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SURFACE MEASUREMENTS - PROJECT MIDAS

Defense Atomic Support Agency
Washington, D. C.

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NOTICE

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective was to make surface measurements of the electromagnetic and optical effects in the detonation area (South Atlantic) and in the area geomagnetically conjugate (Azores) during the Argus experiment. The project participated in three events - Argus I, II, and III. Keywords include: High altitude nuclear explosions;

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FOREWORD

This report has had classified material removed in order to make the information available on an unclassified, open publication basis, to any interested parties. This effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

The material which has been deleted is all currently classified as Restricted Data or Formerly Restricted Data under the provision of the Atomic Energy Act of 1954, (as amended) or is National Security Information.

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It is the belief of the individuals who have participated in preparing this report by deleting the classified material and of the Defense Nuclear Agency that the report accurately portrays the contents of the original and that the deleted material is of little or no significance to studies into the amounts or types of radiation received by any individuals during the atmospheric nuclear test program.

ABSTRACT

The objective was to make surface measurements of the electromagnetic and optical effects in the detonation area (South Atlantic) and in the area geomagnetically conjugate (Azores) during the Argus experiment. The project participated in three events—Argus I, II, and III.

In both areas, there were HF radars, all-sky cameras, spectrophotometers (3,914 Å and 5,577 Å), broad-band VLF receivers, magnetometers, and riometers. ELF receivers and ionosounders were placed in the Azores. In other areas, assorted equipment was under the cognizance of various alerted agencies. In addition, some IGY stations yielded interesting data.

In the launch area, for all three events, auroras were observed approximately alined to the magnetic field. Concomitantly, reflections were obtained on the 27-Mc radar. In the conjugate area, a weak aurora was sighted for Argus I and a conspicuous one for Argus III, with the accompanying radar reflections.

The all-sky cameras obtained photographs of Argus II and III in the launch area. For all events, the spectrophotometers in the same regions recorded pulses of 0.20- to 0.05-second duration. Also, in the launch area during Argus III, the VLF receivers recorded pulses approximately 300 μsec long, and magnetic field disturbances of about 10 γ were recorded on the magnetic detectors. The riometer showed some slight absorption but no Argus noise, i. e., synchrotron radiation.

The all-sky camera and spectrophotometer in the conjugate area did not function during Argus III.

The VLF receiver in the Azores recorded a decrease of 6 to 12 db in signal strength of the British Station GBZ (19.6 kc) after Argus III. Signals, i. e., changes in magnetic field, of approximately 1 γ were obtained on the ELF equipment after Argus II and III. The frequency of the signal was predominantly 1 cps and showed a travel time of approximately 11 seconds. If these signals were propagated along the earth's magnetic field from the detonation area, the average speed would be 2,000 km/sec. After Argus III, the Signal Corps reported the recording of 1-cps disturbances by a large loop at a station in Arizona and a station in New Jersey, as well as detection of earth currents in Maine. Effects were also noted in Iceland and Sweden as well as by a number of French magnetic stations in France, Algeria, and the Antarctic. A permanent-magnet-type magnetometer in the Azores recorded no discernible disturbance.

After Argus III, the ionosounders in the Azores showed a sporadic E cloud moving eastward. IGY records examined at the World Data Center at the Slough Radio Establishment show a significant increase in sporadic E in the vicinity of 70° geomagnetic north after Argus III.

At Poitiers, France, 1 day after Argus III, there was a slight decrease in foF_2 and a small elevation in $h'F_2$.

Sferics stations at Bagneux and Poitiers observing on 27 and 10 kc recorded a slight decrease in 27 kc for all events and a slight decrease in 10 kc only after Argus III. However, these effects are not conspicuously different from fluctuations that occur at other places in the records.

VLF and riometer records at Torrejon, Spain, were negative.

Other groups reported negative results with the exception of the Naval Research Laboratory, which reported echoes on the HF radar located near Washington. After Argus III, similar equipment operated by the National Bureau of Standards (Washington), Raytheon (South Dartmouth, Mass.), and Air Force Cambridge Research Center (Plum Island, Mass.) gave negative results. Cosmic ray records at the Carnegie Institute in Washington and at CNET in Paris were reviewed. The results were negative. The records after Argus III were still showing the effect of the strong magnetic disturbance that occurred on 4 September 1958.

VLF propagation records (GBR 16 kc) for the path from Lower Hutt, New Zealand, to Rugby, England, were reviewed by the Dominion Physical Laboratory. No effects were found.

A microlock receiver at Torrejon monitored successfully the transmissions from the satellite, Explorer IV. The satellite was also observed at a station in Palo Alto, California.

PREFACE

In late May 1958, the Air Force Cambridge Research Center (AFCRC) was assigned responsibility for making electromagnetic and optical measurements as part of the Argus experiment, in cooperation with the Stanford Research Institute (SRI). The project had to be executed on a highly crash basis. Experiments were to take place at distant places in August 1958. The deadlines set by the departure of ships in the Navy Task Force placed a strain on both AFCRC and SRI. It was necessary to solve severe logistic problems of setting up communications, obtaining sites, procuring equipment, and moving them. These activities were rendered all the more difficult by the security classification of Top Secret, which had been assigned to the Argus experiment.

Special mention should be made of Major C. Wood, Mr. Norman Oliver, Captain E. Angell, Captain R. Yates, Mr. J. Murphy, Mr. R. Harvey, all of AFCRC, and Mr. Ray Vincent of SRI. The Navy Department supplied the USS Albemarle for the conjugate area operations and support for the launch area measurements. Special mention should be made of LCDR Forrestor, whose USS Tarawa-based air squadron handled the all-sky photography, magnetic airborne detection measurements, and launch area auroral observations.

Also, mention should be made of Messrs. McCabe, Eng, and Straka of AFCRC who, on very short notice, undertook the arduous task of operating equipment on the USS Tarawa and USS Norton Sound in the launch area; and Messrs. Miner, Cameron, and Romano who operated the sounders in the C-97's. Messrs. Light (SRI) and Orange (AFCRC) operated the equipment on the USS Albemarle. Lt Richard Koehler constructed and operated the ELF magnetic detector.

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Chapter 1

INTRODUCTION

1.1 OBJECTIVES

The objective of Project Midas was to make surface measurements of the electromagnetic and optical effects in the detonation area (South Atlantic) and in the area geomagnetically conjugate (Azores) during the Argus experiment.

The basic objective of the Argus experiment was the measurement of properties of the shell of trapped electrons produced by a nuclear detonation (References 1 and 2).

1.2 BACKGROUND AND THEORY

It was realized that a fraction of the electrons initially produced by the detonation would spiral toward the geomagnetic conjugate and, instead of being trapped, would penetrate the lower ionosphere. These might then produce a set of phenomena, which have come to be classed as auroral. In addition to the classic auroral manifestation of visual phenomena — involving the spectral emission lines of oxygen, nitrogen, and hydrogen — there are the phenomena of radar reflections, magnetic disturbances, earth currents, disturbances of the ionosphere, and increased ionospheric absorption of radio waves (References 3 through 7, and Figures 1.1 through 1.4).

In addition, a high-altitude detonation could create electromagnetic disturbances either as a result of an electric current of the prompt electrons or by the interaction of the hydrodynamic disturbance with the magnetic field. One class of electromagnetic waves that propagate in the upper atmosphere are whistlers in the frequency range 1 through 20 kc. Another class of electromagnetic waves are hydromagnetic types, which involve lower frequencies and whose propagation is much more affected by the ions in the atmosphere. Whistlers and some hydromagnetic modes are guided by the magnetic field. However, hydromagnetic modes that are not guided are possible according to current theories (References 8 through 15, and the Appendix to this report). VLF may also be produced according to recent theories by high-velocity protons (References 16 and 17).

1.3 ARGUS EVENTS

Project Midas participated in three nuclear detonations, referred to as Argus I, II, and III (Table 1.1).

1.4 INSTRUMENTATION

A VLF receiver (300 cycles to 30 kc) was placed in the Azores to observe whistlers. In addition, a special ELF receiver in the range (0.5 to 20 cps) was constructed at the Air Force Cambridge Research Center (AFCRC) under the direction of the Propagation Sciences Laboratory to observe possible effects at these frequencies. The top frequency of 20 cps was selected to minimize atmospheric and power line effects. The ELF equipment employed loops so that it measured rate of change of magnetic field.

In the launch area, wide-band VLF receivers with scope presentation to detect VLF pulses from the detonation were employed in addition to a VLF receiver recording continuous wave (CW).

In addition, there were magnetometers at launch and detonation to measure the magnetic field. The launch area magnetometers were Navy airborne magnetic detectors in aircraft based on the carrier USS Tarawa.

Riometers were employed (Reference 18) in both areas to measure absorption of cosmic noise by the ionosphere. These could also measure the noise that might result from synchrotron radiation from the Argus electrons.

HF radars were placed at the launch and conjugate areas. Auroral studies have shown that it is important that the radar beam intersect the geomagnetic field lines orthogonally at ionospheric heights (Reference 6). This condition defines contours of orthogonality at different ionospheric heights for a given observer (Figures 1.5 and 1.6).

Spectrophotometers were used to observe the spectral lines 3,914 Å and 5,577 Å, which are prominent in natural aurora (Reference 19). At subauroral latitudes, the 5,577 Å line is found in the night airglow, while the 3,914 Å is generally absent. Efforts to obtain a cinespectrophotometer were unsuccessful.

All-sky cameras giving hemispherical coverage were employed in the launch and conjugate areas. Airborne ionosondes were carried by two C-97 aircraft based on Lajes Field in the Azores.

A complication in making the auroral tests was the possibility of confusion that might be caused by natural geomagnetic disturbances. In fact, there was a severe disturbance on Argus I and for 3 days preceding Argus III.

The experimental plan called for the detonation area to be selected so that the Azores would be geomagnetically conjugate. Another station was set up at Torrejon in the vicinity of Madrid, which is near the geomagnetic latitude through the Azores (Figure 1.7). An HF radar was on the USS Albemarle sited about 400 miles south of the Azores to satisfy the orthogonality condition. The disposition of the equipment was as follows:

A. Azores.
   1. Lajes.
      a. Riometers at 30, 60, 120 Mc.
      b. VLF receiver loop antenna (300 cycles to 30 kc).
      c. ELF receivers (0.5 to 20 cps) fed by three mutually orthogonal loops with north-south loop in geomagnetic meridian.
      d. Magnetometers (Heliflux and variable μ).
   2. C-97's.
      a. All-sky camera.
      b. Spectrophotometers.
      c. Ionosondes.
   3. USS Albemarle.
      a. HF radar at 27 Mc.
      b. All-sky camera.
      c. Spectrophotometers.
      d. Riometers.

B. Torrejon, Spain.
   1. VLF equipment.
   2. Riometers.
   3. Microlock receiver to monitor transmissions from Explorer IV.

C. Launch Area.

1. USS Norton Sound.
   a. HF radar (27 Mc).
   b. Riometer (30 Mc).
   c. VLF wide-band receiver recording CW.
2. USS Tarawa.
   a. Spectrophotometers.
   b. VLF, wide-band receivers recording pulses.
   c. In carrier-based aircraft, magnetic airborne detectors and all-sky cameras.

In addition, there were VLF receivers and riometers (30, 60, and 120 Mc) on Hawaii and at Stanford University, Palo Alto, California. Also at Stanford, there were HF radars (12 and 23 Mc) to look for possible backscatter from the ionized cloud which would result from the detonation.

Additional HF backscatter sounders were operated by AFCRC at Plum Island (19 Mc) near Boston, by Raytheon at South Dartmouth, Mass. (12 and 22 Mc) and Grand Bahama Island (12 Mc), and by the National Bureau of Standards (NBS) (20.3 Mc) and Naval Research Laboratory (NRL) in Washington, D. C.

The University of Alaska was alerted for Argus I, but communication was difficult for the ensuing shots and complicated by security difficulties, which also made effective utilization of other groups difficult or impossible.

The M.I.T. Lincoln Laboratory operated various equipment including a C-4 ionosonde at Ipswich, Mass., and a magnetometer set up at Sacramento Peak, New Mexico.

The NBS activated its stations involving ionosondes, scatter circuits, and magnetic stations.

The Signal Corps operated magnetic stations in Arizona and New Jersey and an earth current station in Maine.

After the tests, the records of magnetic stations were reviewed, in particular those maintained by Argentina, Portugal, and France. Cosmic ray, sferics, and ionospheric records at the ionospheric station of CNET in Paris were reviewed. Cosmic ray records at Carnegie Institute in Washington were also reviewed.

The Rome Air Development Center (RADC) operated noise receivers at 50, 100, and 8,000 Mc and its experimental radar on 207 Mc in Laredo, Texas.

For Argus I, the Lincoln Laboratory set up a receiving station at the antipodal point in the Aleutians to monitor the frequency range 2 to 108 Mc.

IGY (International Geophysical Year) records of sporadic E at the World Data Center at Slough Radio Establishment were reviewed for effects.

TABLE 1.1 ARGUS EVENTS

Event	Date	Time	Position and Height	Conjugate at Zero Level	Maximum of Magnetic Line	Position of Albemarle
	1958				km	
I	27 August	0227:52.55Z ± 0.01 second	38° 48′ S ± 30′ 11° 55′ W ± 30′ 161 ± 30 km	32° 29′ N 35° 58′ W	3,621	33° 48′ N 31° 04′ W
II	30 August	0317:33.79Z ± 0.01 second	49° 23′ S ± 65′ 08° 43′ W ± 25′ 293 ± 15 km	39° 33′ N 37° 26′ W	6,398	33° 56′ N 30° 57′ W
III	6 September	2212:33.35Z ± 0.01 second	49° 30′ S ± 20′ 10° 24′ W ± 30′ 750 ± 10 km	40° 30′ N 38° 31′ W	7,034	39° 30′ N 30° 05′ W

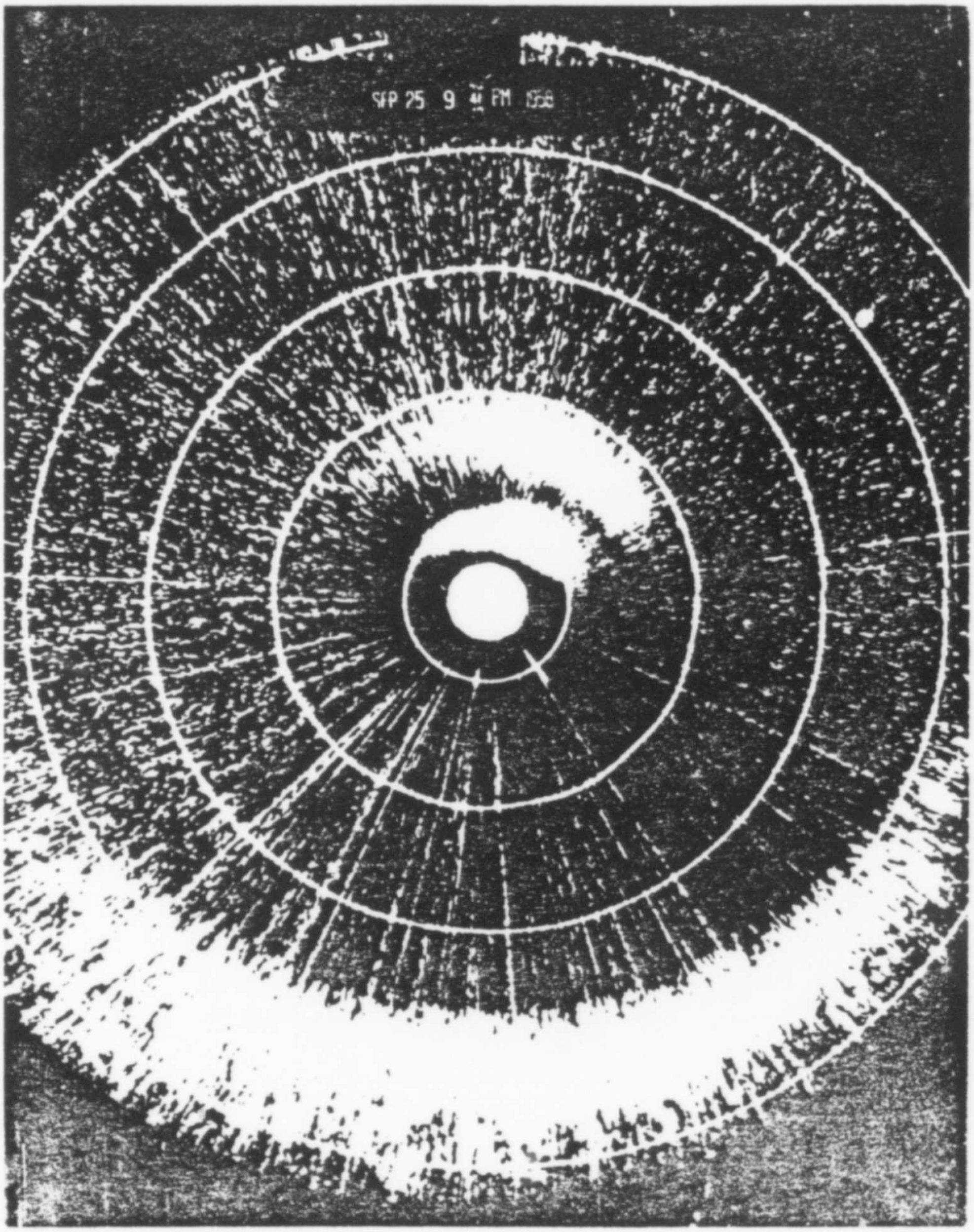

Figure 1.1 Auroral reflections obtained on 19-Mc radar at Plum Island, Mass. Distances between circles correspond to 750-km slant range. Innermost return is auroral reflection. Ground backscatter reflected by F_2 layer appears at bottom of picture.

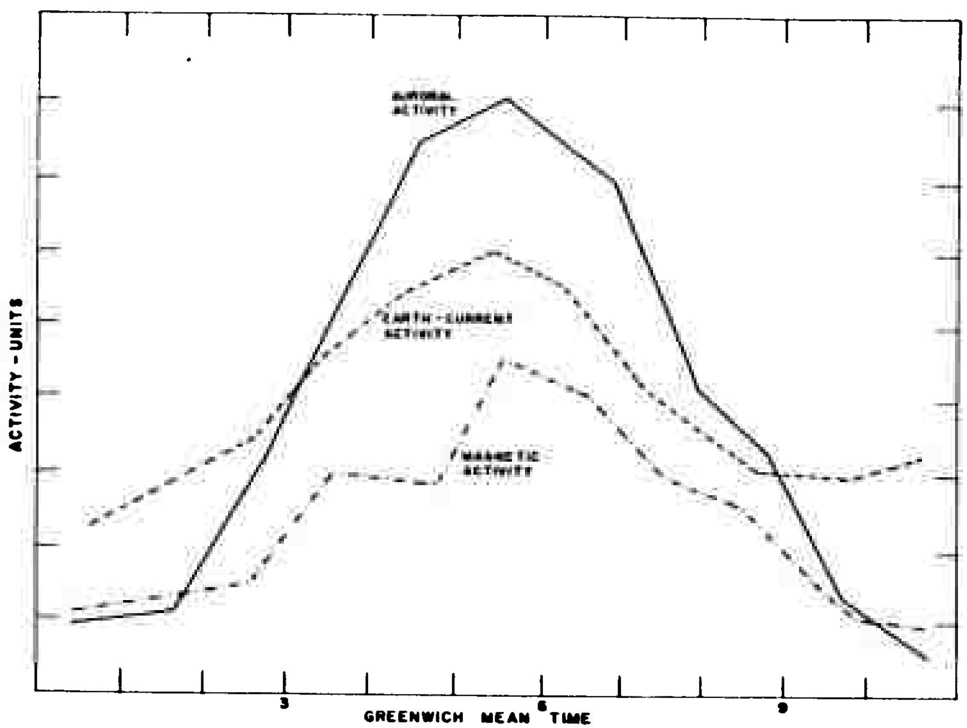

Figure 1.2 Comparison of auroral, earth current, and magnetic activities.

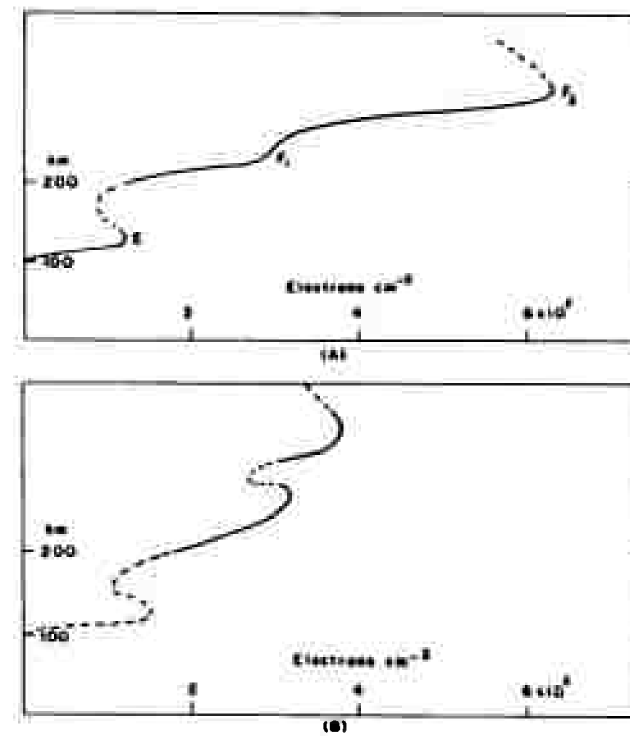

Figure 1.3 Changes in the constitution of the ionosphere from a quiet day to a disturbed day.

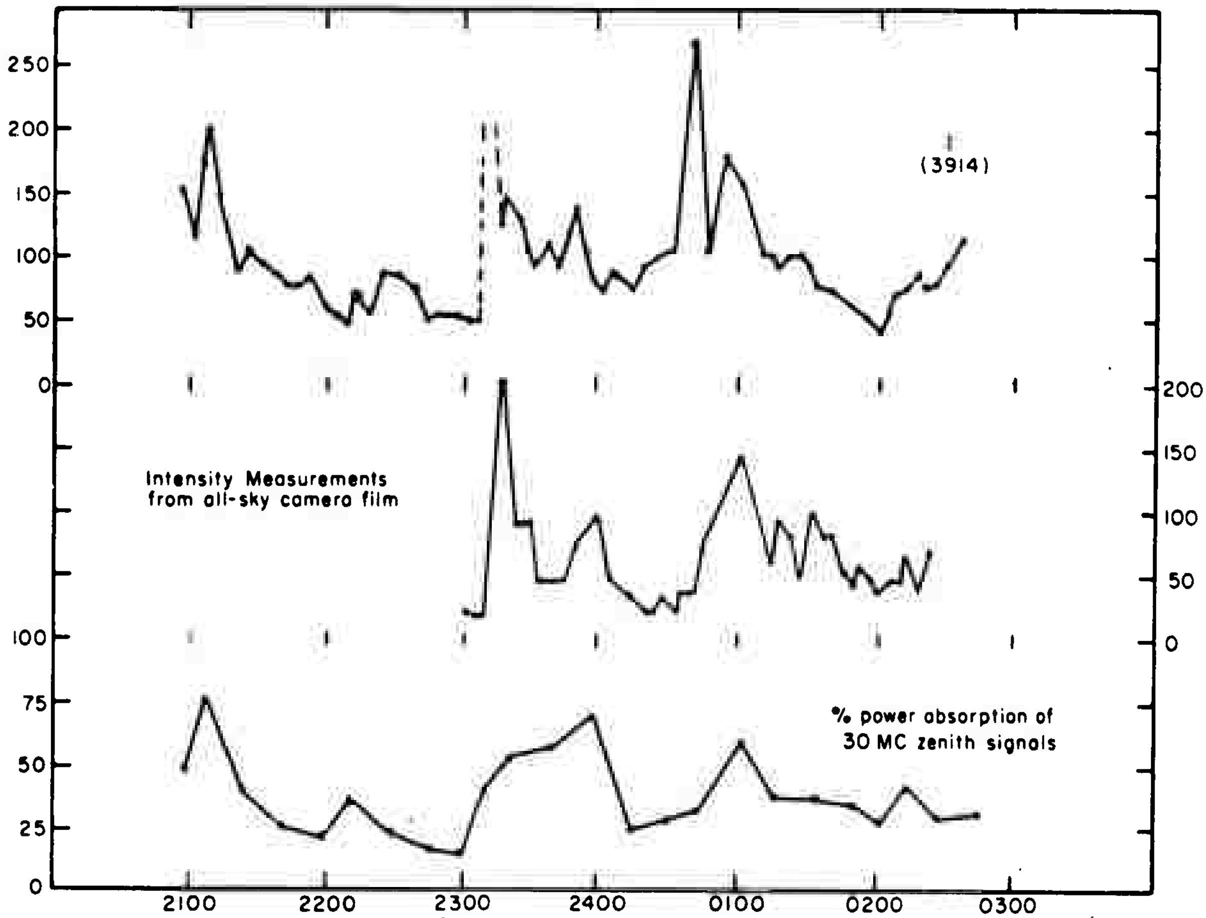

Figure 1.4 Comparison of auroral intensity with zenith absorption, 30 and 31 March 1955.

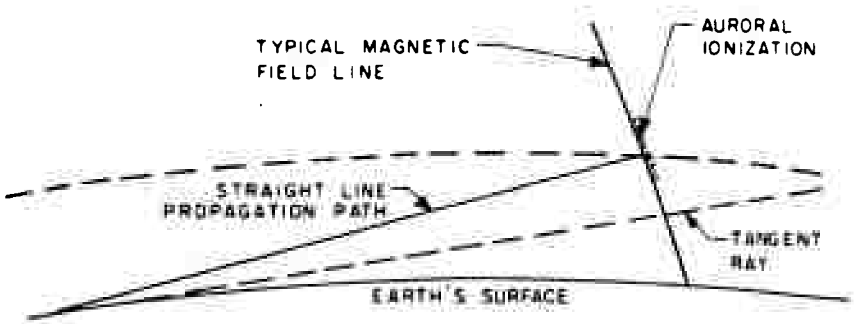

Figure 1.5 Sketch illustrating reflection at perpendicular incidence from elongated ionization irregularities alined with the earth's magnetic field.

