15128



NOTICE

This document has been withdrawn from the DDC bulk storage. It is the responsibility of the recipient to promptly mark it to indicate the reclassification action shown hereon

# Technical Report

distributed by

Defense Technical Information Center
DEFENSE LOGISTICS AGENCY
Cameron Station • Alexandria, Virginia 22314

UNCLASSIFIED/UNLIMITED

UNCLASSIFIED

# SECURITY MARKING

**The classified or limited status of this report applies to each page, unless otherwise marked.**
**Separate page printouts MUST be marked accordingly.**

"This document contains information affecting the National Defense of the United States within the meaning of the Espionage Laws, Title 18, U. S. C., Section 793 and 794. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law."

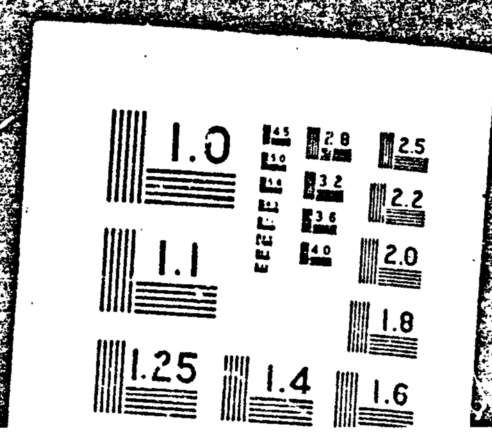
EXCLUDED FROM AUTOMATIC
REGRADING; DOD DIR 5200.10
DOES NOT APPLY

**" ONE HALF ORIGINAL SIZE "** **attachment A**

UNCLASSIFIED

1 OF 2

AD361772



[redacted]

UNCLASSIFIED

Copy No.

*Operation*

# CASTLE

PACIFIC PROVING GROUNDS

March — May 1954

Classification (Changed to

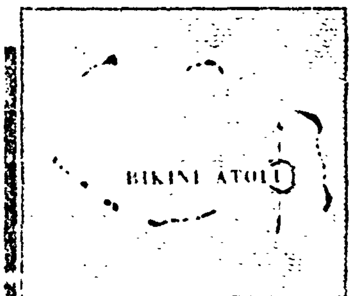
DASA SC 3 Memo 9 Jan 62

Project 6.6

## EFFECTS OF NUCLEAR DETONATIONS ON THE IONOSPHERE

006

Issuance Date: May 22, 1957




RESTRICTED DATA

This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

HEADQUARTERS FIELD COMMAND, ARMED FORCES SPECIAL WEAPONS PROJECT

SANDIA BASE, ALBUQUERQUE, NEW MEXICO

5029(A)

UNCLASSIFIED

Inquiries relative to this report may be made to

Chief, Armed Forces Special Weapons Project
Washington, D. C.

If this report is no longer needed, return to

AEC Technical Information Service Extension
P. O. Box 401
Oak Ridge, Tennessee

[redacted] **UNCLASSIFIED**

This document consists of 75 pages,

No 68 of 70 copies, Series A

WT-929

OPERATION CASTLE—PROJECT 6.6

Report to the Scientific Director

# EFFECTS OF NUCLEAR DETONATIONS ON THE IONOSPHERE


Fred B. Daniels
Arthur K. Harris

Evans Signal Laboratory
Signal Corps Engineering Laboratories
Fort Monmouth, New Jersey


APRIL 1957

U. S. MILITARY AGENCIES MAY OBTAIN COPIES OF THIS REPORT DIRECTLY FROM DDC. OTHER QUALIFIED USERS SHALL REQUEST THROUGH Sponsoring Agency to:

Director
Defense Atomic Support Agency
Washington, D. C. 20301

RESTRICTED DATA

CANCELLED

This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

This document ... affecting the National Defense of the ... meaning of the Espionage Laws, ... 793 and 794. Its transmission or ... of its contents in any manner to an unauthorized person is prohibited by law.



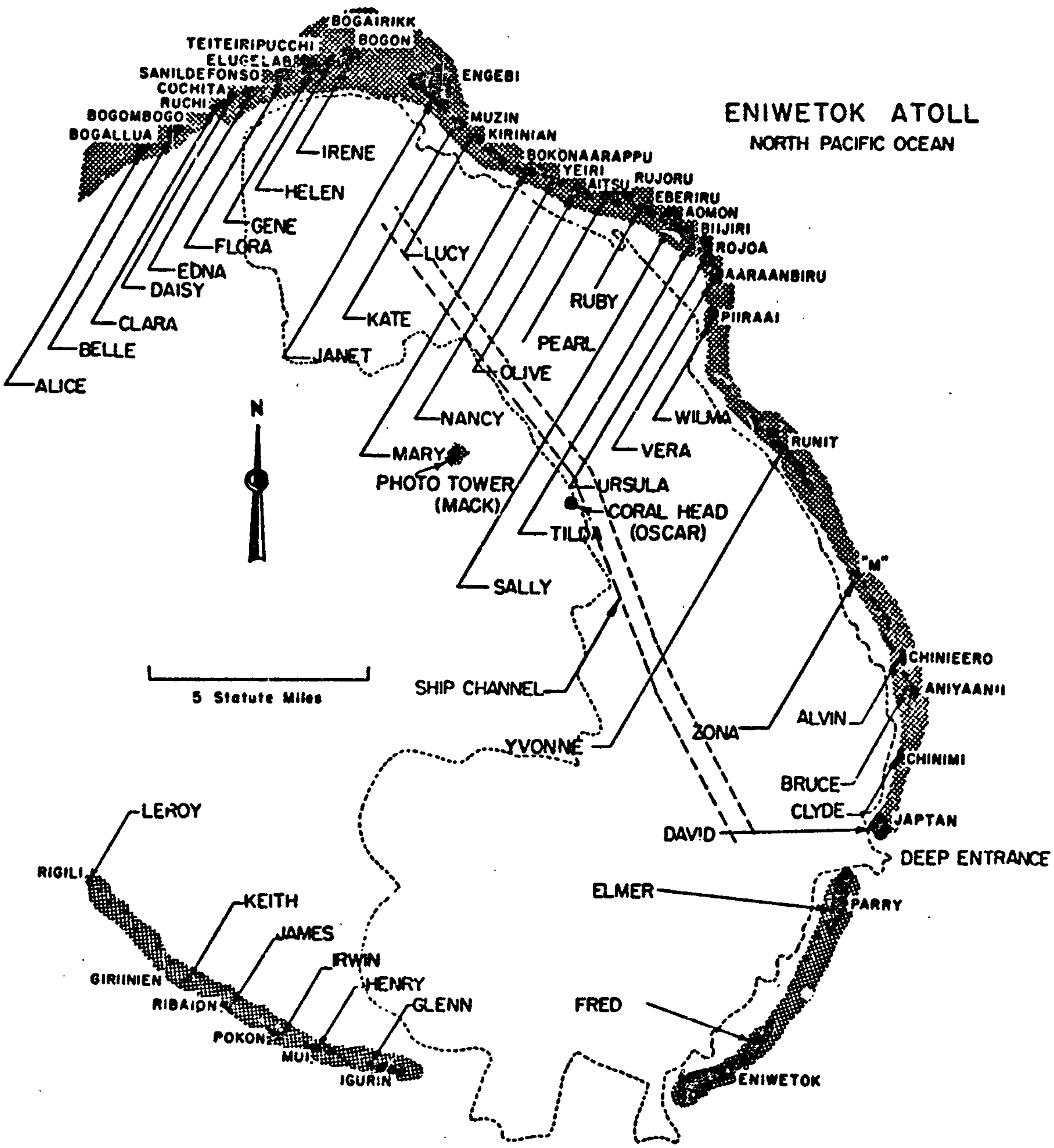
[redacted]

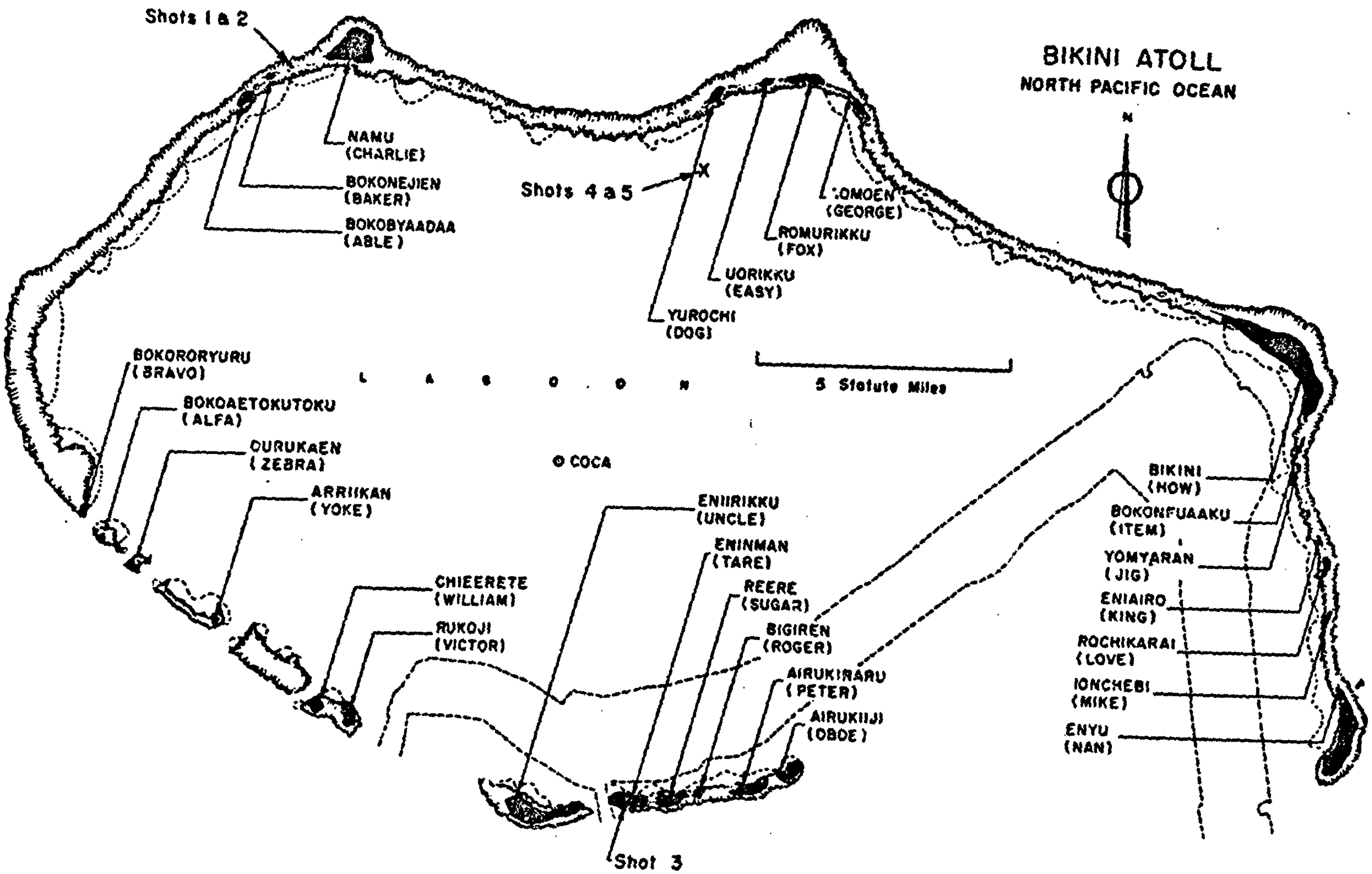
FORMERLY RESTRICTED DATA
HANDLE AS RESTRICTED DATA IN FOREIGN DISSEMINATION
SECTION 144b, ATOMIC ENERGY ACT 1954

**UNCLASSIFIED**

USASRPA NO. 2270

GROUP 1
Excluded from automatic downgrading and declassification


ENIWETOK ATOLL
NORTH PACIFIC OCEAN
BOGAIRIKK
BOGON
TEITEIRIPUCCHI
ELUGELAB
SANILDEFONSO
COCHITA
RUCHI
BOGOMBOGO
BOGALLUA
ENGEBI
MUZIN
KIRINIAN
BOKONAARAPPU
YEIRI
AITSU
RUJORU
EBERIRU
AOMON
BIIJIRI
ROJOA
AARAANBIRU
PIIRAAI
IRENE
HELEN
GENE
FLORA
EDNA
DAISY
CLARA
BELLE
ALICE
LUCY
KATE
JANET
RUBY
PEARL
OLIVE
NANCY
WILMA
VERA
RUNIT
MARY
PHOTO TOWER
(MACK)
URSULA
CORAL HEAD
(OSCAR)
TILDA
SALLY
N
"M"
5 Statute Miles
SHIP CHANNEL
YVONNE
ZONA
ALVIN
CHINIEERO
ANIYAANII
CHINIMI
BRUCE
CLYDE
JAPTAN
DAVID
DEEP ENTRANCE
ELMER
PARRY
LEROY
RIGILI
KEITH
JAMES
IRWIN
HENRY
GLENN
GIRIINIEN
RIBAIDN
POKON
MUI
IGURIN
FRED
ENIWETOK



BIKINI ATOLL
NORTH PACIFIC OCEAN
N
Shots 1 a 2
NAMU (CHARLIE)
BOKONEJIEN (BAKER)
BOKOBYAADAA (ABLE)
Shots 4 a 5
OMOEN (GEORGE)
ROMURIKKU (FOX)
UORIKKU (EASY)
YUROCHI (DOG)
5 Statute Miles
L A G O O N
BOKORORYURU (BRAVO)
BOKOAETOKUTOKU (ALFA)
OURUKAEN (ZEBRA)
ARRIIKAN (YOKE)
COCA
CHIEERETE (WILLIAM)
RUKOJI (VICTOR)
ENIIRIKKU (UNCLE)
ENINMAN (TARE)
REERE (SUGAR)
BIGIREN (ROGER)
AIRUKIRARU (PETER)
AIRUKIIJI (OBOE)
Shot 3
BIKINI (HOW)
BOKONFUAAKU (ITEM)
YOMYARAN (JIG)
ENIAIRO (KING)
ROCHIKARAI (LOVE)
IONCHEBI (MIKE)
ENYU (NAN)




SECRET

GENERAL SHOT INFORMATION

| | Shot 1 | Shot 2 | Shot 3 | Shot 4 | Shot 5 | Shot 6 |
|---|---|---|---|---|---|---|
| DATE | 1 March | 27 March | 7 April | 26 April | 5 May | 14 May |
| CODE NAME (Unclassified) | Bravo | Romeo | Koon | Union | Yankee | Nectar |
| TIME* | 06:40 | 06:25 | 06:15 | 06:05 | 06:05 | 06:15 |
| LOCATION | Bikini, West of Charlie (Namu) on Reef | Bikini, Shot 1 Crater | Bikini, Tare (Eninman) | Bikini, on Barge at Intersection of Arcs with Radii of 6900' from Dog (Yurochi) and 3 Statute Miles from Fox (Aomoen). | | Eniwetok, IVY Mike Crater, Flora (Elugelab) |
| TYPE | Land | Barge | Land | Barge | Barge | Barge |
| HOLMES & NARVER COORDINATES | N 170,617.17<br>E 76,163.98 | N 170,635.05<br>E 75,950.46 | N 100,154.50<br>E 109,799.00 | N 161,698.83<br>E 116,800.27 | N 161,424.43<br>E 116,688,15 | N 147,750.00<br>E 67,790.00 |

* APPROXIMATE

# ABSTRACT

During Operation CASTLE, two ionosphere recorders were operated in the Marshall Islands — at Site Elmer, about 200 miles west of Bikini Atoll, and at Rongerik Atoll, about 150 miles east of Bikini — in order to study the effects of the detonations on the ionosphere. Normal data from existing stations at Maui and Adak and special data furnished by existing stations at Guam and Okinawa were examined for effects at distances of 1,400 to 3,000 miles.

Severe absorption was observed 200 miles west of all multimegaton shots, lasting several hours, presumably due to ionization caused by radioactive material carried by high-level winds. Turbulence in the E region after each major shot was indicated by the diffuse sporadic-E returns at Rongerik. Also, for shots of megaton range, an effect on the F2 layer similar to that first found following Shot Mike of Operation IVY was observed, its nature varying from shot to shot. This phenomenon is apparently far more complex than originally assumed, but it is still attributed to the large-scale convection resulting from the conversion of blast-wave energy into heat in the upper atmosphere.

Ionospheric disturbances, apparently resulting from the three largest explosions, were found up to 2,600 miles away, with indicated velocities of about 8 to 16 km/min.

# FOREWORD

This report is one of the reports presenting the results of the 34 projects participating in the military effect tests program of Operation CASTLE, which included six test detonations. For readers interested in other pertinent test information, reference is made to ITR-934, Summary of Weapons Effects Tests, military effect program. This summary report includes the following information of possible general interest: (1) An overall description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation, etc., for the six shots; (2) Discussion of all project results; (3) A summary of each project, including objectives and results; and (4) A complete listing of all reports covering the military effect test program.

# ACKNOWLEDGEMENTS

The assistance and cooperation of the following individuals and organizations is hereby gratefully acknowledged:

Captain Albert Giroux, Signal Corps, CO Mobile Section A, 9471st Technical Unit, Project Officer (Operations), who planned and executed the operational phase of Project 6.6 in an outstanding manner, despite numerous unforeseen difficulties.

The enlisted men of Mobile Section A (including the alternates who served) performed their duties excellently, usually doing more than was required, so as to insure the success of the project.

Personnel of the National Bureau of Standards ionosphere station on Guam and Signal Corps personnel of the 9465th Technical Service Unit at the ionosphere station on Okinawa, who cooperated so fully in the special operation of their stations.

Central Radio Propagation Laboratory of the National Bureau of Standards, which provided one of the ionosphere recorders used and loaned the film from which Guam and Maui ionograms reproduced herein were obtained.

Signal Corps Radio Propagation Agency, which provided the services of Mobile Section A, 9471st Technical Unit, and loaned the film from which Okinawa ionograms reproduced herein were obtained.

Corporal Robert E. Nowell, of the 9471st Technical Unit, who aided immeasurably in analyzing the data and in writing parts of the first draft of this final report.

Personnel of the Photographic Section, Reproduction Branch, Signal Corps Engineering Laboratories, who were exceedingly cooperative in the preparation of the figures used in this report.

## CONTENTS

# ILLUSTRATIONS

# TABLES

# Chapter 1

# INTRODUCTION

## 1.1 OBJECTIVES

### 1.1.1 Rising F2 Layer

The first objective of this experiment was to firmly establish the cause-and-effect relationships for an ionospheric phenomenon first observed following Shot Mike of Operation IVY, namely, the large increase in virtual height of the F2 layer and associated effects.

### 1.1.2 Distant Effects

The second objective was to obtain corroborative data on effects at a great distance, first observed for Shot Mike of Operation IVY, in order to determine the possibility of the use of such effects as a means of long-range detection and to determine whether any indication of the magnitude of the yield could be obtained at distant locations.

### 1.1.3 Upper Ionospheric Knowledge

It was also anticipated that detailed study of both the local and the distant data would provide a better insight into the mechanisms involved in F2-layer phenomena, thus furthering the state of knowledge of the upper ionosphere.

### 1.1.4 Effects of Blast Wave on Lower Ionosphere

This experiment also furnished the opportunity to continue to investigate the effects of the blast wave on the ion-density distribution in the E and F1 layers of the ionosphere and to study the absorptive effects occurring below the E region.

## 1.2 BACKGROUND

### 1.2.1 Rising F2 Layer

Following Shot Mike of Operation IVY, the F2 layer was observed to rise to abnormal heights, and its ion density, measured by critical frequency, was found to fall below normal values (see Reference 1). Although, during previous operations, ionosphere recorders had been operated following at least a dozen atomic explosions, occurring at various hours, seasons, and locations and under various ionospheric conditions, none of the records obtained exhibited this phenomenon of the rising F2 layer. Since the yield of Shot Mike was much greater than that of any previous test explosion, it was concluded that the effect was a consequence of the magnitude of the shot. It was recommended that, inasmuch as Operation CASTLE would include shots of comparable magnitude, confirmation should be sought and that, by locating two ionosphere recorders in different directions from the source, a better insight into the mechanism might be obtained.

A possible explanation of the phenomenon was given, based on the assumption that the blast-wave energy, arriving at ionospheric heights as a shock wave, was absorbed there and converted into thermal energy, thus raising the average temperature of a large region of the upper atmosphere, causing expansion and rising of the heated volume. If the charged particles were to move in the same direction as the neutral air molecules, the F2 layer would rise with the rising air mass, and the depressed critical frequency would be explained by the decreased electron density resulting from expansion. However, the effect of the earth's magnetic field on charges moving across it casts doubt on this simple explanation; so a more involved hypothesis was necessary to account, in part, for the phenomenon. Recent publication of new ionization drift theory has made possible a more-complete explanation (see Section 4.2).

In order to test the theory given for IVY Mike results, it was at first proposed that two ionosphere recorders be so located that propagation of the blast wave to the two operating sites would take place across and along the earth's magnetic field, respectively. However, it was not logistically practicable to obtain such locations. Rongerik Atoll (about 150 miles east of the Bikini shots) and Eniwetok Atoll (about 200 miles west of Bikini) were selected as the best available locations from which to obtain ionospheric data that might result in a better understanding of the phenomenon.

### 1.2.2 Effects at a Great Distance

Irregularities found in ionograms recorded at Guam, Maui, and Okinawa were interpreted as due to an indirect effect of Mike shot on the F2 layer. From the times at which the irregularities were first observed, it was hypothesized that an ionospheric disturbance, initiated by the blast, was propagated horizontally in the F region at a velocity of approximately 13 km/min (about two thirds of the speed of sound near the earth's surface). This velocity was shown to be within the ranges reported by several observers for naturally caused disturbances. However, this appears to have been the first time that a traveling ionospheric disturbance emanating from a known source was reported.

### 1.2.3 Absorption

A decrease in intensity of certain high-frequency signals, lasting for about 1/2 hour, was attributed to abnormal absorption in the D region (about 50 to 80 km high) resulting from the heating effect of the shock wave and the consequent increase of collision frequency. This was observed following Shots Mike and King of IVY. It was concluded that this absorption, though significant, would probably not seriously hamper communications.

### 1.2.4 Other Effects

Initiation of effects in the E region, due to local changes in ion density, was shown (in the TUMBLER-SNAPPER report) to coincide with the arrival time of the compressional wave (see Reference 2). Both E-layer and F1-layer effects of this nature were observed at Bikini for Shot King, which took place at Eniwetok and which was relatively small compared with Mike and the majority of the CASTLE shots. An increase in sporadic-E activity has almost always been found to follow atomic explosions. This appears to be another aspect of the effects due to local changes in ion density, as it seems to be increased backscatter from a region that is "roughened" by turbulence.

# Chapter 2

# EXPERIMENT DESIGN

## 2.1 INSTRUMENTATION

The equipment consisted principally of automatic vertical-incidence ionosphere recorders, Model C-2 and Model C-3, similar to each other in performance. The location of each of these recorders and its approximate distance from Bikini are indicated on a map (Fig. 2.1).

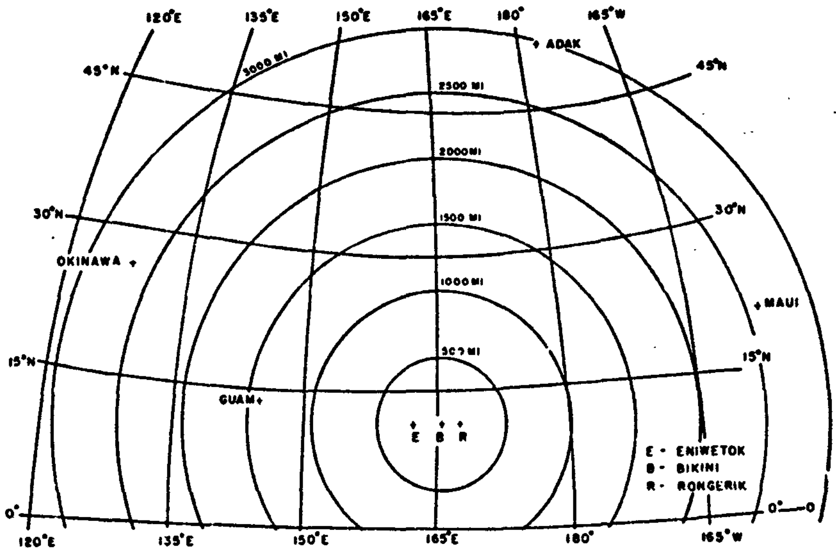



Fig. 2.1 - Map Showing Location of Stations and Approximate Distances from Bikini.

