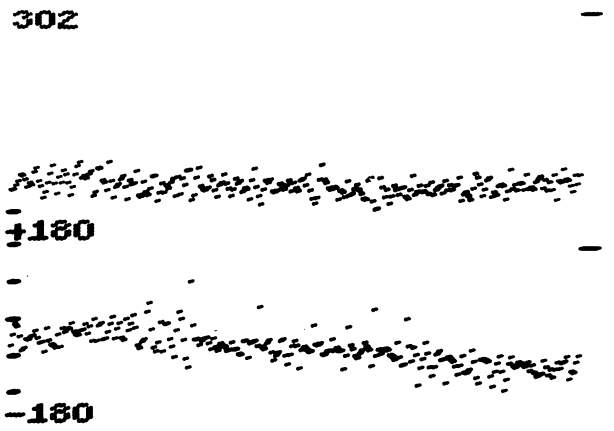
See Note 1

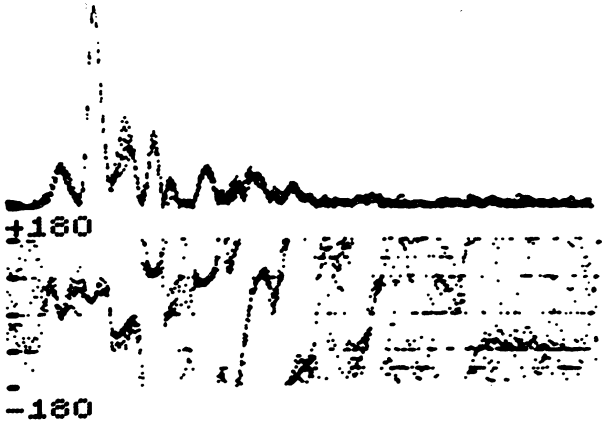


25 December 1966 1243 - 1249

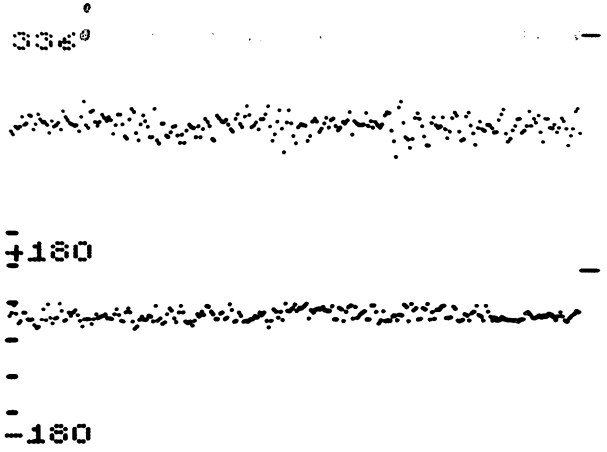
First 3 minutes

Second 3 minutes

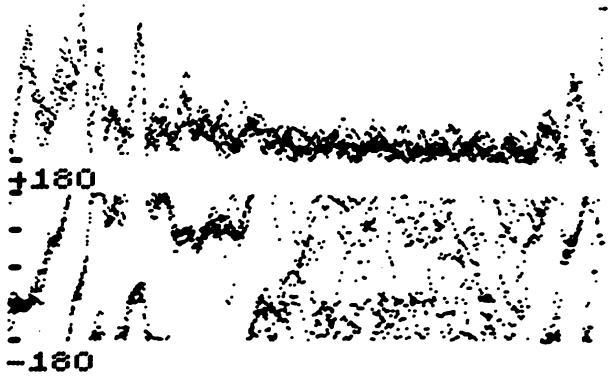
Carrier (entire 6 minutes)



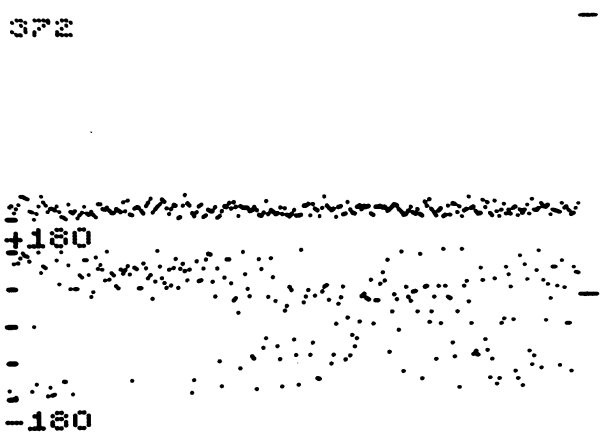
See Note 1



25 December 1966 1443 - 1449



See Note 1

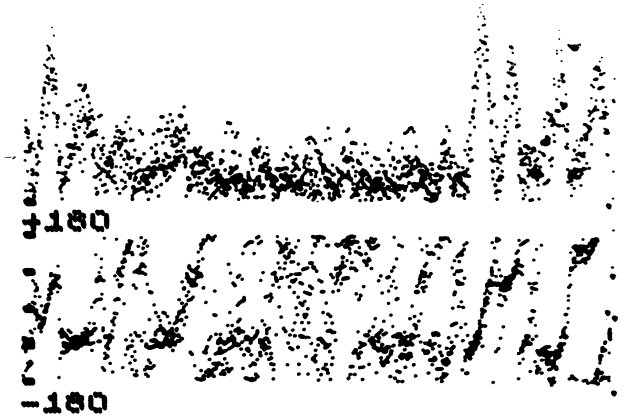


25 December 1966 1643 - 1649

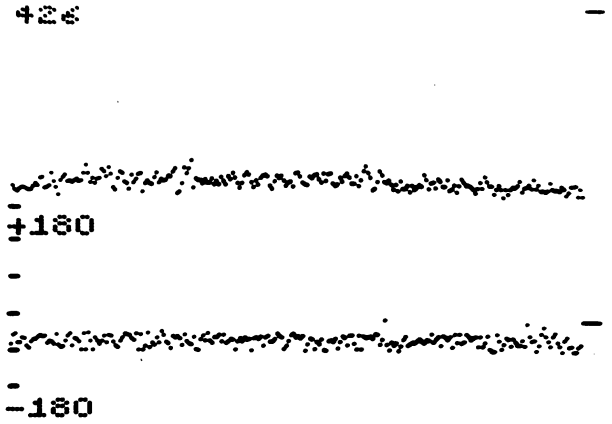
First 3 minutes

Second 3 minutes

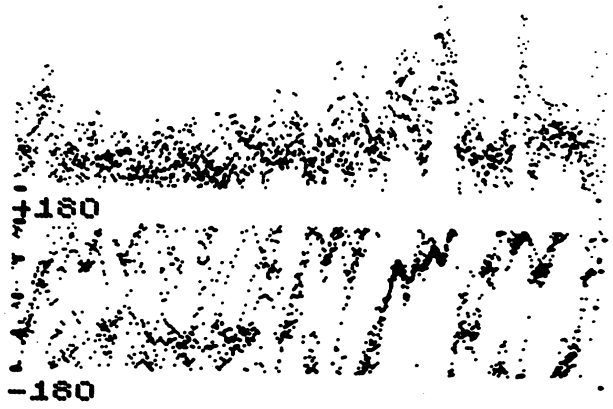
Carrier (entire 6 minutes)



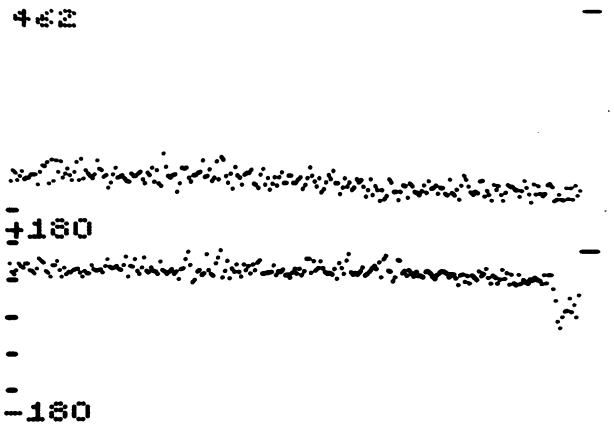
See Note 1



25 December 1966 1843 - 1849



See Note 1

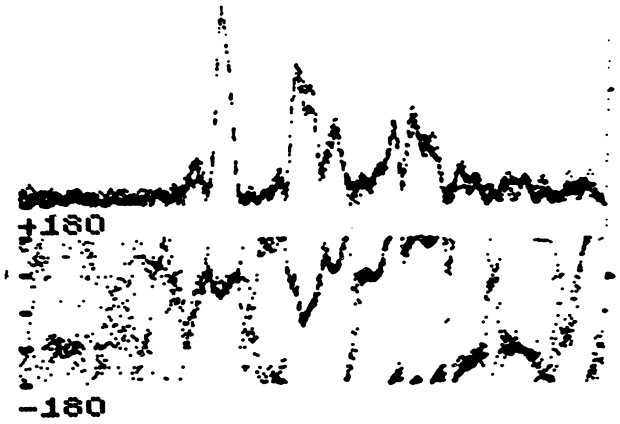


25 December 1966 2043 - 2049

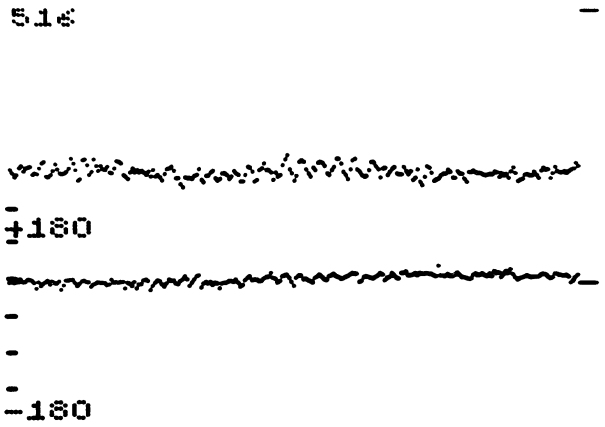
First 3 minutes

Second 3 minutes

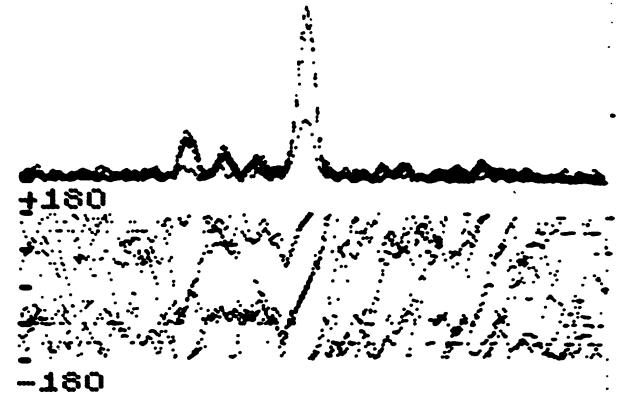
Carrier (entire 6 minutes)



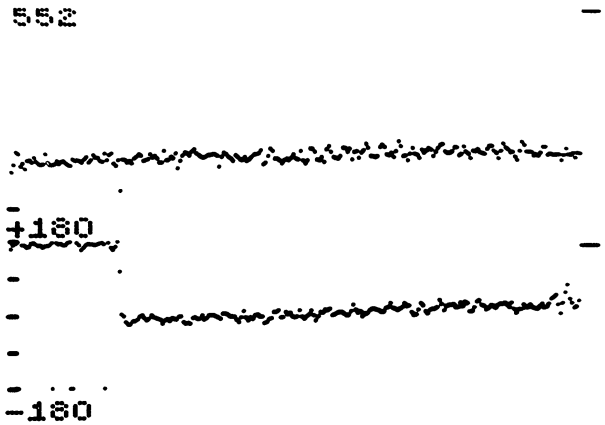
See Note 1



25 December 1966 2243 - 2249



See Note 1

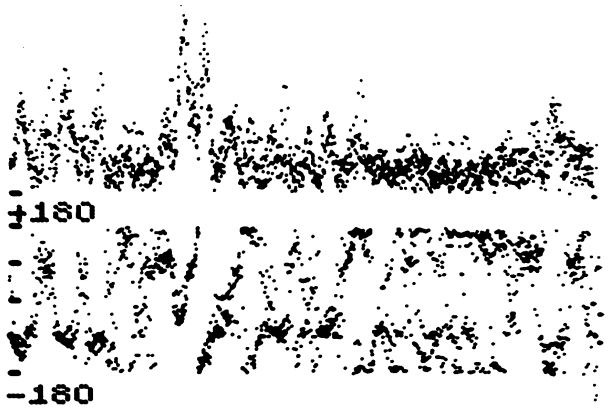


26 December 1966 0043 - 0049

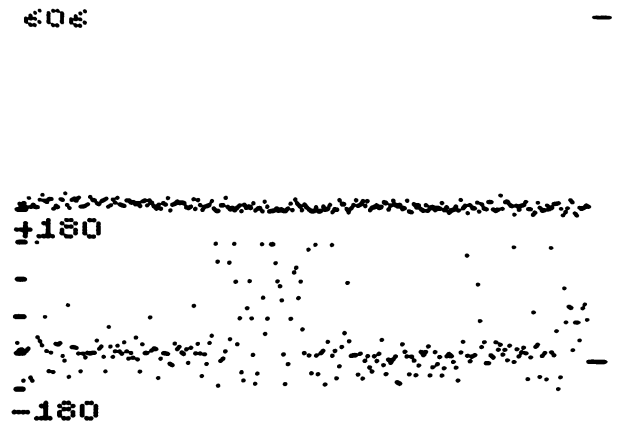
First 3 minutes

Second 3 minutes

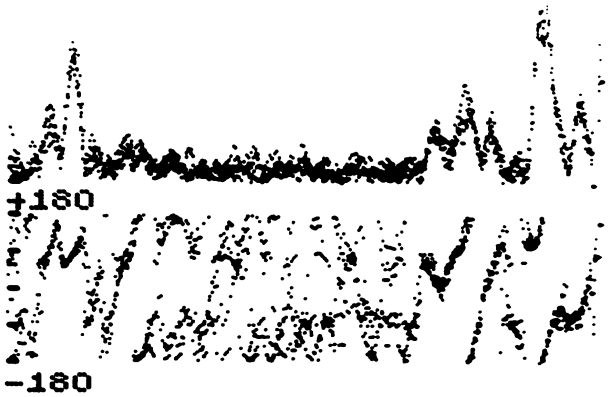
Carrier (entire 6 minutes)



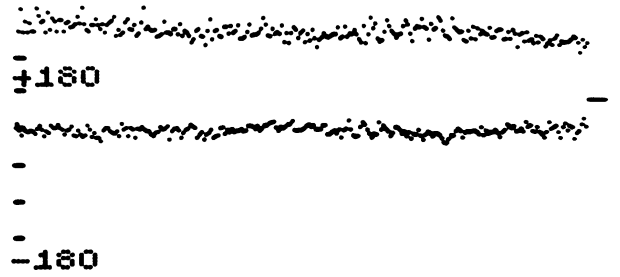
See Note 1



26 December 1966 0243 - 0249



See Note 1

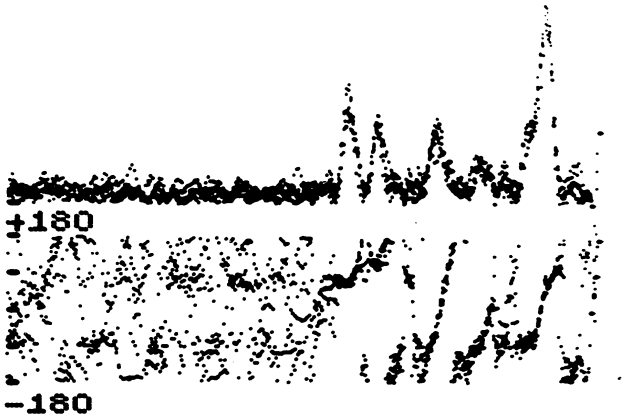


26 December 1966 0443 - 0449

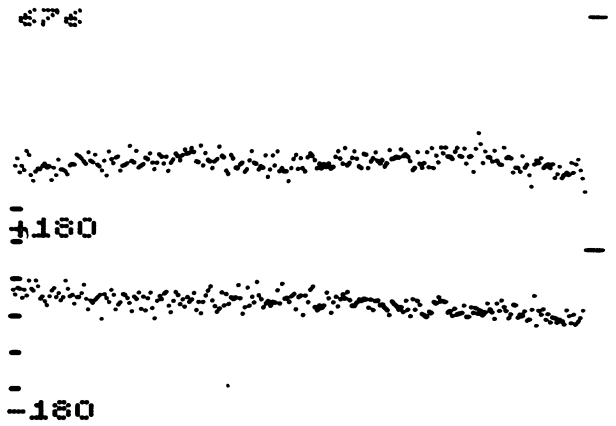
First 3 minutes

Second 3 minutes

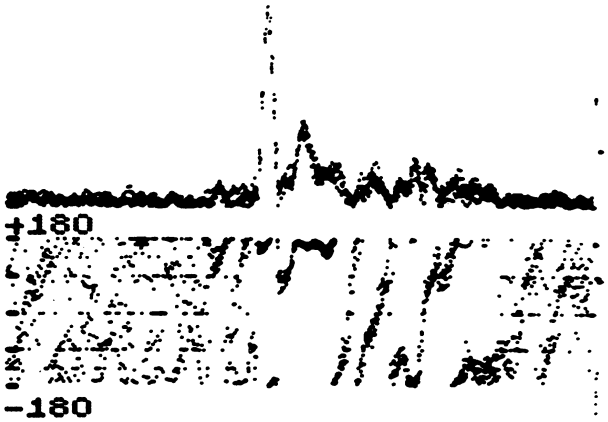
Carrier (entire 6 minutes)



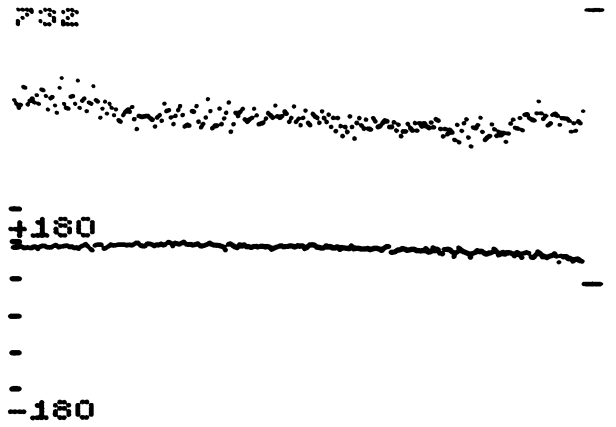
See Note 1



26 December 1966 0643 - 0649



See Note 1

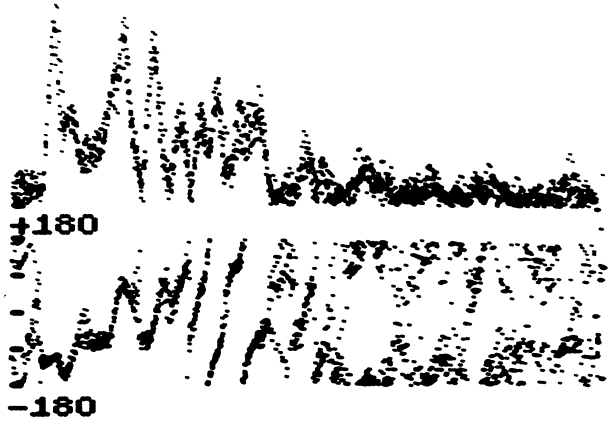


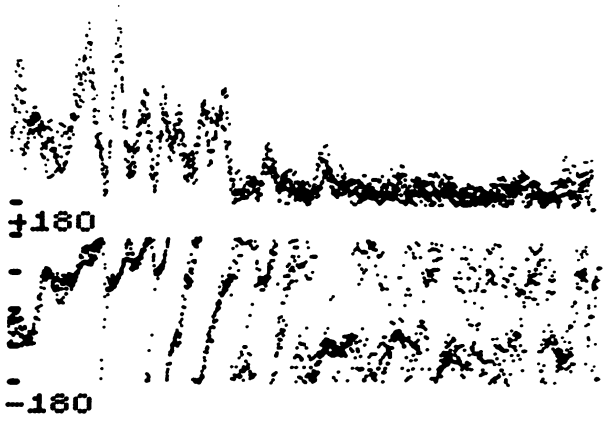
26 December 1966 0843 - 0849

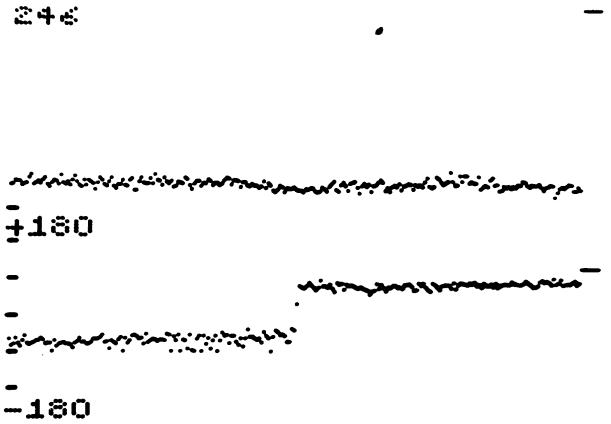
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)