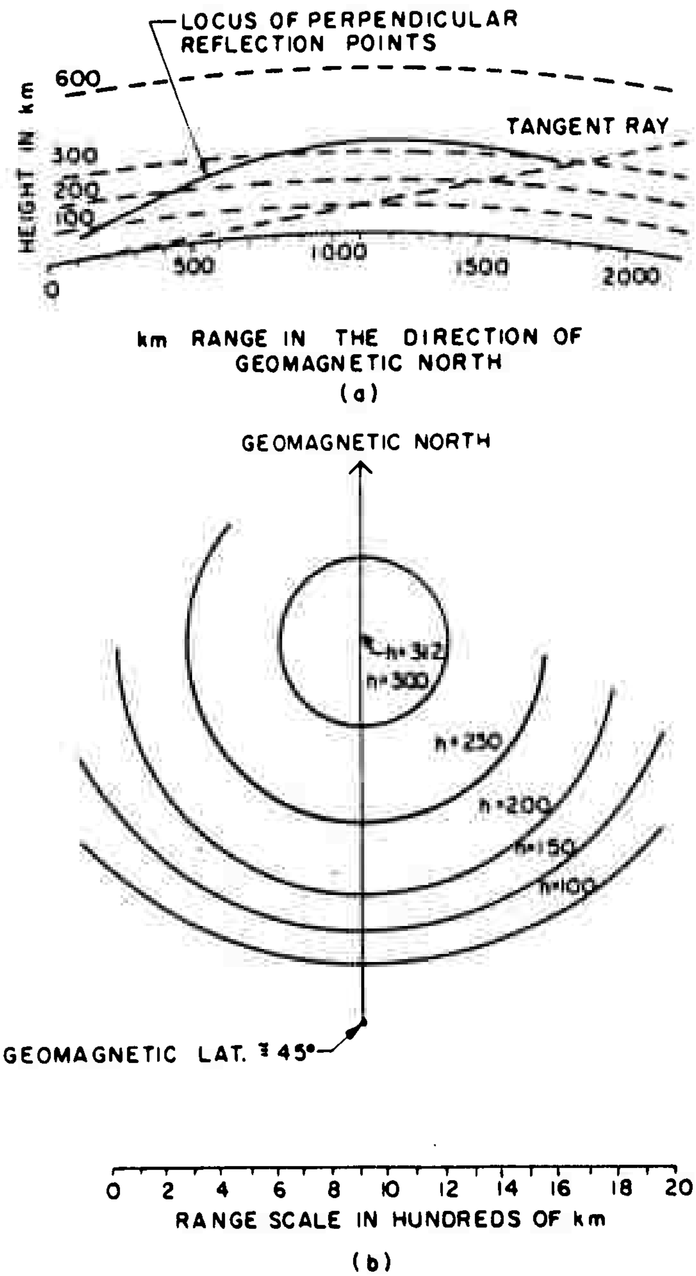

Figure 1.6 Regions at which perpendicular reflection at an earth's magnetic field line can take place.

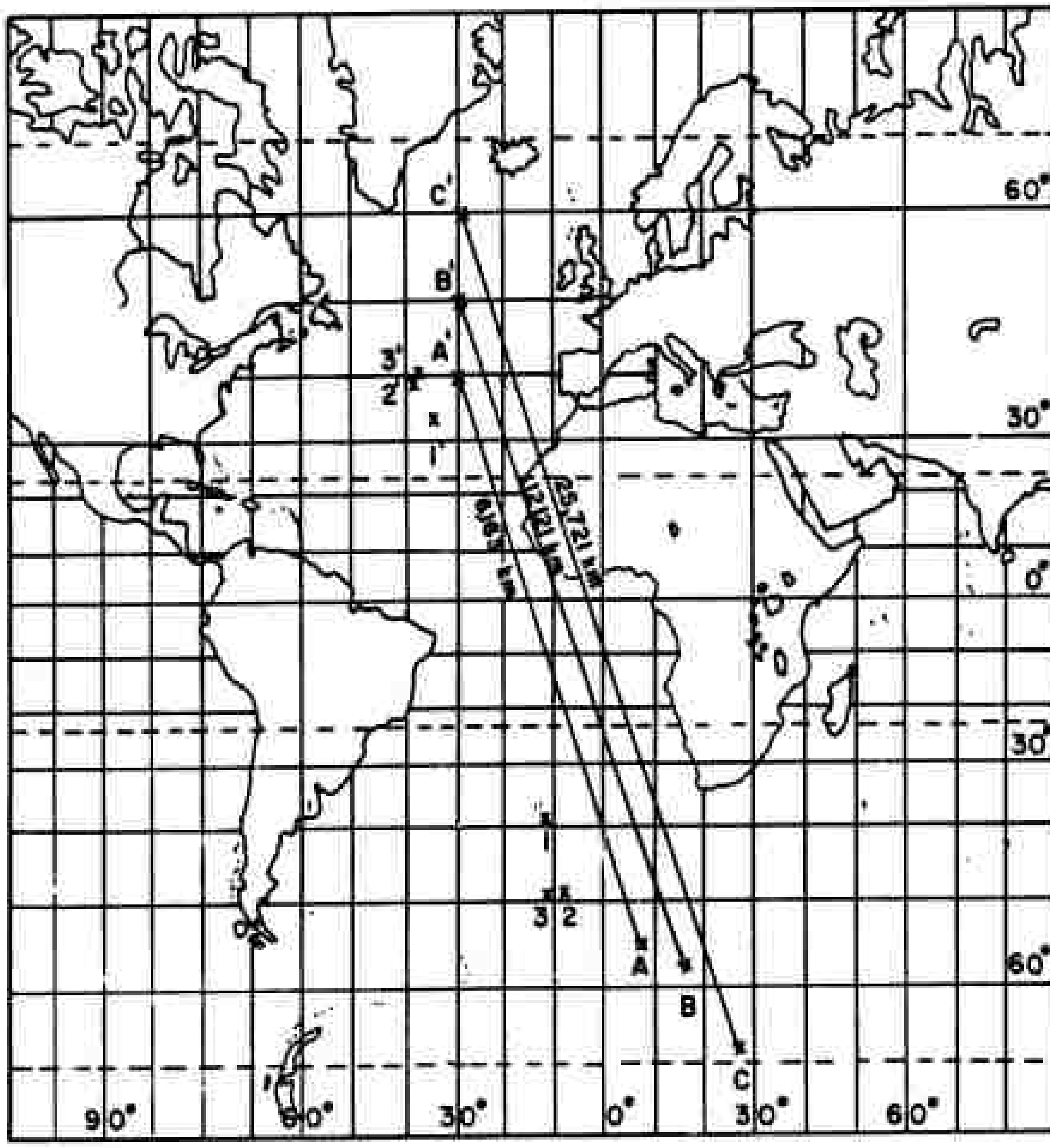

Figure 1.7 Magnetic lines of force projected on the earth's surface. Distances indicated are from magnetic equator to outermost point of force line. A, B, and C and their primes indicate possible firing points and the magnetic conjugates. Actual firing points and their conjugates are given by 1, 2, 3, and their primes.

Chapter 2

VISUAL OBSERVATIONS

2.1 CONJUGATE AREA

After Argus I, one of the AFCRC C-97 aircraft reported an orange glow at a true bearing of 240° from Santa Maria in the Azores. Well-defined rays rose at this bearing and diverged with altitude. The time of the sighting was reported as 0250, or about 22 minutes after the detonation (Table 1.1).

No visual sighting of a glow was reported after Argus II.

After Argus III, there was a prompt sighting of an auroral glow containing blue, green, and red colors (Figure 2.1). Five observers—Captain Minter, Commanders Lynn and Story, Lieutenant Commander Ferguson, U. S. Navy, and Mr. Orange, AFCRC—on the USS Albemarle gave detailed visual descriptions of the aurora occurring after Argus III.

Lieutenant Commander Ferguson gave the following description: "On the evening of 6 September 1958, I was standing on the starboard wing of the bridge shortly after 2000 local. The ship was on course 160° true, making 5 knots. The sea was calm and the sky was partially overcast. The clouds were predominantly middle layer of stratus with large areas of breaks. There was sufficient light in the sky so that the clouds and clear areas, as well as the horizon, were clearly distinguishable." Commander Lynn added, "The sky was five- to seven-tenths obscured by clouds with a relatively clear area aft, and the horizon relatively clear below clouds on the starboard quarter."

The outset of the aurora was not too well defined, and two reports conflicted in this matter. One stated that the effect started as a spear, or streamer, low on the horizon; the other observed no such streamer.

The time of first appearance was recorded by Mr. Orange: "The effect began as a blue-green spear starting close to the horizon, climbing in back of a cloud, and reappearing above the cloud. The effect first appeared at about 2213Z, this is within a few seconds as I had previously set my watch to WWV. A short time after the onset of the effect, about half a minute, a red crown developed at the head of the bluish spear. The red was distinct but not as bright as the green. For the next minute the red spread out, while the blue-green lost intensity. The red aurora deepened in color, began to fade, and was no longer visible at 2217Z. The blue-green spread out and became an indistinct luminous glow covering about 45° of horizon up to about 30° high. The brightest part of the initial display was extremely intense as the edges of the cloud which obscured the center of the display were outlined clearly, as if the moon were behind the cloud."

Captain Minter reported: "I first noticed the aurora when a definite glow appeared in the sky off the port quarter in an area which was partially obscured by a band of alto stratus clouds. The initial effect insofar as intensity is concerned was comparable to that which one would have noticed had a full moon been on the verge of rising in that area, except that the glow initially covered a relatively narrow portion of the sky and appeared to originate about 15° above the horizon. In addition, the light had a greenish cast to it as opposed to the golden glow of a rising moon. Almost immediately a distinctive plume of greenish white light became visible above the cloud layer which obscured what appeared to be the center of the light pattern.

"When I next saw the aurora a significant color change was taking place. The plume no longer existed, and the color of the sky above the cloud layer had changed to a very light red, almost pink, which in turn gave way to a much deeper red with purple overtones. This effect covered a sky area approximately 5° to 10° wide, but lasted only a minute or so, following which the distinctive color disappeared, leaving only a slowly deteriorating bright area of sky to mark where the aurora had been. This area gradually decreased in intensity until it became difficult to tell at just what point it was no longer in contrast to the rest of the night sky. I judged that there was some evidence of the brightness for as long as half an hour after the initial observations."

Along with Captain Minter was Commander Lynn, who furnished this description: "I had checked the clock in the van about a minute before scheduled detonation and not having seen anything, turned back to the van to check again. Simultaneously, I saw an echo appear on the oscilloscope face in the van and heard Captain Minter ask in effect 'Is that it?' Turning, I observed that the area below the clouds on the starboard quarter was very softly lighted with a greenish-white color, very pale in tone, and extending to the left from about 40° left of directly astern. Very shortly, the same light, a little more green, but still very pale appeared above the right-hand edge of a cloud shelf, probably starting at about 25° elevation (where it appeared from behind the cloud) and slowly extending up to about 35° elevation. At the same time, a color transition took place with the pale green being replaced with a reddish purple, rather magenta color. About 2 to 3 minutes after onset, the phenomena had completely faded except for the possibility of a gradually fading persistence below the cloud deck. This latter appeared to exist but could conceivably have been solely the net effect of relatively light sky in contrast to dark cloud and dark water. It was not nearly so marked as the initial phenomena, but I believe there was a persistence for about one-half hour."

Good angular observations were obtained by the officers on the bridge. Commander Storey and Lieutenant Commander Ferguson utilized a stadimeter and a sextant. The former stated, "I was surprised to see the phenomena at a location of 282° true, as I was expecting to see it farther abaft the beam or at about 320°. The azimuth angle was at the same time confirmed by the loom of two lighthouses located on the island of Flores and adjacent islands. A subsequent star shot with the sextant verified the approximate altitude angles."

Lieutenant Commander Ferguson gave the following measurements: "From edge to edge the light area extended over about 3°, to 5° of azimuth. From the bottom of the clouds to the lower portion of the light covered about 7° to 10° altitude. The clearly defined lower edges of the clouds were at an altitude of about 15° to 18°. The apparent behind-the-cloud source of the glow I estimated to be at an altitude of about 20° to 25°."

All the above observers stated that their eyes were adjusted to the darkness before the appearance of the aurora.

2.2 LAUNCH AREA

For Argus I, the weather was completely overcast. Only one aircraft was in the clear above the overcast. The detonation was described as a great, luminous ball with the color and intensity about that of the moon but four or five times as large. It had a spiral effect with dark streaks forming the arms of the spiral. The ball was surrounded by a blood-red auroral ring. The white center subtended an angle of about 5°, the auroral effect about 12°. The ball grew, becoming blotched for about $1\frac{1}{2}$ minutes, then began to collapse and elongate north and south. A streamer of green aurora shot out to the north and down to the horizon, lasting about 10 to 20 seconds. The white part opened up at the north end while the outer luminous band looped around the south end, with parallel streaks in the middle. The whole effect gradually assumed faint luminous parallel lines. At 23 minutes after the detonation, it was barely visible.

For Argus II, the weather was overcast at the surface. All aircraft were in the clear, however, except for a thin high cirrus. The fireball had a brilliant yellow center surrounded by a bright hazy red, which rapidly changed to a brilliant white tinged with green and purple. At about a minute after detonation, the ball was elongated and split in half, each part oriented north and south. At about 6 minutes after detonation, a small cloudlike piece came off each end and moved eastward. One observer counted about five streaks soon after detonation.

For Argus III, the weather was clear with a few scattered clouds. There was a blue-white flash appearing to come from an area smaller than full moon. Immediately thereafter the sky became filled with brilliant light from no discernible source. This diffuse light disappeared. To the immediate north of the initial flash, about 5°, a diffuse white circular area of light appeared from which a thin projection—about 1° wide and 15° long—moved northward. The projection was tenuous and milky white. This phenomenon disappeared within a couple of minutes.

In addition, there was a much more spectacular phenomenon to the south of the initial flash. A streamer of brilliant light shot out in a general south magnetic direction, attaining in less than a second a length of about 30° and a width of about 3°. This wedge-shaped light then evolved into an elliptical shape with striations. Initially, it was yellow-white, changing after a few seconds to yellow near the burst point and more reddish in the southerly direction. After about 15 seconds, four filmy white additional streamers were noticed, parallel to but displaced eastward from the initial streamer. The brilliant main streamer gradually faded, turning a dim yellow rather than filmy. All visible phenomena had disappeared by about 5 minutes after the burst.

Additional reports and sketches of the phenomena are given in the appendix of Reference 20. The auroras in the detonation area are discussed in Reference 21.

2.3 COMMENTS ON THE AURORA

In his description of the red crown in the aurora of Argus III, Mr. Orange indicated that the duration was about 4 minutes. During about half this time, the radar range of the aurora (Section 3.2) was expanding rapidly from 800 to 1,600 km. The red crown would appear to come under Type A attributed in natural aurora to proton excitation (Reference 19). Also, Reference 22 gives a high degree of correlation between the occurrence of radar returns from aurora and the presence of protons as evidenced by the hydrogen lines in the auroral spectrum. However, A. Omholt of the Auroral Observatory, Oslo, Norway, originally an adherent of the theory in Reference 19, now believes that 99 percent of all natural aurora are caused by fast primary electrons (paper to be published in the forthcoming Agardograph of the Symposium on Ionization in the Upper Atmosphere held in Paris, May 1959).

Assuming that the aurora is localized, a table can be set up (Table 2.1) showing possible heights for the aurora and corresponding ranges for given elevation angles. The distances estimated by observers on the USS Albemarle correspond to auroral heights of about 240 to 500 km. A height of 100 km at a range of 800 km requires an elevation angle of the aurora from the Albemarle of 3°, which seems below the visual aurora. At an elevation of 15° (as reported from the Albemarle) and a range of 800 km, the height would be 250 km.

However, if contours of orthogonality are taken into account, the possible situation is as shown in Figure 2.2. The elevation angle from the Albemarle, as seen in previous paragraph, would be below the visual aurora. The maximum range of 1,600 km can be explained in various ways, using the contours. One plausible possibility is indicated by the line OB. If the beam is centered at 282° true (along line OA), the change in azimuth represents about half the beam width of the Albemarle radar. This would require an altitude of about 225 km for the later aurora and a drift toward geomagnetic north rather than the northwest drift that would result from merely extending the line OA. The higher altitude would be consistent with slower electrons, which arrive later and do not penetrate far into the atmosphere. This would also be consistent with the red crown in the visual aurora. The angle of elevation for B is about 1°.

In Figures 2.3 and 2.4, contours are represented deviating from orthogonality. Contours corresponding to 88° and 92° are consistent with the other data as explained for Figure 2.2, whereas large deviations from orthogonality do not give plausible results.

If the estimate given by the Albemarle observers for the angular width of the aurora is accepted, the width is about 60 to 80 km for the 800-km radar range, and twice this at maximum range.

The ground point conjugate to the detonation for Argus III is given on Figure 1.6. If the initial aurora were at 100 km and range 800 km, the corresponding ground point would be about 110 km northwest of the computed ground conjugate point. (Computed by Karzas and Vestine, The RAND Corporation.)

TABLE 2.1 HEIGHT (h) VERSUS RANGE (R) FOR VARIOUS ELEVATION ANGLES (Δ)

h	Δ	R	h	Δ	R	h	Δ	R
km	deg	km	km	deg	km	km	deg	km
100	10	475	250	10	1,010	400	10	1,440
	15	350		15	795		15	1,175
	20	275		20	650		20	985
	30	200		30	475		30	740
150	10	670	300	10	1,160	450	10	1,570
	15	510		15	925		15	1,295
	20	405		20	765		20	1,090
	30	285		30	565		30	825
200	10	845	350	10	1,300	500	10	1,695
	15	650		15	1,050		15	1,410
	20	530		20	875		20	1,190
	30	385		30	655		30	905

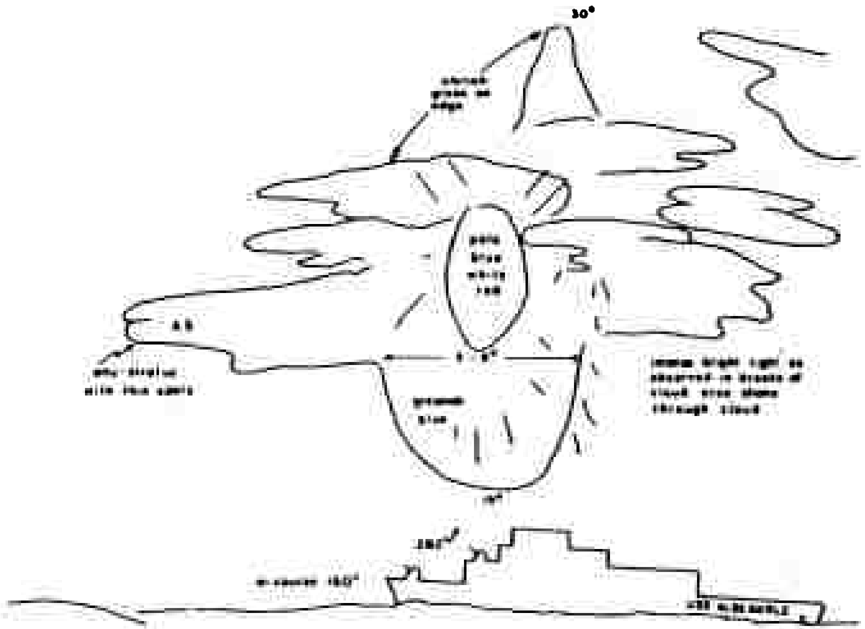

Figure 2.1 Sketch of view from USS Albemarle, Argus III.

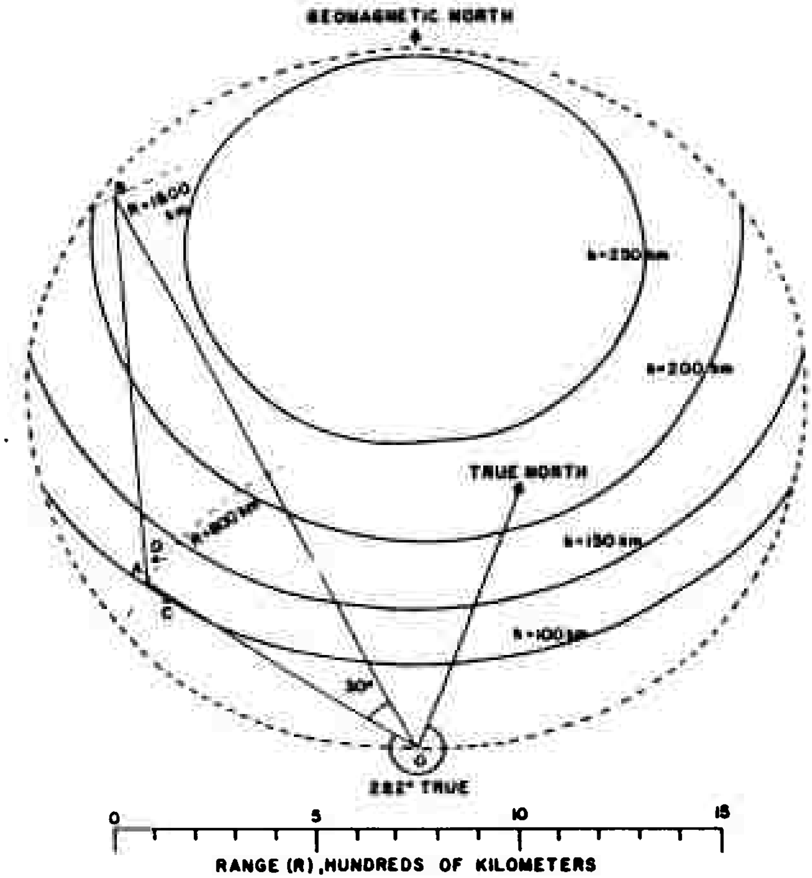

Figure 2.2 Regions of perpendicular intersection of radar beam transmitted from O with magnetic field lines. Geometry of Albemarle radar echoes is superimposed. C is position of computed conjugate point at h = 0. D is position of reflection point extrapolated along field line to ground.

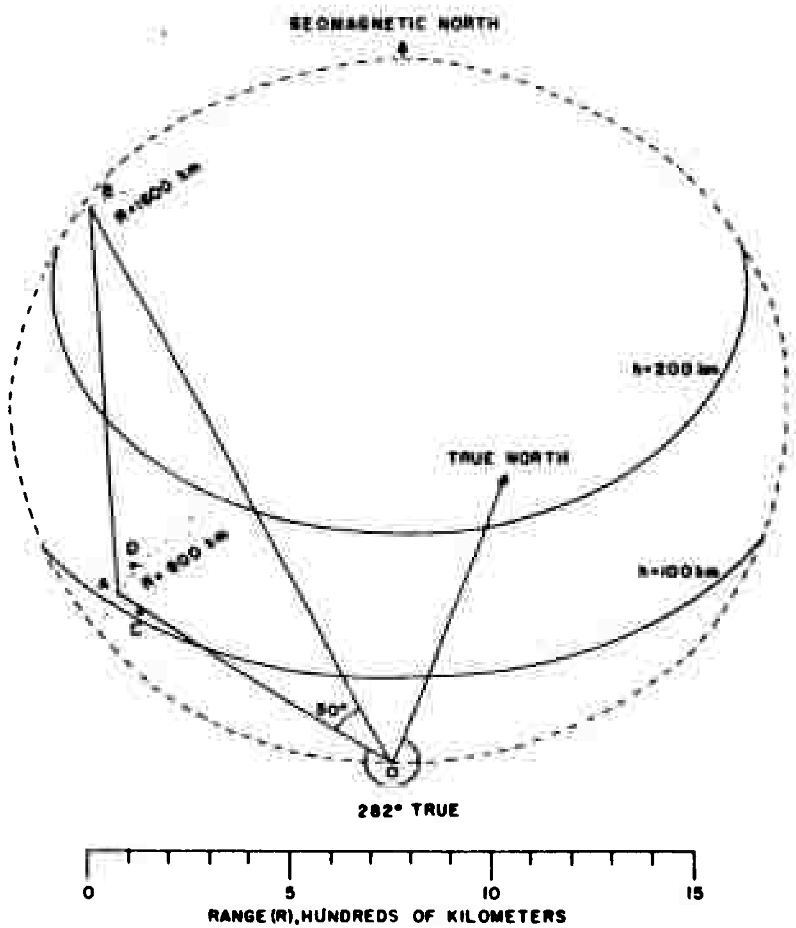

Figure 2.3 Regions of 88° intersection of radar beam and field line. Radar geometry and Points C and D have same meaning as in Figure 2.2.

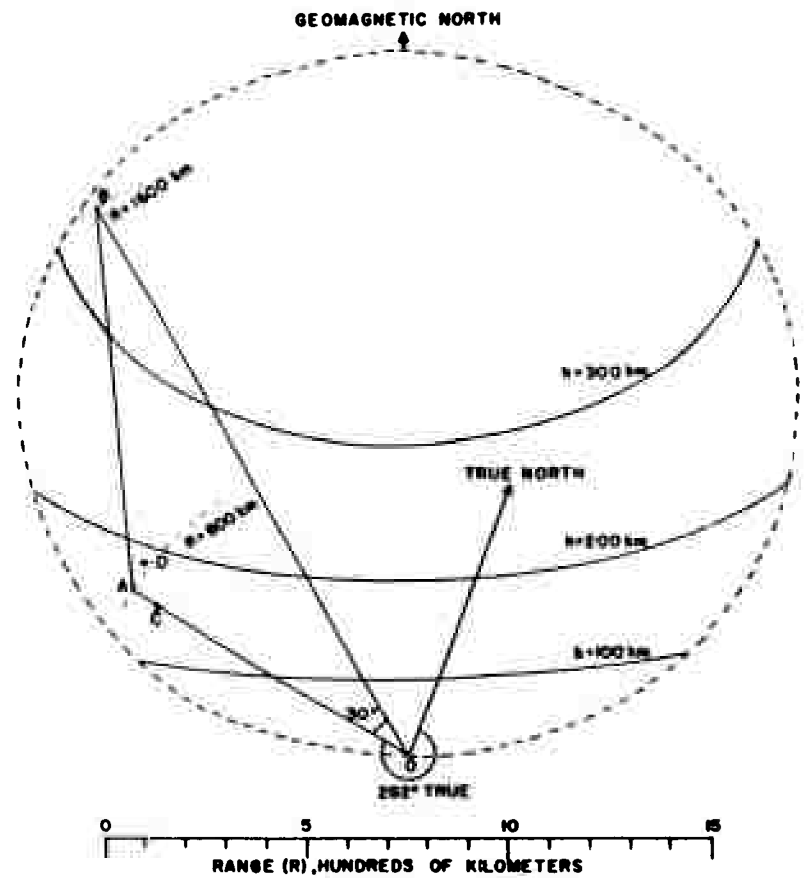

Figure 2.4 Regions of 92° intersection of radar beam and field line. Radar geometry and Points C and D have same meaning as in Figure 2.2.