### 2.1.1 In the Marshall Islands

A Model C-2 recorder was operated in a van located on Site Elmer (Eniwetok Atoll). A Model C-3 recorder was operated in a van located near the southwestern end of Eniwetak Island, Rongerik Atoll.

### 2.1.2 At Distant Locations

Existing distant stations, which are part of a world-wide system, from which data were obtained for this report were the National Bureau of Standards stations on Guam and Maui and the Signal Corps stations on Okinawa and Adak. Each of these stations uses either a C-2 or a C-3 recorder.

### 2.1.3 Description of Recorders

The vertical-incidence ionosphere recorder (C-2 or C-3) is a device which measures and records virtual heights and critical frequencies of the layers of the ionosphere. Transmitted pulses of radio-frequency energy are reflected from the ionosphere and received by the equipment on their return, the travel time indicating the height of the reflecting layer. The frequency is swept through the range of 1 to 25 megacycles. The critical frequency of a layer is indicated by the frequency above which the signal penetrates the layer, thus producing no return, and is a measure of the maximum electron density. The received signal is displayed as an intensity-modulated oscilloscope trace, showing layer height as a function of frequency. The presentation is photographed automatically. A more detailed discussion of the method and of the interpretation of the photographs may be found in Reference 3.

### 2.1.4 Antennas

The antennas used with the ionosphere recorders in the Marshall Islands were single-wire, vertical-delta type ("half-rhombics"), 50 ft high, with the slanting legs 78 ft long, the transmitting and receiving antennas and the ground plane being in mutually perpendicular planes. The antennas at existing stations are similar, but are multi-wire to provide better impedance match throughout the range, and are longer, the slanting legs being about 90 ft long. All are designed to radiate and receive principally in the vertical direction over the entire band of frequencies. However, at some frequencies the beam is wide, and at others there are side lobes; hence, oblique returns are received under certain ionospheric conditions.

## 2.2 OPERATING PROCEDURE

### 2.2.1 In the Marshall Islands

Scheduled operation of the recorders at both Marshall Islands stations began several days prior to the first shot. It continued in accordance with the planned program (which appears below) except that fallout after the first shot curtailed operations at Rongerik. Afterwards, the recorder at Rongerik had to be started prior to each shot and left to operate unattended, at one sweep per minute, until the film or the gasoline in the power unit ran out. At both stations, a sweep time of 15 sec was used, the entire range of frequencies from 1 to 25 megacycles being covered in that time. In the program which follows, "normal" indicates five sweeps an hour (on the hour, and at 15, 30, 45, and 59 minutes past). "D" and "H" respectively, represent the day and hour of each shot, and minus (-) or plus (+) indicates time before or after the shot, respectively. (Additional data were obtained in the course of test and maintenance runs.)

| Time | Operation |
|---|---|
| D - 6 to D - 2 | Normal (from 0500 to 1300 hour) |
| D - 2 to H - 5 min | Normal (24 hours a day) |
| H - 5 min to H + 30 min (except - 1 min to + 5 sec) | Continuous 15-sec sweeps |
| H + 30 min to H + 5 hr (or longer, if it was indicated) | One sweep per min |
| H + 5 to H + 29 hr | Normal |
| D + 2 to D + 6 (except after last shot) | Normal (for period of day corresponding to H - 1 to H + 5 hr of shot) |

Film was developed on site and scaled by project personnel in the standard manner. Further analysis was made in the field and was continued at Evans Signal Laboratory.

2.2.2 At Guam

Normal operation at Guam is five times an hour (as in Section 2.2.1 above). Additional special data were taken as follows:

After Shot 2 - 4 times a minute from + 1 1/2 to + 2 1/2 hr
After Shot 4 - every 5 minutes from 0 to + 8 hr
After Shot 5 - every 5 minutes from 0 to + 9 3/4 hr
After Shot 6 - every 5 minutes from 0 to + 9 hr

2.2.3 At Okinawa

Normal operation at Okinawa is five times an hour (as in section 2.2.1 above). Additional special data were taken for each shot as follows:

| Time | Operation |
|---|---|
| - 5 min to at least + 5 min | Continuous 15 sec sweeps |
| + 3 hr to + 4 1/2 hr | Continuous 15 sec sweeps |
| + 4 1/2 hr to at least 9 hr | Every 5 min |

2.2.4 At Adak

Normal operation at Adak is five times an hour (as in Section 2.2.1 above).

2.2.5 At Maui

Normal operation at Maui is three times an hour (on the hour and at 3 and 30 minutes past).

# Chapter 3

# DATA AND RESULTS

## 3.1 ABSORPTIVE EFFECTS

The attempt to achieve the first principal objective — verification of the F2-layer rise and related effects following megaton-order explosions — was partially frustrated by severe and protracted absorption, particularly at Site Elmer, causing complete attenuation of the vertically transmitted radio waves until 7 or 8 hours after detonation. The absorption itself thus becomes an important phenomenon.

The difference between the absorptive effect at Rongerik Atoll and at Site Elmer is apparent in Figs. 3.1 and 3.2, originally prepared

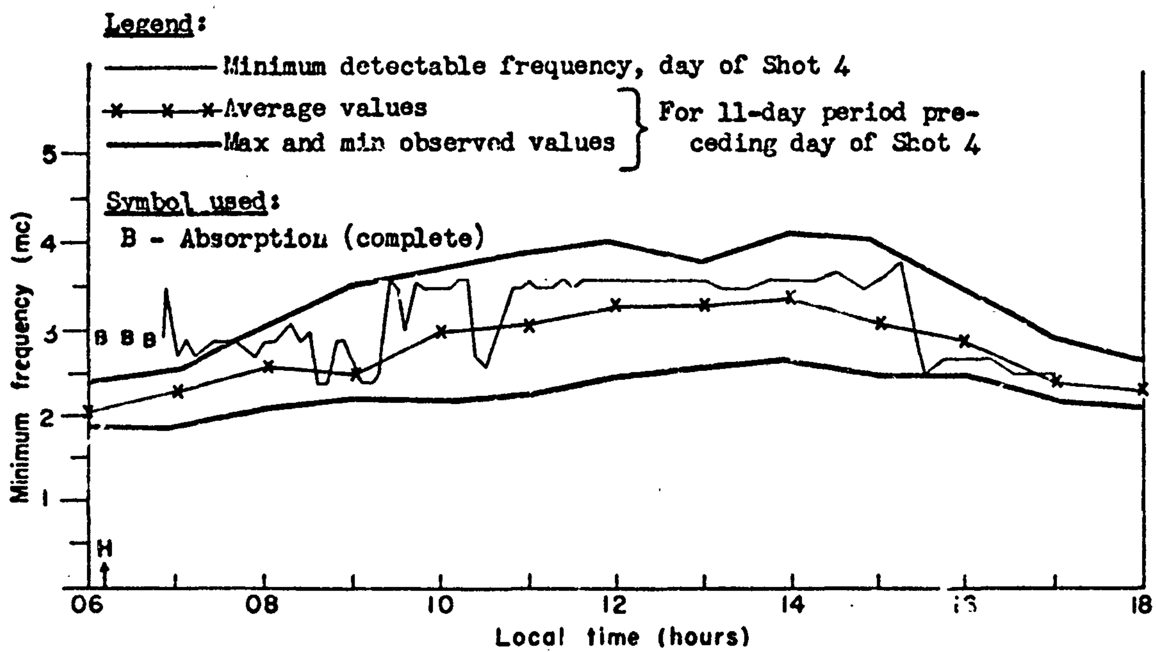



Fig. 3.1 - Minimum Frequency Detected at Rongerik for Day of Shot 4, Compared with Normal Values

for the field report on Shot 4 alone, but used here since these curves typify all shots of very large magnitude. In these figures, the minimum frequency reflected from the ionosphere and detected at each station is plotted against local time, using a light line. The standard symbol "B" is used to denote times when complete absorption apparently prevented any ionospheric return; occasionally, for very brief intervals during these periods, an extremely weak signal was perceived, hence the symbols are located in the vicinity of the frequency involved.

While it is true that there are other factors influencing the minimum frequency value, it is principally a function of the degree of absorption. This may be inferred from the normal-day average-value curves of Figs. 3.1 and 3.2. The trend of these curves indicates that the minimum detected frequency is greatest when the sun is highest and the absorption (which is due to the ionizing radiation from the sun) is also a maximum.

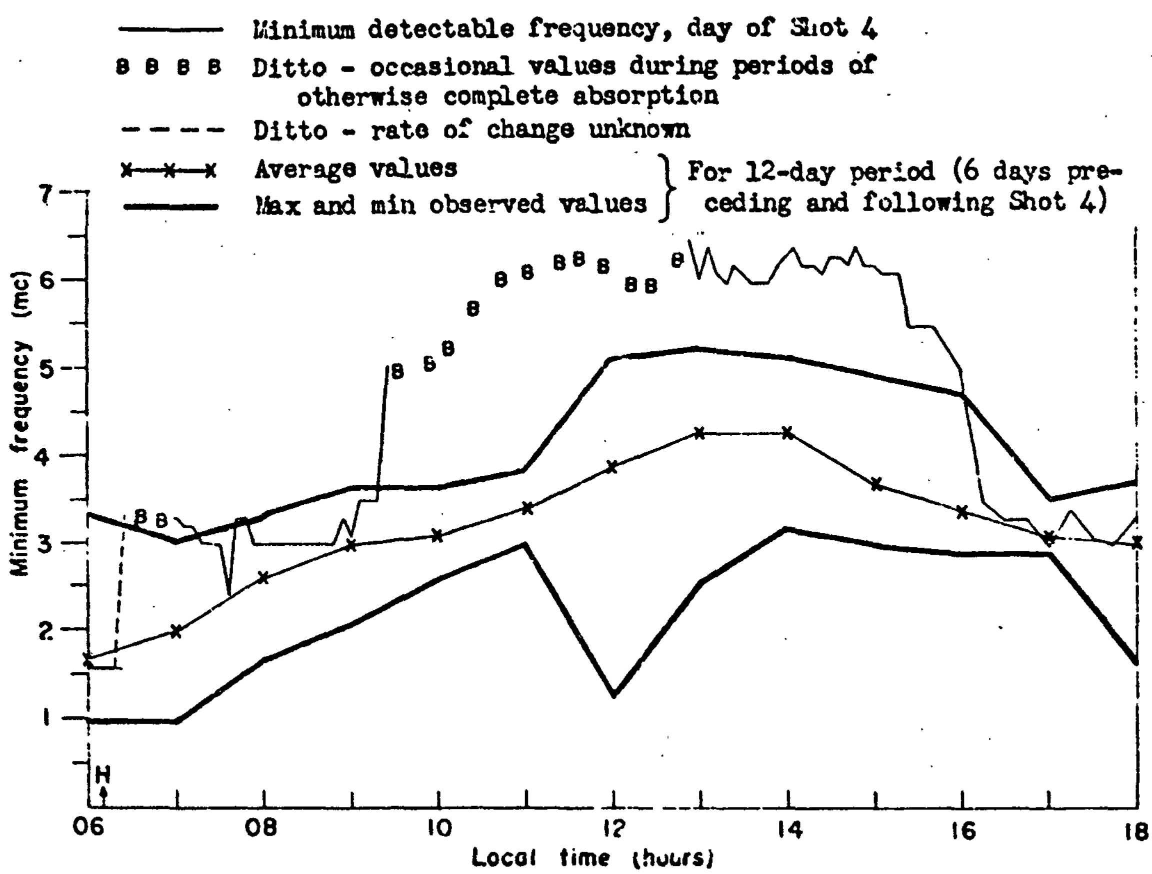



Fig. 3.2 - Minimum Frequency Detected at Site Elmer for Day of Shot 4, Compared with Normal Values

The late absorptive effects of Shot 4 observed at Site Elmer (Fig. 3.2, 0915 to 1600 hours) were found also in the data taken there following Shots 1, 2, and 5, but not 3, as shown in Table 3.1. This table and the corresponding Table 3.2 for Rongerik were compiled from a thorough examination of the scaled data. Although there was, of necessity, a certain amount of subjective interpretation (due to definition of "normal" and to some erraticism of absorption), Tables 3.1 and 3.2 present a fairly accurate overall picture. There appears to have been striking similarity, for all four very large shots, in the ending time of complete absorption at Rongerik and of the renewed absorption at Elmer, as well as in the time of return to normal minimum frequencies at each location.

TABLE 3.1 - Absorption at Site Elmer

| Shot | Time (180°) | Complete absorption | | Renewed absorption | | Min Freqs. Normal by |
|---|---|---|---|---|---|---|
| | | Began | Ended | Began | Ended | |
| 1 | 0645 | + 17 min | + 79m | + 1h52m | * | * |
| 2 | 0630 | Before shot | No separation | | +6h46m | +12 h 30m |
| 3 | 0620 | " " | + 31m | (None) | (None) | + 0 h 32m |
| 4 | 0610 | + 10 min | + 48m | + 3h6m | +6h46m | + 9 h 50m |
| 5 | 0610 | Before shot | + 59m | + 1h36m | +8h6m | + 9 h 50m |
| 6 | 0620 | **Not known | No separation | | +2h5m | **Not known |

* Equipment failed at plus 3 h 45 m - absorption still present.
** Photographic Failure - direct visual observation only.

TABLE 3.2 - Absorption at Rongerik

| Shot | Time (180°) | Complete absorption | | Min. Freqs. Normal by |
|---|---|---|---|---|
| | | Began | Ended | |
| 1 | 0645 | *+3 min | +33 min | +42 min |
| 2 | 0630 | Before shot | +38 min | +53 min |
| 3 | 0620 | " " | +20 min | +25 min |
| 4 | 0610 | " " | +39 min | +45 min |
| 5 | 0610 | *+1 min | +28 min | +53 min |
| 6 | 0620 | Station not operating | | |

* Conditions before shot time were becoming poor.

One difficulty arose in interpreting the early absorption: there was a weakness or complete lack of echo traces over the entire frequency range during early morning hours even on days when no shot took place. This has been attributed to a combination of low receiver-gain settings and antennas with poor low-frequency sensitivity.

Despite the above-mentioned difficulty, it seems possible to state that, on shot days, there appear to have been three periods of absorption which more or less overlapped. A separate cause may probably be attached to each. First, due largely to the equipment inadequacies discussed above, the normal pre-sunrise decrease caused the signal intensity to fall below the threshold of detectability. Since this coincided with shot time, it accounts for the beginning of what was called complete "absorption" coming just before or after each shot. Second, an effect connected with the overhead arrival of the shock wave in the lower ionospheric layers was expected to start at about plus 15 min at Rongerik and about plus 20 min at Elmer for shots at Bikini. This effect is the increased absorption of radio signals passing through the highly disturbed D region. From Tables 3.1 and 3.2, it appears that this effect lasted until about plus 35 min at Rongerik and somewhat longer at Elmer (which is about 50 miles more distant from Bikini). The third period of absorption, which seems to have occurred only at Elmer, began about 1 1/2 to 3 hr after Shots 1, 4, and 5, and an indeterminate time after Shot 2. It lasted until about plus 10 hr (plus 12 1/2 hr for Shot 2). A conjectural explanation of this protracted effect is given in Section 4.1. The lengthy absorption after Shot 6, detonated across the Eniwetok Lagoon from Site Elmer, may be attributable to a similar cause.

## 3.2 SPORADIC-E EFFECTS

In common with results of previous ionospheric experiments connected with nuclear tests, a tremendous amount of sporadic-E activity occurred following all shots, as evidenced by the data taken at Rongerik. At Elmer, the data were very scanty due to absorption (see Section 3.1) and equipment inadequacy, but occasional glimpses ofunusual sporadic-E returns indicated that E-region conditions there were similar to those above Rongerik.

In order to obtain a quantitive comparison between post-shot and normal sporadic-E conditions, the graph of Fig. 3.3 was plotted. The normal curve (dashed) depicts hourly median values of highest sporadic-E frequency (fEs) at Rongerik for three weeks prior to Shot 1; it is placed with reference to the time axis so that zero time for it corresponds to the average zero time for Shots 1 and 2. Curves for Shots 1 through 5 (solid) connect points each representing the average, over a 15-minute period centered thereon, of the highest sporadic-E frequency found each minute (each five minutes, for Shot 3).

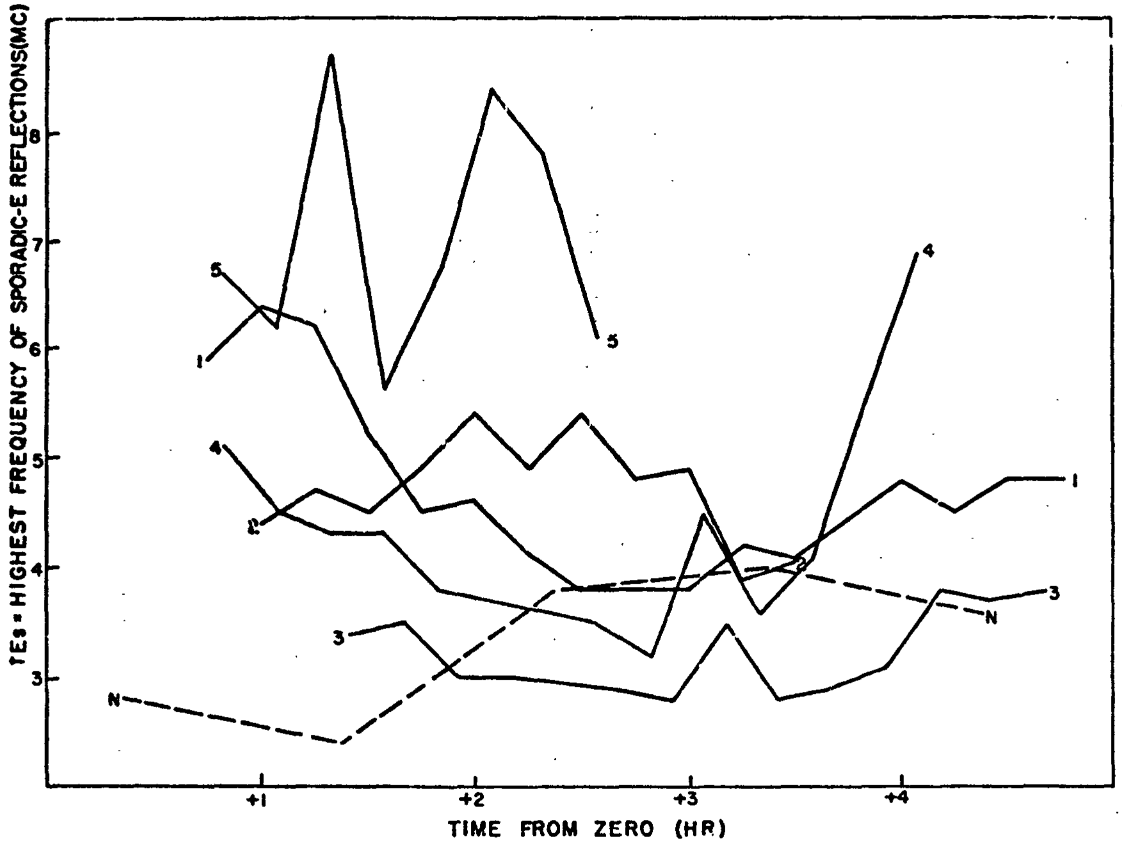



Fig. 3.3 - Highest Frequency of Sporadic-E Reflections at Rongerik following Shots 1 through 5, Compared with Normal Values.

From Fig. 3.3 it is seen that the highest sporadic-E frequencies were decidedly above normal when first observed near plus 1/2 hr (as absorption abated), then came very near to normal value by plus 2 or 3 hr. (The high value suddenly attained near plus 4 hr for Shot 4 seems extraneously caused.[1/])

The curve for Shot 3 is not as much above nor as long above normal as the others. This should not be surprising in view of the small relative yield of Shot 3. The amount of data is insufficient to be conclusive.

1/ Shot 5 apparently occurred on a day when frequencies were above normal even before the shot.

For purposes of comparison, an ionogram for a normal day is given in Fig. 3.4, showing a typical sporadic-E trace from 2.4 to 4 mc at 115 km (intermittent above 3.3 mc).

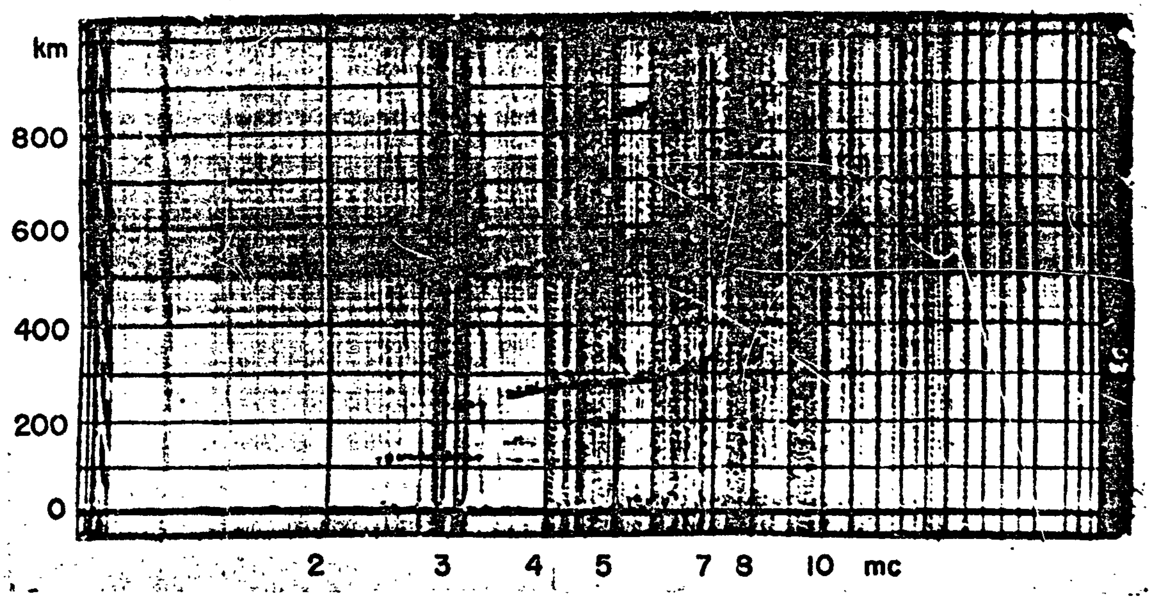



Fig. 3.4 - Ionospheric Record for 0817 hours on a Normal Day, Showing Typical Sporadic-E and F-layer Traces at Rongerik

To illustrate the unusual nature of the sporadic-E echoes observed at Rongerik following the shots, Figs. 3.5 through 3.8 are presented, each arranged to be read from top to bottom, starting at the left, with the elapsed time from zero indicated in hours and minutes. A brief description follows:

<u>Shot 1 plus</u> (see Figs. 3.5 and 3.6)

34 1/2 min - first visible echo of any kind after the shot; Es at 110 km
42 1/2 min - Es at two levels - 110 and 150 km
46 min - Es (at two levels) goes above 8 mc
47 min - Es at several levels
52 min - further development of multiple Es
55 min - more scattering

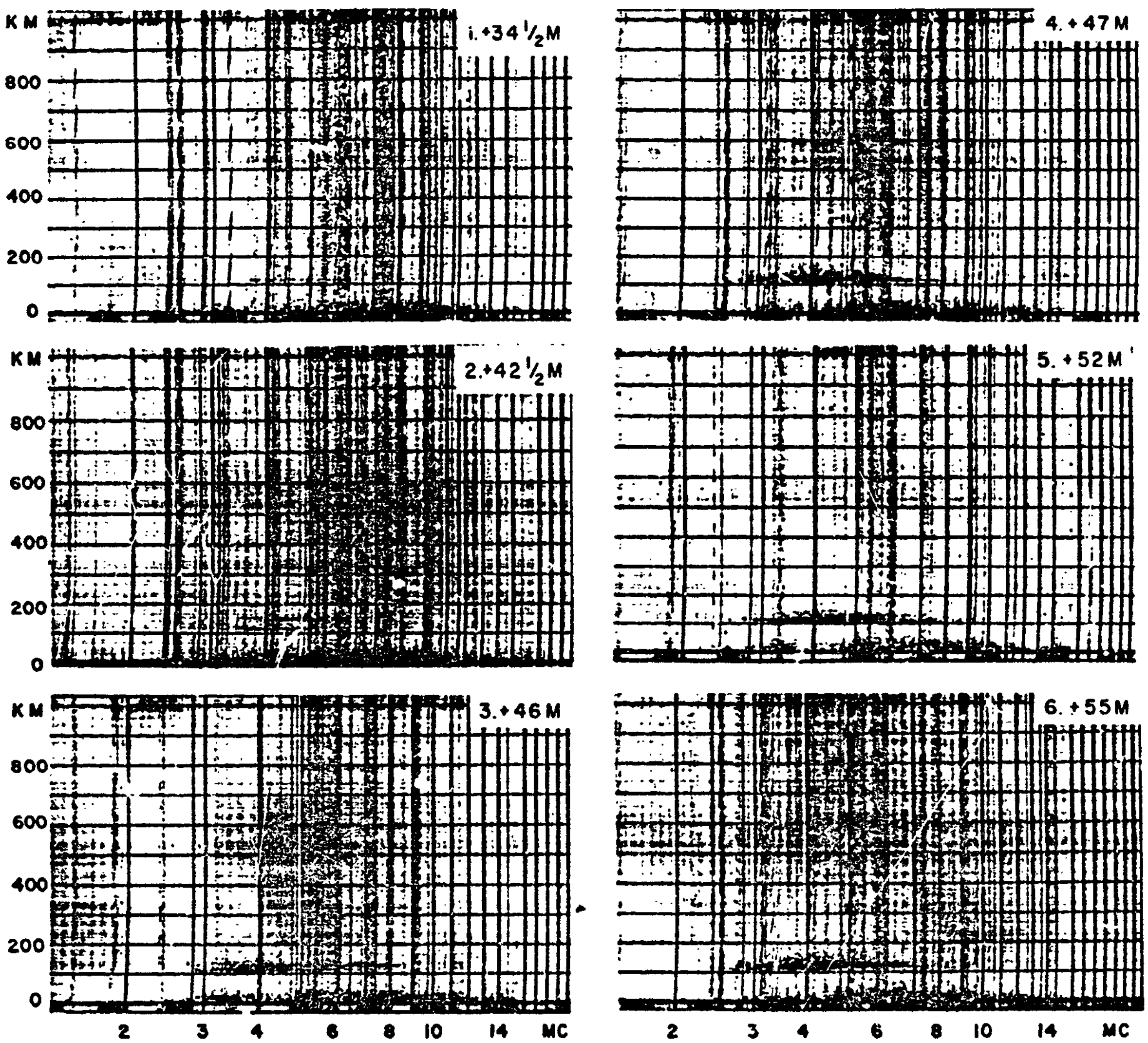



Fig. 3.5 - Ionospheric Records at Rongerik Following Shot 1 by 34 1/2 to 55 min, Showing Sporadic-E Development

59 min - a picture typical of this period showing a strong lower boundary and considerable scatter above

1 hr 18 min - two principal levels of Es (also first indications of F1 at 200 to 300 km, 3 to 4 mc)

1 hr 27 min - Es continues strong but F1 is "seen" through it

1 hr 45 min - Es continues unusual, (F1 ordinary and extraordinary are clear but "spread")

1 hr 59 min - Es less complicated but still unusual, (F1 returns show continued turbulence)

2 hr 14 min - Es still present, (F1 appears to be stratified - it later developed into F2).