26 December 1966 2243 - 2249

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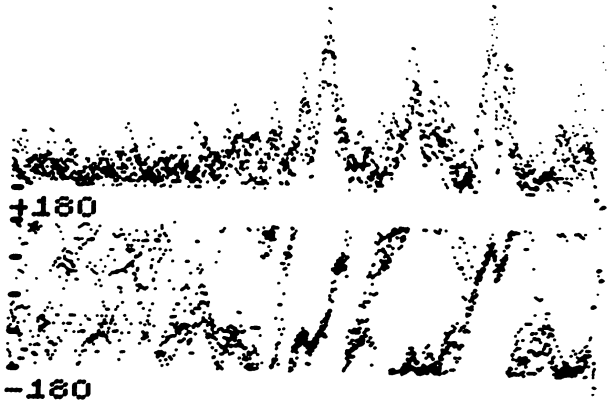
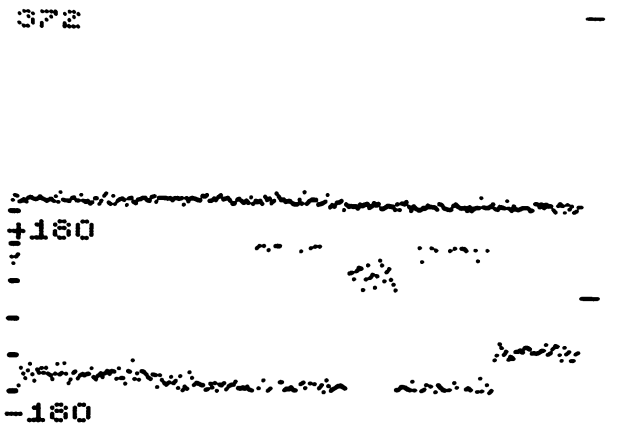
See Note 1



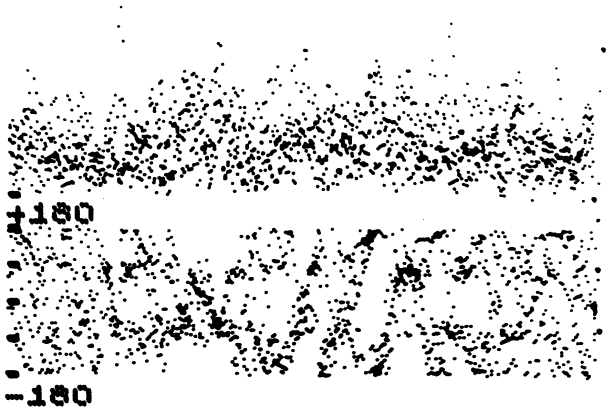


27 December 1966 0443 - 0449

First 3 minutes

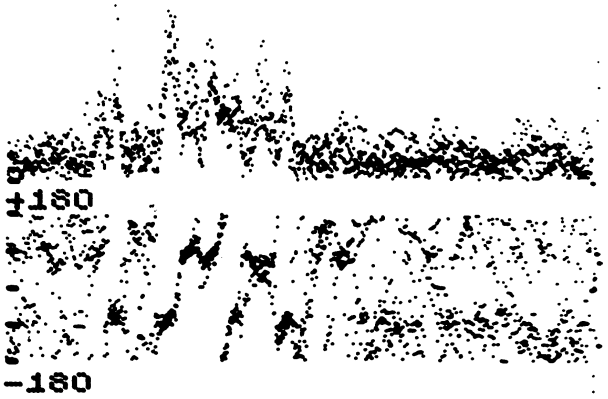
Second 3 minutes

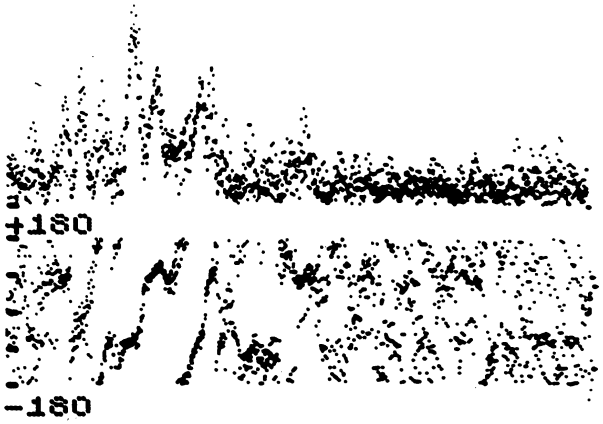
Carrier (entire 6 minutes)

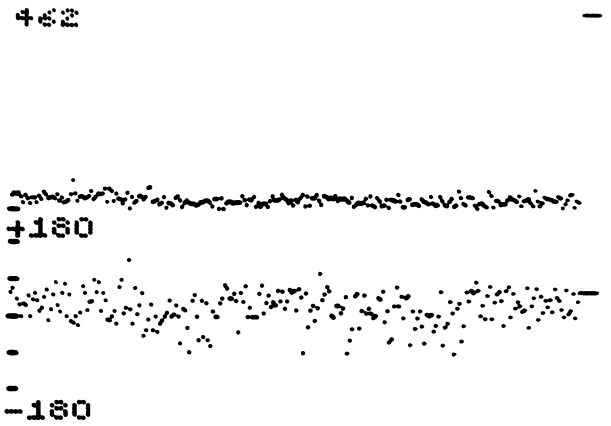


See Note 1

27 December 1966 0643 - 0649





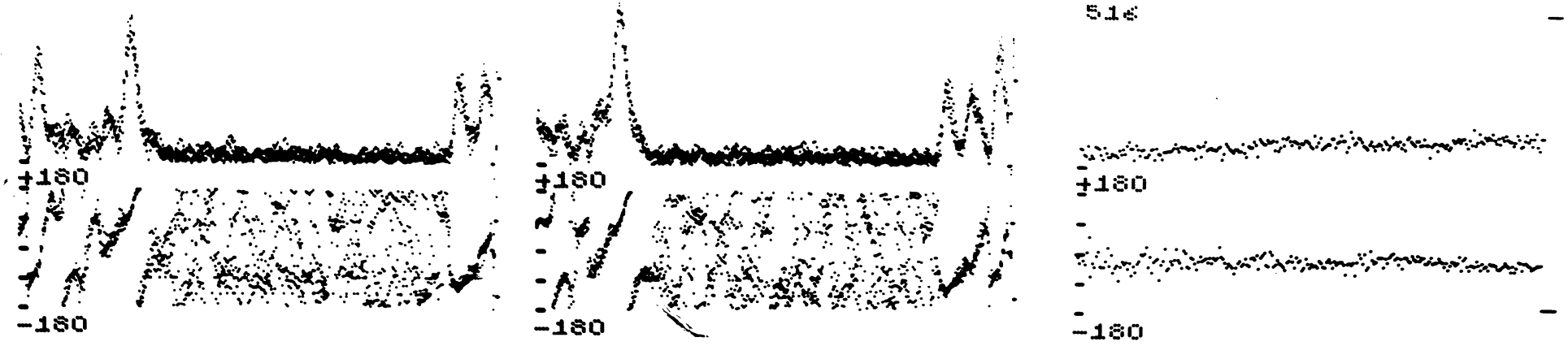


27 December 1966 0843 - 0849

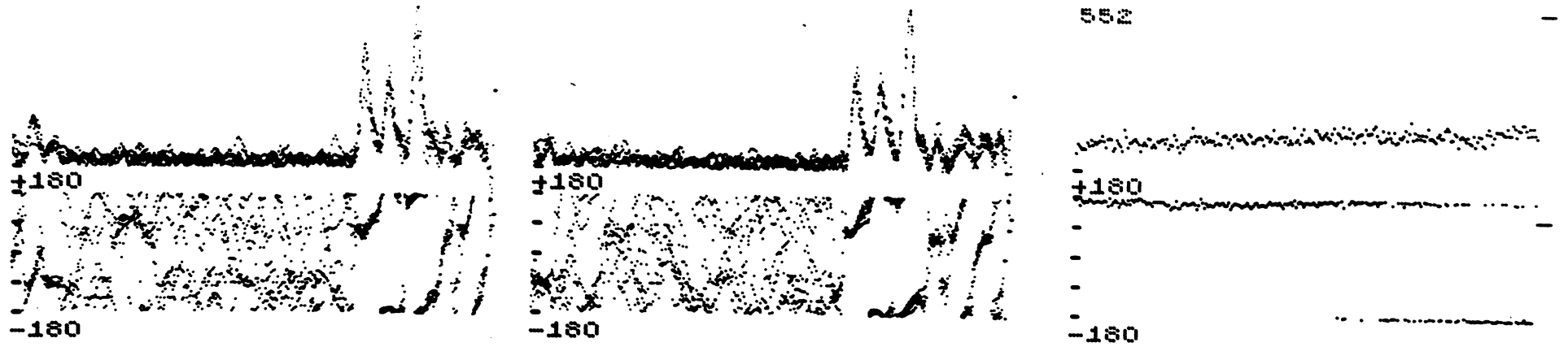
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



27 December 1966 1043 - 1049



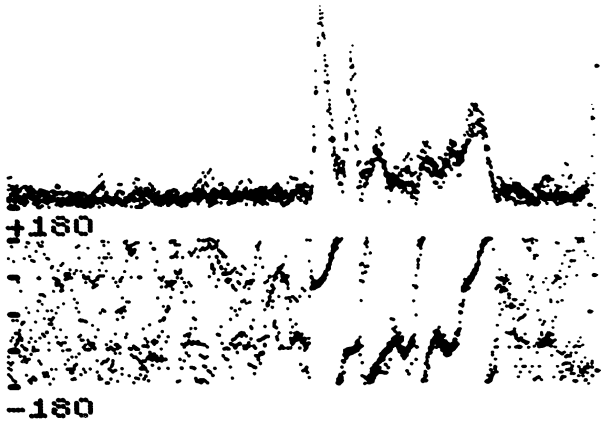
27 December 1966 1243 - 1249

First 3 minutes

Second 3 minutes

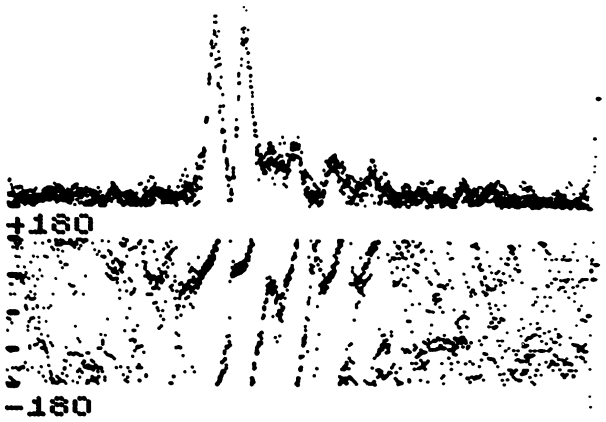
Carrier (entire 6 minutes)

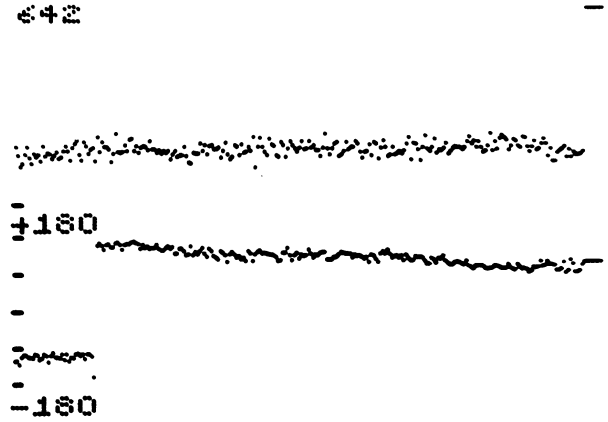
See Note 1



27 December 1966 1443 - 1449

See Note 1



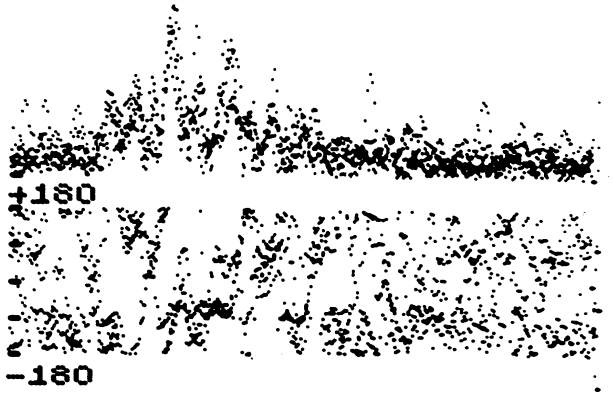


27 December 1966 1643 - 1649

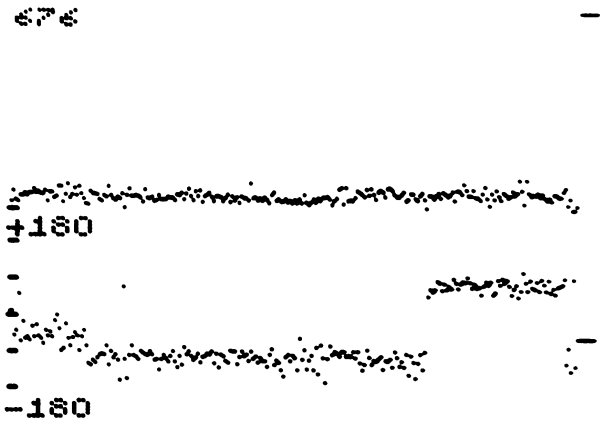
First 3 minutes

Second 3 minutes

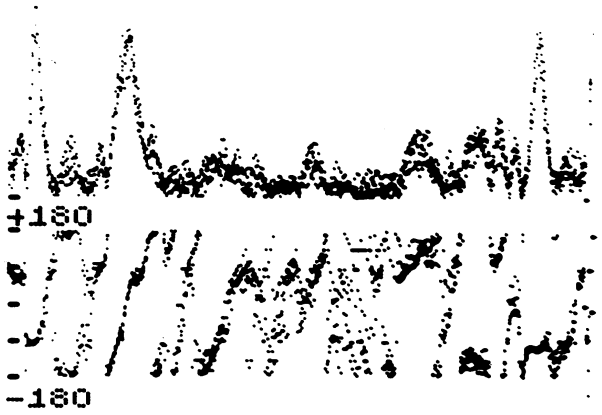
Carrier (entire 6 minutes)



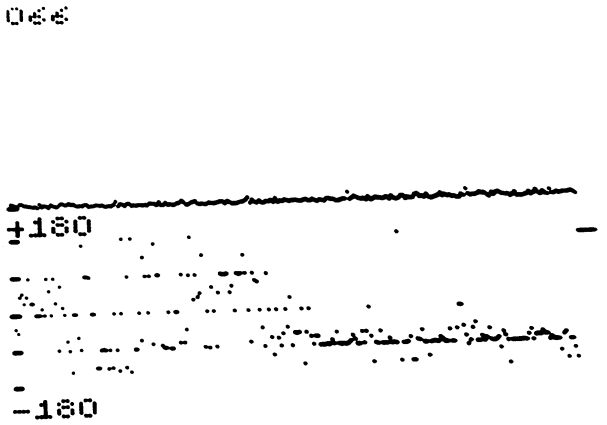
See Note 1



27 December 1966 1843 - 1849



See Note 1



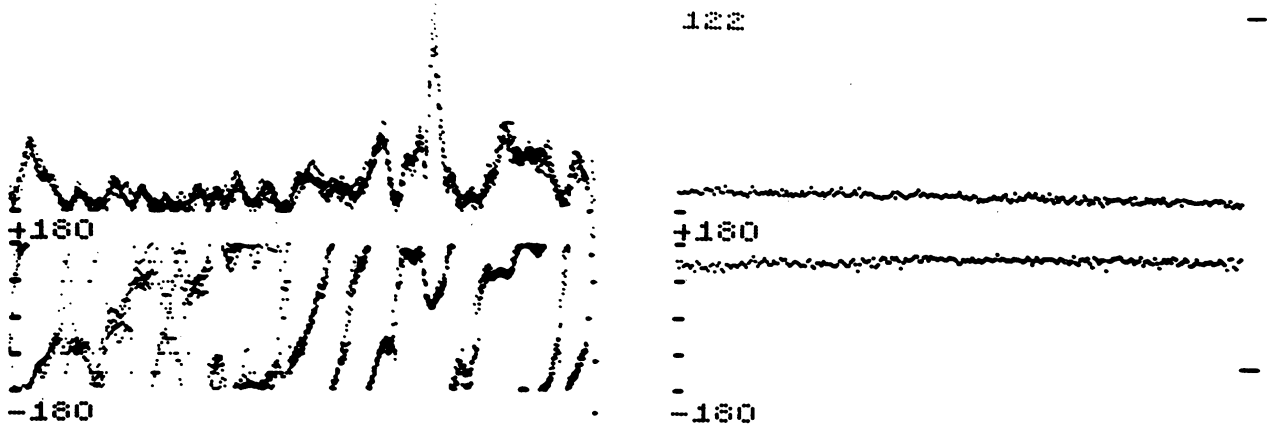
28 December 1966 2043 - 2049

First 3 minutes

Second 3 minutes

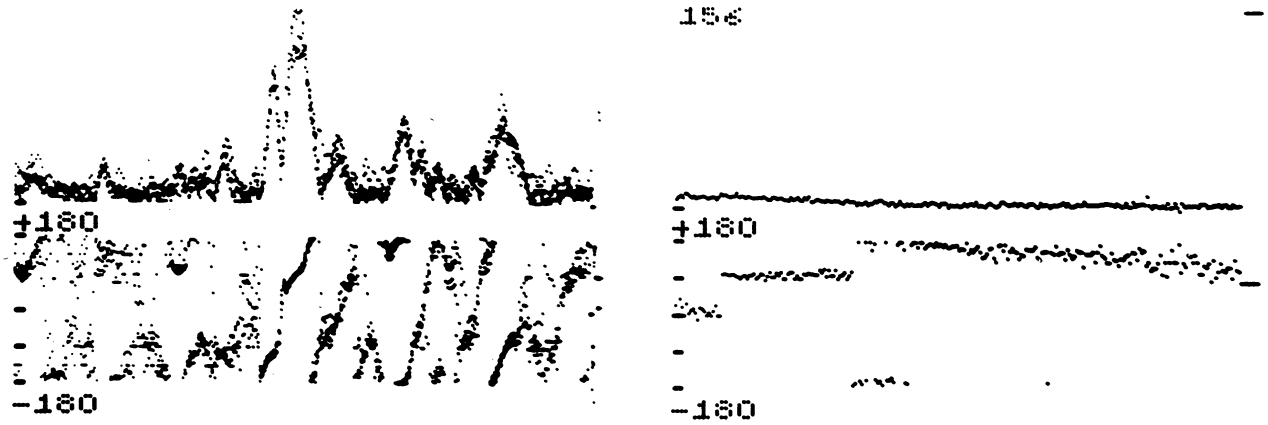
Carrier (entire 6 minutes)

See Note 1



28 December 1966 2243 - 2249

See Note 1



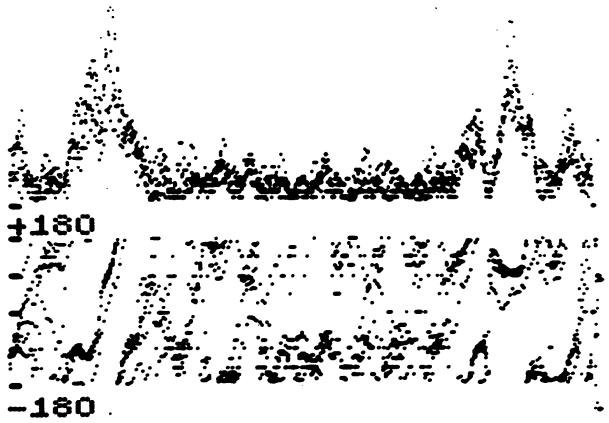
29 December 1966 0043 - 0049

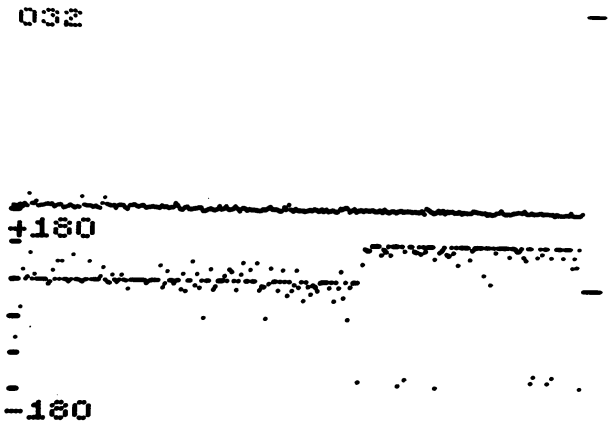
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

See Note 1





30 December 1966 0643 - 0649

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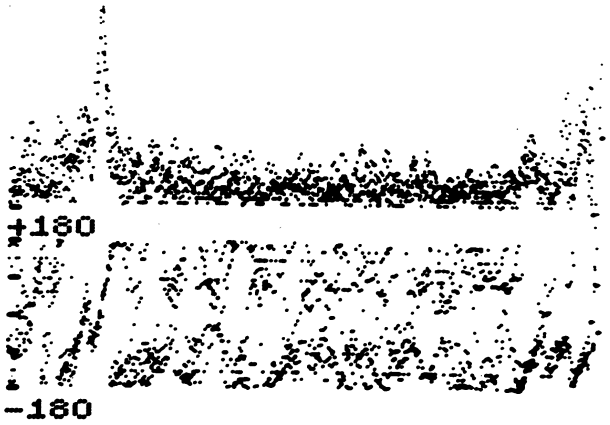
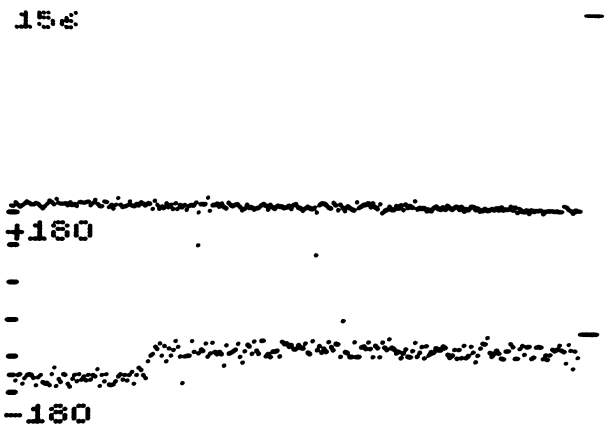
See Note 1





