DOE/ER/10003-T1

Impact of SPS Heating on VLF, LF, and MF Telecommunications Systems Ascertained by Experimental Means

July 1980

Prepared for:
U.S. Department of Energy
Office of Energy Research
Satellite Power System Project Division

Under Contract A102-79CH-10003

DOE/NASA
Satellite Power System
Concept Development
and
Evaluation Program

DISCLAIMER

DISCLAIMER

Available from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price: Printed Copy: $9.00
Microfiche: $4.00

Master

DOE/ER/10003-T1
Dist. Category UC-13

Impact of SPS Heating on VLF, LF, and MF Telecommunications Systems Ascertained by Experimental Means

July 1980

Prepared for:
U.S. Department of Energy
Office of Energy Research
Satellite Power System Project Division
Washington, D.C. 20585

Prepared by:
C. M. Rush, E. J. Violette,
R. H Espeland, J. C. Carroll,
K. C. Allen
Institute for Telecommunication Sciences
National Telecommunications and Information Administration
U.S. Department of Commerce
Boulder, CO 80303
Under Contract A102-79CH-10003

DOE/NASA
Satellite Power System
Concept Development
and
Evaluation Program

PAGES ii to iv

WERE INTENTIONALLY

LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES CONTINUED.

LIST OF FIGURES CONTINUED.

LIST OF FIGURES CONCLUDED.

LIST OF TABLES

IMPACT OF SPS HEATING ON VLF, LF, AND MF
TELECOMMUNICATIONS SYSTEMS ASCERTAINED BY EXPERIMENTAL MEANS

C.M. Rush, E.J. Violette, R.E. Espeland, J.C. Carroll,* and K. C. Allen**

This report summarizes the results of experiments undertaken to assess the potential impact of the operation of the Satellite Power System on the D and E regions of the ionosphere, and on telecommunication systems that are dependent upon the structure of the lower ionosphere. Using the high-power high-frequency transmitter facility located at Platteville, Colorado, power densities comparable to the Satellite Power System can be delivered to the heights of 70 to 100 km above the surface of the earth. Observations of the performance of telecommunication systems that operate in the VLF, LF, and MF portions of the spectrum have been investigated during times when the ionosphere was modified with SPS comparable power density and when it was not. The results obtained indicate that the SPS, as currently configured with a peak power density of 23 mW/cm^2, will not adversely impact upon the performance of VLF, LF, and MF telecommunication systems.

Key Words: D and E region heating; D and E region telecommunications effects; LF propagation; LORAN-C; MF propagation; OMEGA; satellite power system; VLF propagation

1. INTRODUCTION

The Department of Energy is currently investigating the feasibility of employing a Satellite Power System (SPS) as a means of helping to meet the energy needs of the United States in the twenty-first century. As part of the feasibility study, questions are being directed toward whether or not the operation of the SPS will lead to changes in the earth's natural environment and whether or not such changes, if they occur, will adversely impact upon terrestrial inhabitants. One of the principle concerns that has been voiced with regard to potential environmental impacts is the degree to which the earth's ionosphere would be modified by the passage of the high-power microwave transmission beam associated with SPS operation. If the ionosphere is substantially modified, then there exists the possibility that telecommunication systems that rely upon the transmission of electromagnetic waves within and through the ionosphere would be likewise affected. This could result in performance degradation of telecommunication systems unless alternate operational strategies or mitigation techniques are developed.

* The authors are with the U. S. Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences, Boulder, Colorado 80303.

** The author is with the Boulder Experimental Studies Institute, Longmont, Colorado 80501.

In order to assess the degree to which the ionosphere would be affected by SPS operation, the Department of Energy is undertaking a research and development program of national scope. This program involves government, industry, and university personnel working in areas that will improve our theoretical and experimental understanding of the impact of high-powered microwaves upon the ionosphere. We present in this report the results of a ground-based simulation of the heating of the lower ionosphere that would be associated with a single SPS and the effects of such heating on telecommunication systems operating in the very low frequency, low frequency, and medium frequency portion of the spectrum.

Simulation of the ionospheric heating resulting from the operation of a Satellite Power System is made possible by use of a high-powered, high frequency radio transmission facility that is located at Platteville, Colorado, and operated by the Institute for Telecommunication Sciences. The manner in which such a ground-based facility can be used to simulate SPS operation and how telecommunications experiments can be designed around a simulated SPS ionospheric heating experiment is described in the next section. The results of selected telecommunication system experiments conducted under simulated SPS operational scenarios are described in Sections 3 through 5. In order to provide information that can be used to determine in a more direct fashion how the ionosphere is modified by high powered HF radio waves, a number of diagnostic experiments were undertaken. These are discussed in Section 6. In Section 7 the findings of the studies discussed herein are summarized and areas where further work is required are pointed out.

2. EXPERIMENTAL CONSIDERATIONS

2.1 Background

Heating the ionosphere with high-power, high-frequency (HF) radio waves has been conducted on an intentional basis since the late 1960's. High-power HF facilities located at Platteville, Colorado, and Arecibo, Puerto Rico, have been extensively used to increase our knowledge of the physical mechanisms that lead to changes in the plasma concentration of an ionosphere that is subjected to intense electromagnetic radiation. A recent review by Utlaut (1975) describes the status of knowledge garnered by intentionally heating and modifying the ionosphere. This review significantly updates the discussions provided by Utlaut and Cohen (1971) and Gordon and Carlson (1974). In recent years, a great deal of theoretical emphasis has been placed on the understanding of plasma processes that lead to instabilities and irregularities in the ionospheric electron density that proceed as the result of the application of intense heating by radio waves (Fejer, 1979; Gurevich, 1978).

The current Satellite Power System concept calls for the operation of satellites in geostationary orbit beaming microwave energy to the surface of the earth at a frequency of 2.45 GHz (U.S. Department of Energy, 1980). The power that is envisioned with the passage of the microwave beam is on the order of 5 to 10 gigawatts. The beam is expected to be on the order of 10 kilometers in diameter as it passes through the ionosphere. The power density associated with the beam at its center is designed to be 23 mW/cm^2. This power density is on the same order as that which has been postulated as giving rise to enhanced electron heating and the creation of thermal self-focusing instabilities (Meltz et al. 1974).

Because of the frequency involved (2.45 GHz), the heating that the SPS power beam will provide to the ionosphere is believed to be that arising from ohmic interactions between the power beam and the electrons, ions, and neutral particles comprising the ambient ionosphere. The rate of energy that is input into the D region of the ionosphere by ohmic heating due to radio waves is given:

$$Q = \frac{E^2}{8\pi} \frac{(f_p \pm f_H)^2}{f_o^2} \times \left(\nu_{ei} + \nu_{en}\right) \qquad (1)$$

where,
- Q = the energy input;
- E = the electric field amplitude of the perturbing (heating) wave;
- f_p = the local plasma frequency;
- f_H = electron gyrofrequency;
- f_o = the wave frequency;
- ν_{ei} = the electron-ion collision frequency; and
- ν_{en} = the electron-neutral collision frequency.

Under conditions of ohmic heating, the resulting power flux at microwave frequencies can be related to the resulting power flux at another frequency through the relationship (Gordon and Duncan 1978):

$$\frac{P_{SPS}}{f^2_{SPS}} = \frac{P_{HF}}{f^2_{HF}} \qquad (2)$$

where P_{SPS} and f_{SPS} are the SPS microwave power density and frequency and P_{HF} and f_{HF} are the power density and frequency at another frequency in the spectrum. It follows from Equation (2) that heating the ionosphere using radio waves at a lower frequency than that of the SPS requires a smaller amount of power density to achieve a SPS-comparable effect. Provided the heating is accomplished by radio waves that pass through the ionosphere--the heating is said to be "underdense"--high-powered HF waves can be used to simulate SPS heating. This is precisely why facilities such as the Platteville high-power HF transmitter can be used to simulate SPS heating.

2.2 Characteristics of the Platteville High-Power HF Facility

The current Platteville high-powered HF Facility is essentially the same as that described by Carroll et al. (1974). The Facility is equipped with a transmitter consisting of ten identical amplifier channels that are tuneable in the frequency range from 2.7 to 25 MHz. However, because of antenna limitations, the effective upper frequency is 10 MHz. The transmitter is connected to a 10-element, ring-array antenna. The average input power to the transmitter is about 2 MW. The antenna used in the current experiments is a ten-element, ring-array consisting of crossed double-conical dipoles made using a wire-cage design that contains 24 wire elements. Each dipole is 30 m in overall length and is 6.9 m at the point of maximum diameter. The center feed point of the dipole is supported 10 m above the wire mesh ground screen by two steel tubes 25 cm in diameter, which also serves as a balanced-to-unbalanced coaxial transformer. Fiberglass poles support the ends of the dipole, and the structure is steadied by mylar and dacron rope.

Using antenna characteristics of the Platteville Facility as listed in Table 1 (Mark Ma, private communication) and assuming that the total output power of the transmitter that is delivered to the antenna is 2.0 MW and that the antenna efficiency is on the order of 60%, the power density at any height in the ionosphere and for any frequency between 5 and 10 MHz can be determined. The SPS equivalent power densities at 100 km (taken as representative of the lower E region) and at 300 km (taken as representative of the F region) are given in Table 1. The equivalent power density was determined by multiplying the appropriate values of P_{HF} and f_{HF} in Equation (2) by $f_{SPS}^2 = 6 \times 10^6$ MHz^2.

It can be seen that for frequencies near 5 MHz the Platteville facility provides SPS comparable power densities to the lower ionosphere. Frequencies of on the order of 5 MHz almost always pass through the lower ionosphere when transmitted vertically from the ground. Hence they can be regarded as heating the ionosphere in an underdense fashion. It should be pointed out that the power densities given in Table 1 were deduced under the assumption that there was no absorption of the heater wave as it passes through the lower ionosphere (75 - 90 km). This is not a valid assumption during daytime hours when a significant portion of the radio energy can be absorbed in the ionosphere between 75 and 90 km. This can lead to enhanced heating of the lower D region. Telecommunications systems operating in the VLF and

Table 1. Antenna Characteristics of Platteville Facility and SPS Comparable Power Densities

Frequency (MHz)	Beamwidth (degrees)	Element Gain (dB)	Array Directivity (dB)	Power Density at 100 km (mW/cm^2)	Power Density at 300 km (mW/cm^2)
5	22.0	6.93	13.08	23.0	2.60
6	19.0	7.70	10.43	10.8	1.20
7	17.0	9.22	10.18	10.3	1.14
8	14.8	10.05	10.68	10.6	1.18
9	13.2	10.18	9.41	6.5	0.73
10	11.9	9.54	9.14	4.3	0.48

LF portions of the spectrum rely upon propagation of energy that is principally effected by the structure of the lower D region during daylight hours. Therefore, even though absorption of the heater wave occurs below 100 km, it is occurring at the height where the telecommunications systems of interest in this study are impacted the most by the ionospheric structure. During nighttime hours, however, it is felt that little absorption of the radio waves used to heat the lower ionosphere takes place below 100 km and the power density at 100 km is as given in Table 1.

2.3 Telecommunications Experiment Design

The Platteville Facility is able to provide SPS comparable power density to an area of the lower ionosphere that is approximately 40 km in diameter at 100 km. This area is four times larger than that anticipated from the SPS microwave beam. Thus, from the viewpoint of size, the Platteville Facility provides a more than worst-case simulation of SPS heating effects in the lower ionosphere. Because the current Platteville Facility provides SPS comparable power density only to the lower ionosphere, the telecommunication studies reported upon herein were directed toward obtaining performance information for those systems whose radio waves are significantly affected by the structure of the lower ionosphere. The telecommunication systems chosen for investigation were representative of those operating in the very low frequency (VLF, 3kHz-30kHz), low frequency (LF, 30kHz-300kHz), and medium frequency (MF, 300 kHz-3MHz) portions of the electromagnetic spectrum.

The following sources were used to assess the potential impact of SPS operation on telecommunication systems operating in the lower ionosphere:

1. VLF Signal Sources - OMEGA and WWVB
2. LF Signal Sources - LORAN-C Stations
3. MF Signal Sources - AM Broadcast Stations
4. Receiving Sites - Brush, Boulder, and Bennett, Colorado.

At each of the receiving sites, one or more of the source signals were recorded to test specific objectives.

Table 2 provides pertinent information on each of the sources and receiving sites used in the experiments. Station function, operating frequency, station power, coordinates, and range and bearing between the source and receiving site are given. Figure 1 provides an indication of the geometry of each source relative to the region of the ionosphere that is heated by the Platteville Facility and the receiving sites. Segments of this map are reproduced and used in the discussions of the results obtained from the recorded signals of the OMEGA, LORAN-C, and broadcast stations discussed in later sections.

Table 2. Data on Facilities and Sites Used in the DOE Experiment

Station	Function	Frequency	Power (Watts)	Coordinates Lat.(N)	Long.(W)	Bearing from Field Site (°)		Distance to Field Site (km)	
Platteville	Heater	5-10 MHz	1.6 Megawatts	40.18	104.6	Brush Boulder	258.0 71.2	Brush Boulder	78.2 62.8
Brush	Field Site #1	------	---------	40.33	103.7	-----------		----------	
Boulder Bennett	Field Site #2 Field Site #3	------ ------	--------- ---------	39.8523 39.8	105.263 104.4	----------- -----------		---------- ----------	
OMEGA (Hawaii)	VLF Source	11.8 kHz	---------	21.4	157.83	Brush Boulder	264.33 263.1	Brush Boulder	5481.16 5345.27
LORAN-C Fallon, NV	LF Source	100.0 kHz	---------	39.5	118.8	Brush	270.79	Brush	1289.25
LORAN-C Dana, IN	LF Source	100.0 kHz	---------	39.8523	87.4869	Boulder	84.87	Boulder	1516.16
KIIX Fort Collins	AM Broadcast	600 kHz	1,000	40.5	105.1	Brush	279.52	Brush	119.99
KHOW Denver	AM Broadcast	630 kHz	5,000	39.7	105.1	Brush	238.09	Brush	130.98
KERE Denver	AM Broadcast	710 kHz	5,000	39.7	105.1	Brush	238.09	Brush	130.98
KOA Denver	AM Broadcast	850 kHz	50,000	39.7	105.1	Brush	238.09	Brush	130.98
KLMO Longmont	AM Broadcast	1060 kHz	10,000	40.15	105.15	Brush	261.23	Brush	124.66
KNX (CA) Los Angeles	AM Broadcast	1070 kHz	50,000	34.0	118.5	Brush	246.42	Brush	1485.26
KREX Grand Junction	AM Broadcast	1100 kHz	50,000	39.1	108.5	Brush	253.12	Brush	432.58
KSL (UT) Salt Lake City	AM Broadcast	1160 kHz	50,000	41.7	112.0	Brush	285.41	Brush	712.37
KADE Boulder	AM Broadcast	1190 kHz	1,000	40	105.3	Brush	255.41	Brush	140.79
KFKA Greeley	AM Broadcast	1310 kHz	5,000	40.3	104.7	Brush	268.07	Brush	84.83
KSIR Estes Park	AM Broadcast	1470 kHz	5,000	40.25	105.55	Brush	267.35	Brush	157.12
KBOL Boulder	AM Broadcast	1490 kHz	1,000	40	105.3	Brush	255.41	Brush	140.79

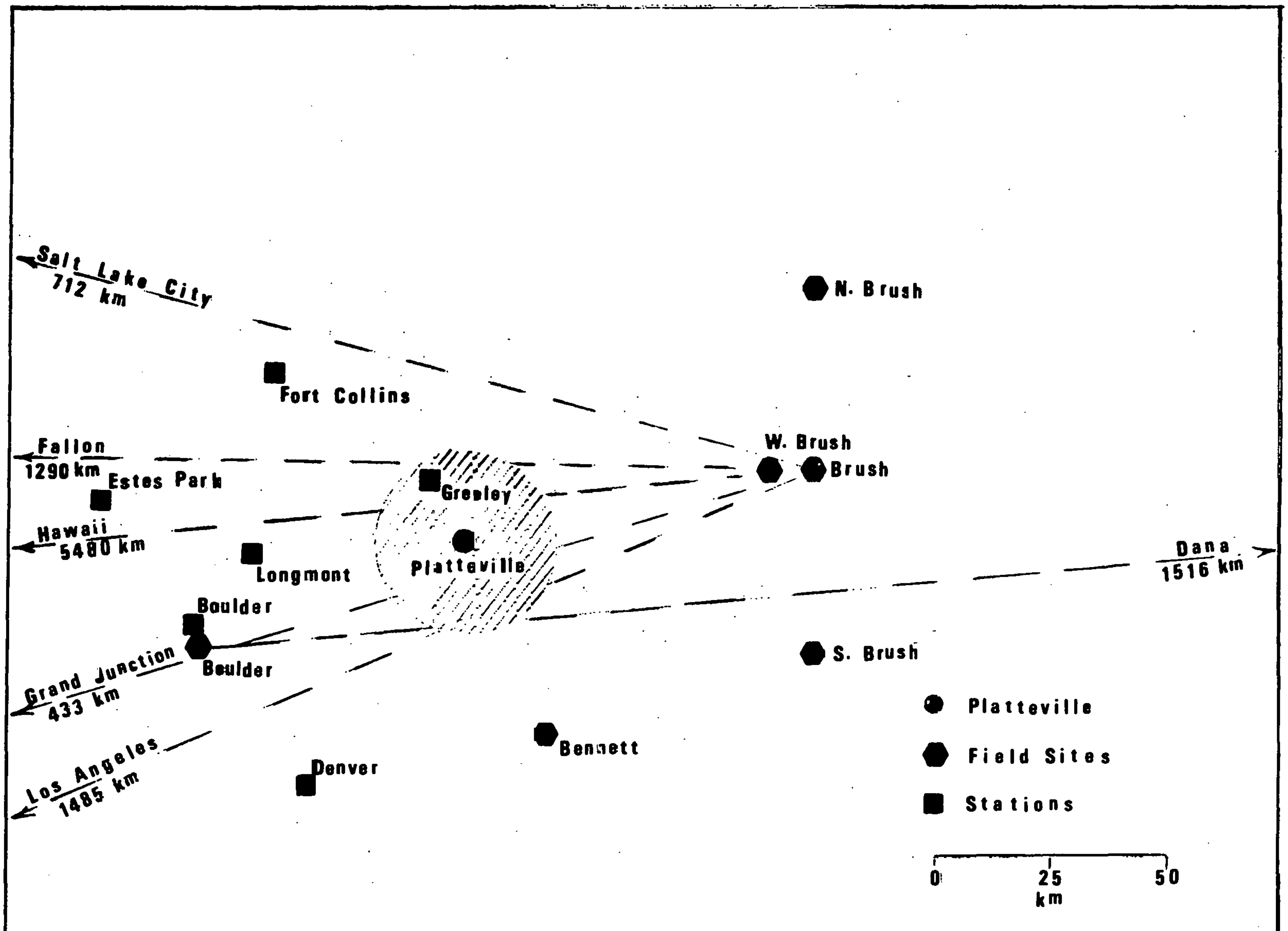


Figure 1. Map of signal sources and recording sites in relationship to the Platteville Facility

For each of the sources all or parts of the recorded data from nine separate test schedules were studied. Approximately 40 hours of Platteville operating time (Platteville Facility in "on-the-air" mode) were accomplished during these schedules. These on-times fall mainly between the hours of 0700 and 2200 (MDT), with principal concentration between 1000 and 2200 (MDT). The normal or basic mode of operation for the Platteville Facility is with the 10 transmitters "on" and the array phased to beam the transmitted energy vertically (zero degree tilt). The basic mode of operation is continuous wave (cw) with the output power control adjustable between half-power and full-power. In addition, the antenna can be phased to provide 10°, 20°, and 30° tilts from the zenith. Various on-off schemes, including short duration pulse modulation and power levels below -3 dB, can also be employed. An additional mode, which simulates sinusoidal modulation, was accomplished by splitting the array and then driving the respective elements at a frequency offset corresponding to desired modulation rate.

The modes of operation used for the experiment reported upon here were primarily continuous wave and sinusoidal modulation rates of 10, 25, and 40 per second. Under certain conditions, the beam was tilted 10° north and south of zenith during heating in an attempt to maximize heating effects in the ionosphere north and south of Platteville.

3. EFFECTS OF SPS OPERATION ON VLF SYSTEMS

3.1 VLF Data

The principal source of VLF signals for this investigation was the OMEGA navigation station at Hawaii. OMEGA is a very-low-frequency (VLF) radio navigation system operating in the internationally allocated frequency band between 10 and 14 kHz. It is designed to provide a precise position location capability over the entire earth, with eight strategically located transmitters. The system is useful for general navigation by ships, aircraft, and land vehicles. OMEGA signals are relatively stable, and the system provides good accuracy considering its long range (extending to over 8,000 kilometers). With propagation corrections, fix errors can be reduced to two or three kilometers under almost any conditions.

The main receiving locations for the OMEGA-Hawaii signals were in the vicinity of Brush, Colorado. The frequency of 11.8 kHz was monitered. The field sites near Brush were chosen in order to locate the modified regions of the ionosphere above Platteville on or near the signal path between Hawaii and the respective field sites.

The map in Figure 2 is a partial reproduction of Figure 1. The respective locations and orientation of the Hawaii station, the Platteville Facility, the modified area, and the receiving sites near Brush are shown. The half-power beam width of

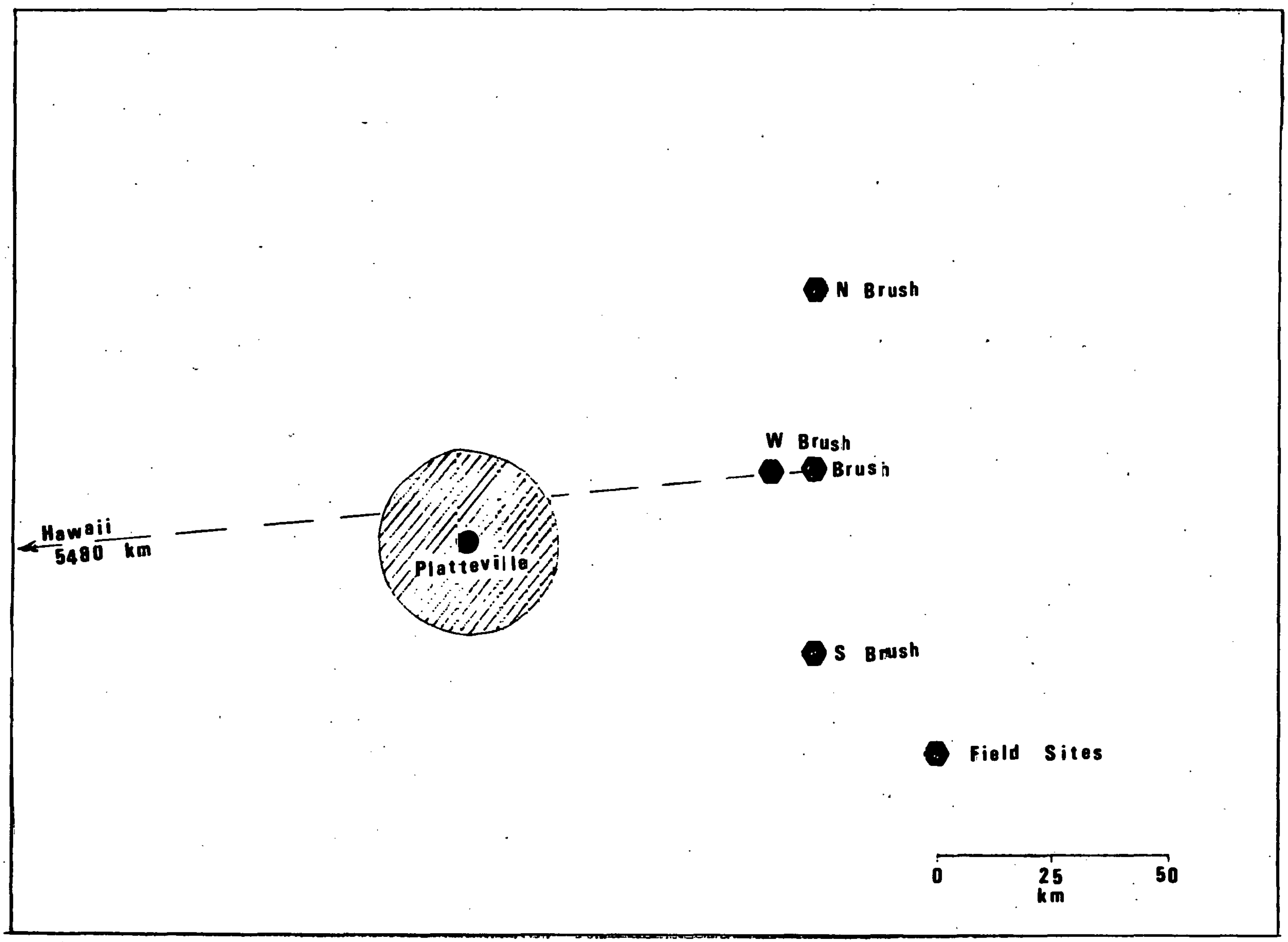


Figure 2. A map showing the orientation of the OMEGA (Hawaii) transmitter, Platteville Facility, and the Brush recording sites.

the antenna array is about 17 degrees at 5-6 MHz which, at D region heights, gives a modified region that is approximately 23 km in diameter. The 23 km modified region is very close to the wavelength of the OMEGA-Hawaii signal - 25.4 km. The first Fresnel zone of the OMEGA-Hawaii path is on the order of 45 km.

From Figure 2 it can be seen that the disturbance in the ionosphere created by the Platteville Facility will not in general be centered on the great-circle Hawaii to Brush path. Crombie (1964) has investigated the effects on VLF propagation of ionospheric disturbances that are not centered on the radio path under study. He found that as the distance of the center of the disturbance from the path increases, the VLF amplitude and phase oscillate about the values observed when the disturbance is not present. When the center of the disturbance is beyond a certain distance from the path only changes in the amplitude of the VLF signal will be observed. Crombie (1964) also found that the effects of ionospheric disturbance on VLF signals are greater when the disturbance is nearer one end of the path as is the case for the disturbance in the ionosphere generated by the Platteville Facility. Thus, it can reasonably be anticipated that changes in the OMEGA-Hawaii signal should be discernible if changes in the ionospheric structure result from the SPS-comparable power densities associated with the operation of the Platteville Facility.

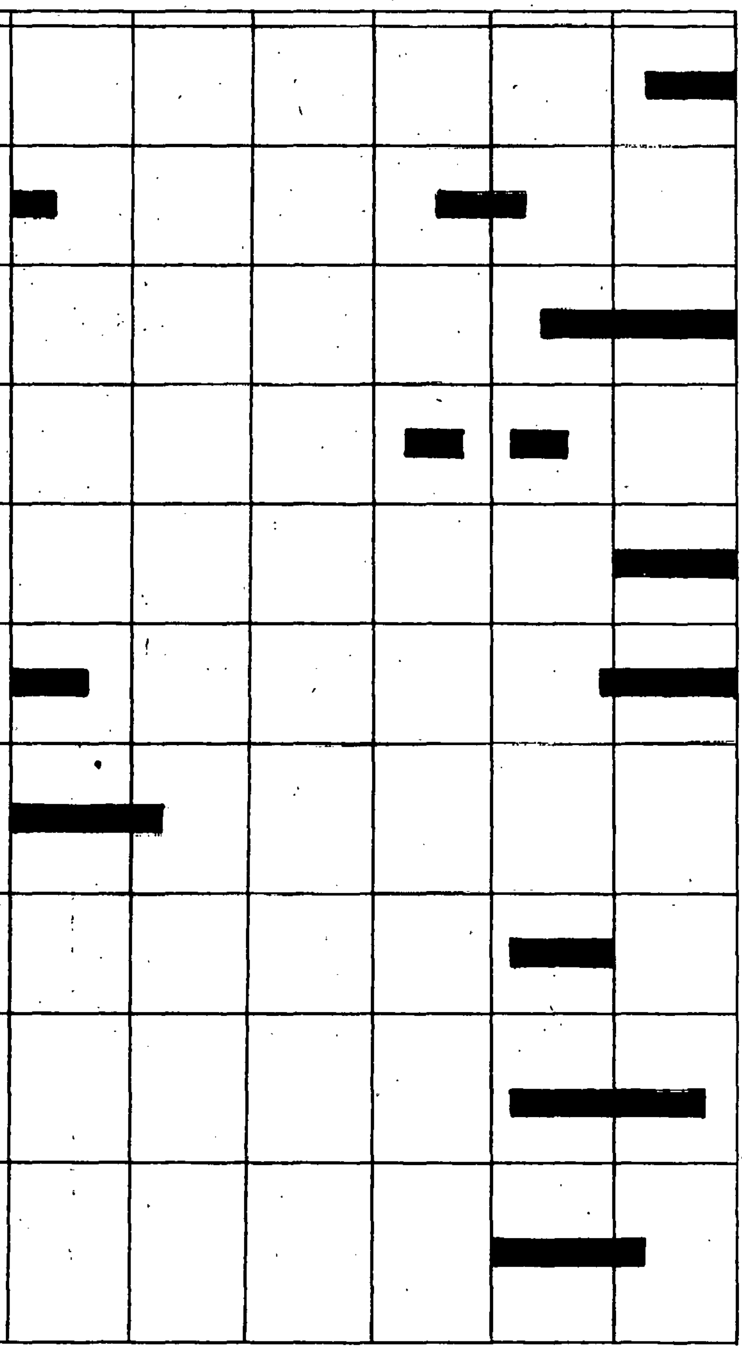
Approximately 40 hours of recordings of amplitude and relative phase of the OMEGA signals from Hawaii were made during the operation of the Platteville Facility. The data in Table 3 give the operating dates and time, the heater modes, and the recording locations pertaining to the VLF experiment. The recorded OMEGA amplitude data for these operating periods are shown in Figures 3 through 7 and in Appendix A. The display format for each of these figures is essentially identical. As an example, the information given in Figure 3 includes tracings of the received amplitude and phase for the times indicated. The cross-hatched blocks immediately above the time scale indicate CW mode, and the shaded blocks indicate square-wave (50% ON - 50% OFF) or dual sinusoidal (split-array) modulation, with the modulation rate indicated in events per second. The amplitude and phase scales are indicated. The phase output from the receiver is designed such that, when either the zero or full scale (10 μs) outputs are reached, a reset occurs which places the record pen at the opposite limit and another 10 μs of trace is then possible.

3.2 Experimental Results

The OMEGA phase and amplitude data in Figures 3 through 7 are included in these sections for specific comment, and the remaining Figures are given in Appendix A

Table 3. OMEGA (Hawaii) Data Recorded Near Brush, CO

Date	Heater Mode	Site Location	(18) 00	(22) 04	(02) 08	(06) 12	(10) 16	(14) 20	(18) 24 (LT) UT
8-16	CW and Square-wave Modulation	Brush							
8-17	CW and Square-wave Modulation	Brush							
8-19	CW and Square-wave Modulation	Brush							
8-20	CW and Square-wave Modulation	Brush							
8-22	CW and Square-wave Modulation	Brush							
8-23	CW and Square-wave Modulation	Brush							
8-24	CW and Square-wave Dual-beam Modulation	Brush							
9-26	CW Modulation N and S Beam-tilt	South of Brush							
10-3	CW and Dual-beam Modulation N and S Beam-tilt	North of Brush							
10-4	CW, Dual-beam and Square-wave Modulation, N and S Beam-tilt	West of Brush							



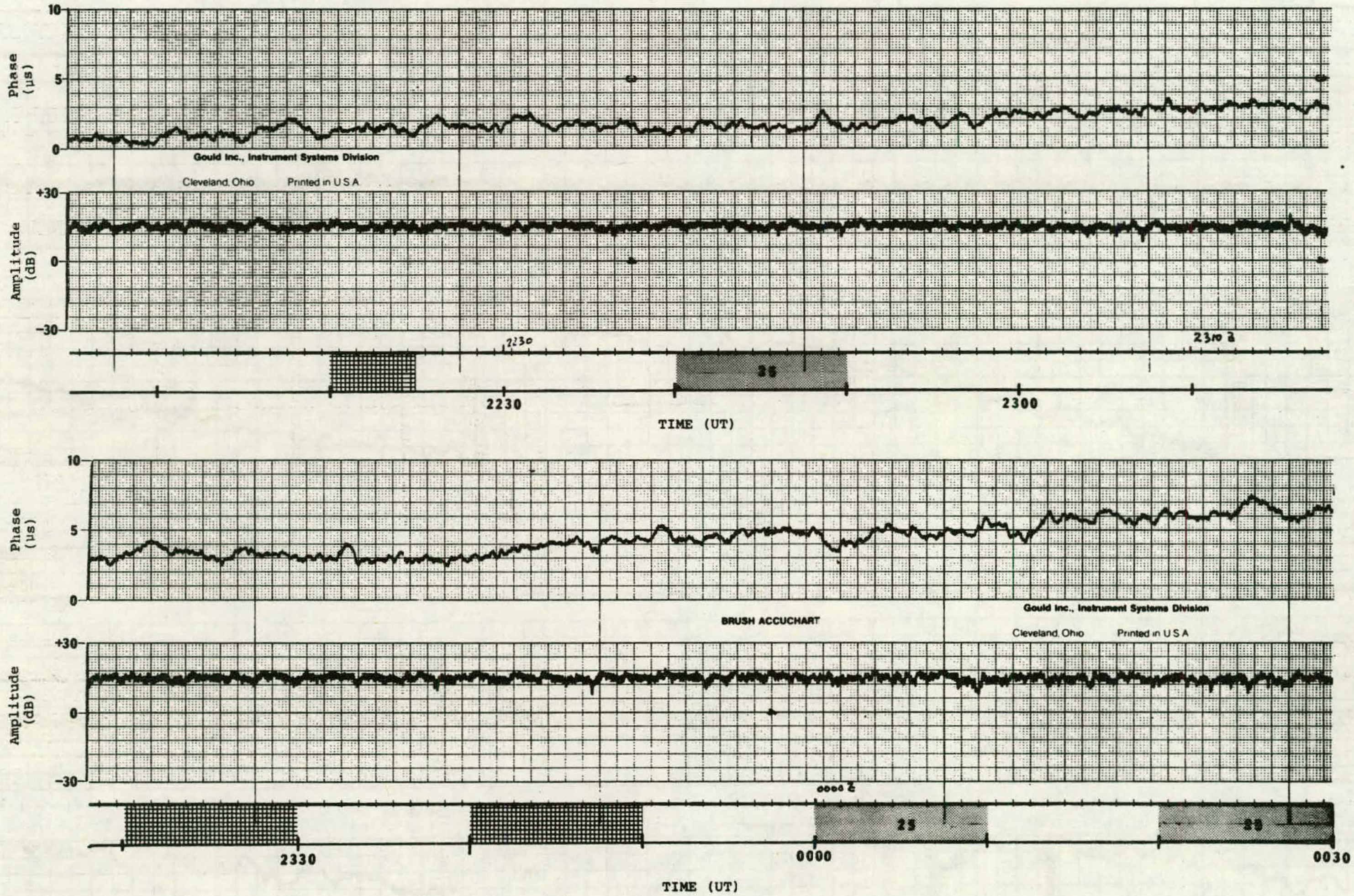


Figure 3. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 16, 1979.