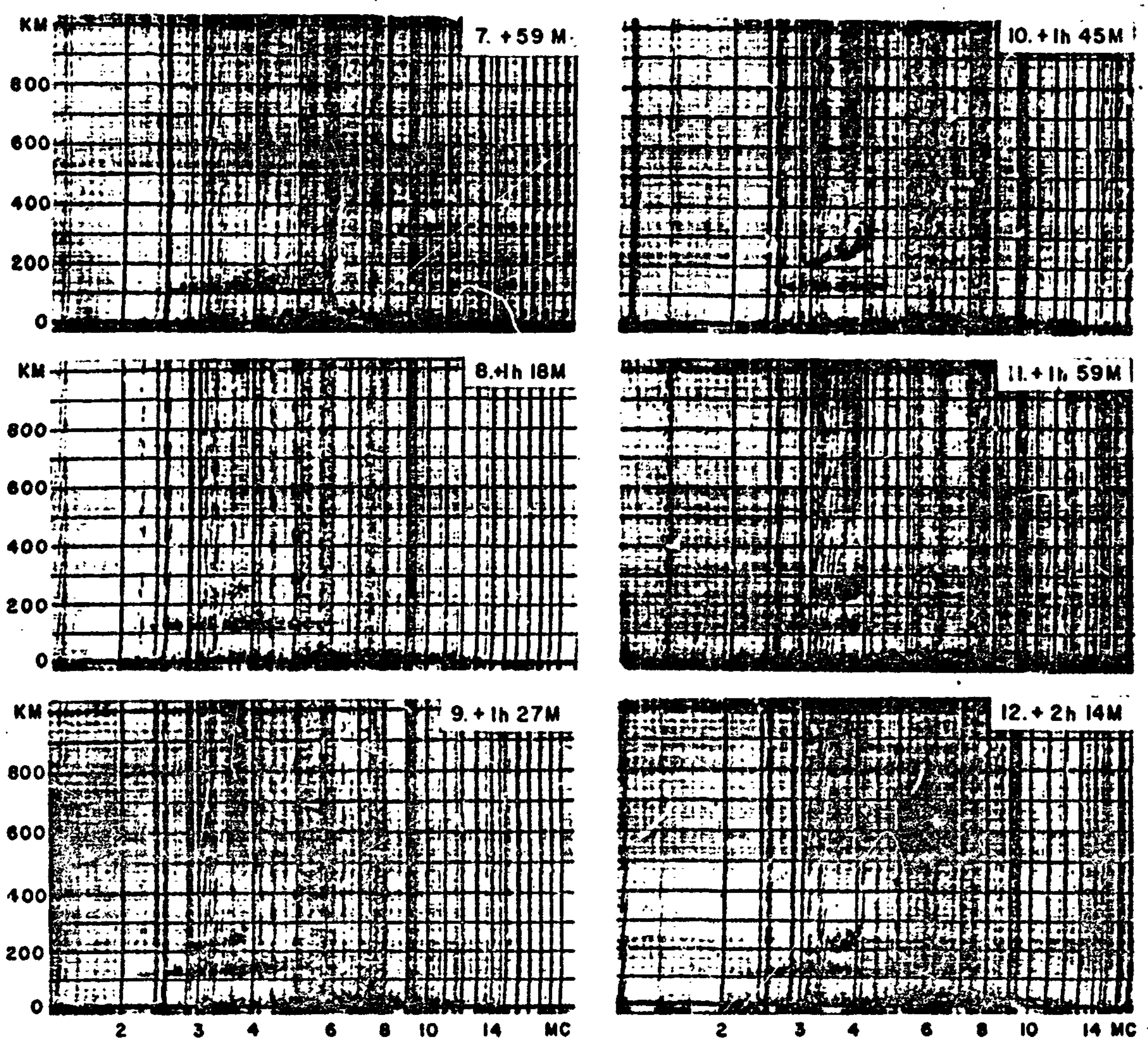



Fig. 3.6 - Ionospheric Records at Rongerik Following Shot 1 by 59 min to 2 hr 14 min, Showing Unusual Sporadic-E and F1 Development

Shot 2 plus (see Fig. 3.7)

39 min - first faint indication of Es (at 110 km just above 4 mc), very weak due to absorption
52 min - "spread" Es echoes, somewhat stronger but still weakened by absorption
1 hr 13 min - many levels of Es
1 hr 34 min - stronger, multiple level Es, typical of half-hour period centered here

1 hr 54 min - Es trace remains unusually thick, (first faint traces of F1 are near 4 mc)

2 hr 23 min - several levels of Es including one at higher frequencies (at 180 km) which may be an oblique return; (Es continued unusual for 45 min more)

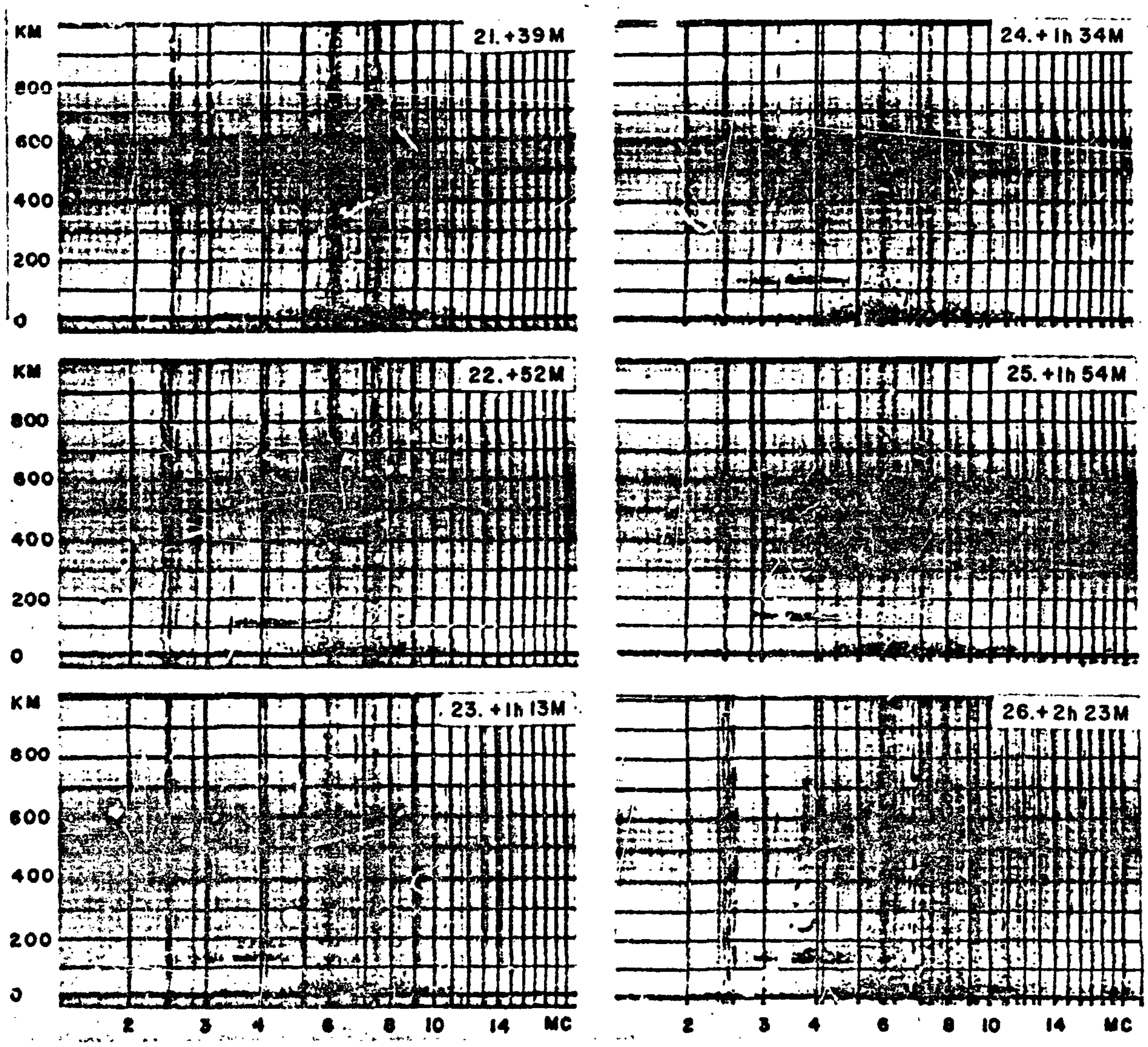



Fig. 3.7 - Ionospheric Records at Rongerik Following Shot 2 by 39 min to 2 hr 23 min, Showing Unusual Sporadic-E Effects

Shot 5 plus (see Fig. 3.8)

40 min - absorption has abated enough so Es can be "seen"
54 min - a strong lower boundary and scattered echoes above
1 hr 11 min - increased scatter
1 hr 25 min - multi-level Es with one level extending to 16 mc
1 hr 42 min - typical post-shot multi-level Es
2 hr 7 min - Es at one level extends up to 19 mc

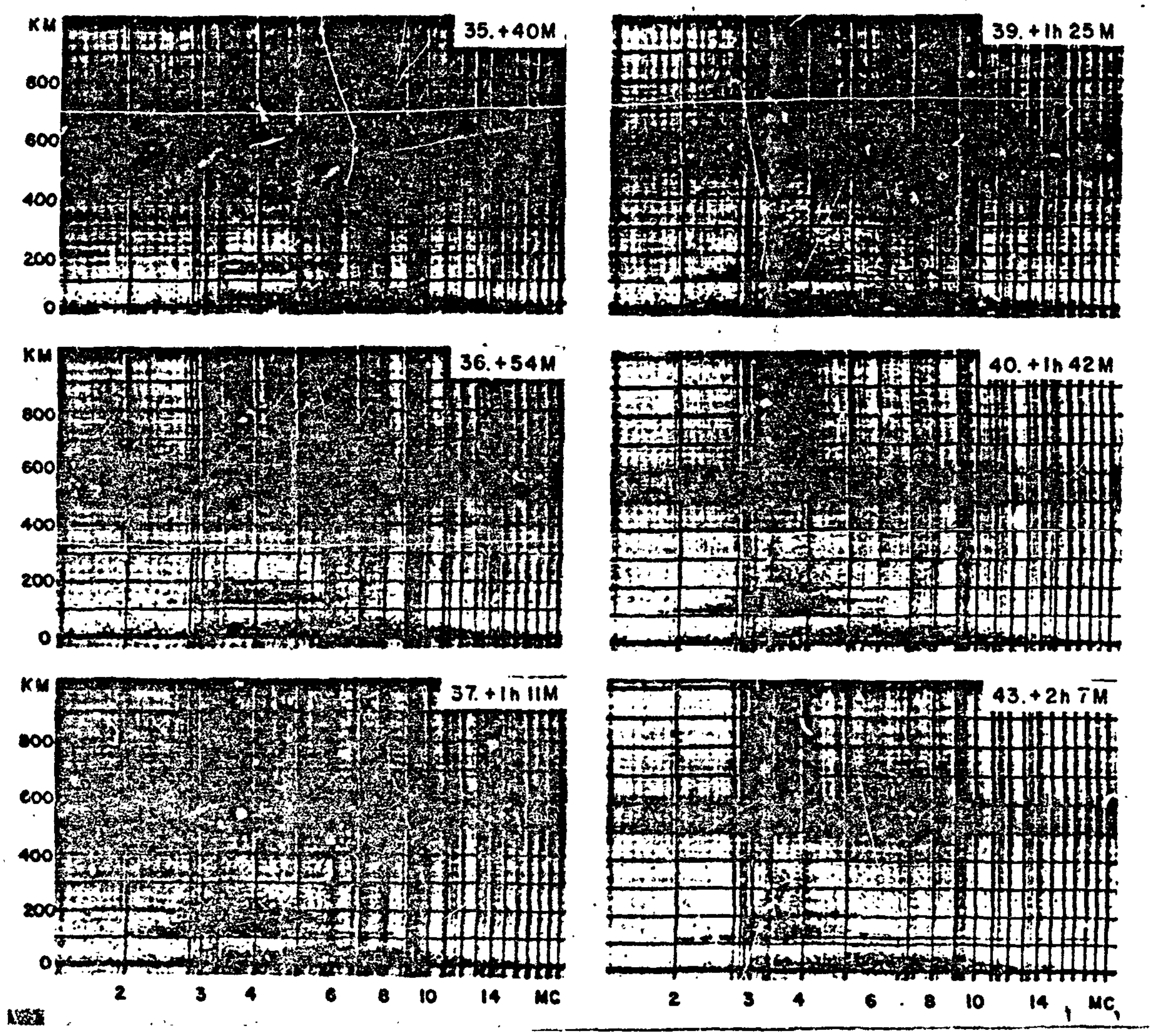



Fig. 3.8 - Ionospheric Records at Rongerik Following Shot 5 by 40 min to 2 hr 7 min, Showing Unusual Sporadic-E Effects

## 3.3 EFFECTS ON THE F2 LAYER

As discussed in Section 3.1, absorption at lower levels precluded observation of the F2 layer, both at Site Elmer and at Rongerik Atoll, for some time after each shot. The greatly prolonged absorption at Elmer rendered that station useless in studying the F2-layer effects. However, sufficient data were obtained at Rongerik to substantiate the rising F2-layer phenomenon first observed after Shot Mike of Operation IVY. Since the ionosphere above Rongerik exhibited differences following the various shots, the results of each detonation are examined here separately, except that Shots 1 and 2, which produced similar effects, are discussed together.

### 3.3.1 Shots 1 and 2

The similarity between the F2-layer effects of Shot 1, Shot 2, and Shot Mike is evident in both the virtual height and critical frequency curves of Fig. 3.9, wherein these two characteristics are plotted against elapsed time measured from zero hour. (For comparative purposes such a presentation is more useful than curves plotted against time of day; it is also justifiable because each of the three shots involved was detonated shortly after ionospheric sunrise and so conditions in the F2 region were similar.) In each case, the virtual height of the layer rose to well above normal and returned to normal at a similar rate and after a nearly equal time interval. Likewise, the critical frequency was depressed below normal by about the same amount after each shot. Thus, the F2 region above the Rongerik station, 243 km east of CASTLE Shots 1 and 2, seems to have undergone perturbations physically similar to those which had been observed at Bikini, 360 km east of Shot Mike, Operation IVY.

As indicated in Fig. 3.9, no returns from the F2 layer appeared in the Rongerik ionograms until about 2 1/2 hours after Shots 1 and 2. Complete absence of returns near shot time has been attributed to equipment inadequacies and to increased absorption associated with arrival of the shock wave in the lower ionosphere (see Section 3.1). Starting at about plus 3/4 hour, the absorption effect abated and sporadic-E and F1 traces took form (see Section 3.2). Neither absorption nor blanketing by sporadic-E, then, is the cause of the failure of any echo to return from the F2 layer at Rongerik between plus 3/4 hour and plus 2 1/2 hours. In order to investigate possible explanations for this lack of F2 returns, let us now consider the manner in which the F2 layer began to appear in the ionograms.

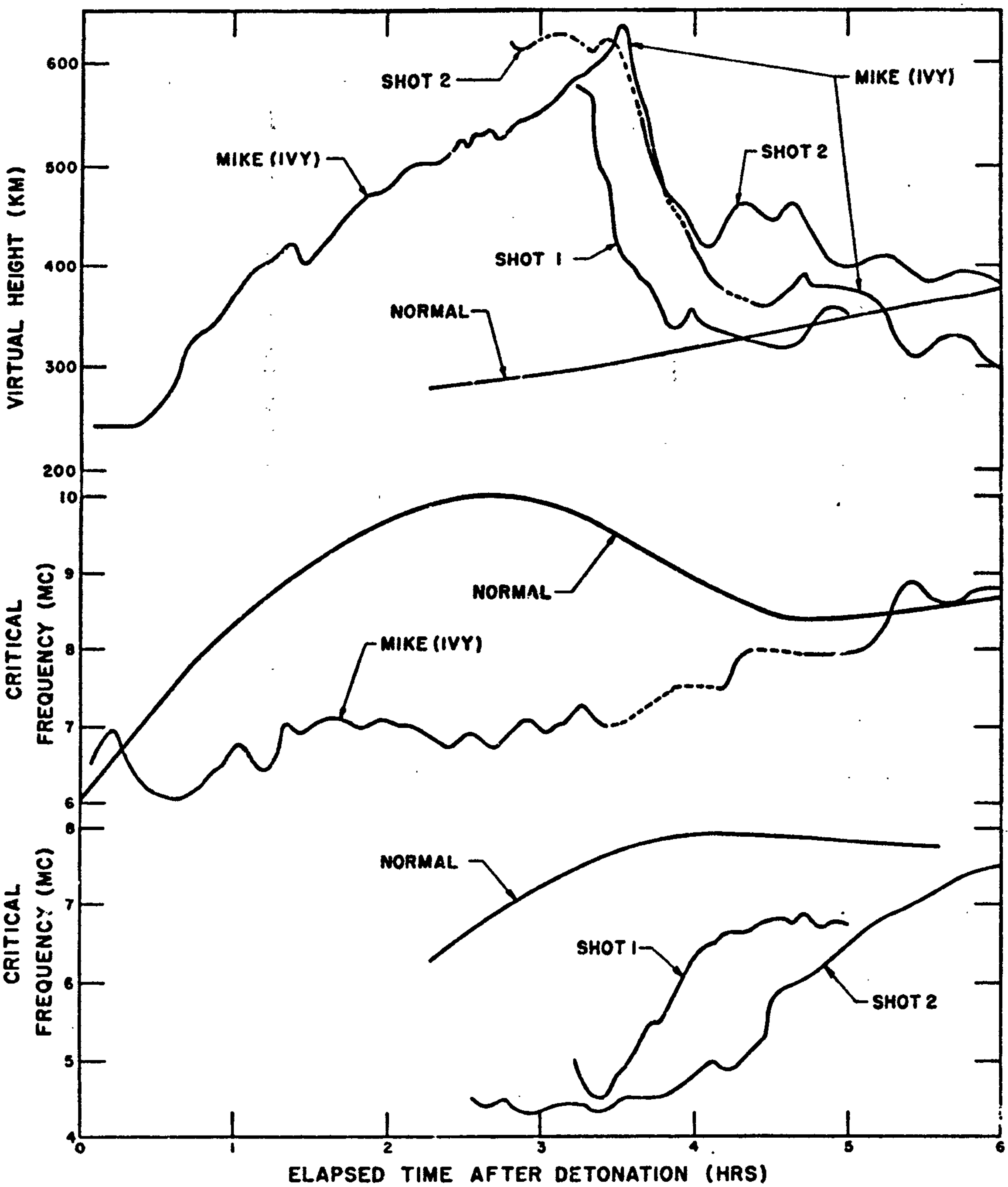



Fig. 3.9 - F2-Layer Virtual Height and Critical Frequency at Rongerik Following Shots 1 and 2 and at Bikini Following Mike Shot (Operation IVY), Compared with Normal Values

The first indications of returns from above the F1 layer (see top two ionograms of Fig. 3.10) were weak echoes appearing in scattered areas above 850 km between 4 and 5 1/2 mc. These early returns did not have regular shapes which would yield minimum virtual height and critical frequency data, nor did they show consistency from one record to the next. The F2 echoes continued to be irregular and sporadic for about 45 minutes, soon beginning to appear over a greater range of heights. There was a prevalence of returns in the region of 600 to 700 km, as well as in the original 850 to 1000 km region, typified by the lower two ionograms of Fig. 3.10. (The right-hand example also includes one of the less-frequent returns at heights between these two regions, possibly oblique or the extraordinary ray, but not significant alone). The irregular echoes took shape gradually and became adequate for scaling by 3 1/4 hours after both shots, with two short periods scalable somewhat sooner in the case of Shot 2 (see Fig. 3.9).

The study resulting in the above generalized description of the F2-layer reappearance led to the hypothesis that there were maxima of ion density at two levels, both extraordinarily high, with the ion density of the higher stratum greater than that of the lower. Under some circumstances, such a condition would yield an F2 trace having the appearance of two distinct layers. This did actually occur frequently between about 3 1/2 and 4 hours after Shots 1 and 2. (See Fig. 3.11, particularly the lower right ionogram which shows this stratification within the F2-layer most clearly).

An accurate calculation of the electron density distribution implied by the shape of the curve in such ionograms is impossible, but a rough approximation of the situation that may have existed will be helpful. In Fig. 3.12 a possible distribution, based on Shot 2 at plus 3 hours 49 minutes, is compared with a purely conjectural normal distribution which might have been present had the disruption not taken place. Discussion of the ion movement which may have caused such a distribution appears in Section 4.2.

Although F2-layer stratification appeared in many ionograms between plus 3 1/2 and 4 hours, the two strata hypothesized above were not simultaneously present in earlier records (as the F2 layer was first reappearing). The upper stratum was often missing, probably due to horizontal inhomogeneity and general irregularity of its ion distribution. Such deviations from the normal layer-like structure may have been responsible also for the frequent lack of returns from the lower stratum. It is more likely, however, that absence of the lower stratum can be attributed to transitory reduction of ion density to values near or below the F1-layer maximum. Furthermore, this latter hypothesis can be extended to explain the complete absence of F2-layer returns between plus 3/4 hour and plus 2 1/2 hours by the assumption that the ion distribution had been such that the F2-layer critical frequency was less than that of the F1-layer.