1 January 1967 0043 - 0049

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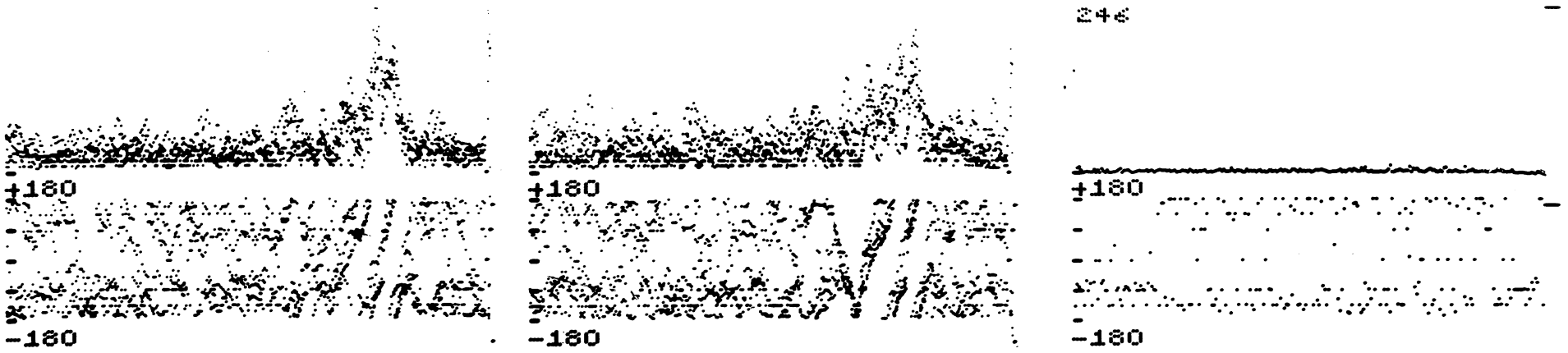
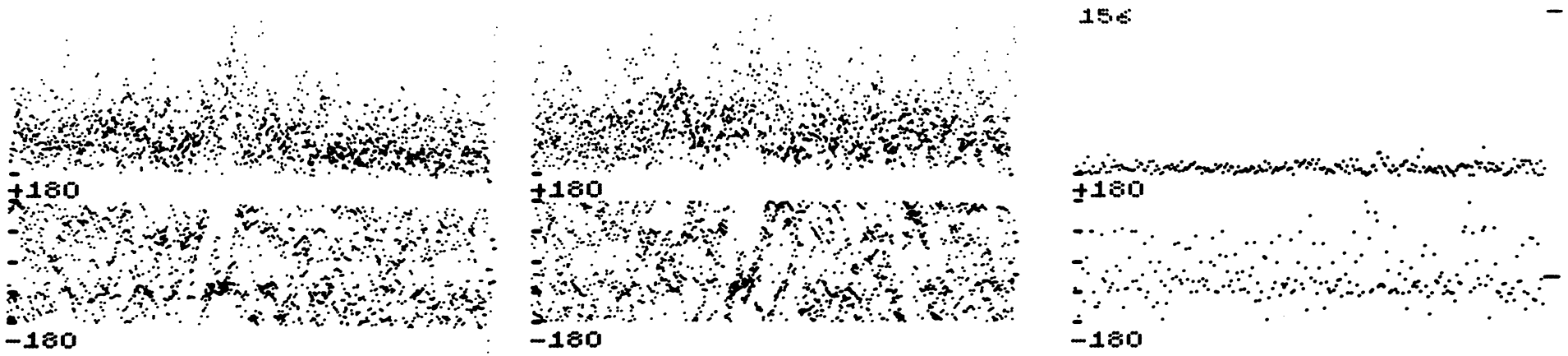
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



1 January 1967 0443 - 0449

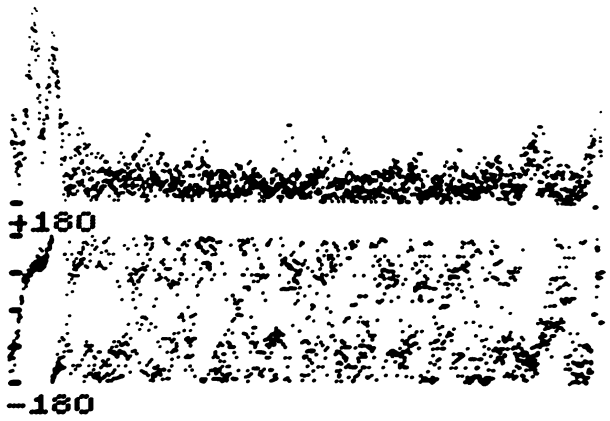


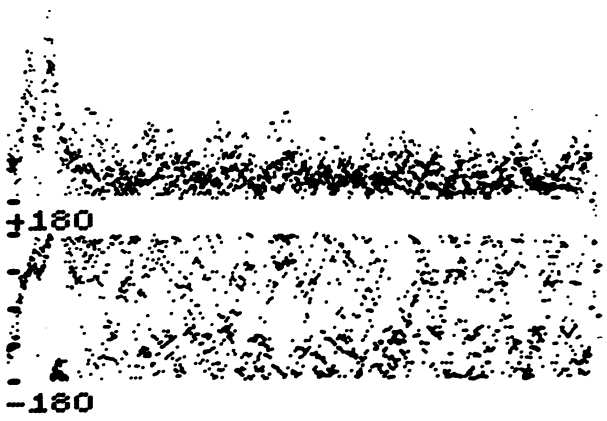
1 January 1967 1843 - 1849

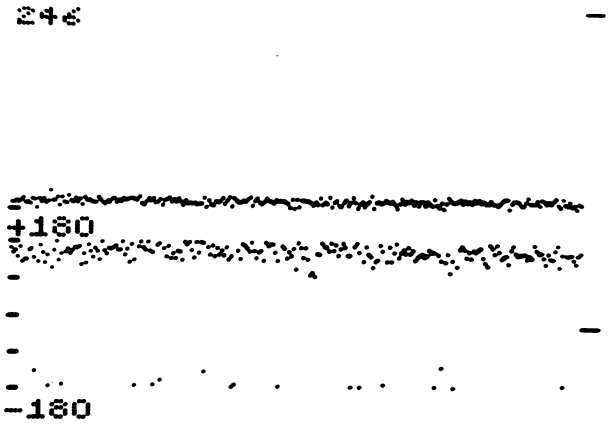
First 3 minutes

Second 3 minutes

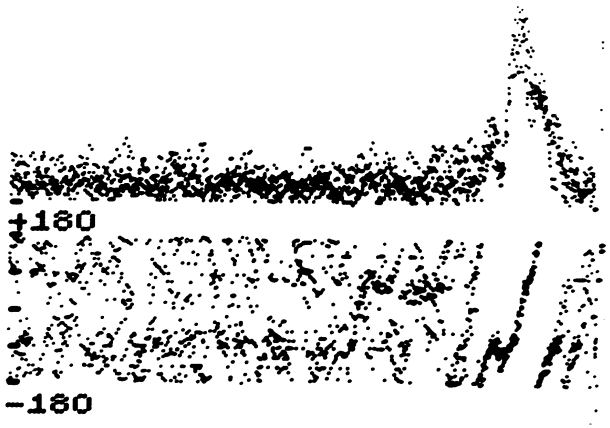
Carrier (entire 6 minutes)







1 January 1967 2243 - 2249



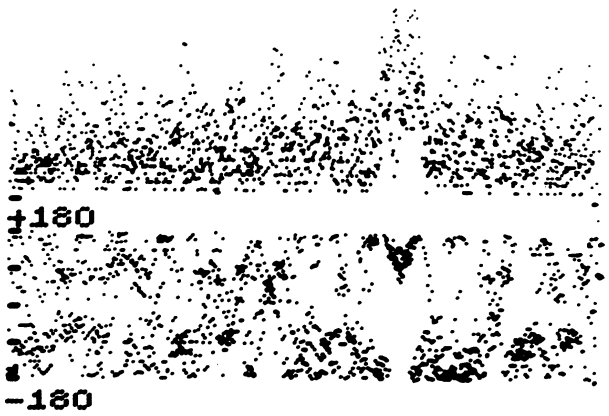
See Note 1

2 January 1967 0043 - 0049

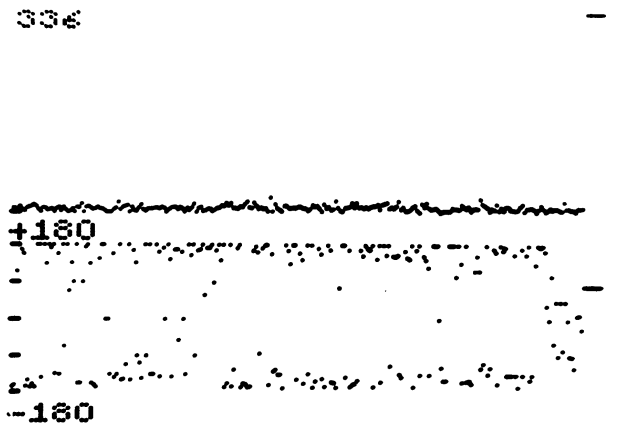
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

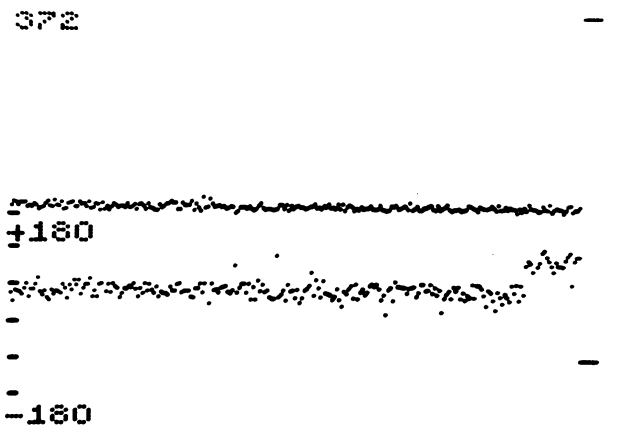


See Note 1



2 January 1967 0243 - 0249

See Note 1

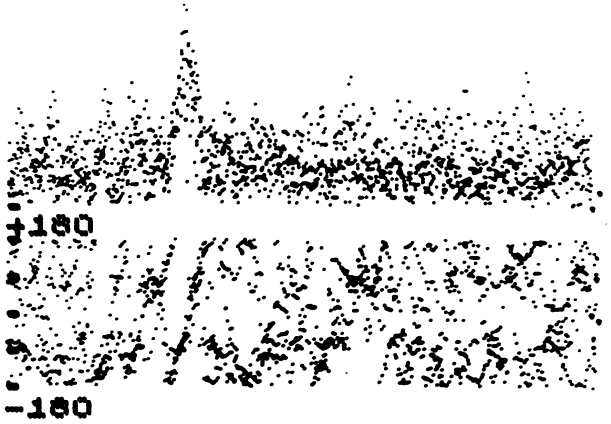


2 January 1967 0443 - 0449

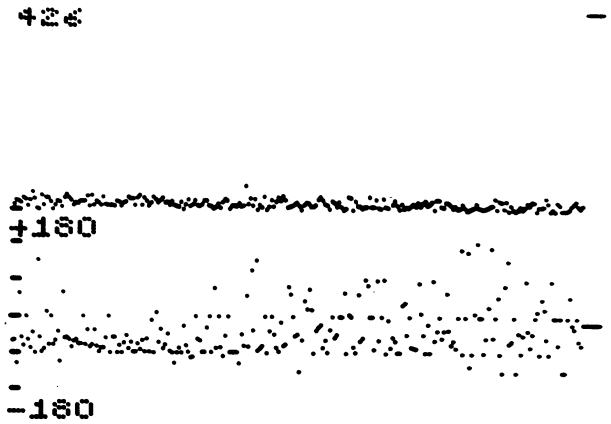
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

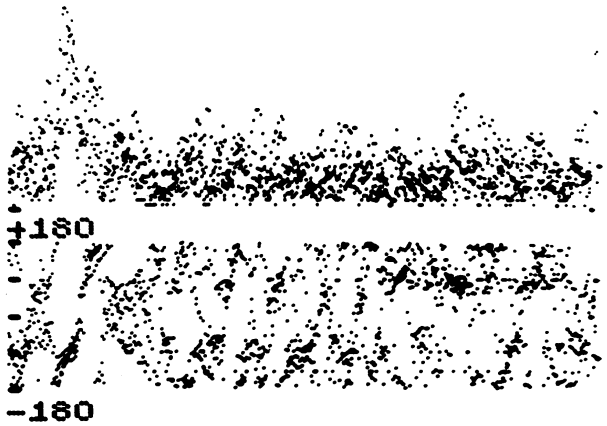


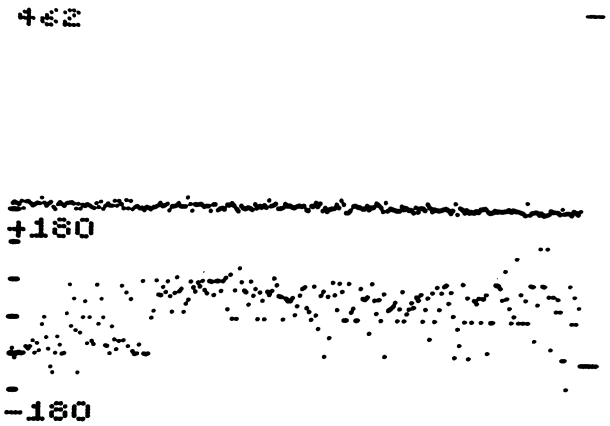
See Note 1



2 January 1967 0643 - 0649

See Note 1





2 January 1967 0843 - 0849

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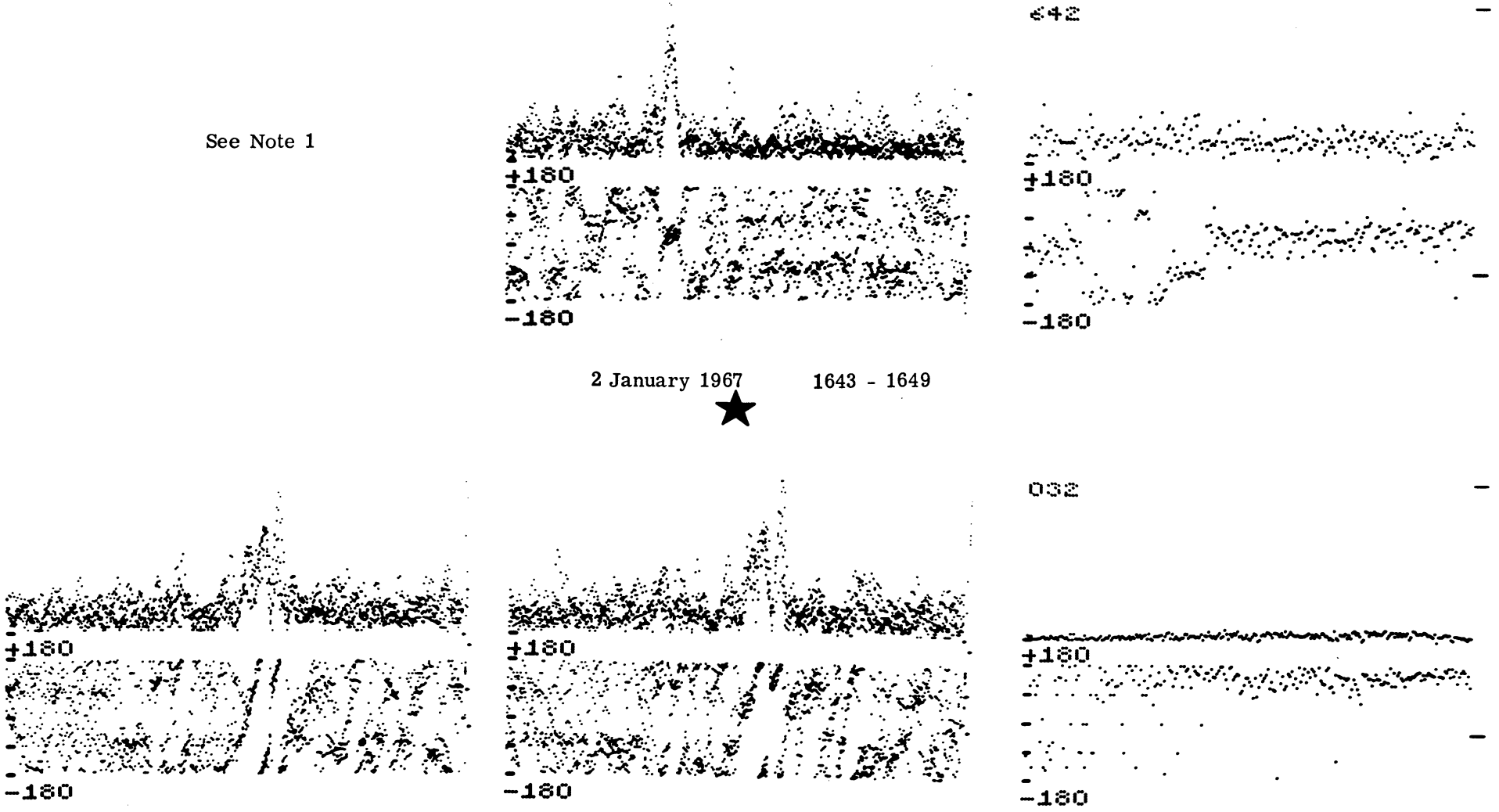
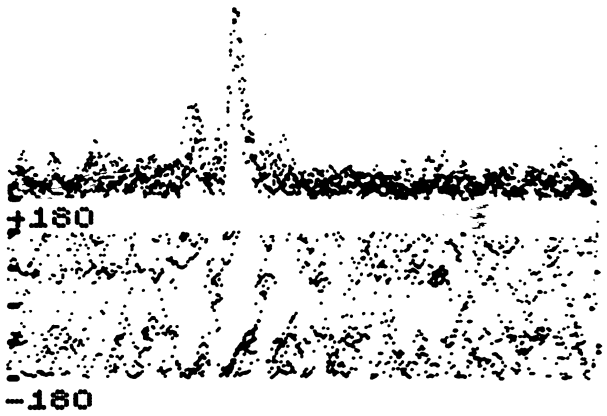
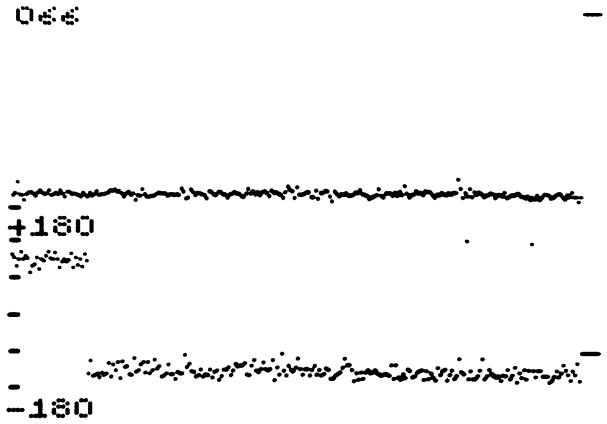
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

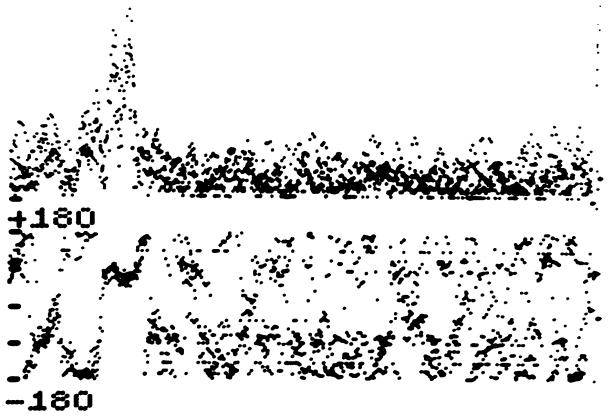

See Note 1
+180
-180
2 January 1967 1643 - 1649
+180
-180
3 January 1967 0043 - 0049
+180
-180
First 3 minutes
Second 3 minutes
Carrier (entire 6 minutes)

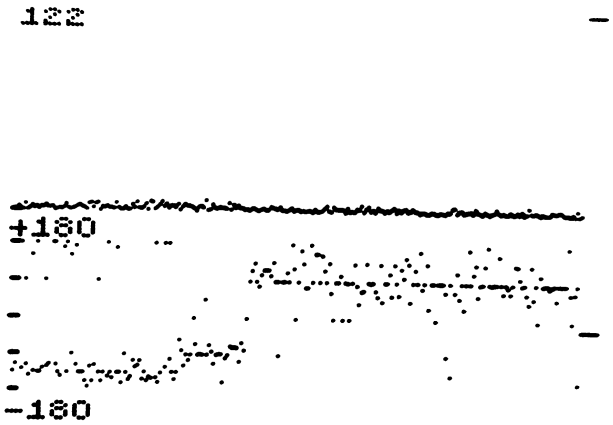




3 January 1967 0243 - 0249

See Note 1



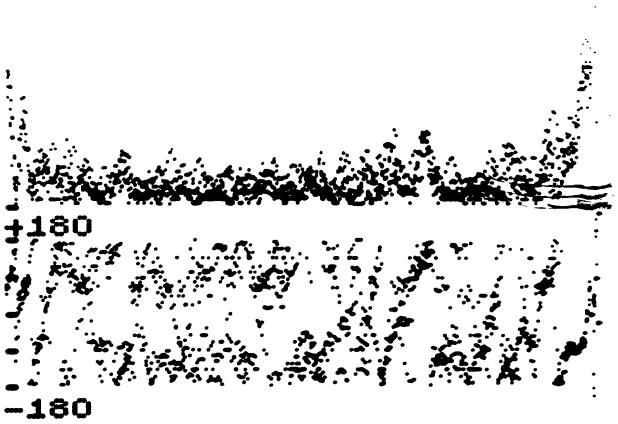


3 January 1967 0443 - 0449

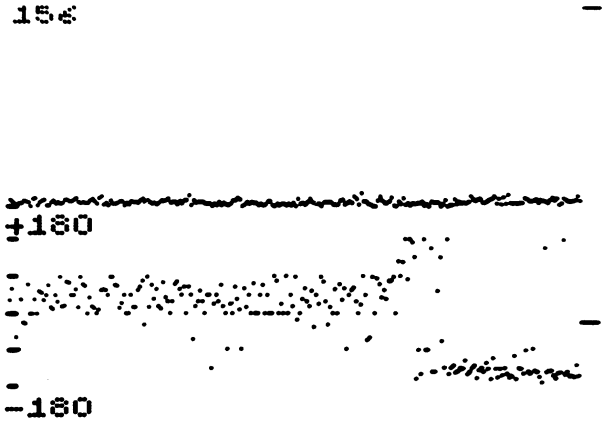
First 3 minutes

Second 3 minutes

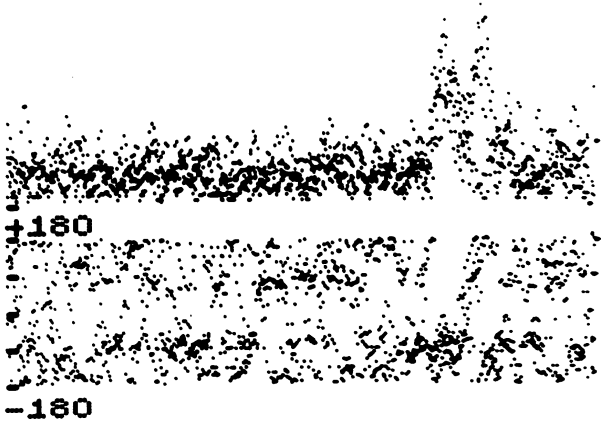
Carrier (entire 6 minutes)