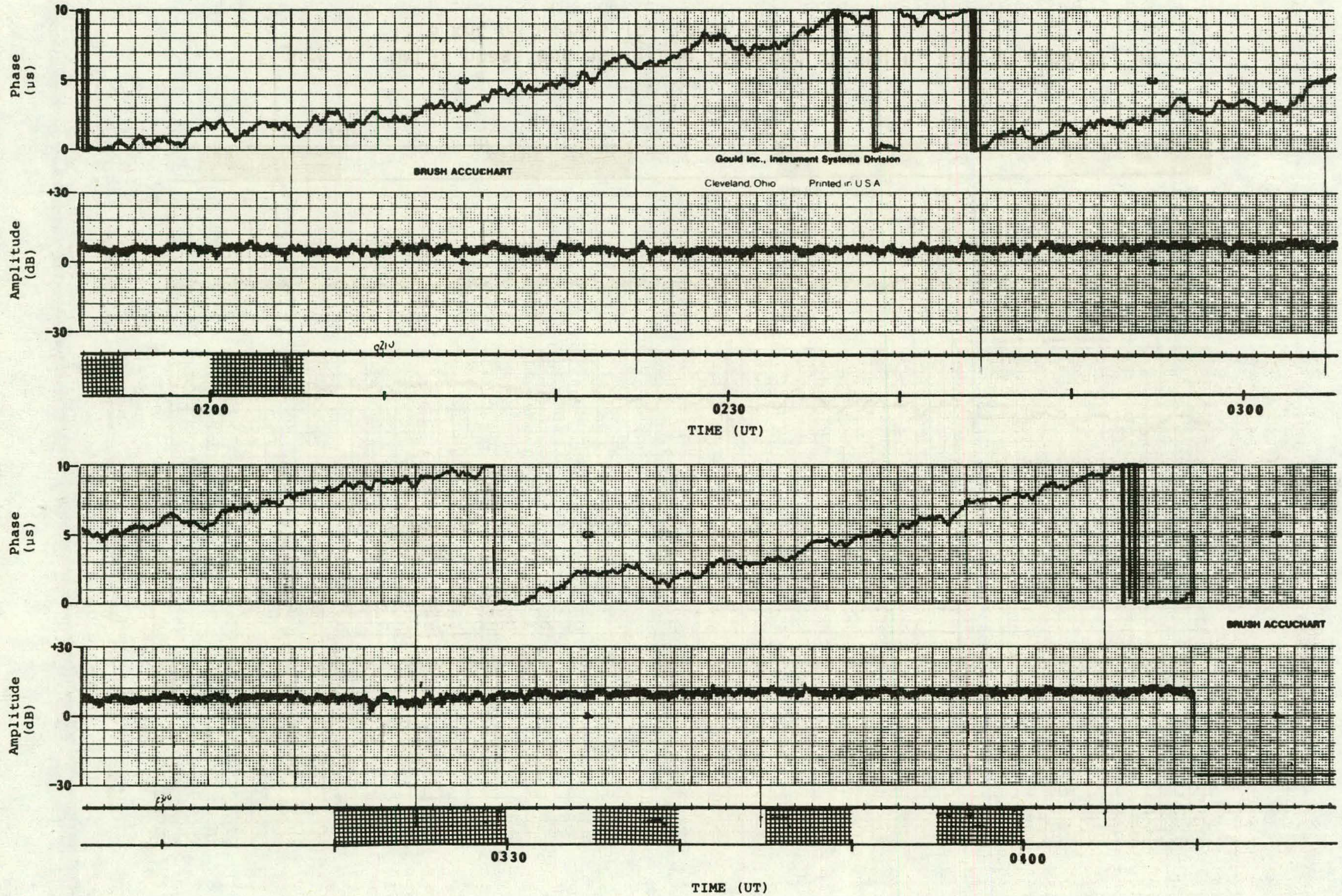


Figure 4. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 24, 1979.

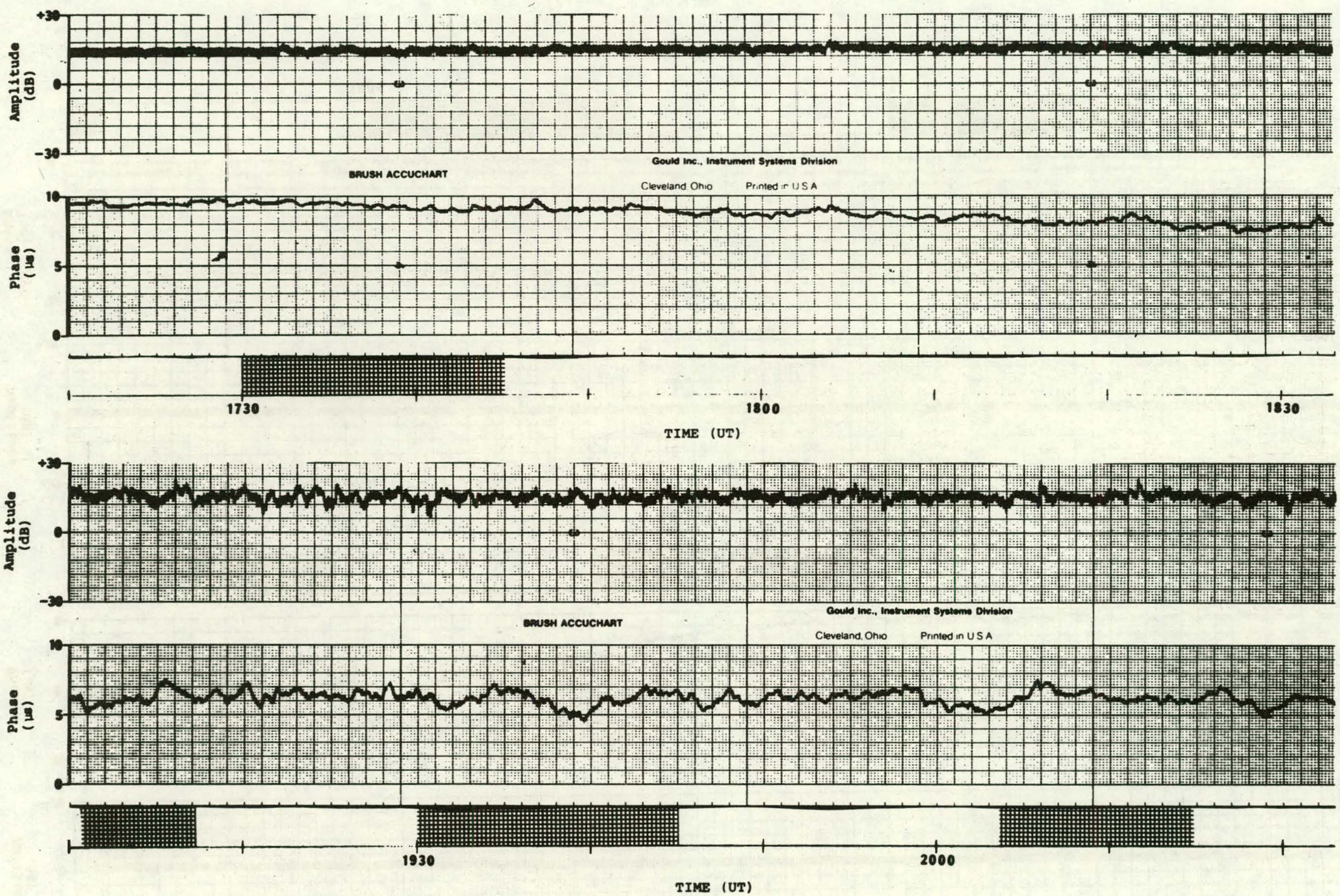


Figure 5. OMEGA phase and amplitude recorded at the site south of Brush, CO, from Hawaii at 11.8 kHz on September 26, 1979.

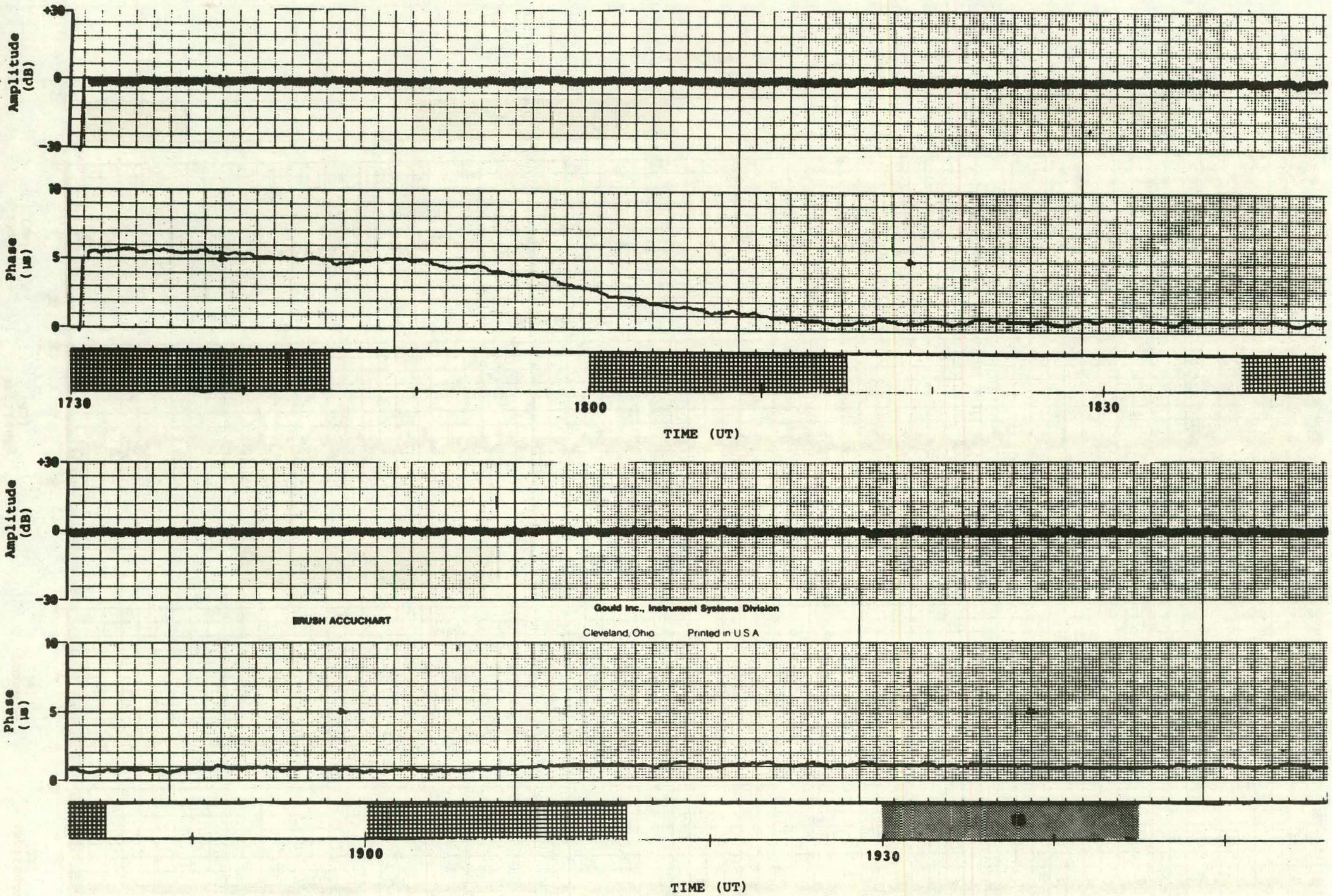


Figure 6. OMEGA phase and amplitude recorded at the site north of Brush, CO, from Hawaii at 11.8 kHz on October 3, 1979.

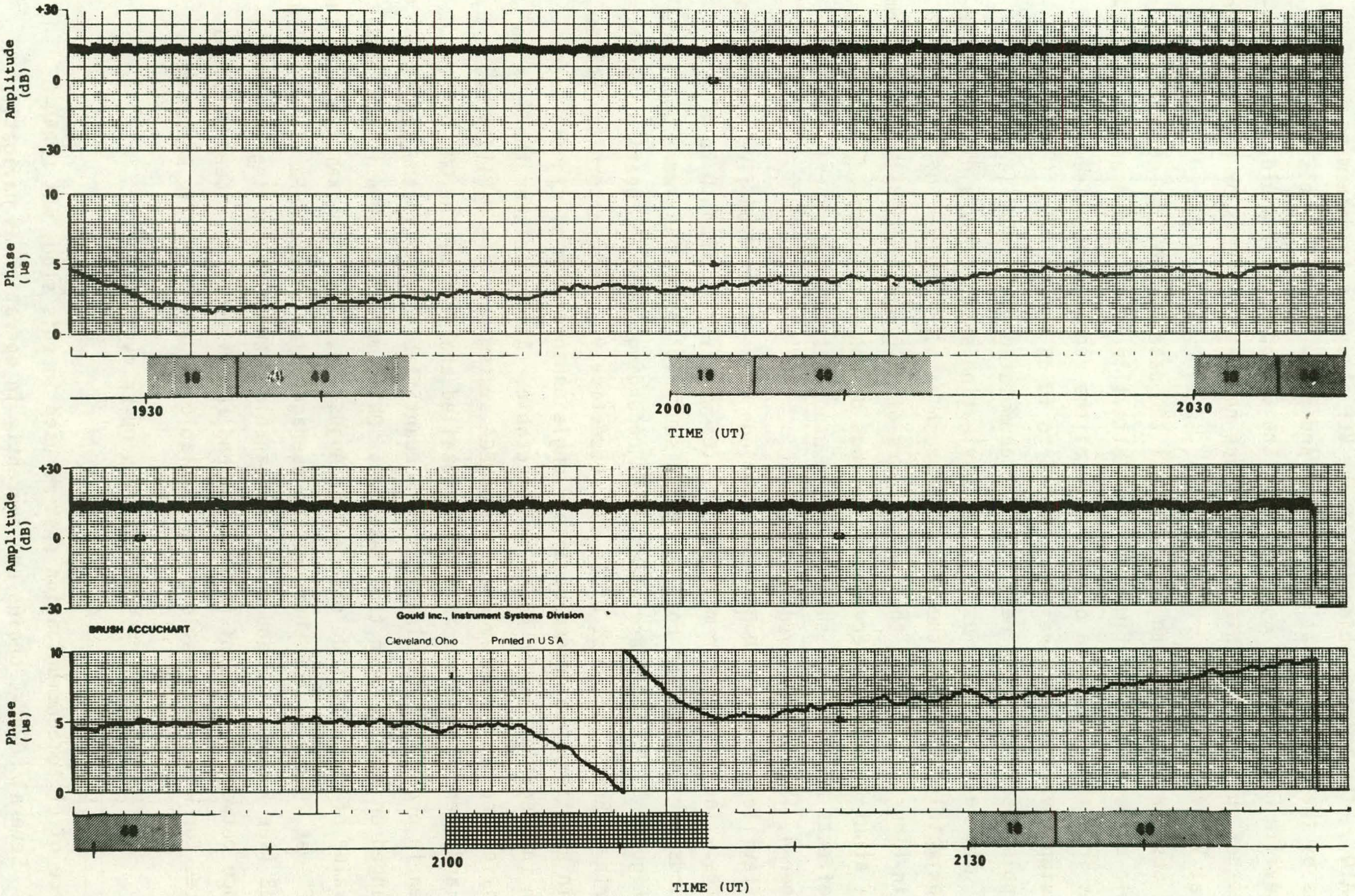


Figure 7. OMEGA phase and amplitude recorded at the site west of Brush, CO, from Hawaii at 11.8 kHz on October 3, 1979.

(Figures A1-A10). The primary objective of the VLF study was to determine if modifications of the ionosphere at frequencies and power density levels generated by the Platteville Facility (and comparable to the SPS operation) would cause propagation effects of sufficient magnitude to produce navigation errors or communication disruptions at VLF frequencies.

A first observation made with regard to all the data, is that no correlations are observable between the "ON" times of the Platteville Facility and any characteristic changes in either the phase or amplitude of the recorded signals. The amplitude of the signal varies not more than about 5 to 10 dB as a maximum. The high frequency ripple observed is the result of the commutated duty cycle (4 secs ON - 6 secs OFF). The relative phase used in the navigation systems has a diurnal variation of approximately 60 μs for the Hawaii to Brush path. A segment of this change is observed in Figure 4, between the sunset hours of 0200 and 0400 (UT). Short term variations of about 2 μs are observed over periods of about 5 minutes. Frequently, solar flare effects are observed such as the 10 μsec phase change starting at 2104 (UT) on October 4, 1979 as observed in Figure 7.

The Platteville Facility "ON-OFF" time periods were varied from five minutes to fifteen minutes. The transmitter modulation rates were varied from 10 to 40 "ON-OFF" periods per second, and both north and south 10° beam-tilts were employed. The data in Figures 5, 6, and 7 are examples of recordings made at locations south of Brush, north of Brush, and west of Brush, respectively. These alternative sites were chosen in an attempt to determine if off-angle enhancements of signals propagated through the modified region might be detectable. As can be seen there is no detectable difference in the behavior of the OMEGA system when the Facility was transmitting and when it was not. A further detailed analysis of the OMEGA data was undertaken in order to determine in a more quantifiable sense if the amplitude and phase changed on average when the heater was "ON" compared to when it was "OFF." The average value of the amplitude observed on August 19, 1979, for example, with the Facility "OFF" was 14.9 $\pm$ 0.76dB whereas, the average value with the Facility "ON" was 14.9 $\pm$ 0.59 dB (see Figures A-2 and A-3). Comparable results indicating no significant difference between periods of Facility-ON and Facility-OFF have been obtained for other dates for which observations are available and are listed in Appendix A.

4. EFFECT OF SPS OPERATION ON LF SYSTEMS

4.1 LF Data

The source of LF telecommunication systems used in this study was LORAN-C transmitters. Several LORAN-C chains are currently in operation as navigation systems. In the United States, LORAN-C navigation depends on the highly stable ground-wave portion of its propagated signal for system accuracy. The LORAN-C stations used in this study were chosen as LF signal sources not because interference of LORAN-C navigation was anticipated from the heater modification, but because the LORAN-C station provided a convenient stable source at 100 kHz.

The two LORAN-C stations used as sources were the East Coast-chain station at Dana, Indiana, recorded at the Boulder, Colorado, site, and the West Coast-chain station at Fallon, Nevada, recorded at the Brush, Colorado site. The map in Figure 8 shows the relationship of the Platteville modified region to the Dana-to-Boulder propagation path and the Fallon-to-Brush propagation path. It can readily be seen that both these paths only pass through the edges of the ionospheric volume that is modified by the Platteville Facility. The wavelength of the LORAN-C signal is 3 km and the first Fresnel zone of the Fallon-Brush and Dana-Boulder path is about 15 km. Although the effects of the disturbance induced by the Platteville Facility on the LORAN-C signal is expected to be small, the sensitivity of the receivers (0.02 μs and 0.1 dB) is felt to be sufficient to detect significant changes in the performance of the LORAN-C system due to operation of the Platteville Facility. Approximately 19 hours of relative phase only and 13 hours of relative phase and amplitude recordings were made of the LORAN-C signals from Fallon, Nevada, during the operation of the Platteville Facility. The data in Table 4 gives the summary of the operating dates and time, the Facility modes, and recording locations. A summary of similar data for the Dana, Indiana, station is made in Table 5. A total of 35 hours of recorded amplitude and relative phase were made from this station.

The LORAN-C amplitude and phase data recorded from the two stations are shown in Figures 9 through 12 and in Appendix B. The display format for this data is similar to the OMEGA data presented in Section 3. The amplitude and phase records are identified and the scales are indicated. The cross-hatched and shaded patches above the time scale identify the Platteville "on" times and operating modes. The cross-hatched blocks indicate continuous wave mode and the shaded blocks indicate square-wave (50% ON - 50% OFF) or dual sinusoidal (split-array) modulation, with the modulation rate indicated in events per second. The receiver phase output is designed, such that, when either the zero or full scale (1 μs) levels are reached, a reset occurs which places the record pen at the opposite limit and another 1 μs of trace is then possible.

4.2 Experimental Results

The objective of the LF experiment was to determine if modifications of the ionosphere generated by the Platteville Facility and comparable to that anticipated

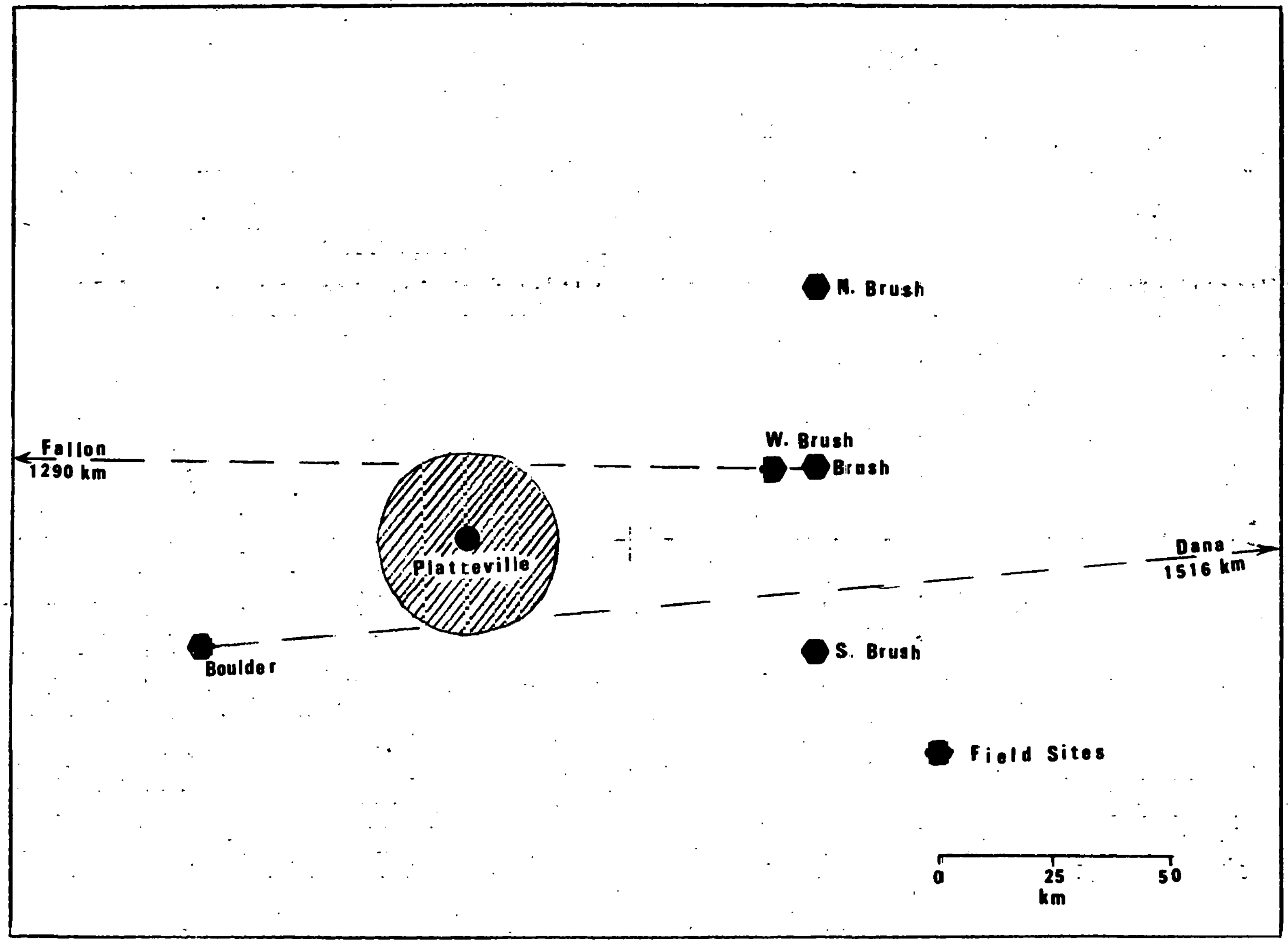


Figure 8. A map showing the orientation of the LORAN-C stations (Dana and Fallon), the Platteville Facility, and the Brush and Boulder recording sites.

Table 4. LORAN-C (Fallon) Data Recorded Near Brush, CO

Date	Heater Mode	Site Location	(18) 00	(22) 04	(02) 08	(06) 12	(10) 16	(14) 20	(18) 24	(LT) UT
8-16	CW and Square-wave Modulation	Brush			Phase			■		
8-17	CW and Square-wave Modulation	Brush	■		Phase	■	■			
8-19	CW and Square-wave Modulation	Brush			Phase			■		
8-20	CW and Square-wave Modulation	Brush			Phase	■	■			
8-22	CW and Square-wave Modulation	Brush			Phase					
8-23	CW and Square-wave Modulation	Brush			Phase			■		
8-24	CW and Square-wave Modulation	Brush	■		Phase					
9-26	CW and Square-wave Modulation	South of Brush		Phase	and	Amplitude	■	■		
10-3	CW and Square-wave Modulation	North of Brush		Phase	and	Amplitude	■	■		
10-4	CW and Square-wave Modulation	West of Brush		Phase	and	Amplitude	■	■		

Table 5. LORAN-C (Dana) Data Recorded at Boulder, CO

Date	Heater Mode	Site Location	(18) 00 – (22) 04	(22) 04 – (02) 08	(02) 08 – (06) 12	(06) 12 – (10) 16	(10) 16 – (14) 20	(14) 20 – (18) 24 (LT) UT
8-16	CW and Square-wave Modulation	Boulder						■
8-17	CW and Square-wave Modulation	Boulder	■			■	■	
8-19	CW and Square-wave Modulation	Boulder						■
8-20	CW and Square-wave Modulation	Boulder	■			■	■	■
8-22	CW and Square-wave Modulation	Boulder						■
8-23	CW and Square-wave Modulation	Boulder	■					■
8-24	CW, Square-wave, and Dual-beam Modulation	Boulder	■	■				

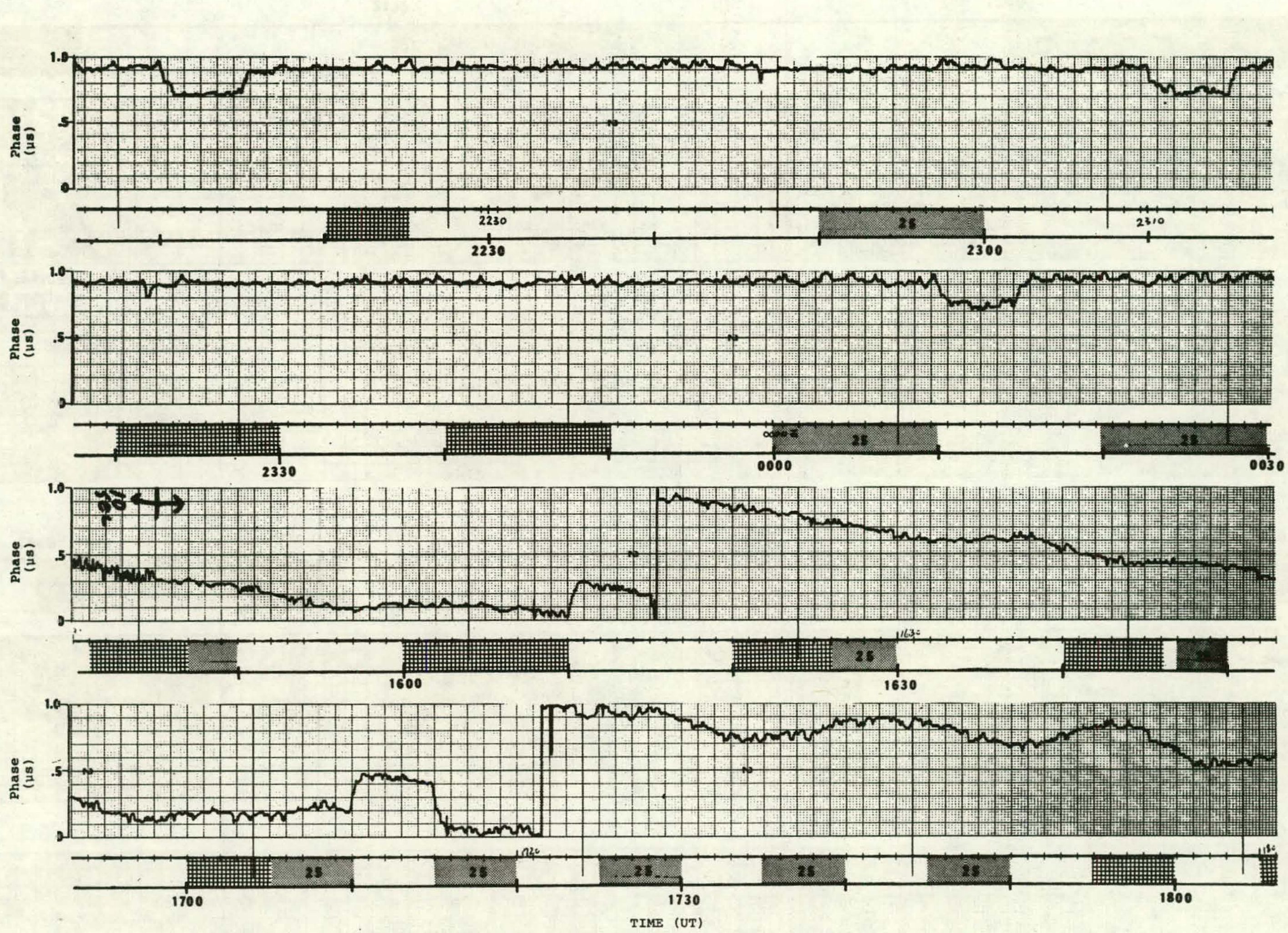


Figure 9. LORAN-C phase recorded at Brush, CO, from Fallon, NV, at 100 kHz on August 16 and 17, 1979.

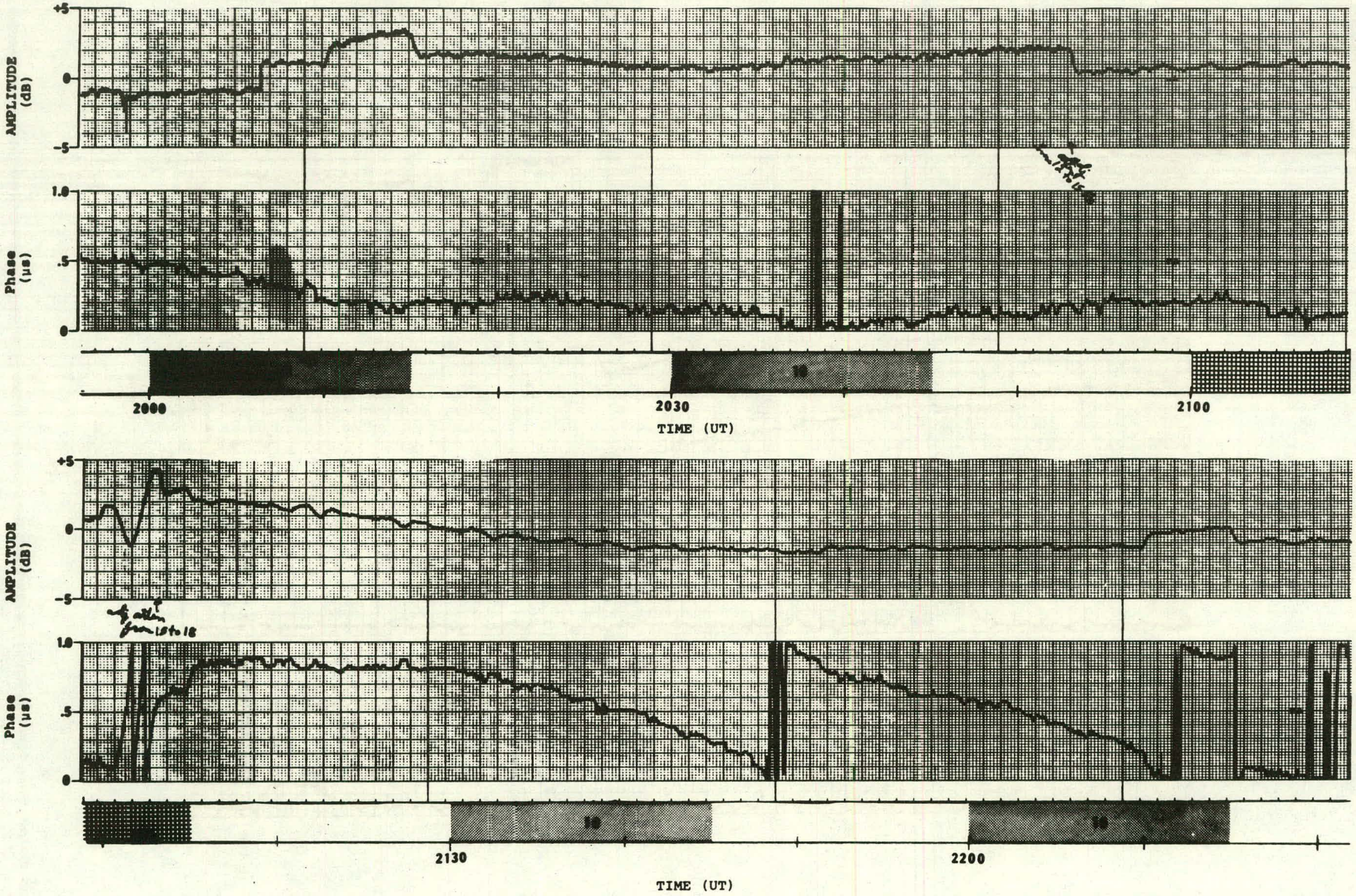


Figure 10. LORAN-C amplitude and phase data recorded north of Brush, CO, from Fallon, NV, at 100 kHz on October 3, 1979.

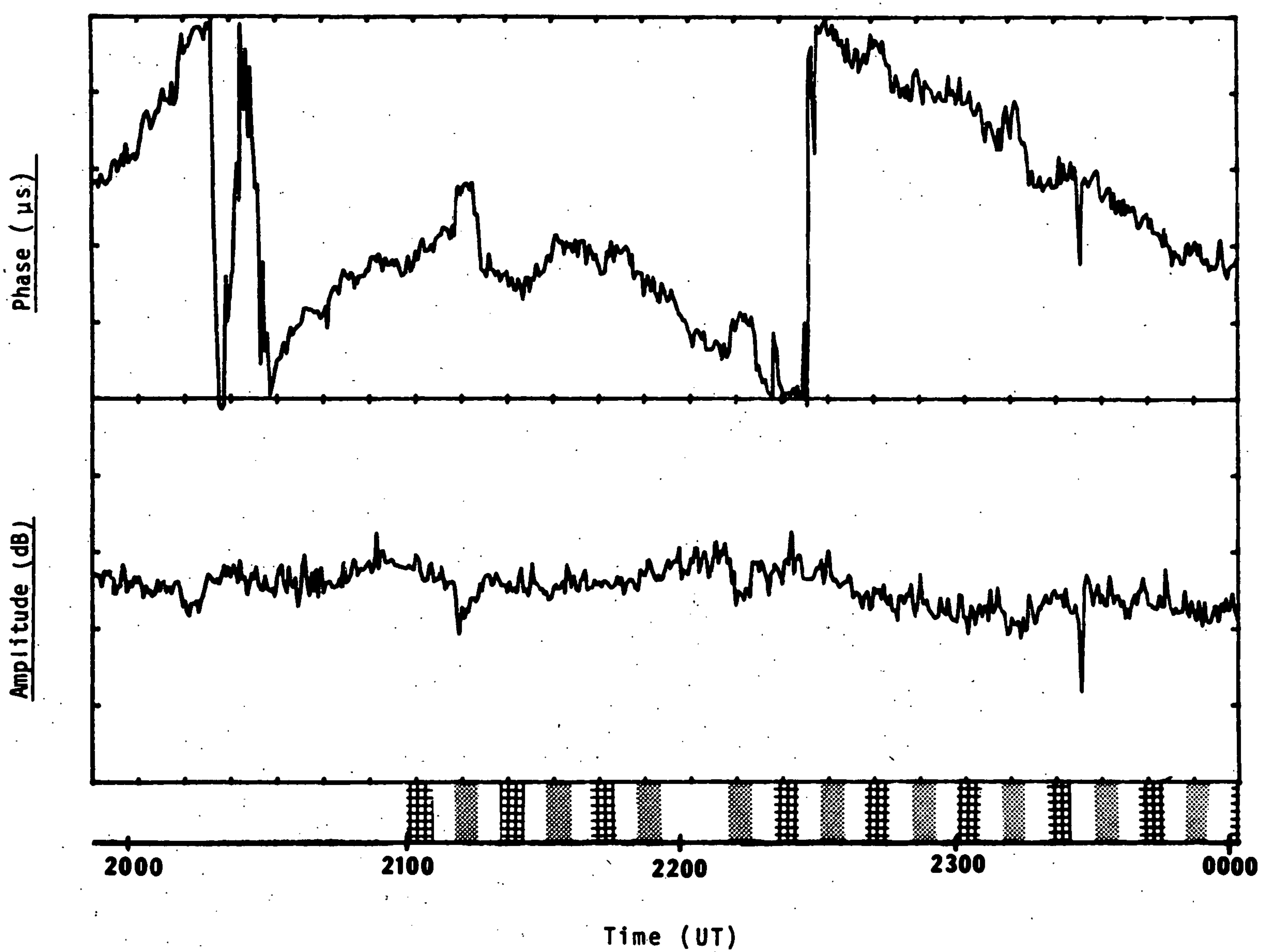


Figure 11. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 22, 1979.