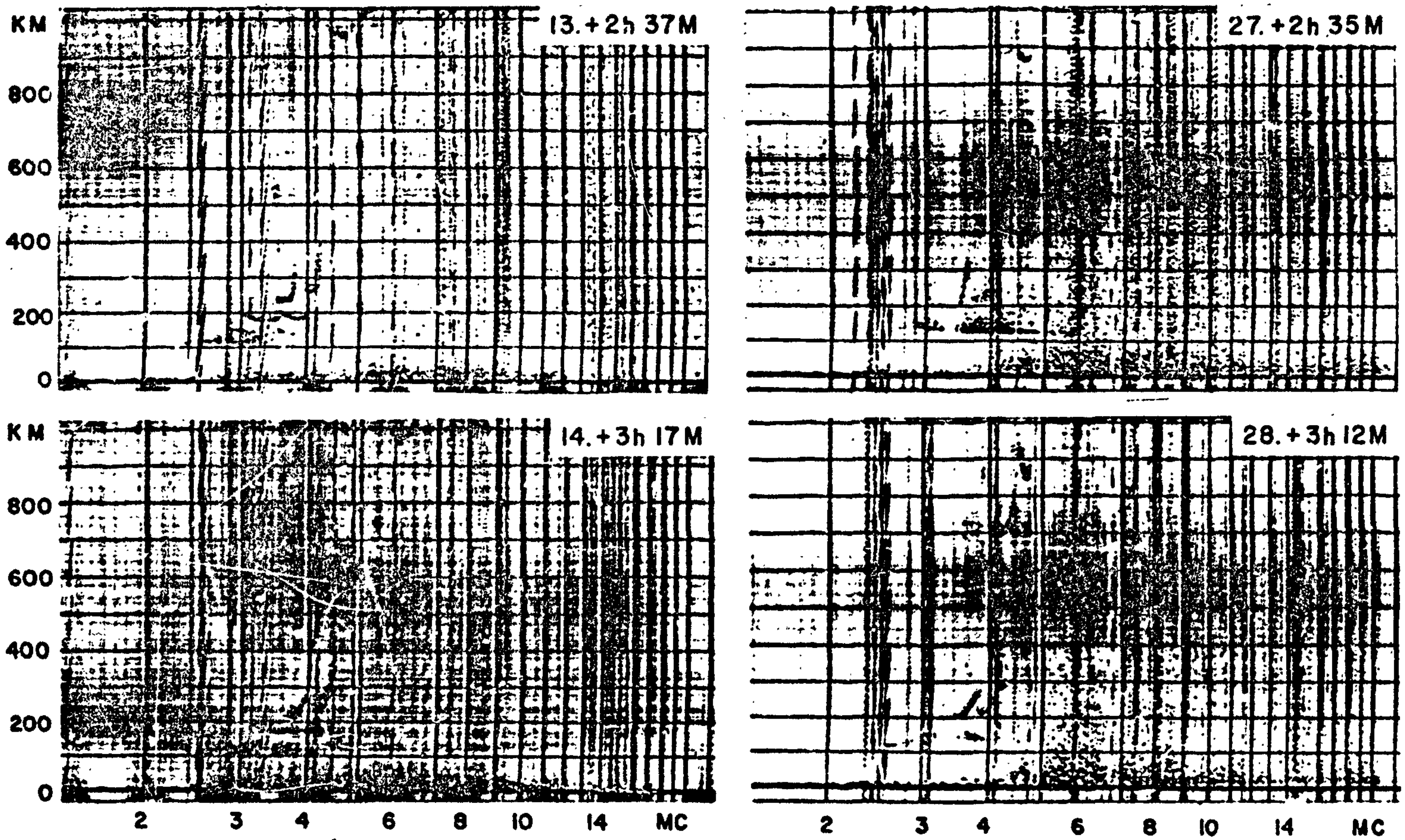



Fig. 3.10 - Ionospheric Records at Rongerik Following Shot 1 (left) and Shot 2 (right), Showing Earliest F2 Returns at about 2 1/2 hr after Each Shot and also F2 Returns from Several Levels about 3 1/4 hr after Each Shot

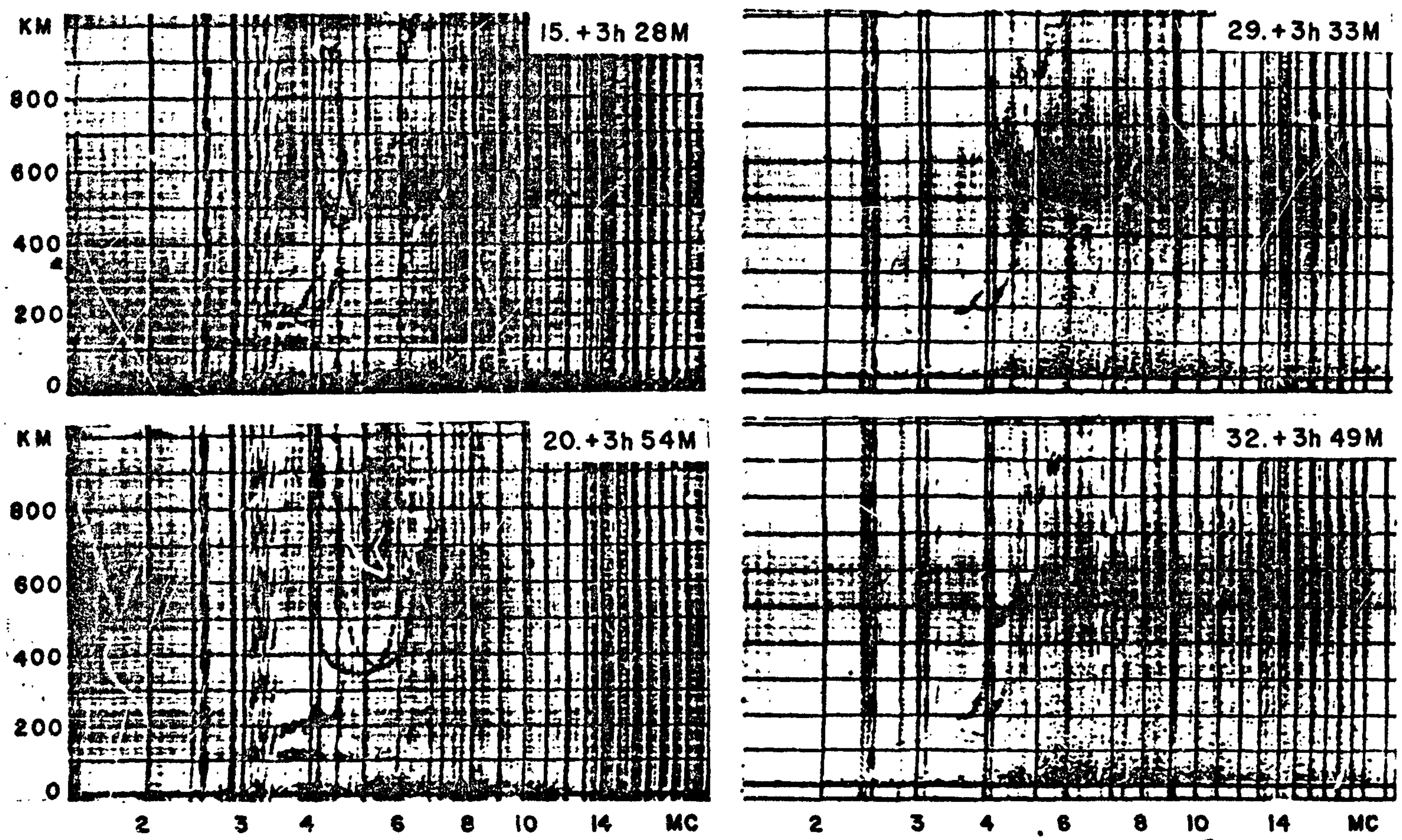



Fig. 3.11 - Ionospheric Records at Rongerik Following Shot 1 (left) and Shot 2 (right) by about 3 1/2 to 4 hr, Showing Stratification of F2 into Two Distinct Layers

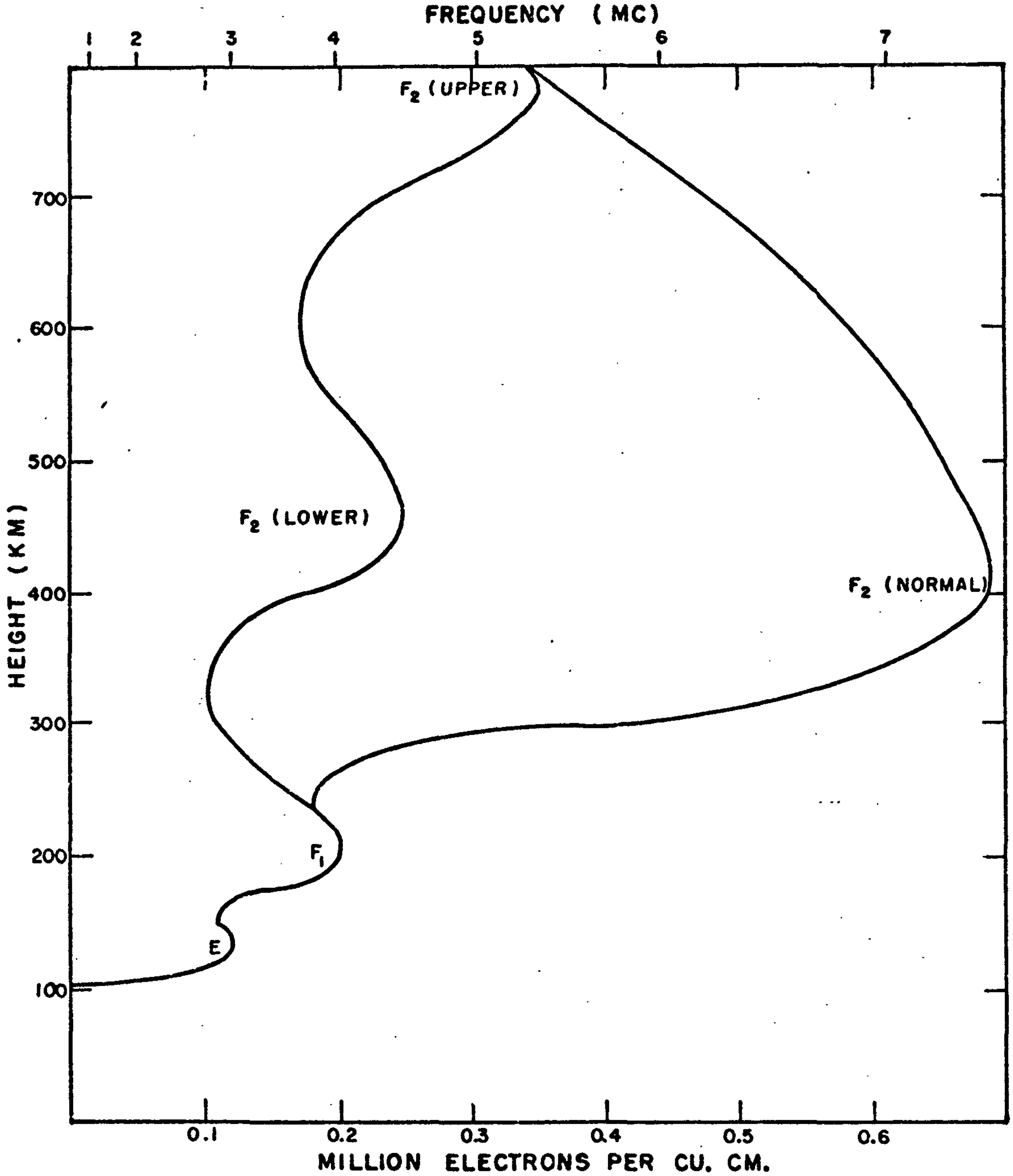



Fig. 3.12 - A Possible Electron-Density Distribution Above Rongerik at Shot 2 Plus 3 hr 49 min, Compared with a Hypothetical Normal Distribution

This is known as a "G condition".[2]

It should be noted that the G condition adduced here does not indicate any major difference between the effects of IVY Mike and CASTLE 1 and 2. It may be seen from Fig. 3.9 that, during Operation IVY, normal values of F2 critical frequency were much greater than during the first month of Operation CASTLE. The F1 critical frequencies, however, were of the same order for these two periods. Consequently, while observation of the F2 layer may have been impossible following CASTLE 1 and 2 because of a G condition, a comparable depression of the F2-layer critical frequency resulting from IVY Mike would not have been sufficient to cause such condition.

Figs. 3.13 and 3.14 give, for Shots 1 and 2 respectively, sequences of ionograms showing the descending virtual height of the F2 layer as it returned to normal. There are indications of oblique returns, particularly in the last picture of Fig. 3.14, evidencing effective layer tilt.

### 3.3.2 Shot 3

No effect on the height or critical frequency of the F2 layer was observed after Shot 3. This is consistent with the inference drawn from Operation IVY that the minimum energy release required to produce the rising-F2 phenomenon is apparently greater than 1/2 megaton (see Section 5.2 of Reference 1).

### 3.3.3 Shot 4

The effect on the F2 layer above Rongerik following Shot 4 was less pronounced than that observed following Shots 1 and 2. The F2 layer was observable almost continuously after the absorption that has been attributed to the effect of the shock wave on the D region had abated. Scaled values of virtual height and critical frequency are shown in Fig. 3.15. Also plotted for comparison are maximum, minimum, and median values of data taken over a period of eleven days prior to the shot. It may be seen that, following the shot, virtual heights were consistently greater than the height

[2] A "G Condition" is an ionospheric abnormality, observed occasionally in all parts of the world, usually associated with a magnetic storm. The condition is simply that the maximum density of the F2 layer (as measured by its vertical-incidence critical frequency) is equal to or less than that of the underlying F1. When an analyst finds an ionogram in which the F1 layer appears and the F2 layer does not, he suspects a G condition. However, positive identification is made only after studying records taken immediately preceding or following the suspected condition. If these records show an F2 critical frequency just greater than the F1 critical frequency, a trend is established and it is a safe assumption that a G condition existed.

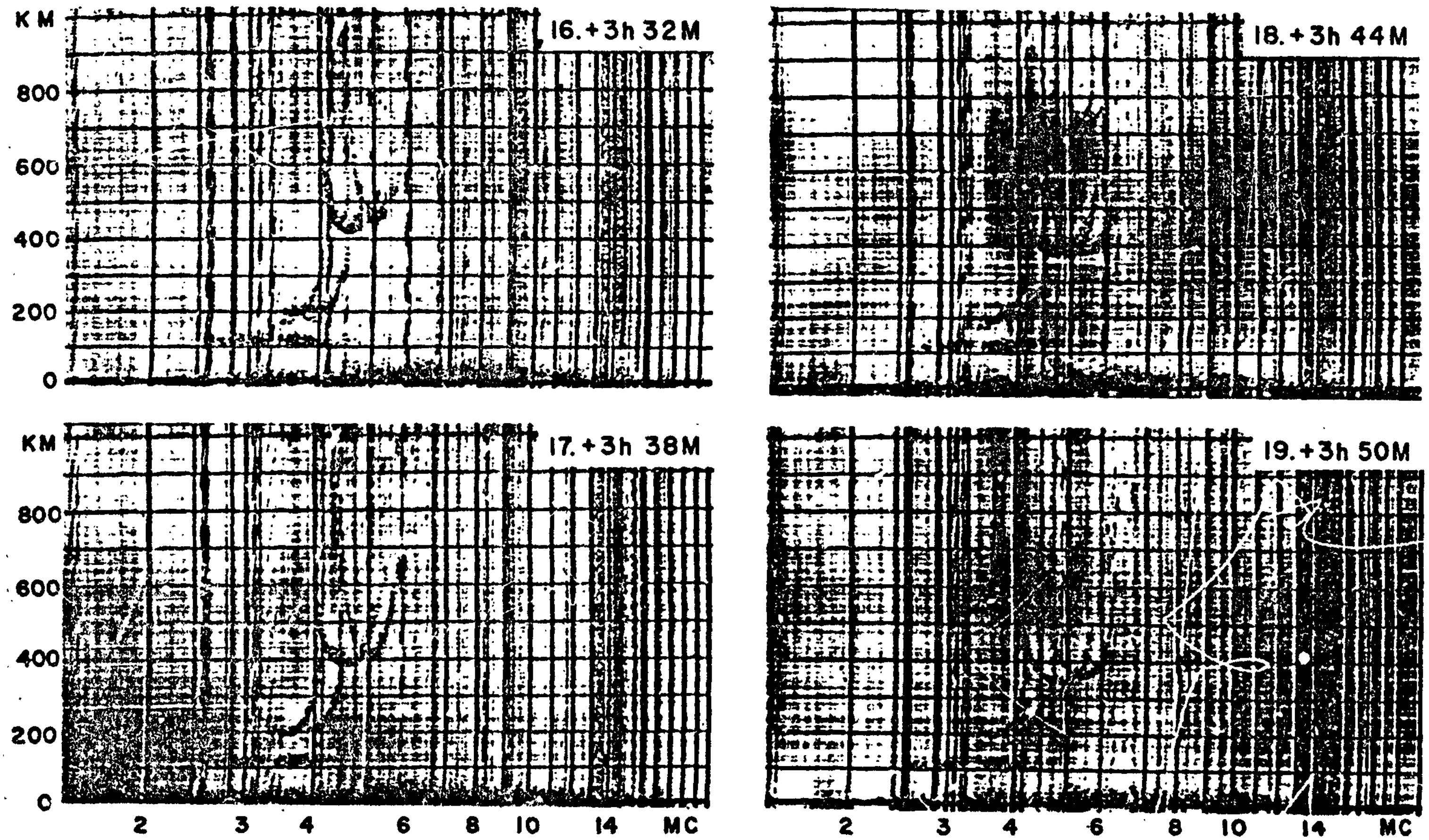



**Fig. 3.13 - Ionospheric Records at Rongerik Following Shot 1 by 3 hr 32 min to 3 hr 50 min, Showing Decreasing Virtual Height of the F2 Layer**

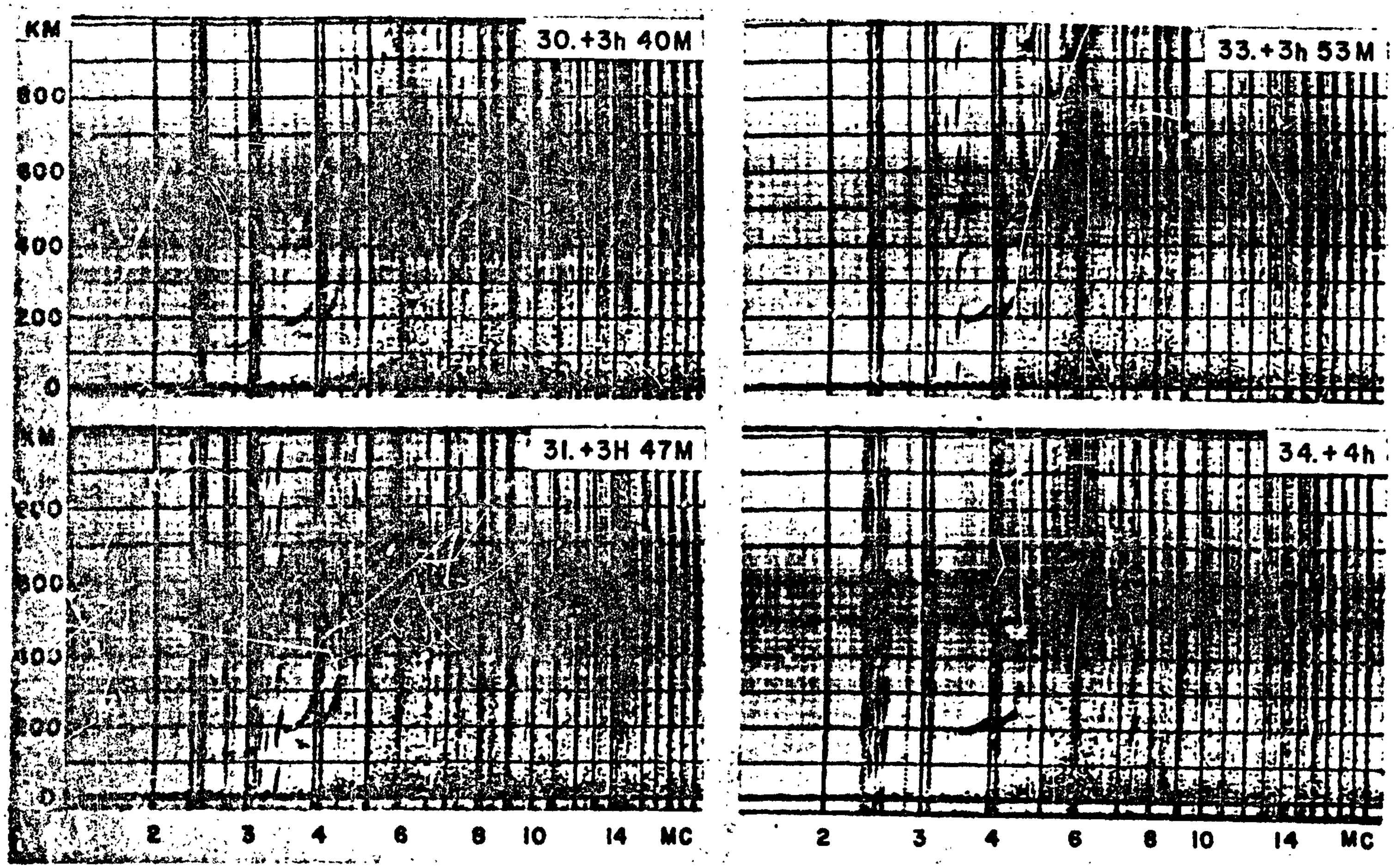



Fig. 3.14 - Ionospheric Records at Rongerik Following Shot 2 by 3 hr 40 min to 4 hr, Showing Decreasing Virtual Height of the F2 Layer



SECRET

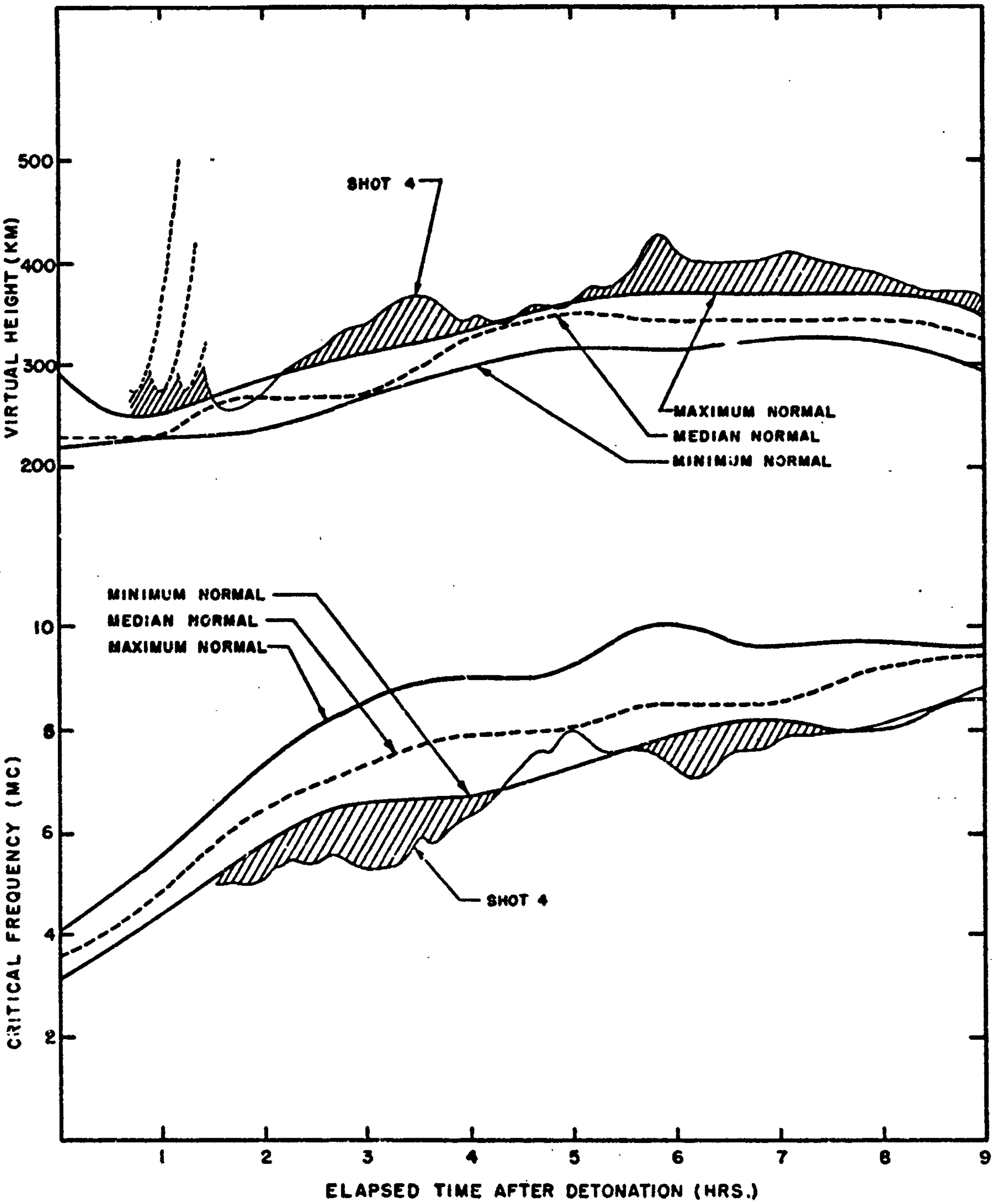



Fig. 3.15 - F2-Layer Virtual Height and Critical Frequency at Rongerik Following Shot 4, Compared with Maximum, Minimum, and Median Normal Values

maxima of the comparison period and critical frequencies were consistently less than the frequency minima. However, the extreme rise in virtual height which occurred after Shots 1 and 2 and Shot Mike (Operation IVY) was not observed at Rongerik following Shot 4.