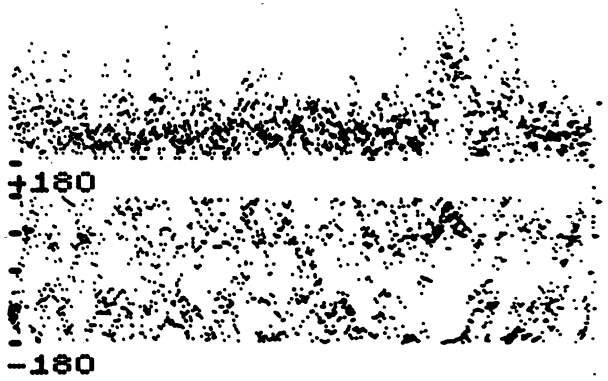


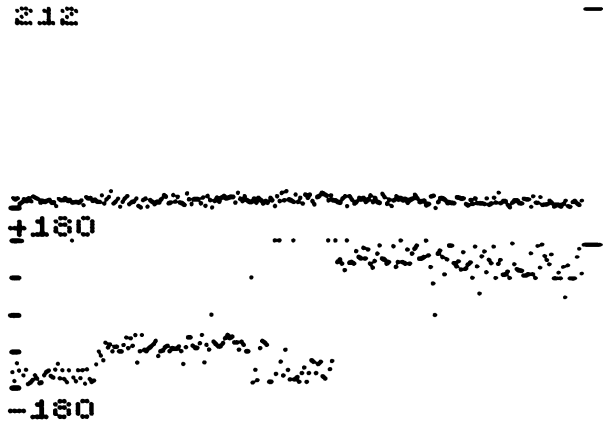
See Note 1



3 January 1967 0643 - 0649





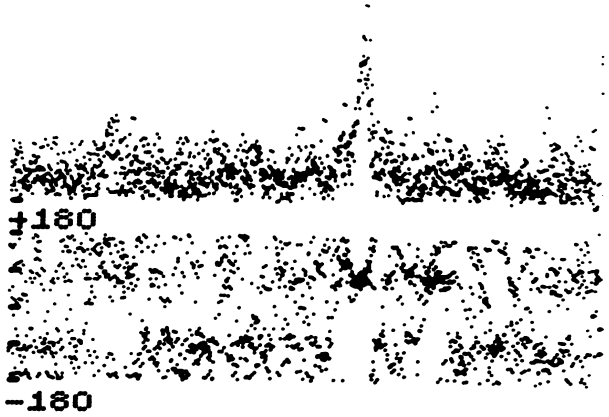


3 January 1967 0843 - 0849

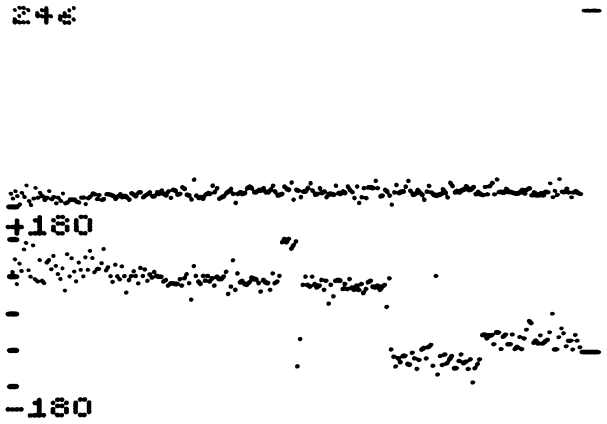
First 3 minutes

Second 3 minutes

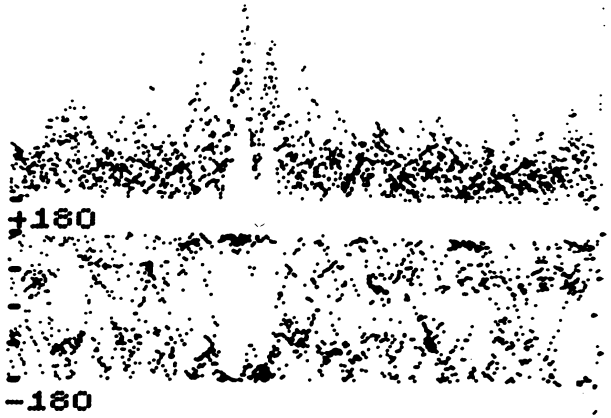
Carrier (entire 6 minutes)



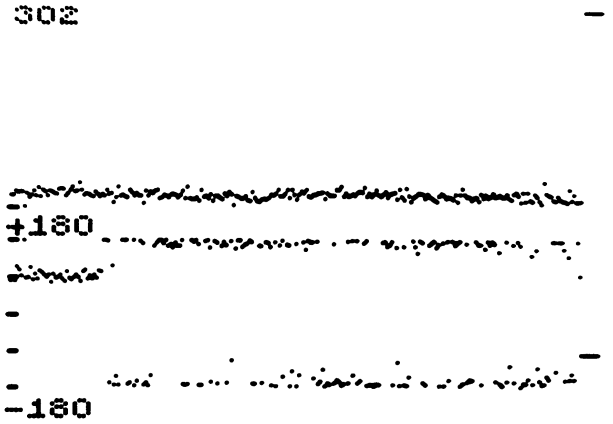
See Note 1



3 January 1967 1043 - 1049



See Note 1

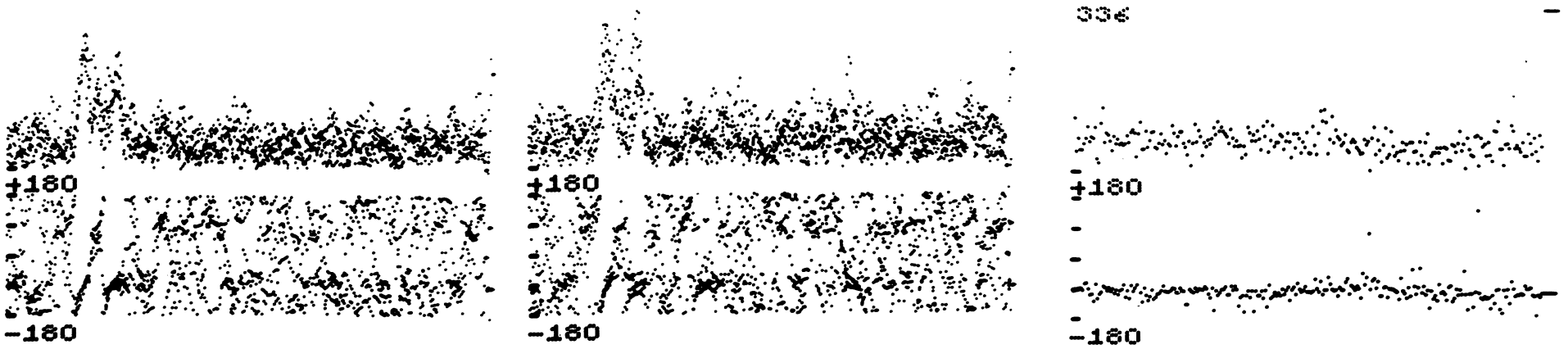


3 January 1967 1243 - 1249

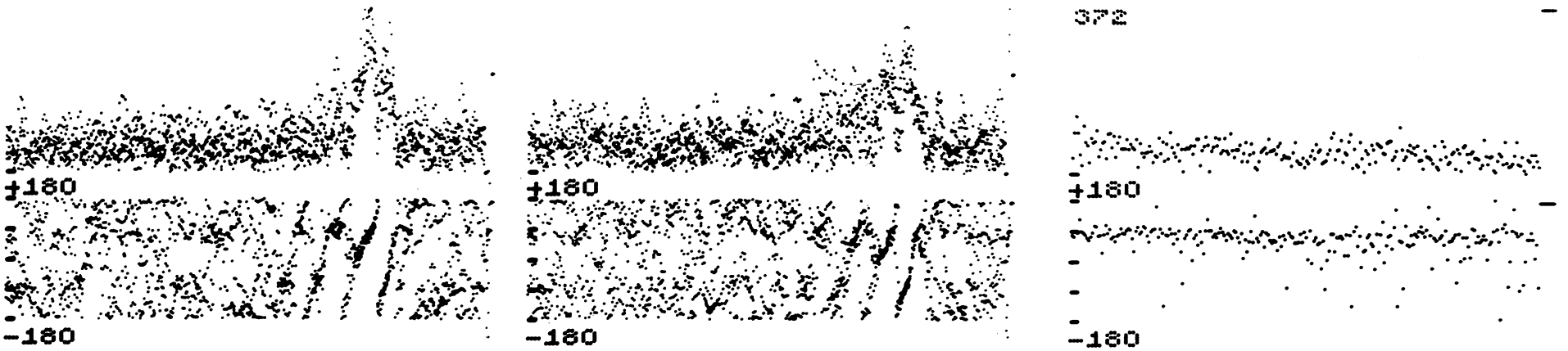
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



3 January 1967 1443 - 1449



3 January 1967 1643 - 1649

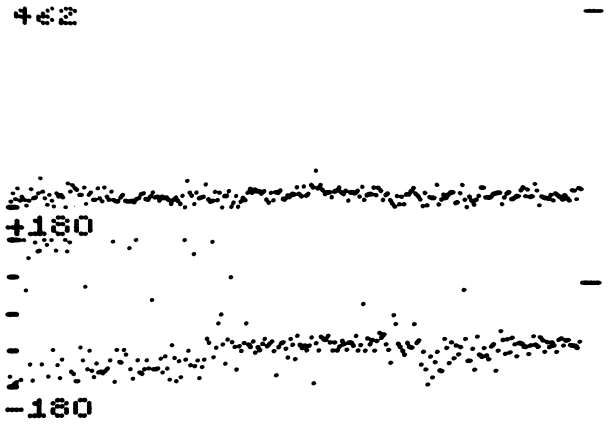
First 3 minutes

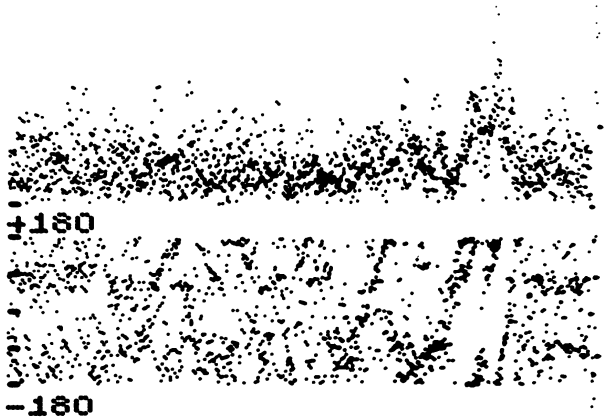
Second 3 minutes

Carrier (entire 6 minutes)

See Note 1

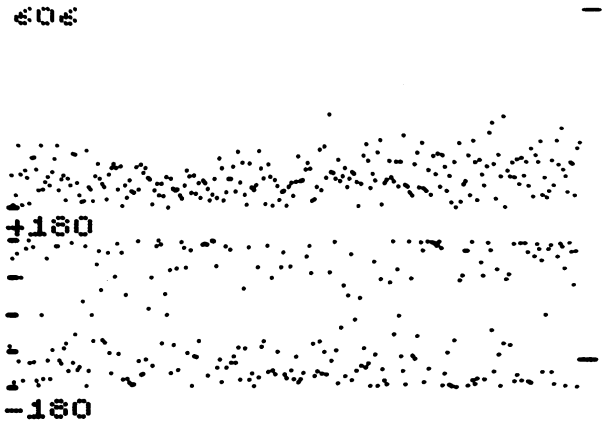
3 January 1967 2043 - 2049





See Note 1

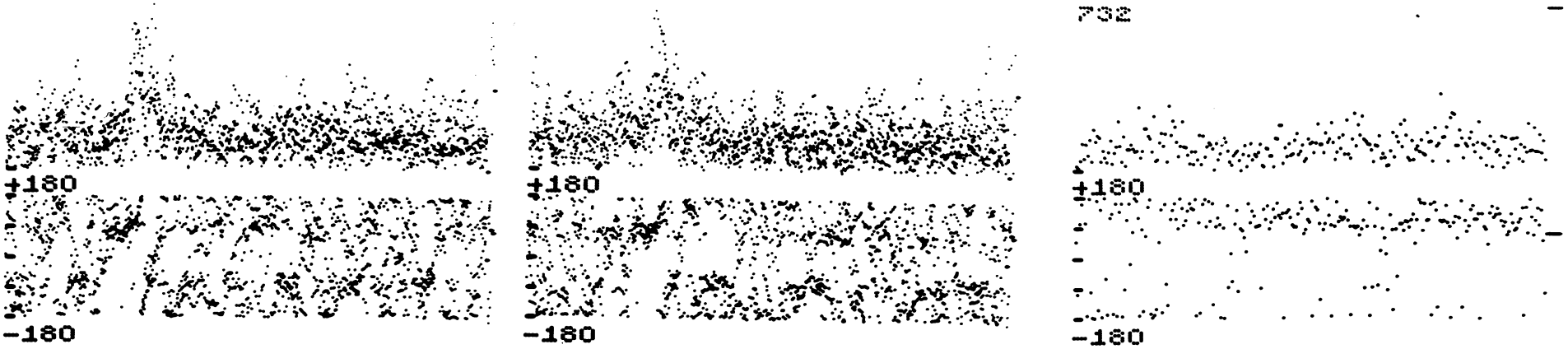
4 January 1967 0243 - 0249



First 3 minutes

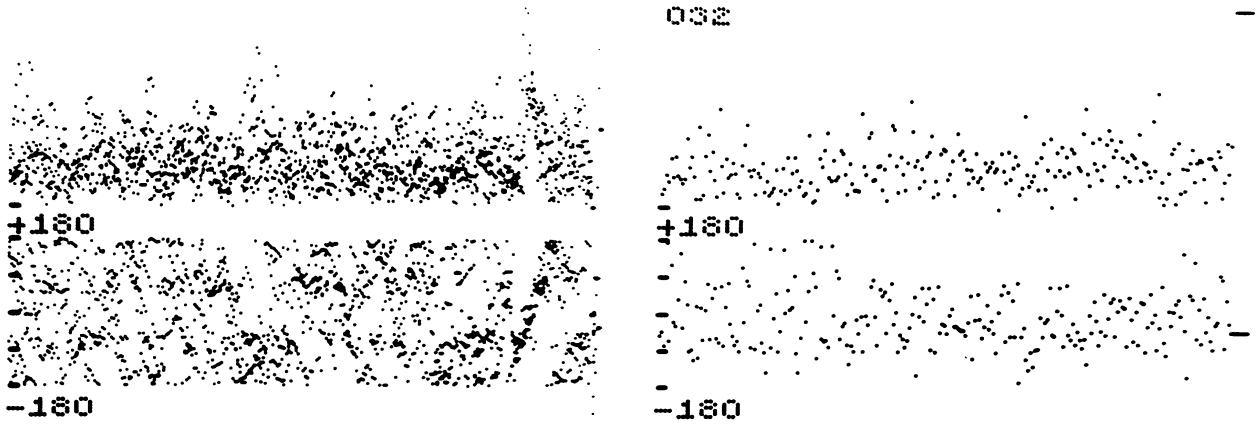
Second 3 minutes

Carrier (entire 6 minutes)



4 January 1967 0843 - 0849

See Note 1

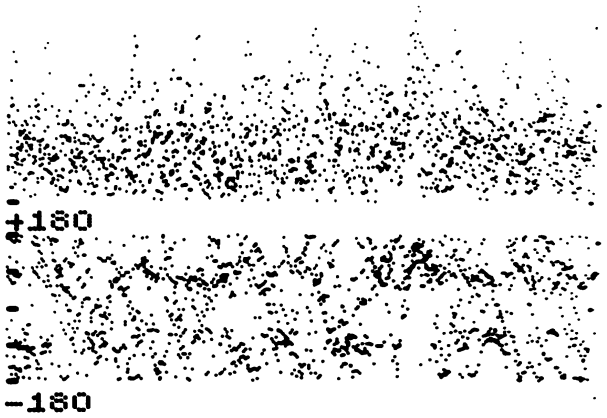


4 January 1967 1243 - 1249

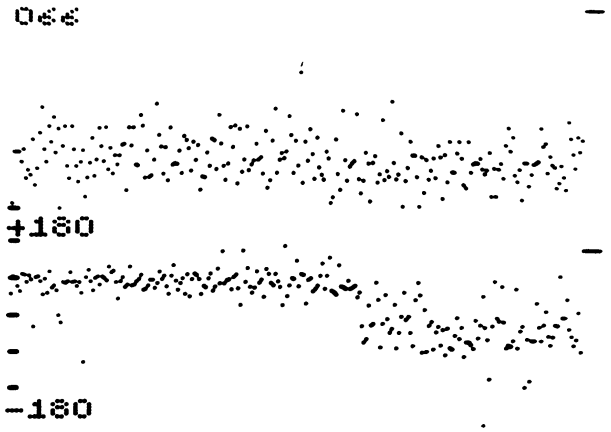
First 3 minutes

Second 3 minutes

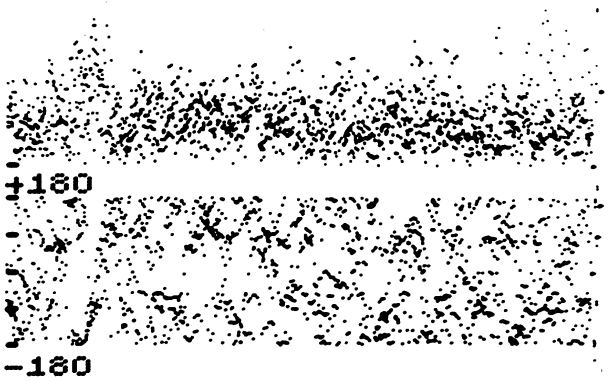
Carrier (entire 6 minutes)



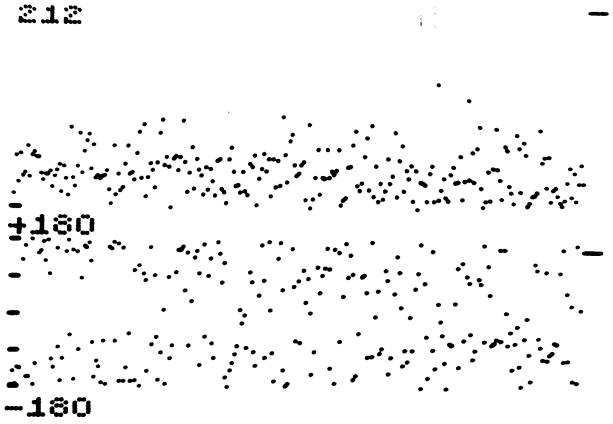
See Note 1



4 January 1967 1443 - 1449



See Note 1



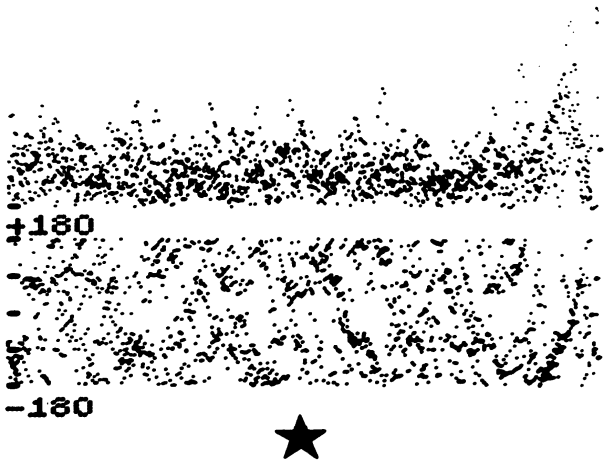
4 January 1967 2043 - 2049

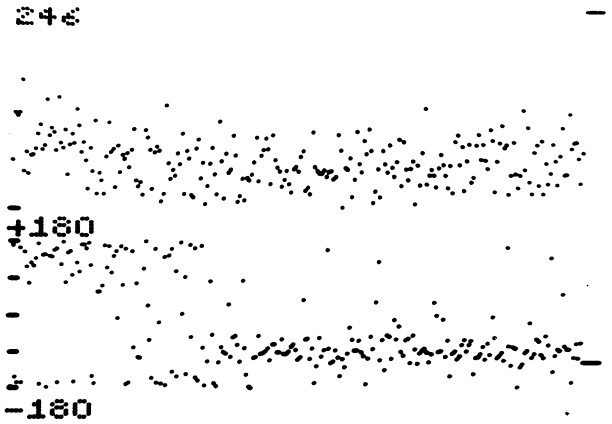
First 3 minutes

Second 3 minutes

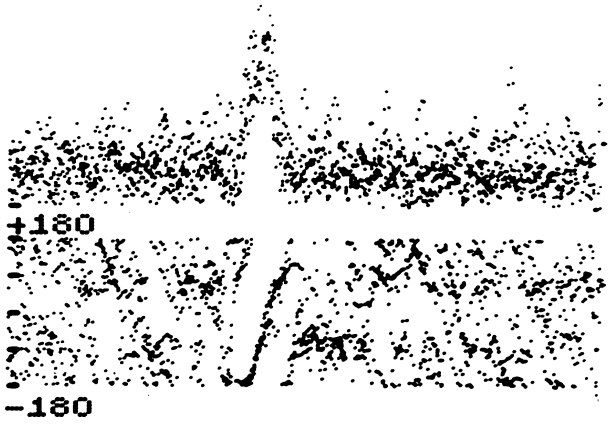
Carrier (entire 6 minutes)