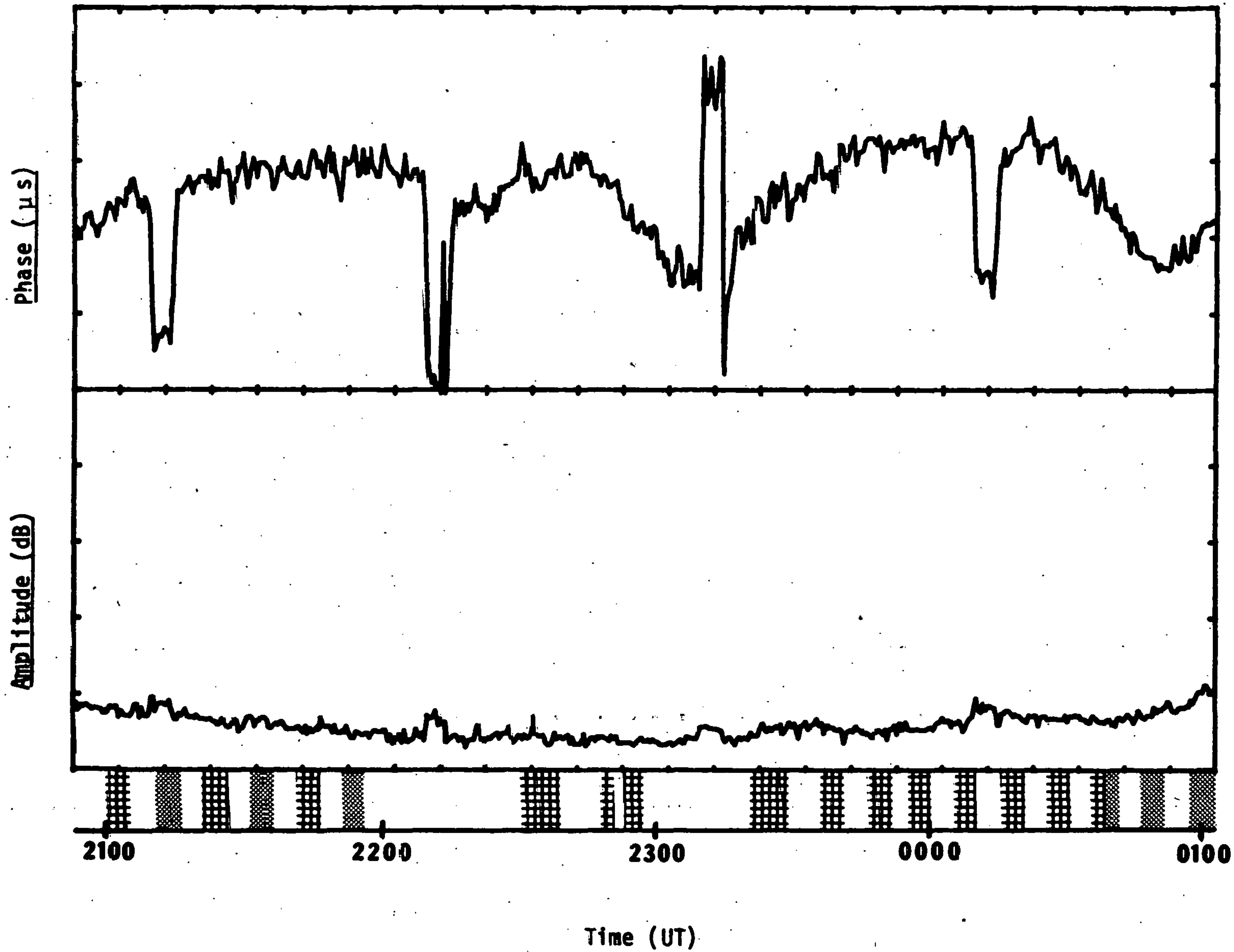


Figure 12. LORAN-C phase and amplitude data recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 23, 1979.

from SPS operation would cause propagation effects of sufficient magnitude to be observable in the skywave propagated phase and amplitude records.

LORAN-C monitor receivers were used in the receiving systems. These receivers are normally set to lock to one of the cycles (3rd) of the leading slope of the ground-wave pulse. The receiver is then used to track and monitor relative phase from this point. This signal is generally very stable both in amplitude and phase when monitored in a LORAN-C coverage area. To record the skywave signals for this experiment, the receiver lock point was moved to a point on the lagging slope of ground-wave propagated and the sky-wave propagated signals. Because this combination of signals is not very stable with time, only short term variations that are highly correlatable to the Platteville operating schedule could be attributable to that source.

In Figure 9, the upper two records taken on the 16th of August are very stable over the period shown and exhibit no variations attributable to Platteville operation. The offsets that occur at 10 minutes after the start of each hour and last for 5 minutes are interference due to the strong 60 kHz time and frequency signal (WWVB) from Fort Collins, Colorado getting into the front end of the receiver. This effect is readily apparent in several of the LORAN-C records. The data in the lower two records of Figure 9 show a slowly varying phase change which may be diurnal in effect but again no correlatable effects associated with Platteville operations.

Both amplitude and phase records are shown in Figure 10. This data also contains no Platteville correlated changes. The phase and amplitude records in Figures 11 and 12 were recorded at Boulder, Colorado, from Dana, Indiana. The Fort Collins 60 kHz effect are prominent in both records, but no Platteville modification results are apparent.

Detailed studies of LORAN-C records were also undertaken in order to determine in a more statistically reliable manner if there were any phase changes associated with the Facility operation. Data observed on August 19, 1979, for example, indicate that the average value of the LORAN-C phase on the Fallon, Nevada to Brush, Colorado circuit was 0.65 $\pm$ 0.17 μs with the Platteville Facility operating. When the Platteville Facility was in the off mode, the average phase was observed to be 0.71 $\pm$ 0.12 μs. The results for other time periods are listed in Appendix B. As was the case for the OMEGA data, all the LORAN-C data studied reveals no apparent telecommunications effects associated with the operation of the Platteville Facility.

5. EFFECTS OF SPS OPERATION ON MF SYSTEMS

5.1 Broadcast Station Results

In addition to the OMEGA and LORAN-C data recorded at the Brush, Colorado, site, two receivers were used to monitor stations in the AM broadcast band. Amplitude signals were recorded, and the results are discussed in this section. A map showing the relative positions of the selected broadcast station to the Platteville Facility and the recording site is shown in Figure 13. The KSL signal does not pass through the region of the ionosphere that is modified by the Platteville Facility (see Figure 13) while the KREX and KNX signals do. Signals were recorded from a total of 11 stations, of which eight were local (less than 100 km) and three were remote. A list of the stations and operating times, dates, and heater modes are shown in Table 6. The power indicated in the listings in the table are the maximum values authorized.

The amplitude records for this test are shown in Figures 14 and 15, and in Appendix C. The relative amplitude records are from the receiver AVC, and for some (recorded on August 22 and 23) from a filtered diode-detected output. The filtered output removes some of the voice modulation. The signals from the local stations are most apt to be ground-wave propagated, and signals from the remote stations (KNX, KSL, and KREX) are skywave signals. The more important data as far as potential SPS impact is concerned would be skywave signals. However, only during the early morning hours (UT) of August 23 and 24 did conditions permit recordings from the remote stations. During the other operating times, inadequate skywave paths and local station interference prohibited the monitoring of the remote stations.

The relative amplitude data recorded in Figure 14 are an example of the short distance signals. These recordings were made on August 16 from stations KOA (Denver, CO) and KLMO (Longmont, CO). No amplitude changes in these data are correlatable with the Platteville "on" times, shown in cross-hatch and shading below the amplitude data. Receiver drift had necessitated some retuning as indicated. The data in Figure 15 recorded on August 24 are an example of signals propagated via skywave. The upper trace shows amplitude signals from KSL (Salt Lake City, UT) and the lower trace is from KNX (Los Angeles, CA) and KREX (Grand Junction, CO). As mentioned before, the KSL-path does not pass through the modified ionosphere while the KNX and KREX-paths do. There appears to be little difference between the KSL results and those for KNX and KREX when the Facility was operating and when it was not (see Table C-1). Some receiver gain adjustments and retuning are indicated on the charts, but again these data show that no changes are correlatable with Platteville operations. The additional data are shown in Figures C-1 through C-8 in Appendix C. No changes that can be correlated with the Platteville ionosphere modifications are apparent in these data either.

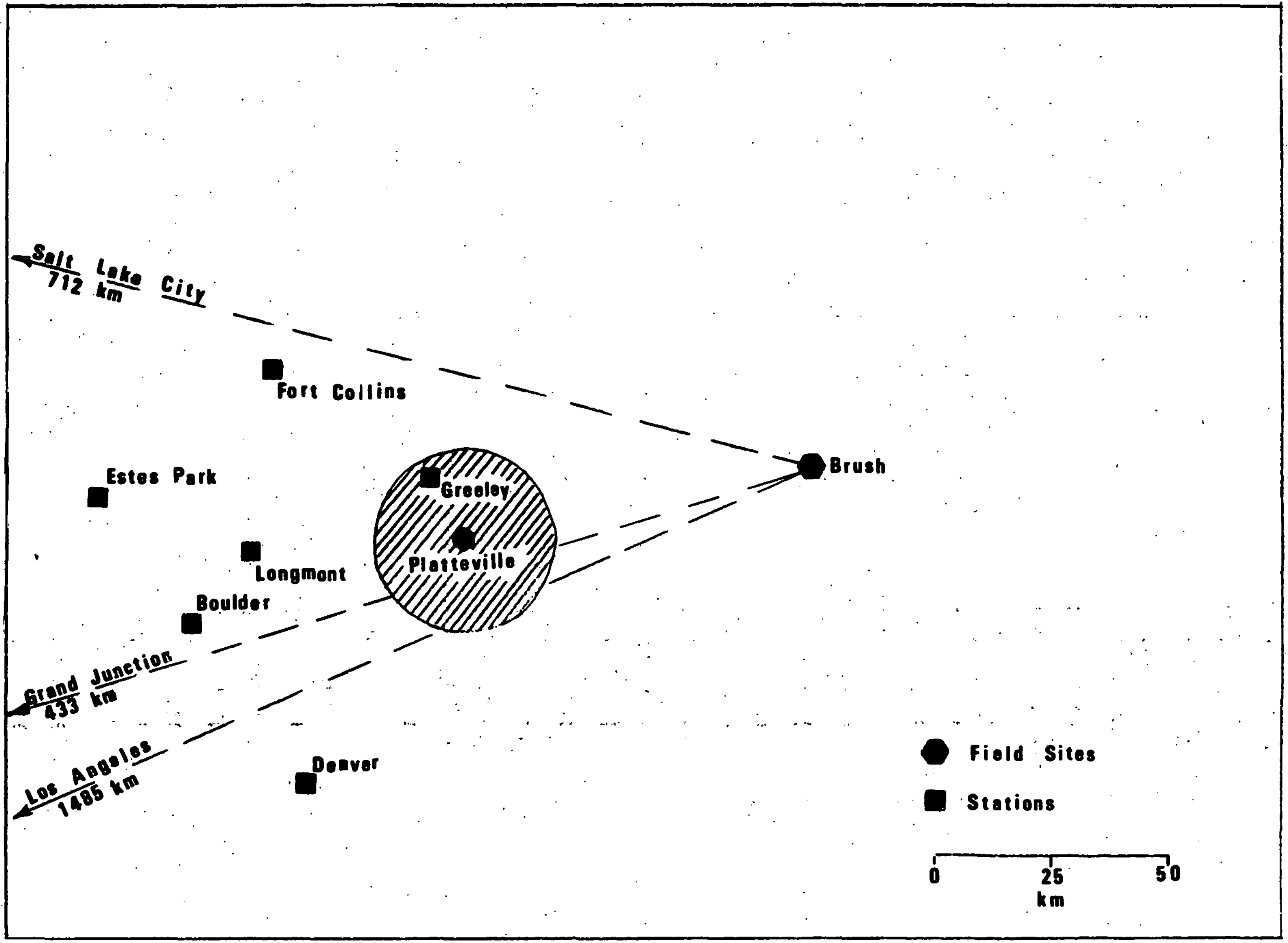


Figure 13. A map showing the orientation of the broadcast station, the Platteville Facility, and the Brush recording site.

Table 6. Broadcast Station Signals (.5-1.6 MHz) Recorder Near Brush, CO

Date	Heater Mode	Station Monitored	(18) 00 – (22) 04	(22) 04 – (02) 08	(02) 08 – (06) 12	(06) 12 – (10) 16	(10) 16 – (14) 20	(14) 20 – (18) 24 (LT) UT
8-16	CW and Square-wave Modulation	KOA KLMO						■
8-17	CW and Square-wave Modulation	KADE KLMO	■			■	■	
8-19	CW and Square-wave Modulation	KADE KBOL KIIX KHOW KLMO KERE					■	■
8-20	CW and Square-wave Modulation	KSIR KLMO KBOL KFKA				■	■	
8-22	CW and Square-wave Modulation	KLMO KSIR						■
8-23	CW and Square-wave Modulation	KADE KSIR KNX	■					■
8-24	CW, Square-wave, and Dual-beam Modulation	KSIR KBOL KSL KNX KREX	■	■				

KIIX	600	1KW	KREX	1100	50KW
KHOW	630	5KW	KSL	1160	50KW
KERE	710	5KW	KADE	1190	1KW
KOA	850	50KW	KFKA	1310	5KW
KLMO	1060	10KW	KSIR	1470	kKW
KNX	1070	50KW	KBOL	1490	1KW

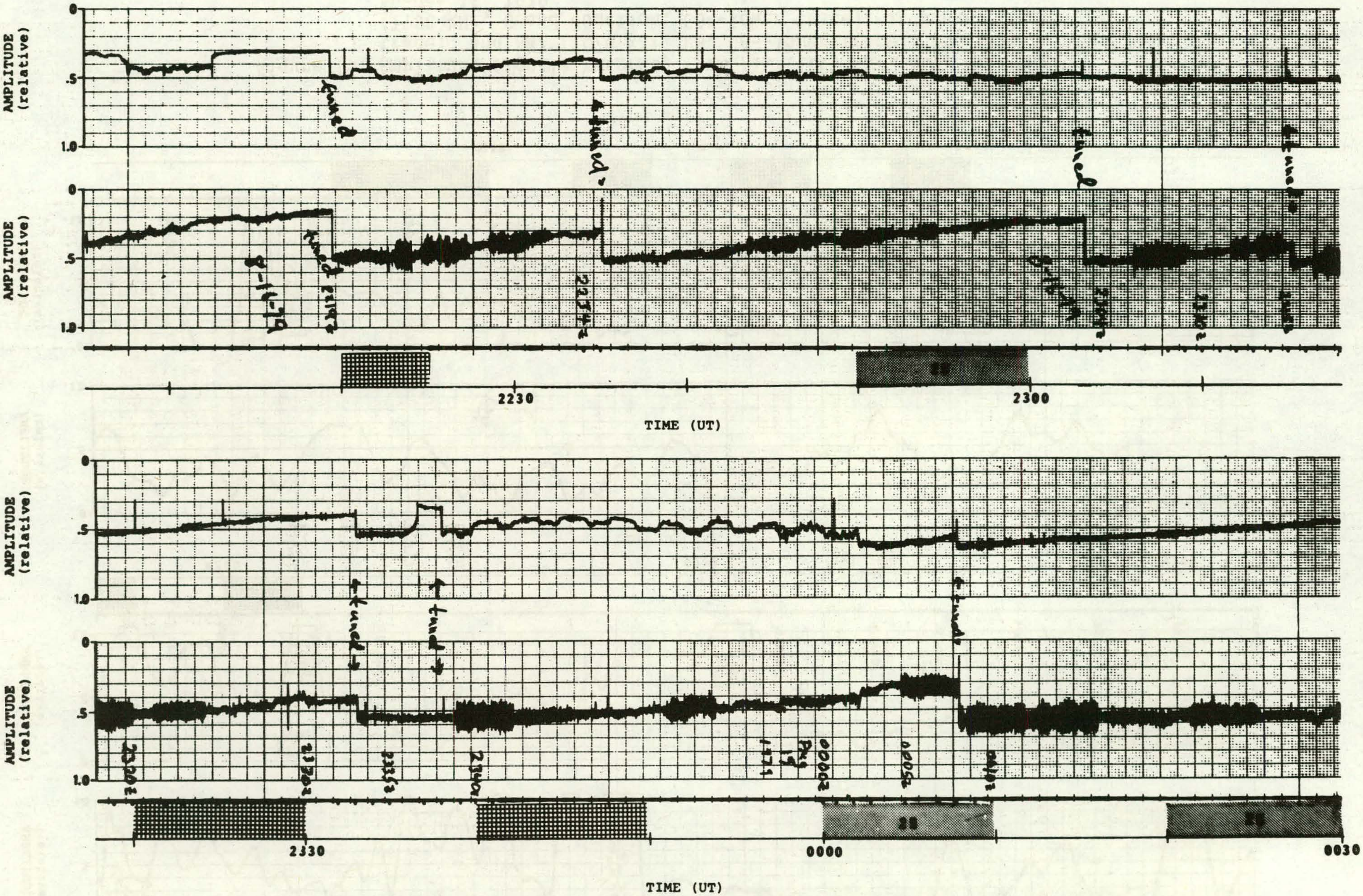


Figure 14. Amplitude signals recorded from broadcast stations KOA (850 kHz, Denver, CO--upper trace), and KLMO (1060 kHz, Longmont, CO--lower trace), at Brush, CO, on August 16, 1979.

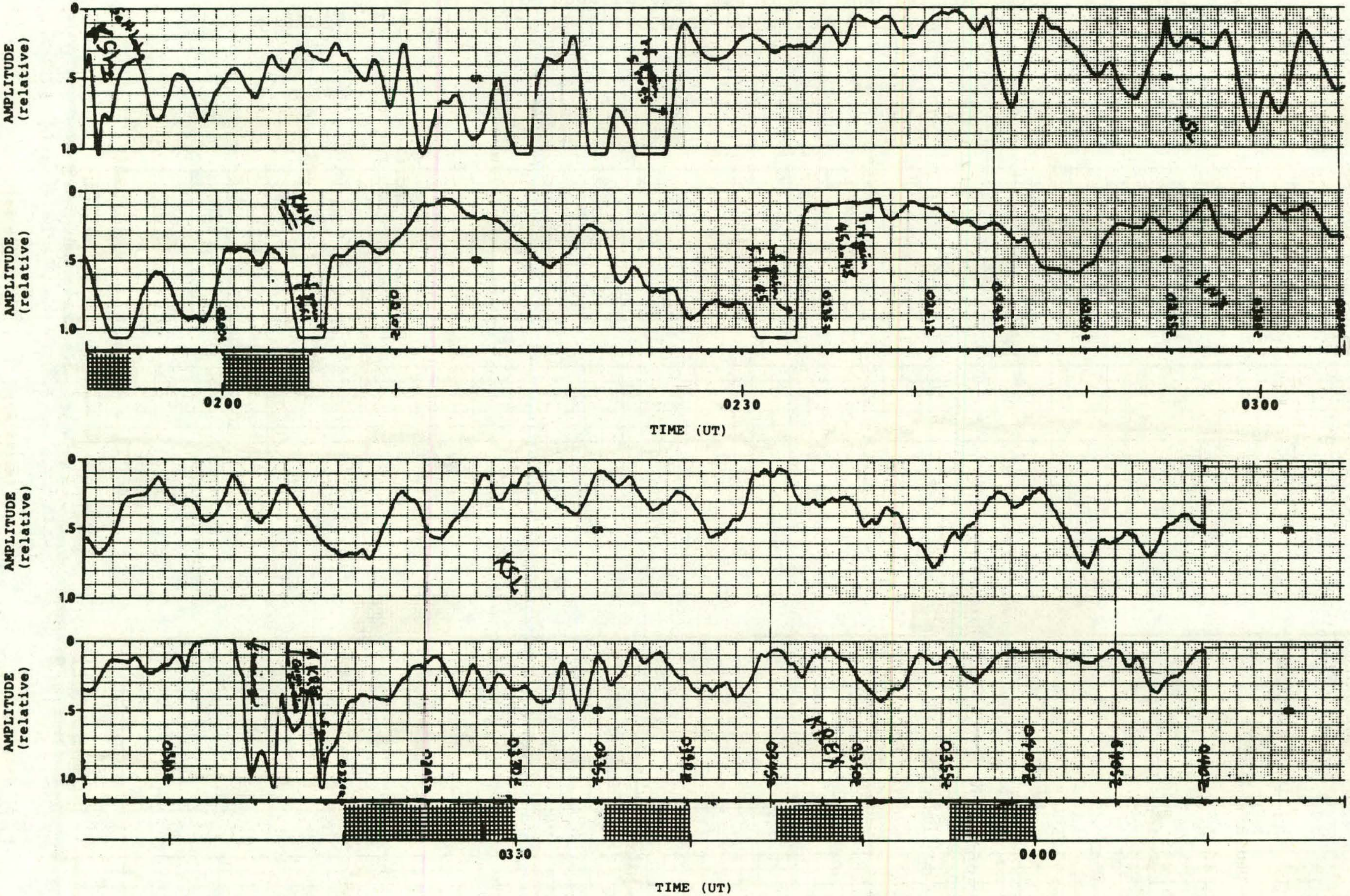


Figure 15. Amplitude signals recorded from KSL (1160 kHz, SLC, UT--upper trace), and KNX (1070 kHz, LA, CA--lower trace), and KREX (1100 kHz, Grand Junction, CO--lower trace), at Brush, CO, on August 16, 1979.

6. IONOSPHERIC DIAGNOSTIC STUDIES UNDERTAKEN DURING OPERATION OF THE PLATTEVILLE FACILITY

During the time that the Platteville high-power HF Facility was operating in a mode to simulate SPS heating of the lower ionosphere, a number of experiments were conducted in order to determine how the ionosphere responded to the high-powered transmissions. These experiments were designed to provide information about ionospheric temperature and structure changes in a more direct manner than can be inferred from analysis of telecommunication data alone. The experiments undertaken included ionosonde observations and cross-modulation observations.

6.1 Ionosonde Observations

The ionosonde which was employed as a diagnostic tool was operated in a pulsed mode. The ionosonde can record signal amplitude at a 60 kHz rate with a 0.2 dB resolution, signal phase at 4 degree increments, and signal delay time at 0.1 km increments. Maximum pulse repetition frequency is 500 pulses per second.

There is evidence that an increase in electron temperature and, consequently, electron collision frequency at D region heights occur when a large amount of rf power passes through the D region--70 to 90 km--(Utlaut, 1970; Jones et al., 1972). This change in collision frequency will affect the propagation characteristics of signals passing through the region. Both signal amplitude and signal phase will be affected. The change in amplitude is due to an increase in absorption, and the change in signal phase is due to a change in refractive index (Davies, 1965, p. 80). The ionosonde provides a rf pulse probe which can be positioned so that the transmitted diagnostic signal will pass through the modified D region and reflect from the higher F region and return again through the modified D region to the co-located diagnostic receiver. Because the rf pulse passes through the modified region twice, any resulting signal attenuation and propagation delay will be doubled.

For the purpose of determining the extent to which the D region is modified by the intense rf field generated by the Platteville Facility, the diagnostic ionosonde was located near the same site. Crystal filters were designed to prevent ionosonde receiver overload for those frequencies chosen for utilization at the Facility. A calibration procedure was undertaken in order to determine the changes in amplitude and phase of the ionosonde signal due to direct coupling of radio energy from the Facility operation into the ionosonde. This calibration was performed by lightly coupling a co-ax cable link between the transmitter, terminated in a resistive dummy load, and the receiving antenna while the Facility cycled "ON" and "OFF." The calibration procedure showed that changes of 0.9 dB in amplitude (0.2 dB quantitizing error plus 0.7 dB gain variation) and eight degrees in phase (four degrees in quantitizing error plus four degrees in gain variation) were associated with operation of the Platteville high-power Facility. For the purpose of determining if significant telecommunication effects occur when a very high-powered rf beam is propagated through the D region, this resolution should be quite adequate.

The relative location of the Platteville 10-element phased array, the ionosonde probe, and the half power points at D region heights are depicted in Figure 16. At 5.2 and 9.9 Mhz, the 3 dB beamwidths of the Platteville array are approximately 17 degrees and 11 degrees, respectively. Even the half power contour which has the shortest radius (6.7 km at 70 km for 9.9 MHz) occurs beyond the ionosonde probe site, assuring that the probe signal must pass through a section of the D region illuminated by the high-power Facility transmissions. Because the ordinary mode of a radio wave reflected from the F region will experience a northward bending of a couple kilometers at D region heights the ionosonde signal will be shifted toward the center of the D region illuminated by the Facility.

Figure 17 is a typical data record during the transition period of Facility "ON" to Facility "OFF". For these time series of data, the ionosonde probe frequency was 4.6 MHz. The top plot, labeled virtual height, indicates the apparent reflection height of the recorded signal which propagates through the D region. A gate of approximately 50 km in width was applied to eliminate all echoes from heights outside the gate. The lower continuous sets of points at about 240 km indicate the desired reflection, and the irregular points at greater heights show an occasional echo which are probably slant path reflections from roughness generated in the F region when the Facility is "ON." This record begins at 2043:50 UT (1443:50 MDT) on the 4th of October 1979 while the Facility was radiating 1.7 MW of cw power at 5.2 MHz with the extraordinary mode of polarization. At 2043 the critical frequency of the F2 region, foF2, was about 12.6 MHz and the ionograms showed no spread-F even though the Facility had been "ON" for 13 minutes. An ionogram taken at 2040 UT is shown in Figure 18 with the Facility and probe frequencies as marked.

On Figure 17, the relative amplitude and phase of the probe signal are recorded on the middle and bottom plots of the time series recording. It is quite obvious that the Facility is producing an unstable condition in the ionosphere up to 2045:00 UT, the time the Facility was turned "OFF", plus an additional five to ten seconds. The amplitude of the signal with Facility "ON" shows a series of enhancements and fades at an almost constant period of 2.6 seconds. There are no millisecond responses visible in these data series to suggest significant D region effects and, in fact, the average amplitude showed no suggestion of decreasing as one would

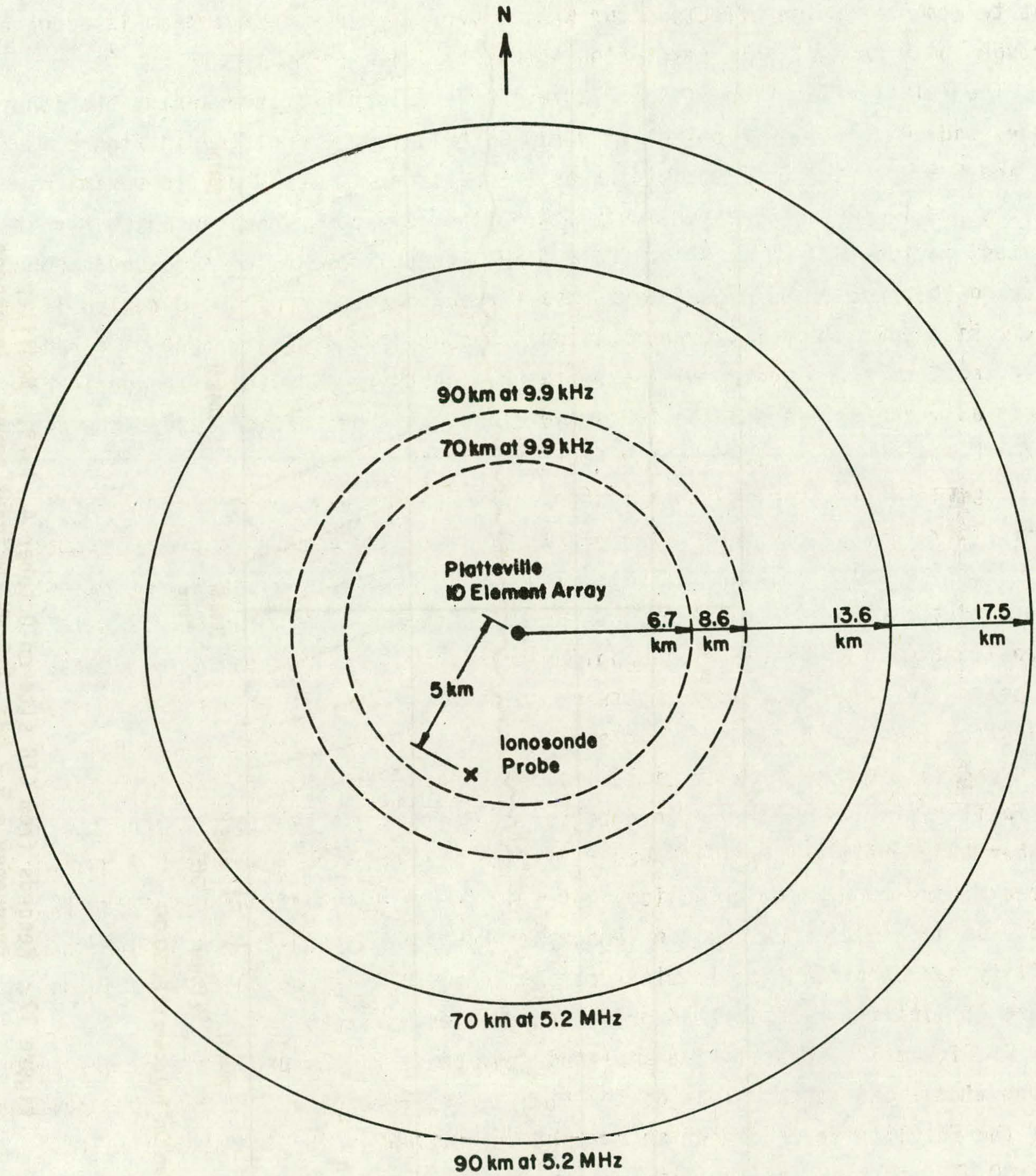


Figure 16. Half power contours of Platteville 10-element array at 5.2 and 9.9 MHz for D-region heights.

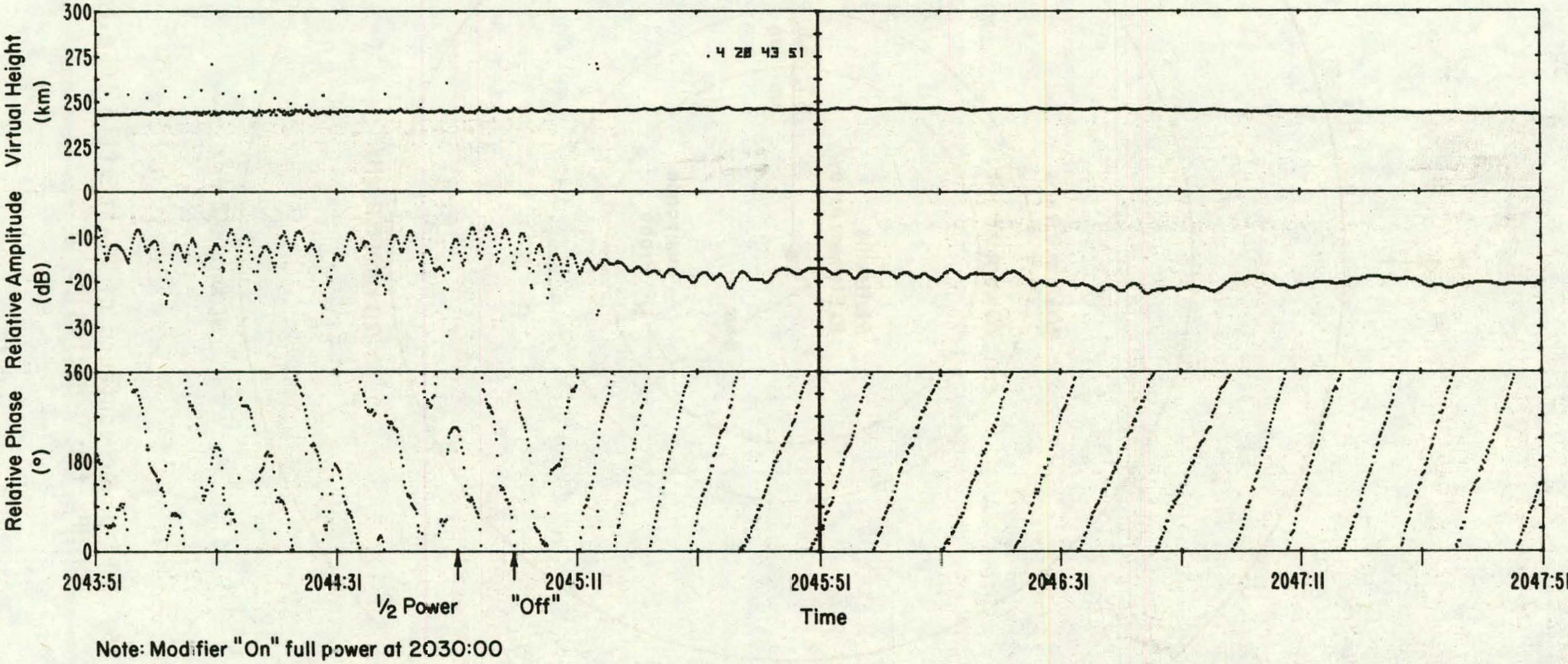


Figure 17. Records from CIG site on October 4, 1979. Modifier frequency = 5.2 MHz, 1.7 MW cw input power. Ionosonde probe frequency = 4.6 MHz.

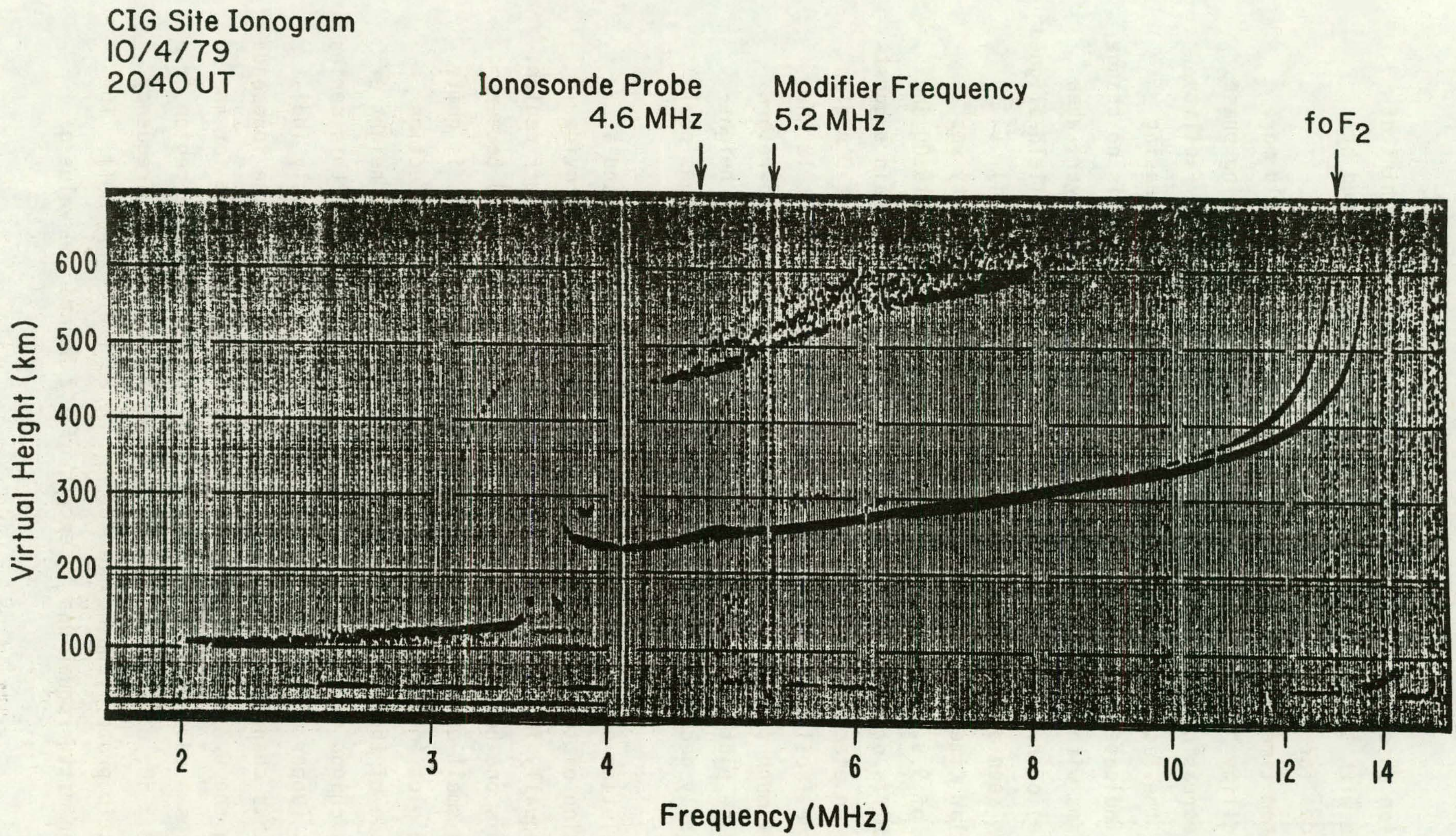


Figure 18. Vertical incidence ionogram showing modifier and diagnostic probe signal locations.

expect if enhanced D region absorption was present. There may even be a hint of reduced average amplitude with the Facility "OFF" which could be determined by averaging signal amplitudes for each case.

The phase plot (bottom time series, Figure 17) also shows considerably more fluctuations with the Facility "ON". There is a definite trend of advancing phase, indicating an apparent decreasing height of the reflection point with the Facility "ON." In contrast, with the Facility "OFF", a retarding phase or an increasing height of reflection is indicated. It should be noted again that there is no change detectable on the ionograms with or without the Facility operating. However, when the ordinary mode (O-mode) of heating is used, very apparent spread-F or field-aligned irregularities are always seen on the ionograms (Utlaut and Violette, 1974).