If there was a region of marked upward displacement of the F2 layer resulting from Shot 4, as seems likely, then it occurred above another geographical location. The most pronounced evidence of abnormal conditions occurred in the ionograms recorded during the period from plus 40 min, when the F2 layer emerged from absorptive obscuration, to about plus 1 1/2 hr. The weak and irregular echoes from plus 40 to plus 55 min are shown in Fig. 3.16. A series of ionograms from plus 57 to plus 70 min shows an F2 return apparently rising to 500 km (Fig. 3.17).

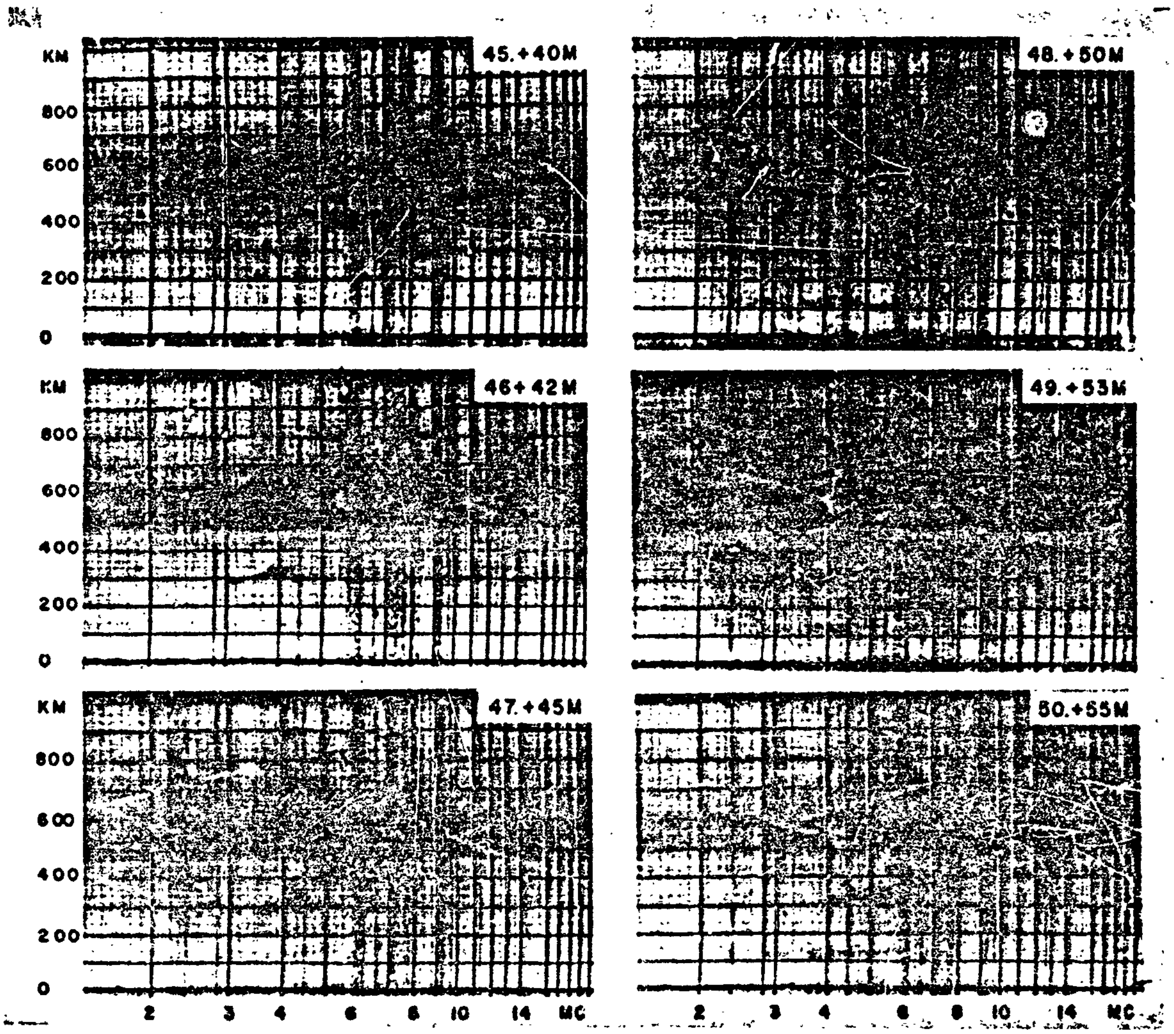



Fig. 3.16 - Ionospheric Records at Rongerik Following Shot 4 by 40 to 55 min, Showing Weak and Irregular F2 Echoes

Clear evidence of obliquity appears in Fig. 3.18, particularly in the first two ionograms (at plus 73 and 79 min), followed by indications of a return to normal (at plus 90 and 95 min). As illustrated by these examples, the F2 returns were very irregular. Interpretation in terms of a critical frequency and a minimum virtual height for the F2 layer was difficult or impossible. Furthermore, throughout much of this period, the lack of consistency from one minute to the next indicated rapid changes in ion distribution, presumably resulting from motion of the air molecules.

Despite the irregularities, an attempt was made to analyze the data recorded during this period. Ranges of height and frequency values for the various groups of echoes in the F2 region were plotted on work sheets. When these were examined, a tendency for the minimum

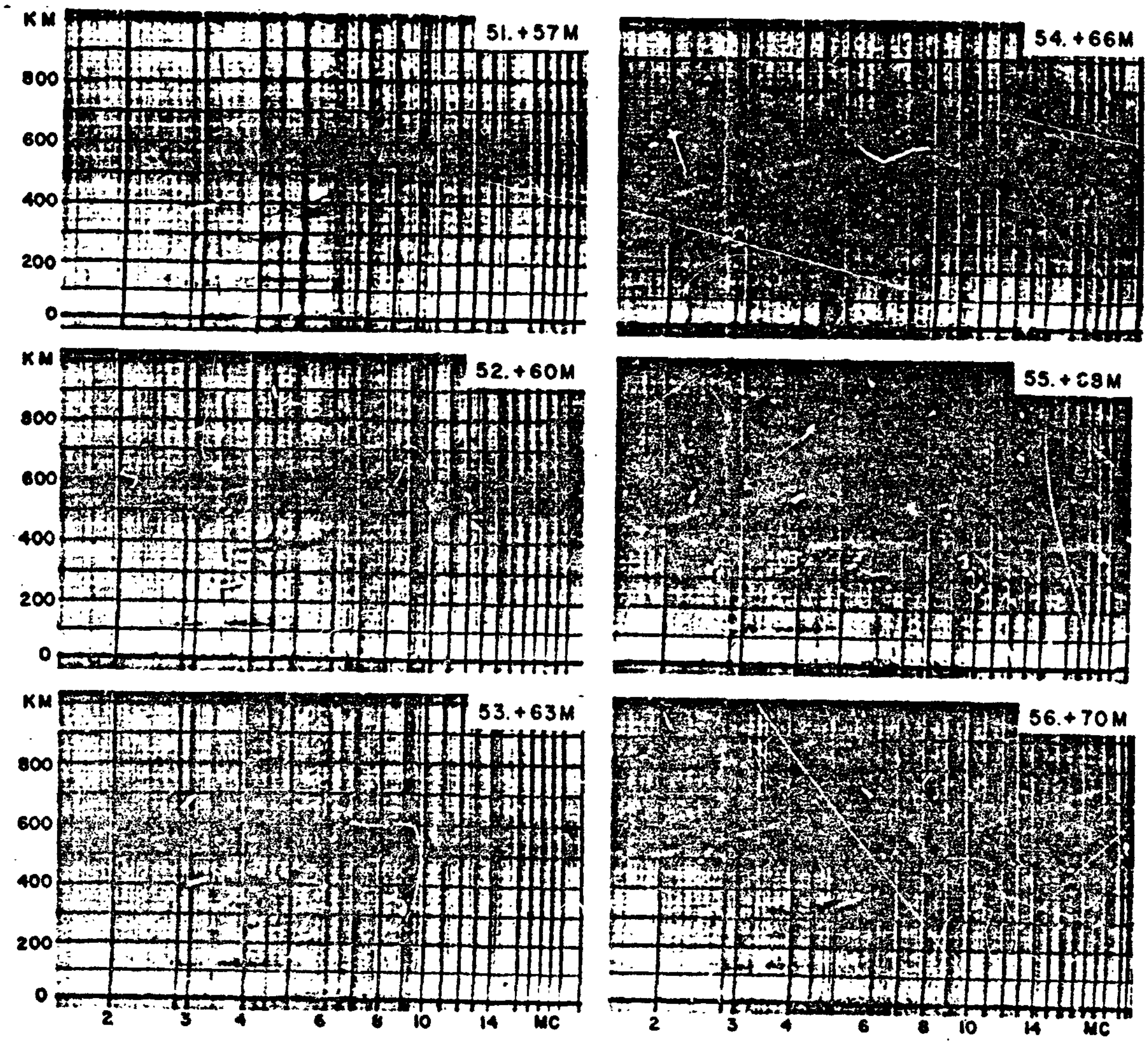



Fig. 3.17 - Ionospheric Records at Rongerik Following Shot 4 by 57 to 70 min, Showing Echo Rising from 350 to 500 km Apparent Height

height to rise was noted in several sequential groups. Consequently, a plot was made with the minimum height of each group represented by a cross (Fig. 3.19). A possible explanation for the increasing heights was immediately seen. The hypothesis is that the rising sequences of points resulted from regions of relatively intense ionization moving horizontally in some direction away from the operating site as part of a radial motion originating above the explosion. (The antennas, though designed for vertical radiation and reception, are not restricted to this direction, and oblique returns are often encountered when horizontal inhomogeneities are present in the ionosphere. The "height" at which such echoes appear is greater by virtue of the greater path length and is, hence, called "apparent height" in Fig. 3.19.)

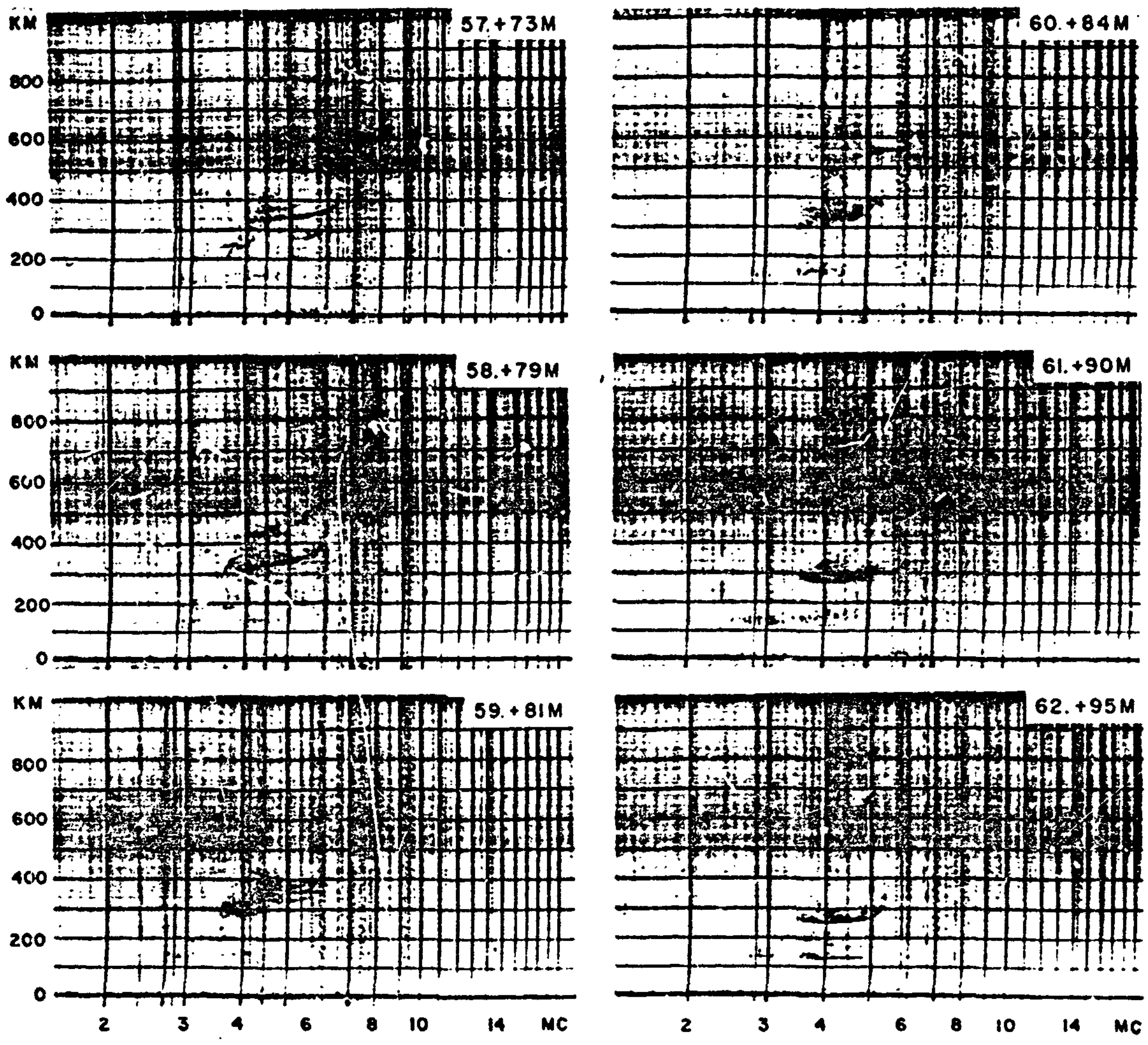



Fig. 3.18 - Ionospheric Records at Rongerik Following Shot 4 by 73 to 95 min, Showing Clearly Oblique Echoes and Trend Toward Normalcy

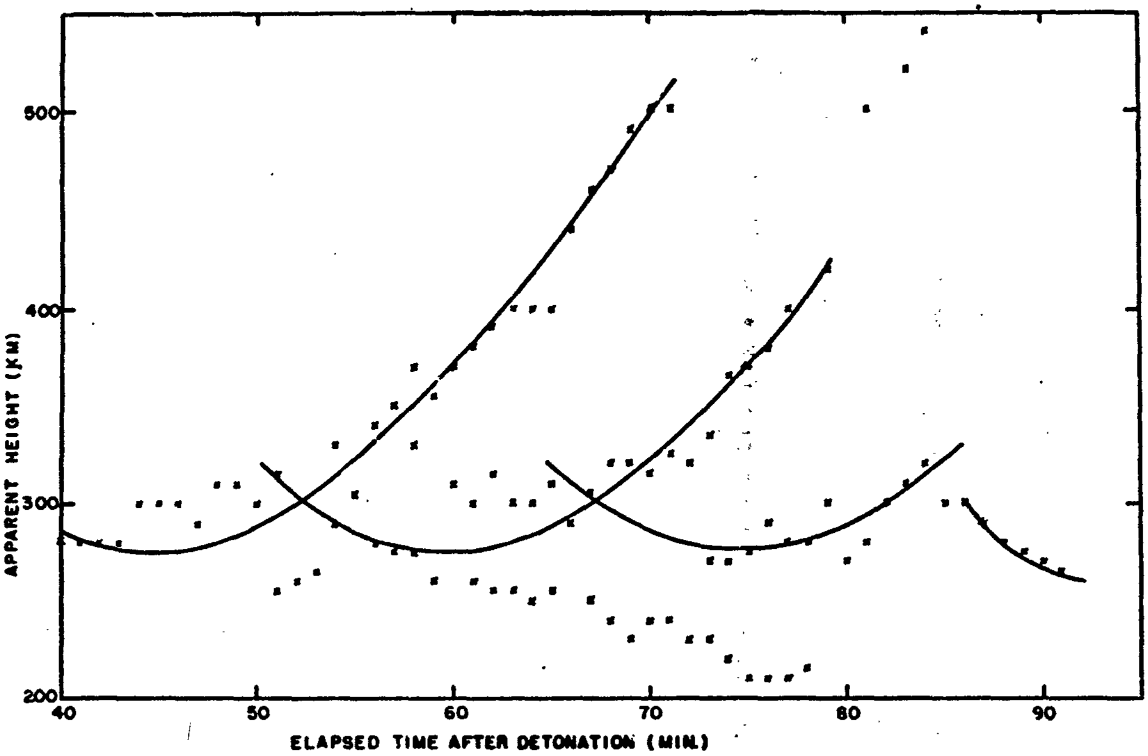



Fig. 3.19 - Apparent Minimum Height of Groups of Echoes at Rongerik from 40 to 95 min after Shot 4, with Fitted Hyperbolic Curves

Assuming that the point of reflection moved horizontally at a height h with a velocity v, passing overhead at time $t_o$, the slant range R at time t may be found from the right-triangular relationship

$$R^2 = h^2 + v^2(t - t_o)^2. \tag{3.1}$$

By selecting three well-distributed points which represent the trend of the sequence between plus 40 and 70 min, it is possible to establish values of h, v, and $t_o$ which yield the first hyperbolic curve shown in Fig. 3.19. Equation 3.1 may be solved for h, v, and $t_o$ in terms of the three selected points ($R_1$, $t_1$; $R_2$, $t_2$; $R_3$, $t_3$) to give

$$\left.\begin{aligned} t_o &= 1/2 \left[ \frac{R_1^2(t_2^2 - t_3^2) + R_2^2(t_3^2 - t_1^2) + R_3^2(t_1^2 - t_2^2)}{R_1^2(t_2 - t_3) + R_2^2(t_3 - t_1) + R_3^2(t_1 - t_2)} \right] \\ v &= \left[ \frac{R_2^2 - R_1^2}{(t_2 - t_1)\,(t_2 + t_1 - 2t_o)} \right]^{1/2} \\ h &= \left[ R_1^2 - v^2 \, (t_1 - t_o)^2 \right]^{1/2} \end{aligned}\right\} \tag{3.2}$$



SECRET

For selected times + 40, + 59, and + 71 min, with corresponding ranges (apparent heights) of 285, 360, and 510 km, respectively, the resulting values are

$$t_o = +44\ 3/4 \text{ min}$$
$$v = 16.4 \text{ km/min}$$
$$h = 274 \text{ km} \tag{3.3}$$

After plotting the resultant curve (from plus 40 to plus 71 min in Fig. 3.19), it appeared that a similar height variation occurred about 15 min later. It was found, in fact, that duplicating the first curve in a position translated just 15 min to the right (later) produced an excellent approximation to the crosses. A further translation of 15 min again resulted in a good fit, but over a smaller region, as is evident in the Figure. The line approximating the points after plus 85 min was fitted merely by eye, and is a duplication of the corresponding portion of Fig. 3.15 on a different scale. The group of points below 260 km developed into the F1 layer.

As may be seen from Fig. 3.19, the first curve, which was obtained using the values of Equation 3.3, agrees well with the trend of the crosses. From this it appears likely that, as hypothesized, there was a horizontal movement of ionization at a height of about 275 km, traveling at about 16 km/min, and passing overhead at Rongerik about 45 min after Shot 4 was detonated. (The second and third curves, following the first by 15 and 30 min, seem to indicate some sort of periodic motion.) The analysis is, of course, subject to inaccuracies of several types, including these: the actual slant range may have been less than indicated because of retardation of the radio wave, the motion may not have been horizontal or of constant velocity, and, furthermore, there is no positive assurance that the sequence of echoes represented a continuous motion.

After an F2-layer trace that appeared nearly normal (last ionogram of Fig. 3.18) and after a brief interval of normal F2-layer parameters (see Fig. 3.15 at about plus 1 1/2 hr), a period of over 2 hours ensued during which the F2-layer height was abnormally great and its critical frequency was abnormally low. Representative ionograms from that period are shown in Fig. 3.20.

### 3.3.4 Shot 5

The effect on the F2-layer above Rongerik took still a different form after Shot 5. Near shot time and up to about 1/2 hr thereafter, as was the case for the other detonations, there were no returns from the F region. Then, sporadic E, which was unusually strong on this day, began to be observed; it "blanketed" any possible echoes from above for at least 1/2 hr (for example, see ionogram at + 54 min in Fig. 3.8). Returns from the F1 layer, (albeit they were extremely "spread" or scattered), were "seen" through the sporadic E starting

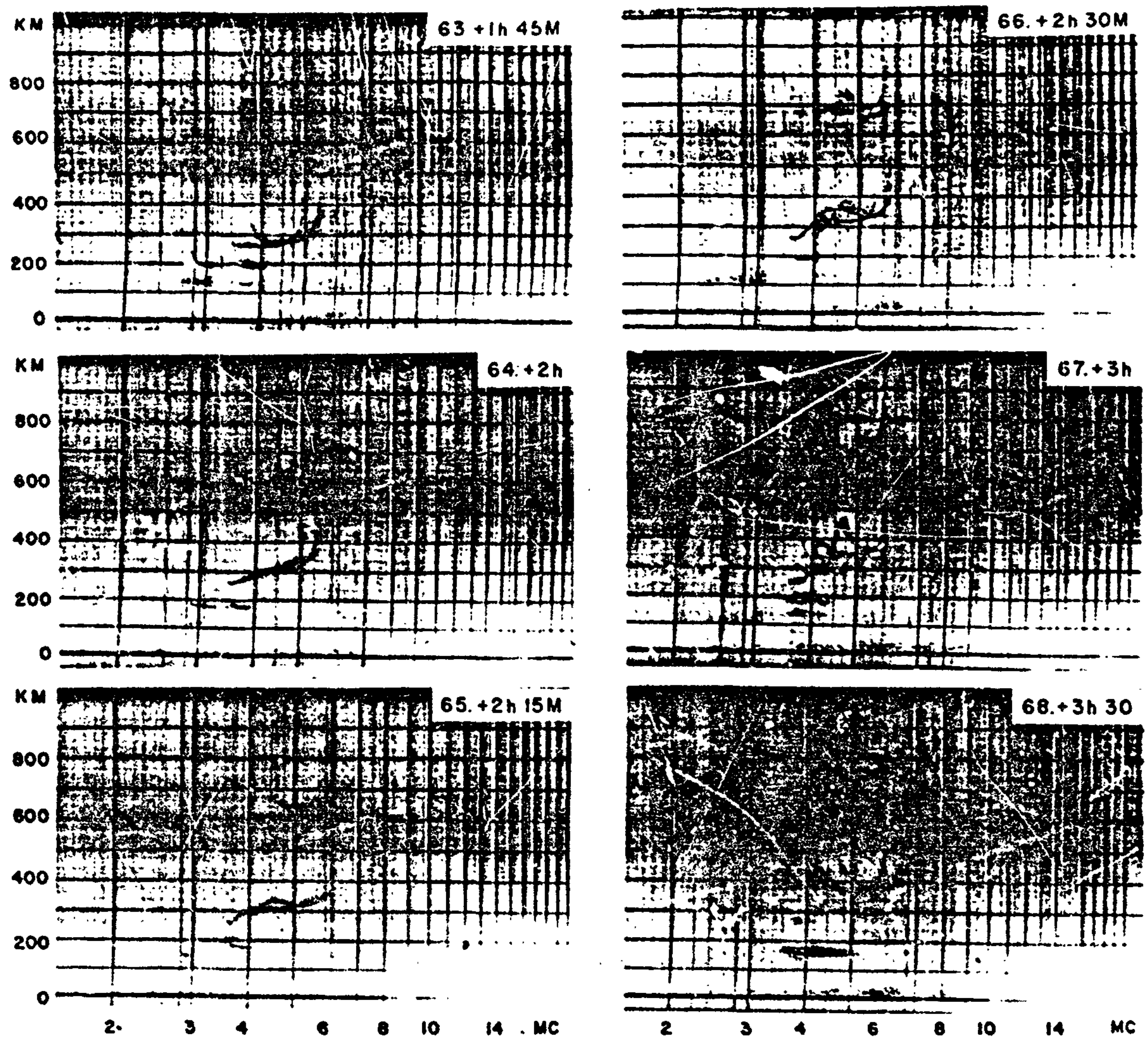



Fig. 3.20 - Ionospheric Records at Rongerik Following Shot 4 by 1 3/4 to 3 1/2 hr (F2 Higher with Critical Frequency Less than Normal)

about 1 hr 10 min after the shot. When the shape of the F1 trace could be discerned (as in the last ionogram of Fig. 3.8), the values of virtual height and critical frequency appeared to be more or less normal.