See Note 1

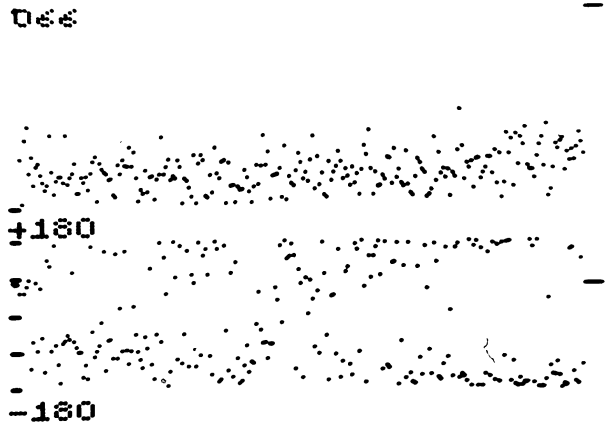




4 January 1967 2243 - 2249



See Note 1

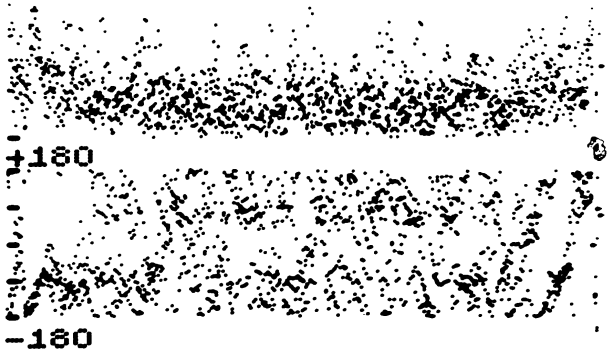


5 January 1967 0643 - 0649

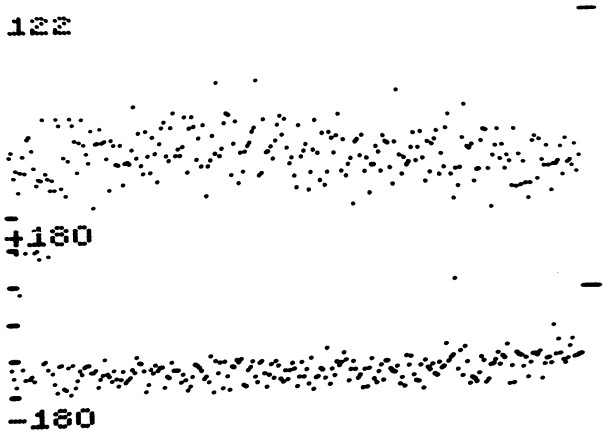
First 3 minutes

Second 3 minutes

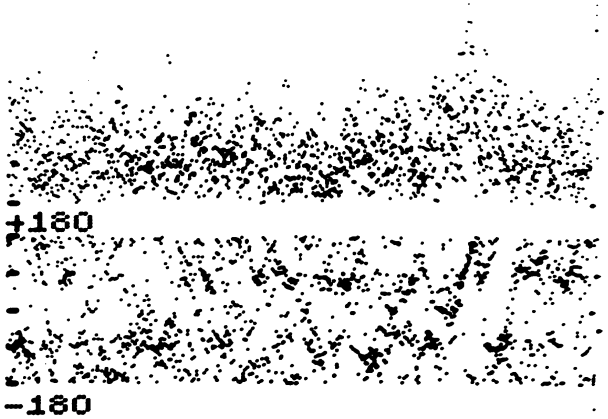
Carrier (entire 6 minutes)



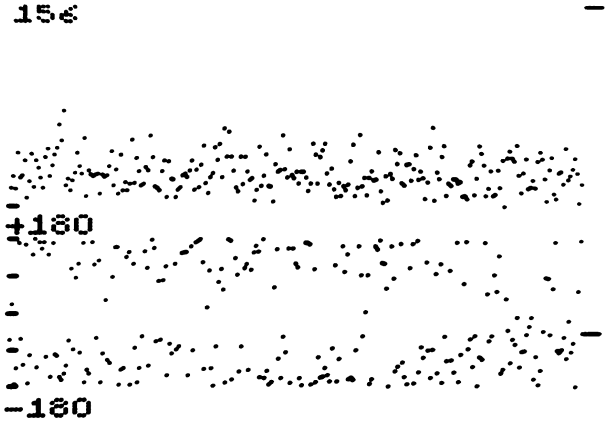
See Note 1



5 January 1967 0843 - 0849



See Note 1

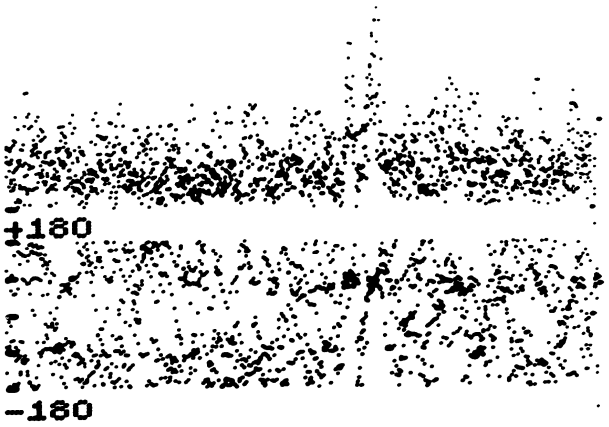


5 January 1967 1043 - 1049

First 3 minutes

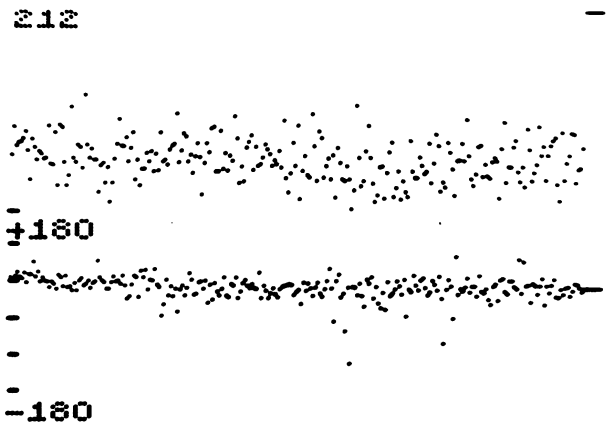
Second 3 minutes

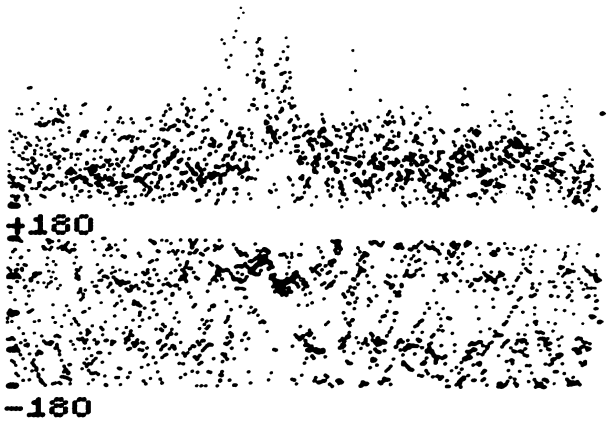
Carrier (entire 6 minutes)



See Note 1

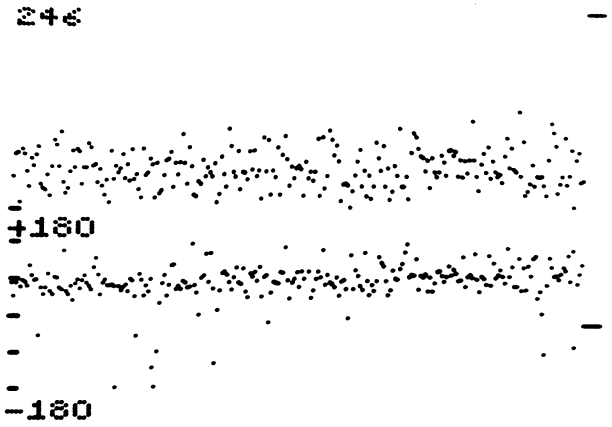
5 January 1967 1243 - 1249





See Note 1

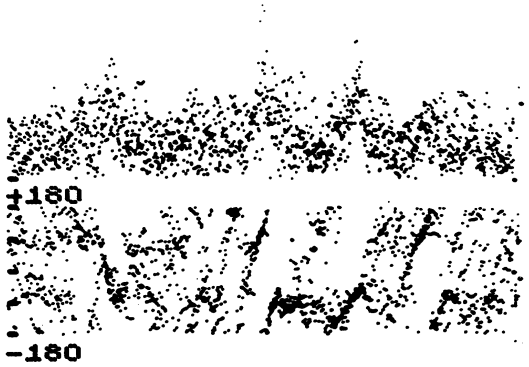
5 January 1967 1443 - 1449



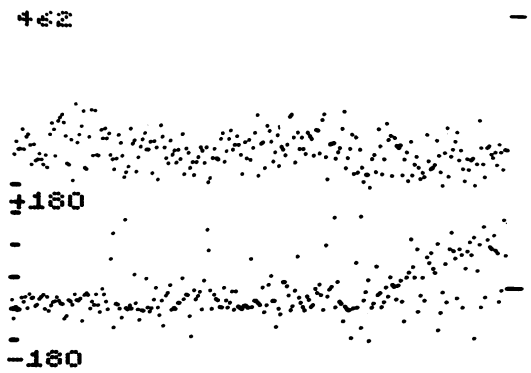
First 3 minutes

Second 3 minutes

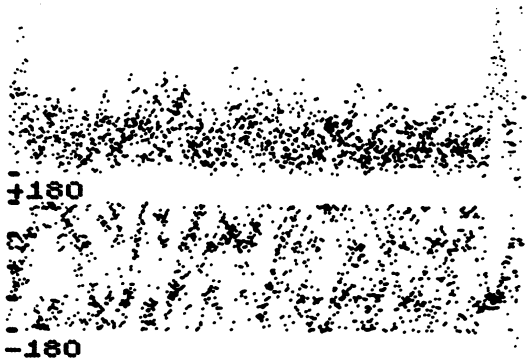
Carrier (entire 6 minutes)



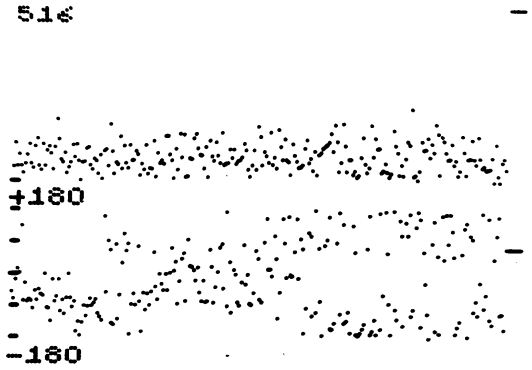
See Note 1



6 January 1967 0043 - 0049



See Note 1

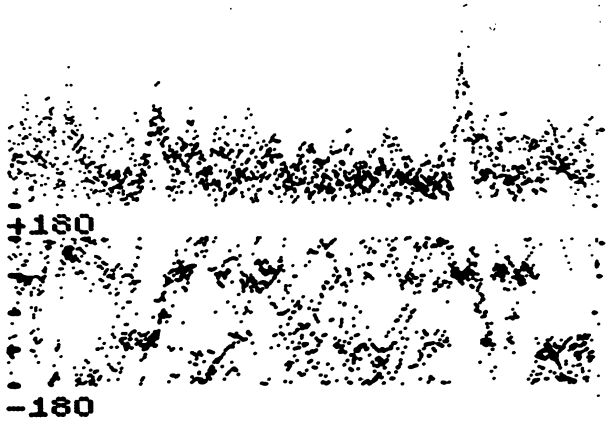


6 January 1967 0243 - 0249

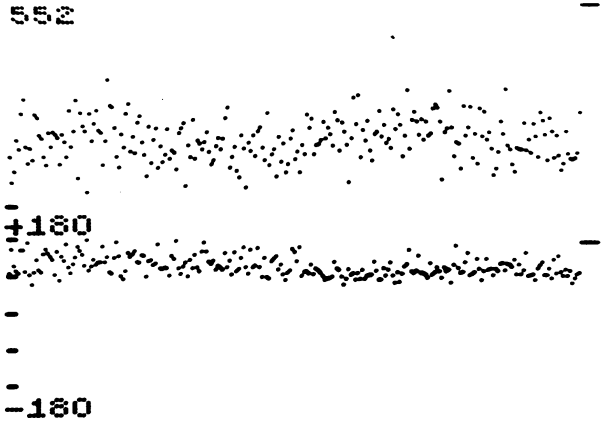
First 3 minutes

Second 3 minutes

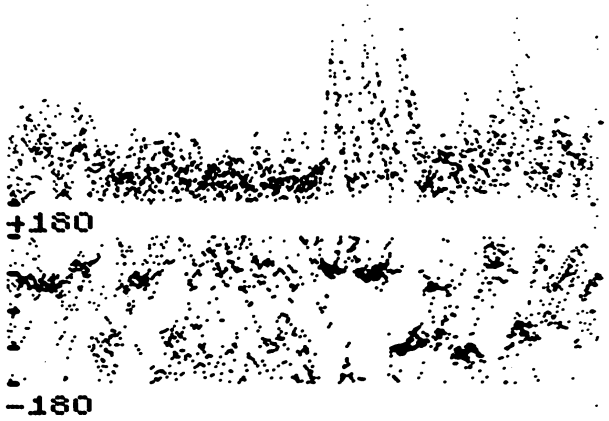
Carrier (entire 6 minutes)



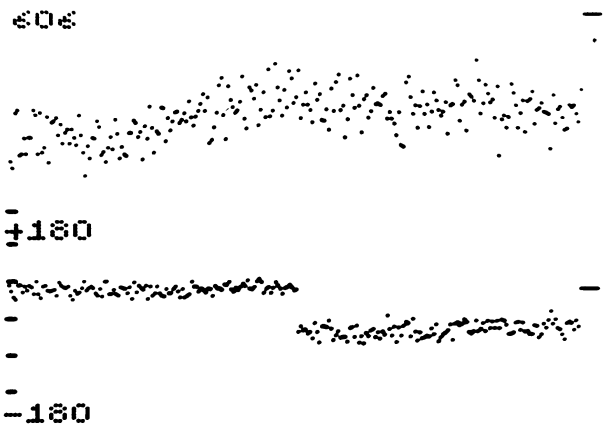
See Note 1



6 January 1967 0443 - 0449



See Note 1

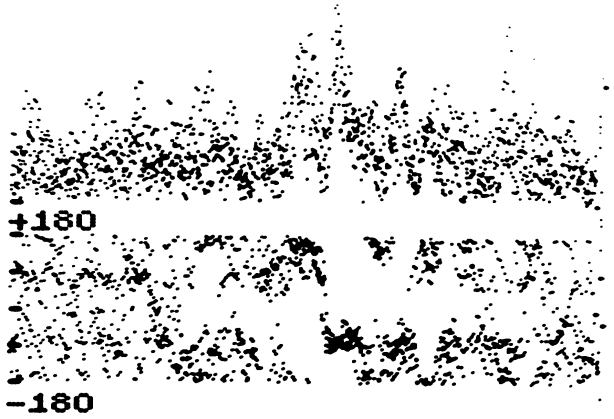


6 January 1967 0643 - 0649

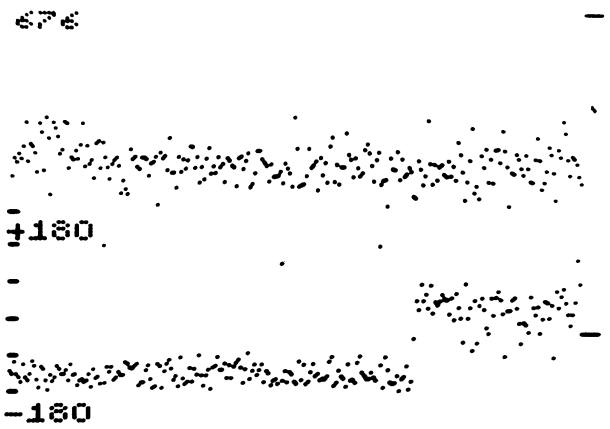
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



See Note 1



6 January 1967 1043 - 1049

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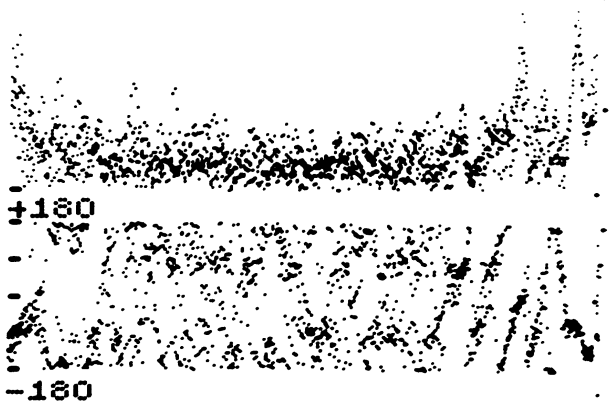
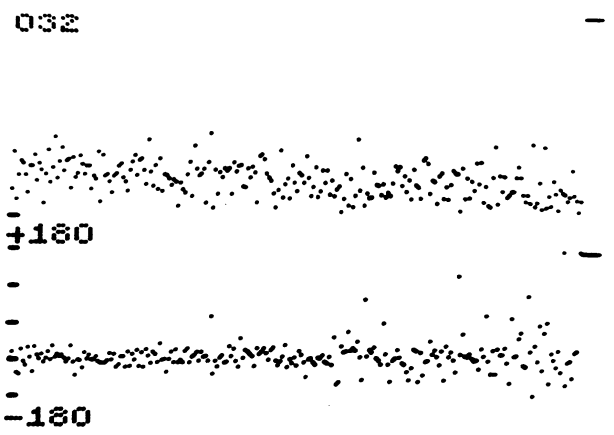


See Note 1

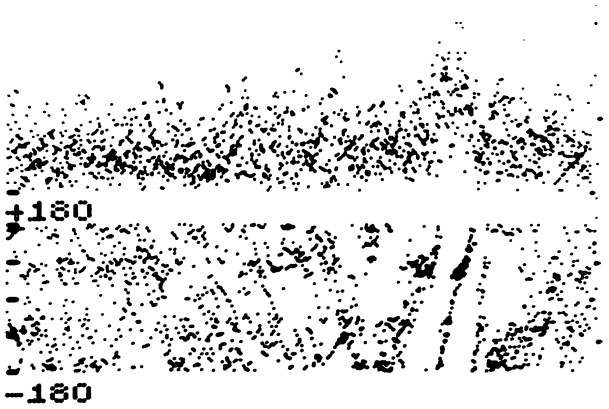


6 January 1967 1643 - 1649

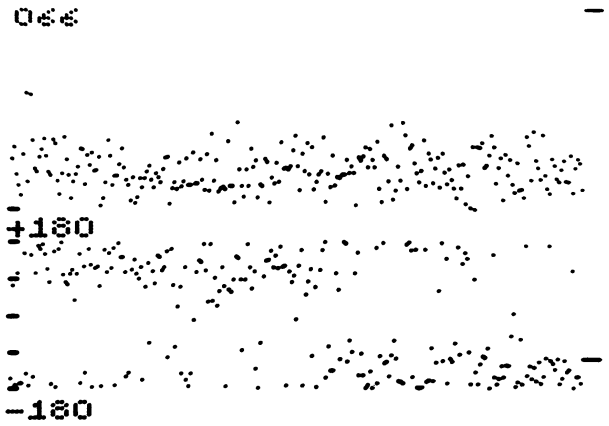
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



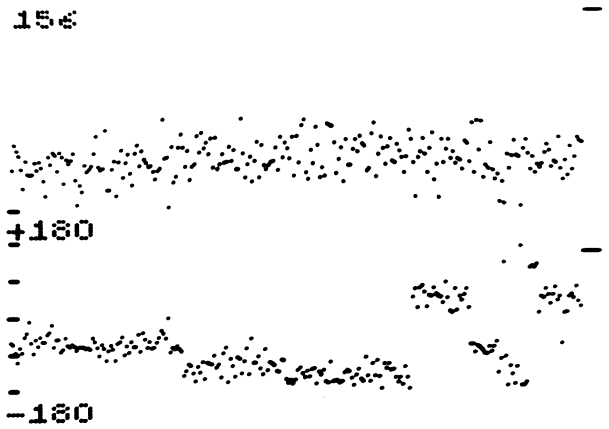
See Note 1



6 January 1967 1843 - 1849

★

See Note 1



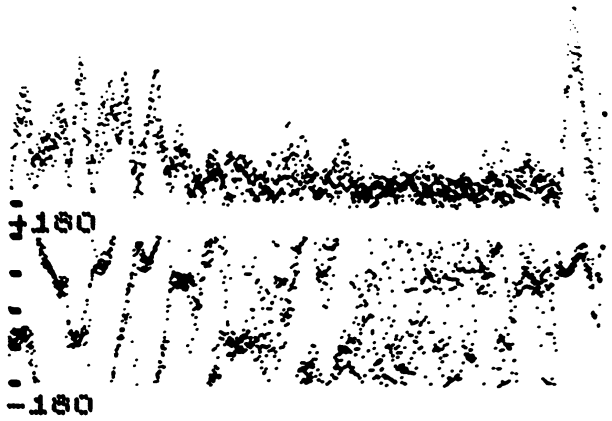
6 January 1967 2243 - 2249

★

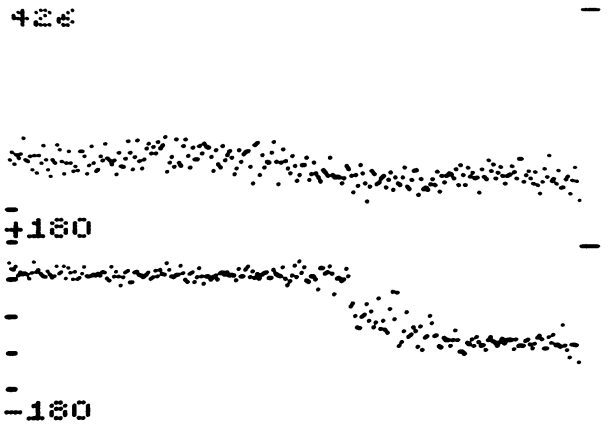
First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