Figure 19 is a similar time series as in Figure 17 except the Facility was operating at a frequency of 9.9 MHz. The Facility was turned "OFF" at 2115:00 and there were no apparent shifts occurring in less than a second in time, again suggesting no detectable change in electron temperature or in electron density at D region heights. In this case the Facility operating at 9.9 MHz and foF2 at about 12 MHz, the F region recovery was much slower, requiring more than five minutes to return to normal. Also, the phase plot indicated a slight increasing reflection height before turn-off and slightly decreasing after turn-off. No ionogram changes could be detected as before.

To improve the resolution of the ionosonde probe, a one second "ON" and a one second "OFF" modulation of the Platteville Facility was selected to provide many transitions (and, equally important, a minimum of disturbance) to the F region. As seen in Figure 20, this one-half Hertz square wave modulation permitted better resolution for detecting small changes in the ionospheric structure. This is quite evident in the amplitude plot (middle plot). In this case, the first reflection seen was the ordinary mode of the ionosonde signal occurring at a virtual height of about 245 km. A maximum change of 1.3 dB is observed for the duration of this series for the ionosonde signal (upper curve of the amplitude plot). As previously indicated, up to 0.7 dB of this change is a result of the Facility reducing the ionosonde receiver gain. Assuming the 0.7 dB correction to obtain the maximum value for the D region, absorption gives a value of 0.6 dB for a round-trip through the region or a one-way attenuation of 0.3 dB. This measurement was made for a modifier frequency of 5.2 MHz and a diagnostic probe frequency of 4.6 MHz at 2311 UT (1711 MDT). The Platteville Facility transmitter power was in excess of 1.2 MW and the value of foF2 was about 11.8 MHz.

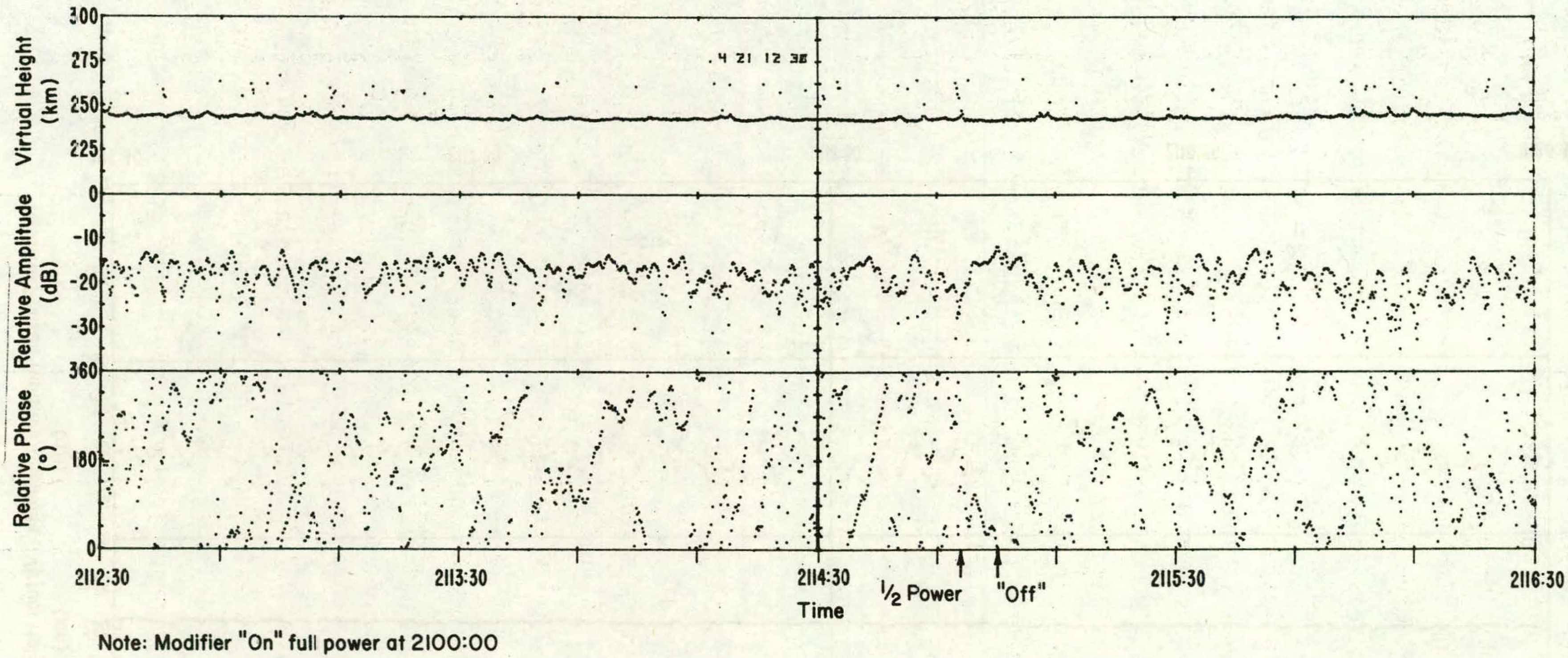


Figure 19. Records from CIG site on October 4, 1979. Modifier frequency = 9.9 MHz, 1.7 MW cw input power. Ionosonde probe frequency = 4.6 MHz, 10 Hz sample rate.

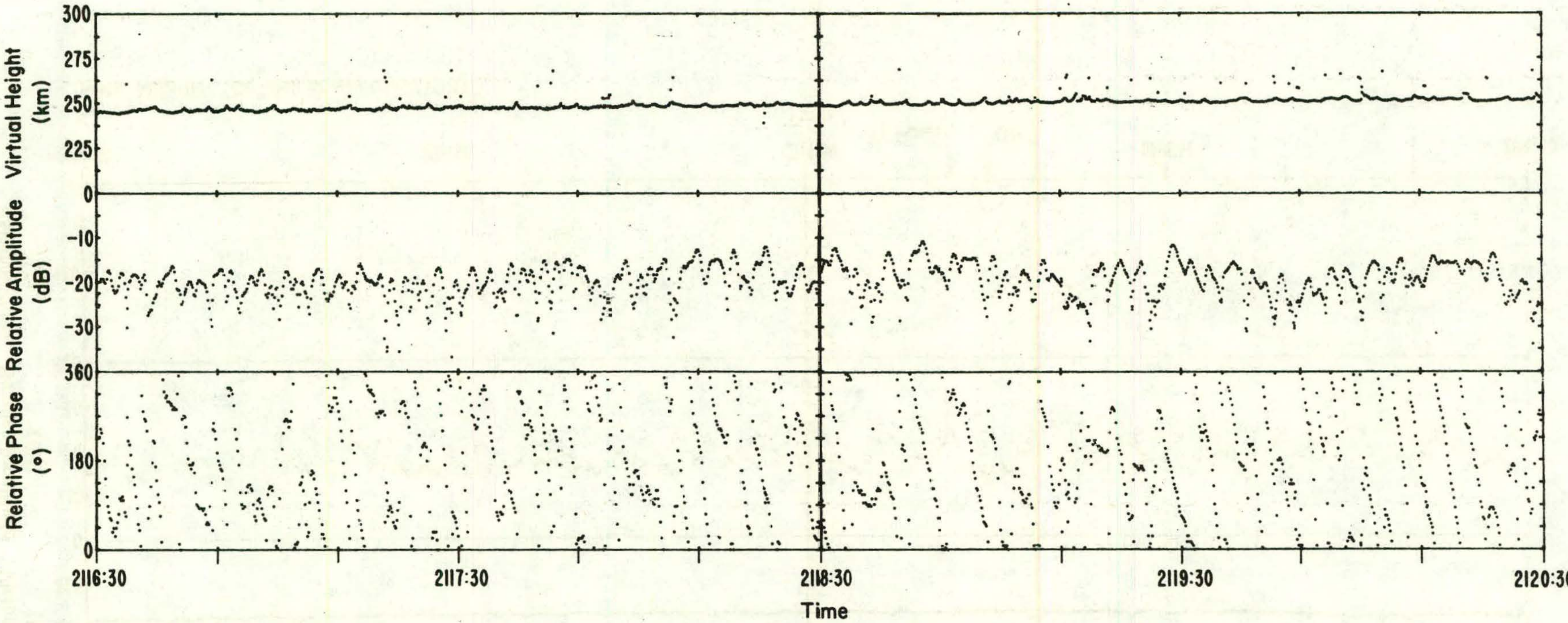


Figure 19. Continued.

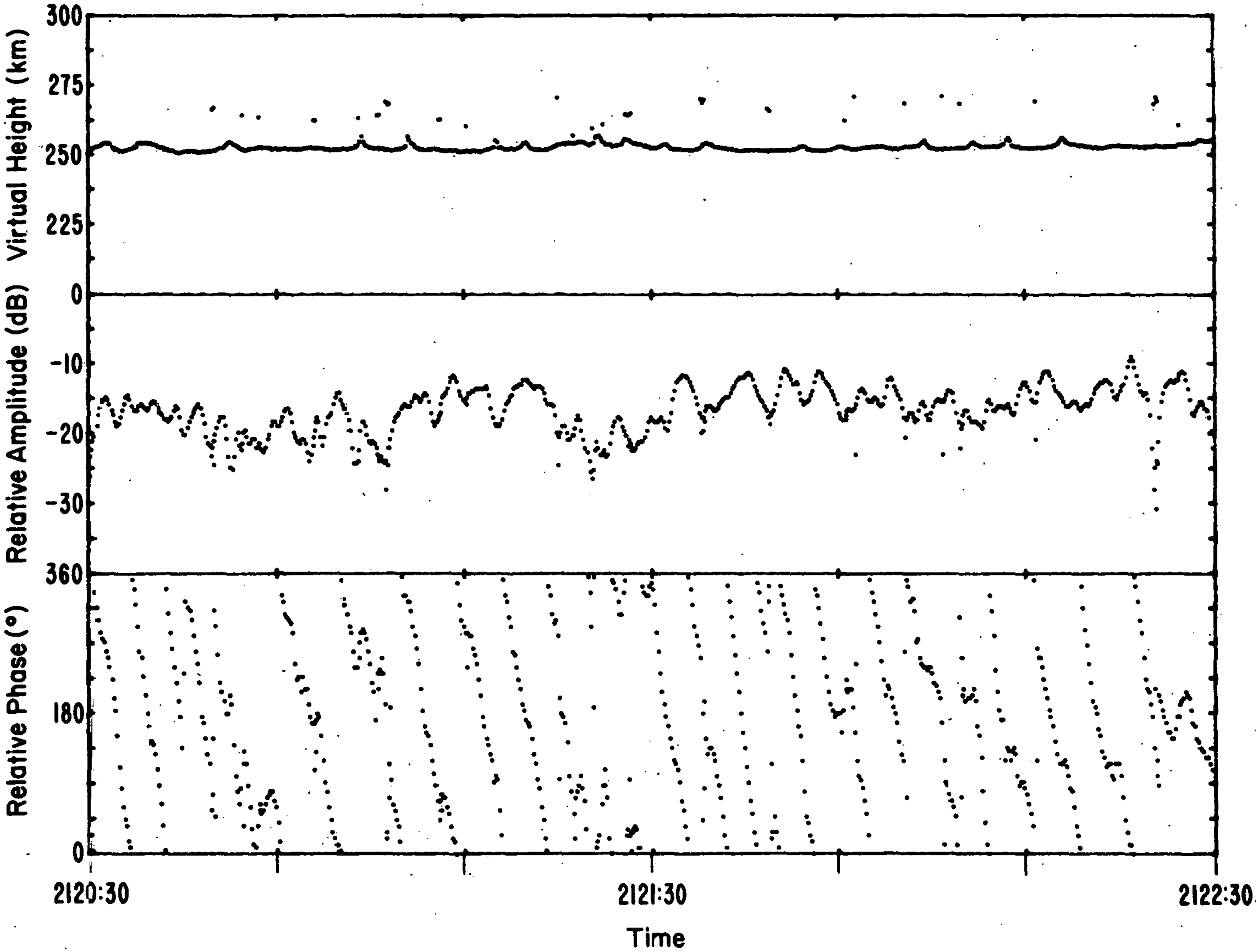


Figure 19. Continued.

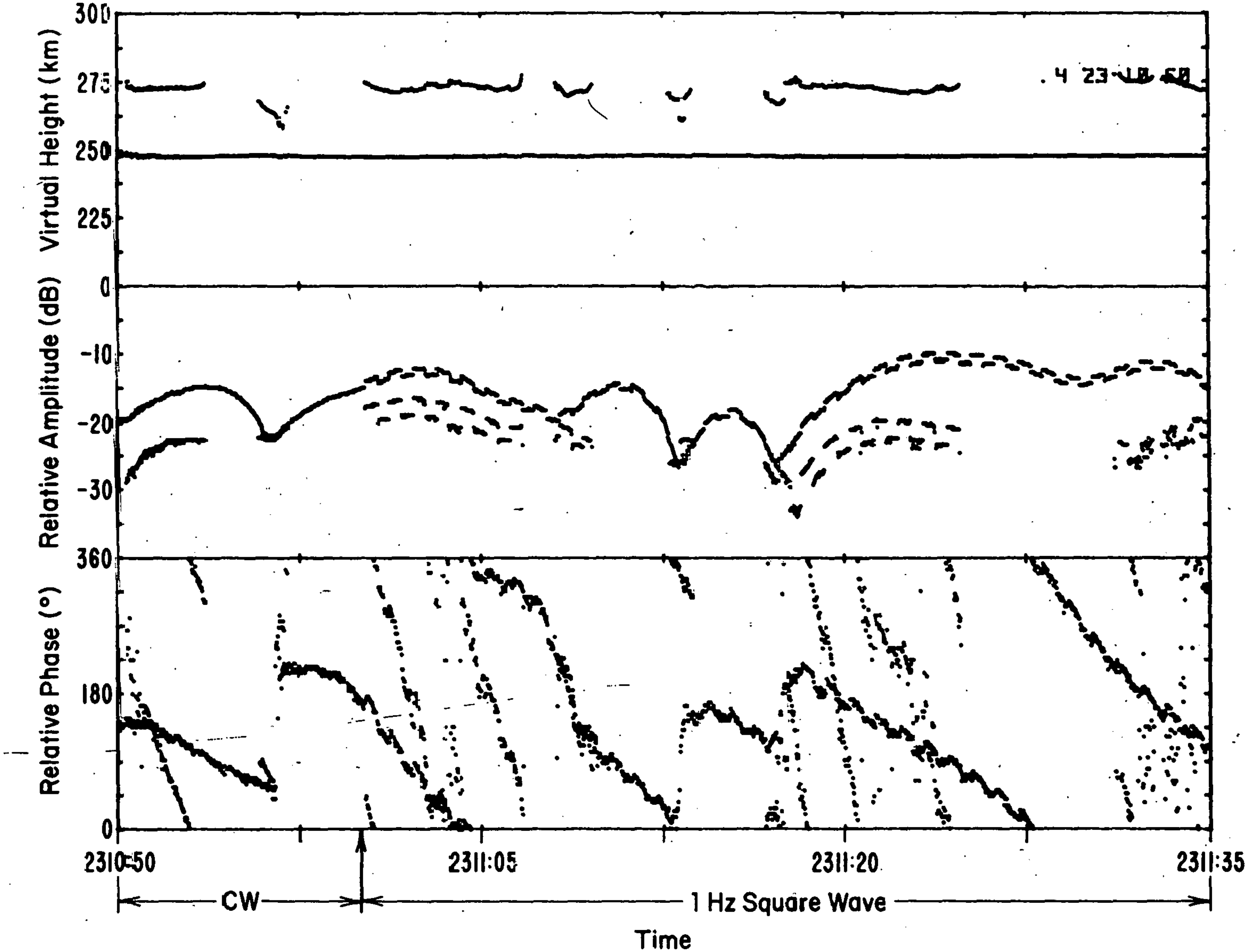


Figure 20. Records from CIG site on October 4, 1979. Modifier frequency = 5.2 MHz. Ionosonde probe frequency = 4.6 MHz, 25 Hz sample rate.

On Figure 20, the ionosonde extraordinary mode is seen to be reflected at about 275 km. This appears below the ordinary mode reflection on the amplitude plot, but because of the two-mode overlap during the duration of the received pulse, there is a constructive and destructive interference pattern generated at the receiver front end. Because of this interference pattern, the signal appears intermittent in the time series.

Figure 21 is a second time series example with a one hertz square wave modulation beginning at 2313:30 UT with identical parameters as in Figure 20. As in Figure 20, the results show a maximum of 0.3 dB decrease in signal amplitude in passing once through the D region with the Facility "ON". A portion of Figure 21 was chosen for closer observation to provide a better estimate of phase shift of the probe signal. This portion indicated by the brackets along the time axis was expanded and appears as Figure 22. Figure 22 shows the expanded scale of the 4.6 MHz probe signal phase on the lower plot. An effort was made to trace, on this figure, the phase line if the Facility had not been "ON." Careful scaling of this tracing and subtracting the actual phase plot with the Facility operating provides a range of phase shift of 8 to 12 degrees in a lagging or retarded direction. Applying corrections because of the effects of the Facility on the ionosonde receiver suggests that the signal in passing twice through the modified D region experienced a phase delay of from 8 to 20 degrees compared to the delay with the Facility "OFF." These values of phase delay were taken at 1714 MDT, with the Facility operating at 5.2 MHz and a radiated power of approximately 1.2 MW.

At 2329:56, the time series of Figure 23 was started. In this plot the ionosonde frequency was changed to 6.4 MHz with Platteville operating again at 5.2 MHz, transmitting a one hertz square wave beginning at 2330:00. The digital sampling rate for Figure 23 was only eight hertz. The maximum amplitude decrease was again near 0.3 to 0.4 dB.

Amplitude and phase data were recorded for nearly all the September-October observations during the regular experiment schedule. The D region effects on the vertical rf probe signal due to the ionosonde were much smaller than anticipated, and the results indicate that the impact on VLF, LF, and MF signals used in telecommunication systems would be slight.

6.2 Cross-Modulation Effects

It is well-known that when a high-powered HF radio wave is amplitude modulated and is propagated into the ionospheric plasma, the plasma itself becomes modulated (Gurevich 1978, p. 176). This modulation of the ionosphere can be transferred to other radio waves that pass through the region perturbed by the high-powered radio

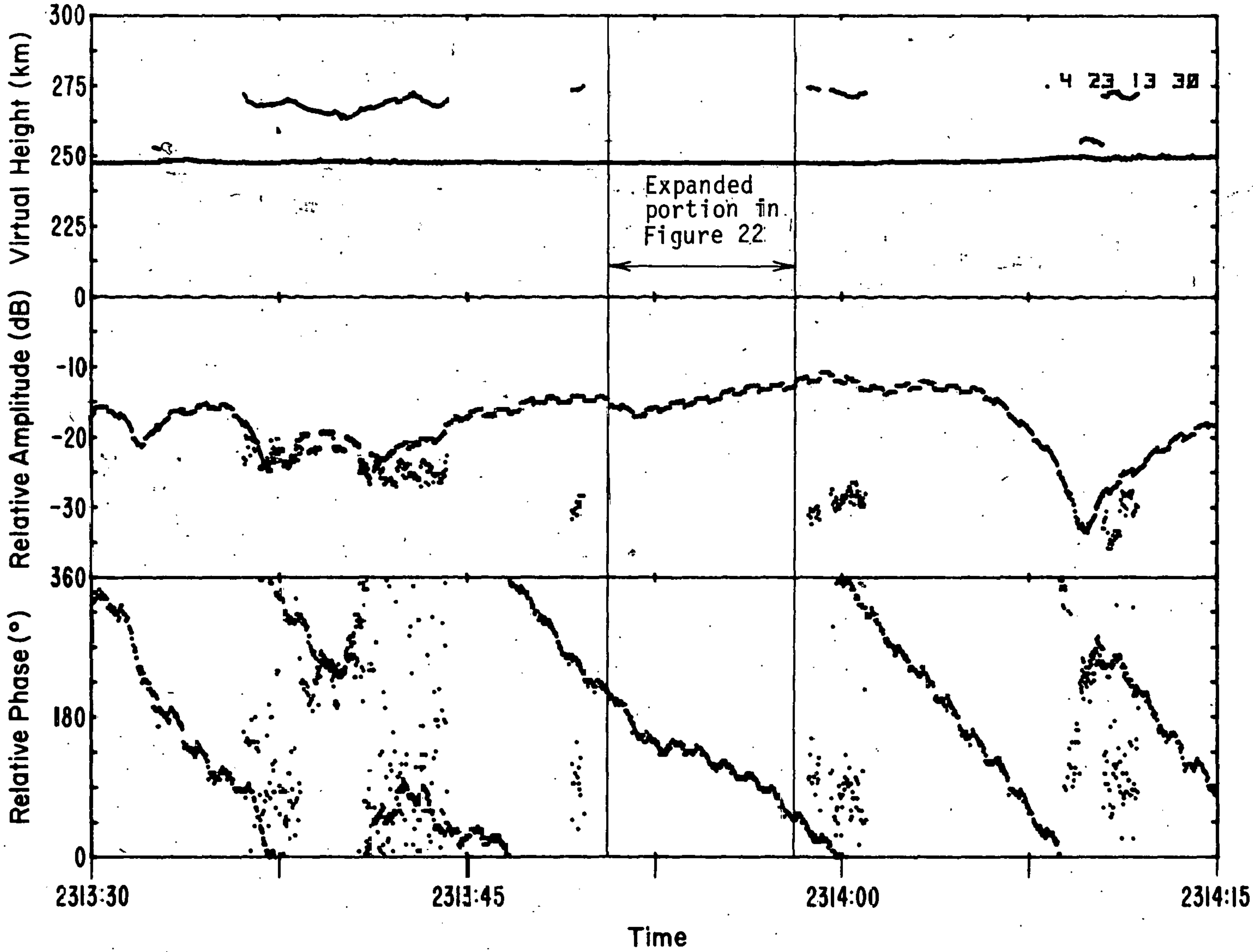


Figure 21. Records from CIG site on October 4, 1979. Modifier frequency = 5.2 MHz, 1 Hz square-wave. Ionosonde probe frequency = 4.6 MHz, 33 Hz sample rate.

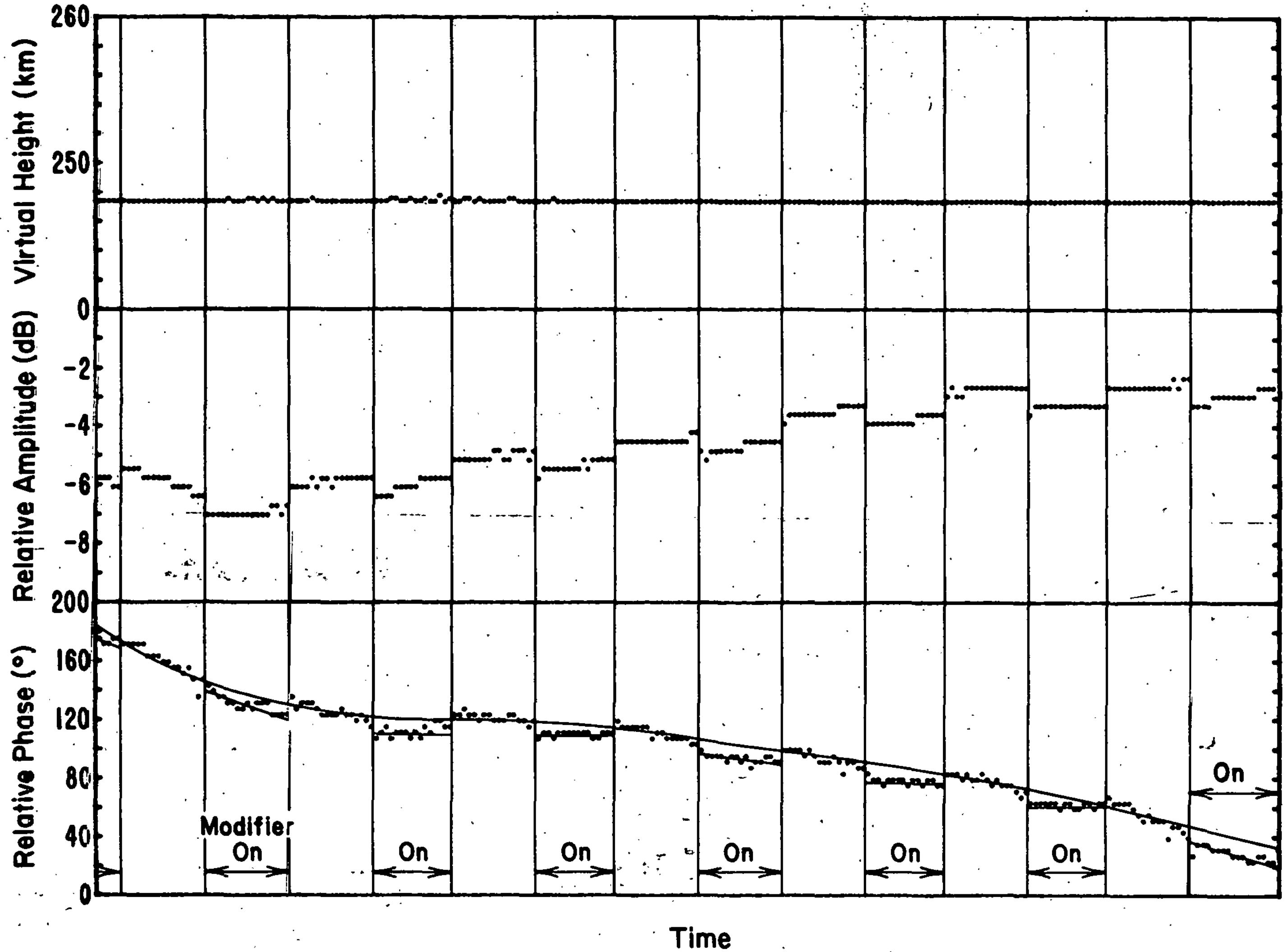


Figure 22. Expanded portion from Figure 21. Records from CIG site on October 4, 1979. Modifier frequency = 5.2 MHz, 1 Hz squarewave. Ionosonde probe frequency = 4.6 MHz, 33 Hz sample rate.

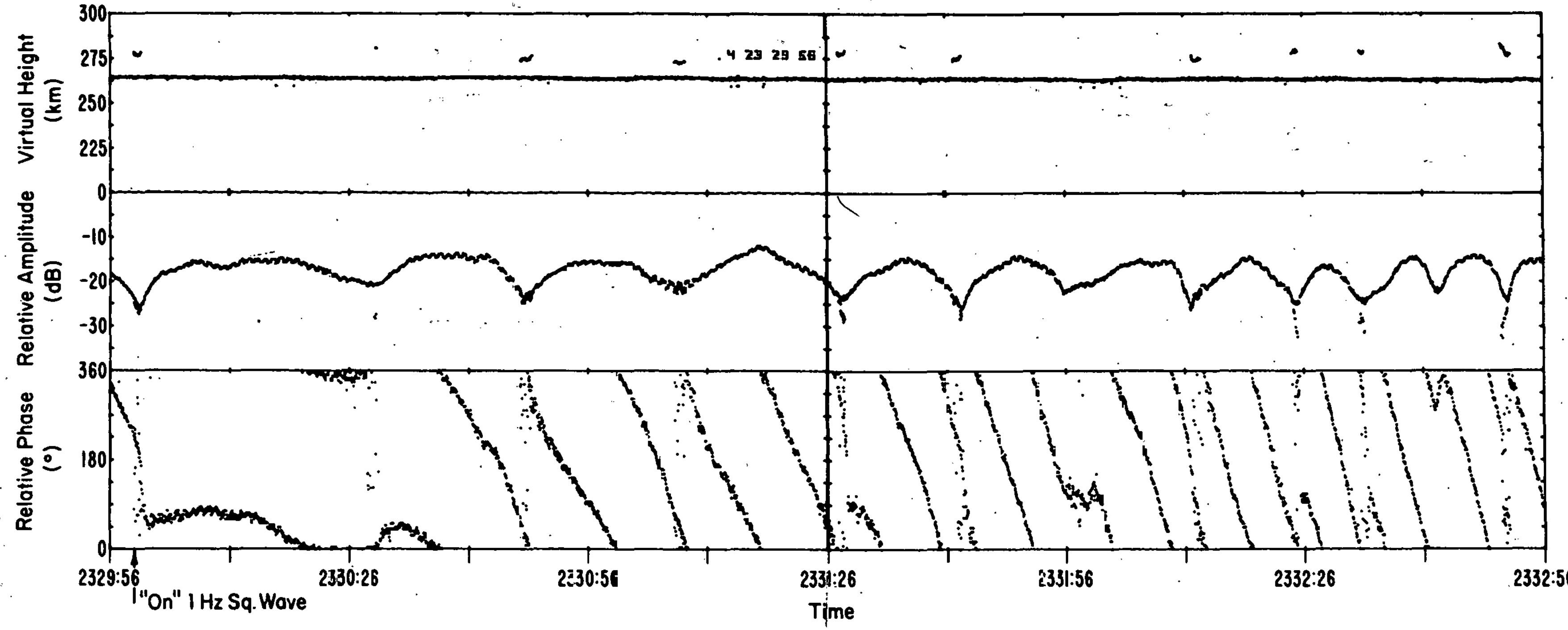


Figure 23. Records from CIG site on October 4, 1979. Modifier frequency = 5.2 MHz, 1 Hz square-wave. Ionosonde probe frequency = 8 Hz sample rate.

wave. The process, known as cross-modulation, results from changes in the electron temperature induced by the modulated radio wave which, in turn, lead to changes in electron collision frequency and electron density. By observing the behavior of radio waves propagated from a known source and passing through the region of the ionosphere heated by transmissions from the Platteville Facility, it is possible to utilize cross-modulation observations to deduce whether or not the electron temperature in the lower ionosphere was substantially changed during times of operation of the Facility. Studies by Jones et al., (1972) and Chilton (NTIA TM 79-4, limited distribution) have shown that significant ionospheric cross-modulation results from the operation of the Platteville Facility. Signals propagated 60 kHz from WWVB located in Fort Collins, Colorado, have been observed with modulation depths up to 30 percent.

In conjunction with the SPS simulation experiments conducted at Platteville, the Remote Measurements Laboratory of Stanford Research Institute, International, conducted tests of cross-modulation effects. The tests were designed to determine the possible effects of changes in the Dregion due to ionospheric heating. Details of the experiments and the results obtained are discussed elsewhere (Showen 1980). In this report we briefly describe the pertinent results. Transmissions of opportunity were used, and four receiver sites near Platteville were selected so that the propagation paths would pass through the volume heated by the Platteville Facility. Sources used in the cross-modulation experiments were OMEGA (10.2, 131 kHz), WWVB (60 kHz), ADF (387 kHz), AM broadcasts (1060, 1410 kHz), and WWV (2.5, 5.0 MHz). Table 7 taken from Showen (1980) gives the operating parameters for these sources, and also indicates if any effects were seen on each path.

The experimental studies show that the electron temperature was changing in the D and E regions during the time the Platteville Facility was operating. Studies by Chilton (NTIA TM 79-4, limited distribution) indicate that the electron temperature above Platteville can be raised from a background level of 200°K to between 300 and 500°K using powers such as employed in the experiments. This change in electron temperature corresponds very closely to recent theoretical calculations of changes in D region electron temperatures due to the passage of a 23 mW/cm^2 SPS power beam (Gerald Meltz, private communication). The same studies show, however, that increases in electron density of 10 to 15 percent should be accompanied by the electron temperature increases. The cross-modulation data as well as the telecommunication data seem to indicate that electron density in the lower ionosphere was not changed appreciably by the Platteville Facility, or if it was, such changes are not significant in terms of adverse telecommunication system impact.

Table 7. Experimental Summary for Cross Modulation Effects*

Transmitter			Receiver		Results
Location	Call	Frequency	Location	Type	
Longmont	KLMO	1060 kHz	Brush	Spectrum	negative
Ft. Collins	KCOL	1410 kHz	Bennett	Spectrum	cross-mod.
Ft. Collins	WWVB	60 kHz	Bennett	Spectrum	cross-mod.
Ft. Collins	WWVB	60 kHz	Bennett	Phase	negative
Ft. Collins	WWV	2.5, 5.0 MHz	Bennett	Spectrum	cross-mod.
Ft. Collins	LLD	387 kHz	Bennett	Spectrum	negative
N. Dakota	OMEGA	10.2 kHz	N. Denver	Phase	negative
N. Dakota	OMEGA	10.2 kHz	Conifer	Phase	negative
N. Dakota	OMEGA	10.2, 13.1 kHz	Conifer	Spectrum	negative

* Data obtained from Showen (1980).

7. CONCLUSIONS

The results presented in the previous sections provide strong evidence that heating the lower ionosphere with radio waves having power densities comparable to the SPS microwave power beam will not lead to adverse impacts upon the performance of VLF, LF, and MF telecommunication systems. In numerous instances, the D and lower E regions of the ionosphere above Platteville, Colorado, were illuminated with radio waves in the high frequency portion of the spectrum whose power density scales to 23 mW/cm^2 - the current design power density of the SPS microwave beam. Signals propagated through and near D and E regions illuminated by the Platteville Facility displayed no obvious change that could lead one to suspect adverse system performance attributable to SPS operation. Whether the same conclusions can be reached for telecommunication systems operating at higher frequencies and influenced by the upper levels of the ionosphere, remains to be demonstrated.

During the course of the SPS simulation using the Platteville Facility, every attempt was made to heat the lower ionosphere with the SPS equivalent power density of 23 mW/cm^2. Heating at frequencies near 5 MHz provides this equivalent power density. It is possible that during the daytime hours, the HF radio waves used to heat the D and E regions suffered absorption at even lower altitudes with the result that SPS equivalent power densities were less than 23 mW/cm^2 at 100 km. While this is a distinct possibility, it does not vitiate the conclusions reached here. During daytime hours telecommunication systems operating in the VLF and LF portions of the spectrum that rely upon skywave propagation are reflected low in the ionosphere (75-90 km). This is the height region where most of the energy associated with the Facility operation is deposited. During the nighttime hours when the performance of VLF, LF, and MF systems is dependent upon radio waves reflected at higher ionospheric heights, the current Platteville Facility provides the SPS power density equivalent of 23 mW/cm^2 to the pertinent heights in the ionosphere. Recent calculations by Meltz (G. Meltz, private communication) have been performed in order to simulate the ionospheric heating due to the operation of the Platteville Facility. The results indicate that the Platteville Facility operating at 5 MHz with the X mode of polorization heats the ionospheric region between 70 and 90 km more than will result from SPS operation. These calculations are based on the fact that the frequency scaling for ohmic heating depends not simply on a $1/f^2$ relationship, but rather on an effective frequency, f_e, defined by:

$$f_e^2 = f^2 \left[(1 \pm f_H / f \cos \theta)^2 + (\nu_{en} / 2\pi f)^2 \right] \quad (3)$$

where θ is the angle between the propagation direction and the magnetic field and the other terms are as defined previously.

The distances that radio waves propagate in the telecommunications systems monitored during the study are large compared to the size of the ionosphere that was modified by the Platteville Facility. Only for those frequencies where the dimensions of the modified area is on the order of the first Fresnel zone would a considerable effect in signal characteristics be expected. The major axis of the first Fresnel zone (i.e. the distance of the Fresnel zone along the propagation path) for the OMEGA-Hawaii to Brush, Colorado, path is determined to be at least 2000 km. The monor axis of the first Fresnel zone (the distance of the Fresnel zone perpendicular to the propagation path) for the same path is on the order of 200 km. The first Fresnel zone of the LORAN-C paths - Fallon, Nevada, to Brush, Colorado, and Dana, Indiana, to Boulder, Colorado - is on the order of 700 km long and 60 km wide.

The area of the ionosphere that is modified by the Platteville Facility is about 30 to 40 km in diameter at D region heights. This size is small compared to the major axis of the OMEGA and LORAN-C paths but is a substantial fraction of the minor axis of the LORAN-C paths. The results presented here indicate that there was no discernable change in the observations of the OMEGA and LORAN-C signal characteristics associated with the operation of the Platteville Facility. The size of the ionosphere that was modified by the Facility is about three to four times the size of the modified area associated with the passage of the SPS microwave power beam through the ionosphere. Thus it is reasonable to expect that changes in the propagation characteristics of the OMEGA and LORAN-C signals would not be any larger than were produced by operation of the Platteville Facility.

The MF signals whose skywaves can pass through the ionosphere modified by the Platteville Facility - KNX from Los Angeles, and KREX from Grand Junction - have Fresnel zones that are smaller than the area of the ionosphere that was modified by the Facility. The experimental simulations for MF skywave signal propagation were conducted under conditions of an ionospheric disturbance that was larger than that associated with SPS operation. As was the case for the OMEGA and LORAN-C signals, no changes in the characteristics of the MF signals were noted that could be attributed to the operation of the Platteville Facility.