Chapter 3

RADAR OBSERVATIONS

3.1 EQUIPMENT

Two radars having the characteristics listed in Table 3.1 were employed to detect manmade ionization. One was located aboard the USS Norton Sound at the launch point. The other was located on board the USS Albemarle, which was positioned south of the Azores. The radar beams were directed to magnetic south and magnetic north, respectively.

3.2 CONJUGATE AREA

On the USS Albemarle, strong echoes were obtained after Argus I and III (Table 3.2). Negative results were obtained for Argus II, possibly because of the unfavorable location of the ship. Time is known with an accuracy of ± 1 second. Bearings are discussed in the text.

Prior to and during Argus I, the radar antenna was pointed 360° true. The visual observation of aurora from Santa Maria now indicates that the antenna would have been better pointed 280°. The echo that was observed was presumably occurring in the side lobes of the antenna (60° between half-power points). About 2 minutes and 10 seconds after the shot, the antenna was moved in an attempt to locate the maximum echo. The best azimuth appeared to be about 270° to 300° (Figure 3.1) in good agreement with the position of an echo in the E-region (100-km height) satisfying the orthogonal condition to the magnetic field.

For Argus II, the calculated conjugate point lay 5°37′ northward and 6°29′ westward of the ship's location. The radar antenna was aimed magnetically north (340° true) before, during, and for about 2.5 minutes after shot time. For this positioning, orthogonality to the magnetic field occurs directly over the conjugate point at a height of 250 to 300 km. Aurora is not anticipated at this height.

The lack of echoes can also be explained by the fact that Argus II injected about a factor of 5 fewer electrons into the shell than Argus I and was also about a factor of 5 below Argus III (see Pages 90, 91, and 100 of Reference 21).

For Argus III, the ship's position and antenna azimuth were correct. The radar was aimed magnetically north (340° true) during the shot and turned toward the aurora after the event. No echo was obtained, however, until 1 minute and 8 seconds after detonation. The striking feature of this echo was the steady increase of range of the trailing edge of the echo (Figure 3.2). Possibly, the ionization was moving or being generated in a westward direction. This was in contrast with the expected eastward motion of the electrons. The speed of this motion (4.5 km/sec) was much smaller than the expected migration speed of the electrons (about 150 km/sec at the earth's surface). Possibly the westward motion was due to westward motion of positively charged ions. (However, see Section 2.3.)

Taking visual bearing and initial radar range, there is good agreement with the Karzas-Vestine calculation of the conjugate point. Assuming the height of the aurora to be 100 km, both longitude and latitude are within 1°.

3.3 LAUNCH AREA

At the launch point, echoes were obtained from shot-produced aurora (Table 3.3 and Figures 3.3 through 3.5). From range versus time, the following data can be summarized.

For Argus I, the radar was pointed magnetically south in the hope of observing field-alined echoes. However, the detonation and its extrapolation (along the magnetic field line) to the ground were both behind the antenna, so that the observed echo was obtained by the back radiation of the antenna. The shot location lies within the range intervals when radar echoes were obtained.

For Argus II, the minimum range of the radar echo and the shot location extrapolated down to ground altitude are in strikingly good agreement, and the echo is well alined with the field for an altitude of 100 km.

For Argus III, the echo range is about 40 percent too great to fit the shot location extrapolated to the ground, despite the fact that this location satisfied orthogonality conditions.

3.4 CONTINENTAL UNITED STATES

The Stanford University Radio Propagation Laboratory operated two backscatter sounders (HF radars) at 23.1 and 12.2 Mc during intermittent periods from 24 August to 7 September 1958.

The 23.1-Mc sounder was directed north, and its returns were scanned for field-alined scatter. The 12.2-Mc sounder was directed alternately to the north and to the southeast, and returns were examined for either field-alined scatter or any other echo anomalies at target range.

The 23.1-Mc transmitter was built originally to observe meteor echoes and had a maximum power output of about 70 kw. The pulse rate was about 30 cps, and the pulse width was 100 μsec. The antenna was a broadside array of 48 4-element Yagis cut for 23 Mc and directed toward the north celestial pole. This gave a beam width of 1.2° between the half-power points. The forward gain was about 26 db over a dipole, and the first side lobe was 14 db down.

The 12.2-Mc transmitter was a specially built Granger Associates pulse transmitter with a peak power output of 50 kw. It was operated with a 1-msec pulse width at a pulse repetition frequency of 10 cps. The energy was fed alternately into one of two rhombic antennas. The first was a specially constructed 2-wire rhombic with a major axis 360 feet long and 80 feet high. It was alined so as to fire along the great circle to the target. The other antenna was alined with the magnetic meridian and pointed north.

The receiving equipment for both transmitters was assembled as follows: a Hammerlund SP 600 was driven by a specially built low-noise preamplifier containing a biased diode TR switch. The IF output was detected in a specially built video detector and amplifier. The bandwidth was 8 kc throughout, and the display was a conventional A-scope. In the case of the 12.2-Mc equipment, there were in addition two doppler channels in quadrature, that is, two channels in which a bit of the stable oscillator voltage was coherently detected with the returning signal. Thus, changes of average phase path length from pulse to pulse gave the video signal successively changing positive and negative values. If two such channels use oscillator reference signals in phase quadrature, the sense or direction of change of the phase path can be learned.

Detection of shot-caused ionization at Stanford (longitude 122°6′ W, latitude 37°16′ N) was negative even though the Argus I shell, extrapolated down the field line, intersected the earth just south of Stanford and the second and third shells intersected slightly to the north.

The periods of operation, all in Universal Time, were as follows:

1. The Granger pulse transmitter on 12.2 Mc:
   - (a) Start 0000Z 25 August, off 1530 25 August; recording 40 min/hr
   - (b) Start 0100 26 August, off 2140 26 August; recording 40 min/hr
     (Magnetic north 20 minutes, southeast 20 minutes, off 20 minutes)
   - (c) Start 0135 27 August, off 1800 27 August; recording continuously
   - (d) Start 1800 27 August, off 0245 28 August; recording 30 min/hr
     (Magnetic north and southeast alternately in 5-minute intervals)
   - (e) Start 0515 29 August, off 1232 29 August; recording 30 min/hr
   - (f) Start 0200 30 August, off 0800 30 August; recording continuously
   - (g) Start 0800 30 August, off 1300 30 August; recording 30 min/hr
   - (h) Start 0040 31 August, off 0300 31 August; recording 30 min/hr
   - (i) Start 0645 31 August, off 1130 31 August; recording 30 min/hr

2. The 23.1-Mc Stanford meteor transmitter:
   (a) Start 0135 27 August, off 1800 27 August; recording continuously
   (b) Start 1800 27 August, off 1925 27 August; recording 30 min/hr
   (c) Start 0030 28 August, off 0245 29 August; recording 30 min/hr
   (d) Start 0515 29 August, off 1232 29 August; recording 30 min/hr
   (e) Start 0200 30 August, off 0800 30 August; recording continuously
   (f) Start 0800 30 August, off 1300 30 August; recording 30 min/hr
   (g) Start 0040 30 August, off 0300 30 August; recording 30 min/hr
   (h) Start 0645 31 August, off 1130 31 August; recording 30 min/hr

The high-gain antenna was aimed north on 23.1 Mc and observed occasional field-alined echoes. These echoes bore no clear relationship to the shot time and could well have been of natural origin. A careful search was made of the 23.1-Mc tape recordings, but no field-alined scatter was noted. Considerable meteor activity, of course, was present in the range interval in which an echo might have been expected.

As mentioned previously, additional HF backscatter sounders were operated by AFCRC at Plum Island (19 Mc) near Boston, by Raytheon at South Dartmouth, Mass. (12 and 22 Mc) and Grand Bahama Island (12 Mc), and by NBS (20.3 Mc) and NRL in Washington, D. C.

The Plum Island radar is similar to those described in Section 3.1 but with a peak power of 1 kw. The antenna, a 3-element horizontally polarized Yagi, rotates 360° degrees in azimuth in 6 minutes. Film strip recordings of a PPI scope presentation show no effects from the Argus shots.

The characteristics of the Raytheon equipment are listed in Table 3.4. Raytheon did not receive a notification of Argus I; however, equipment at South Dartmouth was turned on for another purpose at 0335Z. Backscatter soundings at 12 Mc were made with the antenna directed 209° true. The backscatter appeared normal at a range of 15 msec.

At both South Dartmouth and Grand Bahama Island, soundings were made over the period of 0308Z to 0325Z, 30 August, for Argus II. At South Dartmouth, records were made on 22 Mc using a 5-element Yagi antenna directed 135° true and on 12 Mc using a rhombic antenna directed 209° true. Backscatter appeared at both frequencies, but no change in the signal was observed during the time interval covered. At Grand Bahama Island, backscatter soundings were made with the antenna directed 305° true, again with no change in backscatter signals.

Notification of the Argus III test was received an hour late. Backscatter signals at this time looked normal.

TABLE 3.1 CHARACTERISTICS OF RADARS IN CONJUGATE AND LAUNCH AREAS

Frequency	27 Mc
Peak power	7.5 kw
Pulse length	Adjustable, 150 to 1,000 μsec
PRF	Adjustable, 15 to 30 cps
Antenna	3-element Yagi, horizontally polarized, mounted for azimuth rotation
Receiver bandwidth	1 to 6 kc

TABLE 3.2 OBSERVATIONS IN CONJUGATE AREA

Argus	Time of First Appearance	Time After Shot of First Appearance	Time When Last Observed	Range
				km
I	0229:27 ± 1 second	+ 1 minute 34 seconds *	0238 ± 1 minute	450
II	No echo	—	—	—
III	2213:41 ± 1 second	+ 1 minute 8 seconds	2335 ± 1 minute	800 to 1,600

* Antenna not pointed in direction of echo so this may have appeared earlier.

TABLE 3.3 OBSERVATIONS IN LAUNCH AREA

Argus	Time After Shot of Echoes First Observed	Time When Echoes Last Observed	Range
			km
I	Shot time ± 1 minute	+ 2 hours 45 minutes	Began at 450 and moved smoothly to 1,200
II	Shot time ± 1 minute	+ 5 hours	Began at 375 and moved smoothly to 1,950
III	Transmitter off −9 minutes to + 3 minutes. Echo present when turned on.	+ 58 minutes Echoes observed from + 3 to + $4\frac{1}{2}$ minutes from + 22 to + 58 minutes	450. No motion

TABLE 3.4 CHARACTERISTICS OF RAYTHEON RADARS

	South Dartmouth	Grand Bahama Island
Peak transmitter power	200 kw	20 kw
Pulse width	200 μsec	150 μsec
Pulse repetition rate	20 per second	20 per second
Antenna gain	Rhombic, 16 db Yagi, 10 db	Yagi, 10 db
Receiver bandwidth (IF)	15 kc	15 kc

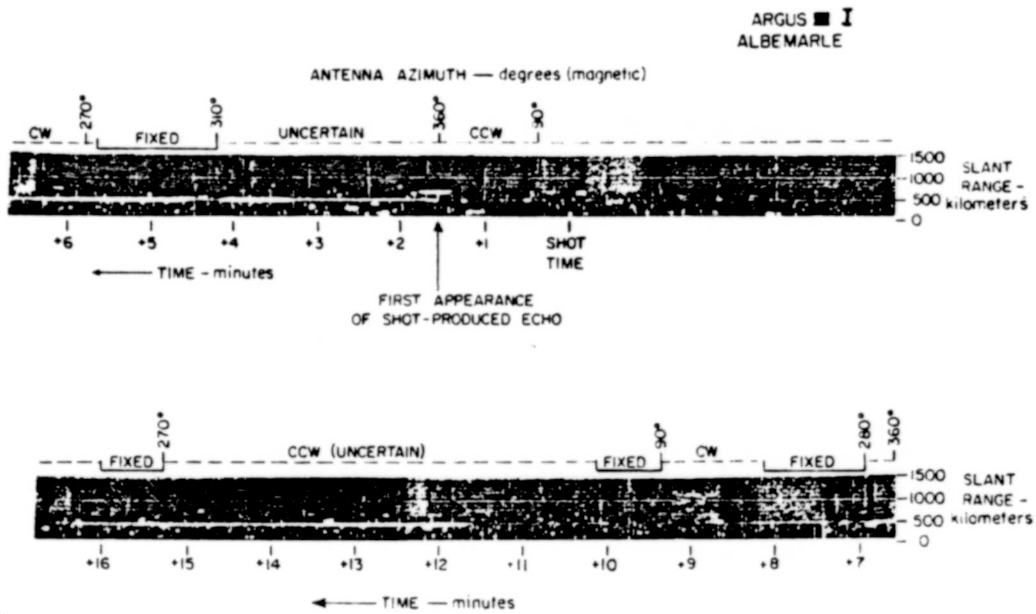

Figure 3.1 Conjugate area radar echoes, Argus I.

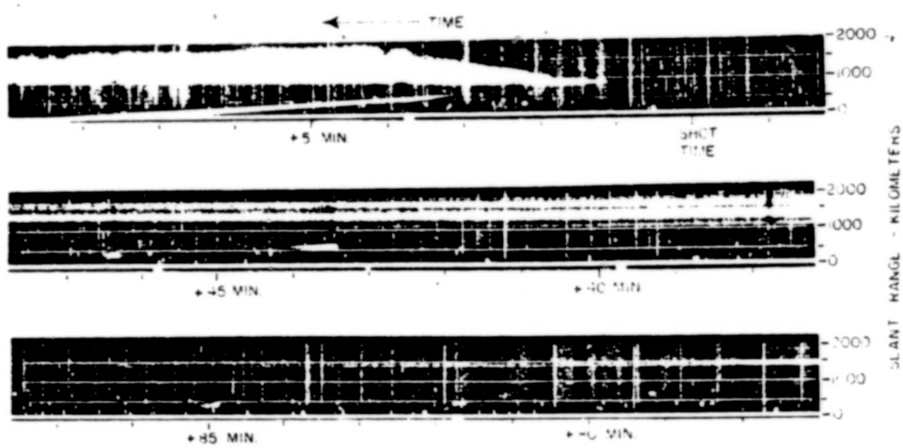

Figure 3.2 Conjugate area radar echoes, Argus III.

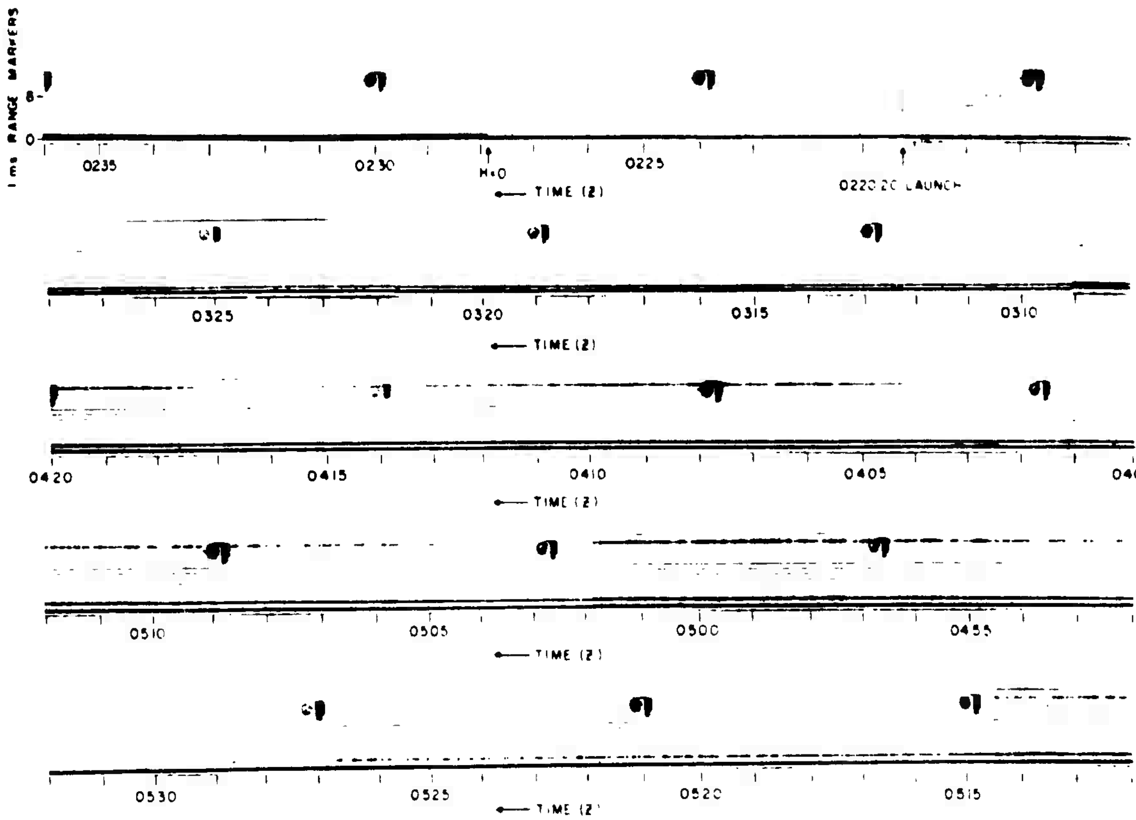

Figure 3.3 Launch area radar echoes, Argus I.

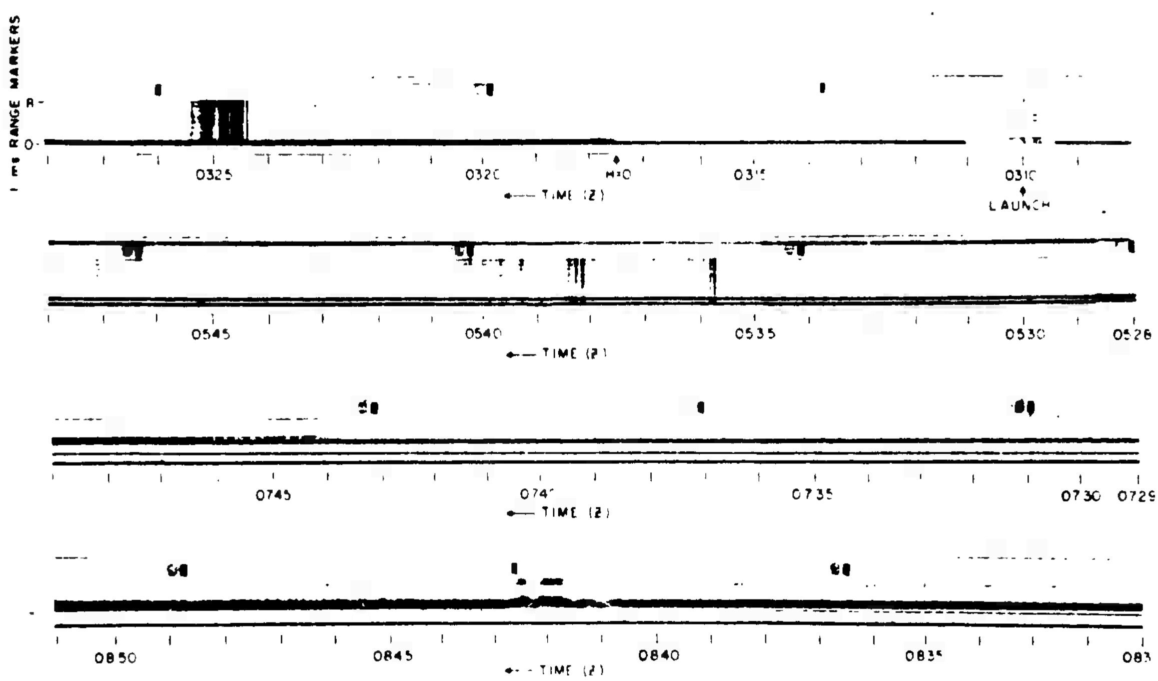

Figure 3.4 Launch area radar echoes, Argus II.

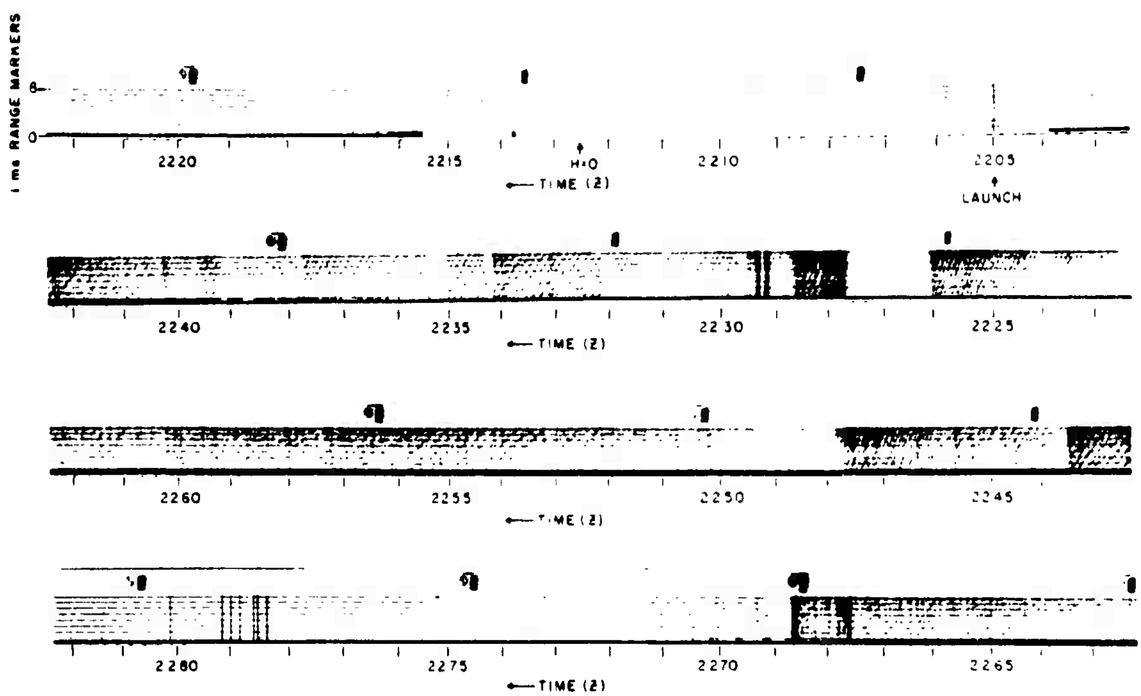

Figure 3.5 Launch area radar echoes, Argus III.

Chapter 4

LOW-FREQUENCY MEASUREMENTS

4.1 EQUIPMENT

As pointed out in Chapter 1, it was anticipated that electromagnetic effects would be generated by the detonation—as the result of electric currents, hydromagnetic interaction with the magnetic field, or radiations from high-speed charged particles, in particular electrons and protons. At the launch and conjugate areas, there was VLF equipment in the range 300 cycles to 30 kc. At Lajes, there were ELF (extremely low frequency) receivers or magnetic induction equipment in the range 0.5 to 25 cps. Operating in dc to 1-cps range was the Heliflux (Schonstedt Mfg. Co., Silver Spring, Md.), a static magnetometer of the saturated-coil type driven at 5 kc; the resultant second harmonic measured the change in the magnetic field. This equipment has a threshold sensitivity of about 1 γ. There was also a variable variometer (Electro-Mechanics Co., Austin, Texas, described in AFCRC Report TR-59-208, ASTIA 210483). The change of magnetic field is proportional to the frequency of the output. Although a change can be read to 0.1 γ, the threshold sensitivity appeared to be about 1 γ.

The ELF equipment was built in the AFCRC shops. The ELF receivers and magnetometers were connected to three coils to measure the N-S, E-W, and V components of the field. The Heliflux magnetometer picked up an excessive amount of RF noise; the variable variometer could not be adjusted in time. However, the ELF and VLF equipment show effects. In the launch area, results were obtained on VLF pulse-recording equipment and on the airborne magnetic detectors.

Each ELF unit consisted of a loop followed by a dc amplifier. The loop output, proportional to dH/dt, was filtered to remove 60 cps, amplified, and recorded on a Brush chart recorder and on an Ampex FM tape recorder (Figure 4.1). The N-S and E-W loops each had a radius of 0.52 meter and 10,088 turns. The vertical loop (loop in horizontal plane measuring vertical component) had a radius of 47.1 meters and 4 turns (Figure 4.2). The lead-in cable was a twisted pair 250 meters long. Loops and lead-in were electrostatically shielded and insulated from earth. To avoid unwanted induced currents, the loops and lead-in were buried. The amplifiers had a sensitivity of about 0.75 γ per chart line for the N-S channel and 1.5 γ per chart line for the E-W and V channels. The calibration of the equipment in terms of the amplitude of H in γ per chart line for sinusoidal variations is given in Figure 4.3. The amplifiers represented state-of-the-art capability from the standpoint of gain, low noise, and stability. Various sources of interference would have tended to mask any quasi-dc signals that might have been picked up by the equipment. Because of the frequency characteristics of the equipment, the background noise is predominantly 10 cps.