The F2 layer, however, was mostly absent. On its few appearances, its critical frequency was but a few tenths of a megacycle greater than that of the F1 layer and its form was characteristic of a near "G condition." (See the footnote to Section 3.3.1.) Up to plus 2 hr 22 min, there were only three definite appearances of the F2 layer. Two of these are shown in Fig. 3.21 (at +1 hr 23 min and 1 hr 53 min). Also shown in Fig. 3.21 are a more typical ionogram (+2 hr 5 min) and one ( 2 hr 36 min) representative of the last 15 min of records, when 8 of 15 ionograms showed a segment of an F2 trace.

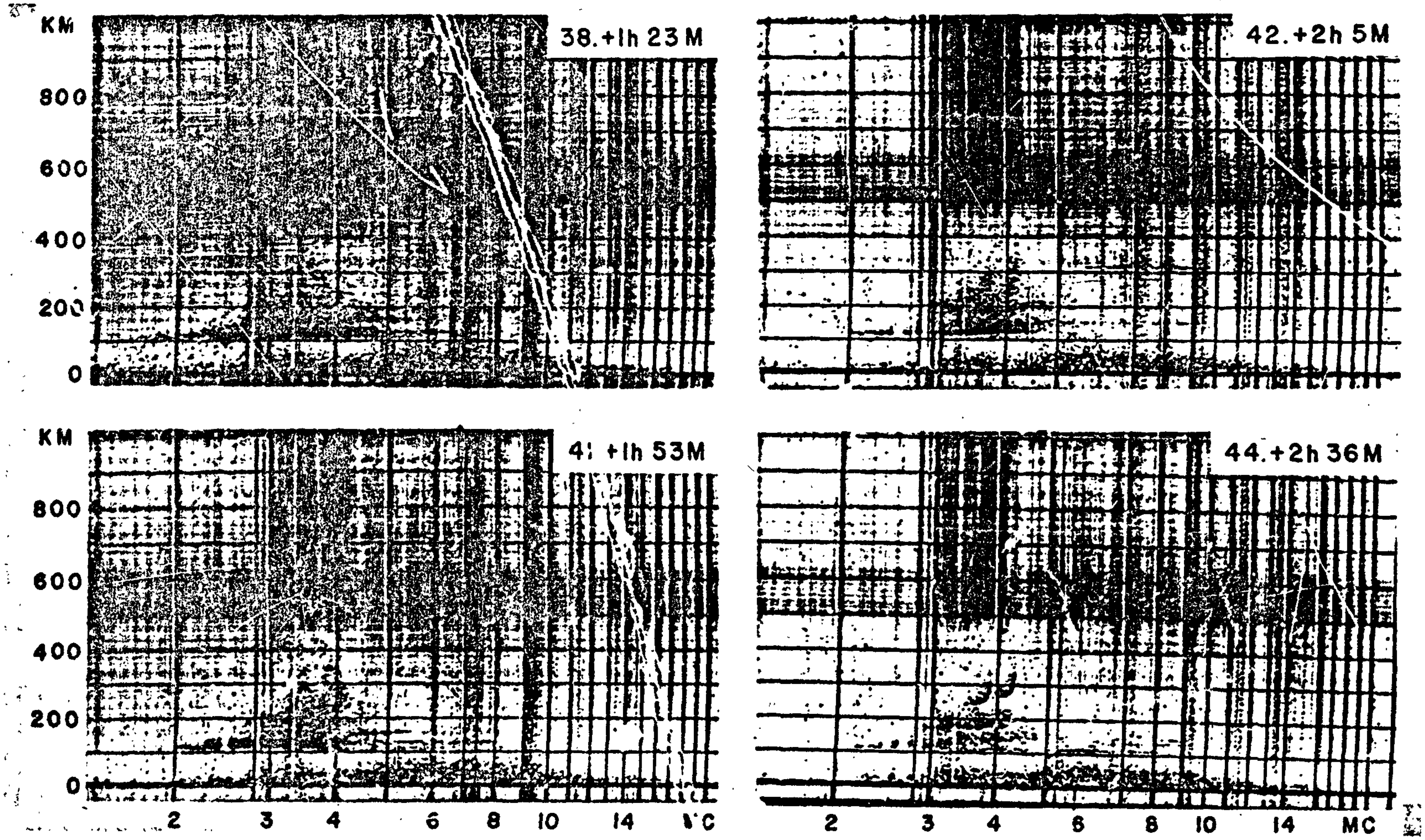



Fig. 3.21 - Ionospheric Records at Rongerik Following Shot 5, Showing Occasional Appearances of F2 Traces

(The F2 echo alluded to may be found between 400 and 500 km and between 3 and 4 mc for the two earlier pictures and just above 4 mc for the later one. In the earlier pictures, the two "smudges" are the magneto-ionically split ordinary and extraordinary F2 traces, in the later one, only the ordinary return is clearly delineated.)

The occasional appearance of the F2 layer in a near G condition renders it a safe assumption that a G condition existed when the F2 layer did not appear. Thus, the data show that the maximum ion density of the F2 layer above Rongerik following Shot 5 was again abnormally low, as it was after Shots 1, 2, and 4. The virtual height at which the F2 layer occasionally appeared was of the order of 350 to 600 km. This range is definitely higher than normal, but must be accepted with some reservations, as, under these conditions, the true height may be appreciably less than the virtual height (scaled from the ionograms) due to the severe retardation that a signal with a frequency near the F1 critical frequency suffers in passing through the F1 layer. Our knowledge, then, of the distribution of ionization in the F2 region following Shot 5 is quite limited. A further limitation is due to the curtailment, perforce, of data after plus 2 hr 37 min.

### 3.3.5 Shot 6

Unfortunately, there are no recorded observations of the ionosphere following Shot 6. The station at Rongerik was dismantled prior to the shot for administrative reasons. At Site Elmer, although visual observations of the oscilloscope were made, the photographic apparatus failed to record.

From the notes made during visual observations at Elmer, it seems that absorption effects prevented F2-layer returns from appearing until plus 2 hr 5 min. Sporadic E appeared then and may have blanketed returns from higher levels until plus 2 hr 39 min, at which time faint F2 returns appeared above 350 km between 5 and 6 mc. A clearer, more layer-like echo soon appeared, and its virtual height dropped from 350 km to 300 km between plus 2 hr 47 min and 3 hr 7 min, remaining near there until plus 3 hr 33 min, and dropping to 285 km at plus 4 hr. During that period, the critical frequency increased from about 5.7 mc at first to about 6.7 mc at 3 hr 7 min, 7.2 mc at 3 hr 33 min, and 7.5 to 8 mc at plus 4 hr.

The scanty visual data indicate the possibility that Shot 6 had an effect on the F2 layer above Elmer. The virtual height, at +2 hr 47 min, was slightly higher than normal, and the 50 km decrease in the ensuing 20 min was contrary to the normal tendency to increase (by about 50 km per hr) at that time of day; the value of 28 km (at +4 hr) was about 90 km below normal height. In addition, the 1 mc increase of critical frequency in 20 min was much more rapid than the normal rate of 0.4 mc per hr between 0900 and 1000 hr; also, critical frequencies above 6.7 mc, as indicated between + 3 and 4 hr, were greater than any occurring at that time of day during the preceding ten days.

## 3.4 DISTANT EFFECTS

It was expected that, following the large CASTLE explosions, effects at distant locations would be found in the F region, similar in nature to those attributed to a disturbance emanating from IVY Mike, starting at a time corresponding to a velocity of about 13km/min. The presence of such a disturbance might be manifested in the ionograms in various ways, principally by the appearance of some sort of oblique echo, that is, a signal which leaves the recorder and returns to it over a path oblique to the earth (instead of vertically), indicating that a portion of the reflecting layer is effectively tilted and not concentric with the earth's surface. Instead of a direct oblique echo, however, one is more likely to find a return which has traversed two or more hops with intermediate reflections from the earth's surface or from sporadic-E ionization. Breaking up of the reflecting layer into several strata might also be seen, possibly indicating a horizontal movement of ions accompanying the moving disturbance. Since all of these irregularities occur naturally from time to time, the likelihood of their resulting from a shot-caused disturbance must be judged by their magnitude, duration, and particularly by their temporal consistency. It is also advisable to note the frequency of natural irregularities for the season and the time of day involved.

### 3.4.1 At Guam

Careful study of the Guam ionosphere records for the period following each shot by 2 to 10 hours reveals that, although the possibility of a disturbance in the F region was indicated several hours after each of the five largest shots, marked and continuing irregularities were present only after the three largest shots, and these were fairly consistent in time of appearance relative to shot time. After each of Shots 1 and 2, there seemed to be a period of relatively minor effects,[3] starting shortly after the expected time of arrival (ETA) based on a velocity of 13 km/min, then an interval when the F2 layer appeared quite normal, and finally a period of unusual disturbance. After Shot 5 there were clearly two distinct periods of unusual disturbance. Re-examination of Shot Mike ionograms revealed that two periods of marked effects had occurred then also. Table 3.3 gives a survey of these overall results.

[3] Although these effects were rather weak, their appearance at this time and for several consecutive records seems to be significant when compared with this result of examining the records for 29 normal days in April: Six instances of oblique echoes found between 0600 and 0800 hours, none of which extended into two consecutive ionograms.

TABLE 3.3 - Effects at Guam

| Shot | ETA at 13 km/min | First Period | Second Period | Indicated Velocity (km/min) |
|---|---|---|---|---|
| 1 | +2h 52m | +3h 15m to 4h 15m | +4h 45m to 8h | **11.5 or 7.8 |
| 2 | +2h 52m | +3h 15m to 3h 50m | +4h 50m to 6h 31m | **11.5 or 7.7 |
| 5 | +2h 52m | +3h 30m to 4h 40m | +5h 50m to 6h 35m | 10.6 |
| Mike | +2h 24m | +2h 24m to 4h 5m | +4h 45m to 6h 15m | 13.0 |

** Doubtful due to questionable first period effects.

Ionograms showing some of the details for Shot 1 are presented in Figs. 3.22 and 3.23, with the elapsed time from zero indicated in

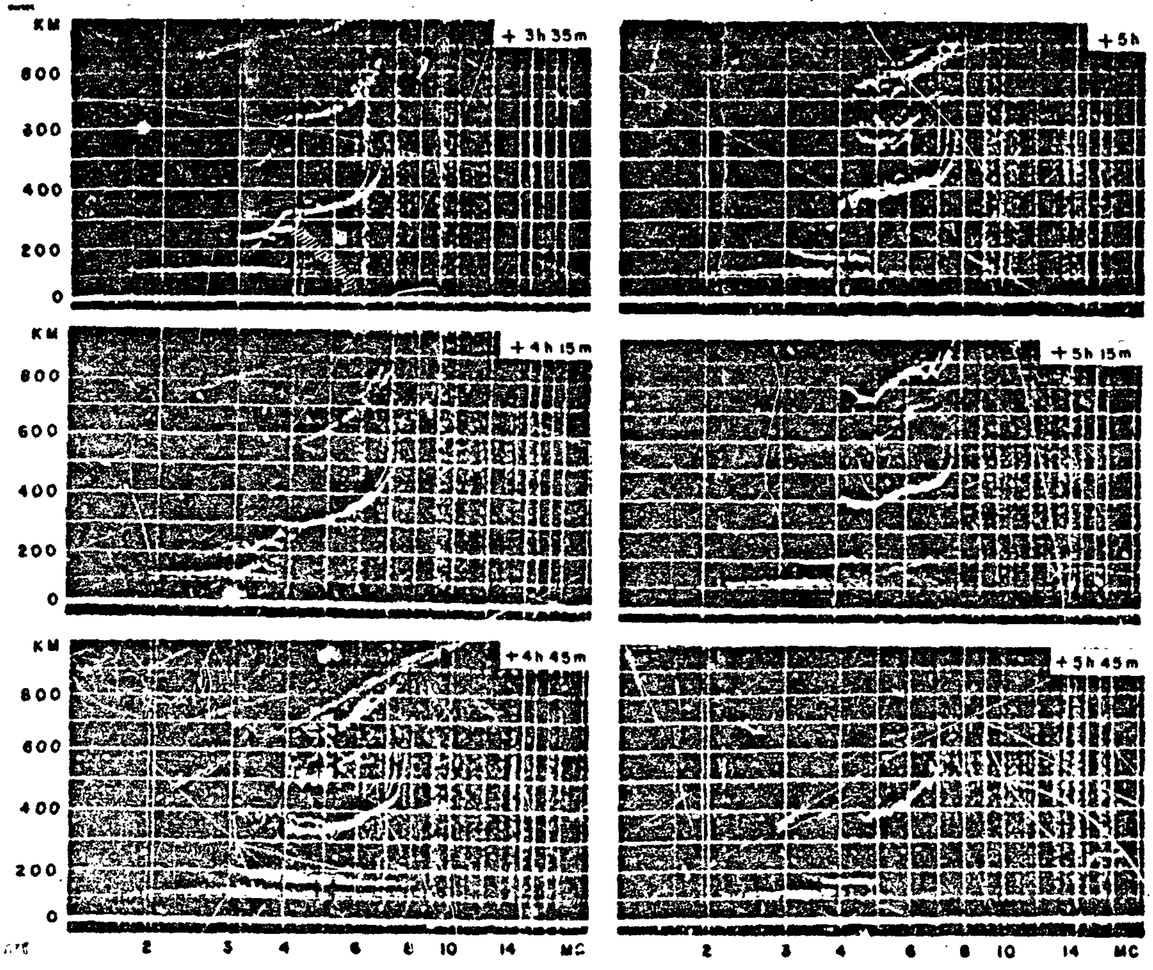



Fig. 3.22 - Ionospheric Records at Guam Following Shot 1 by 3 hr 35 min to 5 hr 45 min, Showing Early Possible Effects and Later Probable Effects

hours and minutes. A brief description follows:

+3h 35m - possible 2-hop oblique echoes from 5.5 to 6.5 mc (an ionogram 20 min earlier exhibited thickening of trace in this region)

+4h 15m - various unexplained traces near 4.5 mc; also peculiarities in both 1-hop and 2-hop traces near 6 mc

+4h 45m - start of second period (much more definite effects); oblique 1-hop echo 4.5 to 5 mc; 2-hop trace at less than twice height of 1-hop trace near 7 mc

+5h - obvious 2-hop obliques; also an oblique M-type echo between 1- and 2-hop traces (via F2, sporadic E, then F2)

+5h 15m - similar to +5h

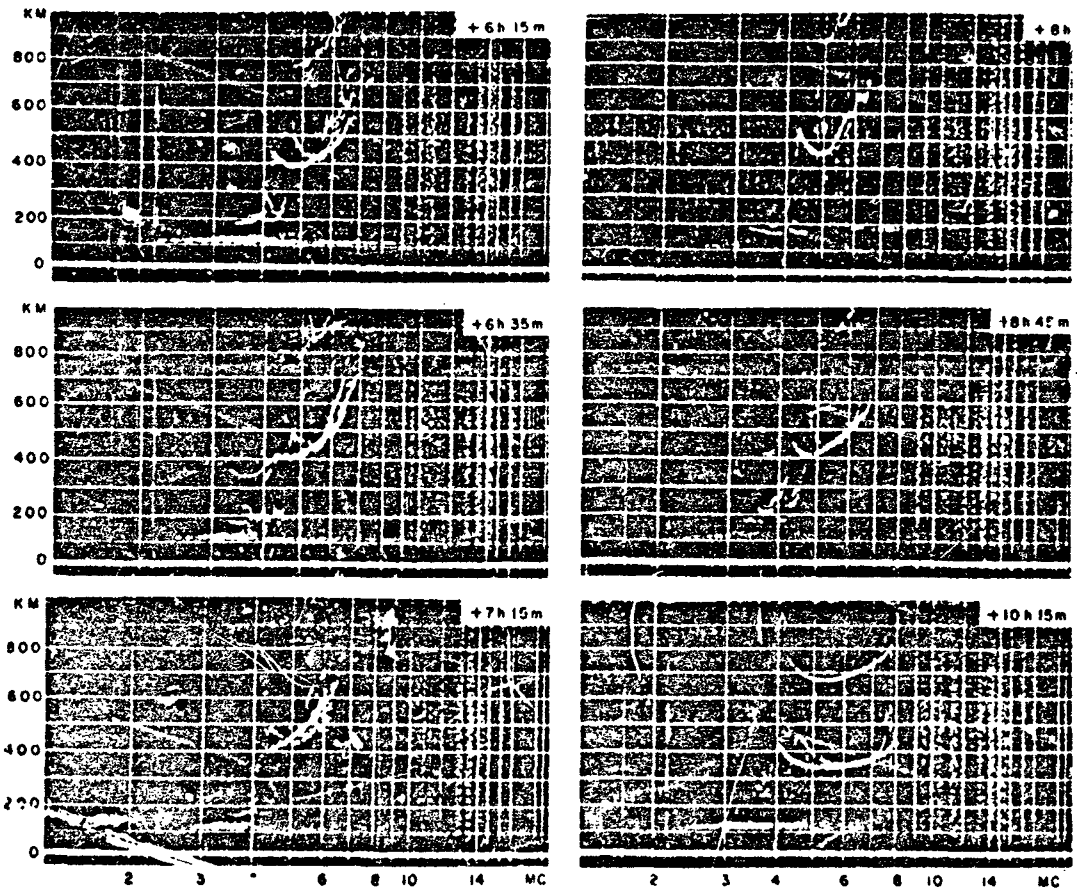



Fig. 3.23 - Ionospheric Records at Guam Following Shot 1 by 6 hr 15 min to 10 hr 15 min, Showing End of Effects and Return to Normal

+ 5h 45m - 1-hop return broken (as if oblique) between 5 and 6mc

+6h 15m - many 1-hop obliques; also 2-hop oblique going above range of oscilloscope (1000 km)

+6h 35m - 2-hop trace at 6mc at 900 km but no 1-hop at 450 km

+7h 15m - obliques clear in 1-hop region; weak 2-hop obliques

+8h - last ionogram with marked peculiarities in F2 region

+8h 45m - F2 getting normal, F1 contains peculiarities

+10h 15m - definitely normal again

To illustrate how unusual are the ionograms in the vicinity of Shot 1 + 5 hr 15 min, a series of records taken at the same time of day (1000 hrs) during the week following Shot 1 is shown in Fig. 3.24.

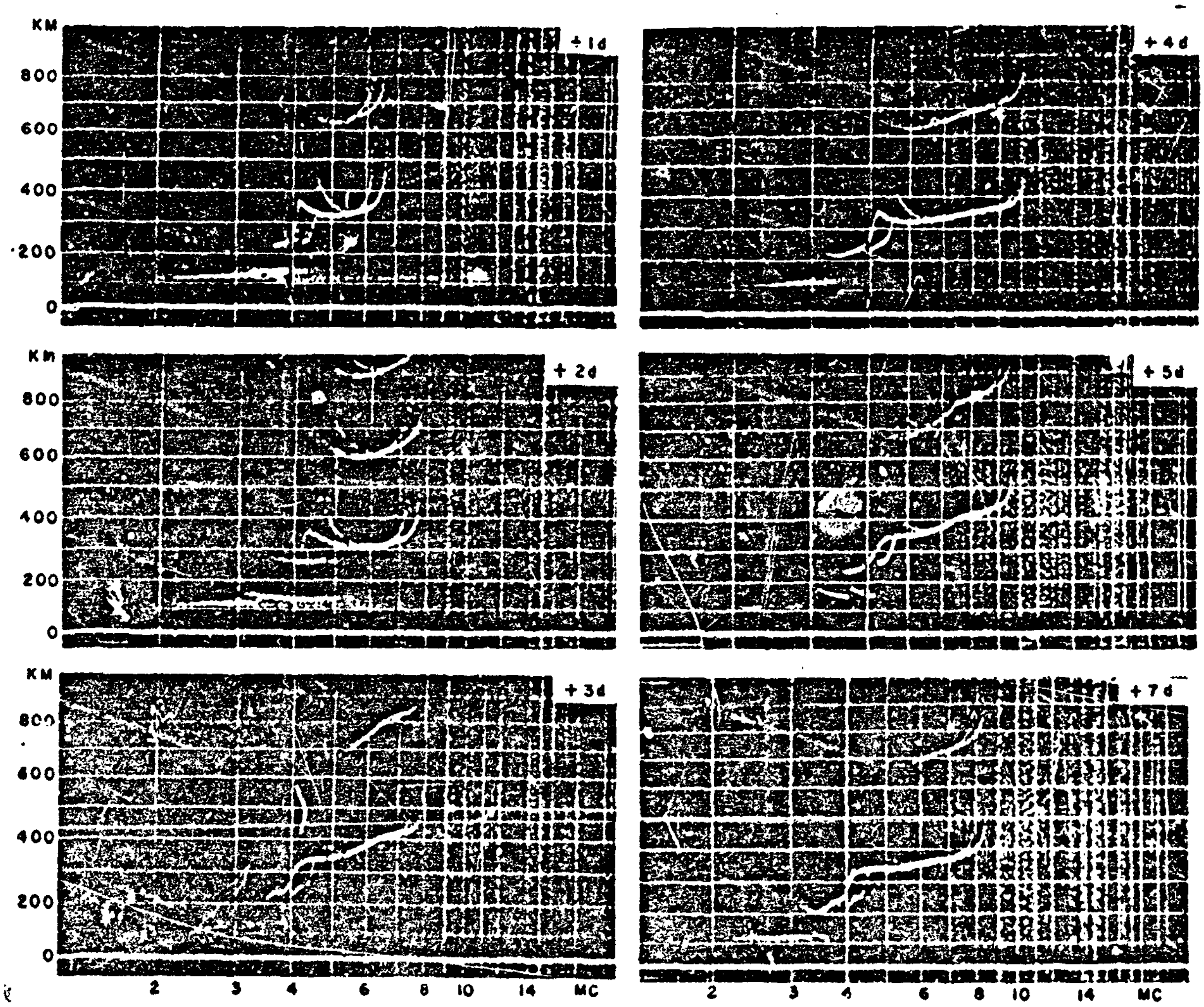



Fig. 3.24 - Ionospheric Records at Guam at 1000 hours of Normal Days Following Shot 1

(There is nothing special about this particular hour - any other morning hour would have shown a similar lack of irregularities.)

Selected ionograms following Shot 2, presented in Fig. 3.25, show the following:

- + 3h 30m - possible 2-hop oblique near 4mc (15 min earlier the 3-hop trace appeared doubled)
- + 3h 50m - definite obliques in 2-hop trace near critical frequency
- + 4h 50m - absence of 2-hop F2 trace from 4.8 to 6mc indicates probable horizontal irregularities; also note marked stratification
- + 5h 30m- several strata in F2 layer; 2-hop mostly absent due to irregularities in layer

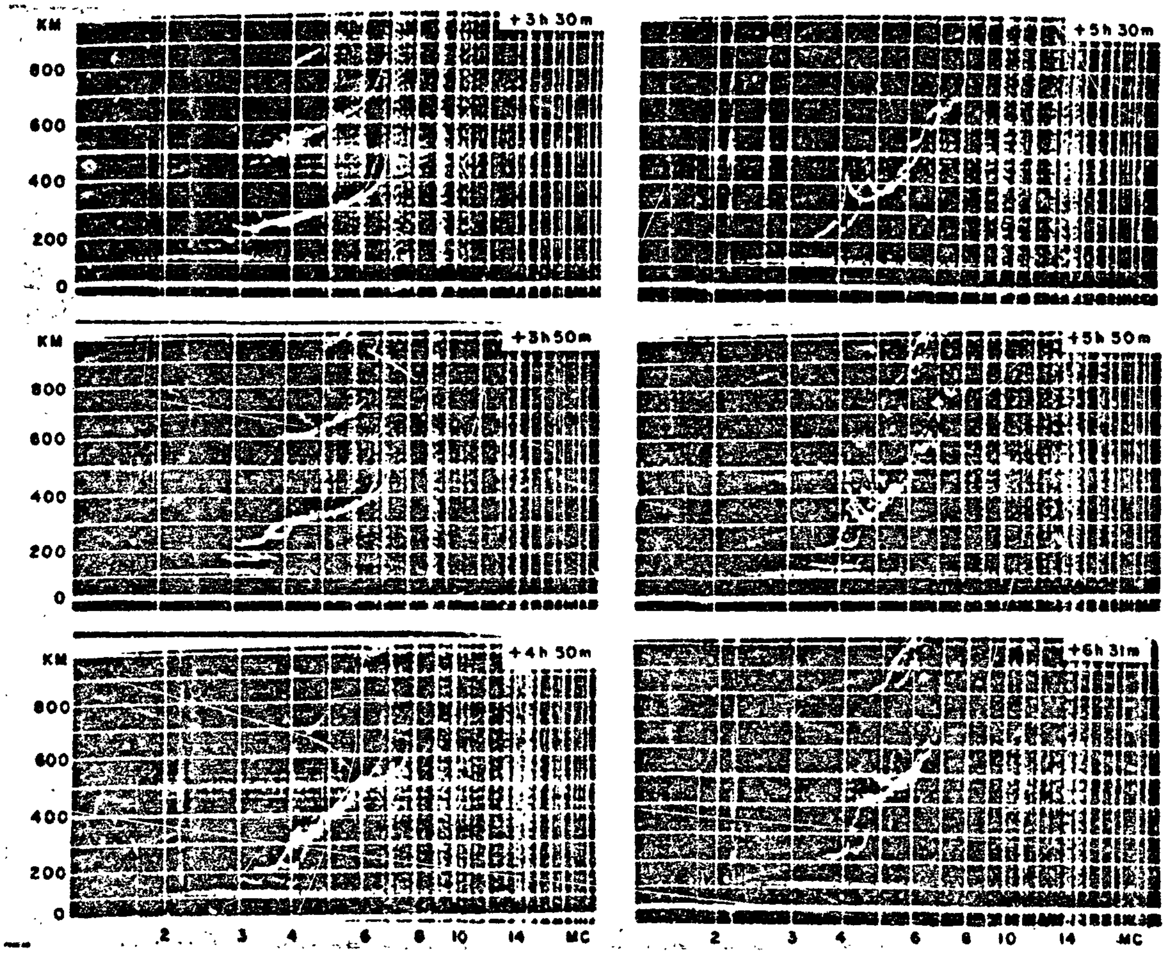



Fig. 3.25 - Ionospheric Records at Guam Following Shot 2, Showing Early Possible Effects and Later Probable Effects

+ 5h 50m - confused record but obliques are clearly present

+ 6h 31m - last greatly-disturbed record; oblique 2-hop return evident; (marked stratification continued for another hour).