The telecommunication systems that were monitored during the operation of the Platteville Facility were done so in a manner that realistically simulates the propagation of VLF, LF, and MF radio waves in an ionosphere impacted by the SPS microwave power beam. As was seen in Section 3 through 5, no changes in system

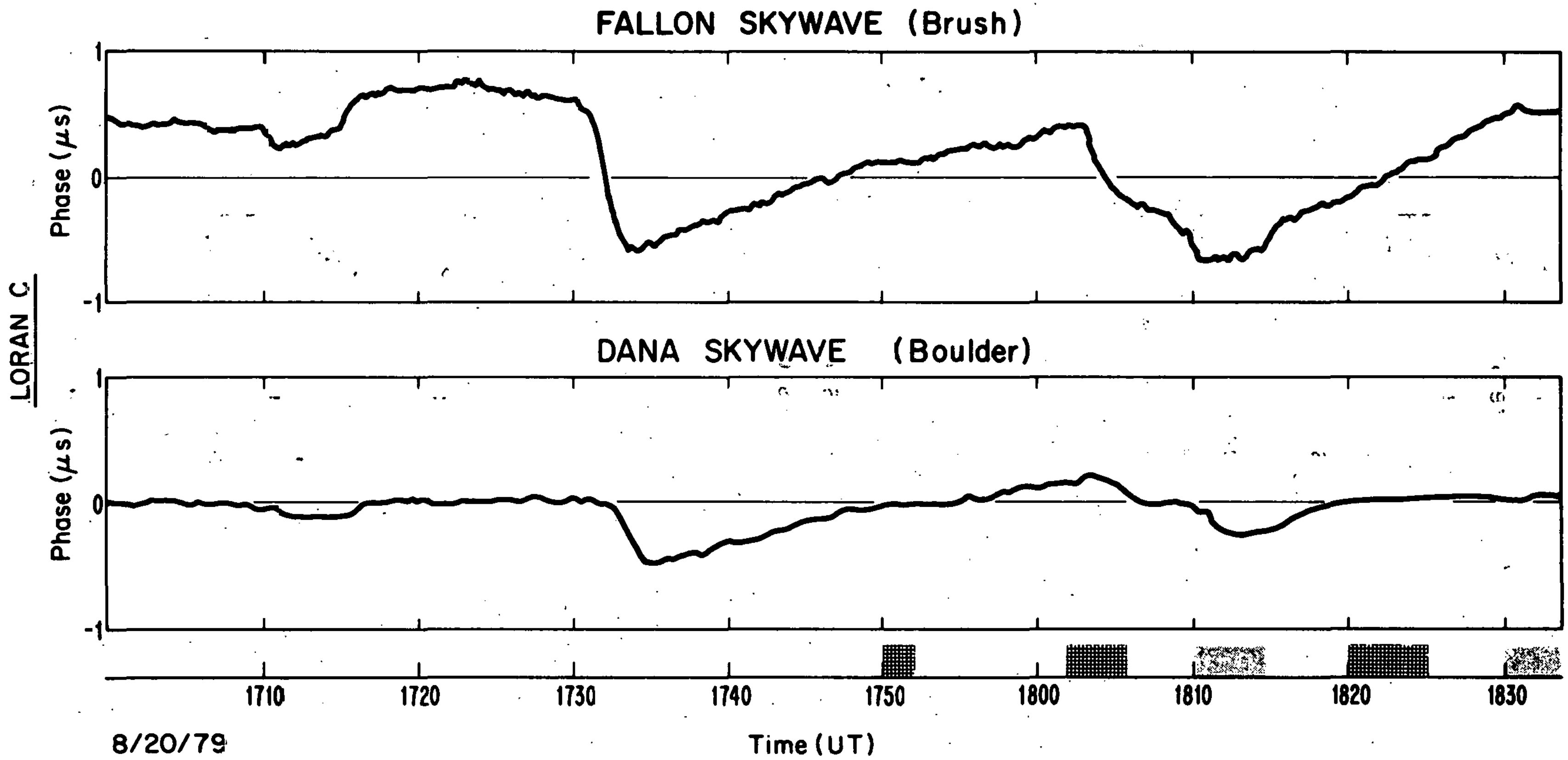


Figure 24. Recorded relative phase data from LORAN-C station at Fallon, NV, at Boulder, CO, and from LORAN-C station at Dana, IN, at Boulder, CO, on August 20, 1979.

performance were noted that could be associated with ionospheric heating-induced disturbances. Changes in the amplitude and phase of the OMEGA, LORAN-C and MF signals were observed that were associated with normal day-to-day changes in propagation conditions. These changes obviously are much greater than any changes in system performance due to ionospheric heating which were undetectable. During the time periods for which telecommunication systems data were collected, large-scale geophysical disturbances--notably solar flares--occurred. These disturbances produced changes in telecommunication system performance that far exceeded any possible change induced by intentional ionospheric heating.

Figure 24 shows a record of the phase changes seen in LORAN-C signals propagated from Fallon, NV, to Brush, CO (top curve), and from Dana, IN, to Boulder, CO (bottom curve), between 1700 and 1835 hours (UT) on August 20, 1979. At 1731 hours a small solar flare was reported. This flare produced a phase shift of more than 1 μs in the Fallon-Brush signal and 0.5 μs in the Dana-Boulder signal. The smaller phase shifts of five minute duration commencing at 1710 and 1810 hours were caused by interference from the 60 kHz time and frequency standard (WWVB) at Fort Collins, CO. The times during which the Platteville Facility was "ON" are also indicated on the time scale beneath the Dana-Boulder trace.

Figure 25 provides another example of changes in telecommunication system performance resulting from solar flare activity. Shown in the figure is a portion of the normal diurnal phase change of about 60 μs for the OMEGA Hawaii-to-Boulder VLF signal for five consecutive days beginning on 16 August 1979. Two solar flares were reported on 18 August, one commencing at 1356 hours (UT) and the other at 1406 hours (UT). These flares produced a shift in the phase of the OMEGA signal of more than 10 μs compared to the average behavior observed on the other four days. This shift is about five times the changes in phase seen on a day-to-day basis. Even if these day-to-day changes were associated with intentional ionospheric heating, the effect of the solar flare far outweighs any heating-induced effect. Thus, both OMEGA (VLF) and LORAN-C (LF) data show that naturally-induced changes in the ionosphere, which occur on a routine basis, yield effects in propagation systems that are many times greater than any effects that could be associated with the ionospheric heating resulting from a 23 mW/cm^2 SPS power beam.

The experimental study undertaken at Platteville, CO, to assess SPS-related ionospheric heating effects stressed telecommunication system impacts. However, observations recorded using a vertical incidence ionosonde and instrumentation to measure ionospheric cross-modulation effects provide evidence that the ionosphere above Platteville was heated and modified. The amount of the increase in electron

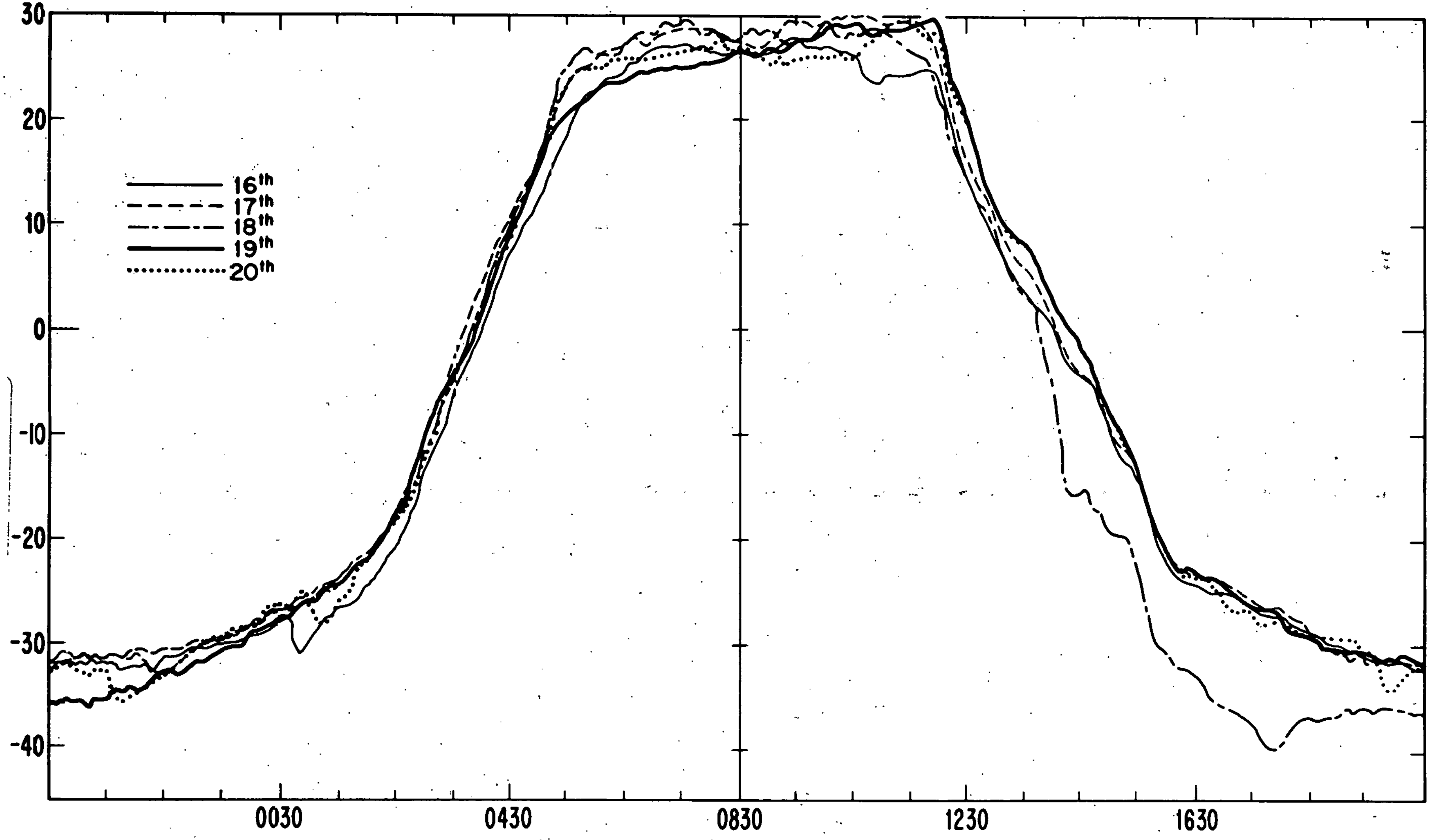


Figure 25. Relative phase records from OMEGA, Hawaii, recorded at Boulder, CO, on August 16, 17, 18, 19, and 20, 1979.

temperature due to the SPS simulation cannot be determined unambiguously using equipment available at Platteville. It is hoped that diagnostic capabilities available at the National Ionospheric Observatory located at Arecibo, Puerto Rico, would lead to an amelioration of this situation in the near future. Previous studies conducted by Chilton (NTIA TM 79-4, limited distribution) indicate that electron temperatures on the order of 300 to 500° K can be achieved using the Platteville high-power, high-frequency Facility. These temperatures agree with recent predictions of the increase in electron temperature resulting from a 23 mW/cm^2 microwave beam passing through the ionosphere, lending confidence that the Platteville based SPS simulation is indeed a realistic simulation.

The results discussed in this report and the conclusions drawn from them are applicable to the operation of a single Satellite Power System with a microwave beam having a power density of 23 mW/cm^2 at the beam center. For system design purposes, it is desirable to have knowledge of the upper power density limit at which the SPS can operate before inducing adverse telecommunication effects. In order to determine this, however, the existing ground-based ionospheric heating facilities must be enhanced to provide more power density to the ionosphere. Such a facility would permit experiments to be conducted in support of system design concepts as well as in support of assessing potential SPS telecommunication impacts in the HF, VHF, and UHF portion of the radio frequency spectrum. The investigation discussed in this report relies upon simulating SPS operation by use of frequency-scaling laws. These laws need to be tested and verified with experimental observation obtained from ground-based facilities operating at higher powers and higher frequencies than the current Platteville Facility.

8. REFERENCES

Carroll, J. C., E. J. Violette, and W. F. Utlaut (1974), The Platteville high-power facility, Radio Sci. 9, No. 11, pp. 889-894.

Crombie, D. D. (1964), The effects of a small local change in phase velocity on the propagation of a VLF radio system, Radio Sci., 68D, No. 6, pp. 709-715.

Davies, K. (1965), Ionospheric Radio Propagation, National Bureau of Standards Monograph 80, U.S. Government Printing Office, Washington D. C.

Fejer, J. A. (1979), Ionospheric modification and parametric instabilities, Rev. Geophys. Space Sci. 17, No. 1, pp. 135-153.

Gordon, W. E., and H. C. Carlson, Jr. (1974), Arecibo heating experiments, Radio Sci. 9, No. 11, pp. 1041-1047.

Gordon, W. E., and L. M. Duncan (1978), Ionosphere/Microwave beam interaction study, William Marsh Rice University Report DRL T01349, Houston TX.

Gurevich, A. V. (1978), Nonlinear Phenomena in the Ionosphere, Springer-Verlag New York Incorporated, New York, NY.

Jones, T. B., K. Davies, and B. Wieder (1972), Observations of D-region modifications at low and very low frequencies, Nature, 238, pp. 33-34.

Meltz, G., L. H. Holway, Jr., and N. M. Tomljanovich (1974), Ionospheric heating by powerful radio waves, Radio Sci., 9, No. 11, pp. 1049-1063.

Showen, R. L. (1980), Measurements of possible D- and E-region telecommunications effects during ionospheric heating, SRI International Report, In Press.

United States Department of Energy (1980), SPS Environmental Assessment Revision 1, Preliminary Environmental Assessment for the Satellite Power System, Volume 2--Detailed Assessment, January 1980.

Utlaut, W. F. (1970), An ionospheric modification experiment using very high-power high frequency transmission, J. Geophys. Res., 75, No. 11, pp. 6402-6405.

Utlaut, W. F. (1975), Ionospheric modification induced by high-power HF transmitters--A potential for extended range VHF-UHF communications and plasma physics research, Proc. IEEE, 63, No. 7, pp. 1022-1043.

Utlaut, W. F. and R. Cohen (1971), Modifying the ionosphere with intense radio waves, Science, 174, pp. 245-249.

Utlaut, W. F. and E. J. Violette (1974), A summary of vertical incidence radio observations of ionospheric modification, Radio Sci., 9, No. 11, 895-903.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A: OMEGA AMPLITUDE AND PHASE DATA

This Appendix provides illustrations of the OMEGA data recorded in conjunction with the SPS simulation experiment. These data were not discussed in the main text. In addition, in Table A.1, average values of recorded amplitude and phase with the Platteville Facility "ON" and Platteville Facility "OFF" are presented. These values were averaged over the Facility "ON" and Facility "OFF" times indicated on the appropriate figures.

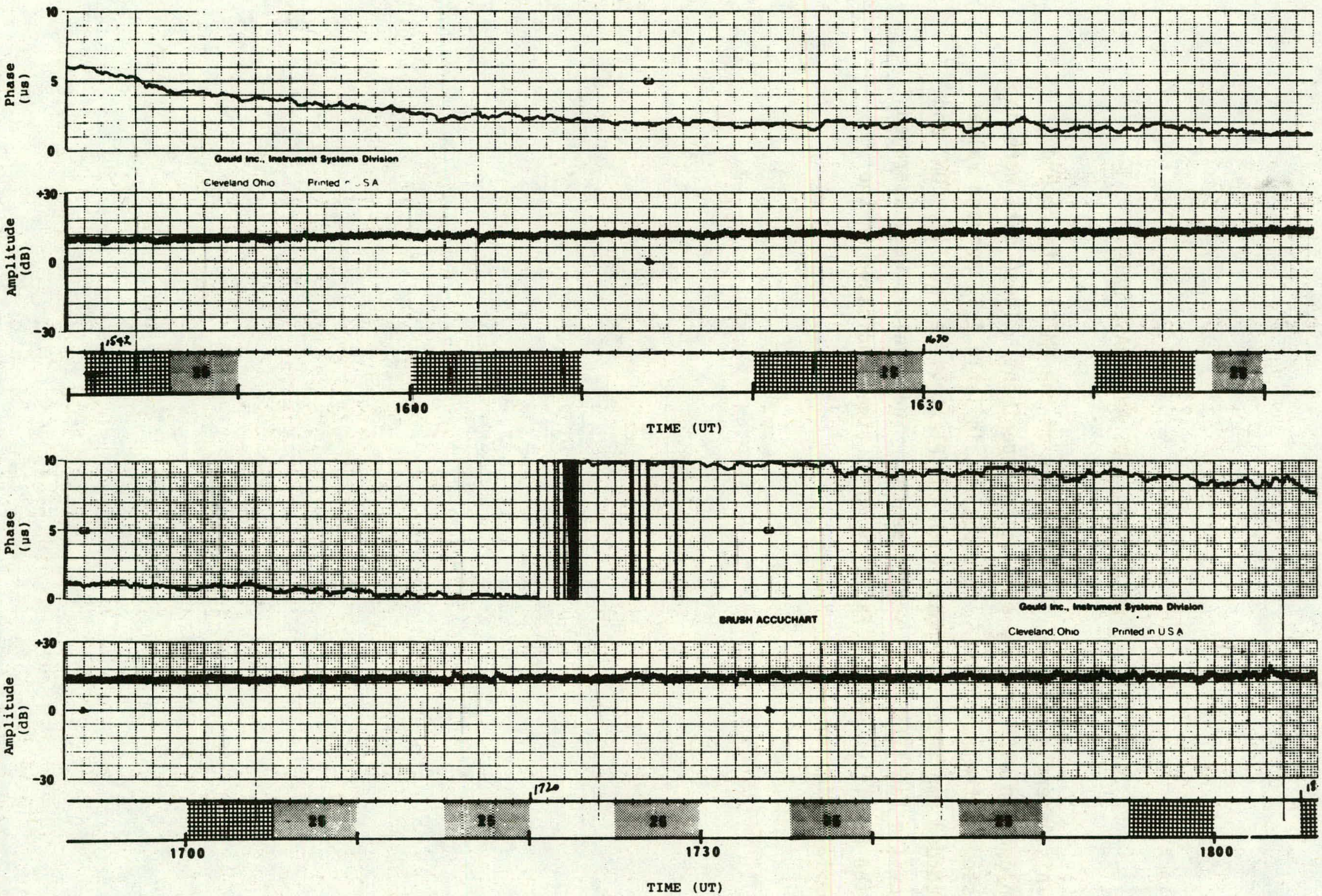


Figure A-1. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 17, 1979.

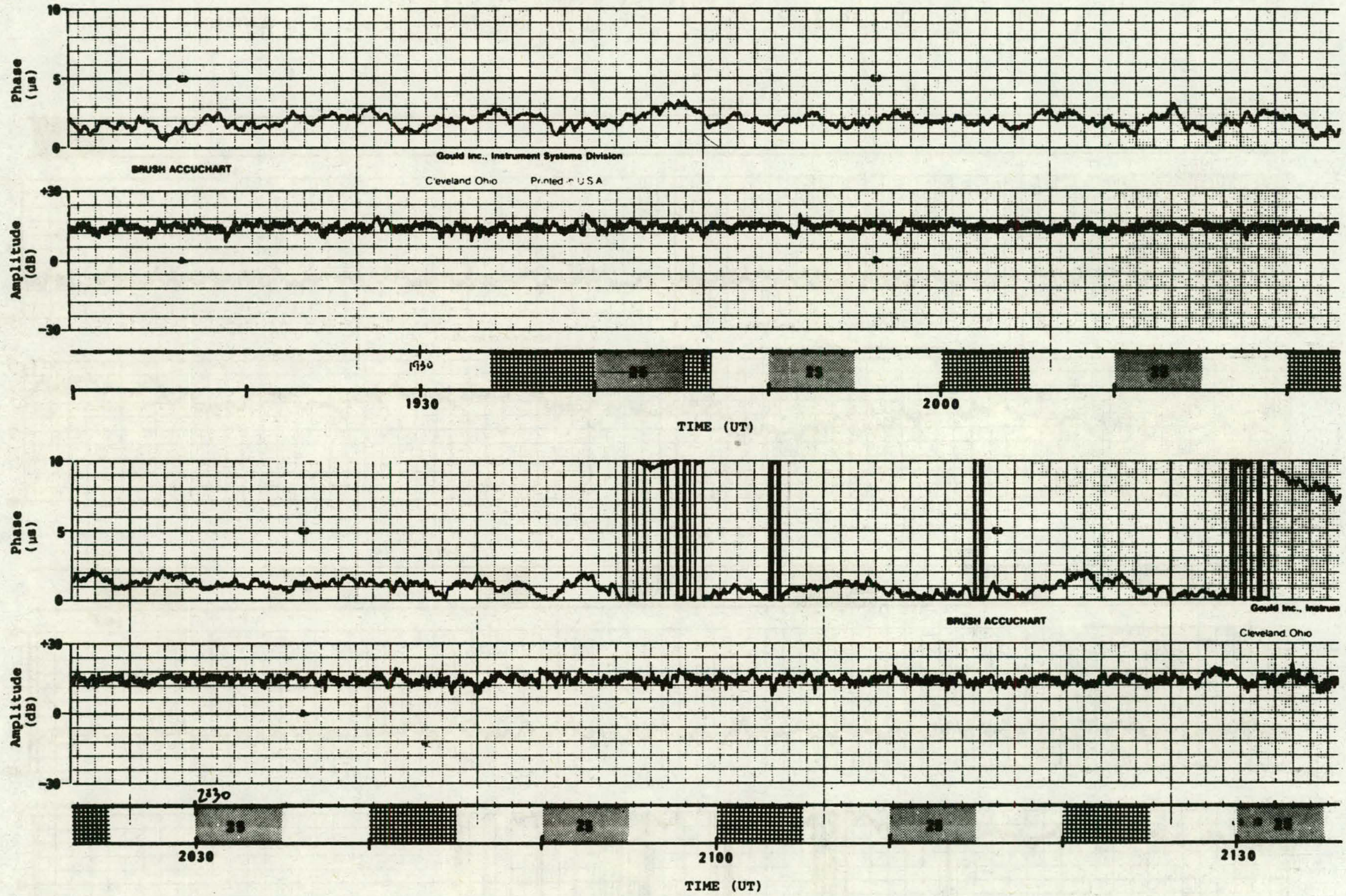


Figure A-2. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 19, 1979

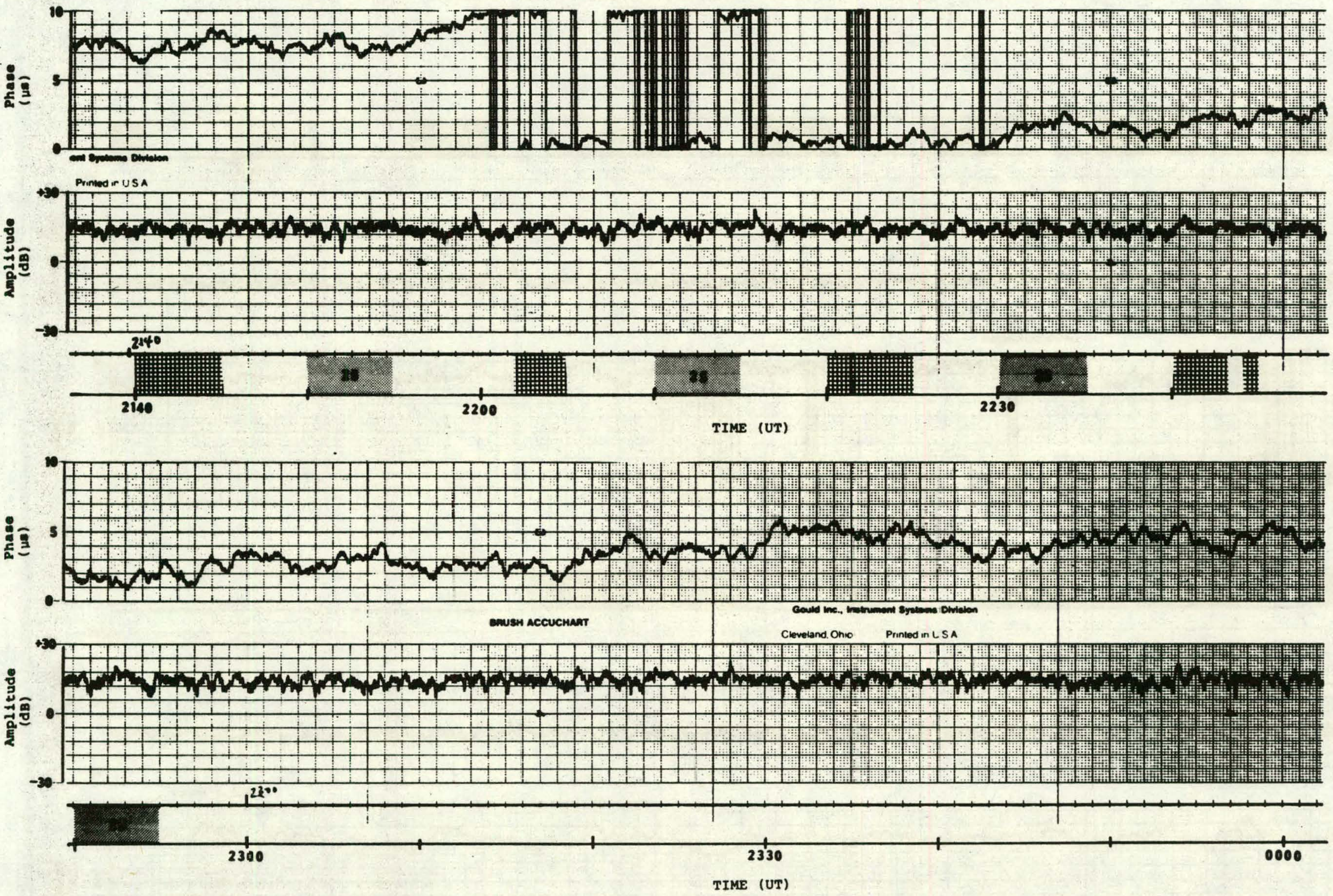


Figure A-3. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 19, 1979.

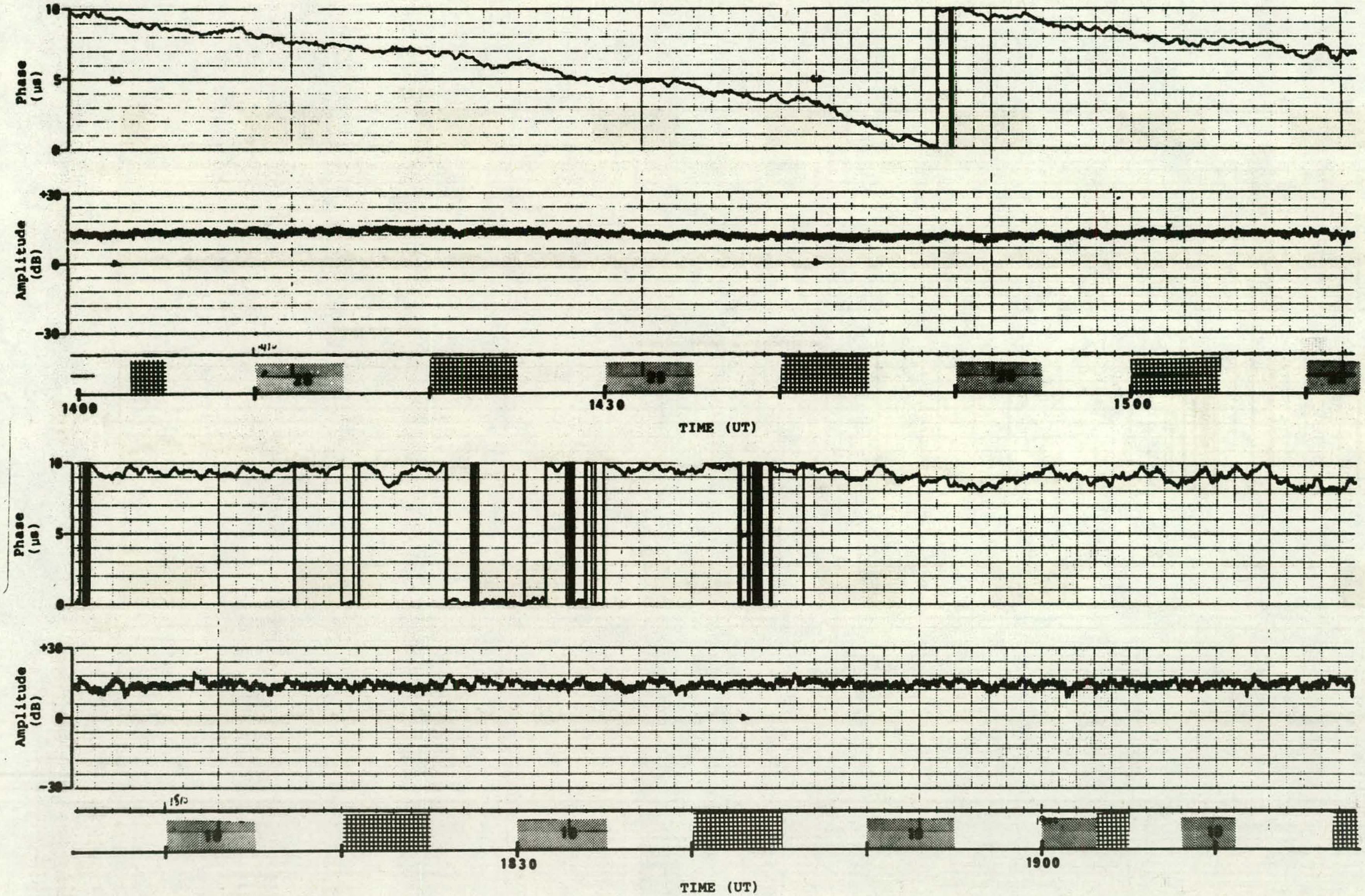


Figure A-4. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 20, 1979.

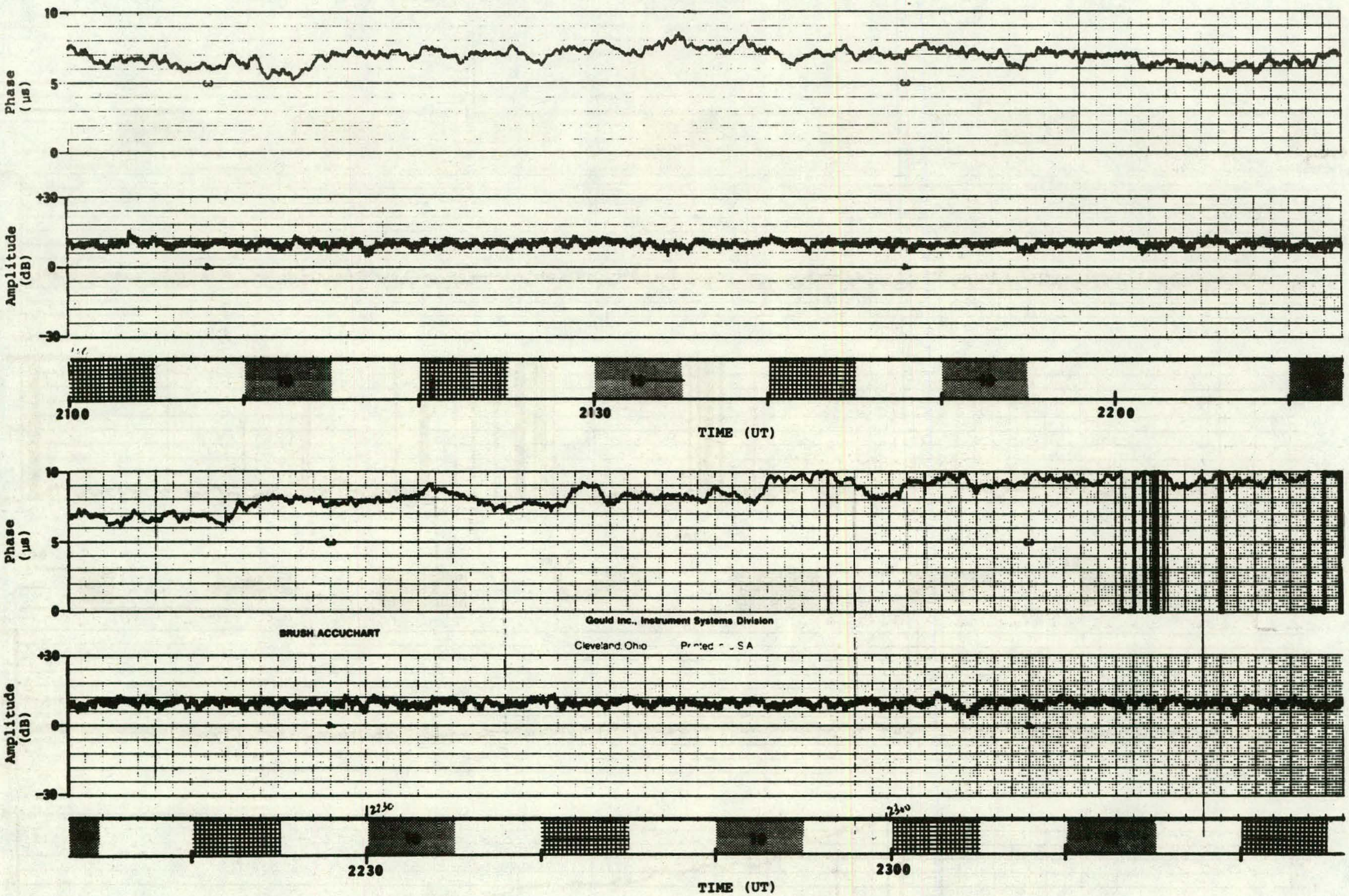


Figure A-5. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 22, 1979.

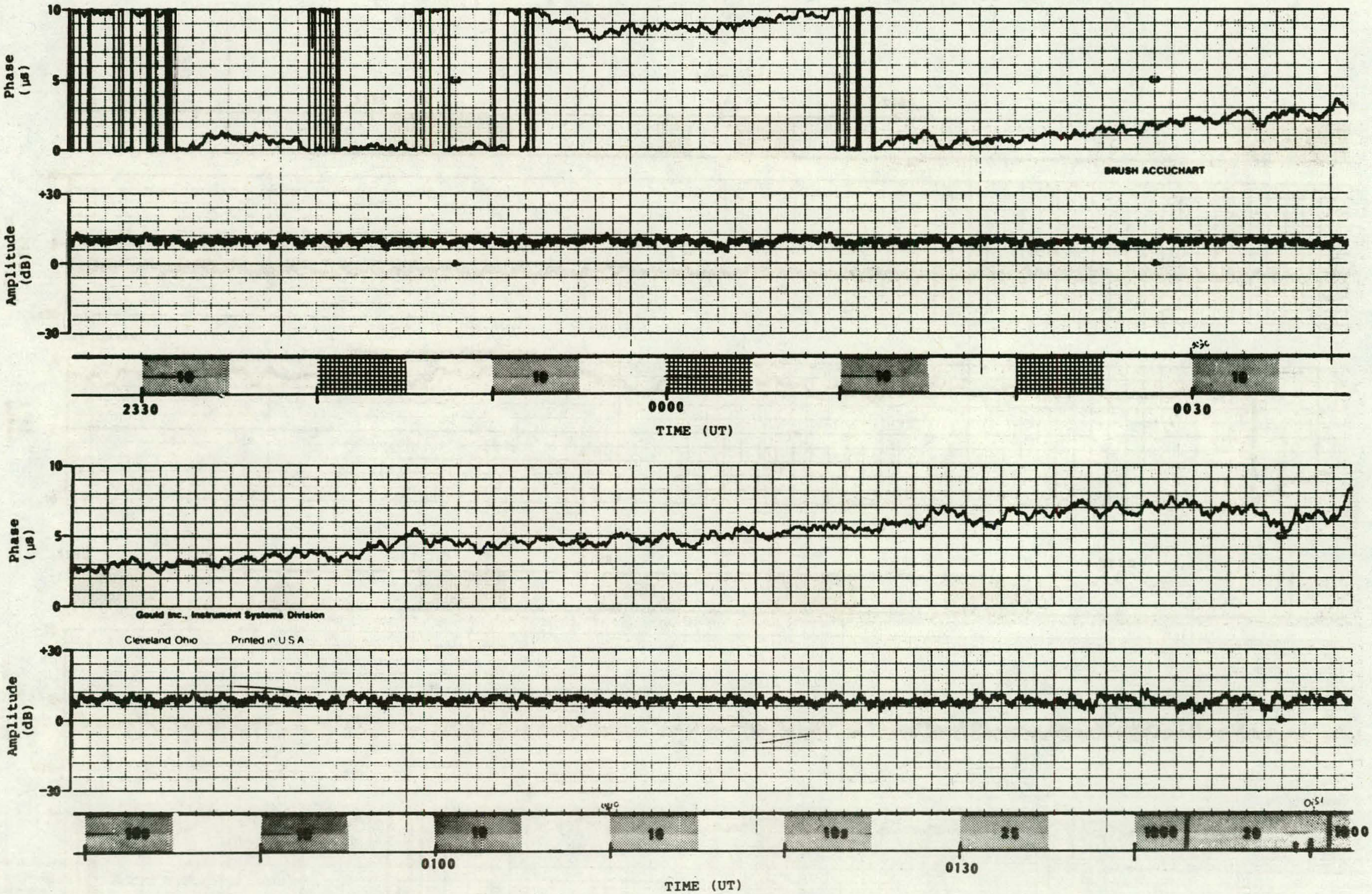


Figure A-6. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 22, 1979.