4.2 RESULTS ON ELF

4.2.1 Azores. In interpreting the records, unmistakable signals could be read by their large amplitudes and the fact that their frequency composition was different from the dominant 10-cps background. Some of the records show possible earlier signals than those given below, but they do not differ sufficiently from other noise bursts found on the records to be accorded full faith. The large signals show steep onsets, which indicate strong HF components in the disturbance.

No signal was obtained for Argus I. A magnetic disturbance was in progress on the day of Argus I. The noise level on the equipment was higher than for the later events, which may account for the negative results.

After Argus II, signals were recorded on the N-S and V coils (Figure 4.4). In the N-S equipment, the deflection was over full scale and about four times the half-scale amplitude of the noise. The signals had periodicities ranging from 0.5 second to somewhat more than a second. The first definite indication on N-S occurred at about +13 seconds, lasting for about 13 seconds. The initial decrease was followed by equal rates of increase and decrease after 0.25 second, 0.5 second, and about a second. The largest rate of change, an increase, occurred at about +16 seconds. The V component attained its maximum rate of change about 0.5 second earlier. The V signal was small; the N-S signal was about 0.5 γ at the maximum.

For Argus III, all equipment was operating, and the signals were strong (Figures 4.5 and 4.6), going off scale. The first large rates of change occurred at about +12 seconds on the E-W equipment and stronger at about +14 seconds. The largest rate of change occurred at +19 seconds on E-W and +17 for the vertical and N-S components. The period was approximately 1 second, but the signal was not a regular harmonic type. Estimates of amplitude assuming a 1-cps pulse gave values of 0.75, 0.50, and 0.50 γ for N-S, E-W, and vertical components respectively.

4.2.2 Navy Airborne Magnetic Observations at Launch. Airborne magnetic observations were made at the launch area for Argus III from three Navy aircraft (from USS Tarawa) equipped with the AN/ASQ 8, magnetic airborne detector (MAD) equipment. Each of these consists of a pair of saturated core magnetometers driven at 400 cps. The second harmonic at 800 cps amplified and rectified measures the total external magnetic field. The equipment is gimballed so that the aircraft's motion does not give false readings. Compensation is also made for the permanent field of the aircraft. The full range of the scale is 50 γ at lowest sensitivity. The equipment was operated at higher sensitivity.

Initially, large and rapid changes were observed for Argus III, attaining values in excess of 12 to 13 γ (Figure 4.7). The initial pulse was about 1 second in duration, followed by changes in the opposite direction, lasting 2 to 3 seconds. The subsequent behavior was erratic and differed among the three records; this disturbance lasted about 1 minute. The aircraft, all at 10,000 feet, were separated 55 to 75 nautical miles. The distance to the detonation was about 400 nautical miles.

The apparatus did not function for Argus I and Argus II because of mechanical difficulties.

4.2.3 Signal Corps Magnetic Results. During Operation Hardtack, the Signal Corps operated stations near the Grand Canyon, Arizona, and in southern New Jersey, designed to be sensitive to the vertical magnetic component and to variations of the order of 1 cps, with a sensitivity of 10^{-4} γ under quiet conditions. Two signals in Arizona were judged to be identifiable with Argus III, 3.4 seconds and 25.3 seconds after the event (Figure 4.8). The strength of the signal was estimated to be about 1/2,000 γ. Less certain are signals for Argus III on the New Jersey records at 3.0 and 17.5 seconds after the event, with a strength of about 3/200 γ.

In addition, earth currents were detected at a Signal Corps station in Maine, 2.9 and 17.3 seconds after Argus III (Reference 23).

4.2.4 Magnetic Observatories. No significant fluctuations were reported by the Portugese Magnetic Observatory at San Miguel, Azores. The equipment, however, is relatively insensitive—a fiber-suspended balanced magnet. The instrument records at a chart speed of 2 cm/hr with a time resolution of 1 minute. A significant deflection requires a fluctuation larger than those present in the Argus events.

Results were reported by a number of French magnetic stations (References 24 through 26). These stations, equipped with the so-called bar-fluxmeter, employed a high permeability core with a sensitivity of 0.05 γ and were capable of detecting signals with periodicity of 2 seconds to 2 minutes. These French stations located in Africa, Antarctica, as well as near Paris, are shown in Figure 4.9.

The periodicities reported are from 1 to 10 seconds with durations up to 40 seconds. The amplitudes vary from 0.02 to 5 γ, the last having been found on the Z trace at Dumont D'Urville in the Antarctic for Argus III (Reference 25).

Results were also reported at Uppsala, Ghana, and Iceland (Reference 23).

4.2.5 Velocity of Propagation. The ground speed of propagation of the definitely determinable disturbances recorded by the ELF equipment in the Azores was about 700 km/sec. If it is assumed that the disturbance was guided by the geomagnetic field as an Alfven wave, the average speed would be about 2,000 km/sec. Whereas original estimates in References 27 and 28 gave propagation speeds for hydromagnetic waves in the upper atmosphere of 300 to 1,000 km/sec, revised estimates in References 29 and 30 give higher values (Figure 4.10). These new values are also in harmony with the speeds required by the Signal Corps and French magnetic station records—speeds of at least 3,000 km/sec. The latter records presumably are caused by the isotropic mode (see Appendix in this report).

References 31 and 32 present an alternative to hydromagnetic waves to explain the effect on the ELF equipment. According to this explanation, the effects are caused by the plasma produced by the detonation, which sets up currents that, in turn, modify the magnetic field. Effects noted in the Pacific Ocean after Shot Teak have received this type of explanation (References 33 and 34).

4.3 VLF RADIO OBSERVATIONS

4.3.1 Procedure. Variations in radio-wave propagation characteristics in the VLF band (10 to 30 kc) have for many years been known to be a sensitive indication of conditions in the lower ionosphere (below 100-km height). In addition to VLF communication transmitters operated in many parts of the world, lightning strokes (giving rise to atmospherics) provide a source of energy that can be recorded in the VLF range. The VLF signals can either be enhanced by increased ionization at the ionospheric reflection height or reduced by absorption caused by increased ionization at denser levels of the atmosphere through which the signals must pass. The VLF strength also depends on the nature of the interference among the ground and several ionospheric modes.

During the Argus experiment, broad-band VLF recordings were made approximately under the detonation at a number of locations near the conjugate region and at Stanford University. The recorded data has been studied by various methods, for effects on the ionosphere that might have resulted from the trapped shell of electrons that extended around the world, or for possible effects in the launch or conjugate area due to radiations from the fission debris. Data was recorded on magnetic tape on a sampling basis (2 minutes each hour) to determine general VLF propagation conditions and also on a continuous basis to attempt to identify shot-associated effects and possible after-effects.

The VLF equipment was designed, constructed, and installed by personnel of the Stanford University Radio Propagation Laboratory under the direction of Professor Robert A. Helliwell. Briefly stated, it consisted of a broad-band receiver, loop antenna, magnetic tape recorder, and associated calibration equipment. These were similar to the whistler recorders employed at IGY stations.

Semiportable VLF equipment was employed at Torrejon, Lajes, Stanford, and Hawaii. The semiportable receiver was comprised of a large, single-turn loop antenna, broad-band vacuum-tube preamplifier, and a 2-channel Ampex 350 magnetic tape recorder. The tape recorder operated at 15 in/sec giving the system an approximate bandwidth of 300 to 30,000 cps. The minimum detectable signal was approximately 20 μv/m. A radio receiver was provided for the reception of WWV signals for timing purposes, and its output was recorded on the second channel of the tape recorder.

Portable receivers, used aboard the USS Norton Sound and the USS Albemarle, were each comprised of a small (about 1 m^2), many-turn loop antenna, a broad-band transistor preamplifier, and a 2-channel Ampex 350 magnetic tape recorder. The tape recorder operated at $7\frac{1}{2}$ in/sec, giving the overall system an approximate bandwidth of 300 to 15,000 cps. The minimum detectable signal was approximately 50 μv/m. WWV signals from an available receiver were recorded on the second channel of the tape recorder for timing purposes. The upper frequency limit of the recorder prohibited a study of the manmade transmissions from the VLF radio stations in England (GBZ) and Seattle (NPG).

Preliminary results were obtained by methods normally applied to broad-band VLF records when studying such phenomena as whistlers or VLF emissions. First, the broad-band recording is aurally monitored using earphones. This method is useful in detecting unusual sounds, such as the whistler and rather large changes in background noise level or atmospherics activity, but it requires considerable experience. A second method produces an intensity-modulated record of the frequency spectrum as a function of time. This spectrum analysis is useful for displaying sounds of higher frequency than detectable by the human ear. It also provides rough spectrum character of specific signals and detects relatively large changes in background noise level. The disadvantages of spectrum analyzers are: (1) the time required to produce a spectrogram, (2) the difficulties encountered in obtaining proper level adjustments, and (3) the limited dynamic range of the spectrogram paper.

Amplitude-versus-time records were made by passing the broad-band tape recorder output through adjacent channels of 5-kc bandwidth covering the frequency range of 300 to 30,000 cps; the output of each filter was demodulated and applied to a pen recorder. The field strength of several VLF radio stations was similarly investigated by the use of a tunable, narrow-band filter (500-cps bandwidth). The recorded timing source (WWV in all but one case) was displayed on the second channel of the pen recorder. Thus the tape recorder served to directly encapsule the received energy for later demodulation by filters playing the role of receivers. It was not possible to observe changes in phase with this equipment.

4.3.2 Observations. Successful recordings complete with timing signals were obtained from two-thirds of the stations, as listed in Table 4.1.

The results to be described are primarily from Argus II, because the records and analysis for this shot are most complete. A survey of the records from Argus I shows that this shot caused much smaller effects. Results from the available records from Argus III provide strong support for the results found for Argus II.

The VLF records yield an unexplainable disagreement with the official shot times. For example, following Argus II, an abrupt decrease of approximately 10 db in signal strength from VLF Station GBZ (England, 19.6 kc) received in the Azores occurred at 0317:32.7Z ±0.1 second, approximately 1 second ahead of the official detonation time. WWV time ticks were used as the source of timing for these VLF records. Following Argus III, an abrupt decrease of approximately 6 db observed over the same path occurred at 2212:35.6Z ±0.1 second, or 2.3 seconds following the official time.

No detectable whistlers were generated by the Argus detonations. Only seldom was a distinct pulse present that could be related to the detonation. The observations are summarized in Table 4.2 and are described in greater detail in the text.

Argus I.

1. USS Albemarle: No VLF data.

2. Azores: A spectrogram (0 to 30 kc) through shot time shows no significant impulse exceeding the sferics present in that period. No whistler was detected. Significant changes in noise level or radio signal strength were not present.

3. USS Norton Sound: Effects associated with the detonation were not noted. The small yield of the shot, and the limited efficiency of the whistler mode may not have given an adequate impulse to be observed at the ship above the prevailing sferics level of about 100 μv/m.

A burst of noise lasting several seconds was received at missile launch, confirming a simultaneous RF noise that appeared on the radar receiver at 27 Mc.

4. Stanford: Same negative report as at the Azores.

5. Madrid: Same negative report as at the Azores.

Argus II.

1. USS Albemarle: Local pulse interference (at 20 pps) as well as severe harmonics from the 60-cps power source were present on these records. No shot-associated pulse was detectable on either the VLF record or the WWV timing record.

2. Azores: Several shot-associated effects occurred:

(a) An abrupt decrease of approximately 10 db in the signal strength from GBZ (England, 19.6 kc) occurred at 0317:32.7 ±0.1 second (Figure 4.11). Following this abrupt change, the signal strength returned to within 6 db of the preshot signal strength during the next 25 seconds and then began a slow decrease to at least 12 db below preshot level, reaching this minimum approximately 5 to 8 minutes after shot time. The signal from GBZ returned to preshot level in approximately 35 minutes.

(b) The signal from NPG (Seattle, 18.6 kc) increased approximately 2 db following the shot. The average level of signal strength remained above preshot level, although rather large fluctuations in signal strength were present, which made exact time of the change difficult to determine.

(c) Chart recordings of the integrated 5-kc passbands show that there was a general decrease in VLF noise over the region from 300 cps to 25 kc. The greatest decrease in noise level occurred in the 5- to 10-kc region and least decrease in the 10- to 15-kc region.

(d) On the WWV receiver (15 Mc) a pulse stronger than normal sferics was noted at 0317:32.7Z. Later at approximately 0317:48, a marked increase in fading rate occurred.

3. USS Norton Sound: There was again a large amount of shipboard interference at a PRF of 20 pps. No large disturbance at shot time could be positively identified. A distinct pulse appeared either at 0317:32.7Z or 0317:33.7Z on an amplitude-versus-time recording of the total broad-band noise. A strong signal lasting several seconds was received at missile launch.

4. Stanford: General increases in propagation performance were noted as follows:

(a) The signal strength from NPG (Seattle, 18.6 kc) increased slowly for approximately 10 seconds and then increased more rapidly for about 3 seconds to a level approximately 2 db above preshot level. Total duration of the signal strength enhancement has not been determined, but it is greater than 2.5 minutes.

(b) The signal strength from NDT (Japan, 17.1 kc) appeared to increase ≤ 2 db above preshot level. This signal was not keying at shot time but returned at a higher level 11 seconds after shot.

(c) The noise in all 5-kc passbands increased slowly for approximately 10 seconds and then increased rapidly for approximately 3 seconds to a level roughly 3 db above preshot level.

5. Madrid:

(a) The signal strength of GBZ (England, 19.6 kc) began to decrease approximately 5 seconds after the shot to a level roughly 1 db below preshot level and remained near this level for more than 1 minute. Following this period, the signal strength began a slow decline reaching a minimum of approximately 6 db below preshot level 5 minutes after shot. The signal returned to preshot level in about 25 minutes.

(b) The integrated chart recordings of the 5-kc passbands show that the noise in the 10- to 15-kc band decreased markedly. The noise level in all other 5-kc bands did not change significantly.

(c) At 0317:32.7Z a sferic was present but was not even as strong as neighboring sferics occurring many times per second.

(d) On the WWV (15 Mc) receiver, no pulse was noted, although a better spectrum analysis may be rewarding. If anything, the signal strength of WWV appeared to be stronger after the shot than before.

Argus III.

1. Azores: An abrupt decrease of approximately 6 db in the signal strength from GBZ (England, 19.6 kc) occurred at 2112:36.0Z ±0.2 second. Following this abrupt change, the signal strength increased slightly for a few seconds and then slowly decreased to at least 12 db below preshot level. The signal strength returned to preshot level in approximately 20 minutes.

2. Madrid: This record has not yet been analyzed.

4.4 VLF PULSE IN LAUNCH AREA

At the last minute, equipment to observe the electromagnetic pulse that might be produced by the detonation was placed aboard the USS Tarawa. This equipment was neither elaborate nor particularly complex. A whip antenna was used to detect the pulse. Equipment associated with the antenna included a cathode follower, a Tektronix 121 amplifier, a Krohn-Hite 310AD band-pass filter (600 cps to 200 kc), and three oscilloscopes. These oscilloscopes were a Tektronix 513D triggered sweep, a Tektronix with a raster sweep, and a Hughes 104D triggered sweep memoscope. On the first two oscilloscopes, 35-mm cameras were used. One camera with a running time of about a half hour was used with the triggered sweep oscilloscope; the second camera, with a running time of 20 seconds, recorded the raster sweep presentation. After each detonation, the memoscope was disconnected and a polaroid picture taken (Figure 4.12).

The triggered sweep scope with only 20 seconds of photography available caught only Argus III (Figure 4.13). Although the calibration indicates 0.2 mv/m, the actual field strength was probably greater, because the sea spray affected the input impedance of the equipment, virtually shorting out the antenna. The record shows a duration of more than 70 μsec and apparently a phase shift possibly caused by a second pulse at about 10 μsec.

Results from the other two oscilloscopes were less satisfactory. Background noise was so high that the film record from the triggered sweep oscilloscope was unusable. Although the memoscope failed to trigger promptly, losing the rise and peak, enough of the pulses were recorded to show a width of the main part of the pulse of about 20 μsec. The tail of the pulse for Argus I showed a ripple of about 30 kc. The tails of the other two are smooth.

4.5 OTHER OBSERVATIONS

The French observatories at Bagneux and Poitiers continuously record atmospherics on 27 and 10 kc. Effects are observed on the records after the Argus events. Similar effects, however, are readily seen at other places on the records so that the results must be treated with considerable reservation.

About 1 minute after Argus I, the mean 27-kc field at Bagneux shows a decrease of about 1 mv lasting for about 20 minutes. The rate of occurrence of sferics shows a slight decrease at 0230Z, lasting about 40 minutes. The 10-kc record shows a dip for about 20 minutes. At Poitiers no change was observed on the 27-kc record.

For Argus II, the 27 kc at Bagneux shows a decrease for about 10 minutes. The rate of sferics shows a more pronounced decrease than for Argus I for about 15 minutes. No change or very slight one occurred on 10 kc. At Poitiers, there was an abrupt fall of the mean level on 27 kc lasting for about 30 minutes.

For Argus III, the 27 kc at Bagneux was out of order. On the 10 kc, there was a diminution lasting about 5 minutes. At Poitiers there was nothing unusual.

The records for the path from Lower Hutt, New Zealand, to Rugby, England, GBR (16 kc) were examined at the Dominion Physical Laboratory for Argus effects. No observable effects were found.

TABLE 4.1 AVAILABLE VLF RECORDS

Station	Argus I	Argus II	Argus III
USS Albemarle	Timing only	VLF	No records
Azores	VLF	VLF	VLF
USS Norton Sound	VLF	VLF	No records
Stanford	VLF	VLF	No records
Madrid	VLF	VLF	VLF only

TABLE 4.2 OBSERVED VLF EFFECTS

Station	Argus I	Argus II	Argus III
USS Albemarle	—	Severe interference. No effects noted.	—
Azores	No effect	1. 10-db decrease of signal from England. 2. 2-db increase of signal from Seattle, Wash. 3. Decrease of noise level (300 to 25,000 cps). 4. Pulse on 15 Mc simultaneous with above effects. Increase in fading rate.	12-db decrease of signal from England
USS Norton Sound	No effect	Severe interference. * No effects noted.	—
Stanford	No effect	1. Gradual 2-db increase of signal from Seattle, Wash. 2. 2-db increase of signal from Japan. 3. Gradual increase of noise to 3 db above preshot level.	—
Madrid	No effect	1. 6-db decrease of signal from England. 2. Decrease of noise level.	Not analyzed.

* A large burst of noise was observed at missile launch.

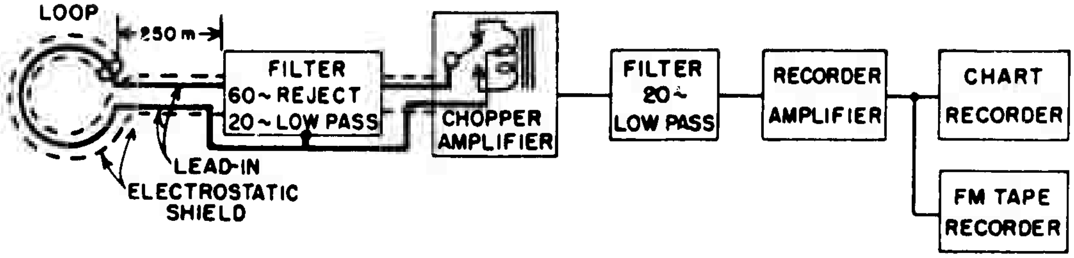

Figure 4.1 Block diagram of one channel of ELF detector.

N-S and E-W loops, 0.52 m radius, 10,088 turns. Vert. loop 47.1 m radius, 4 turns.

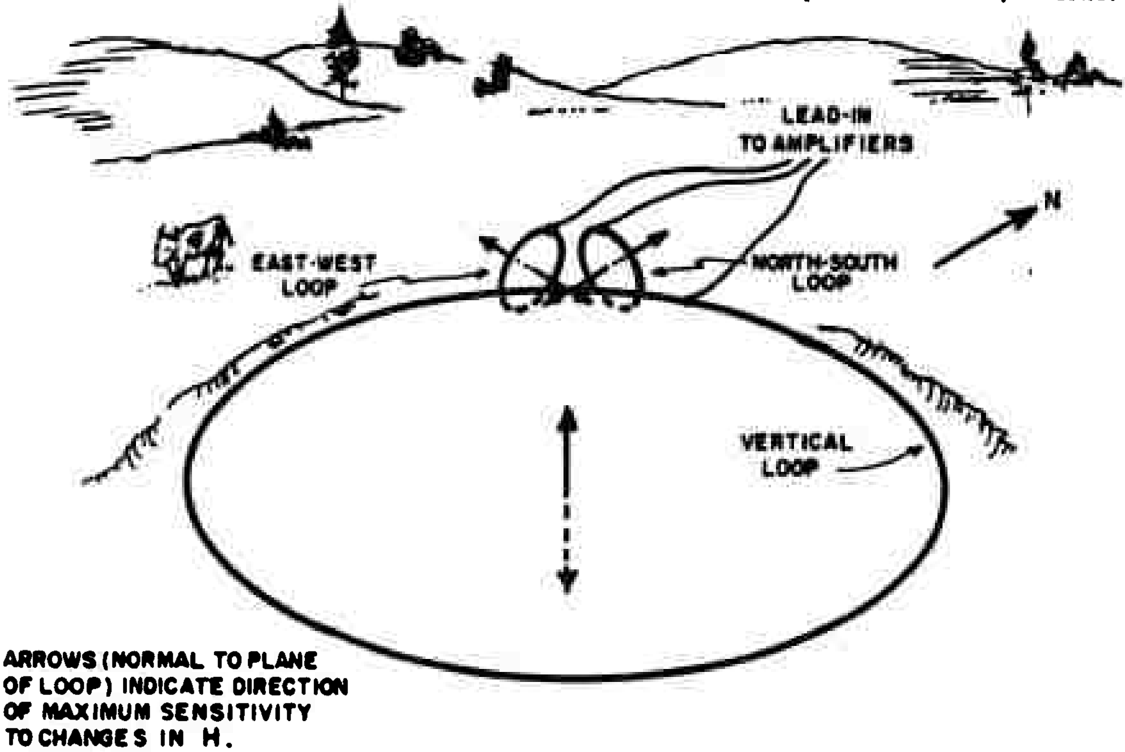

Figure 4.2 Position of loops used for ELF detector.

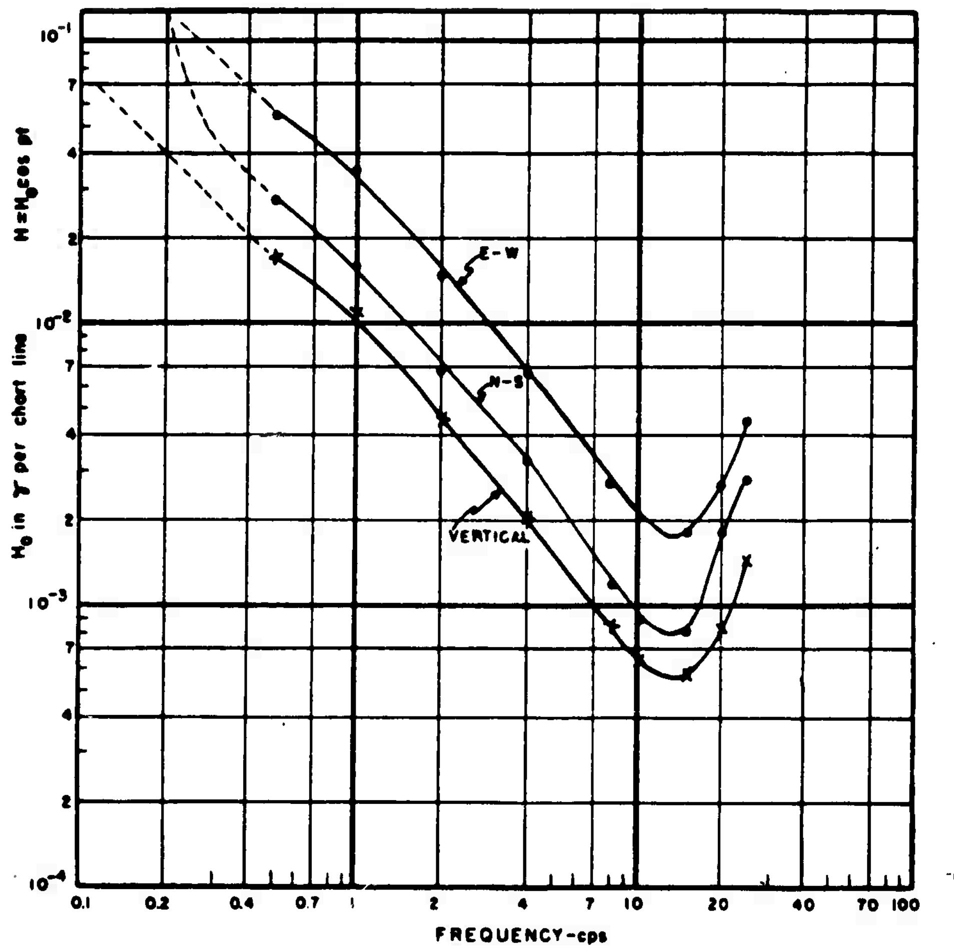

Figure 4.3 Calibration of ELF detector coils.