See Note 1



7 January 1967 1043 - 1049

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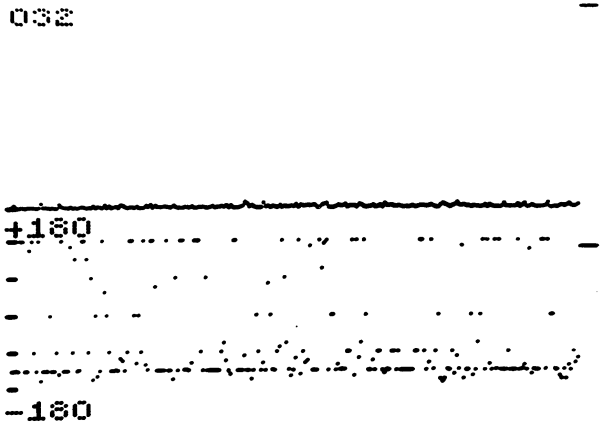
See Note 1

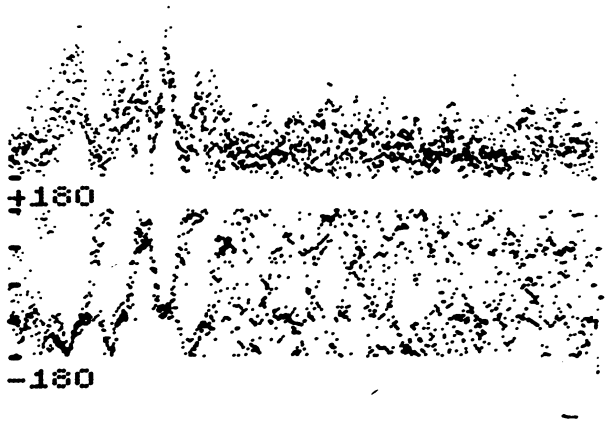


8 January 1967 0443 - 0449

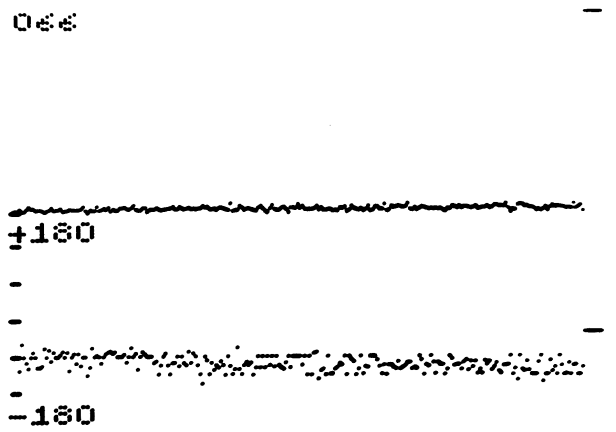
First 3 minutes

Second 3 minutes

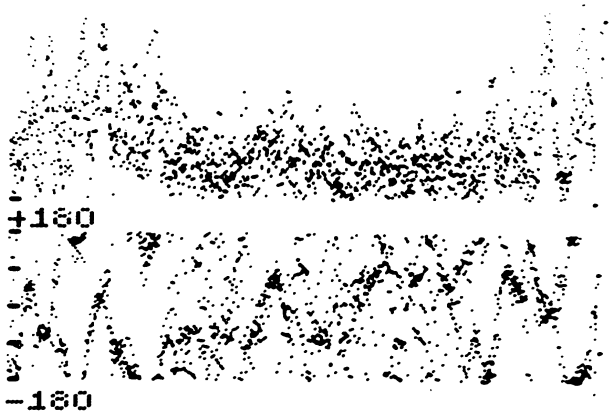
Carrier (entire 6 minutes)



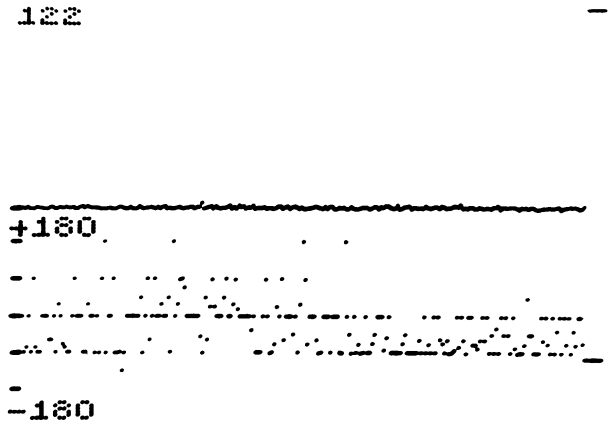
See Note 1



8 January 1967 0643 - 0649



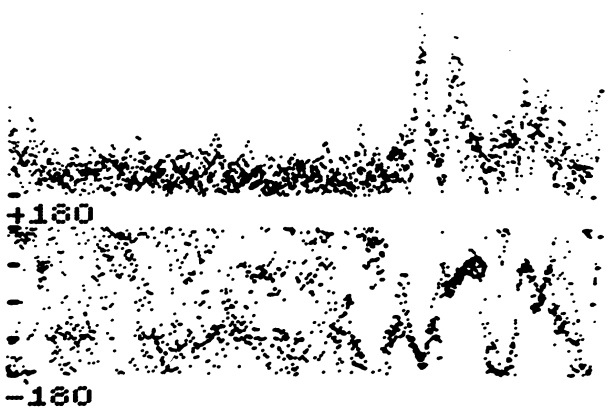
See Note 1



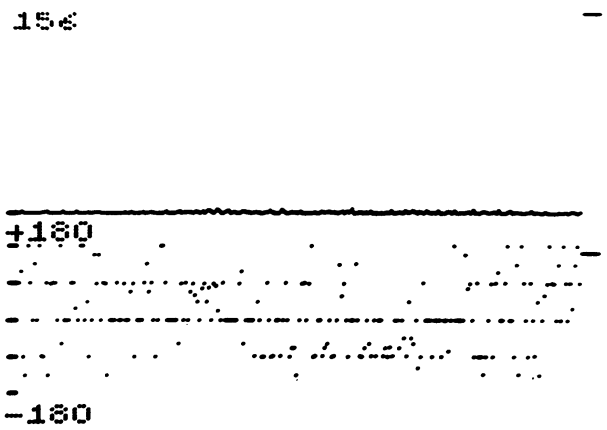
8 January 1967 0843 - 0849

First 3 minutes

Second 3 minutes

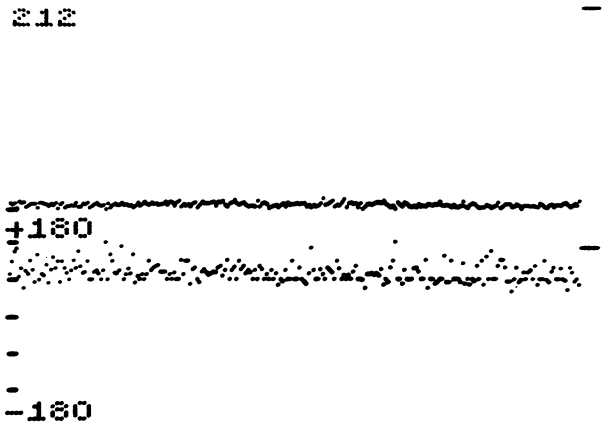


See Note 1



8 January 1967 1043 - 1049

See Note 1

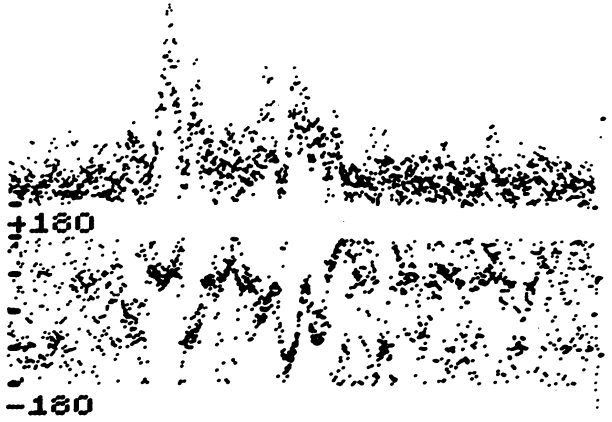


8 January 1967 1243 - 1249

First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)



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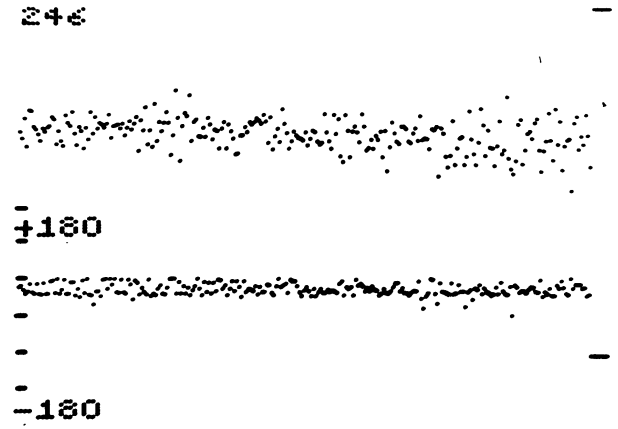
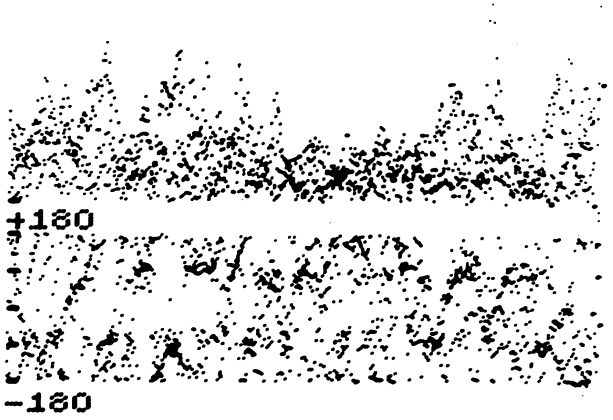


8 January 1967 1443 - 1449



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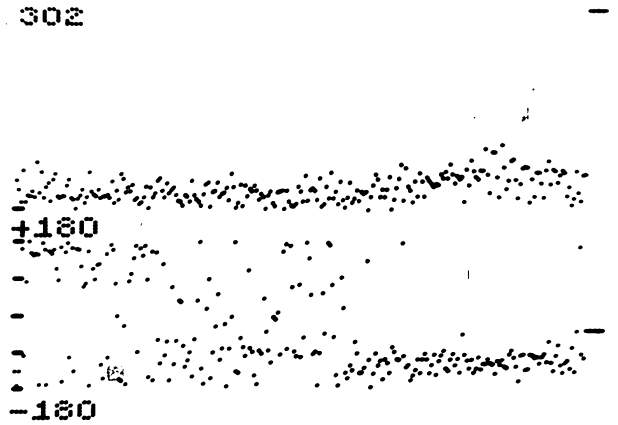

8 January 1967 1643 - 1649

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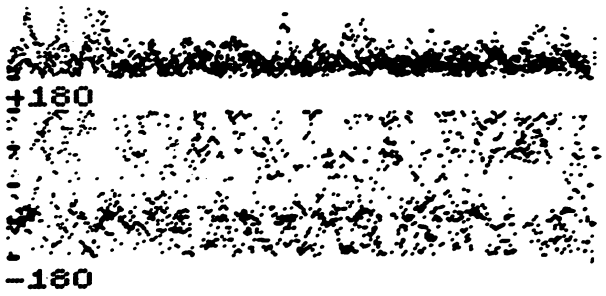

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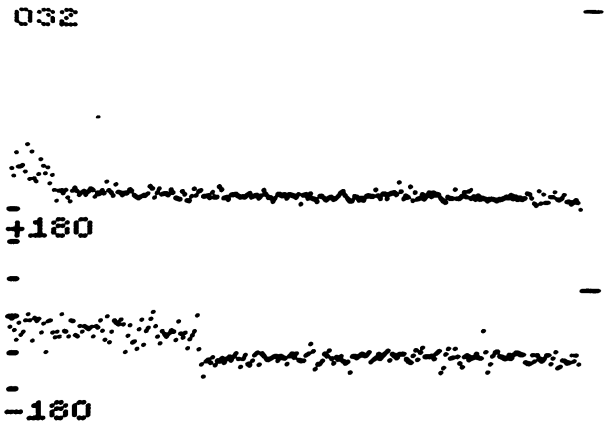

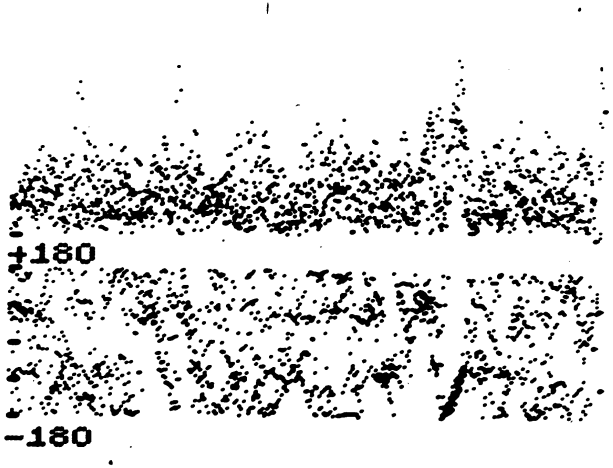

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8 January 1967 2243 - 2249

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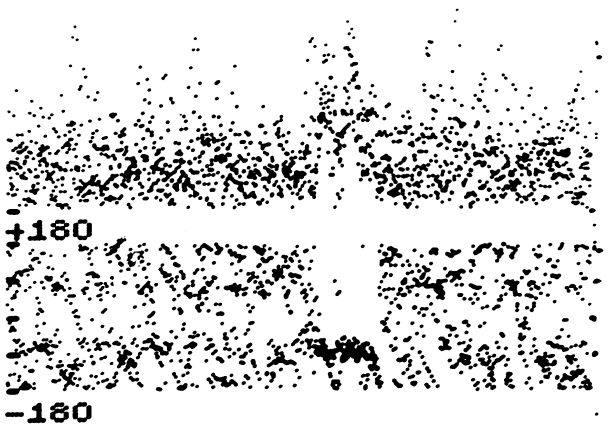

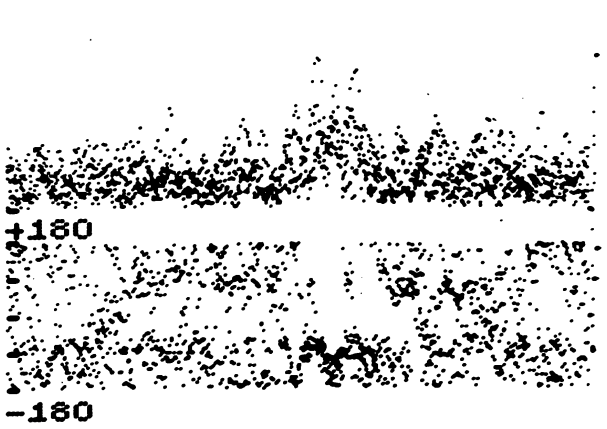

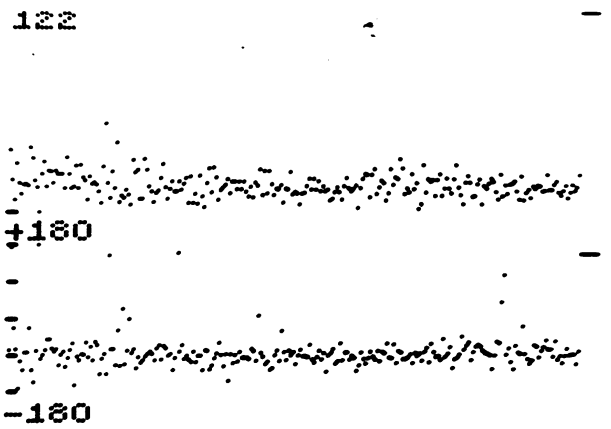

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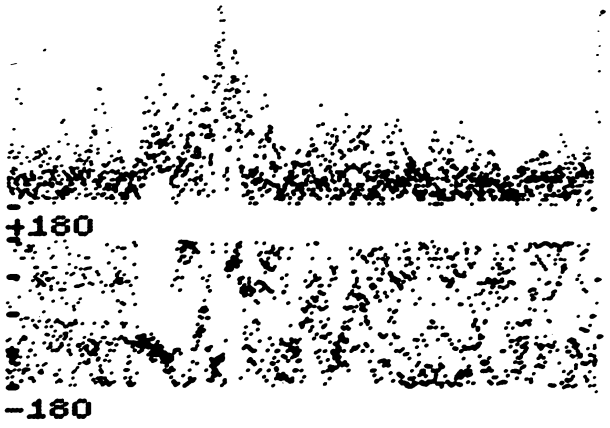

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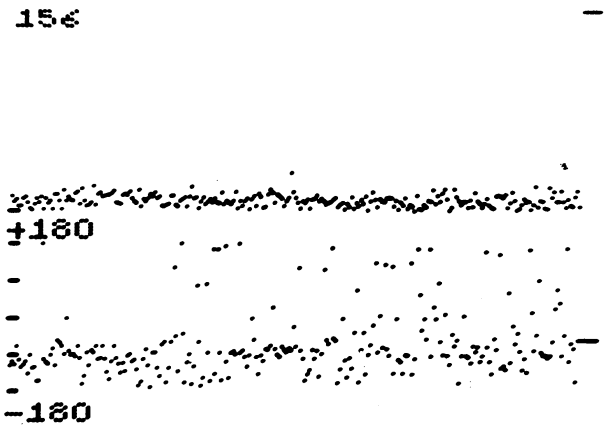

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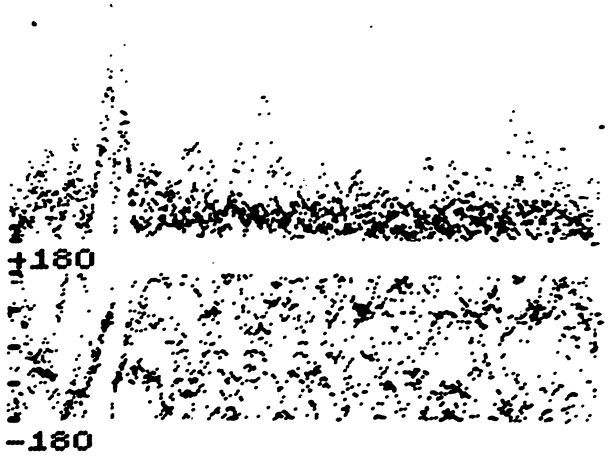

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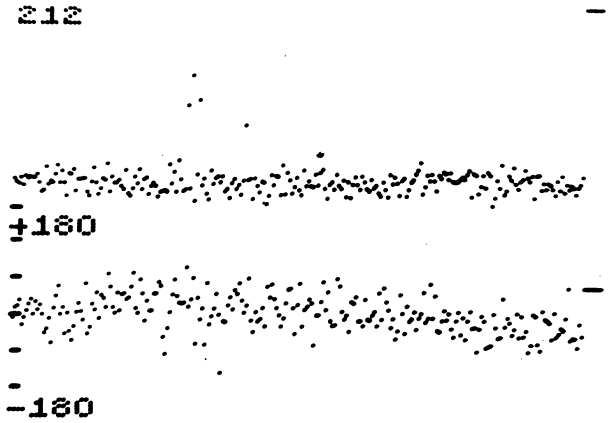

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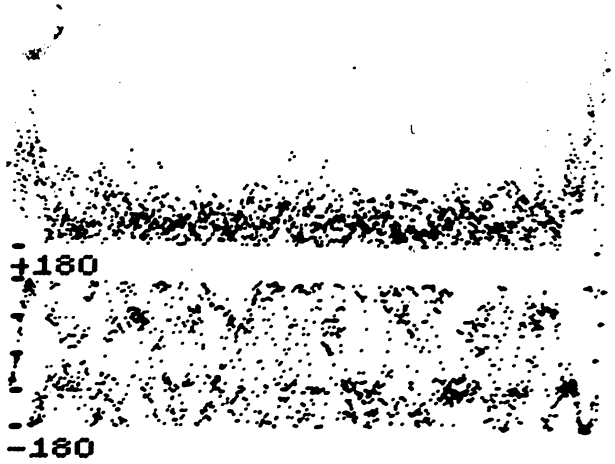

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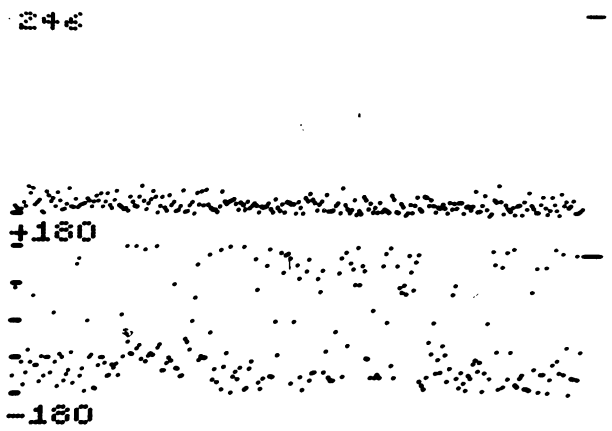