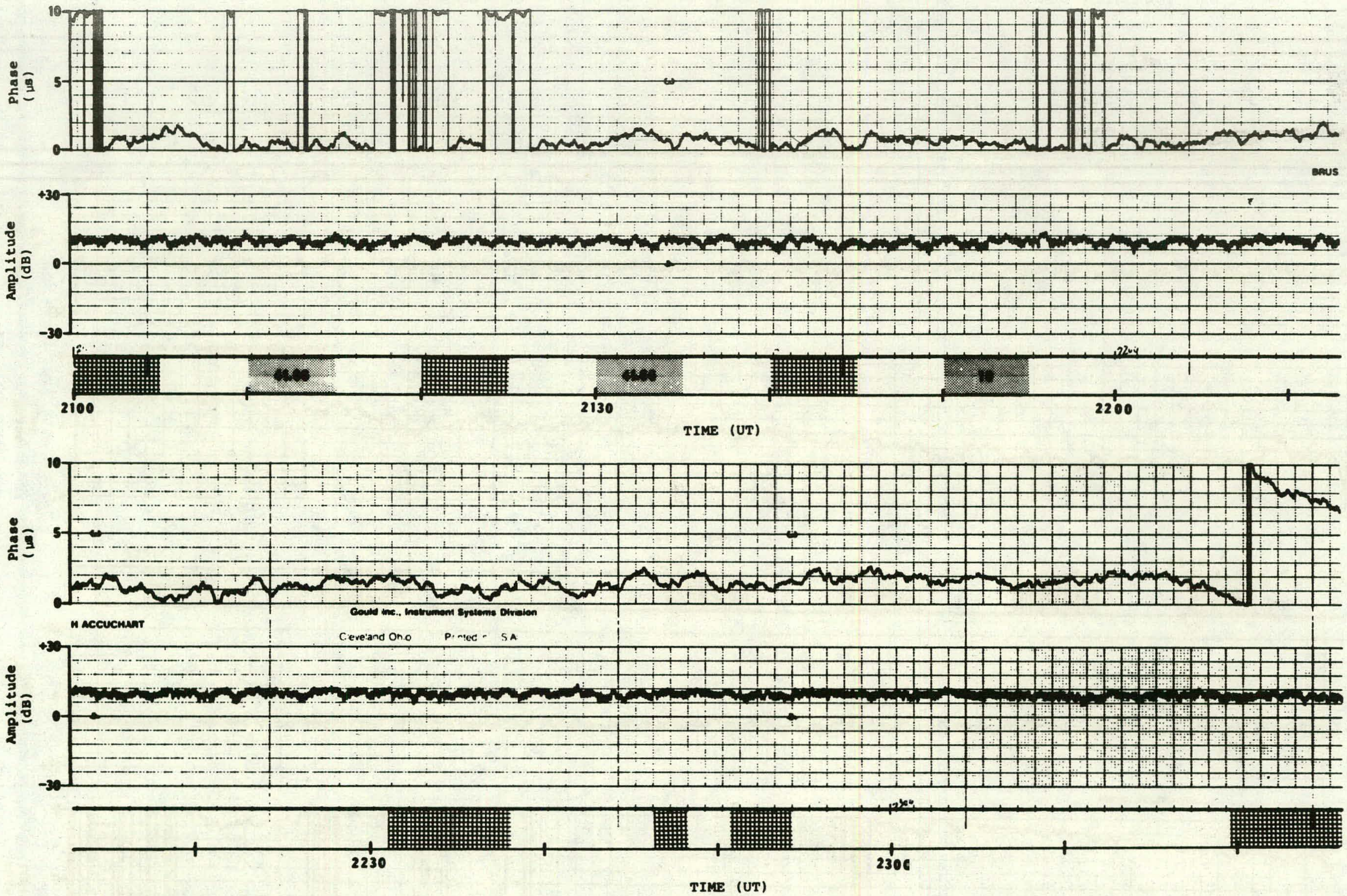


Figure A-7. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 23, 1979.

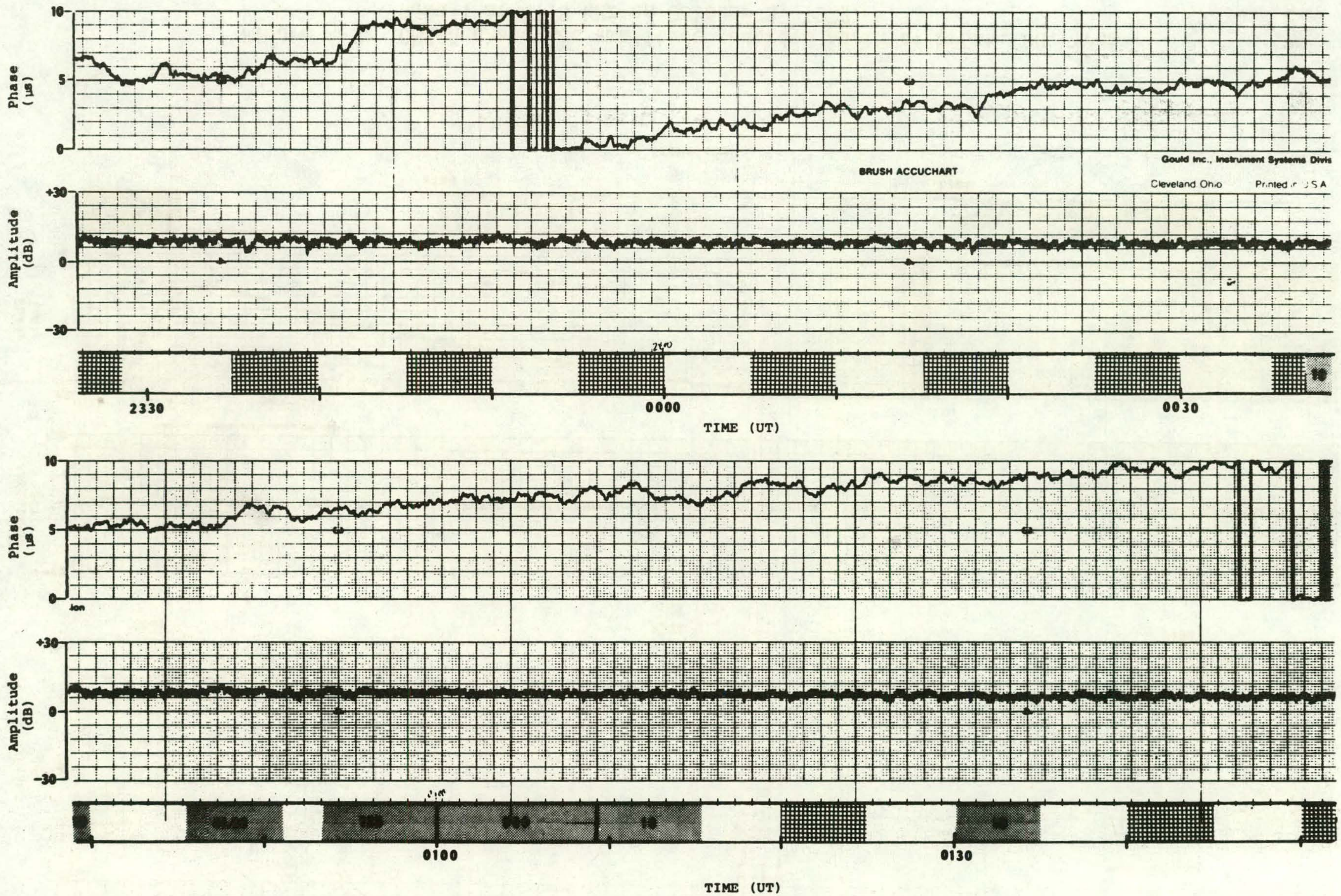


Figure A-8. OMEGA phase and amplitude recorded at Brush, CO, from Hawaii at 11.8 kHz on August 23, 1979

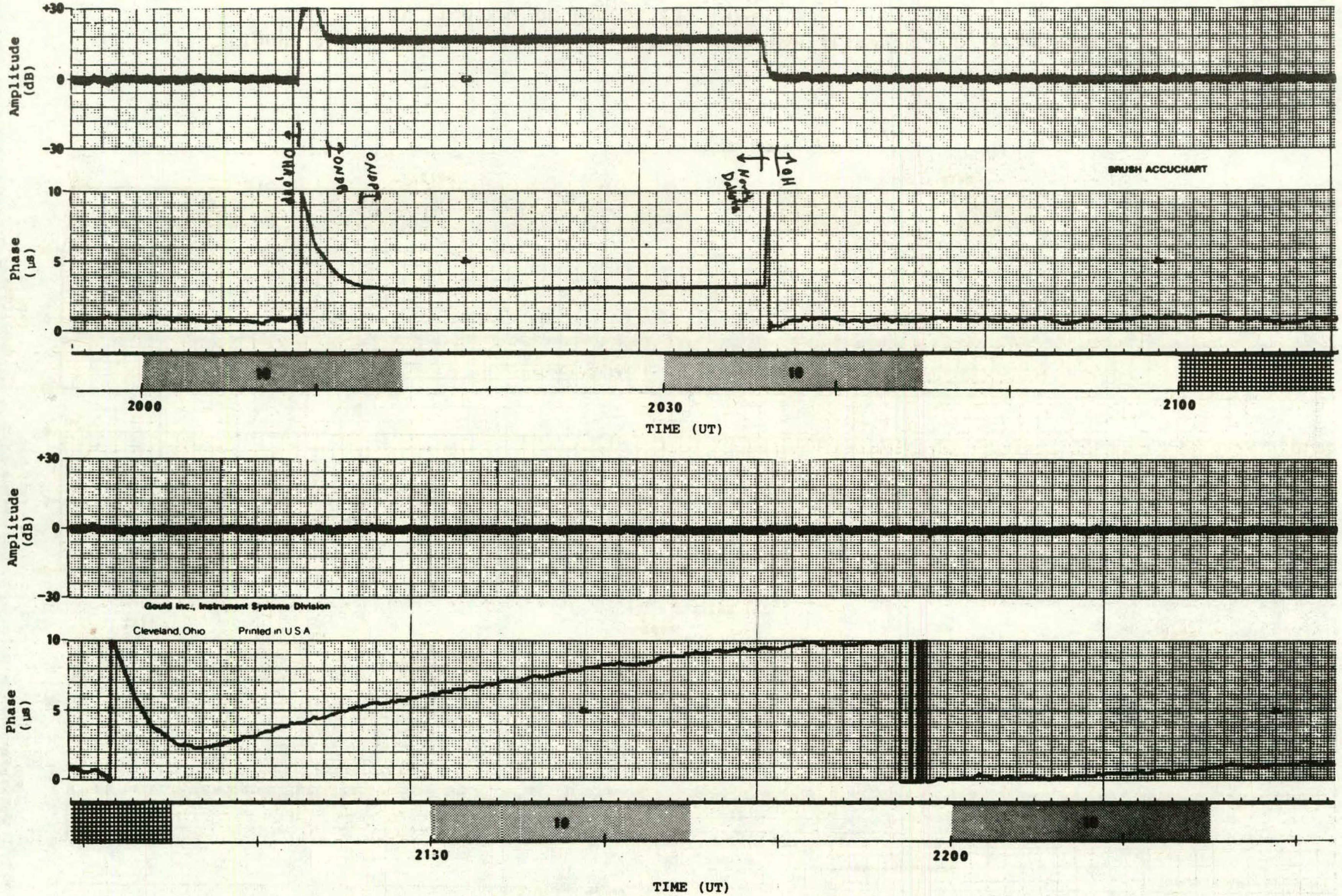


Figure A-9. OMEGA phase and amplitude recorded north of Brush, CO, from Hawaii at 11.8 kHz on October 3, 1979.

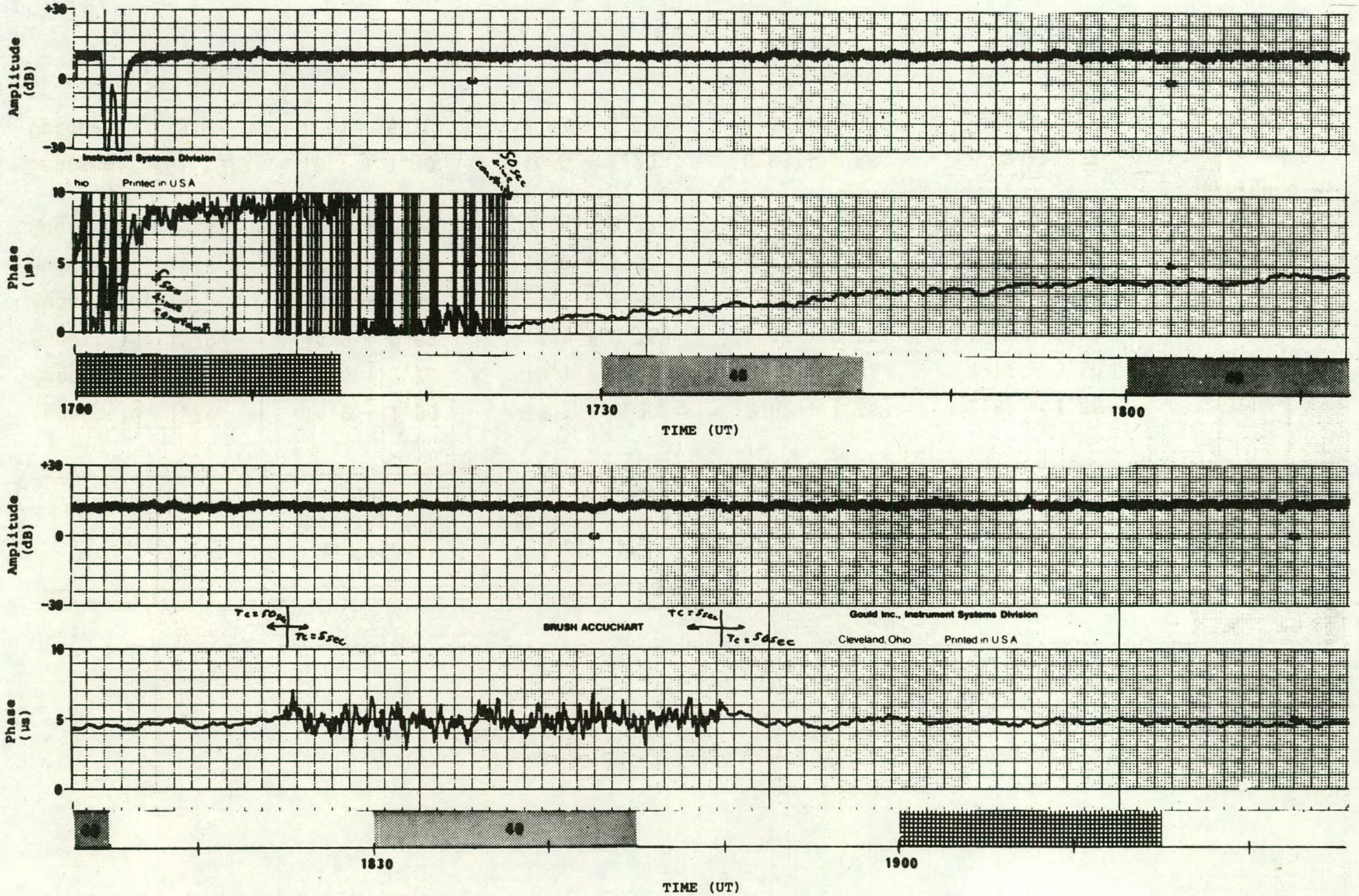


Figure A-10. OMEGA phase and amplitude recorded west of Brush, CO, from Hawaii at 11.8 kHz on October 4, 1979.

Table A. 1. Average Values of OMEGA Amplitude and Phase Recorded During Times of Platteville Facility "ON" and "OFF"

Date	Amplitude Facility "ON" (dB)	Amplitude Facility "OFF" (dB)	Phase Facility "ON" (μs)	Phase Facility "OFF" (μs)	References Figures
August 16, 1979	14.9 ± 1.30	15.1 ± 0.90	3.82 ± 1.54	2.82 ± 1.45	Figure 3
August 17, 1979	12.4 ± 2.72	13.1 ± 3.07	4.05 ± 3.33	4.17 ± 3.50	A.1.
August 19, 1979	14.9 ± 0.59	14.9 ± 0.76	2.35 ± 2.07	3.10 ± 1.89	A.2. & A.3.
August 20, 1979	13.8 ± 1.34	14.1 ± 1.50	7.05 ± 2.38	8.00 ± 1.70	A.1.
August 22, 1979	9.7 ± 1.83	10.0 ± 1.51	6.28 ± 2.14	6.02 ± 2.28	A.5. & A.6.
August 23, 1979	9.39 ± 1.69	9.08 ± 1.83	4.59 ± 3.12	3.63 ± 2.70	A.7., A.8. & Figure 4.
September 26, 1979	16.7 ± 1.20	16.9 ± 1.20	6.93 ± 1.55	7.73 ± 1.32	Figure 5
October 3, 1979	1.54 ± 5.10	1.83 ± 5.50	2.73 ± 2.88	2.56 ± 2.54	Figures 7 & A.9.

APPENDIX B. LORAN-C AMPLITUDE AND PHASE

This Appendix provides illustrations of the LORAN-C data recorded in conjunction with the SPS simulation experiment. These data were not discussed in the main text. In addition, in Table B. 1, average values of recorded amplitude and phase with the Platteville Facility "ON" and Platteville Facility "OFF" are presented. These values were averaged over the Facility "ON" and Facility "OFF" times indicated on the appropriate figures.

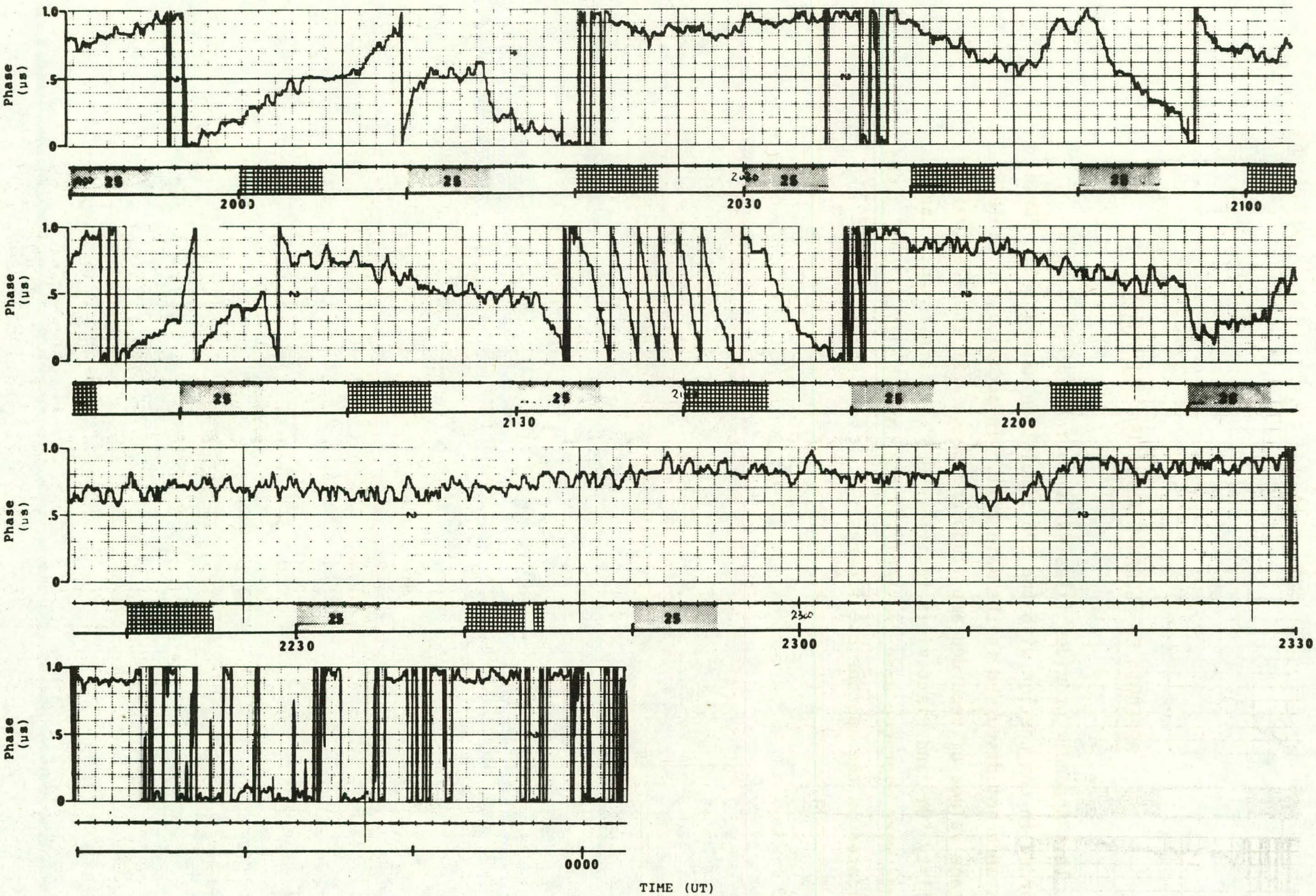


Figure B-1. LORAN-C phase recorded at Brush, CO, from Fallon, NV, at 100 kHz on August 19, 1979.

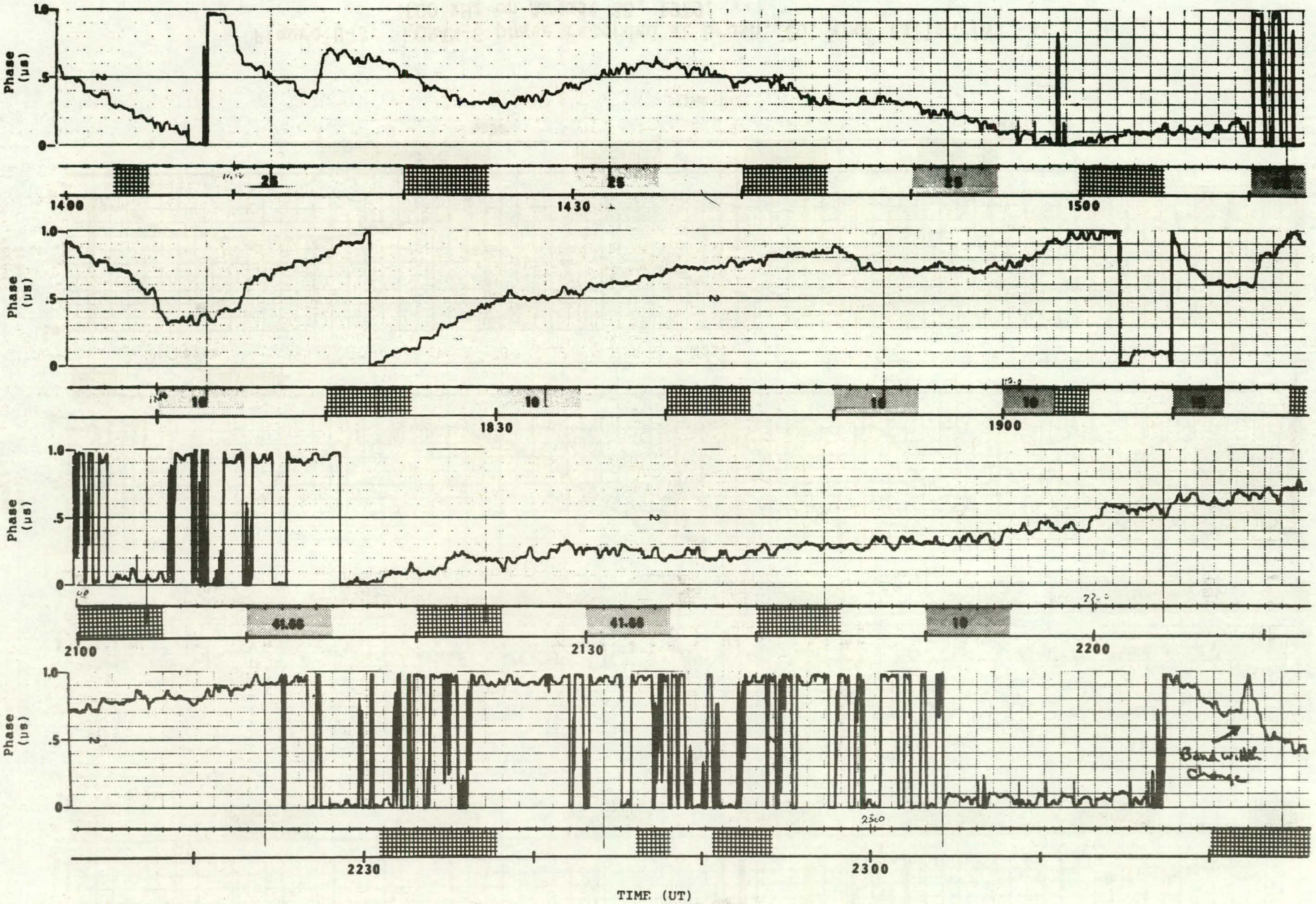


Figure B-2. LORAN-C phase recorded at Brush, CO, from Fallon, NV, at 100 kHz on August 20, 1979 (top 2 frames) and on August 23, 1979 (bottom 2 frames).

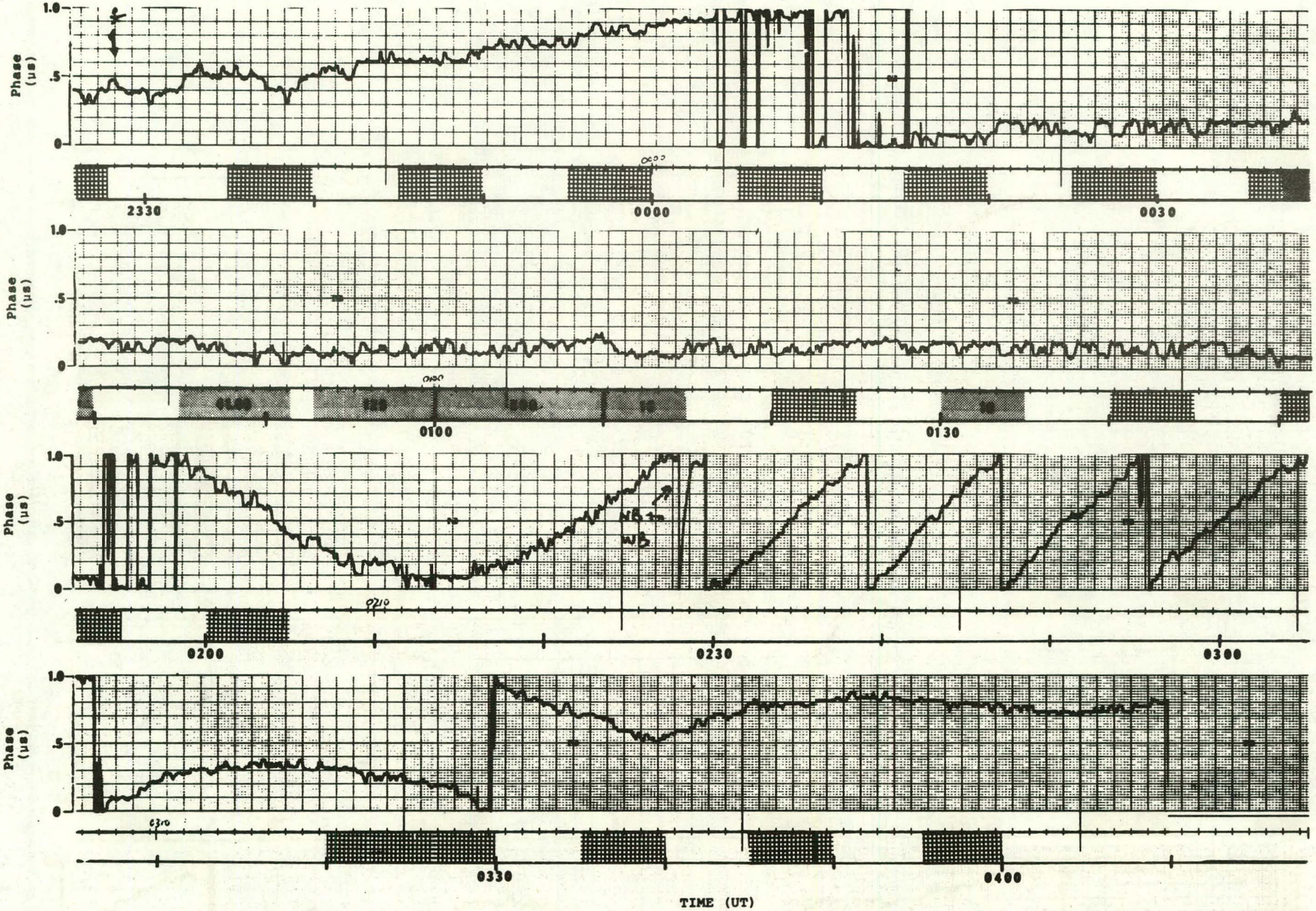


Figure B-3. LORAN-C phase recorded at Brush, CO, from Fallon, NV, at 100 kHz on August 23, 1979.

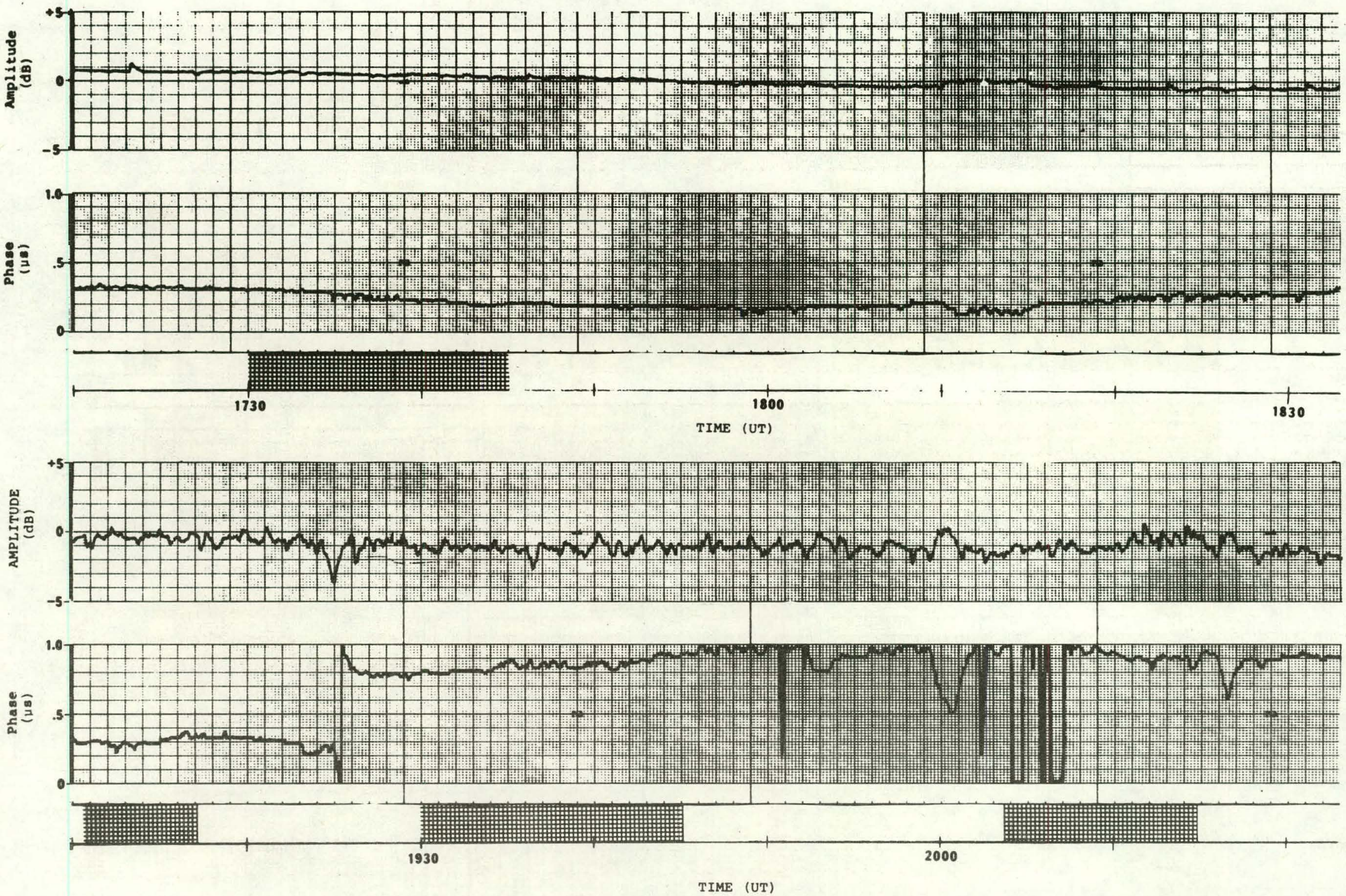


Figure B-4. LORAN-C amplitude and phase recorded south of Brush, CO from Fallon, NV, at 100 kHz on September 26, 1979.

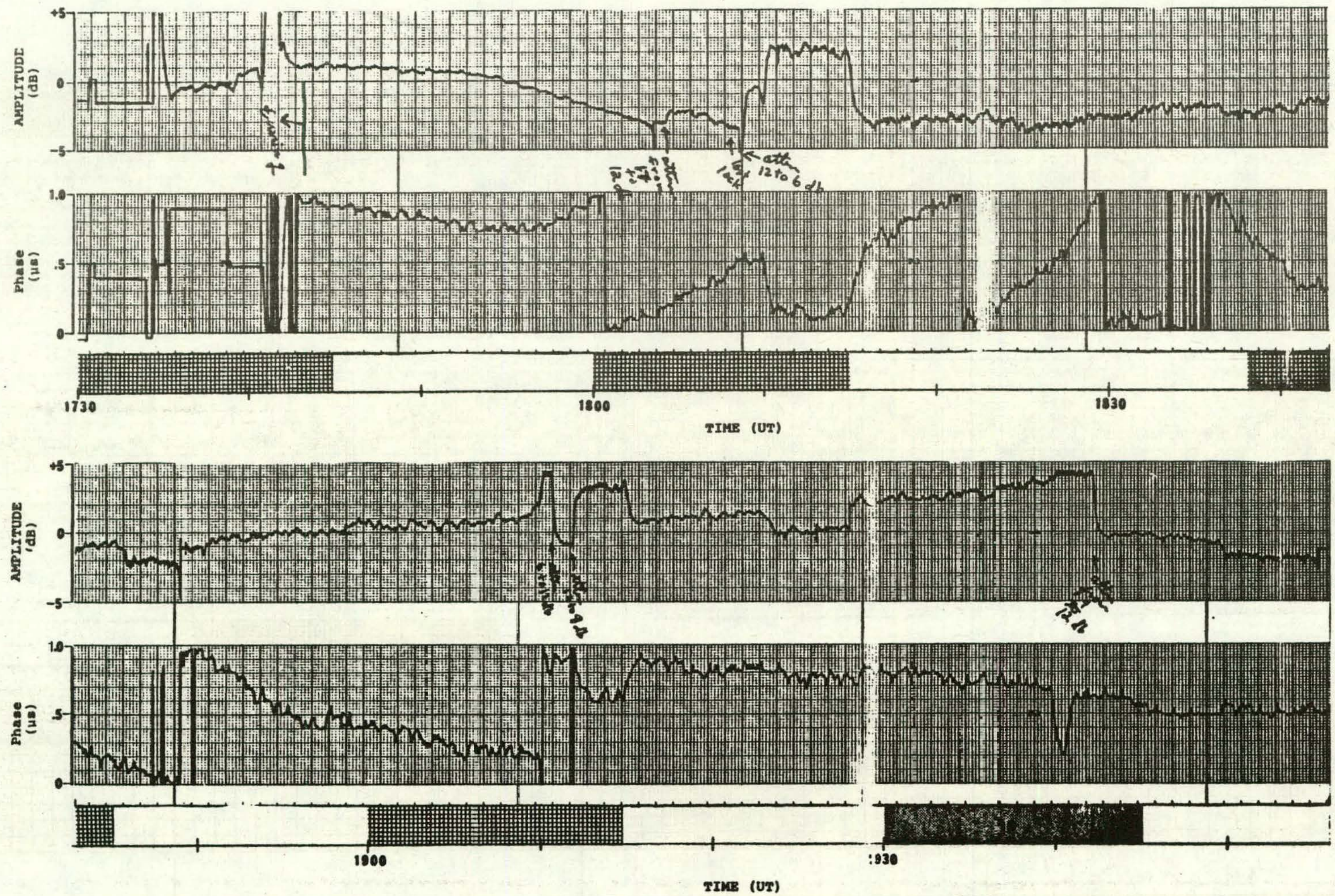


Figure B-5. LORAN-C amplitude and phase recorded north of Brush, CO, from Fallon, NV, at 100 kHz on October 3, 1979.