Selected ionograms following Shot 5 show the following:

+ 2h 30m to + 3h 20m (Fig. 3.26) - first four pictures contain oblique traces believed due to sunrise effects (0640 hours to 0710 hours)4/; last two are quite normal

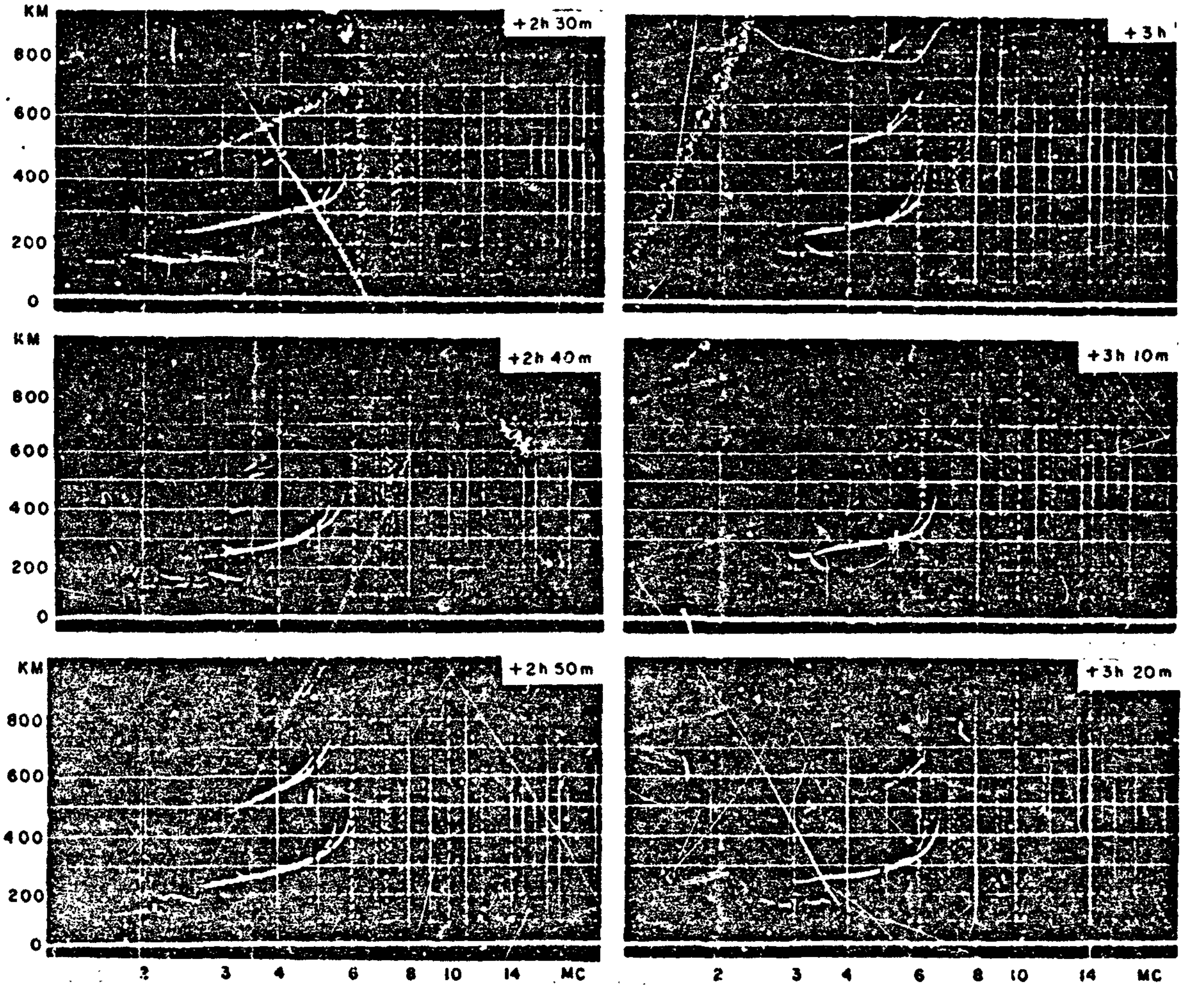



Fig. 3.26 - Ionospheric Records at Guam Following Shot 5, Showing Probable Sunrise Effect

4/ This presumption is based upon examination of ionograms for nine non-shot days between 4 May and 13 May; oblique echoes lasting 1/2 hr or more were found at this time of day for three out of nine days.

+ 3h 30m to + 4h 40m (Fig. 3.27) - definite oblique echoes throughout

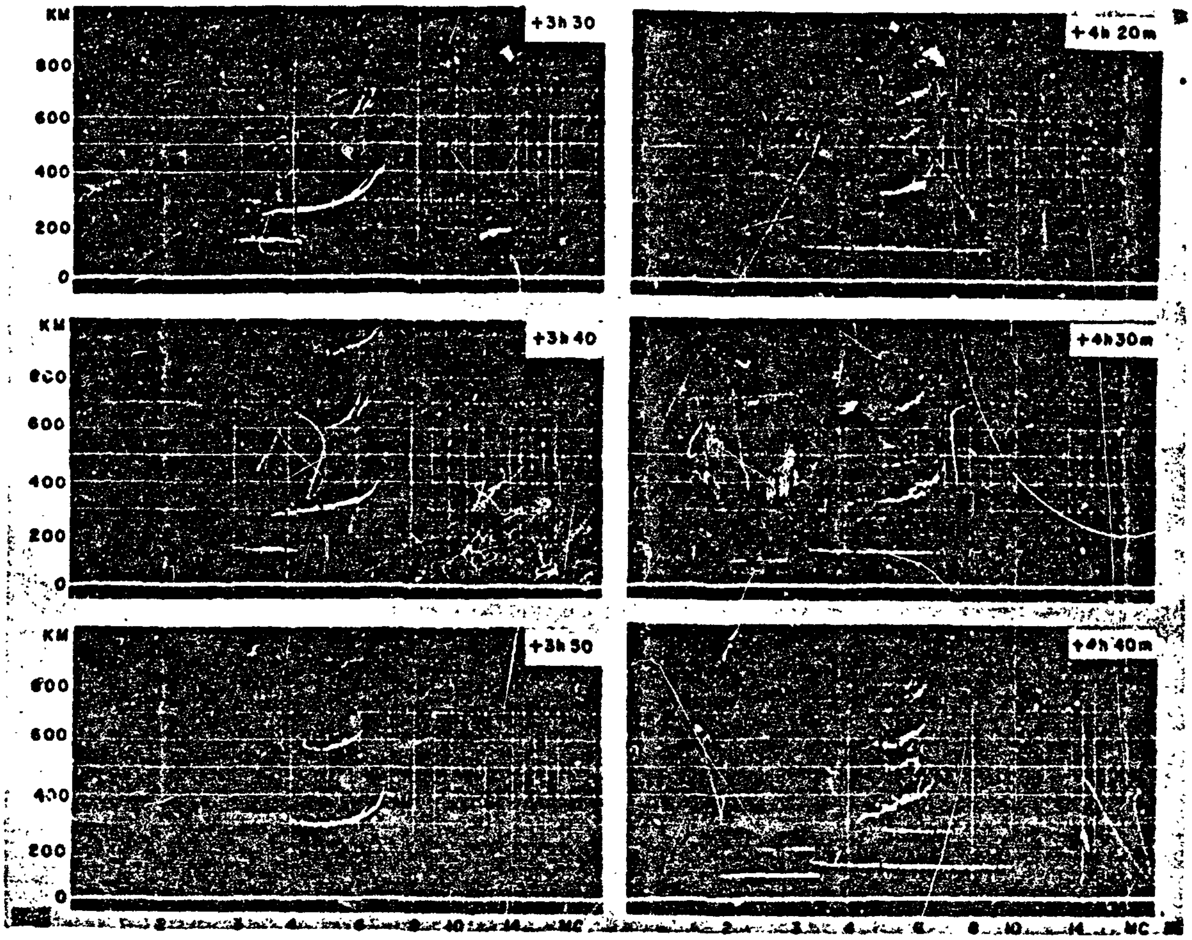



Fig. 3.27 - Ionospheric Records at Guam Following Shot 5, Showing First Period of Effects

+ 5h to + 6h 40m (Fig. 3.28) - first two pictures (at + 5h and + 5h 30m) show quite normal F2 layer with increasing virtual height due to formation of F1 layer (barely visible because of sporadic E); next three pictures show oblique returns; last picture is normal except for unusual stratification.

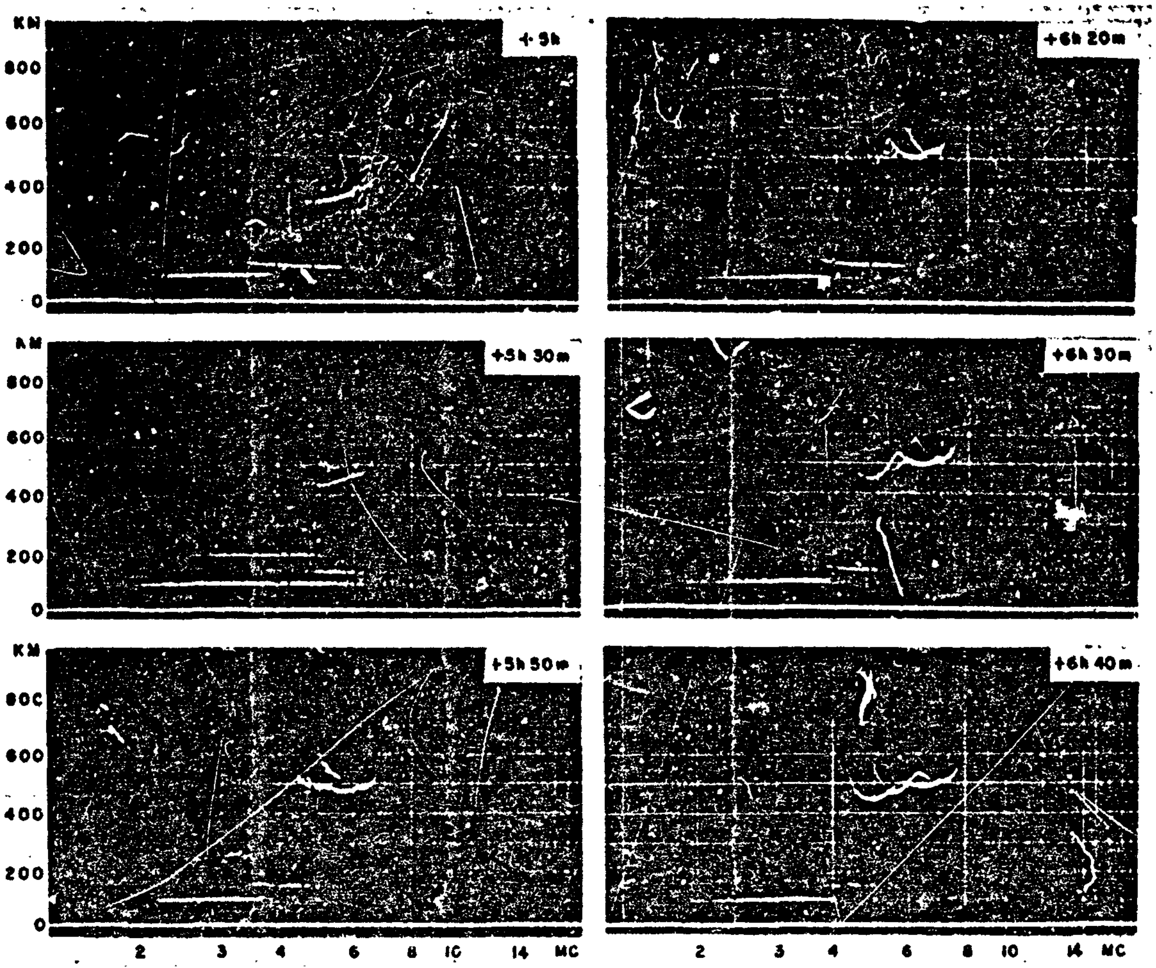



Fig. 3.28 - Ionospheric Records at Guam Following Shot 5, Showing Interval of Normalcy and Second Period of Effects

## 3.4.2 At Okinawa

The Okinawa records reveal occasional evidence of what could have been shot-caused effects, but none were very pronounced. Possible effects were found for Shot 1 at + 6 hr 30 min and Shot 2 at + 6 hr 14 min (indicated velocities of 10.9 and 11.4 km/min, respectively), but the presence of frequent irregularities on other (non-shot) days casts a great deal of doubt on their origin.

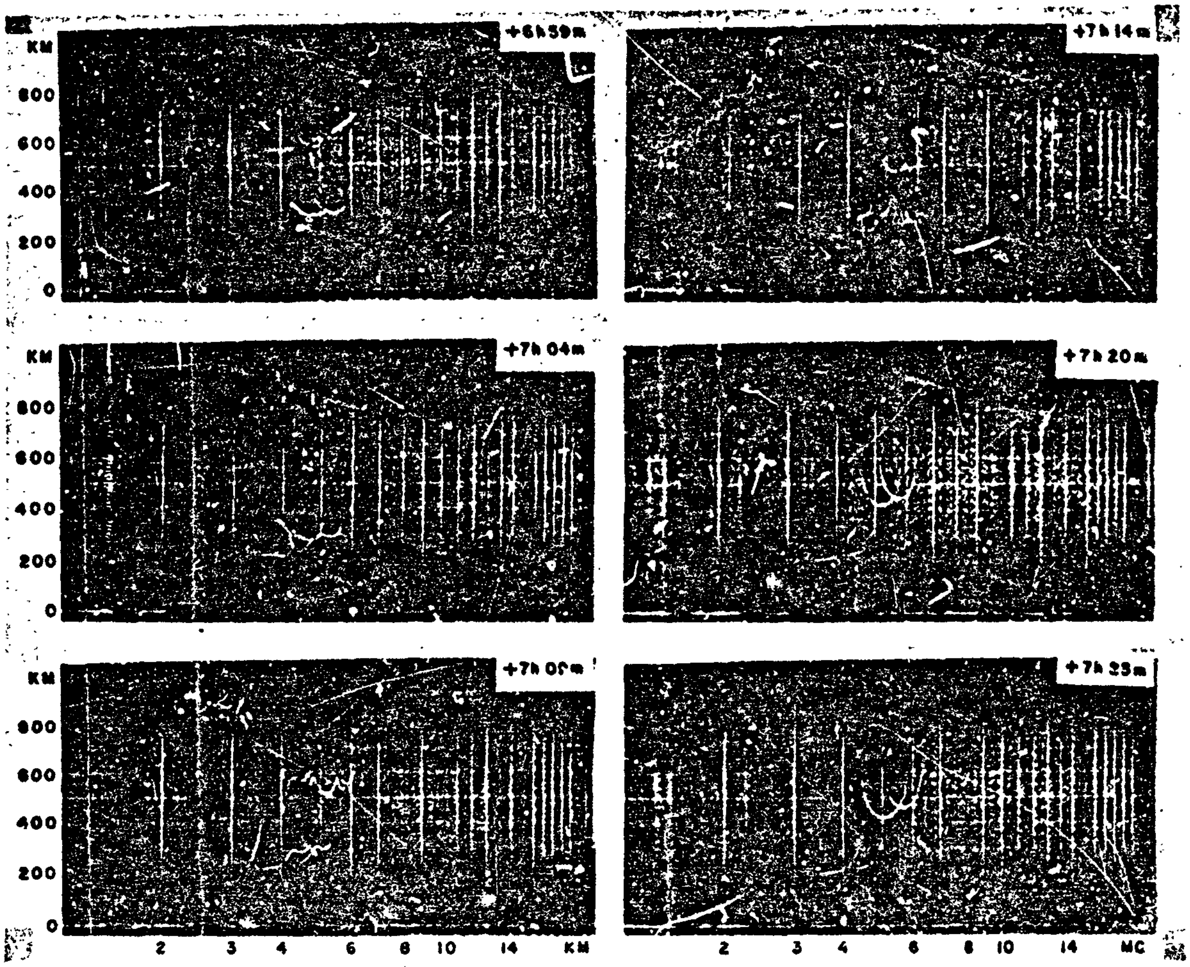



Fig. 3.29 - Ionospheric Records at Okinawa Following Shot 5, Showing Possible Effects

In Fig. 3.29 is shown a sequence constituting an interesting phenomenon that may have been an effect of Shot 5. If it were, its occurrence at about +7 hr 9 min indicates a velocity of 9.9 [illegible]/min. It consisted of a sudden appearance of a region of higher ion density, apparently moving in horizontally (its maximum frequency is seen, in the third ionogram of Fig. 3.29, to be about 5.5 mc for the ordinary wave and 6.0 mc for the extraordinary); this was followed by the smoothing out of the cusp between the F1 and F2 layers at 4.3 mc (ordinary), this cusp being replaced by what had been the F2-layer ordinary critical frequency which dropped from 5.3 mc to 4.5 mc while the new, higher density region became the region of maximum ion density of the F2 layer.

### 3.4.3 At Maui

As at Guam, marked and continuing F2-layer irregularities were found in the records taken at Maui following the three largest shots by a fairly consistent time interval of 6 to 9 hr. From their nature, duration, and consistency, coupled with the low frequency of protracted natural occurrence of similar disturbances, 5/ there seems to be little doubt that these were shot-caused effects. The velocity of travel is uncertain since the time of onset of the disturbance is not well determined. Prior to the period of marked perturbation following each of Shots 1, 2, and 5, there were indications of the possible arrival of the disturbance about 5 hr after the shot. This doubtful arrival is indicated in Table 3.4 as "First Period (doubtful)". Also included in Table 3.4 are data for Shot Mike effects, found upon re-examination to consist of two possible periods seperated by an undisturbed interval.

TABLE 3.4 - Effects at Maui

| Shot | ETA at 13 km/min | First Period (doubtful) | Second Period (definite) | Indicated Velocity* (km/min) |
|---|---|---|---|---|
| 1 | +5h 22m | +4h 45m to 5h 18m | +6h 15m to 8h 15m | 15.5 or 11.6 |
| 2 | +5h 22m | +5h 30m to 5h 33m | +7h to 7h 33m | 13.3 or 10.3 |
| 5 | +5h 22m | +5h 20m to 5h 50m | +7h 20m to 8h 52m | 13.7 or 9.9 |
| Mike | +5h 47m | +4h 45m to 4h 48m | +5h 45m to 6h 15m | 16.7 or 13.7 |

*Due to infrequent records, effects may have started up to 1/2 hr earlier. Velocity is thus based on arrival about 15 min earlier than first observed time.

5/ Only on 7 other days, out of 56 examined, were there oblique reflections lasting for at least an hour during the 6-hour period centered on 1500 hours (the approximate time of the suspected effects). Incidentally, there was a diminishing frequency of occurrence with advance of season - six of the seven being in February and the other one being in the period 15 April to 15 May.

Ionograms from Maui following Shot 1 are presented in Figs. 3.30 and 3.31, with the elapsed time from zero indicated in hours and minutes. A brief description follows:

+4h 15m - normal picture
+4h 45m - possible 2- and 3-hop F2 oblique echoes
+5h 18m - 2-hop oblique near high-frequency end of F2 trace
+5h 45m - normal
+6h 15m - definite oblique 3-hop return; also probable 2-hop oblique
+6h 18m - definite 2-hop oblique returns

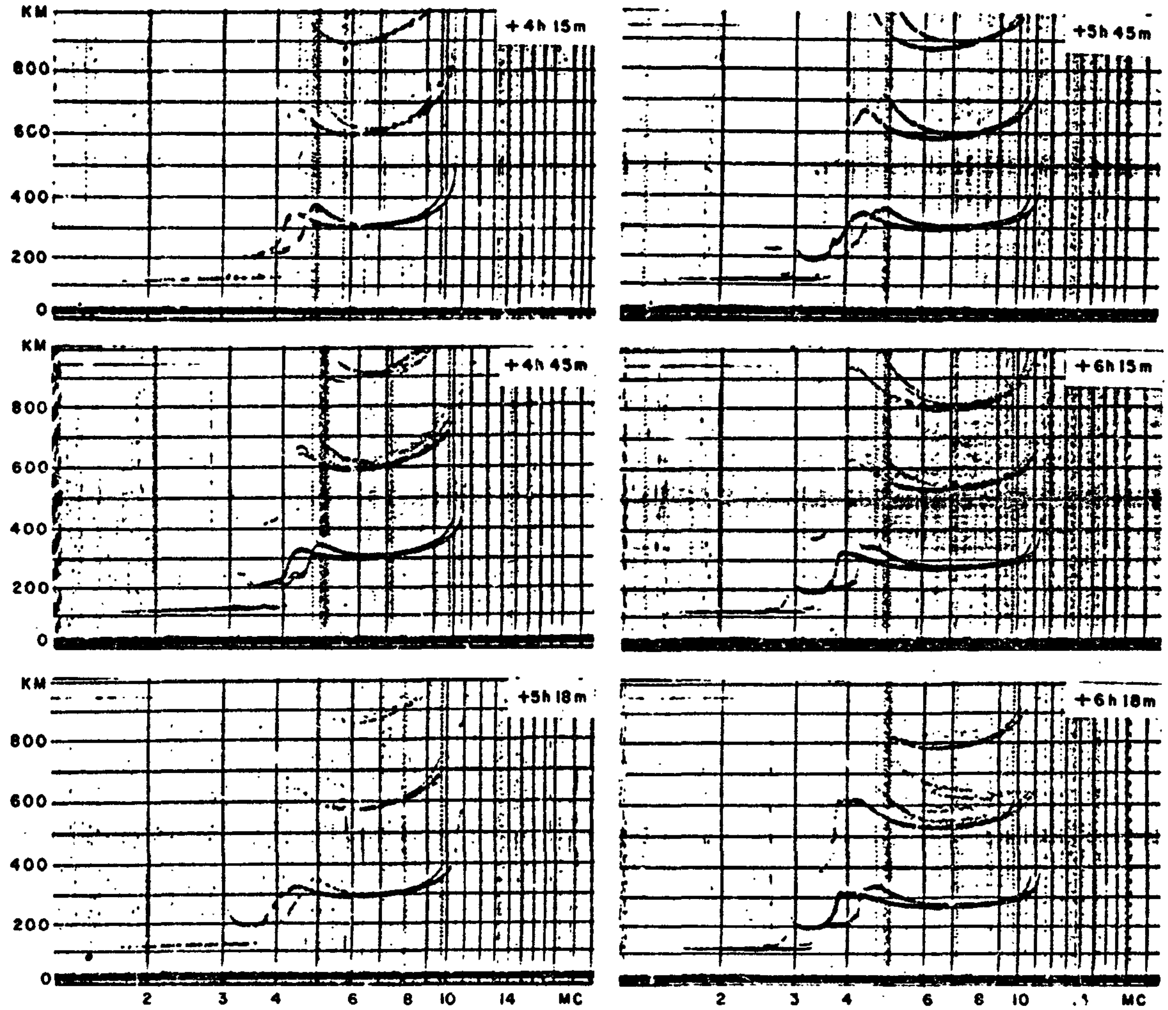



Fig. 3.30 - Ionospheric Records at Maui Following Shot 1, Showing Early Possible Effects and Start of Definite Effects

+ 6h 44m - definite 2- and 3-hop obliques
+ 7h 15m - very pronounced 2-hop obliques
+ 7h 18m - very pronounced 2- and 3-hop obliques
+ 7h 45m - very pronounced 2- and 3-hop obliques continue
+ 8h 15m - effect tapering off, but 2- and 3-hop obliques still present
+ 8h 18m - normal except for M- and N-type echoes (combinations of Es and F-layer reflections).