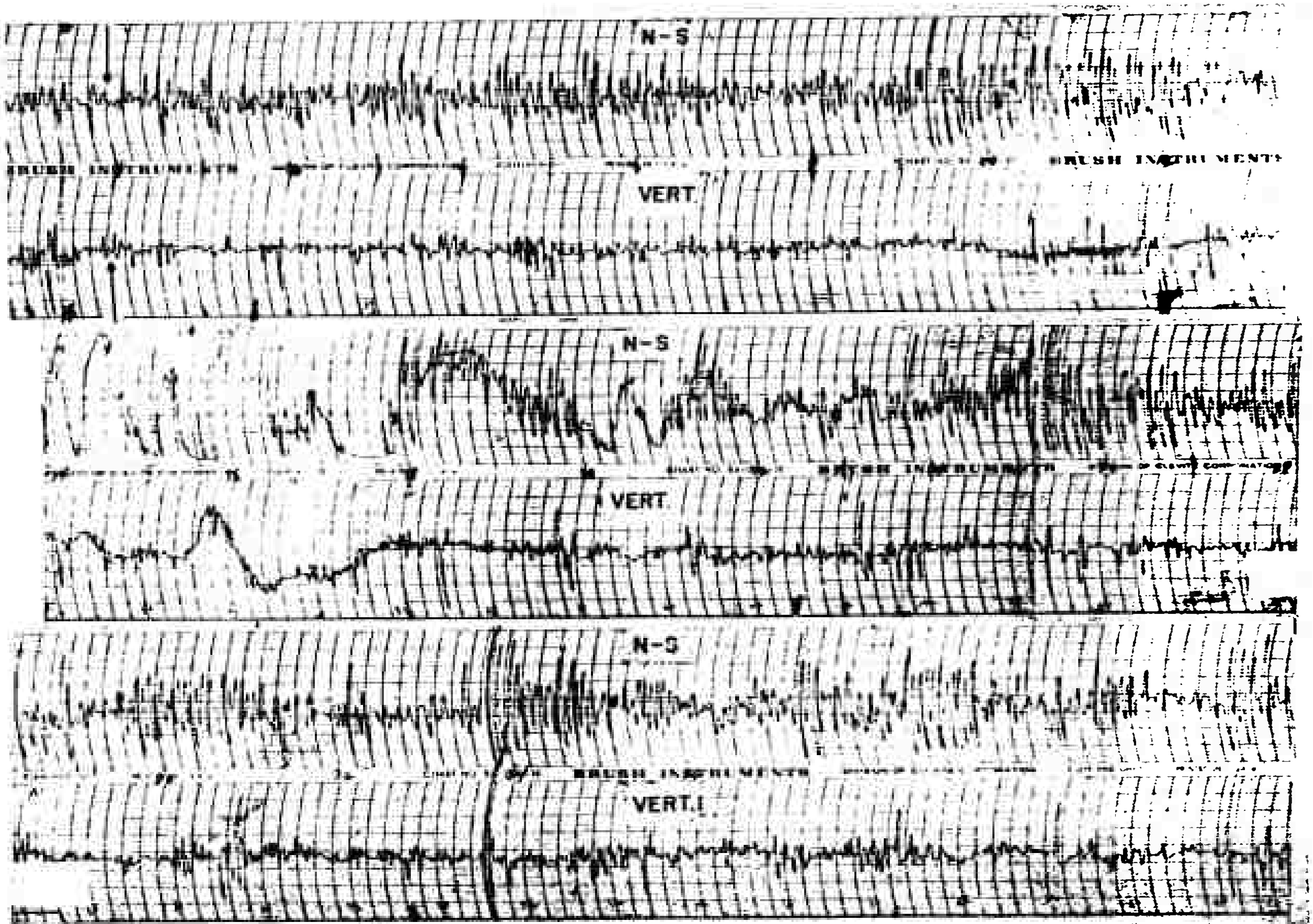

Figure 4.4 ELF magnetic signals received in Acores, 30 August 1958. Chart speed: 5 divisions per second. Arrow indicates detonation.

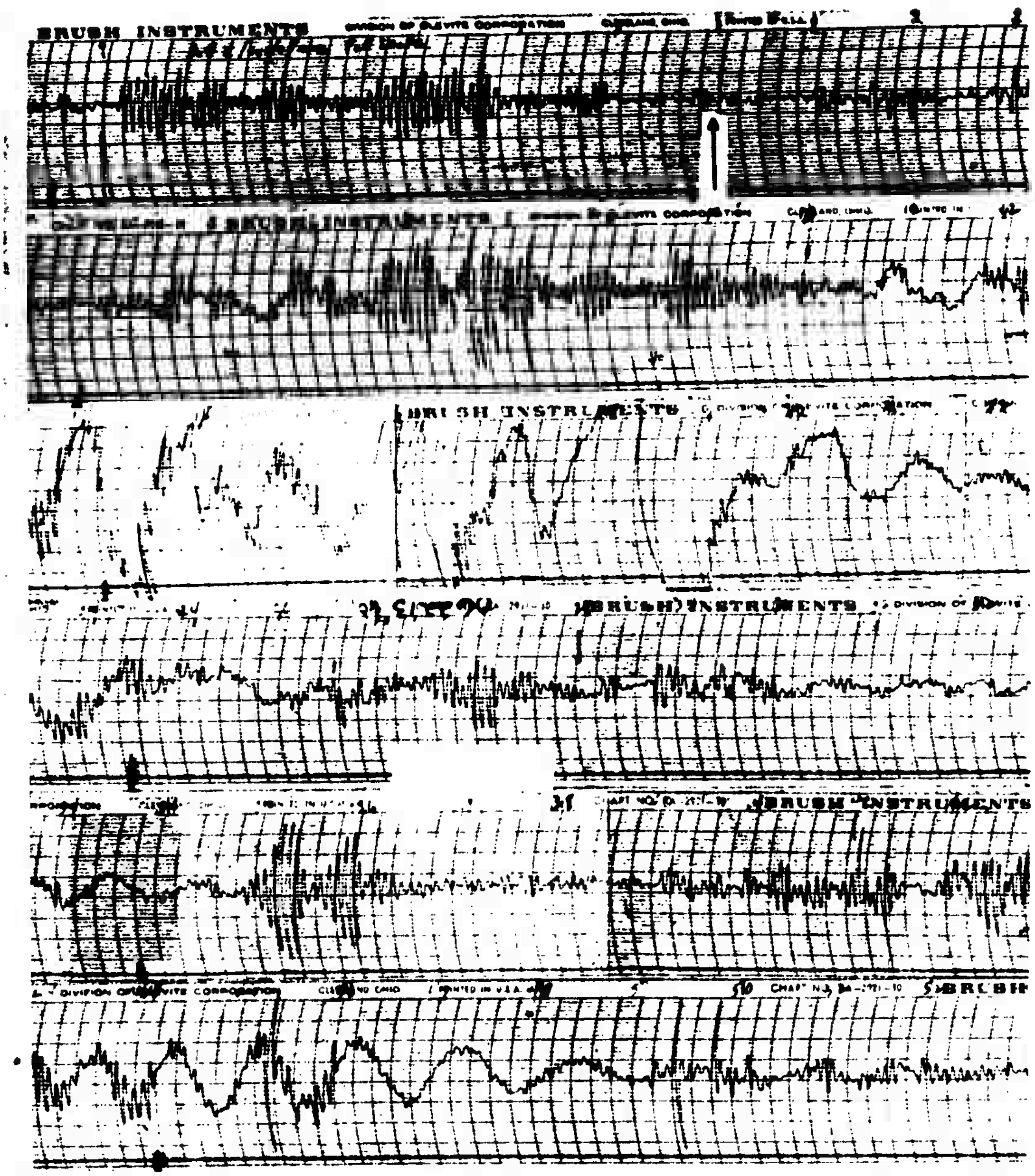

Figure 4.5 ELF magnetic signals received in Azores, 6 September 1958, E-W coil. Chart speed: 5 divisions per second. Arrow indicates detonation.

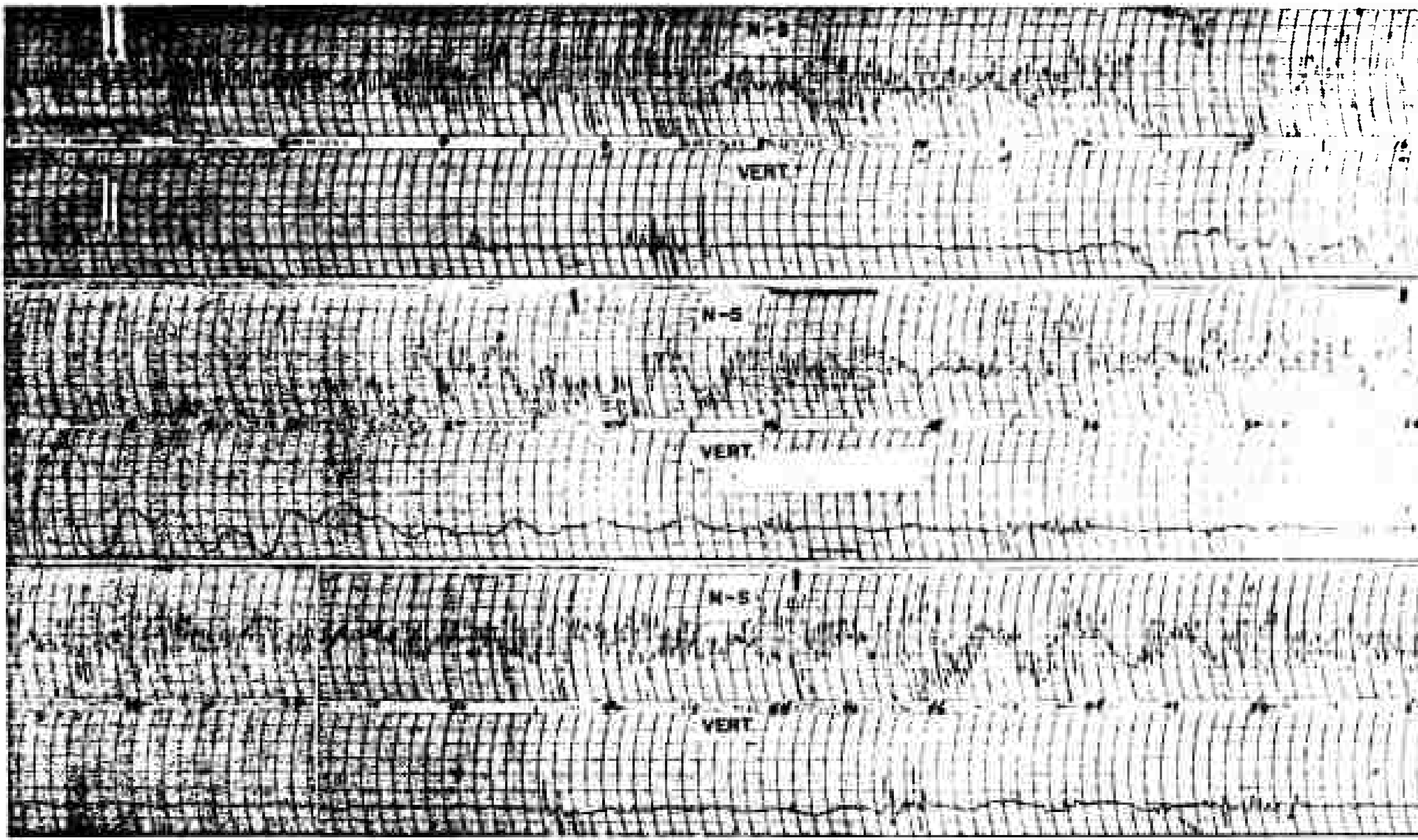

Figure 4.6 ELF magnetic signals received in Azores, 6 September 1958, N-S and V coils. Chart speed: 5 divisions per second. Arrow indicates detonation.

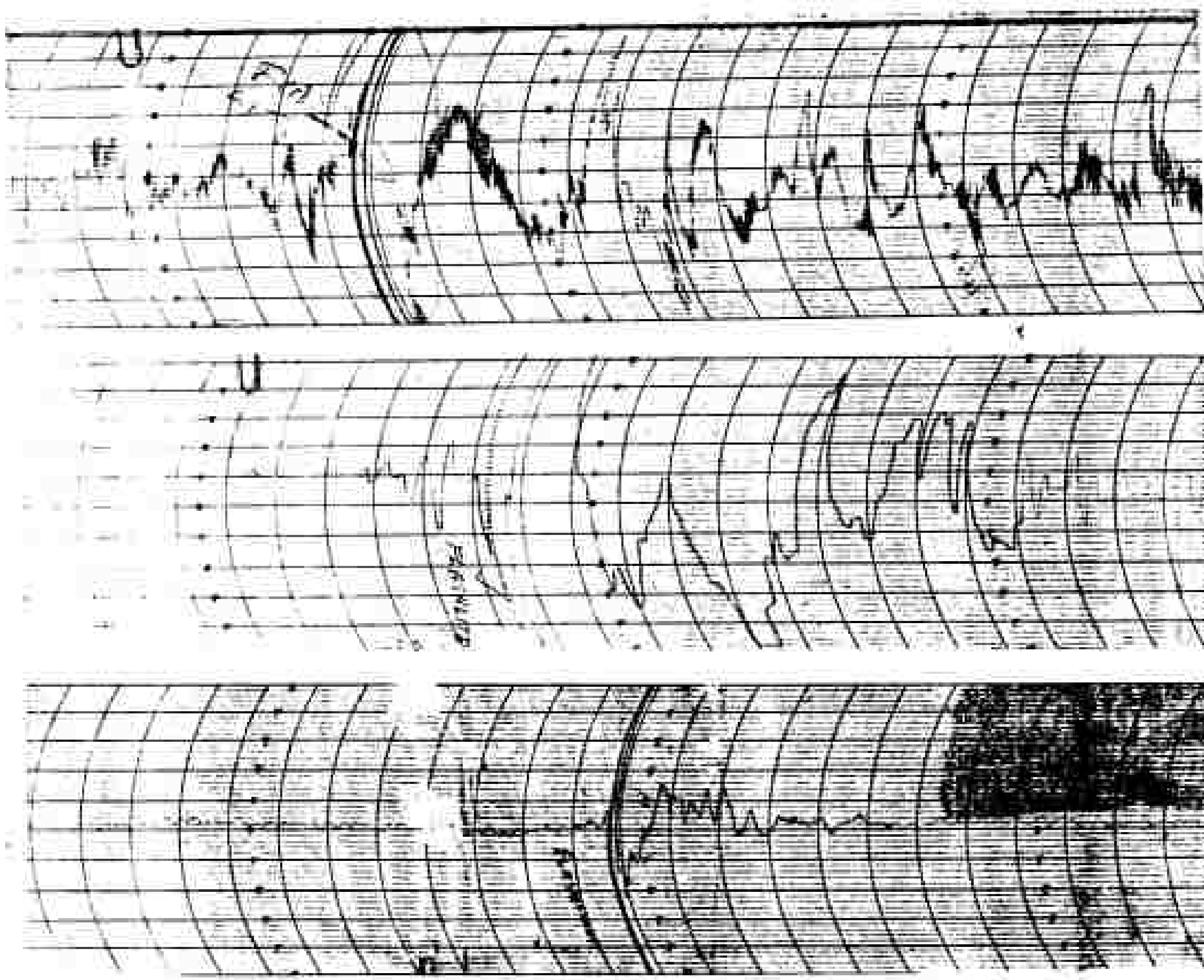

Figure 4.7 MAD record at launch area, 6 September 1958. Chart speed: top two rows, 8 divisions per minute; bottom row, 4 divisions per minute.

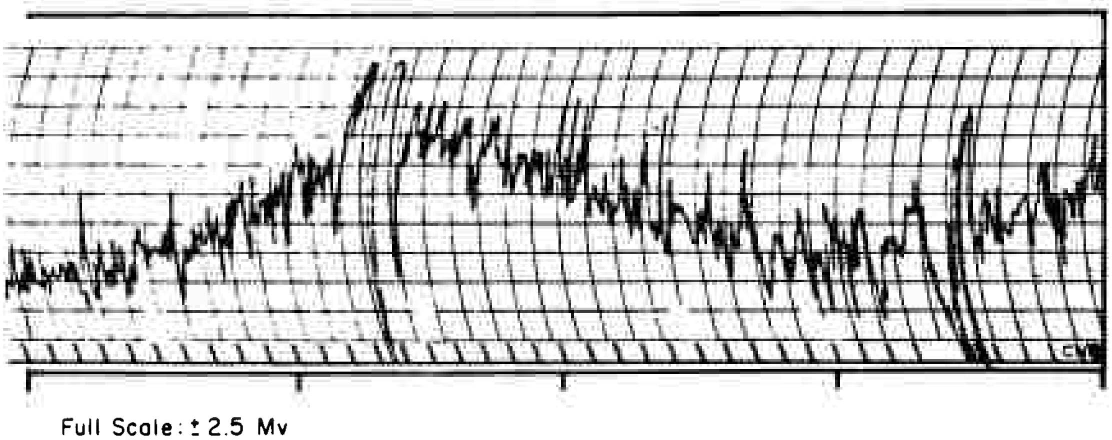

Figure 4.8 1-cps magnetic bursts, Grand Canyon, 6 September 1958.

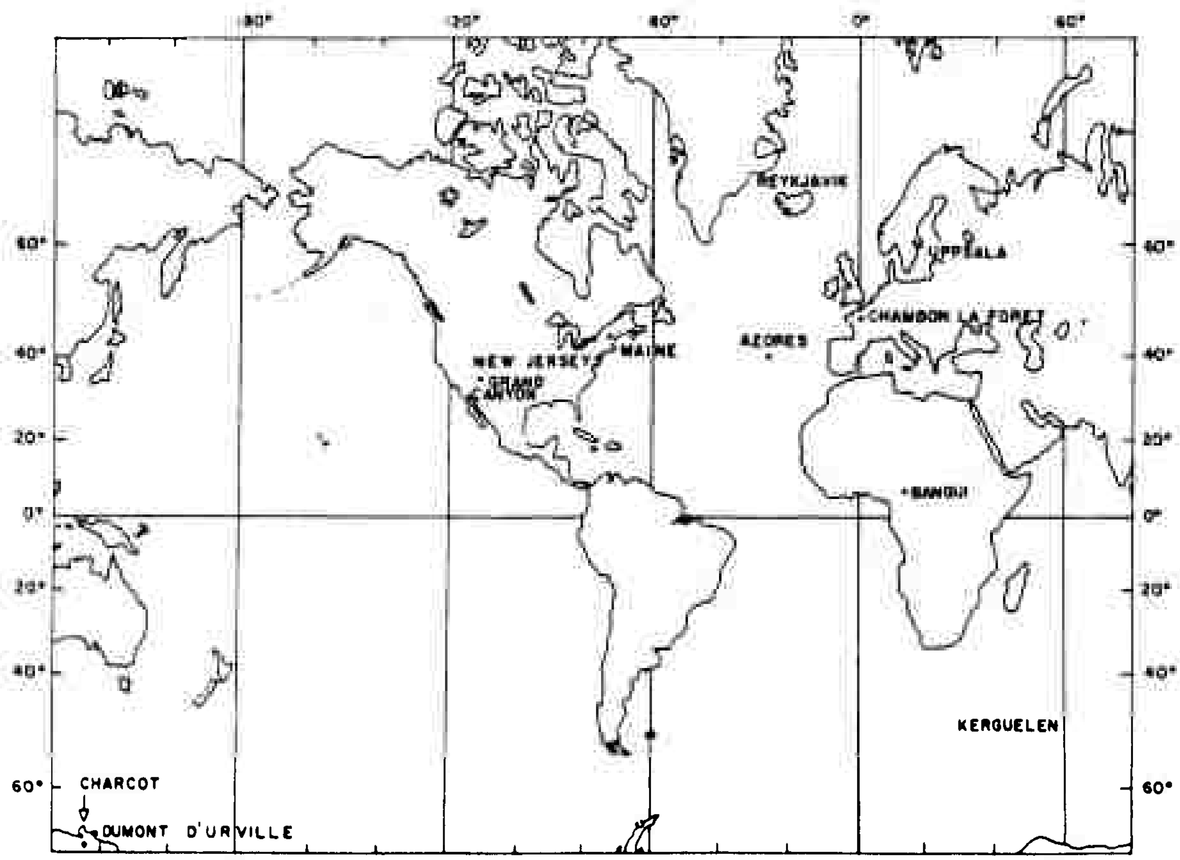

Figure 4.9 Locations of magnetic stations.

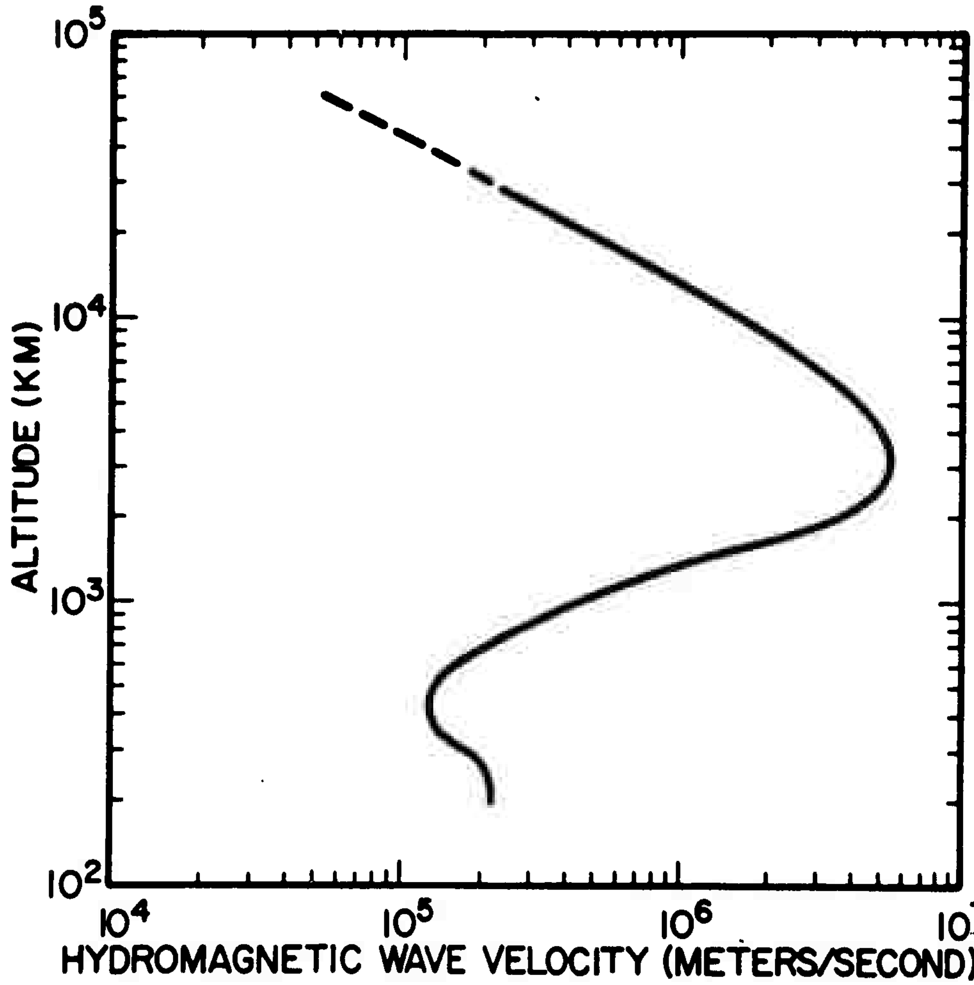

Figure 4.10 Hydromagnetic wave velocity versus altitude.

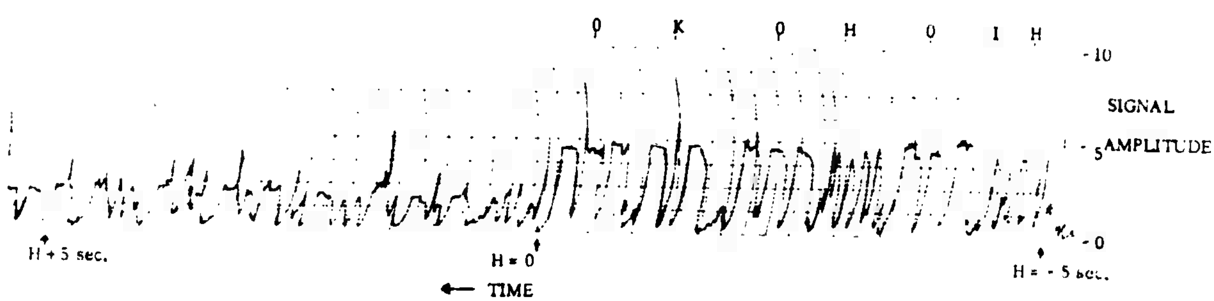

Figure 4.11 Recording taken in the Azores of VLF Station GBZ in England, Argus II.

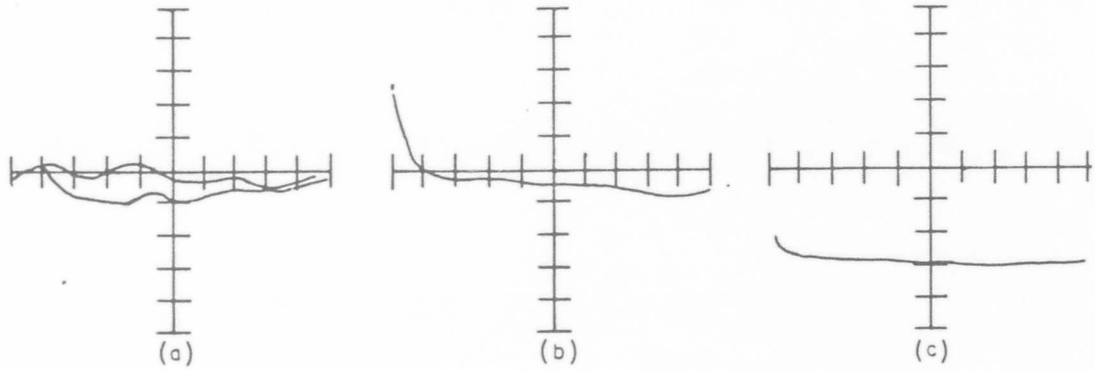

Figure 4.12 Memoscope traces of electromagnetic pulse received on USS Tarawa. All time bases are 20 μsec per division. (a) 27 August 1958. Dots show approximate beginning of pulse. Upper line is second triggering of memoscope by residual energy. (b) 30 August 1958. Dot shows approximate beginning of pulse. (c) 6 September 1958.