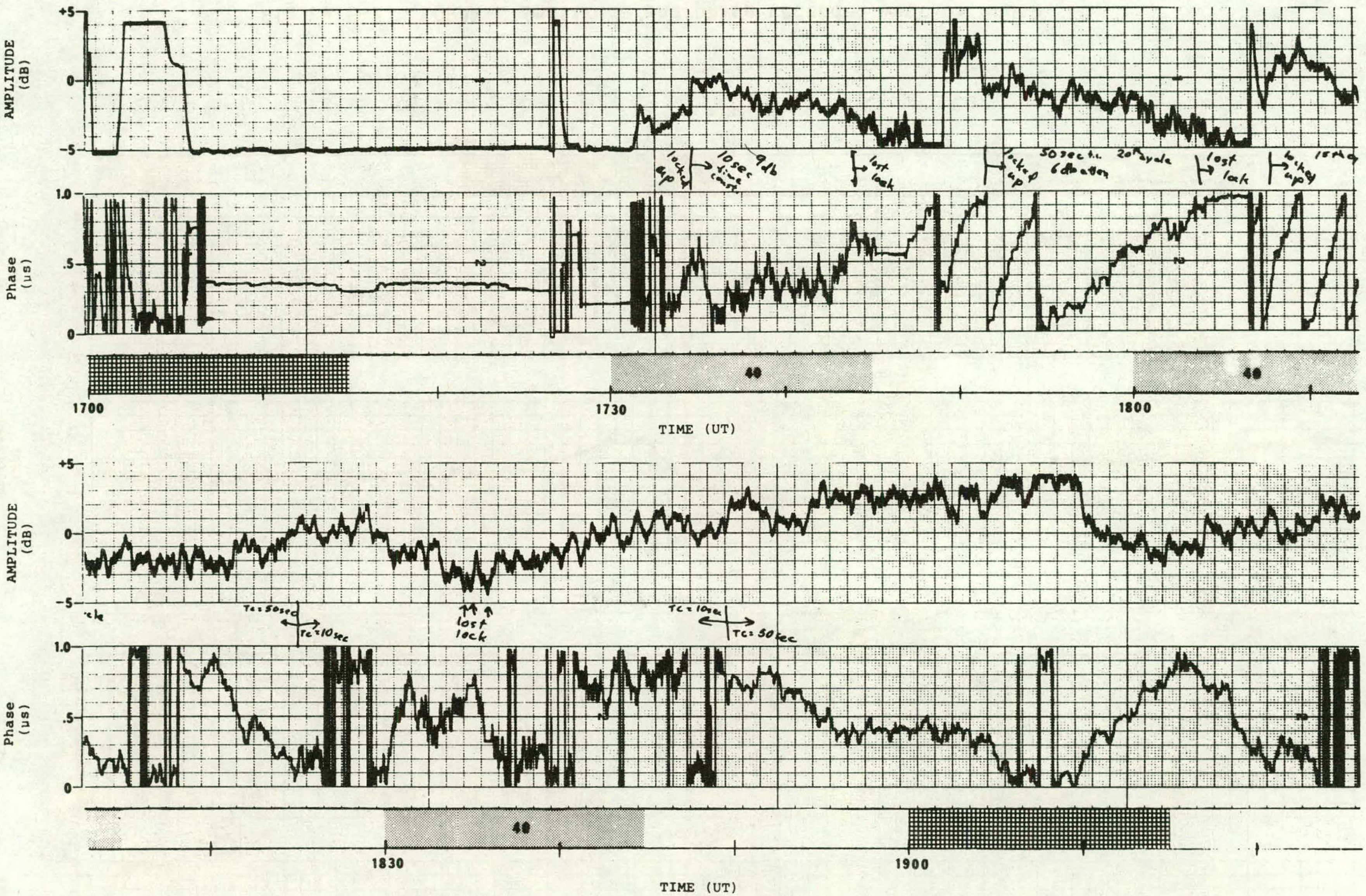


Figure B-6. LORAN-C amplitude and phase recorded west of Brush, CO, from Fallon, NV, at 100 kHz on October 4, 1979.

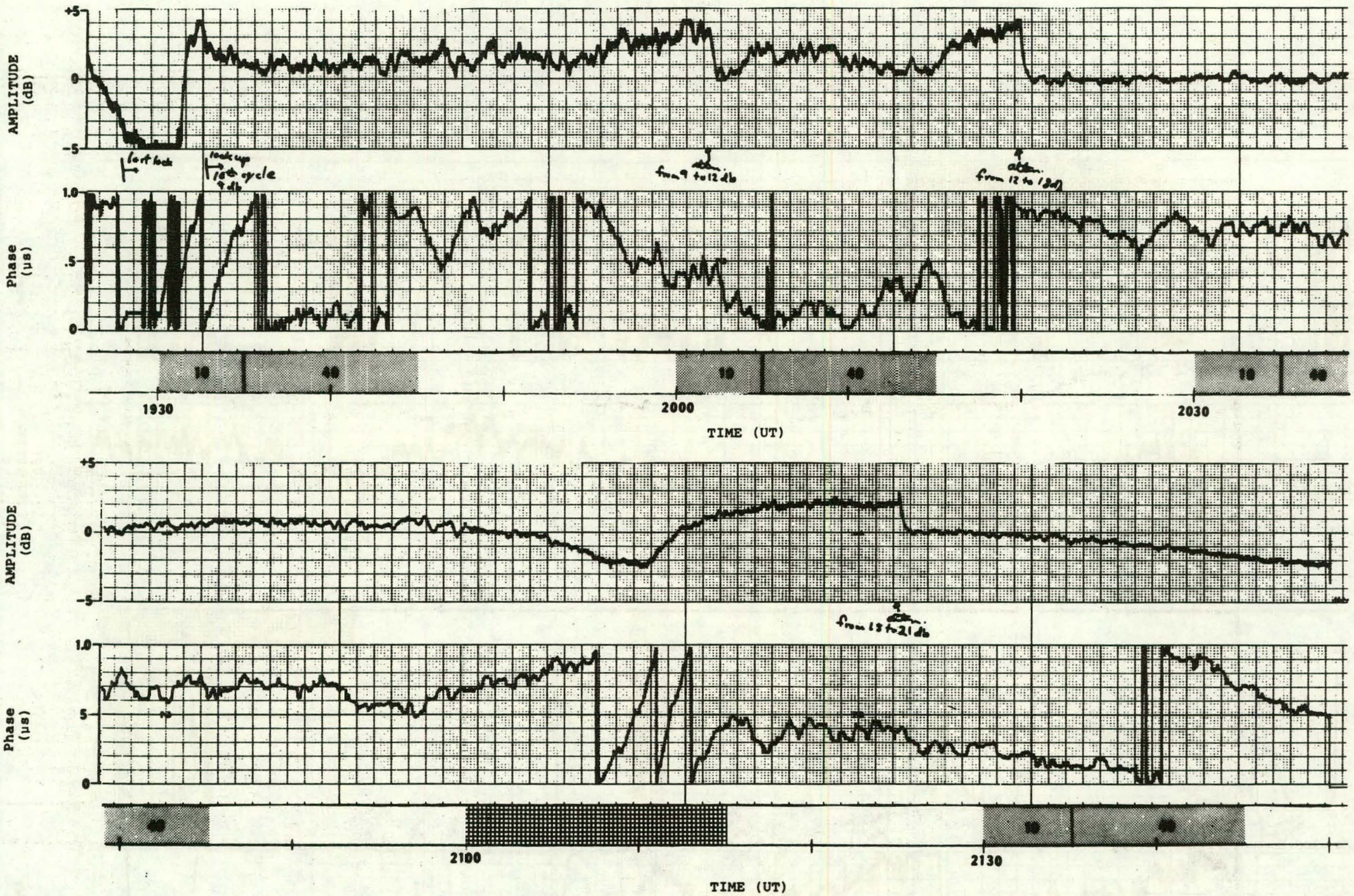


Figure B-7. LORAN-C amplitude and phase recorded west of Brush, CO, from Fallon, NV, at 100 kHz on October 4, 1979.

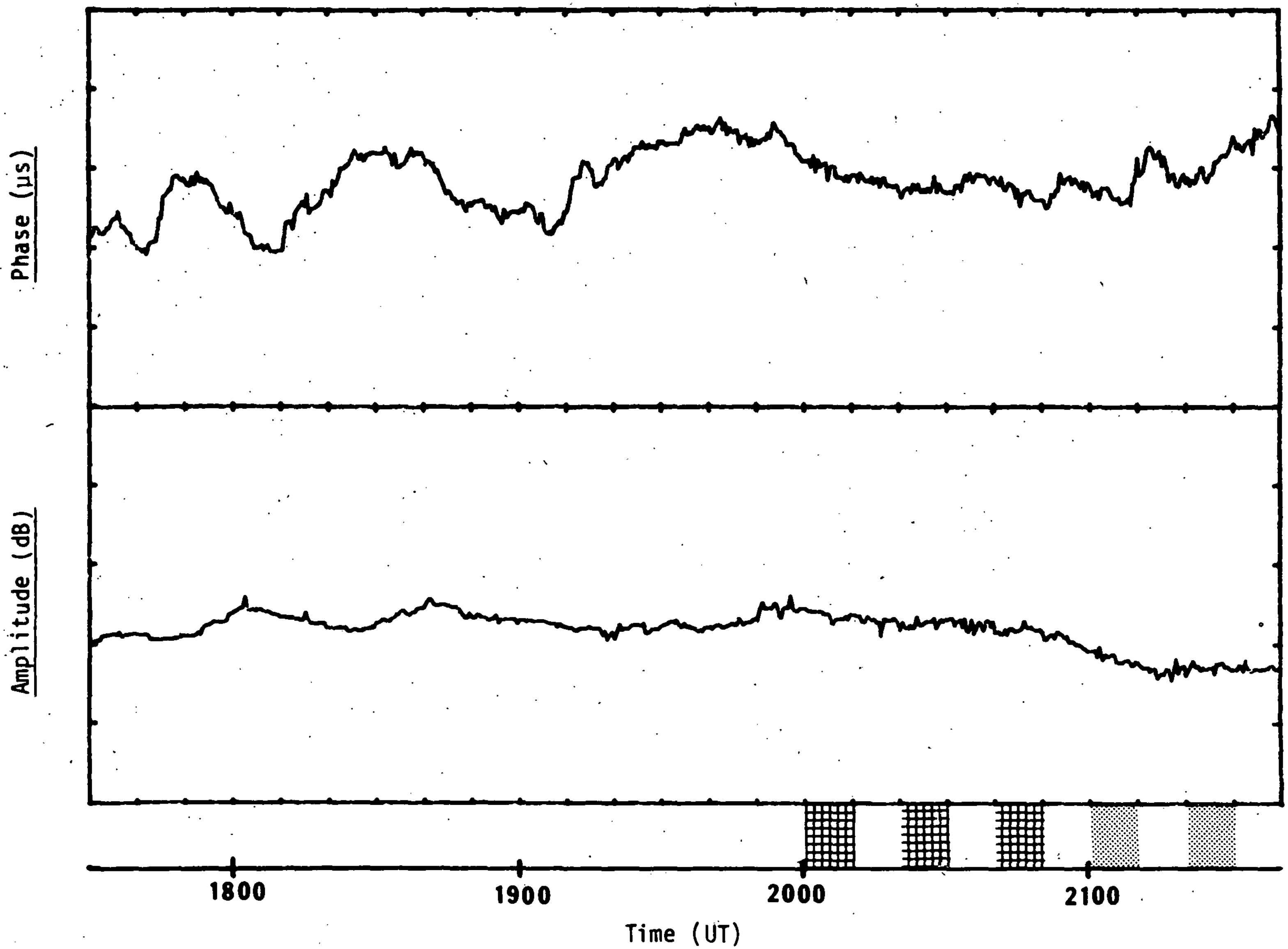


Figure B-8. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 16, 1979.

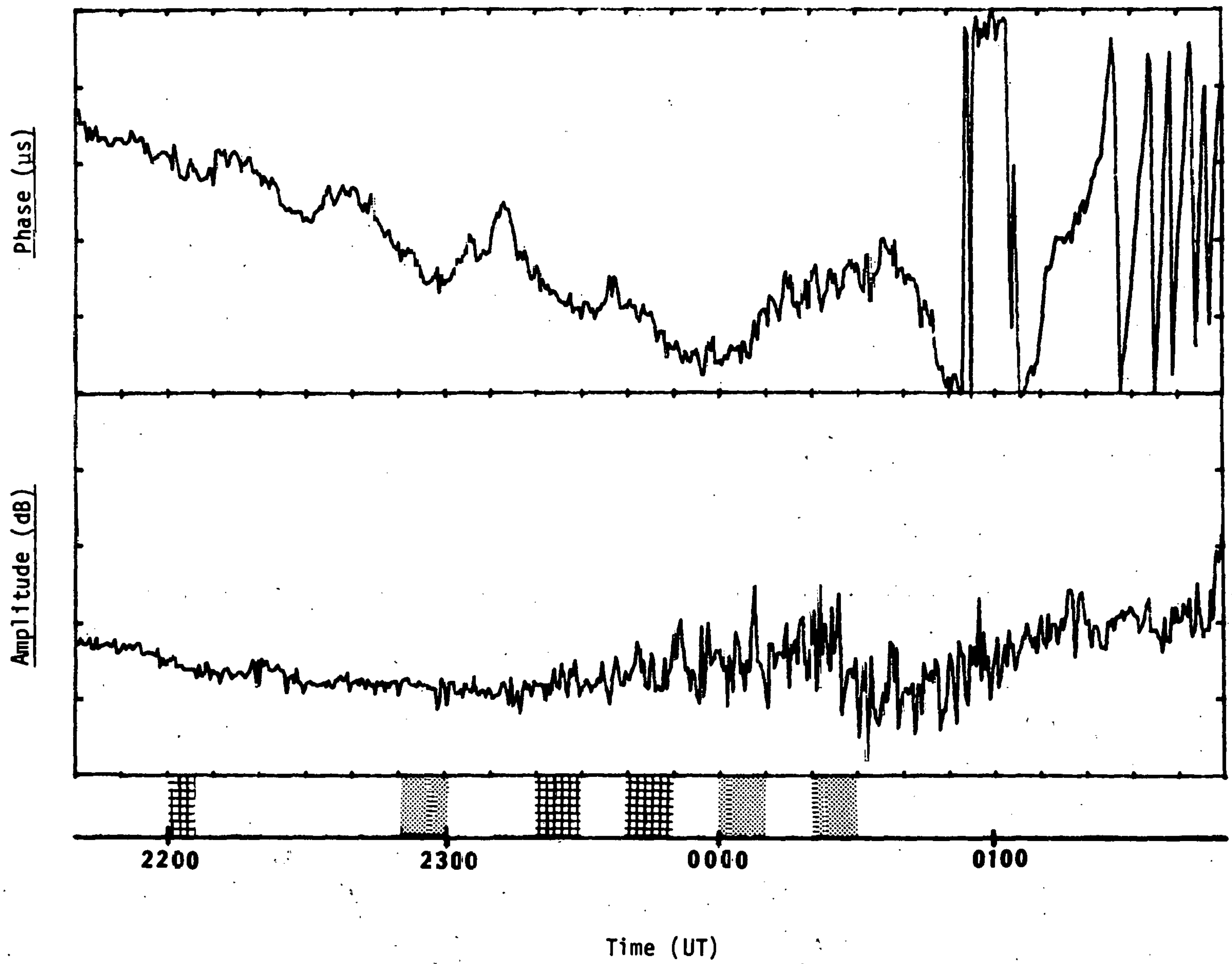


Figure B-9. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 16, 1979.

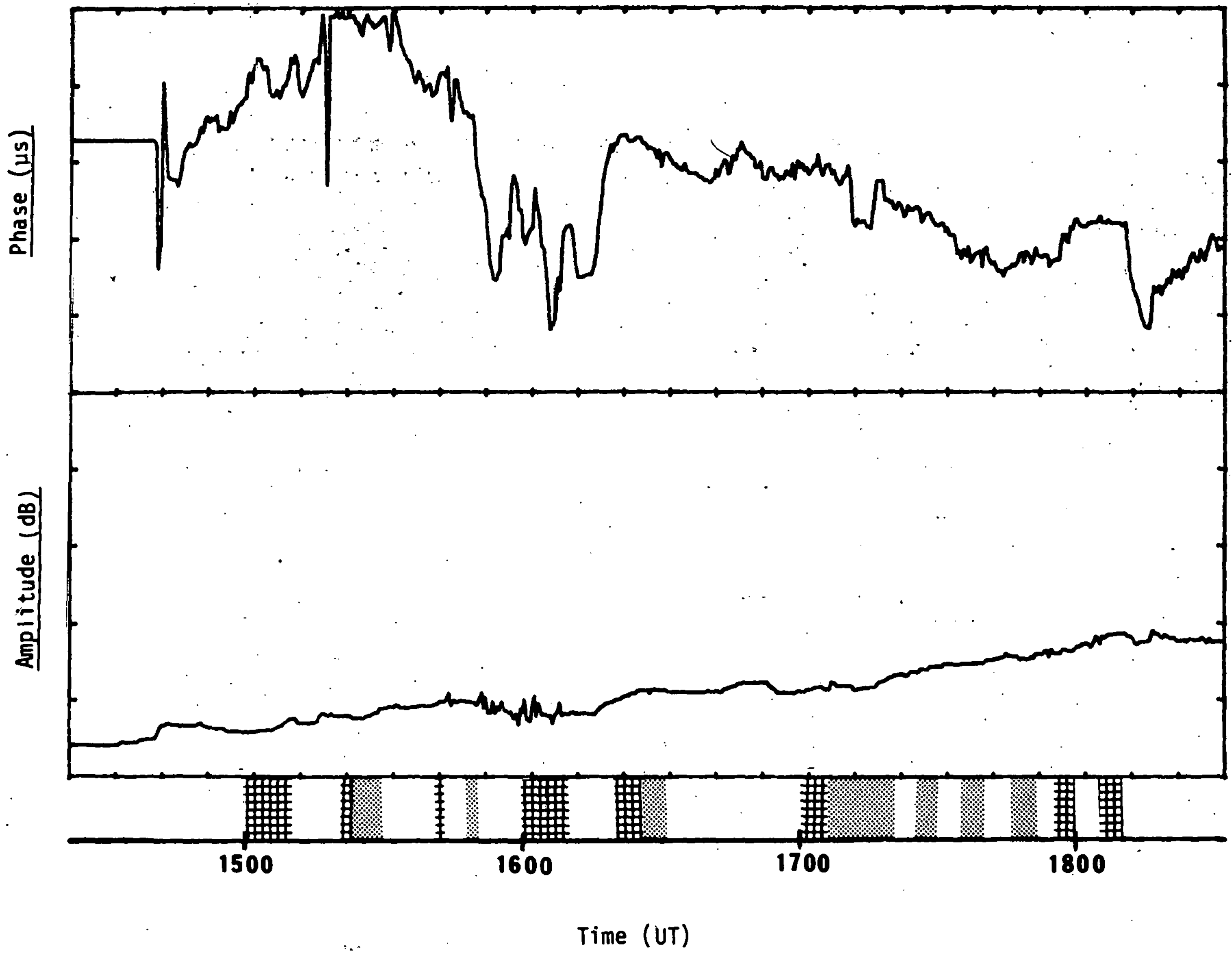


Figure B-10. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 17, 1979.

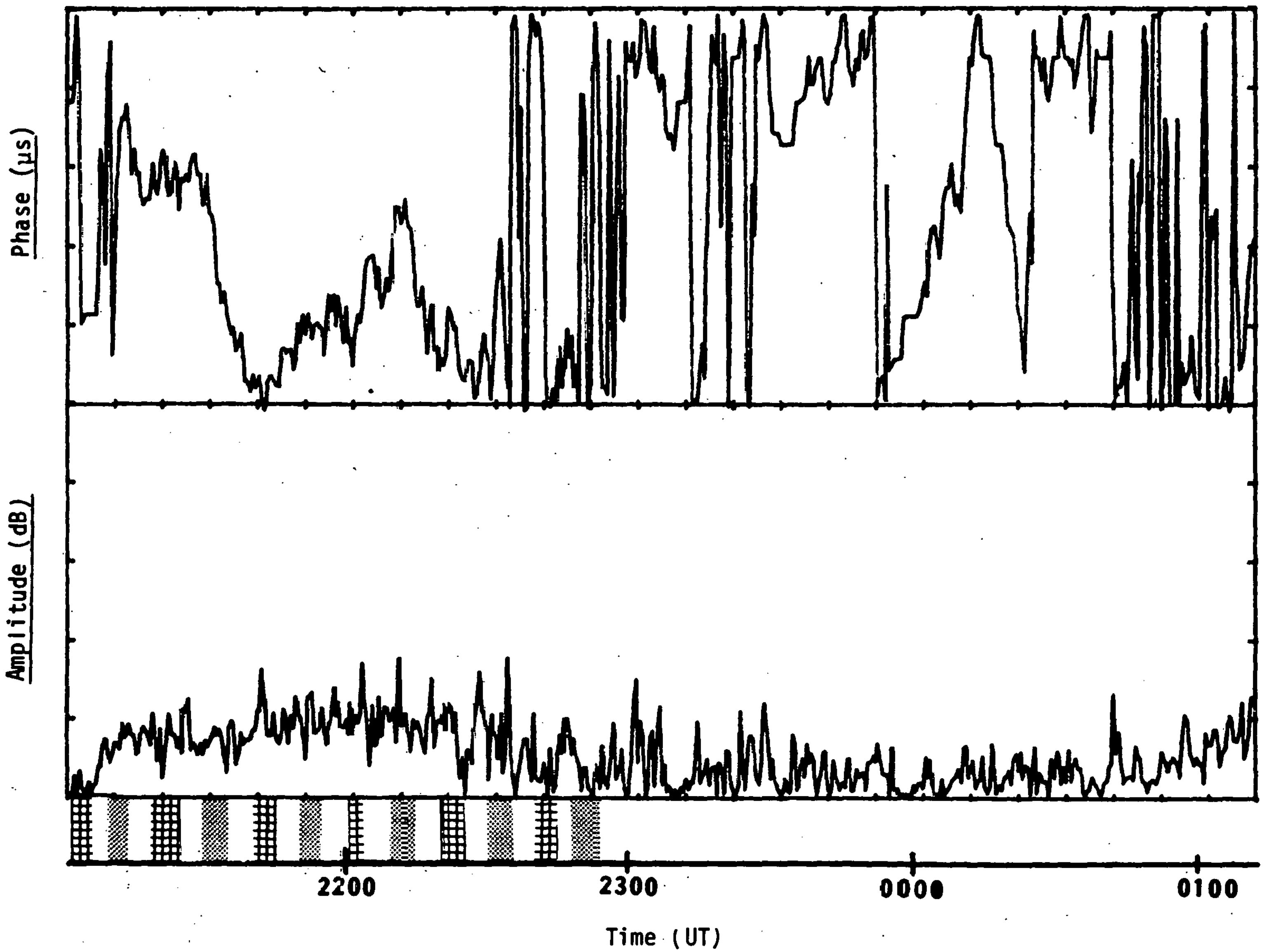


Figure B-1. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 19, 1979.

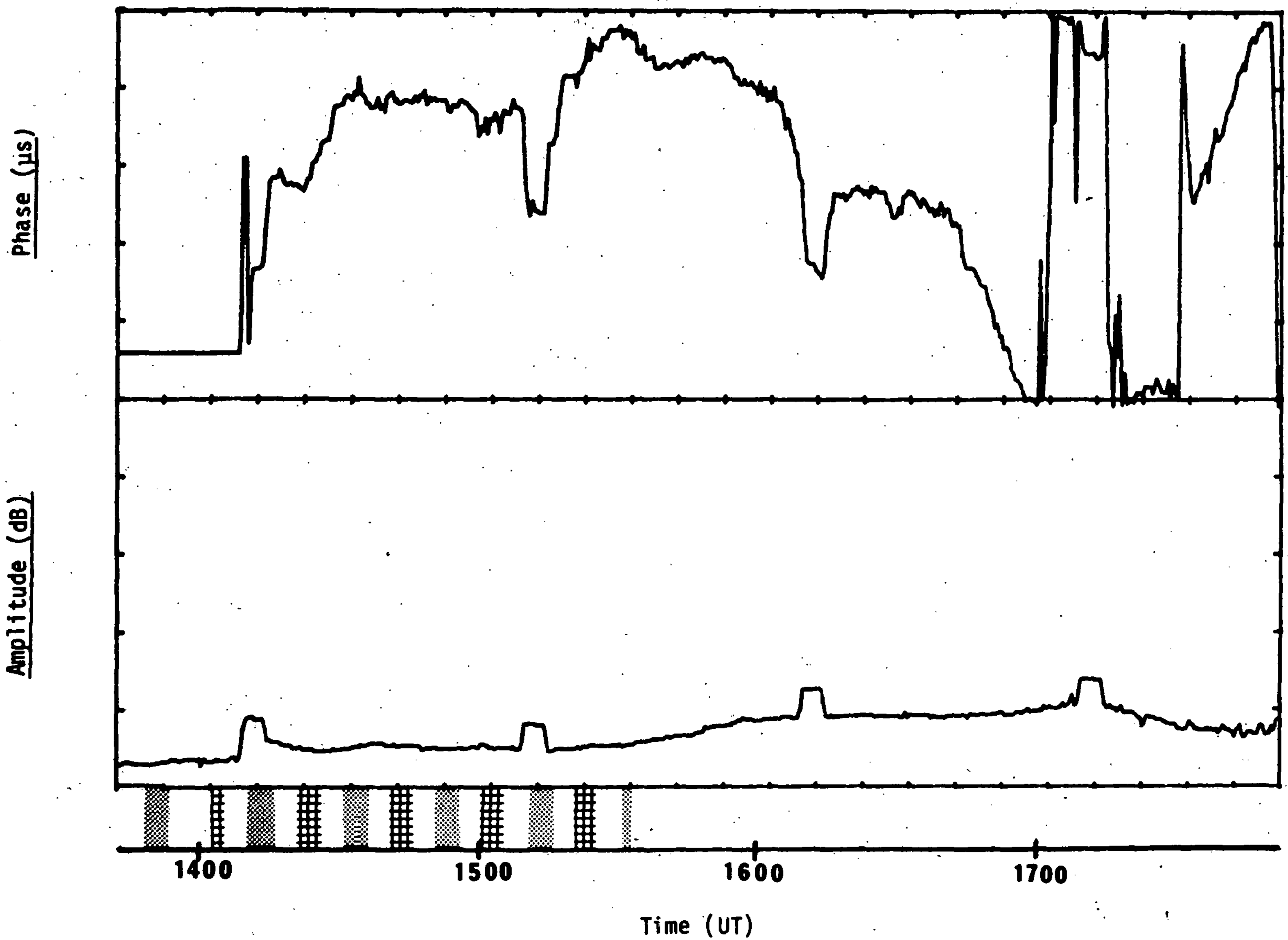


Figure B-12. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 20, 1979.

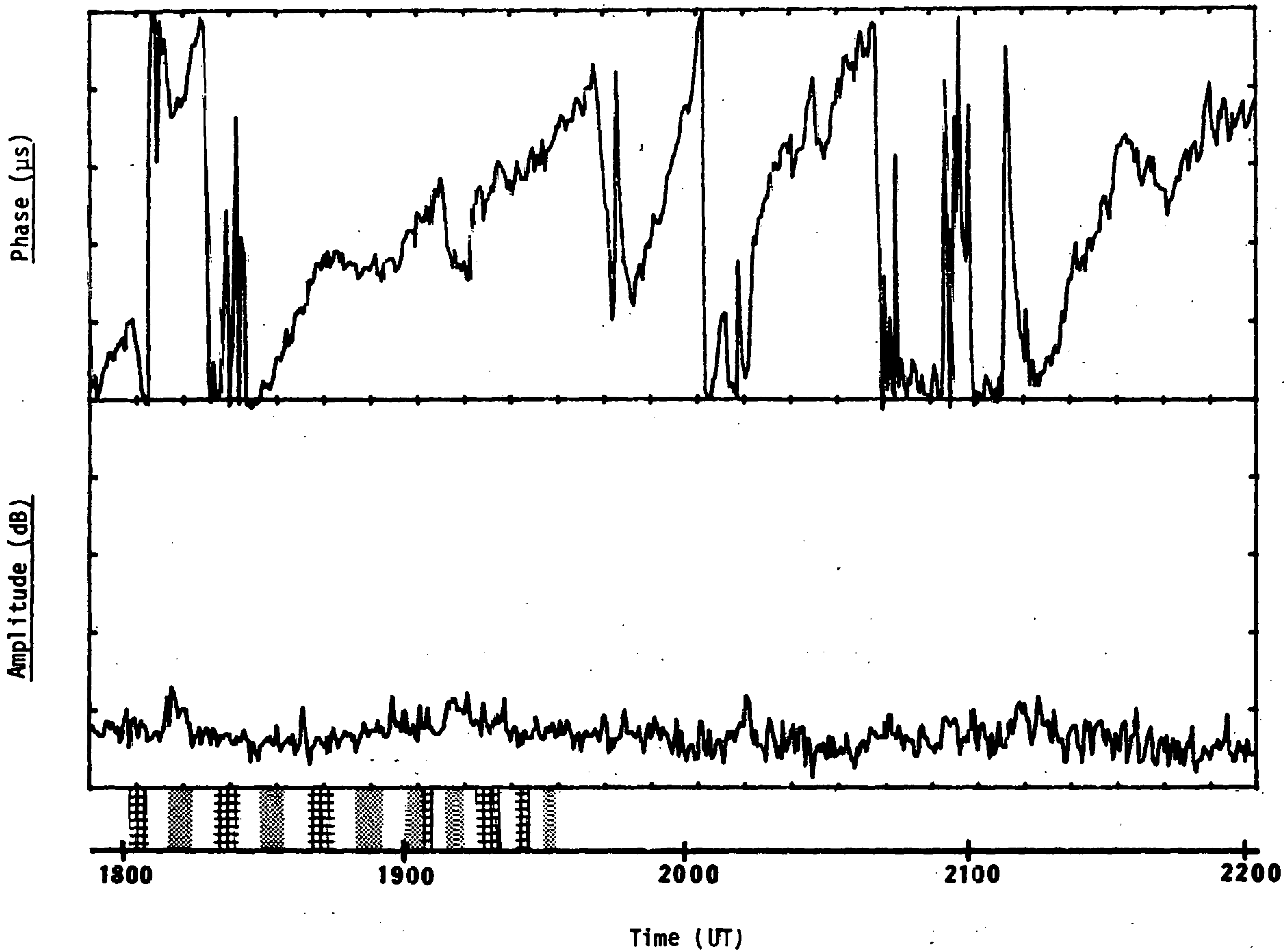


Figure B-13. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 20, 1979.

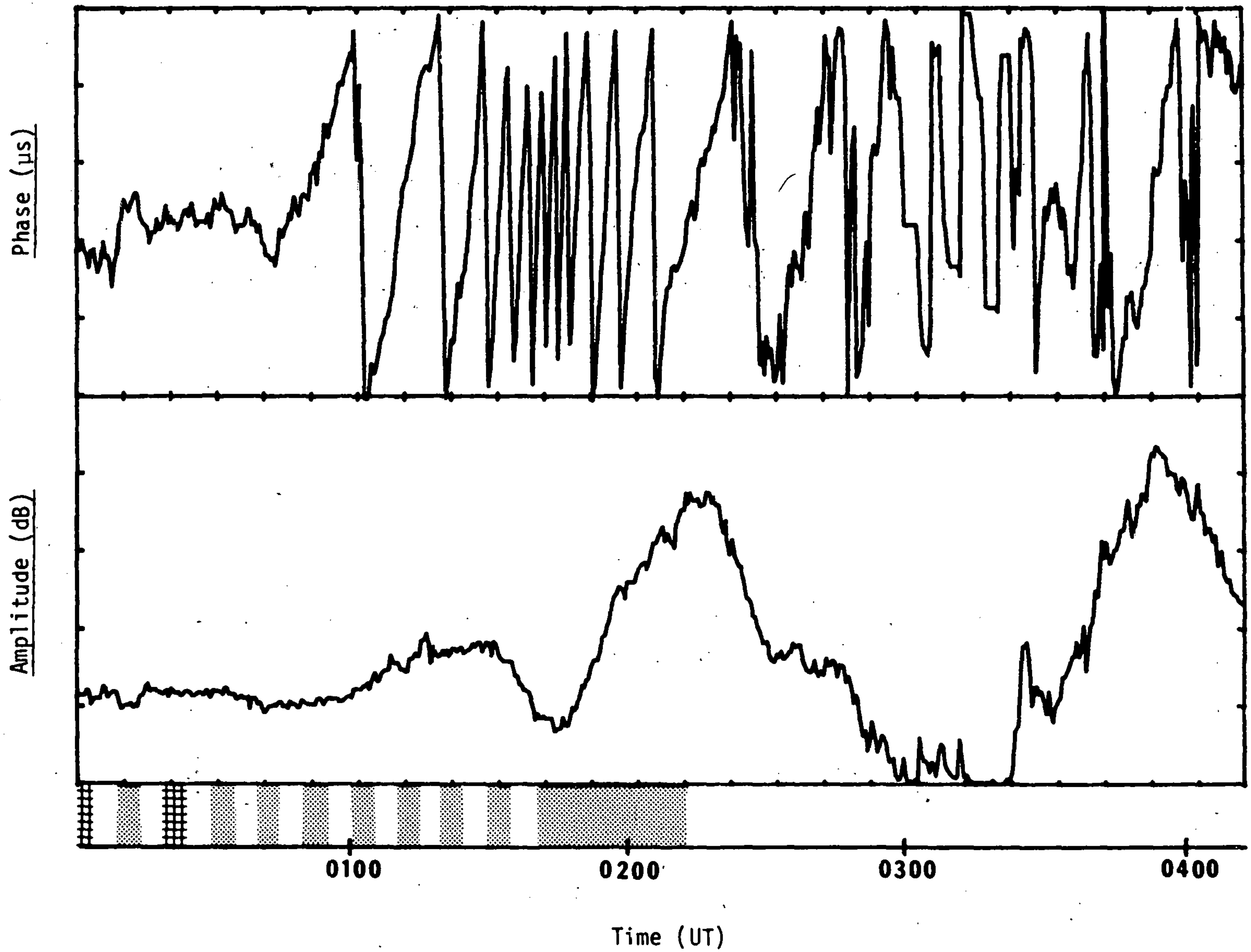


Figure B-14. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 22, 1979.