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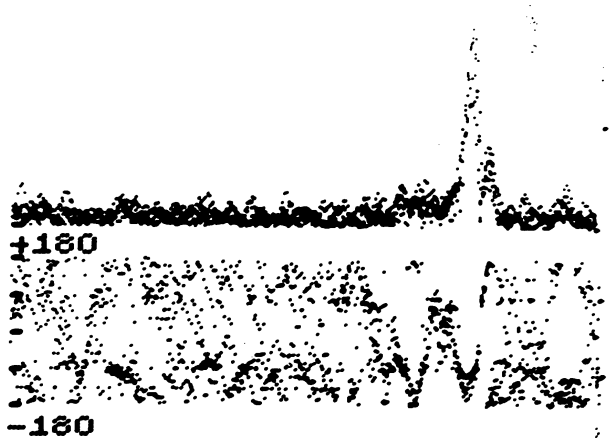

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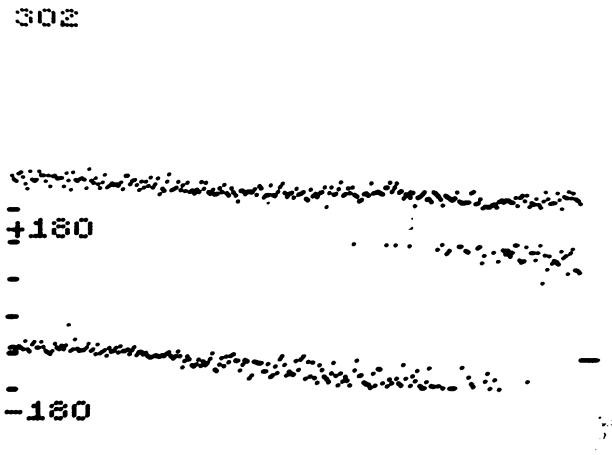

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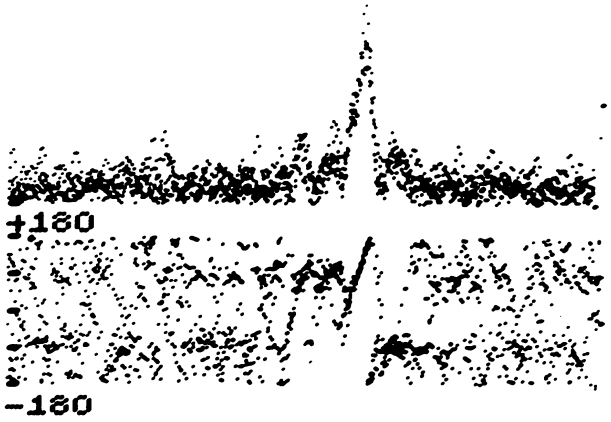

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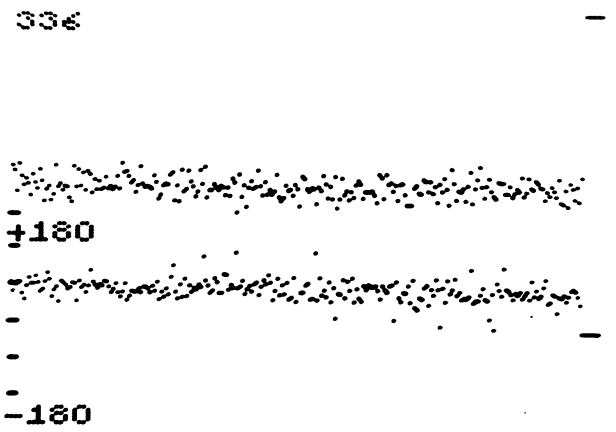

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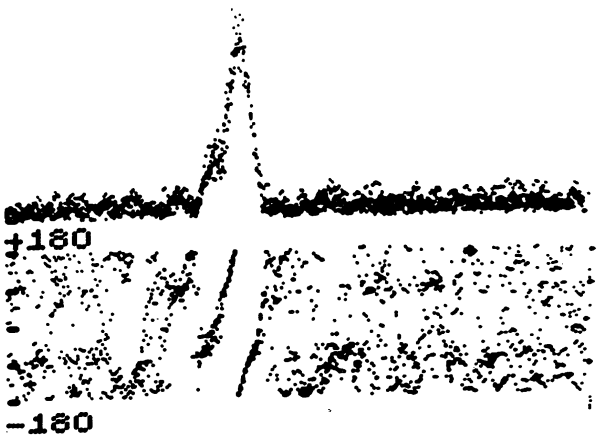

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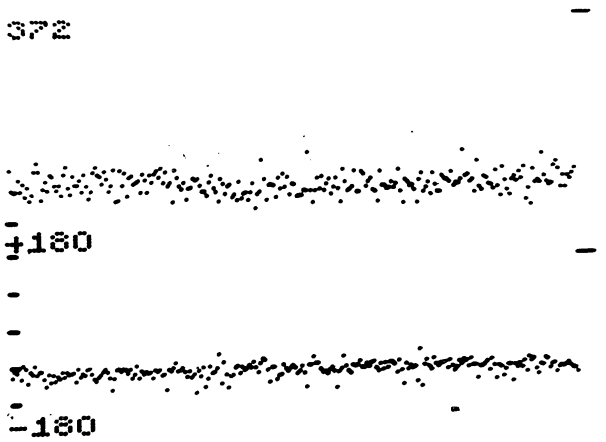

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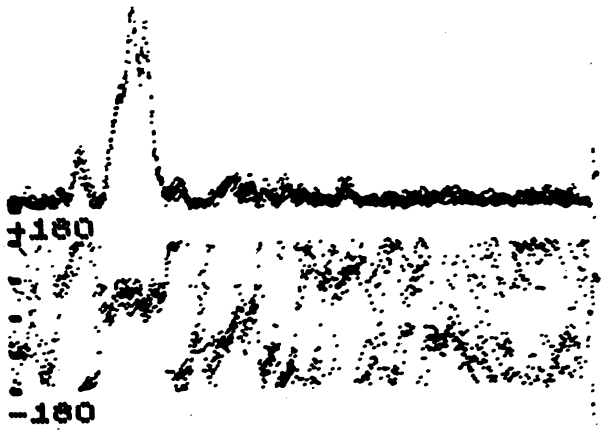

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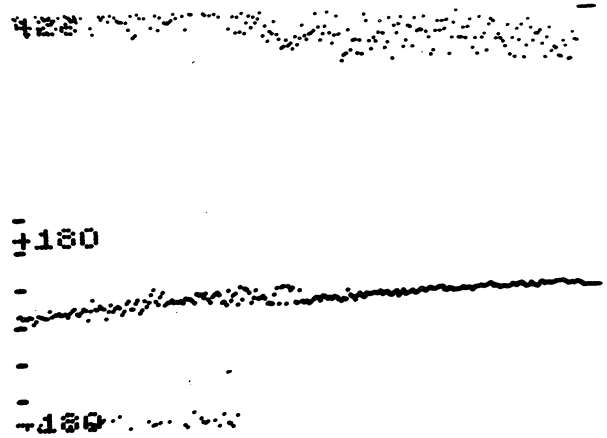

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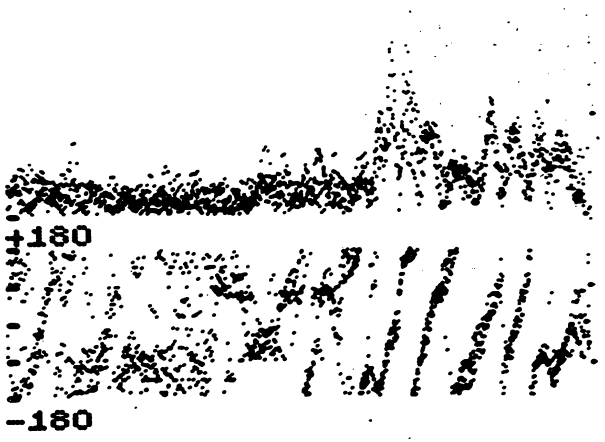

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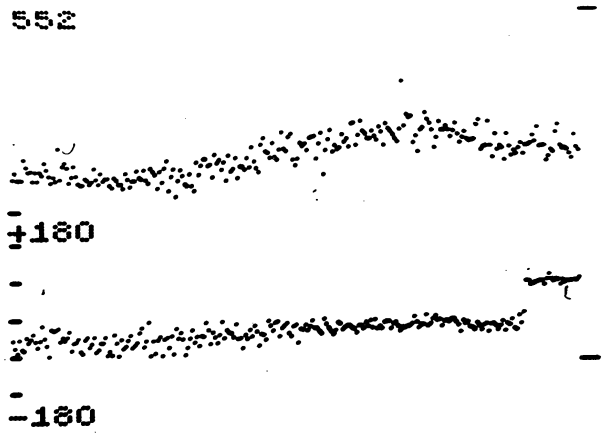

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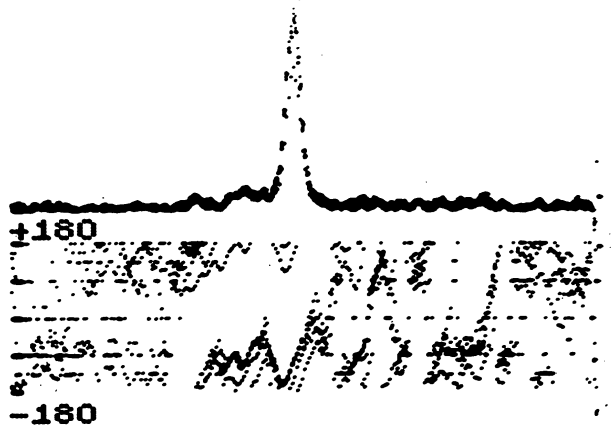

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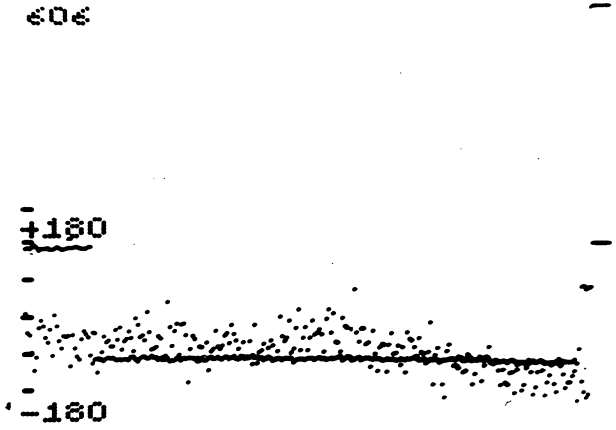

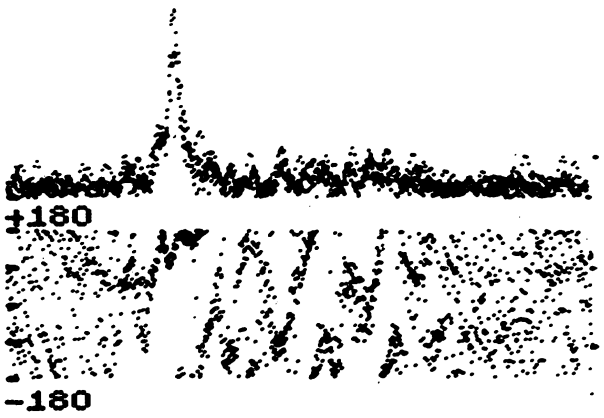

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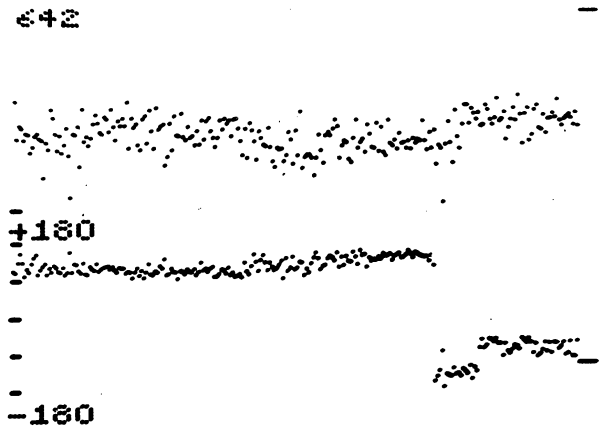

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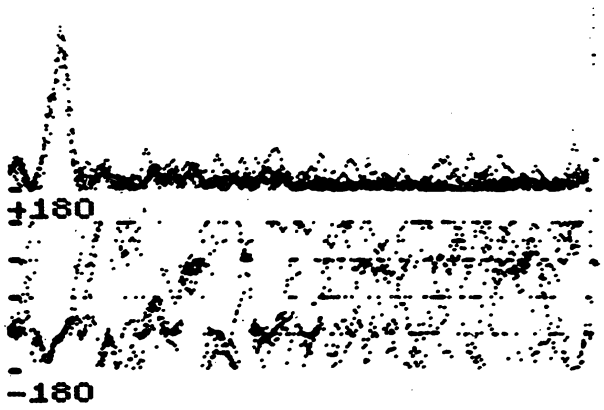

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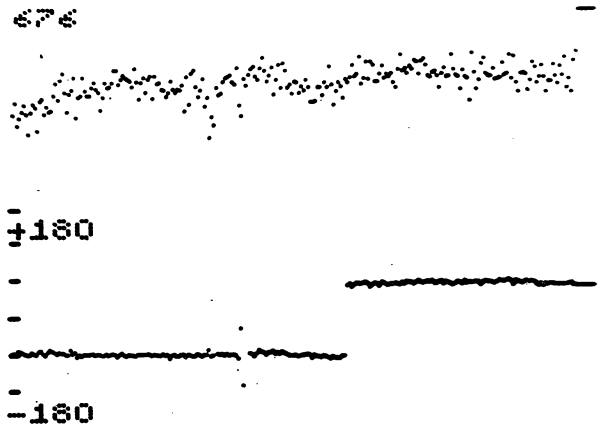

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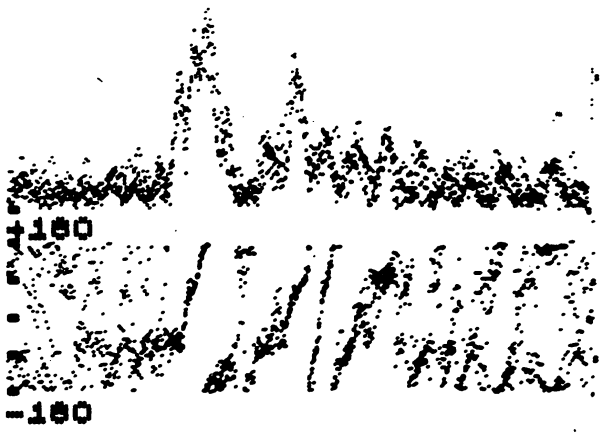

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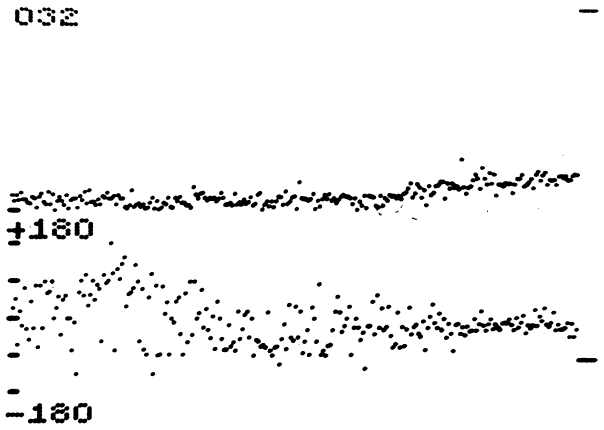

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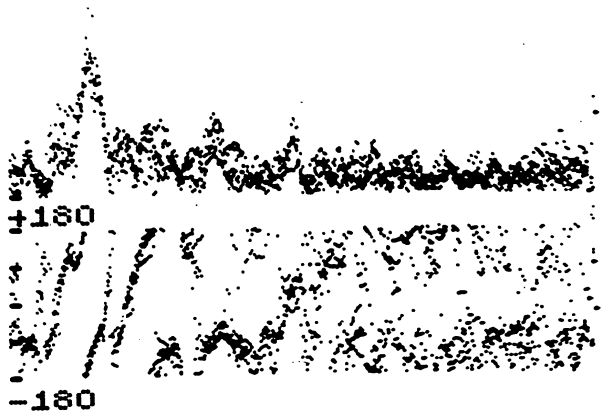

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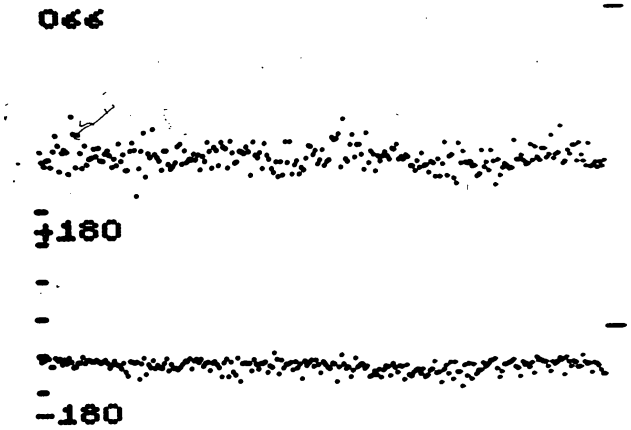

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First 3 minutes

Second 3 minutes

Carrier (entire 6 minutes)

Appendix C

FILTER CHARACTERISTICS AND TRANSFER FUNCTIONS

1. Matched Filters

In a linear system the time response of a filter to its input is given by the convolution integral

$$\phi(t) = \int_{-\infty}^{\infty} h(\tau)\, g(t - \tau)\, d\tau$$

where

$h(t)$ = impulse response of the filter

$g(t)$ = filter input function

$\phi(t)$ = filter output function

To match filter a waveform $m(t)$ with duration T, let the filter impulse response be,

$$h(\lambda) = m(T - \lambda) \qquad 0 < \lambda < T$$

$$= 0 \qquad \text{otherwise}$$

The filter output is determined by

$$\phi(\tau) = \int_{0}^{T} m(T - \lambda)\, g(\tau - \lambda)\, d\lambda$$

The substitution $t = T - \lambda$ yields

$$\phi(\tau) = \int_0^T m(t)\, g(t - T + \tau)\, dt$$

Thus the output of the matched filter is the correlation of the given waveform $m(t)$ and the most recent T seconds of the filter input $g(t)$.

2. Demodulation and Filter Characteristics

The waveforms subject to processing are the output of the analog filter of nominal bandpass 370 Hz to 470 Hz. The sampling rate of 1680 Hz is more than adequate to describe any waveform in these band limits.

The program CMPRES completes the digital demodulation by averaging blocks of four X and four Y samples and thus smooths the effect of the difference in sampling time of X and Y samples. Taking a block of 4 samples for one of the coordinates can be described as a digital filter with impulse response

$$h(t) = \sum_{n=0}^{3} (-1)^n \delta (t - nT)$$

where

$$T = \frac{1}{840} \text{ sec.}$$

To obtain the frequency characteristic we transform $h(t)$ into the frequency domain.

As a result we obtain

$$H(f) = j\, e^{-j3\pi fT}\, \frac{\sin 4\pi fT}{\cos \pi fT}$$

and

$$|H(f)| = \frac{|\sin 4\pi fT|}{|\cos \pi fT|}$$

The frequency of the numerator sine-wave is four times the frequency of the denominator cosine wave. Zero-magnitudes occur every 210 Hz, except where both numerator and denominator equal zero. That is, at 420 and 1260 Hz the magnitude spectrum and the functions of the numerator and the denominator are shown in Fig. 9.

CW1

The program CW1 correlates the compressed samples representing the received signal r(t) with the modulation M(t) = 1 of the 420 Hz carrier in CW transmission.