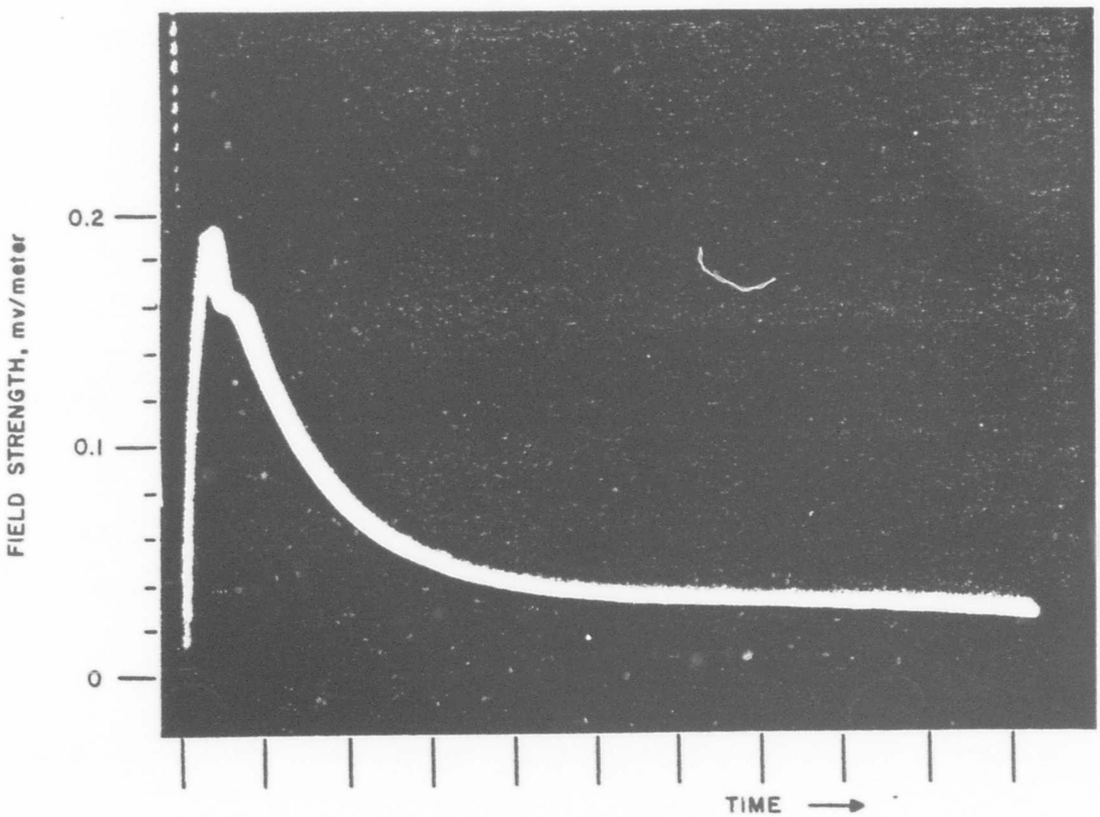

Figure 4.13 Triggered sweep oscilloscope record of electromagnetic pulse received on USS Tarawa, Argus III. Time markers indicate 10-μsec intervals.

Chapter 5

OPTICAL MEASUREMENTS

5.1 ALL-SKY CAMERAS

All-sky cameras were used for observing auroral luminosity. A wide angle (165°) f 1.5 Traid lens was employed with an M-3 800-foot magazine. Tri-X film was used and exposures were generally about 20 seconds. Cameras were located on the USS Albemarle, at Lajes and Torrejon, on one of the C-97 aircraft flying from Lajes, and in two carrier-based aircraft in the launch area.

5.2 CAMERA RESULTS

In the conjugate area, results were negative. The camera on the USS Albemarle could have photographed the auroral display following Argus III, but notice was short and the operator was busy alerting people. As a consequence, he neglected to turn on the equipment.

In the launch area, the cameras installed in the aircraft obtained photographs on Argus II and III (Figures 5.1 through 5.9). At the time of the Argus II, the aircraft was located at 7°55′ W, 48°20′ S. The coordinates during Argus III were 8°50′ W, 50°25′ S. The equipment malfunctioned during Argus I.

During Argus II, there appeared a very intense inner circle, which expanded in area while the intensity diminished during the first 30 seconds; at the same time a larger concentric, but less intense, outer circle decreased in area and intensity so that at the end of 30 seconds one circle of light persisted. In the center of the dark inner circle, there appeared a very bright line source of much greater intensity than the surrounding area. This line source came within 10° of alining with the geomagnetic north. The line source extended its length during the first 200 seconds and persisted for the full time the camera operated — 13 minutes, 50 seconds. At 270 seconds, the circular source was no longer evident. At 390 seconds, the center of the form moved to 25° of Z and 250° geomagnetic.

Argus III had an intense small head about 30° of Z and an equally intense line source reaching almost to the horizon at 225° geomagnetic. The head lasted approximately 80 seconds; the tail maintained its original orientation, diminishing in intensity and length while slightly increasing in width. The total time of detectable light was 510 seconds. This line source was alined within 20° of geomagnetic north.

5.3 SPECTROPHOTOMETERS

The spectrophotometers used were built for lines 3,914 Å (nitrogen) and 5,577 Å (oxygen), which are generally conspicuous in an auroral display. The 5,577 Å line is also present in the normal night sky airglow, whereas the 3,914 Å is generally absent. Bausch and Lomb filters (90 Å wide) and a 6810-A RCA photomultiplier with 14 stages were employed. The acceptance angle of the lens was 165°.

A Brush chart recorder running at 5 mm/sec preceded by a Philbrick universal stabilized amplifier, was used to record the signal. It was not possible to obtain a standard luminous source. An army marker (essentially, a luminous button) made by U.S. Radium Corporation was employed for calibration. The initial brightness of this source is given as 100 microlamberts, but its strength decreased with time. It was found to function only for the 5,577 Å line.

To test the 3,914 Å equipment, the 3,914 Å and 5,577 Å filters were interchanged. The photometers were checked against full moon during a night when there was cloud cover sufficient to make localization of the moon impossible. The 5,577 Å system gave a full-scale deflection (8 divisions) while the radioactive source gave $6\frac{1}{2}$ divisions. The 3,914 Å system gave a deflection of $1\frac{1}{4}$ divisions. The threshold of the equipment was estimated initially at 5×10^5 quanta per second; however, the performance tended to deteriorate in the field. Figure 5.10 shows the spectral response curve of the 6810-A tube.

5.4 SPECTROPHOTOMETER RESULTS

No results were obtained in the conjugate area, although as in the case of the all-sky camera, results might have been obtained on the USS Albemarle during Argus III if the equipment had been turned on.

At the launch area, records were obtained for all events, even though the sky was completely overcast during Argus I (Figure 5.11). The photometers, located on the USS Tarawa, were at the following positions: Argus I 43°15′ S, 9°05′ W; Argus II 48°25′ S, 8°30′ W; and Argus III 49°50′ S, 8°50′ W.

Because there appeared to be ringing in the equipment during Argus II, the duration is estimated to where the main decay appeared to take place. The possibility cannot be excluded that some of the extensions beyond the estimated duration are actually the result of excitation of the relevant constituents of the atmosphere. The peak measurements are listed in Table 5.1.

There appeared to be a progressive narrowing of the width of the pulse as the altitude at which the detonation occurred increased. The ratios are obtained by weighting for the spectral response curve. The aurora persisted for many minutes; therefore, it must be presumed that the equipment had become too insensitive.

TABLE 5.1 PEAK MEASUREMENTS OF PHOTOMETERS

Peaks are given in relative values.

	Argus I	Argus II	Argus III
O (5,577 Å)	0.7	1.4	1.4
N (3,914 Å)	0.08	0.35	0.2
Ratio	13	6	10
Duration	0.20 second	0.10 second	0.05 second

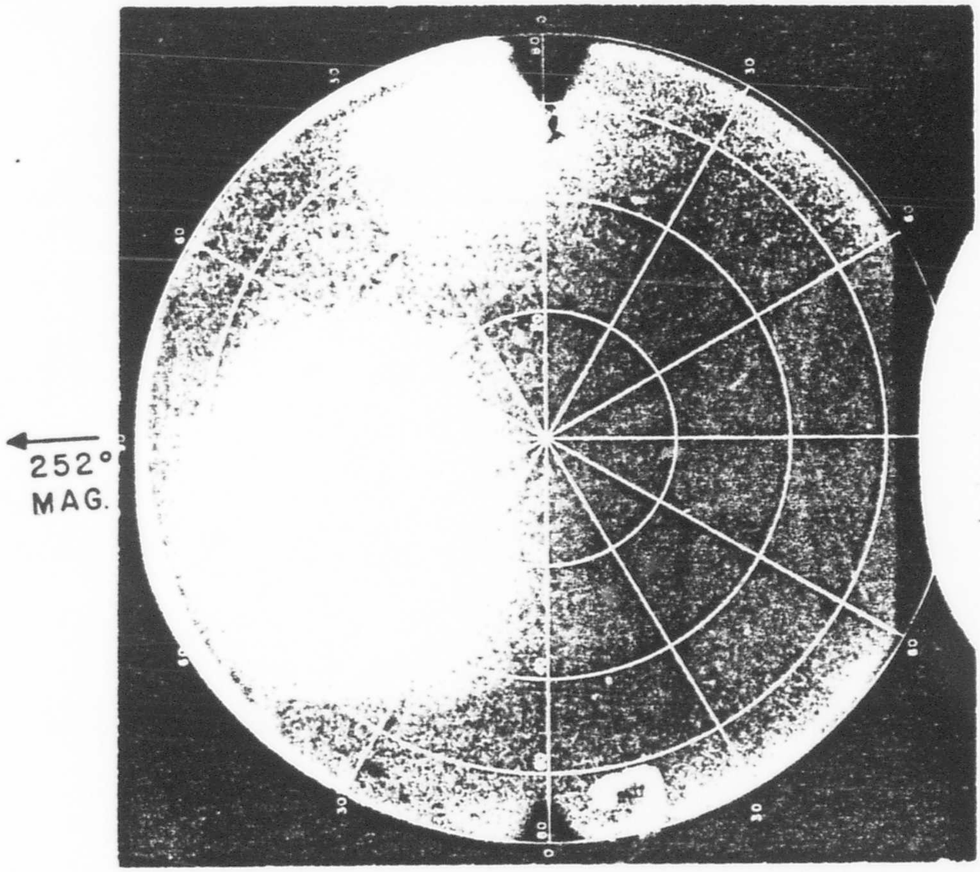

Figure 5.1 All-sky camera photo at launch area, Argus II, for exposure from t_0 plus 10 seconds to t_0 plus 30 seconds. (Bright object at top is the moon.)

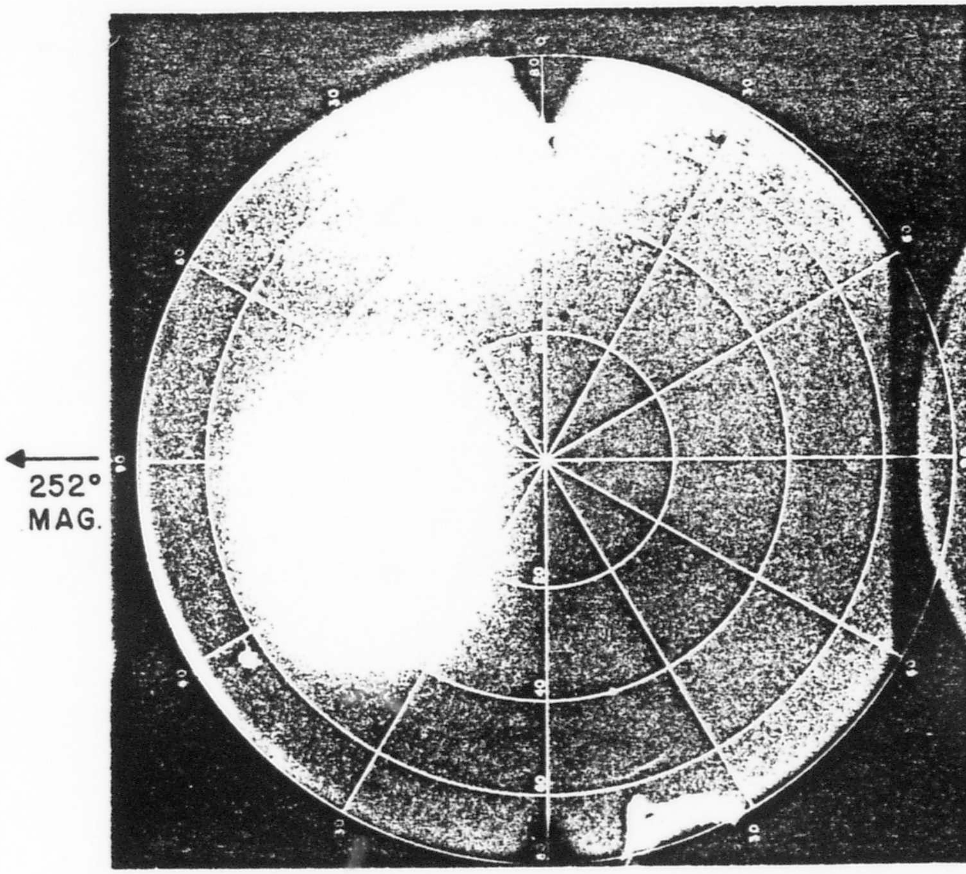

Figure 5.2 All-sky camera photo at launch area, Argus II, for exposure from t_0 plus 50 seconds to t_0 plus 1 minute 10 seconds.

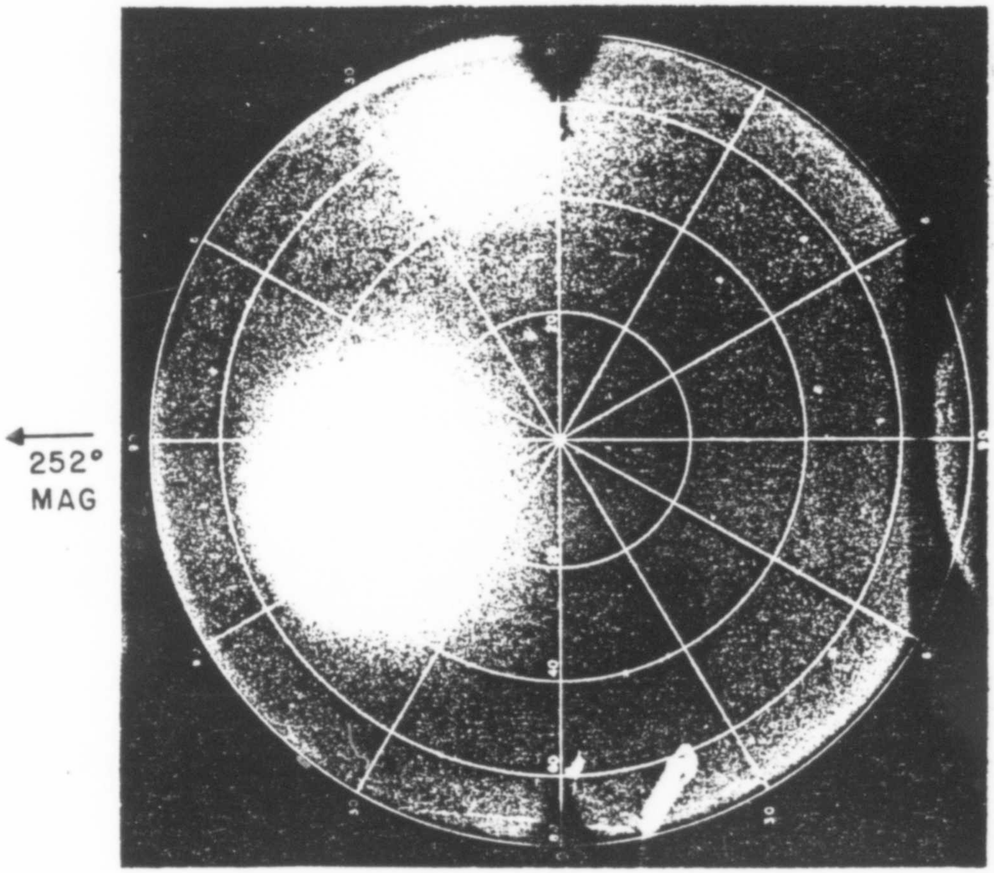

Figure 5.3 All-sky camera photo at launch area, Argus II, for exposure from t_0 plus 1 minute 30 seconds to t_0 plus 1 minute 50 seconds.

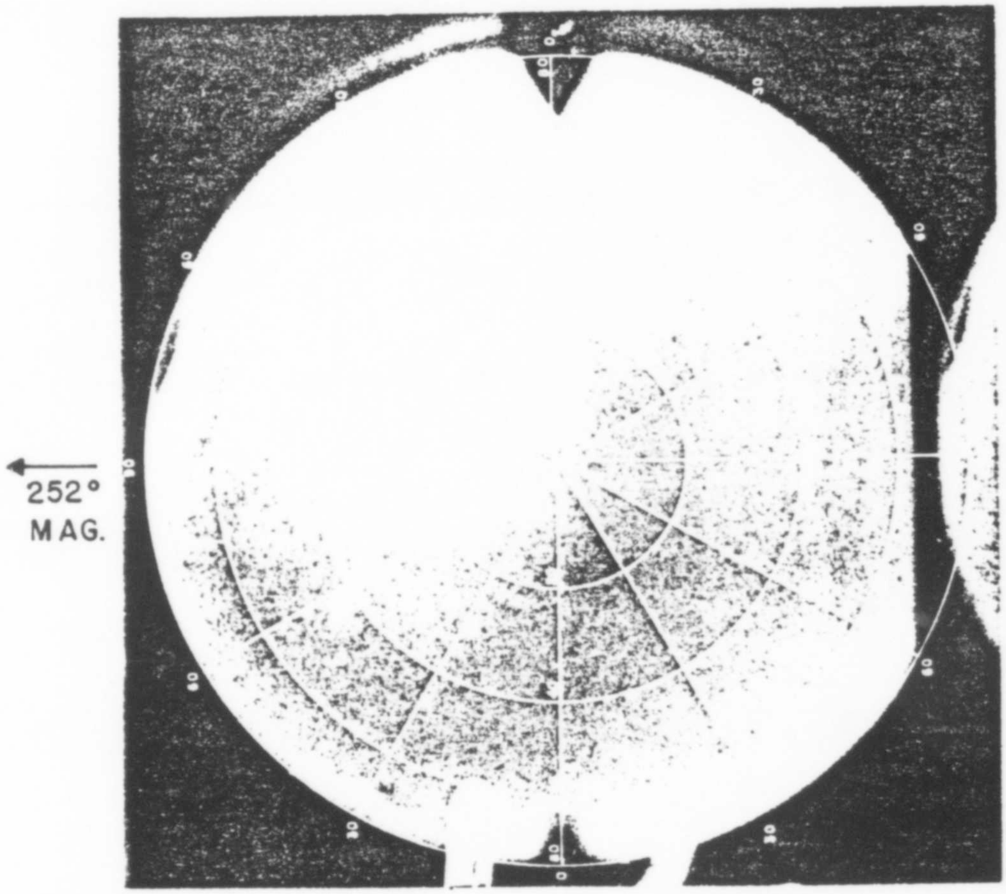

Figure 5.4 All-sky camera photo at launch area, Argus II, for exposure from t_0 plus 3 minutes 10 seconds to t_0 plus 3 minutes 30 seconds.

337°
MAG.

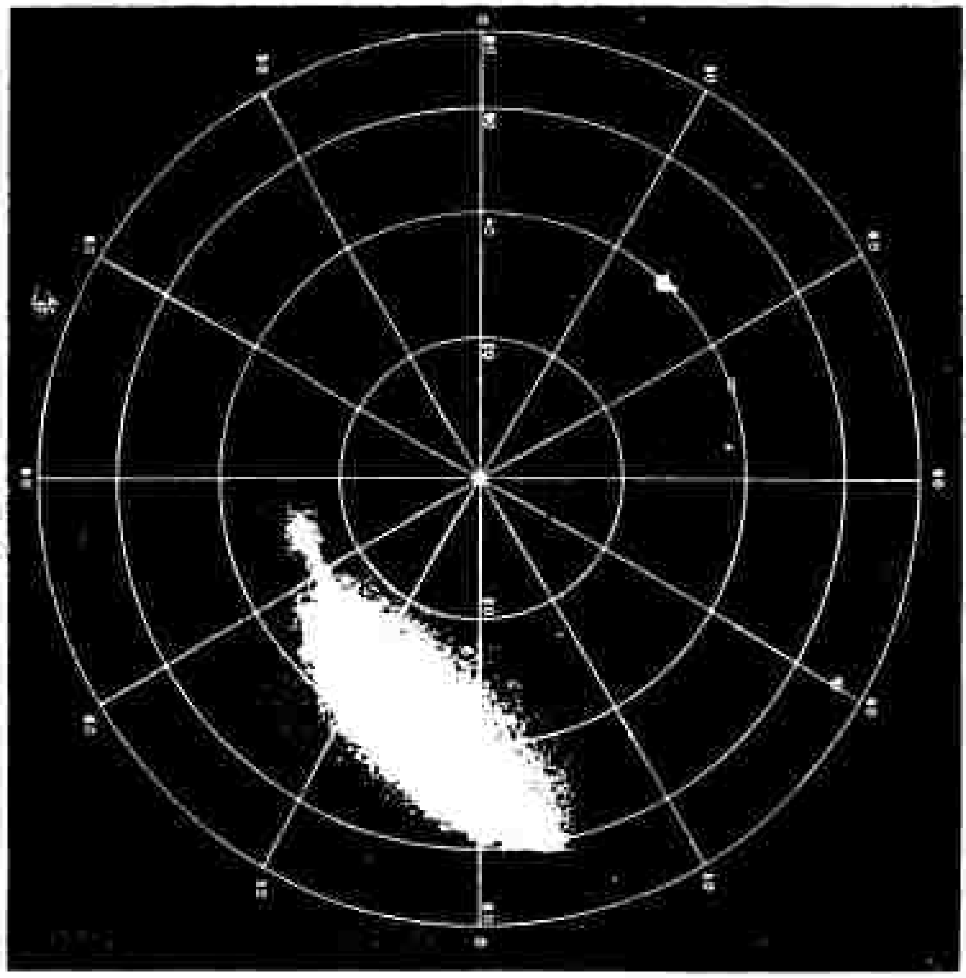

Figure 5.5 All-sky camera photo at launch area, Argus III, for exposure from t_0 plus 5 seconds to t_0 plus 10 seconds.

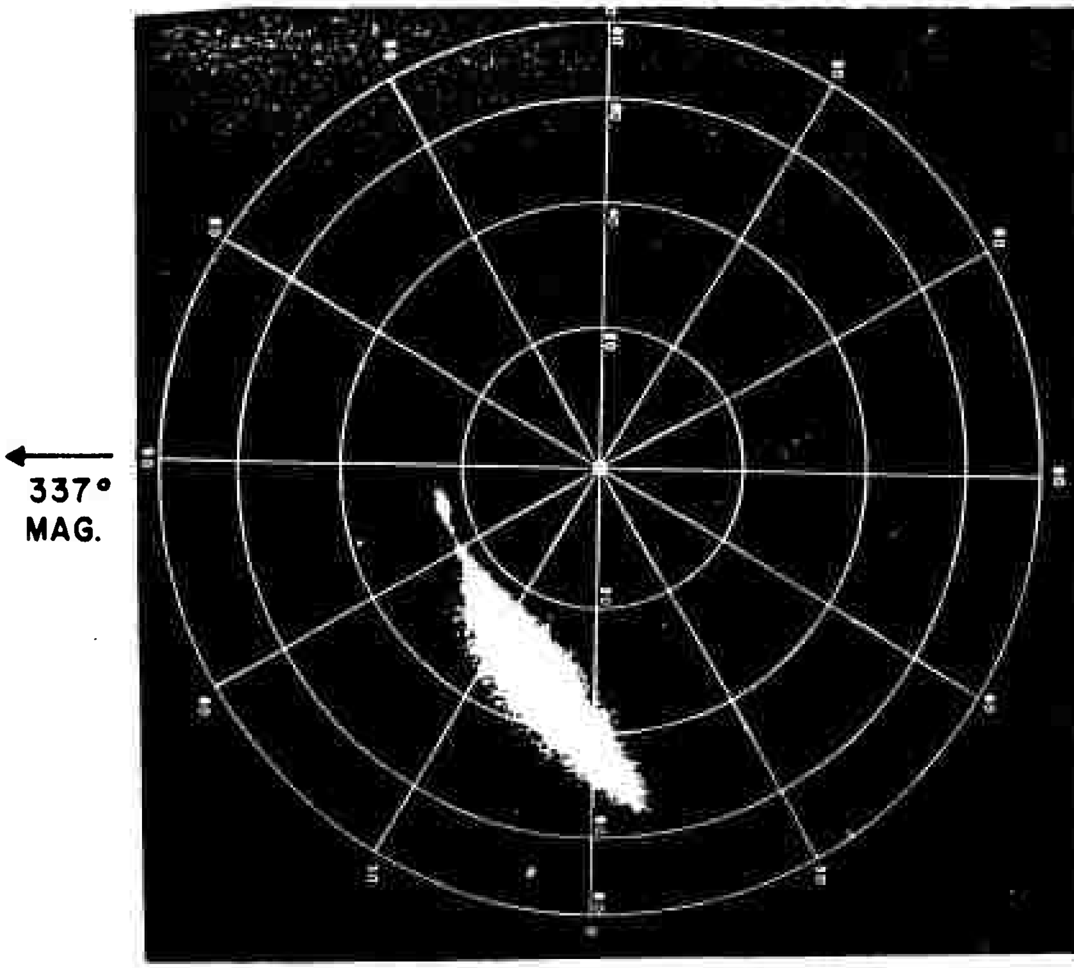

Figure 5.6 All-sky camera photo at launch area, Argus III, for exposure from t_0 plus 10 seconds to t_0 plus 15 seconds.