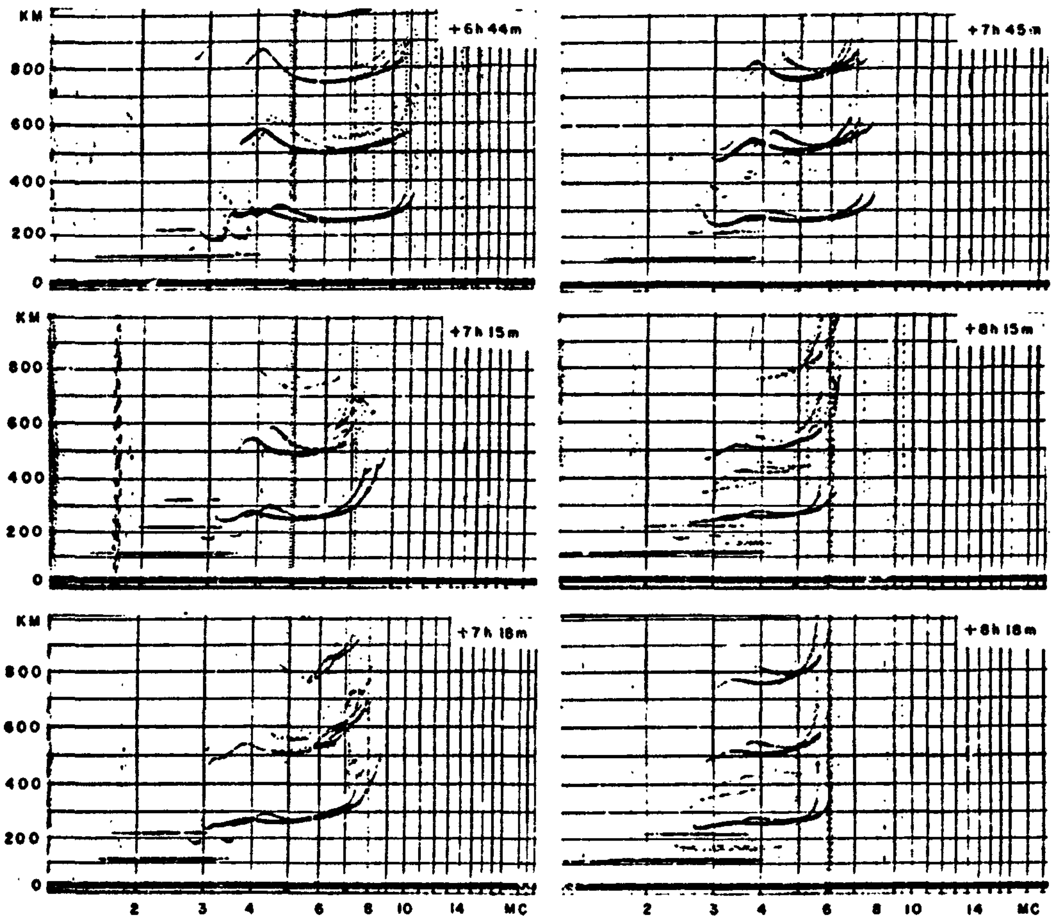



Fig. 3.31 - Ionospheric Records at Maui Following Shot 1, Showing Definite Effects



SECRET

Selected records following Shot 2 at Maui are given Fig. 3.32. These ionograms show:

+ 5h - normal conditions
+ 5h 30m - oblique 1- and 2-hop echoes near low-frequency end of F2 trace; 3-hop echo between 6 and 7 mc
+ 6h 33m - normal record again
+ 7h - strong oblique echoes at 1-, 2-, and 3-hop F2 levels
+ 7h 33m - 2- and 3-hop obliques still present
+ 8h - normal record again

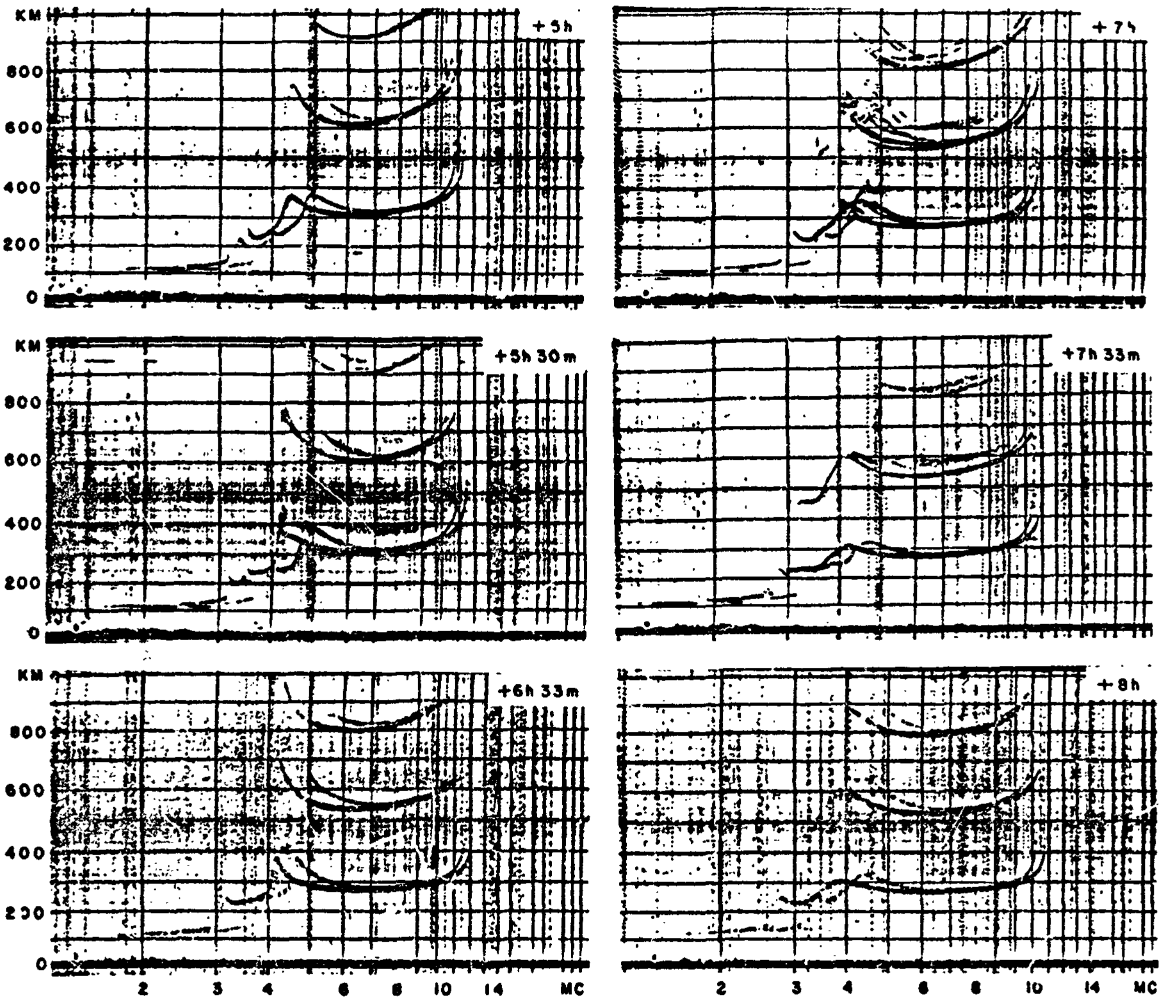



Fig. 3.32 - Ionospheric Records at Maui Following Shot 2, Showing Possible and Definite Effects

The following selected records at Maui after Shot 5 are presented in Fig. 3.33.

+ 5 h 20m - showing doubtful first-period arrival by indication of 2-hop oblique near F2-layer critical frequency

+ 6 h 52m - normal

+ 7 h 20m - 2-hcp oblique echo clearly visible over a wide range of frequencies

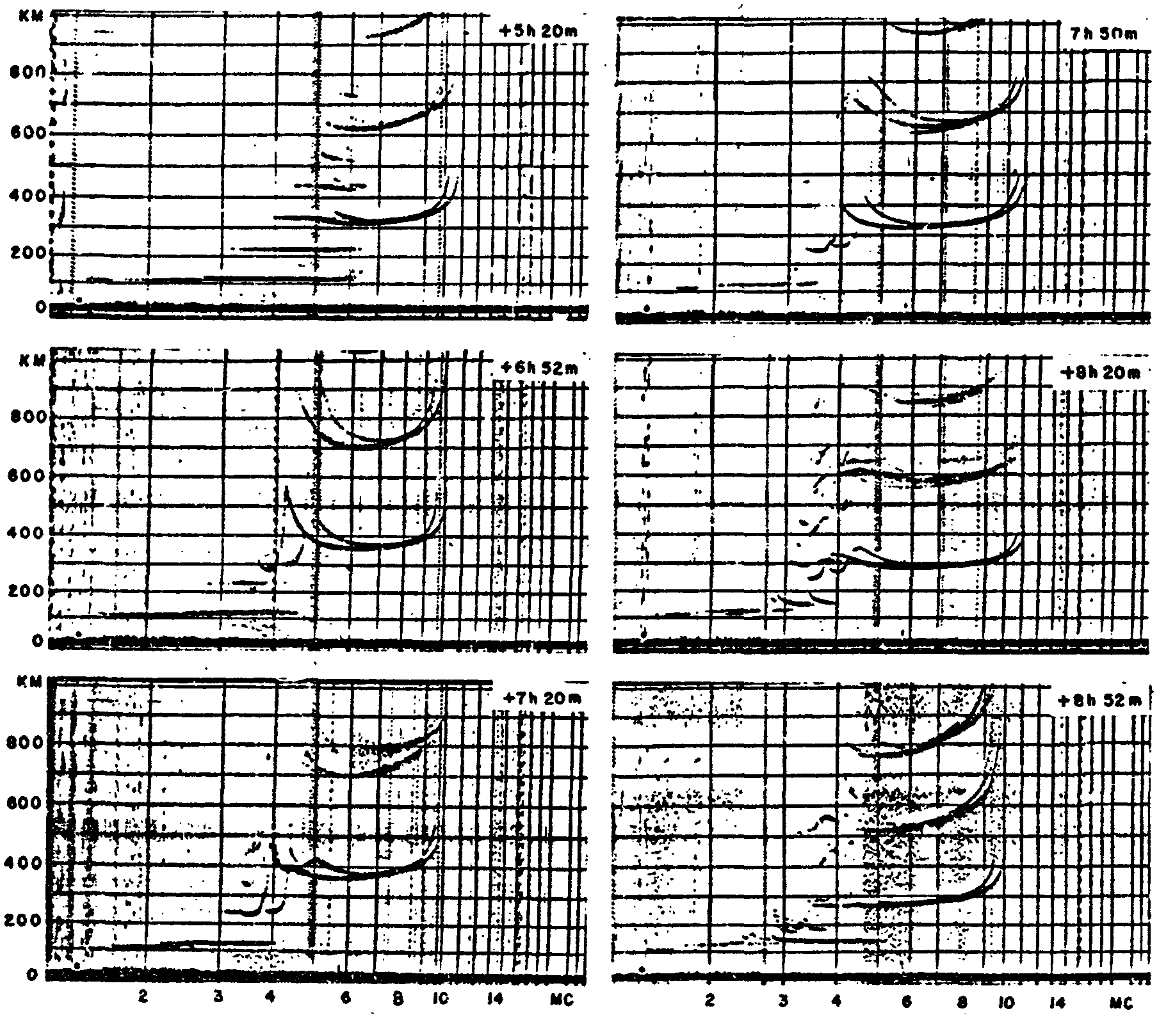



Fig. 3.33 - Ionospheric Records at Maui Following Shot 5, Showing Possible and Definite Effects

+ 7h 50m - three 2-hop echoes are seen between 6 and 7mc

+ 8h 20m - clear 2- and 3-hop obliques continue

+ 8h 52m - obliques may still be seen, although effect is probably near end; sporadic E blankets the F2 layer shortly after this time

### 3.4.4 At Adak

In order that no possible data sources be overlooked, ionospheric records taken at Adak during Operation CASTLE were examined for possible shot effects. It was found, however, that ionospheric irregularities of the type interpreted elsewhere as shot effects occur very often at Adak under normal conditions. Thus, it is impossible to definitely identify any shot effect which might have been present. However, there were definite oblique echoes present after Shot 1, 2, 4, and 5, at times which indicate that they could have resulted from a disturbance propagated at a velocity of the order found at other locations. If these effects were shot-caused, the indicated velocities were: Shot 1 - 12.1 or 9.0 km/min, Shot 2 - 11.6 or 9.2, Shot 4 - 10.3, and Shot 5 - 9.7.

# Chapter 4

# DISCUSSION

## 4.1 ABSORPTIVE EFFECTS

A tentative explanation of the protracted absorption observed at Site Elmer has been evolved. It is based on the fact that the atomic cloud containing radioactive particles rises quickly to about 120,000 ft. At altitudes of about 60,000 to 120,000 ft, there are, at the latitude of Bikini, continuous easterly winds having velocities generally increasing with height to something of the order of 60 to 90 miles per hour. These winds could carry the aforementioned particles to the region above Elmer by about 2 hours after the detonation. These particles are capable of supplying sufficient ionization to the air, despite the rapid recombination rate at these low heights, to cause the onset of the renewed absorption shown in Table 3.1. The time given in the table for renewal of absorption after Shot 5 seems somewhat early (+1 hr 36 min), so either a different cause of absorption was in operation at that time or higher velocity winds existed. The latter possibility seems quite likely, as easterly winds of over 80 miles per hr were reported at altitudes of about 85,000 ft above near-by weather stations earlier that day. At higher altitudes, the westward velocity may well have been 50 percent greater, which would account for an early arrival of radioactive particles over Elmer. The possibility that high velocity winds may have brought the particles there early does not preclude a long duration of absorption (as observed), because continuation of absorption may have been due to lower velocity winds, at lesser altitudes of the same region (60,000 to 120,000 ft), carrying ionizing particles overhead at later times.

## 4.2 F2-LAYER PHENOMENA

From the detailed description, given in Chapter 3, of the phenomena associated with the individual shots, it is apparent that the results obtained from Operation CASTLE are not as useful for studying the F2-layer phenomena as those obtained from IVY Mike. Due to the absorption discussed in Section 4.1, and probably also due to a G condition, the actual period during which the F2 layer was apparently rising was not observed, but only that phase was seen during which the layer was returning to its normal condition (and this at one station only). Furthermore, the extreme height that was found following IVY Mike and CASTLE 1 and 2 was not observed after Shots 4 and 5. (Shot 3 was too small to cause such a rise and data obtained from Shot 6 were insufficient). The results obtained from the IVY shot are therefore still the best available upon which to base an explanation of the rising F2 layer.

Continued study of the data obtained from the IVY shot has led to the conclusion that the results cannot be explained by as simple a mechanism as was assumed in the IVY report (see Section 4.1 of Reference 1). In that report, a simplified model of the ionosphere was used as a basis and computations were made which indicated that a vertical motion of the F-layer electrons could occur at about a twentieth of the velocity of the convection current caused by the thermal effects of the blast. Since the IVY report was written, however, a series of three papers (Reference 4) has been published in which a complete theory of ionization drift is outlined. These papers include detailed computations of both vertical and horizontal drift of ions caused by air currents, for various values of the dip angle of the earth's magnetic field, and for various altitudes above the earth's surface. Reference 4 includes the effect of Hall conductivity, which was not included in the simplified treatment of the IVY report. In that report, it was pointed out that a vertical current of air at the magnetic equator cannot cause an appreciable vertical drift of F2-layer ions. According to the more complete theory of Reference 4, however, a pronounced horizontal drift would occur, which would be in the westward direction for an upwardly directed current of air. In the light of this theory, it would appear that the apparent rise of the F2 layer was not an actual rise at all; the F2 layer only appeared to be rising because ions were swept away horizontally at successively higher levels by the ascending heated mass of air. The tests did not, however, take place exactly at the magnetic equator, the earth's magnetic field being tilted at an angle of about 13 degrees at the Pacific Proving Ground. The rising air current, therefore, would have a small component of velocity along the earth's field and there would be some rise due to this component. There would also be a component directed toward the south, because the field tilts upward in that direction. The net effect would be that ions would be moved in a southwesterly direction, with small vertical velocity superposed upon the horizontal motion. All of the observed phenomena should be consistent with this picture, if it is correct.

The horizontal extent of the phenomena would, of course, depend upon the size of the heated air mass, and this, in turn, would depend upon the energy released by the blast. Furthermore, the distribution of the blast-wave energy would depend upon the wind and temperature structure of the atmosphere, and the volume affected would, in general, not be symmetrical with respect to the source. Should this volume have a fairly sharp boundary (true for atomic clouds observed near the earth's surface), the horizontal extent of the phenomena observed would also have a sharp boundary and, if the ionosphere recorder were located just outside the boundary, a completely different sequence of events would be observed than if the recorder were located nearer to the shot point. Outside the heated air mass, for example, there would be a downwardly directed current of air, and the drift electrons would therefore move eastward instead of westward. In the vicinity of the boundary, this would tend to cause a decrease of ion density. Furthermore, the combination of decrease in atmospheric density with height and the conservation of mass would result in a greater downward velocity of air molecules at higher altitudes than at lower levels. The ions that are moved eastward by the descending air would be swept away more rapidly at higher than at lower levels, and the effective height of the F2 layer might even be lowered. The ionosphere recorder would not, therefore, register the large apparent increase in height that would be observed directly below the rising heated air mass. Of course, turbulence near the boundary, and "piling up" of ions would complicate the picture.

The above discussion is offered as an explanation of the events following Shot 4. The yield of this shot was smaller, which would have resulted in a smaller volume of heated air. Furthermore, because of the later date, seasonal changes in upper atmosphere winds might have caused a different horizontal distribution of blast-wave energy. The net result may have been that, for this shot, the ionosphere recorder was located outside of the boundary of the heated air mass, hence no pronounced change in the height of the F2 layer occurred. (The large apparent increases in level observed at about plus one hour appear to have been due to a horizontal motion of the point of reflection as described in Section 3.3.3, and may have been the early stages of the wave motion which gave rise to the distant effects described in Section 3.4.)

In the case of Shot 5, the occurrence of a G condition (see Section 3.3.4) made it impossible to obtain a complete picture of the F2-layer phenomena.

Another mechanism which may be of importance in explaining the results is the "cyclone" action due to the rising air mass. Air moving in horizontally to replace the ascending air would be deflected by the Coriolis force caused by the earth's rotation, and a counterclockwise whirl would result in the northern hemisphere, just as in the case of an ordinary tropical or extratropical cyclone. The winds of this whirl would have a northwardly directed component east of the shot point (where one of the ionosphere recorders was located). This component would lie along the earth's magnetic field, and, inasmuch as electrons can be moved freely parallel to the field, the F2-layer ions would tend to move northwards and downwards. This may be the mechanism by means of which the F2-layer conditions return to normal (i.e., F2-layer ionization is moved in from the south by this process). This would explain the occurrence of the lower of the two maxima described in Section 3.3.1 (see also Fig. 3.12) and would also explain the gradual descent of the F2 layer as conditions return to normal.

From the above discussion, it is obvious that the F2-layer phenomena that follow a large atomic blast are quite complicated and probably cannot be com letely explained with the limited data available. Data covering a wider range of distances and azimuths would be required in order to obtain a complete picture.

### 4.3 DISTANT EFFECTS

Although distant ionosphere effects were definitely observed as a result of CASTLE shots, the velocity of approximately 13 km/min indicated by the distant effects of Shot Mike of Operation IVY is not borne out by the CASTLE data. Despite the fact that the start of the effects was very difficult to ascertain, large variations of indicated velocity are apparent, with values ranging from 7.7 to 15.5 km/min. A detailed theory of the nature of traveling ionospheric disturbances having velocities in this range has been developed by Martyn (see Reference 5).

It seems advisable to call attention to two apparent consistencies, so that future data may be examined for corroboration of these tendencies. First, the duration of the effect appears to be related to the yield of the device, possibly being proportional to its square. Second, the duration is about inversely proportional to the distance. No theoretical explanation can be given for these possible relations.

# Chapter 5

# CONCLUSIONS

## 5.1 ABSORPTION

Severe absorption of vertically transmitted high-frequency radio signals was observed to the west of all multi-megaton shots, starting about 2 hours after the detonation and lasting several hours. This absorption is presumed to have been due to ionization caused by radioactive material carried westward by high-level winds. It was not observed during Operation IVY, because no ionosphere recorder was situated at a location where this effect may have occurred.

This newly observed phenomenon is of great significance as it points to the possibility of a prolonged and widespread ionospheric communications blackout in the event that a number of cities were hit by megaton weapons during a period of a few hours.

## 5.2 SPORADIC-E EFFECTS

Definite sporadic-E effects were noted at Rongerik, 150 miles to the east of the test site. From the time that echoes were first observable there until at least two hours after each major shot, the maximum frequency of sporadic-E returns was considerably higher than normal. During this period, these echoes also evidenced an unusual amount of "spread" or scattering and multiple-level reflections. Sporadic-E returns are usually considered to be the result of turbulence and are frequently associated with ionospheric storms.

## 5.3 F2 LAYER EFFECTS

For shots of megaton range, an effect on the F2-layer was observed which was similar to that first found following Shot Mike of Operation IVY. The apparent cause of this phenomenon is the large-scale convection resulting from the conversion of blast-wave energy into heat in the upper atmosphere. The nature of the effect varies from shot to shot, presumably because of different atmospheric conditions or yields.

Further study of the data has led to the conclusion that the earlier explanation of the phenomenon was incomplete and that the movement of electrons resulting from large explosions is more complex than originally assumed. Additional experimental data from more locations will be required in order to complete the picture.

## 5.4 DISTANT EFFECTS

A disturbance that is propagated in the upper ionosphere for thousands of miles appears to be initiated by shots of sufficiently large magnitude. The minimum yield requisite for its initiation is indicated as probably between 7 and 11 megatons. The velocity of propagation is indeterminate but has been within the range of 7.7 to 15.5 km/min to date.

UNCLASSIFIED

# Chapter 6

# RECOMMENDATIONS

## 6.1 FURTHER EXPERIMENTATION

The results indicate the possibility of widespread disruption of radio communications due to absorption, presumably caused by wind-borne radioactive material at high altitudes. The lateral extent of this effect is still unknown. It is therefore recommended that, during future large-scale tests, experiments be performed to more accurately locate the boundaries and motion of the material causing the absorption. Such experiments could be carried out with an air-borne ionosphere recorder. Data so obtained, combined with data taken concurrently at suitably located ground stations, would also be of great value in gaining a more complete picture of the convection resulting from large blasts and of the associated ionic motions.

## 6.2 COMPREHENSIVE DATA ANALYSIS

Many of the phenomena observed during Operations IVY and CASTLE are similar to effects that usually accompany ionospheric storms. It is therefore recommended that a comprehensive study be made of the data already obtained in combination with related data from future tests. Such a study should lead to a more complete understanding of the processes involved in naturally caused phenomena.

## 6.3 CONTINUED STUDY OF DISTANT DATA

It is recommended that ionosphere records at distant locations continue to be examined for evidence of traveling ionospheric disturbances initiated by large explosions. Data on the velocity of propagation of such disturbances in different directions from a known source cannot be obtained by any other means.



[redacted]

UNCLASSIFIED

UNCLASSIFIED

# REFERENCES


1. F. B. Daniels, A. K. Harris, and D. T. Goldman, Effects of Atomic Explosions on the Ionosphere, IVY Project 9.2 Report, WT-642, August 1954.

2. F. B. Daniels, and A. K. Harris, Effects of Atomic Explosions on the Ionosphere, SNAPPER Project 9.4 Report, WT-547, Jan. 1953.

3. National Bureau of Standards, U. S., Ionospheric Radio Propagation, Circular No. 462, June 25, 1948.

4. W. G. Baker and D. F. Martyn, Phil. Trans. of the Royal Society of London, Ser. A., Vol. 246, No. 913 pp. 281-320, 1953.

5. D. F. Martyn, Proceedings of the Royal Society of London, Ser. A, Vol. 201, pp 216-234, 1950.




[redacted]

UNCLASSIFIED