A digital filter similar to CMPRES describes this operation

$$h(t) = \sum_{n=0}^{N-1} \delta(t - nT) \quad , \qquad \text{where } T = \frac{1.2}{N}$$

As in CMPRES we find the frequency characteristic by Fourier transformation:

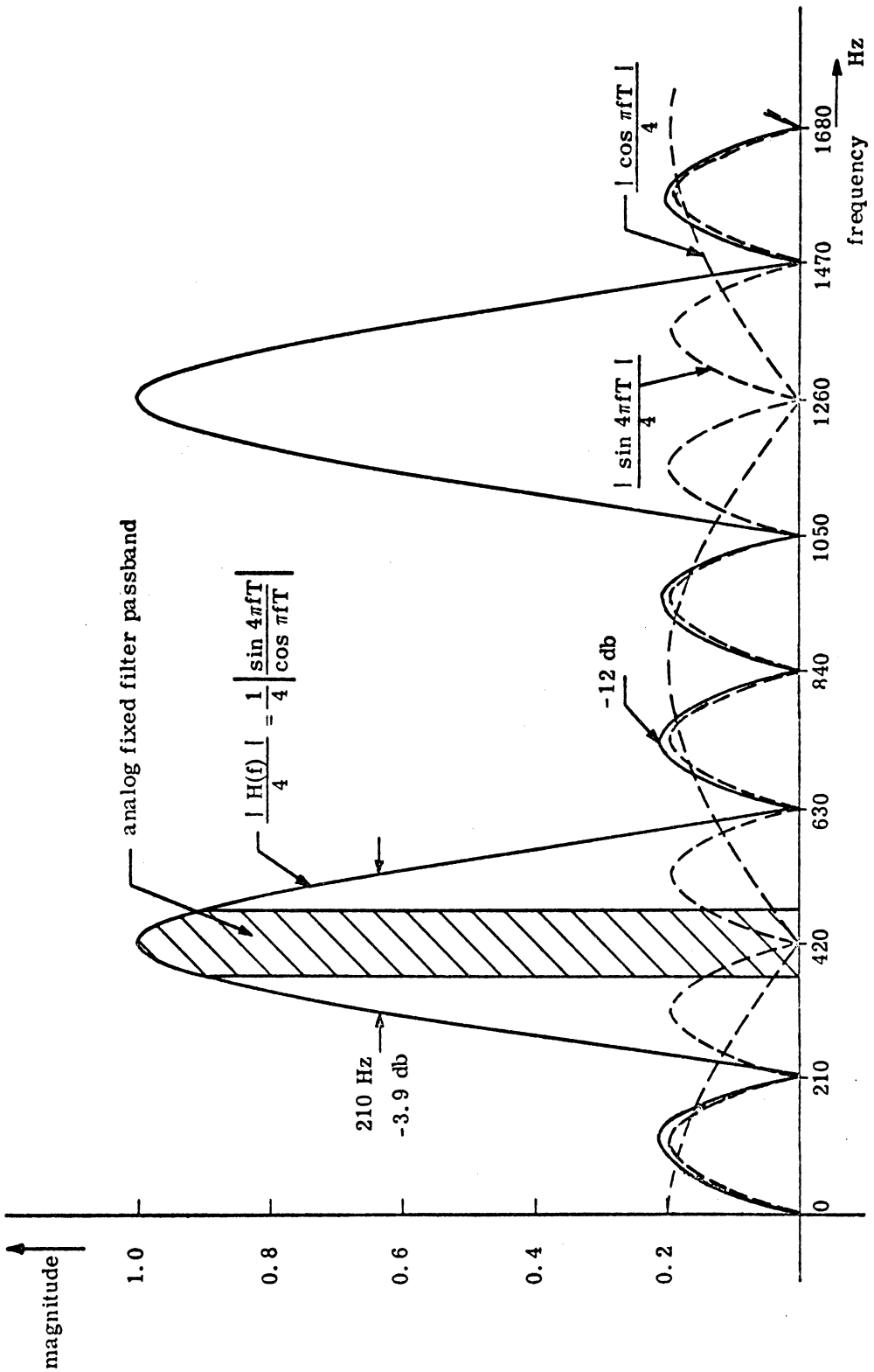

Fig. 9. Normalized low frequency part of CMPRES RMS spectrum

$$H(\omega) = e^{-j(N-1)\frac{\omega T}{2}} \frac{\sin N\frac{\omega T}{2}}{\sin \frac{\omega T}{2}}$$

and

$$|H(f)| = \frac{|\sin N\pi fT|}{|\sin \pi fT|}$$

The normalized spectrum (maximum magnitude = 1) is shown in Fig. 10. The frequency of the numerator sine wave is N times the frequency of the denominator sine wave. Spectral zeros occur at frequencies $f = K/NT$, $K = 1, 2, 3, \ldots, N-1, N+1, \ldots$, that is every $\frac{1}{1.2}$ Hz except zero, $\frac{N}{1.2}$, $\frac{2N}{1.2}$ Hz, etc. At these frequencies, spaced 210 Hz, both the numerator and the denominator are zero and the CW1 transfer function has its maximum magnitude

$$|H(f)|_{max} = N = 252$$

CW2

The program CW2 is the same as CW1 except that CW2 has a value of

$$N = 5292 \quad \text{and} \quad T = \frac{1}{210}$$

The normalized spectrum is shown in Fig. 11.

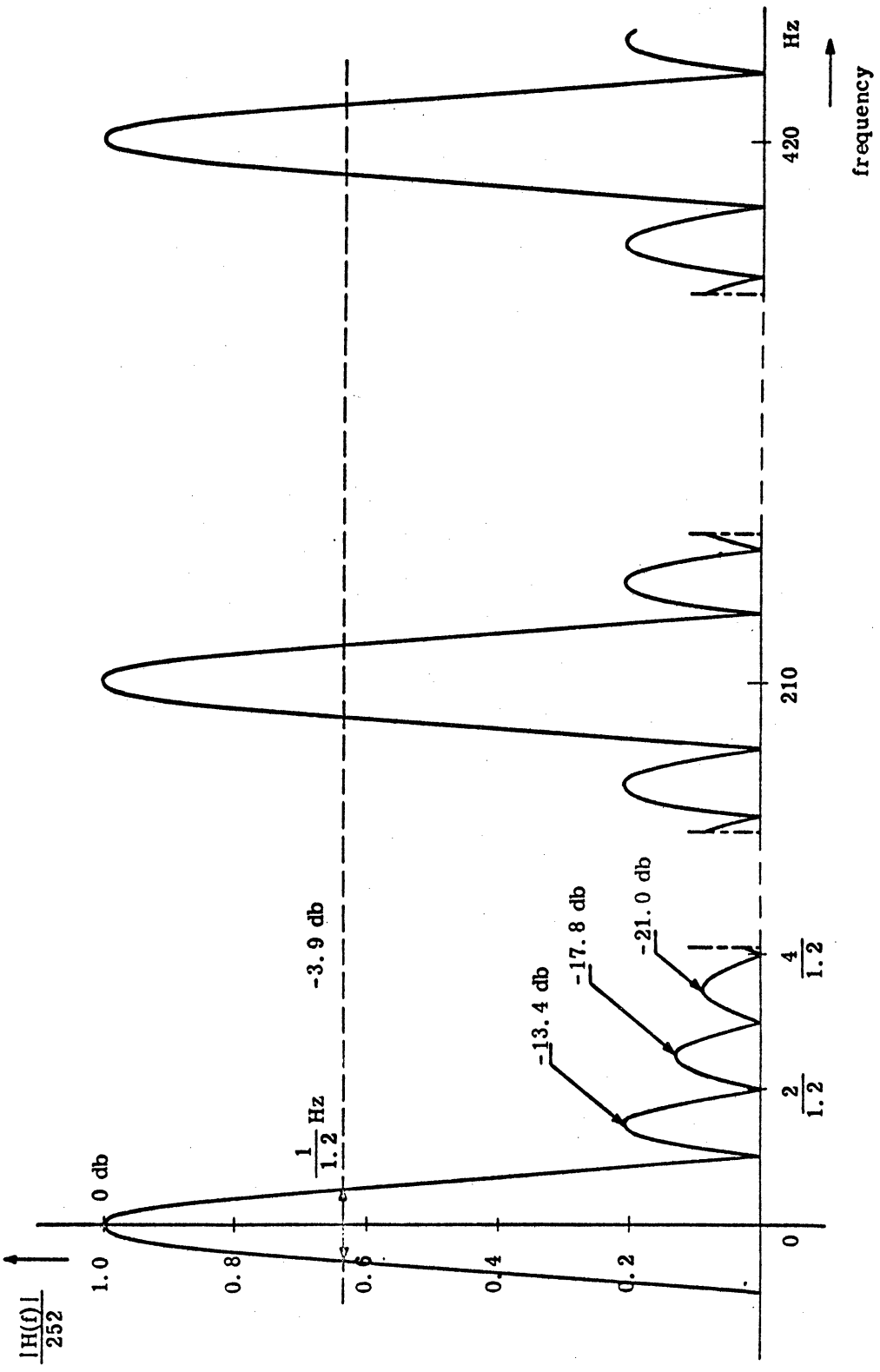

Fig. 10. Details of CW1 normalized magnitude spectrum

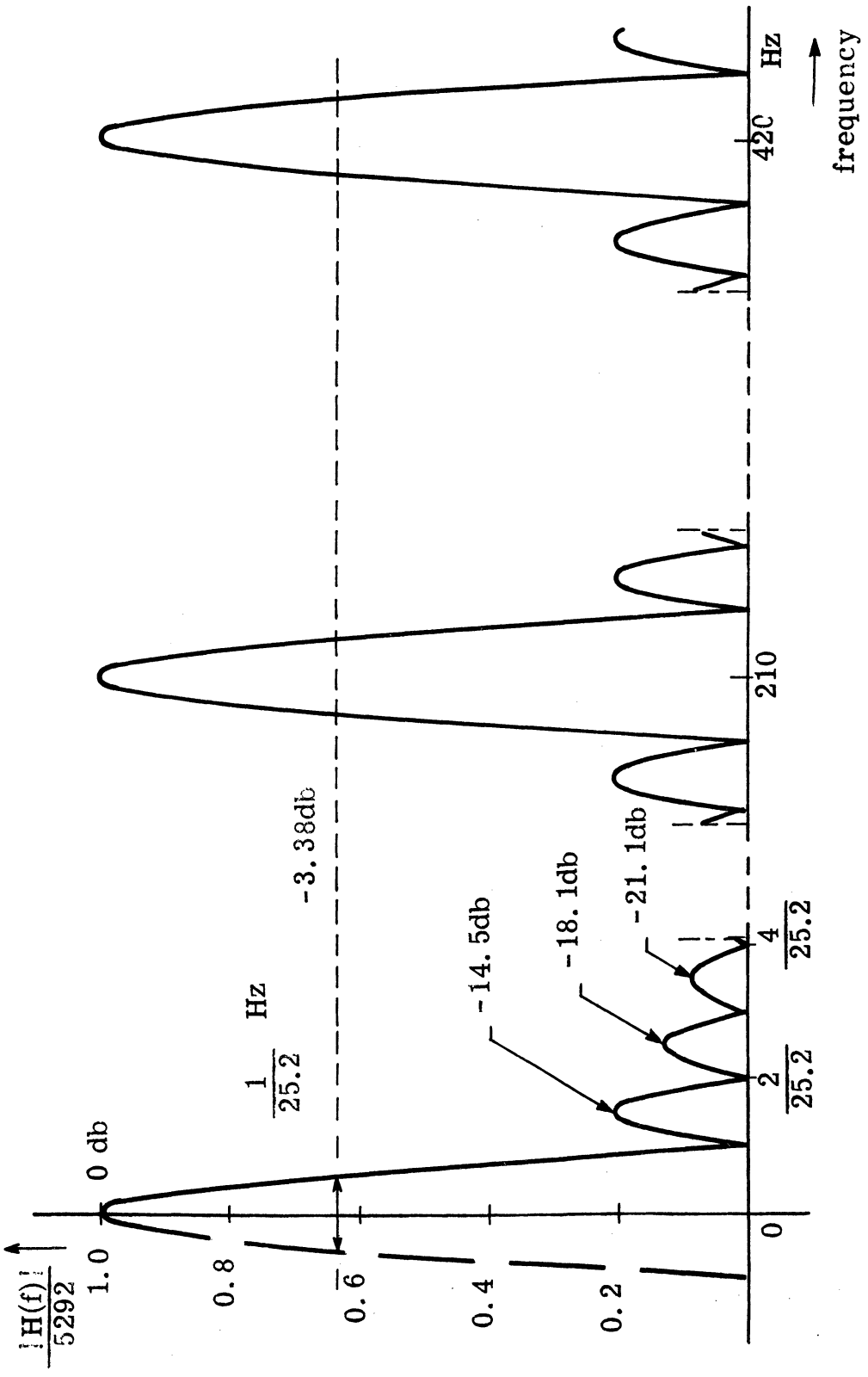

Fig. 11. Details of CW2 normalized magnitude spectrum

CIRAV

To average the data in preparation for sequence analysis, corresponding samples from twenty-one 1.2 second periods, one sample per period, are added together. To describe this process we use the same impulse response as in CW1:

$$h(t) = \sum_{n=0}^{N-1} \delta (t - nT)$$

where $N = 21$ and $T = 1.2$

Fourier transformation results in

$$|H(f)| = \frac{|\sin N\pi fT|}{|\sin \pi fT|} = \frac{|\sin \pi f\ 25.2|}{|\sin \pi f\ \ 1.2|}$$

The CIRAV transfer function has spectral zeros at $f = K/25.2$ Hz, $K = 1.\ 2, 3, \ldots, 11, 13, \ldots$, and maximum magnitude = 21 at $f = 0, 1/1.2, 2/1.2, 3/1.2$, etc.

It should be noted that the period, or frequency interval between the main lobes is determined only by the time interval T between corresponding samples in successive sequences. Thus with a 1.2 sec sequence, the spectral maxima will always occur at frequencies equal to an integer number times 1/1.2 Hz. The normalized magnitude spectrum is shown in Fig. 12.

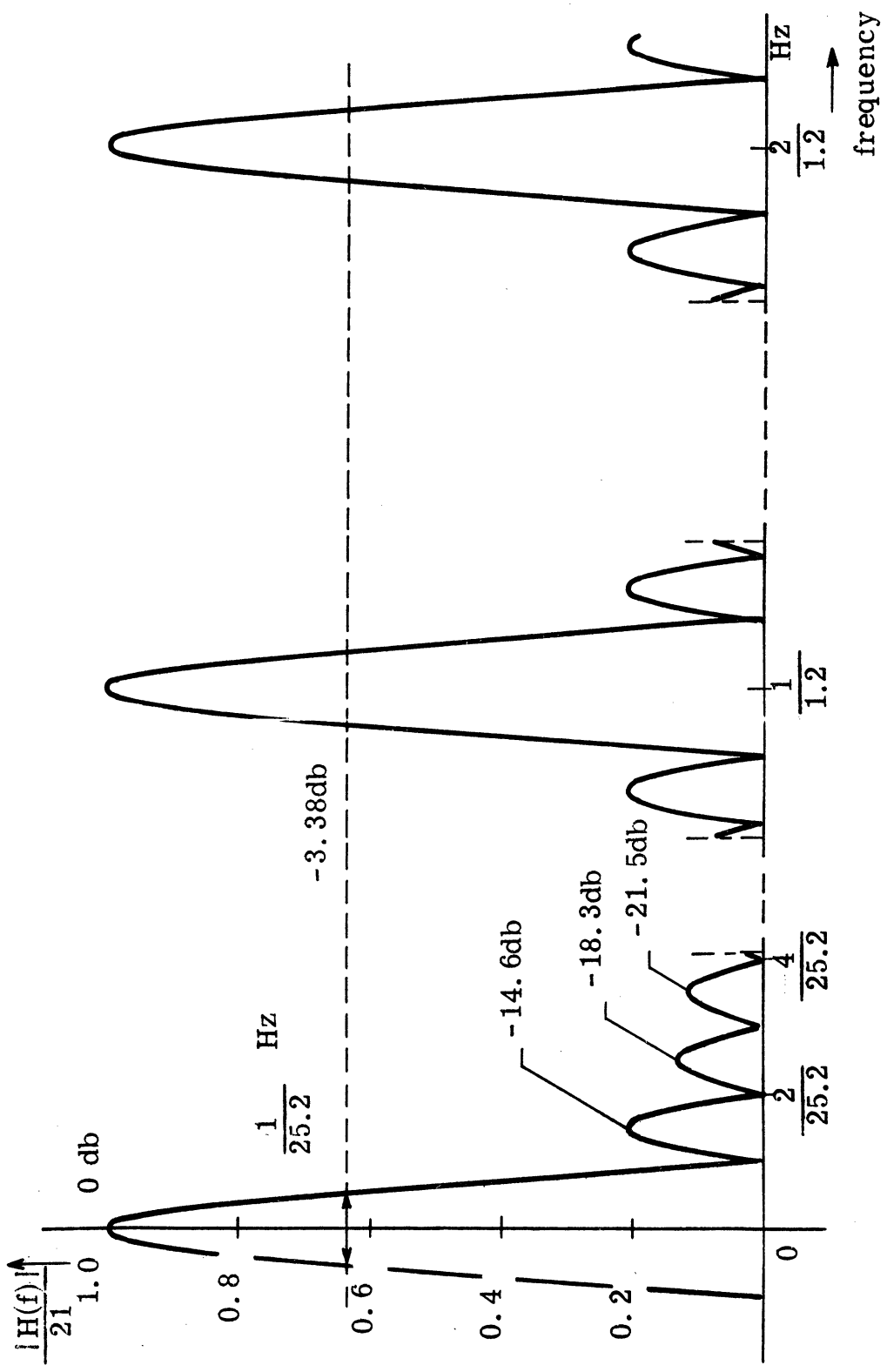

Fig. 12. Details of CIRAV normalized magnitude spectrum

MCOR1

The program MCOR1 performs in digital form the cross-correlation

$$\phi(\tau + 25.2) = \int_0^{1.2} m(t)\, G(t + \tau)\, dt$$

where m(t) is the digitally stored version of the biphase sequence modulation, and G(t) is the representative digital 1.2 sec period of the received signal, obtained from CIRAV. The cross-correlation in the above equation is equivalent to the convolution

$$G(\tau) * m(T - \tau)$$

where T is the 1.2 sec sequence period and $m(T - \tau)$ is the time reversal of the sequence. The single sequence pulse is described by

$$h(t) = 1 \qquad 0 \leq t < b$$

$$h(t) = 0 \qquad b \leq t < T$$

where T = sequence period = 1.2 sec, and b = pulse width = $\frac{T}{L}$ = $\frac{1.2}{63}$ sec.

The Fourier transformation of h(t) yields

$$|H(f)| = b \left| \frac{\sin \pi fb}{\pi fb} \right|$$

The familiar $\left| \frac{\sin x}{x} \right|$ type function.

The spectral power of the sequence is 63 times that of the single pulse. The normalized magnitude spectrum retains the same general shape. However, the d. c. power of the sequence is equal to that of the single pulse. Therefore in the normalized magnitude spectrum the line at 0 Hz has the magnitude $\frac{1}{\sqrt{63}}$ rather than 1 and is 18 db down.

In writing $b = \frac{T}{L} = \frac{1}{f_c}$, f_c = clock frequence of the single pulse (8 carrier cycles) = 52. 5 Hz.

The MCOR1 normalized magnitude spectrum becomes:

$$|M(f)| = \left| \frac{\sin(\pi f/f_c}{\pi f/f_c} \right| = \frac{\sin(\pi f/52.5)}{(\pi f/52.5)} , \quad f \neq f_c$$

and

$$|M(0)| = \frac{1}{L} = \frac{1}{\sqrt{63}} , \qquad f = f_c$$

The magnitude spectrum is shown in Fig. 13.

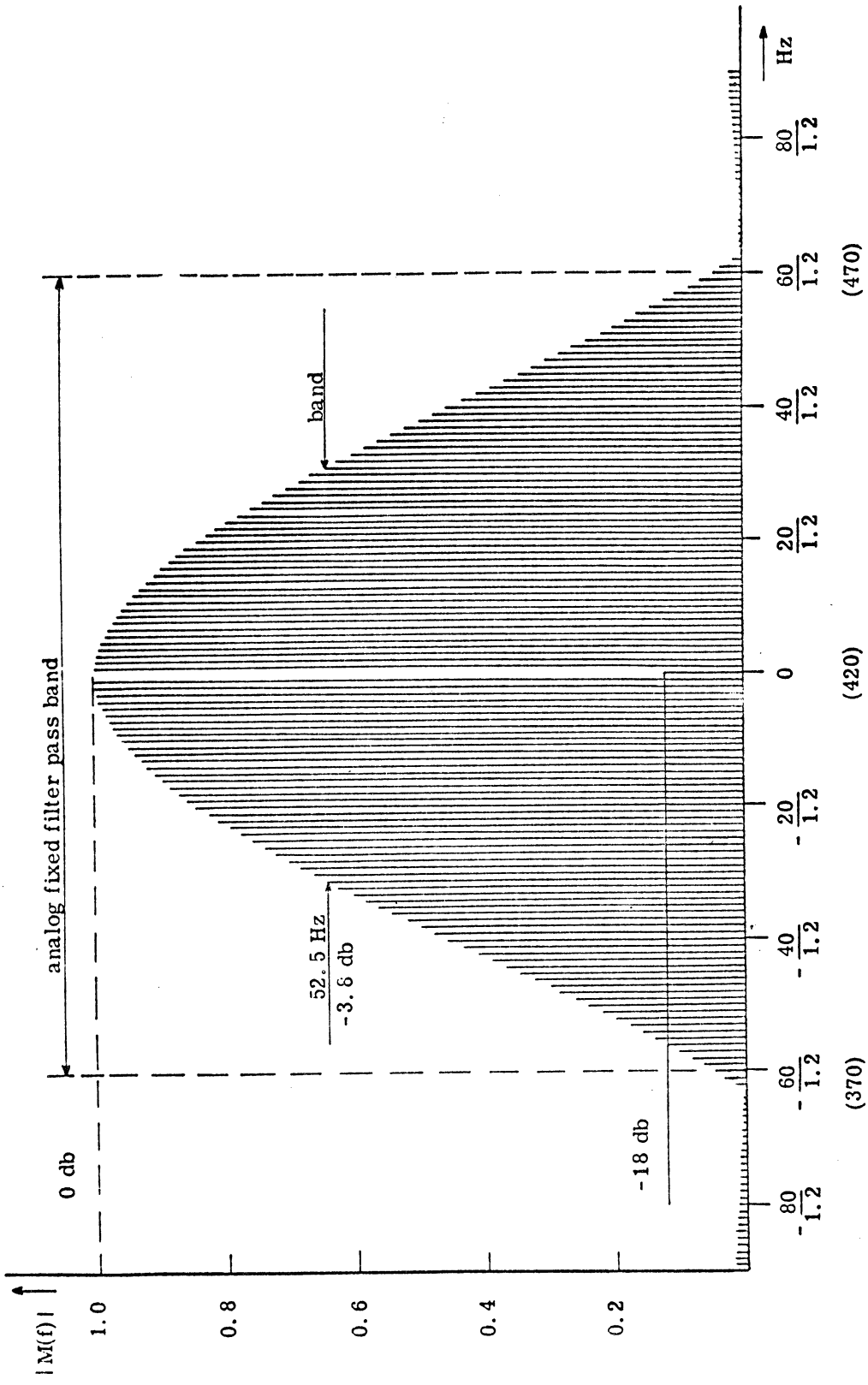

Fig. 13. MCOR1 normalized magnitude spectrum

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13. ABSTRACT

This study is part of a continuing program of underwater sound propagation research called project MIMI. The report covers reception and processing and a limited number of analytic comments. The test timing and duration were chosen to allow closer examination of propagation anomalies previously observed during the early winter and to obtain continuous data on an entire lunar-tide cycle (approximately 28 days). The major objectives were to provide data for the design of more extensive experiments and to test the programs and techniques associated with the LINC-8 computer. Signal processing was designed to yield both multipath information and data on anomalous path conditions. The principal success of the study has been in the improvement of processing programs and experiment design.

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