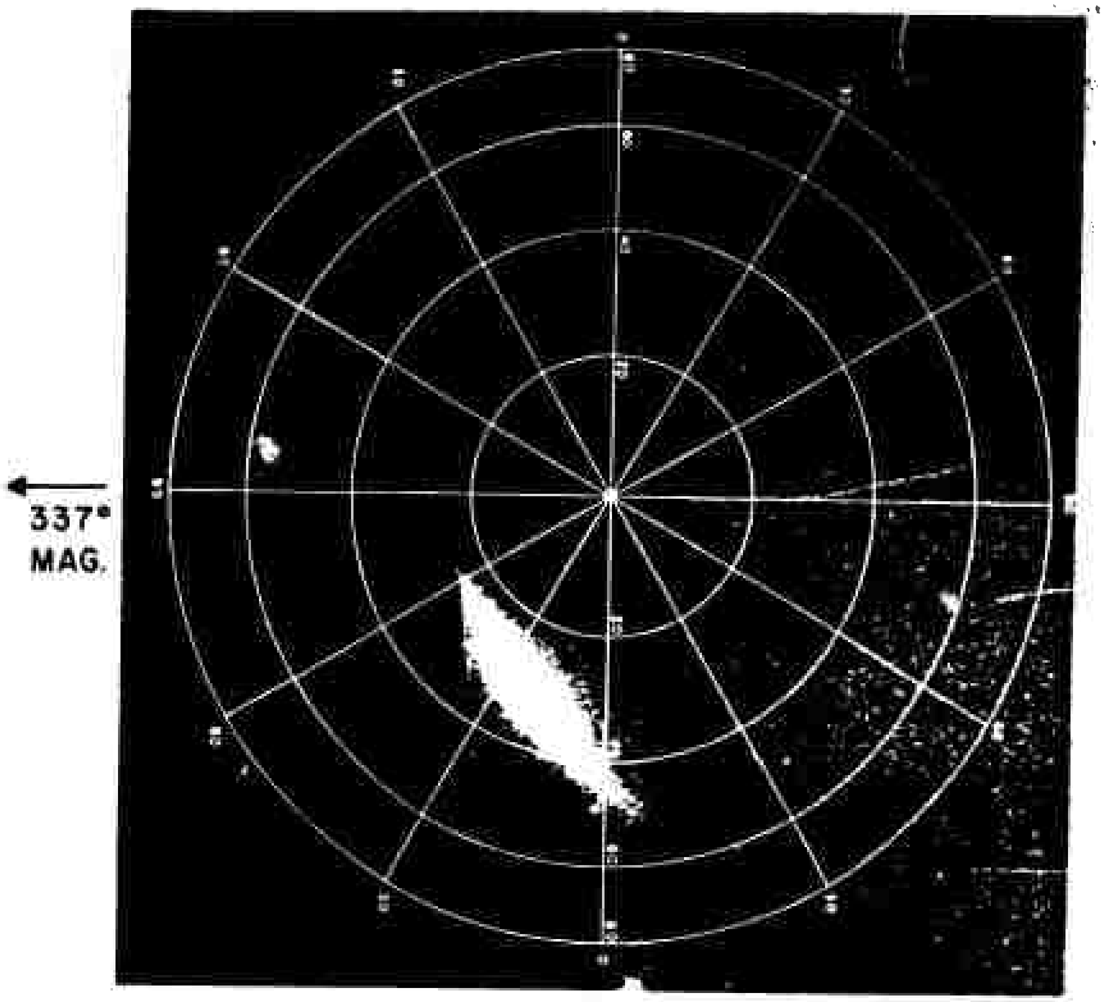

Figure 5.7 All-sky camera photo at launch area, Argus III, for exposure from t_0 plus 15 seconds to t_0 plus 20 seconds.

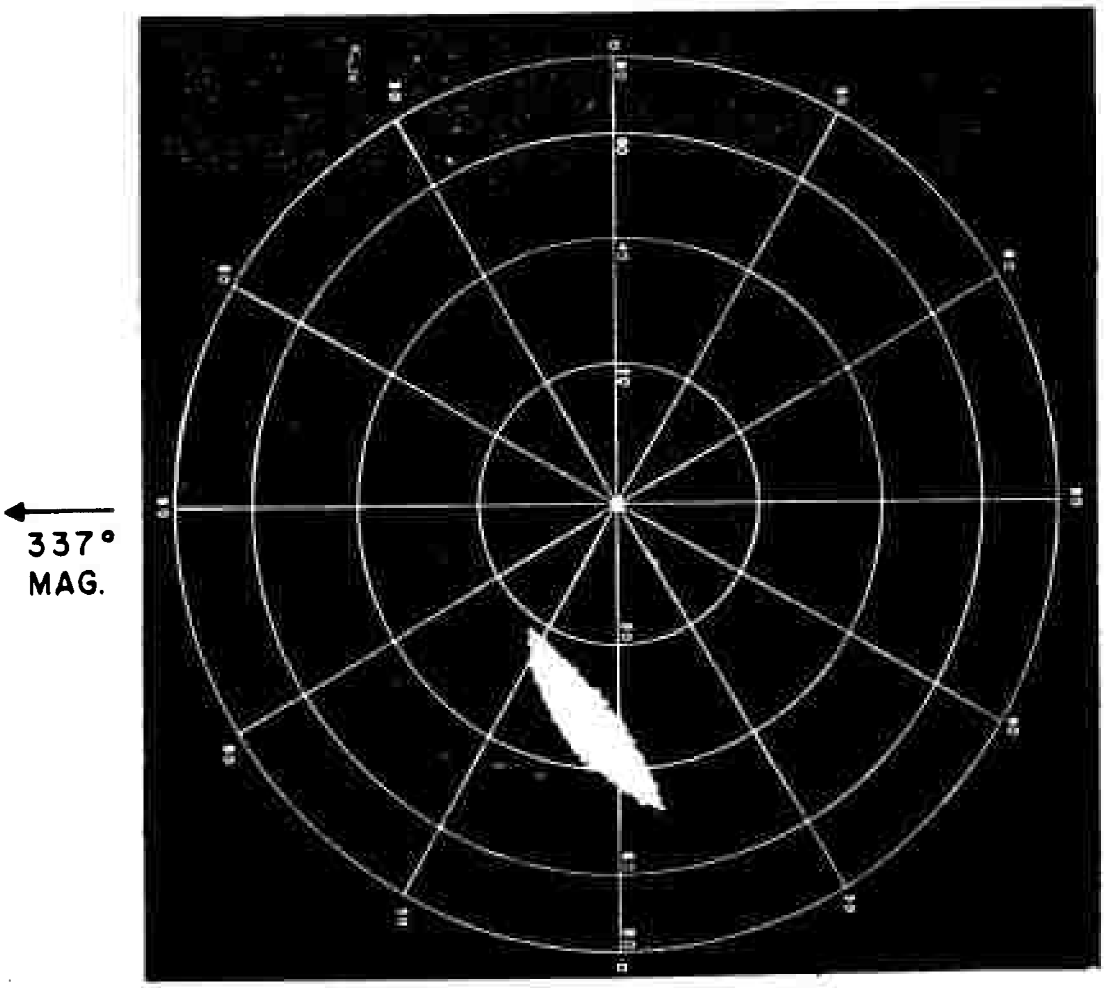

Figure 5.8 All-sky camera photo at launch area, Argus III, for exposure from t_0 plus 30 seconds to t_0 plus 35 seconds.

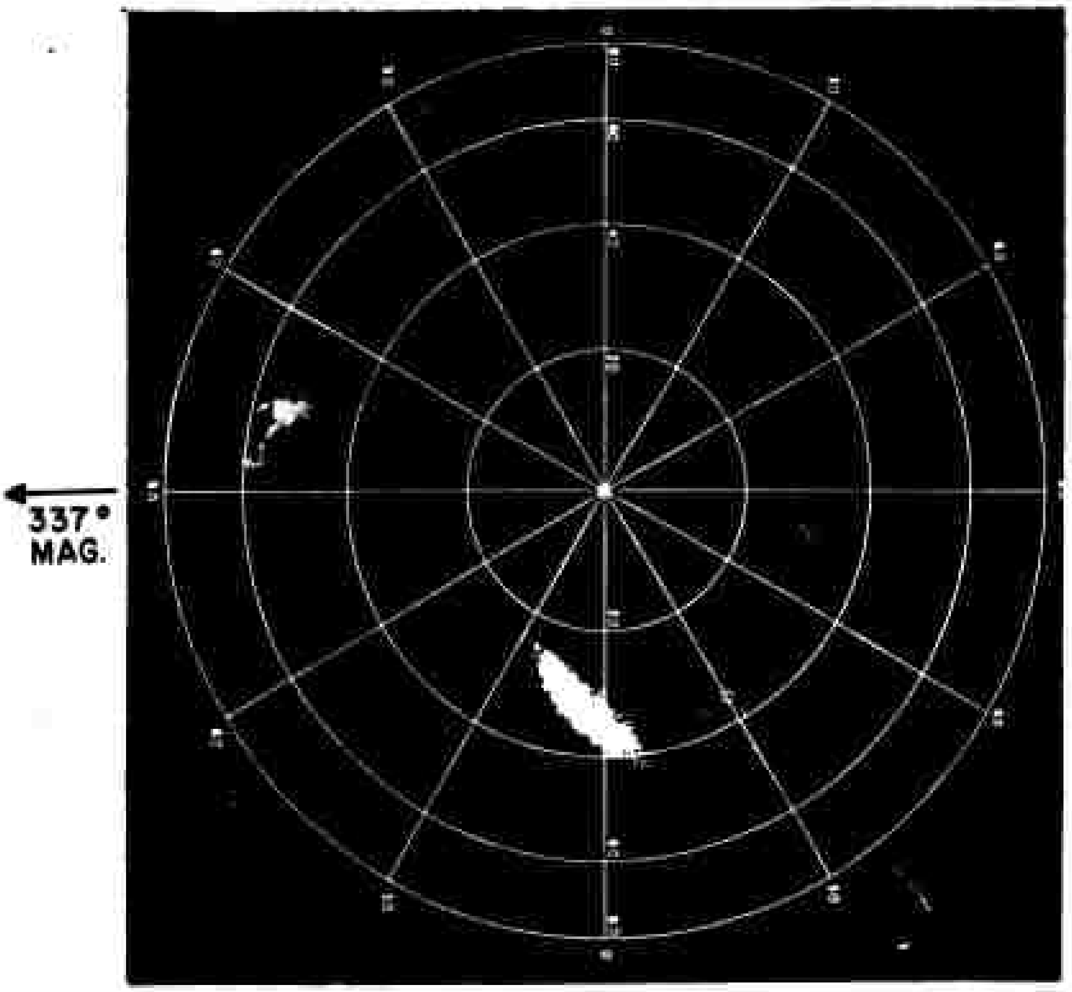

Figure 5.9 All-sky camera photo at launch area, Argus III, for exposure from t_0 plus 55 seconds to t_0 plus 60 seconds.

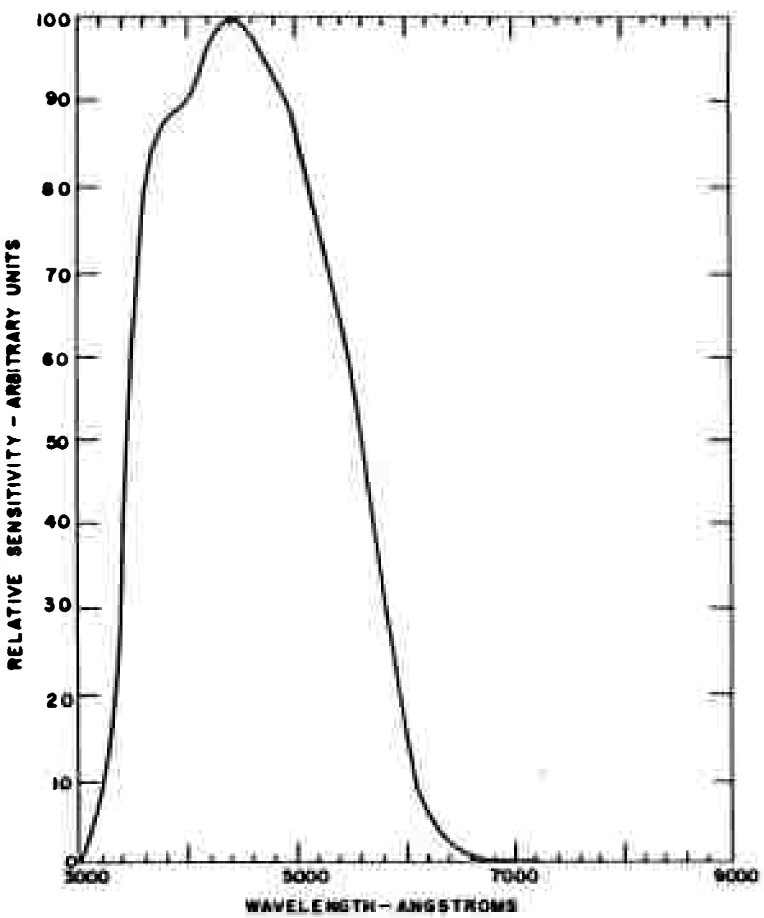

Figure 5.10 Spectral sensitivity characteristic of 6810-A tube. Curve is shown for equal values of radiant power at all wavelengths.

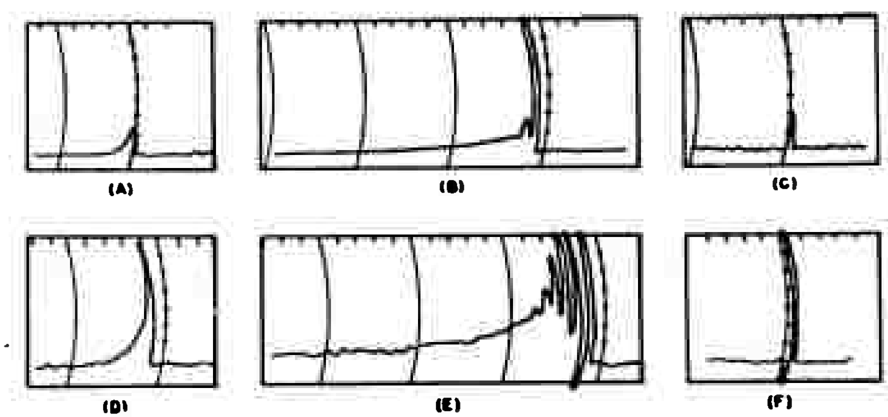

Figure 5.11 Photometer measurements in launch area. Top row shows 3,914 Å line, Argus I, II, and III, respectively. Bottom row 5,577 Å line. Deflections are A and B, 0.05 volt per division; C and D, 0.1 volt per division; E and F, 0.2 volt per division. Chart speed: one large division per second. Time increases from right to left. Detonation times are not available from these records.

Chapter 6

RIOMETER OBSERVATIONS

6.1 PROCEDURE

The sky continuously emits radio noise that can be readily detected with a good VHF receiver. At 30 Mc, in the absence of manmade interference, the wide-band radio noise from the sky is at least 15 db above ambient receiver noise. If a very stable receiver is connected to a pen chart recorder, the noise level can be monitored as a function of time. For a given latitude, time of year, and antenna beam shape and direction, the record will trace out once every 24 hours a pattern that is constant in sidereal time. Depressions below this normal noise level can be interpreted as ionospheric absorption. Of course, the record will also show increases of noise level above the cosmic noise level, if that absorption endures for a time comparable to or exceeding the time constant of the receiver-recorder combination.

An instrument to perform this function is called a riometer (Reference 18). An essential part of this device is an electronic switch that causes the receiver to be rapidly alternated (300 to 400 cps) between the antenna and a controllable noise source. If there is a difference in noise power, an audio signal appears at the receiver output, which, when amplified, serves to correct the noise source. By measuring the noise source current as a function of time, a record is obtained, which is linearly proportional to noise power entering the antenna.

A vertically directed Yagi antenna is customarily used to emphasize the overhead sky and to reduce pattern distortions caused by local objects. (In the Argus experiment, it would have been better to have had a more directive antenna directed perpendicular to the magnetic field lines. However, the location of the Argus shell was not known in advance; therefore, a highly directive antenna could not have been aimed correctly.) The antenna half-power points can be taken approximately as a cone of semiangle of about 45°. For the ionosphere, the absorption expressed in decibels is inversely proportional to the square of the frequency. Hence, the dynamic range of measurement can be extended by the simultaneous use of three frequencies, nominally 30, 60, and 120 Mc.

The riometer is calibrated by replacing the antenna with an accurately constructed noise diode. A measurement of the current flowing through the diode is absolutely related to the wide-band power output appearing at the antenna connector of the riometer. To avoid sustained manmade interference on any one frequency, the riometer automatically sweeps frequency by about 100 kc, completing a cycle and flyback in 1 minute. When such interference is present, a pattern of equally spaced spikes appears on the record.

6.2 NEGATIVE OBSERVATIONS

In general, neither shot-caused noise nor shot-caused absorption was observed by the network of riometers. Possible positive results associated with Argus III were observed by the riometer on the USS Norton Sound.

The quality of each recording is presented in Table 6.1. If the interference within a few minutes of actual detonation was sufficiently small at each site, then the entry "good" is made in the table. An entry of "good" implies that two conditions prevailed: (1) no increase of absorption was detected exceeding about 0.5 db (lasting more than about 15 seconds) and (2) no increases in noise level were detected greater than 2,000°, 500°, and 30° K at 30, 60, and 120 Mc, respectively (lasting for more than 15 seconds).

6.3 OBSERVATIONS ON USS NORTON SOUND

Some shot-caused effects are suggested by the 30-Mc riometer aboard the USS Norton Sound (Figure 6.1). Unfortunately, the 27-Mc radar on the same ship was causing some interference to the riometer. During Argus I and II, the radar was operating throughout shot time and was contributing about half again as much noise as would be present from cosmic noise alone. During Argus III, the radar was deliberately shut down 1 minute before launch and remained off until about 3 minutes after detonation.

The apparent background noise varied from one shot to the next, being about 2×10^{-15}, 0.2×10^{-15}, and 1.3×10^{-15} watt on Argus I, II, and III, respectively. Such changes could have been due to changes in the local interference level or to an electrical alteration in the antenna, resulting in poor energy transfer to the riometer.

The only effect noted during Argus I was a large burst of noise, which occurred simultaneously with rocket launch. The burst lasted slightly less than a minute and contributed a peak value of 32×10^{-15} watt. A 3-element Yagi antenna was used for this riometer atop the aft mast of the ship. (If it were assumed that the antenna had been momentarily engulfed in the rocket flame, then, to give the observed effect, the temperature of that flame would have exceeded 20,000° K.) No shot-caused absorption or noise was observed, although an unknown amount of interference was believed to be present.

No effects were noticed during Argus II. Bursts of heavy interference occasionally occurred before and after the shot, although no such interference was present within about 7 minutes of shot time. During this shot, the background noise was about a factor of five lower than it should have been (probably due to antenna mismatch), but, because noise coming into the antenna governs the detectability at 30 Mc, the data is still valid. The 27-Mc radar (sometimes called COZI) was shut off for 2 minutes beginning just at launch and, therefore, allowed an indication of the no-interference level.

The following effects were associated with Argus III: (1) noise at the time of rocket launch, (2) noise associated with detonation of the shot, and (3) absorption associated with the shot.

Evidence that the interfering transmitter was turned off can be seen as a slight drop in the record (Figure 6.1). At the same time as launch, a noise burst was observed, which exceeded the background radiation by 1.4×10^{-15} watt and which lasted on the order of the time constant of the instrument, but less than 1 minute.

There is a quiet interval as the rocket climbed to altitude, then a burst of noise at the time of detonation. A transient was noted on the radar equipment even with the radar antenna pointed away from the burst point.

After the noise peak at shot time had subsided (a small fraction of a minute), the noise level was about 1 db below the preshot noise level. Extrapolating back to shot time, the absorption may have reached 2 db. Although the interference returned about 3 minutes after detonation, the absorption had apparently vanished by about 5 minutes after detonation.

The possible positive effects observed on the USS Norton Sound are summarized in Table 6.2.

6.4 SYNCHROTRON NOISE ESTIMATES

A consequence of relativistic, geomagnetically trapped electrons is that a small amount of each electron's energy should be lost in the form of synchrotron radiation.

Rough estimates before the Argus experiment indicated that synchrotron radiation would be difficult, if not impossible, to observe at the earth's surface. In fact, the yield of the shots was deliberately chosen to be small to avoid detection and to avoid injury to radio astronomy projects of our own that might be in progress. In the postshot period, further consideration of the theory gives a downward revision of the estimated detectability levels.

The synchrotron radiation of Argus III at +25 minutes (time of a quantitative satellite measurement of Argus shell density) may have been about 10^{-3} below detectability. By extrapolation to earlier time, the detectability level would increase by a factor of 10^2, but the unfavorable magnetic field orientation might lower the radiation (reduction by several orders of magnitude).

The original estimate of the first committee meeting at Livermore now appears too high, because electrons were assumed to be mirroring at heights on the order of only a few hundred kilometers. Subsequent measurements of atmospheric density have revealed that mirroring is very unlikely below about 1,000 km for times exceeding an hour. Explorer IV measurements a few days after Argus III show that the number of electrons at 2,000, 1,500, and 1,000 km is in the ratio of 1.0:0.5:0.1. For the riometer sites used during the Argus experiment, such high altitudes involve very unfavorable magnetic field geometry.

6.5 NOISE RECEIVERS

The Rome Air Development Center operated noise receivers at 50, 100, and 8,000 Mc and an experimental radar on 207 Mc in Laredo, Texas. During the experiment, the radar was used in the receiving mode only. As a result of the recordings obtained, it was determined that nothing was observed that could be correlated with the Argus events.

The noise receivers were in the near field of an FM transmitting station, which was operating at the time of the experiment; therefore, the receivers were completely blocked by the interference.

The Lincoln Laboratory set up a receiving station at the antipodal point in the Aleutians for Argus I only. Frequencies monitored were 2, 20, 40, 80 and 108 Mc and WWVH time ticks. At approximately a half hour before burst time, an almost complete high-frequency blackout was observed in the area. All communications and WWVH were lost. Recordings made between 0200 and 0400Z showed no signals or enhancements of noise distinguishable above the local ambient noise on any of the frequencies.

6.6 COSMIC RAY RECORDS

Cosmic ray records at CNET in Paris and Carnegie Institute in Washington were examined. No effects attributable to Argus were found. The Paris records showed effects after Argus III, which appeared to be the aftermath of the solar flares occurring several days before Argus III.

TABLE 6.1 QUALITY OF RIOMETER RECORDINGS NEAR SHOT TIME

Argus	Frequency	USS Albemarle	Lajes	Torrejon	Stanford	USS Norton Sound
	Mc					
I	30	Fair	Good	Good	Good	Fair
	60	Good	Good	Good	Poor	Not on board
	120	Good	Good	Good	Good	Not on board
II	30	Good	Good	Good	Good	Fair
	60	Good	Good	Good	Poor	Not on board
	120	Fair	Good	Good	Fair	Not on board
III	30	Poor	Poor	Good	Poor	Possible positive effects
	60	Poor	Good	Good	Useless	Not on board
	120	Poor	Good	Good	Useless	Not on board

TABLE 6.2 RIOMETER OBSERVATIONS, 30 Mc, USS NORTON SOUND

Argus	Noise at Launch	Noise at Shot Time	Shot-Caused Absorption	Remarks	Noise at Launch on Radar Receiver	Noise at Shot Time on Radar Receiver
	watt	watt	db			
I	3.2×10^{-15}	None *	None *	—	Yes	No
II	None *	None *	None *	—	Yes	No
III	1.4×10^{-15} †	0.8×10^{-15} †	1 (recovery at about +5 minutes)	By extrapolation may have been 2 db immediately after shot.	Yes	Yes

* 0.3×10^{-15} watt of steady interference was being contributed by the 27-Mc radar at these times.
† This energy may have passed through about 2 db of absorption.

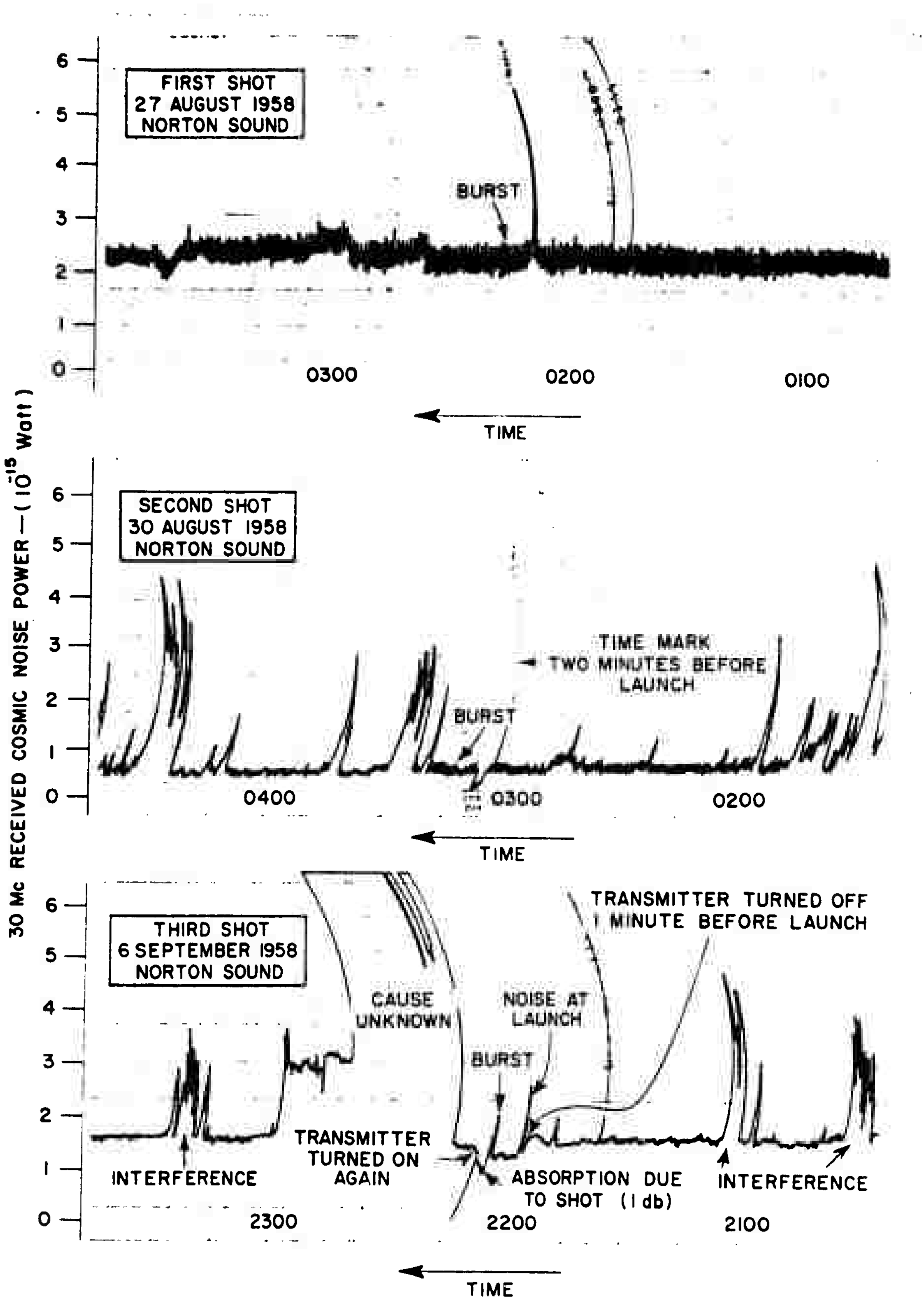

Figure 6.1 Riometer record at launch area.