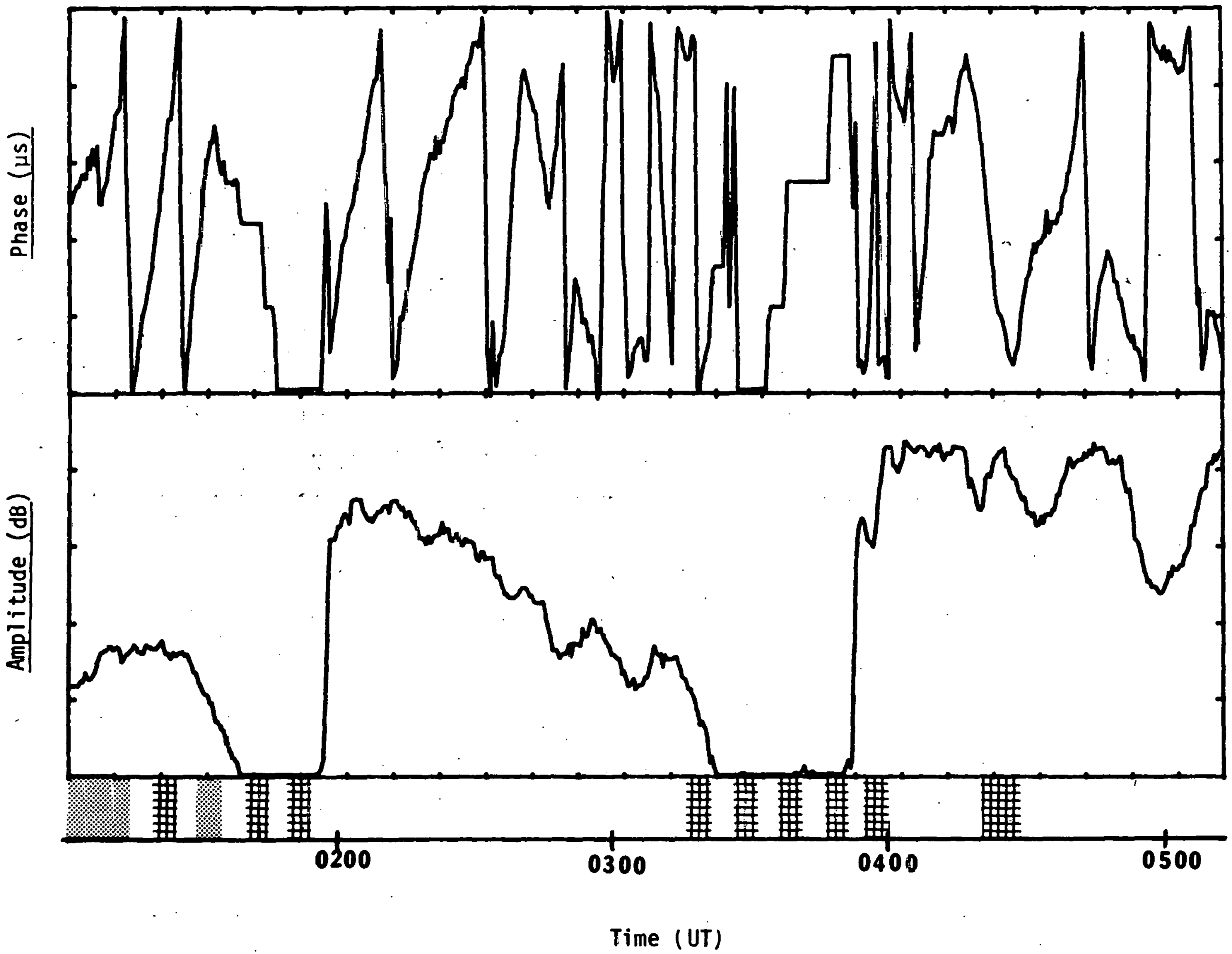


Figure B-15. LORAN-C phase and amplitude recorded at Boulder, CO, from Dana, IN, at 100 kHz on August 23, 1979.

Table B.1. Average Values of LORAN-C Phase and Amplitude Data Recorded During Times of Platteville Facility "ON" and "OFF"

Date	Phase Facility "ON" (μs)	Phase Facility "OFF" (μs)	Amplitude Facility "ON" (dB)	Amplitude Facility "OFF" (dB)	Reference Figures
August 16, 1979	0.91 ± 0.02	0.90 ± 0.04			Figure 9
August 17, 1979	0.46 ± 0.30	0.46 ± 0.26			Figure 9
August 19, 1979	0.65 ± 0.17	0.71 ± 0.12			B.1
August 20, 1979	0.50 ± 0.23	0.49 ± 0.24			B.2
August 23, 1979	0.26 ± 0.06	0.49 ± 0.28			B.2
Sept. 26, 1979	0.53 ± 0.32	0.32 ± 0.24	-0.21 ± 1.06	-0.58 ± 0.85	B.4
Oct. 3, 1979	0.37 ± 0.21	0.57 ± 0.27	0.62 ± 1.48	-0.17 ± 1.78	Figure 10

APPENDIX C: MF BROADCAST AMPLITUDE SIGNALS

This Appendix provides illustrations of the MF broadcast station signals recorded in conjunction with the SPS simulation experiment. These data were not discussed in the main text. In addition, in Table C. 1, average values of recorded relative amplitude with Platteville Facility "ON" and Platteville Facility "OFF" are presented. These values were averaged over the Facility "ON" and Facility "OFF" times indicated on the appropriate figures.

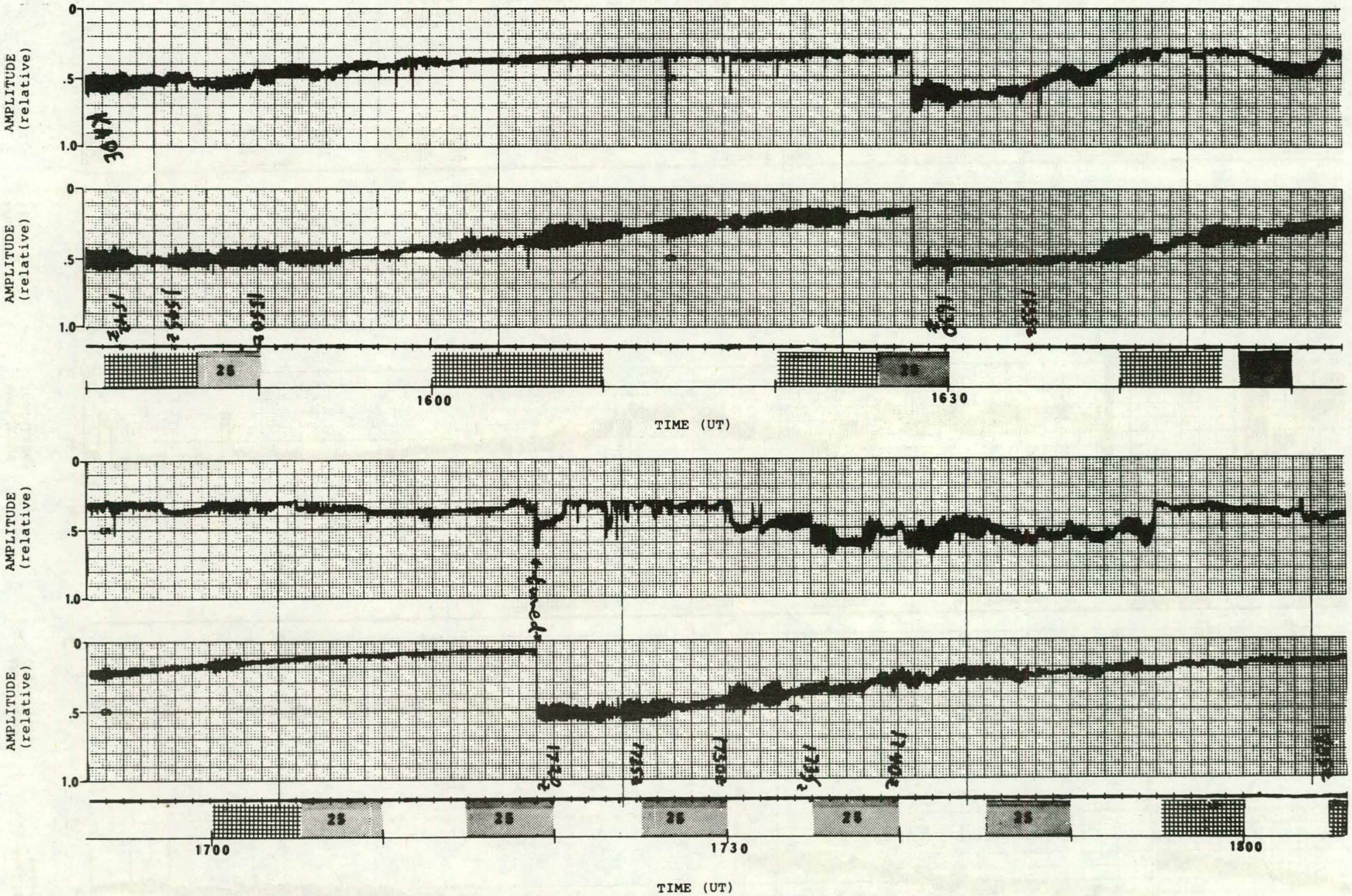


Figure C-1. Amplitude signals recorded from broadcast stations KADE (1190 kHz) and KLMO (1060 kHz) at Brush, CO, on August 19, 1979.

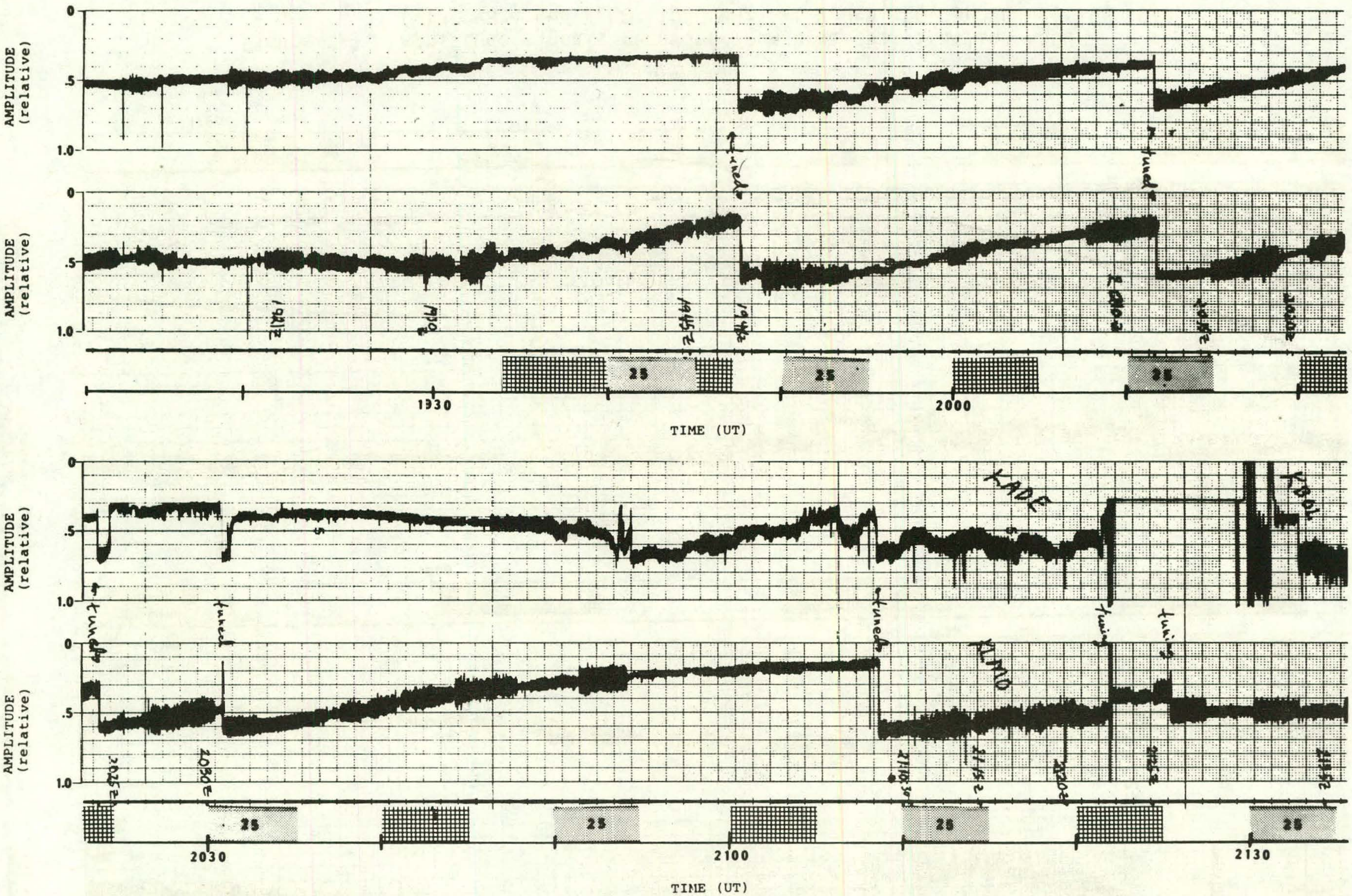


Figure C-2. Amplitude signals recorded from broadcast stations KADE (1190 kHz), KBOL (1490 kHz), and KLMO (1060 kHz) at Brush, CO, on August 19, 1979.

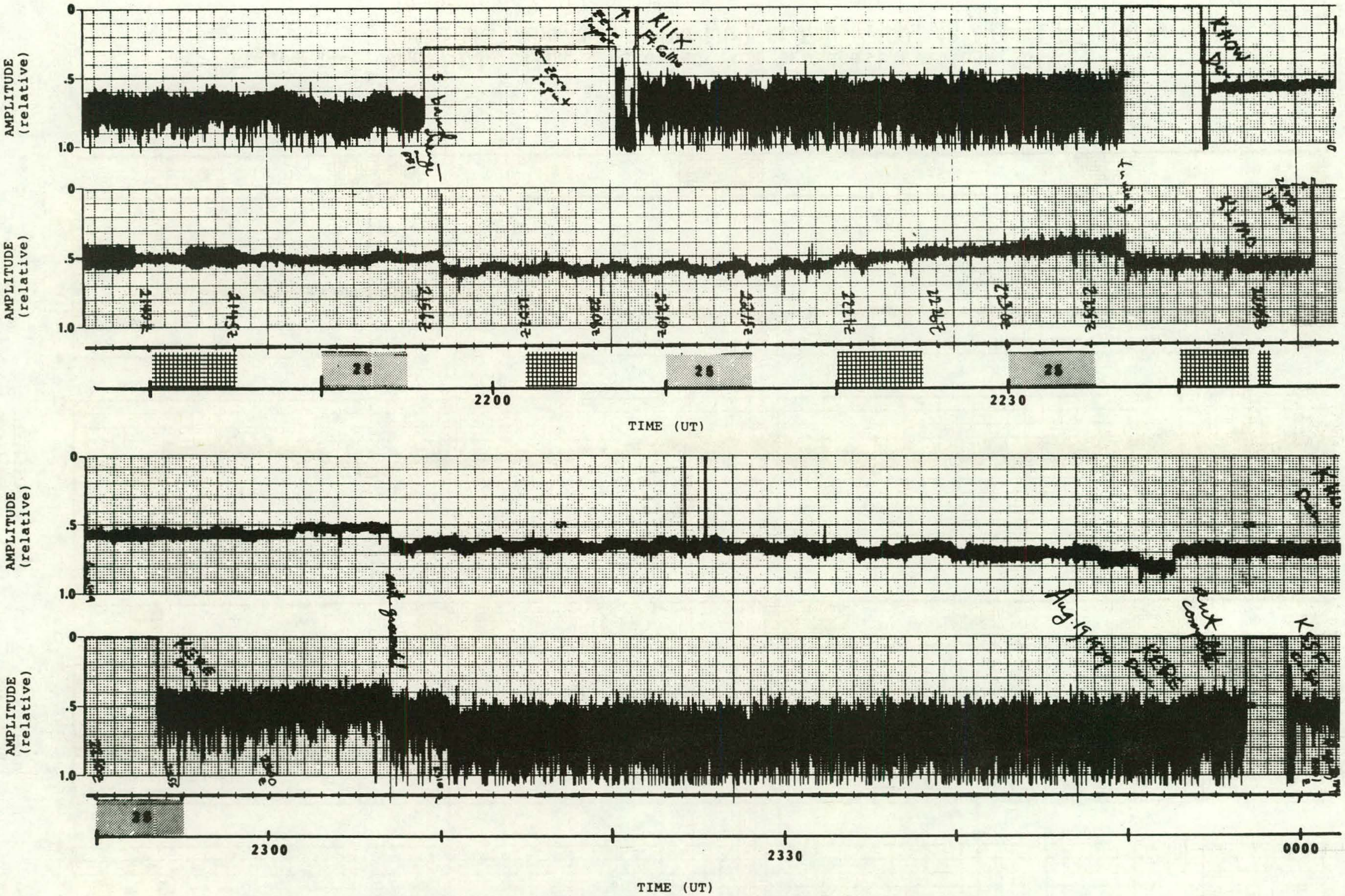


Figure C-3. Amplitude signals recorded from broadcast stations KIIX (600 kHz), KHOW (630 kHz), KLMO (1060 kHz), and KERE (710 kHz) at Brush, CO, on August 19, 1979.

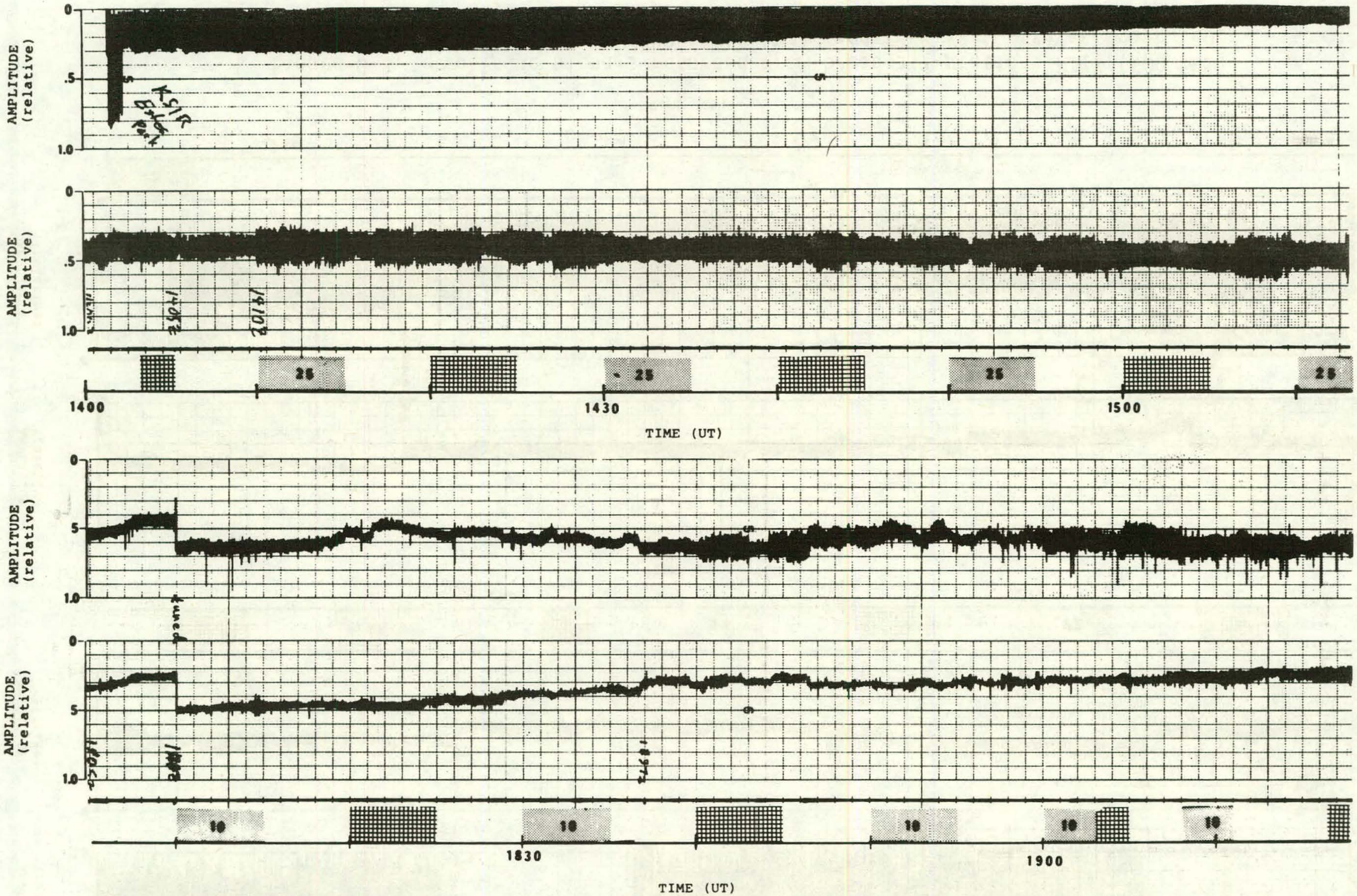


Figure C-4. Amplitude signals recorded from broadcast stations KSIR (1470 kHz) and KBOL (1490 kHz) at Brush, CC, on August 20, 1979.

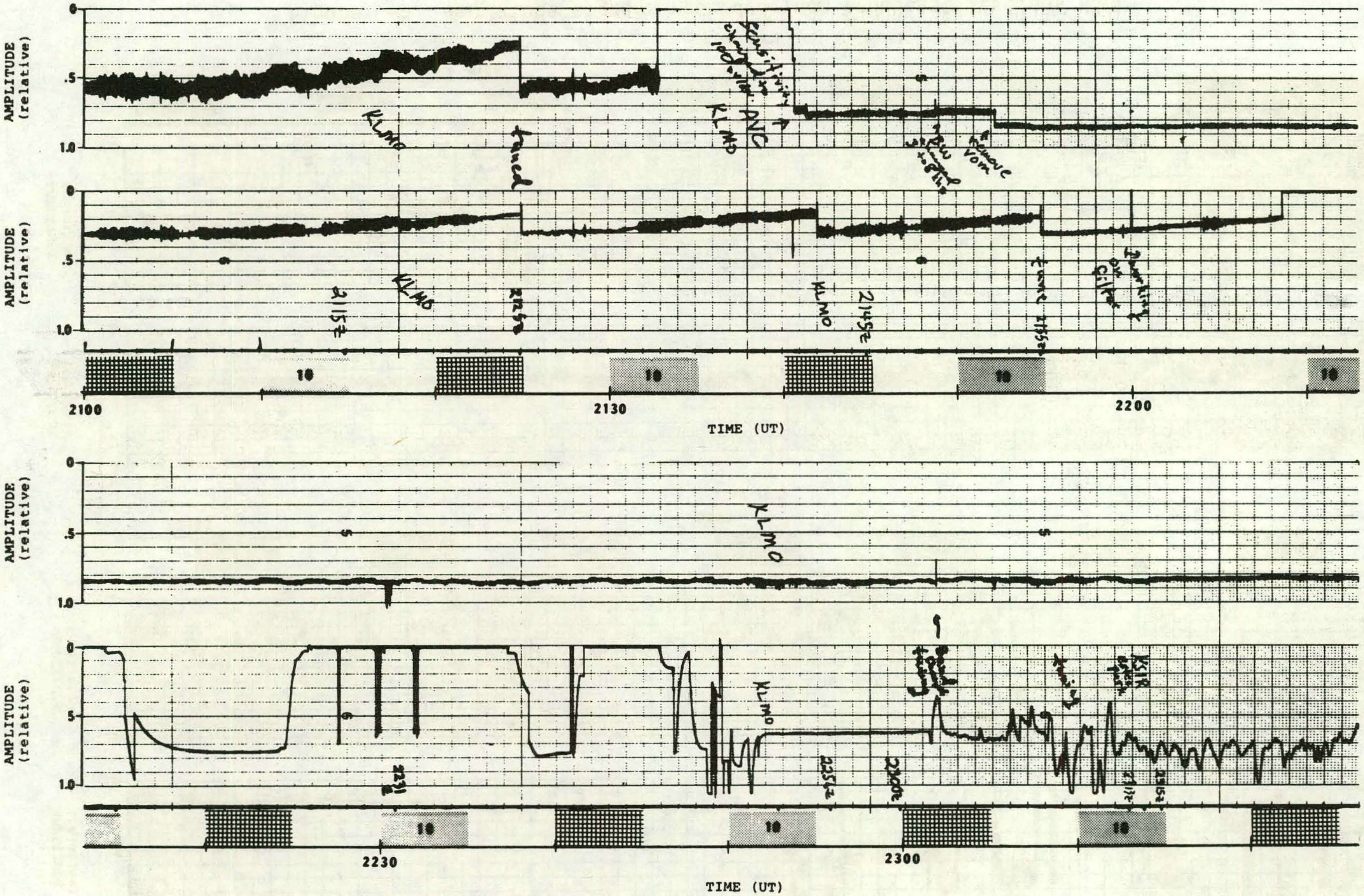


Figure C-5. Amplitude signals recorded from broadcast stations KLMO (1060 kHz) and KSIR (1470 kHz) at Brush, CO, on August 22, 1979.

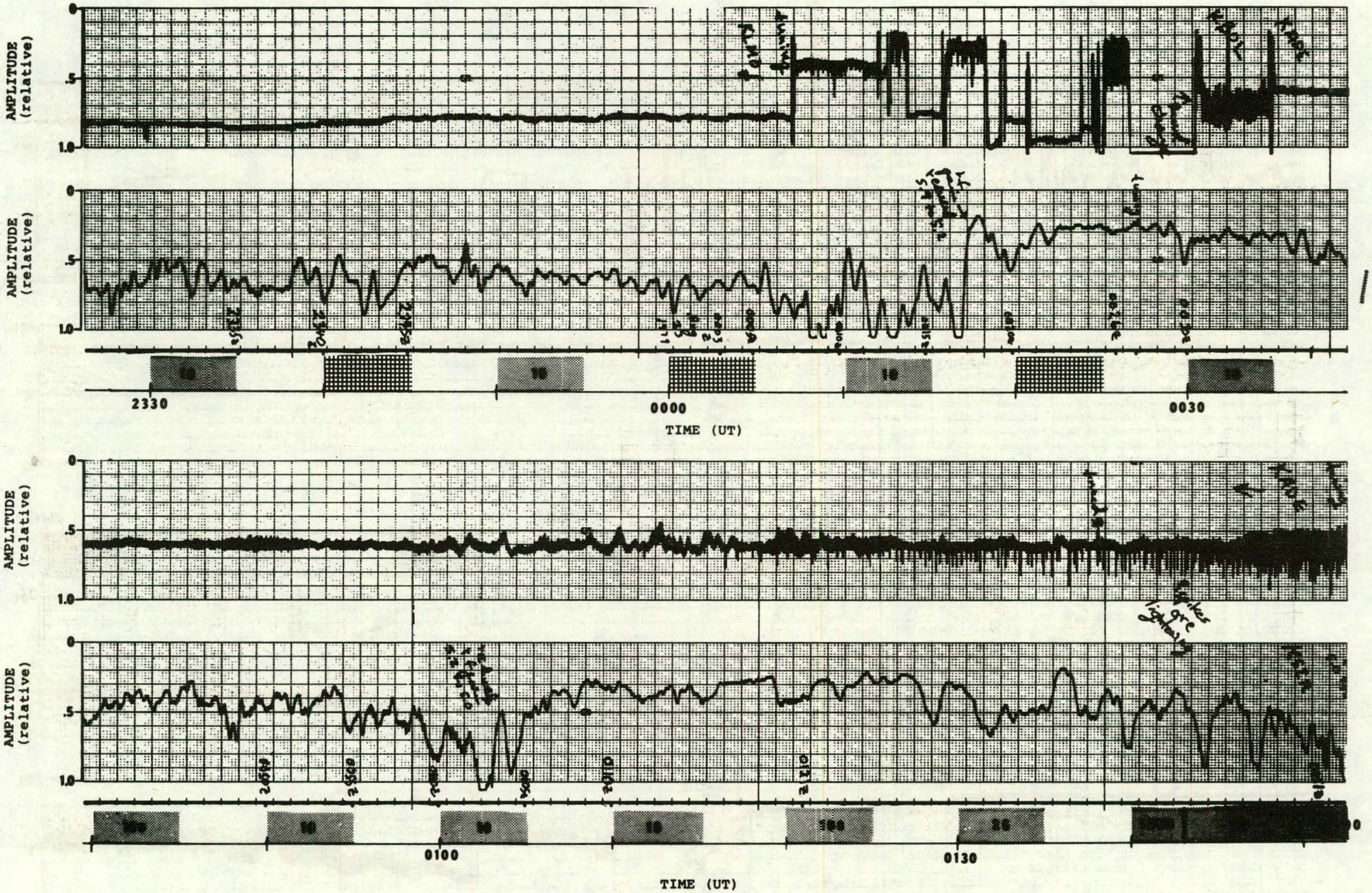


Figure C-6. Amplitude signals recorded from broadcast stations KBOL (1490 kHz), KADE (1190 kHz), and KSIR (1470 kHz) at Brush, CO, on August 22, 1979.

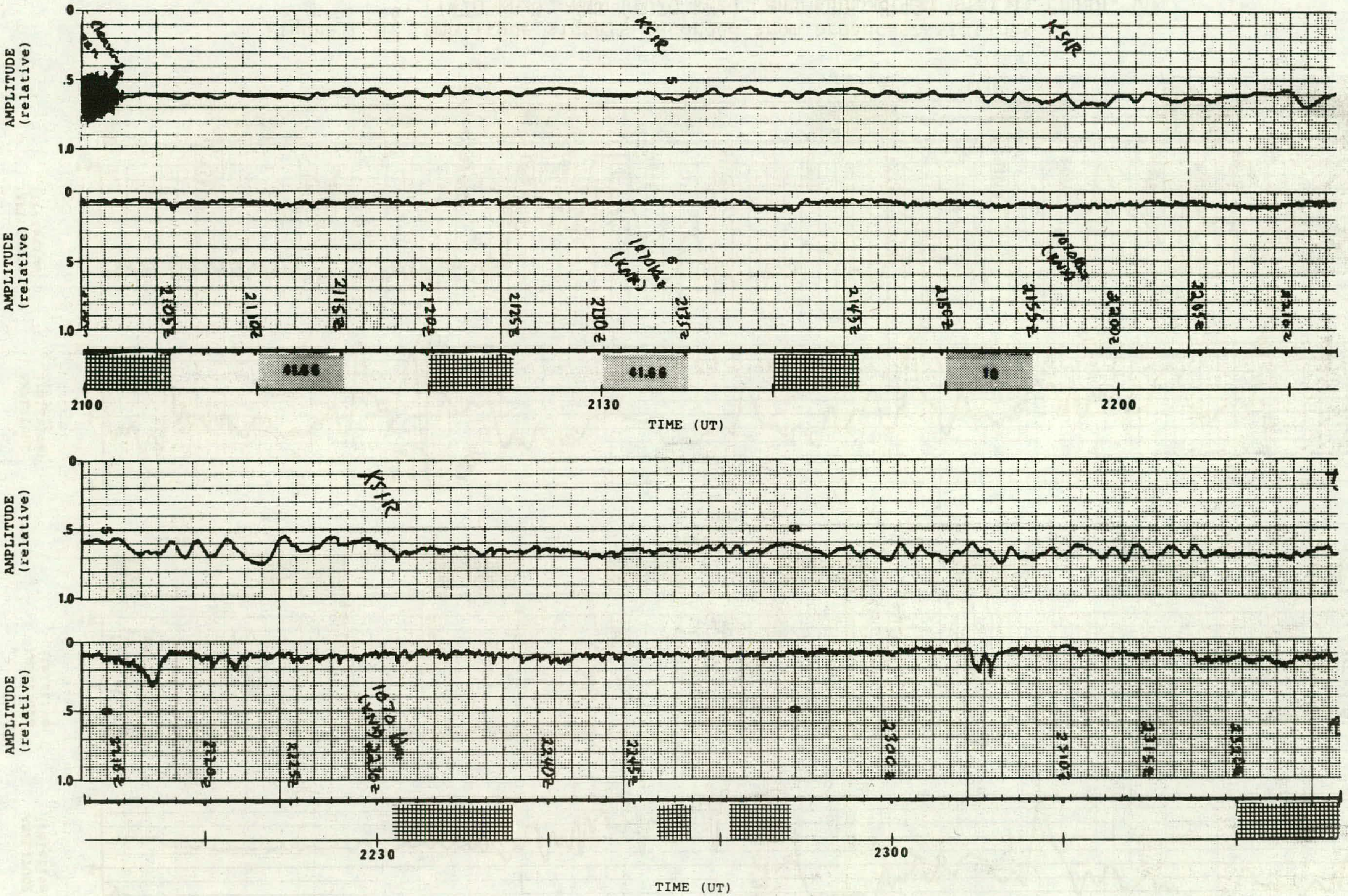


Figure C-7. Amplitude signals recorded from broadcast stations KSIR (1470 kHz) and KNX (1070 kHz) at Brush, CO, on August 23, 1979.

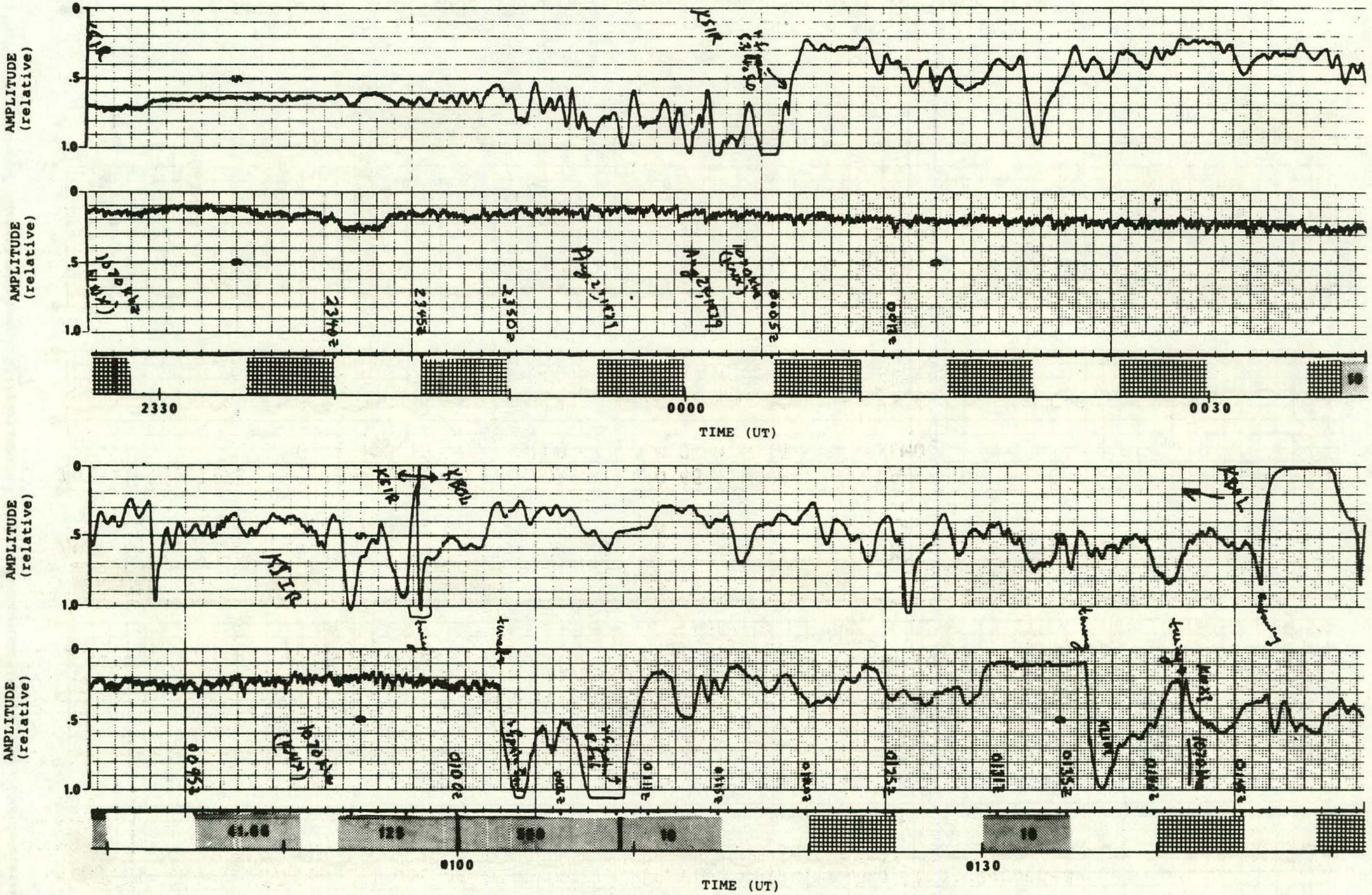


Figure C-8. Amplitude signals recorded from broadcast stations KSIR (1470 kHz), KNX (1070 kHz), and KBOL (1490 kHz) at Brush, CO, on August 24, 1979.

Table C. 1. Average Values of AM Broadcast Station Relative Amplitude Recorded During Times of Platteville Facility "ON" and "OFF"

Date	Amplitude Facility "ON" (dB)	Station	Amplitude Facility "OFF" (dB)	Station	Reference Figure
August 16, 1979	0.49 ± 0.05	KOA	0.38 ± 0.11	KOA	Figure 14
	0.45 ± 0.12	KLMO	0.34 ± 0.11	KLMO	
August 17, 1979	0.42 ± 0.09	KADE	0.45 ± 0.08	KADE	C-1
	0.34 ± 0.13	KLMO	0.33 ± 0.14	KLMO	
August 20, 1979	0.33 ± 0.24	KSIR	0.37 ± 0.24	KSIR	C-4
	0.40 ± 0.07	KBOL	0.39 ± 0.08	KBOL	
August 22, 1979	0.44 ± 0.18	KSIR	0.40 ± 0.18	KSIR	C-6
August 23, 1979	0.63 ± 0.34	KRWX	0.63 ± 0.36	KREX	Figure 15
	0.17 ± 0.12	KNX	0.13 ± 0.06	KNX	Figure 15
	0.35 ± 0.07	KSL	0.41 ± 0.17	KSL	Figure 15

United States
Department of Energy
Washington, D.C. 20585

THIRD – CLASS MAIL
POSTAGE & FEES PAID
U.S. DEPT. OF ENERGY

PERMIT NO. G 20

THIRD CLASS MAIL

Official Business
Penalty for Private Use, $300