Chapter 7

IONOSONDE OBSERVATIONS

7.1 EQUIPMENT

C-3 and C-4 ionosondes were used for observing the ionosphere by reflection of radio waves beamed vertically upward. Some were operated on the surface, and others were installed in C-97 aircraft. (For complete description of ionosondes and their use, see Reference 35.) The characteristics of the equipment are listed in Table 7.1.

7.2 OBSERVATIONS

For Argus II and III, the C-3 was operated on the ground at Lajes.

Apparently, the aircraft were not close to any of the conjugate points of the events. During Argus III, one aircraft was on the ground at Lajes and noted sporadic E at 2230 when equipment was first turned on and continued to observe some sporadic E to about 2306. The other aircraft, because of weather, flew east. At 2230 when the Lajes ionosonde observed sporadic E, the airborne sounder was about 120 miles east of Lajes. At 2306 when the Lajes ionosonde ceased to observe sporadic E, the aircraft was about 200 miles from Lajes. On returning, the airborne sounder found sporadic E about 330 miles east of Lajes at 0020 (Figure 7.1). This lasted to 0112, at about 280 miles east of Lajes.

The Lincoln Laboratory operated a C-4 at Ipswich, Massachusetts, for Argus I, from 0156Z until 1100Z 27 August. From 0351 until 0459, a peculiar reflection appeared above the F-layer trace at a virtual height of 450 km. The apparent critical frequency was 7 to 8 Mc. Because this reflecting layer had an apparent critical frequency less than that of the F-layer, it was not directly overhead. Unfortunately, no determination of azimuth is possible with this apparatus.

CNET (Paris) analysis of ionosonde observations at Poitiers, Washington, Johannesburg, and Port Stanley shows a small decrease in the critical frequency of the F_2 region, which seems attributable to the solar flare at 0000Z 26 August.

On 30 August, the ionosphere appeared normal.

A strong magnetic disturbance was experienced on 4 September. By 6 September the ionosphere appeared normal again and continued so on 7 September. On 8 September, there was a slight decrease in foF_2 and a slight elevation in $h'F_2$ at Poitiers.

The World Data Center at Slough furnished the following information as a result of investigations of IGY data for sporadic E:

"We have attempted to enquire whether the detonations were followed by sporadic E phenomena which were exceptional for the period August and September 1958. The information from some 60 stations has been examined but in general only hourly data are available and this limits the accuracy in timing of any effects. A preliminary examination indicated that the third detonation (22.10 G.M.T. on 6th September 1958) was the most active and our studies have been concentrated on this event.

"The most outstanding effect has been observed at Grand Bahama (27° N, 78° W) from 2300 G.M.T. on 6th September 1958. The marked increase in sporadic E ionization and the low echo heights were unique for the two months considered. We might note that such effects were observed at several stations following the Johnston Island explosions. A similar but shorter increase in sporadic E ionization was shown at Freiburg (48° N, 8° E). The neighbouring station of Budapest (47° N, 19° E) showed a less marked but more prolonged increase in ionization. No significant changes in the height of reflection were detected at these two European stations. It is perhaps significant that these three stations have similar geomagnetic latitude to the conjugate point of the third detonation.

"The only other effects detected directly after the detonation were at stations in a limited range of longitude north of the conjugate point. These stations such as Narsarssuak (61° N, 45° W), Godhavn (69° N, 54° W), and Thule (77° N, 69° W) showed enhancements of sporadic E ionization but these were not exceptional. From a consideration of the two months data we suggest that the effects in this area are statistically significant to the one per cent level.

"Finally, there are strong suggestions of increases in sporadic E ionization some nine hours after the detonation in Europe and a little earlier in North America.

"In view of the character of sporadic E it is stressed that these results derived from an isolated event must be considered as suggestive only."

TABLE 7.1 CHARACTERISTICS OF IONOSONDE EQUIPMENT

Frequency range	1 to 25 Mc
Pulse repetition rate	30 per second
Range	1,000 km
Time for one frequency sweep	15 seconds
Peak power	10 kw

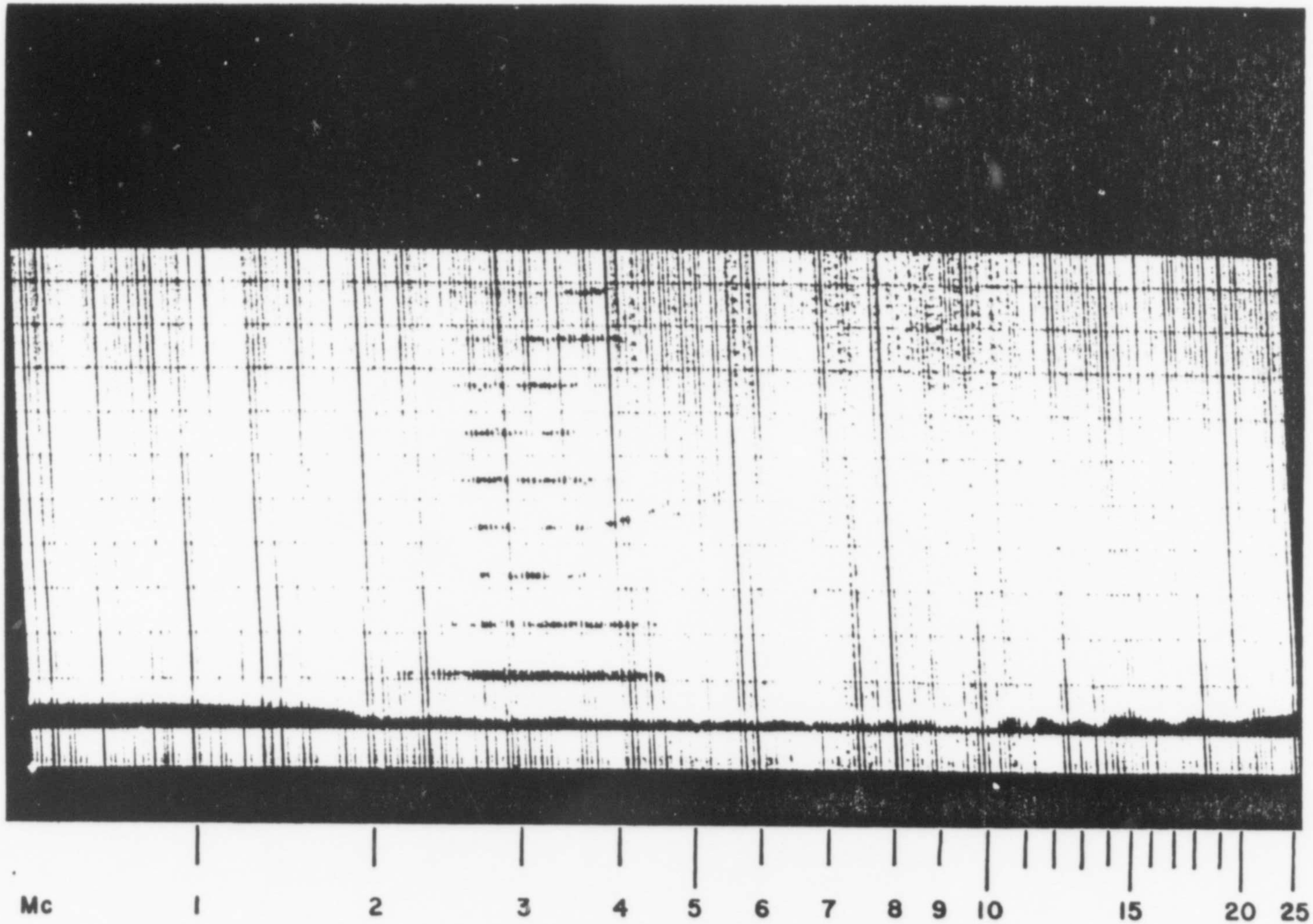

Figure 7.1 Sporadic E and multiple reflections approximately 300 miles east of Azores, 0045Z, 7 September 1958.

Chapter 8

SATELLITE OBSERVATIONS

In addition to the satellite (Explorer IV) observations made by the Army Ballistic Missile Agency (ABMA) at Huntsville, Alabama, and other locations (Reference 36), observations were made at Torrejon, Spain, and Palo Alto, California, as part of this project. Reference 36 contains all the satellite data obtained in the Argus experiment. This chapter covers only the observations at Torrejon and Palo Alto.

8.1 SATELLITE PACKAGE

The satellite package was designed and constructed by the State University of Iowa with a view toward exploring the high-radiation belt found at the equator by earlier satellites. Several particle detectors were provided with different shielding and thresholds. Unfortunately, most of the characteristics of the detectors must be calculated, because no suitable testing devices exist in the laboratory. The detector characteristics are listed in Table 8.1.

8.2 PROCEDURE

Explorer IV satellite (1958 Epsilon) was orbiting at the time of the Argus experiment, sampling high-energy particles between the northern and southern 50° latitudes and at altitudes between 300 and 2,300 km.

The 108.03-Mc telemetry signals were monitored at Palo Alto and at Torrejon. Observations at both stations were begun a few days before Argus I. At Palo Alto, they were discontinued a few days after Argus III. At Torrejon, they were discontinued 14 days after Argus III (at failure of the batteries in the satellite counting circuits).

8.3 RESULTS

In the evening the satellite could be heard where heights were on the order of 1,000 to 1,500 km. During the time that each pass could be monitored, the height decreased by several hundred kilometers. From one day to the next, the height increased by 40 km (making determination of decay law difficult). In the early morning hours, the satellite could be monitored at heights as low as 250 km although these proved to be of little value.

After each shot, the satellite traversed the belt of oscillating electrons during each orbit and registered enhancements lasting approximately 1.3 minutes at the half-energy level, or, with geometry taken into account, a magnetic latitude thickness of about 200 km. This broadened only slightly in the course of 2 weeks' observation.

Enhancements were noted after Argus I in the Palo Alto and Torrejon data, showing a peak-to-background ratio of approximately 3 at Torrejon 22 hours after the shot and at a satellite altitude of 1,050 km. A much stronger indication was noted by ABMA at Huntsville, presumably because the satellite crossed the belt at a lesser geographic latitude and therefore possessed a higher altitude (1,500 km). The data from all three stations lay over the 50° magnetic dip contour.

For many days following Argus I, a small, barely significant enhancement was present along a latitude line a few degrees farther south. The preshot data also showed the same peak. Therefore, it would seem that this effect was of natural origin.

An enhancement due to Argus II was noted at Torrejon but not at Palo Alto.

Twenty-eight minutes after Argus III, a suitable pass was available that was observable at Torrejon. A 20-to-1 peak-to-background ratio showed on Channel 1, and Channel 3 showed more (at a height of 1,400 km). The width of the main peak on Channel 1 was 1.7 minutes or 630 km of satellite path, or approximately 150 km of belt width. However, the count rate seemed to be enhanced to some extent, at least, over a total period of 10 minutes. The next three immediate passes were within monitoring distance of Huntsville although the peak count rates are not known. The last of these was also monitored by Palo Alto 5 hours 48 minutes after detonation and gave a peak-to-background ratio of 8 to 1 (questionable) at an altitude of 1,700 km. The following pass 7 hours 40 minutes after shot time gave a ratio of 15 to 1 at a height of 1,580 km (Figure 8.1).

Approximately 24 hours after the first pass observed at Torrejon, the peak-to-background ratio had diminished to 10 to 1, 1 day later to 5 to 1, the next day to 4 to 1, and so forth, at a diminishing rate each day. Observations were continued until the last telemetry signals were heard at midnight 20 September. At this time, the peak was still clearly discernible at 0.6 background level.

The line described by these observations is seen in Figure 8.2 by the square marks. There is closer correspondence to the dip field than to the geomagnetic field, a fact which is rather surprising because the surface values of the field are generally considered to have fallen off by the height of 1,000 km. Figure 8.2 does not include all of the data but merely shows the approximate trend. Furthermore, the location of the points should be mapped mathematically onto the earth's surface for better comparison with the magnetic field models.

The satellite data shows very positive results from Argus I, II, and III. The strength of the radiation is quite impressive at such a distance, being probably in excess of 1 r/hr. The long lifetime of these oscillating electrons is also impressive. Another feature worth noting is the strong tendency for the oscillating electrons to remain confined in the magnetic north-south direction.

TABLE 8.1 CHARACTERISTICS OF EXPLORER IV PACKAGE

Detector	Type	Directional Properties	Electron Energy Threshold	Scaling Factor *	Telemetry Channel	Remarks
A	Scintillator and phototube	Maximum normal to satellite axis 38° width	600 kev	2,048 16	2 5	Divide counts/sec by 10 to get counts/cm^2-sec-steradian
B	Same as above (Cs-1)	Same as above but opposite direction	Total flux above 25 kev	None	4	Audio tone displacement proportional to count rate
C	Unshielded Geiger	Nondirectional	2 Mev	2,048	3	Calibration curve double-valued peak at 11,000 cps
D	Shielded Geiger	Nondirectional	4 Mev	64	1	Divide counts/sec by 2 or 3 to get counts/cm^2-sec-steradian

* Relating number of counts to number of telemetry channel complete cycles.

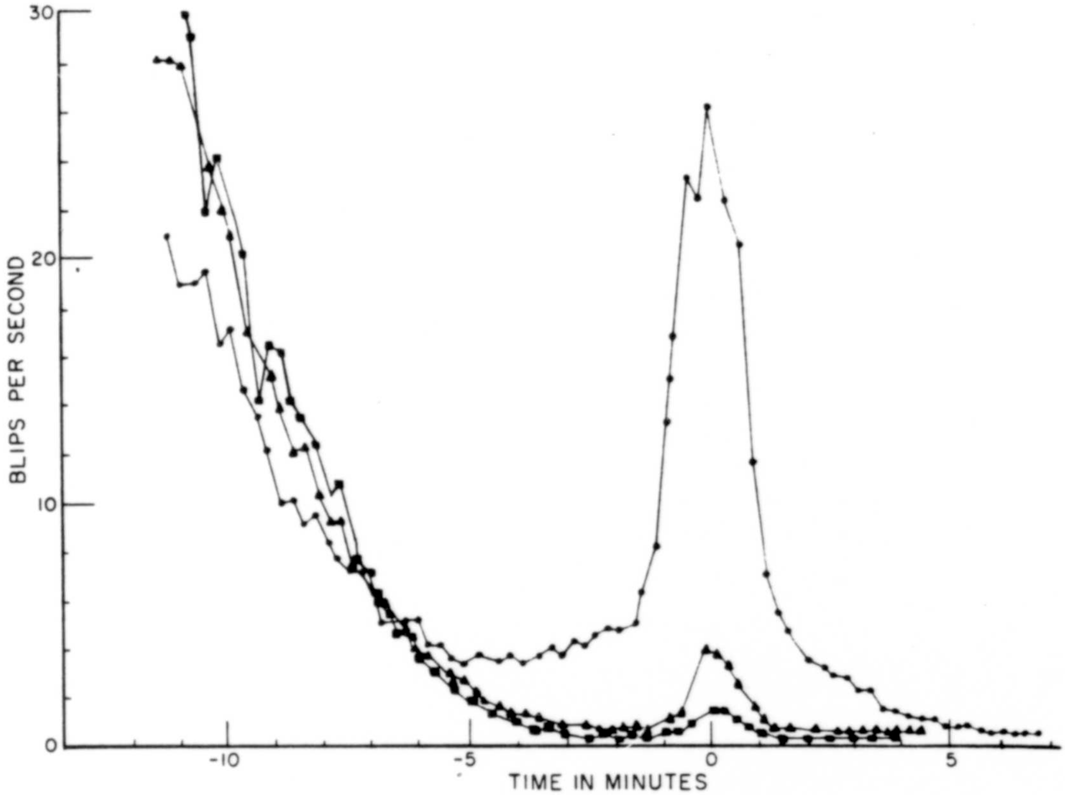

Figure 8.1 Explorer IV count rate enhancements due to Argus III. Channel 1, Torrejon, 6 through 8 September 1958, Passes 556, 569, and 582. Passes separated by 24 hours.

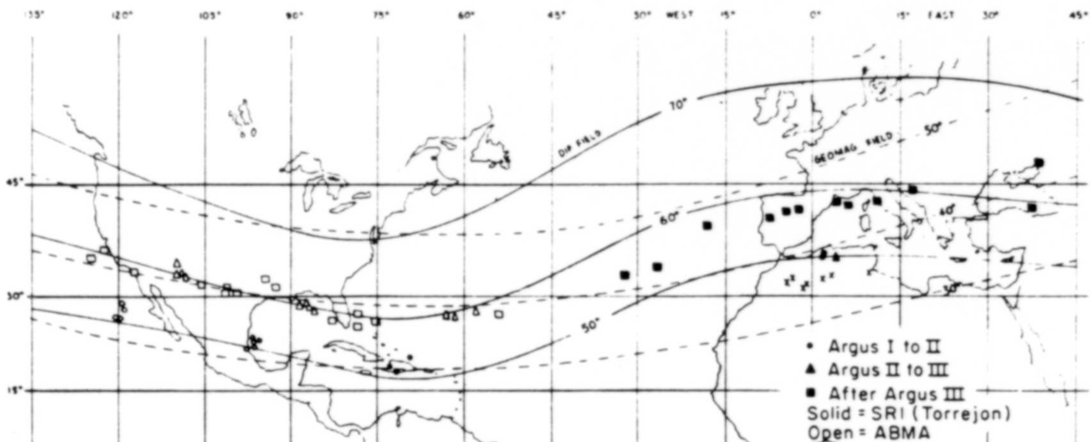

Figure 8.2 Location of enhancements observed by Explorer IV.

Chapter 9

CONCLUSIONS

In view of the shortness of time and the difficulties imposed by security requirements and logistic problems, Project Midas can be adjudged to have been a successful and worthwhile operation. It appears from the data, even though incomplete, that:

1. An artificial aurora, accompanied by radar clutter, can be produced in distant areas, i.e., at geomagnetic conjugates, which can be closely determined by employing the current dipole approximation of the earth's magnetic field. At the same time, magnetic control of high-speed electrons was verified.
2. It appears probable that both the Alfven magnetic field guided mode and the isotropic mode of hydromagnetic wave propagation were generated by the nuclear detonations and detected both in the Azores and at many other stations in North America, Europe, Africa, and the Antarctic.
3. The riometers employed—having a sensitivity to antenna temperatures of the order of 10° K at 118 Mc, 25° K at 58 Mc, and 100° K at 27 Mc—were inadequate for detecting any synchrotron noise generated by the Argus events.
4. Effects in the conjugate area in the ionosphere and on ionospheric radio propagation are suggested by the sporadic E observations in the Azores and at higher latitudes and by the drop in signal level of the VLF signals. It may readily be conjectured that propagation of HF and VHF through the conjugate area would have been affected or could be affected by detonations of greater strength.
5. The hydromagnetic effects, the optical effects given by the all-sky cameras and the spectrophotometers, and the VLF pulses that were detected all have obvious application to the problem of detection of high-altitude nuclear detonations. Whereas the riometer effects were negative, the results from Shot Teak of Operation Hardtack show that more powerful detonations will produce effects. This obviously requires more exploration. The sporadic E effects and the HF backscatter would appear to have value chiefly in connection with the other phenomena.
6. Many questions remain unanswered. Some pertain to the increase in range of the radar, the returns in the Azores, the nature of the VLF pulses recorded in the launch area, and the records from the all-sky cameras and the spectrophotometers. There is also the question whether the debris reached the conjugate area. Other questions pertain to the frequency dependence of the radar clutter in the conjugate area, and the possible effects of the tests on the ionosphere.

Appendix

EMISSION OF ELF AND VLF NOISES FROM SOURCES WITHIN THE IONOSPHERE

This material was prepared by Hermann Poeverlein, Propagation Sciences Laboratory, Air Force Cambridge Research Laboratories, L. G. Hanscom Field, Massachusetts.

A.1 INTRODUCTION

The waves within the ionosphere have the character of hydromagnetic waves at frequencies well below the ion gyroresonances and the character of regular electromagnetic waves at frequencies well above the ion gyroresonances. In the higher ionosphere, two types of ions, protons and positively charged oxygen ions, are presumed to be generally present, with gyrofrequencies of approximately 45 and 700 cps. Those below 45 cps are, consequently, hydromagnetic waves, and those well above 700 cps are conventional electromagnetic waves. Between 1 and 30 kc, free propagation of the extraordinary mode, the mode leading to the ionospheric whistlers, is expected. The ordinary mode at these frequencies is an attenuated wave.

A study of the propagation characteristics in the various frequency ranges will give some indication how the waves may be produced by a source small compared to the wavelength and which mode will be emitted by a particular type of source. An artificial source at the considered frequencies, in general, will be small compared to the wavelength.

A.2 HYDROMAGNETIC WAVES

Basic equations for hydromagnetic waves may be derived from Maxwell's equations with usage of the conductivity quantities entering. Small amplitudes will be assumed, corresponding to linearized theory, and compressional forces will be neglected. Collisions are also neglected.

At frequencies well below ion gyroresonance, the conductivity components of a plasma are:

direct transverse conductivity

$$\sigma_t = i \epsilon_0 \omega \frac{\omega_{0i}^2}{\omega_{Hi}^2} \tag{A.1}$$

Hall transverse conductivity

$$\sigma_h \approx 0 \tag{A.2}$$

longitudinal conductivity

$$\sigma_l = - i \epsilon_0 \frac{\omega_{0e}^2}{\omega} \tag{A.3}$$

(See Reference 37.)

ω_0 and ω_H are the angular plasma frequency and gyrofrequency; the subscripts i and e refer to ions and electrons respectively. Only one type of ions will be assumed.

The longitudinal conductivity σ_l is great, leading to a suppression of electric field components in the direction of the constant (terrestrial) magnetic field. In a coordinate system whose z-axis is parallel to the constant magnetic field, Maxwell's equations become then:

$$\frac{\partial}{\partial y} H_z - \frac{\partial}{\partial z} H_y = \sigma_t E_x \qquad -\frac{\partial}{\partial z} E_y = -i\omega\mu_0 H_x$$

$$-\frac{\partial}{\partial x} H_z + \frac{\partial}{\partial z} H_x = \sigma_t E_y \qquad \frac{\partial}{\partial z} E_x = -i\omega\mu_0 H_y$$

$$\frac{\partial}{\partial x} H_y - \frac{\partial}{\partial y} H_x = J_z \qquad \frac{\partial}{\partial x} E_y - \frac{\partial}{\partial y} E_x = -i\omega\mu_0 H_z$$

E_z has been omitted. This is allowed in case of great σ_l if the constant magnetic field is uniform. $\underset{\sim}{H}$ denotes the magnetic field of the wave only. σ_t will now be assumed as constant in space.

Introduction of a two-dimensional div′ and curl′ (in the x, y - plane) leads to the following equations which are readily obtained from Maxwell's equations:

$$\sigma_t \operatorname{div}' \underset{\sim}{E} = -\frac{\partial J_z}{\partial z} \tag{A.4}$$

$$\operatorname{div}' \underset{\sim}{H} = -\frac{\partial H_z}{\partial z} \tag{A.5}$$

$$\operatorname{curl}' \underset{\sim}{E} = -i\omega\mu_0 H_z \tag{A.6}$$

$$\operatorname{curl}' \underset{\sim}{H} = J_z \tag{A.7}$$

$$\frac{\partial}{\partial z} \operatorname{div}' \underset{\sim}{E} = -i\omega\mu_0 J_z \tag{A.8}$$

$$\sigma_t \operatorname{curl}' \underset{\sim}{E} = -\nabla^2 H_z \tag{A.9}$$

From Equation A.4, together with Equations A.6, A.8, and A.9, two wave equations are obtained:

$$\frac{\partial^2 J_z}{\partial z^2} = i\omega\mu_0\sigma_t J_z$$

and

$$\nabla^2 H_z = i\omega\mu_0\sigma_t H_z$$

or

$$\frac{\partial^2 J_z}{\partial z^2} = -\frac{\omega^2}{\nu_A^2} J_z \tag{A.10}$$

and

$$\nabla^2 H_z = -\frac{\omega^2}{\nu_A^2} H_z \tag{A.11}$$

ν_A is the Alfven velocity according to:

$$\nu_A^2 = \frac{i\omega}{\mu_0\sigma_t} = \frac{1}{\epsilon_0\mu_0}\;\frac{\omega_{Hi}^2}{\omega_{0i}^2}$$

Equations A.10 and A.11, together with Equations A.4 through A.7, show that the entire field can be split up into two parts (denoted by subscripts 1 and 2) for which we have:

$$\left.\begin{aligned}
\frac{\partial^2 J_{1z}}{\partial_z^2} &= -\frac{\omega^2}{\nu_A^2} J_{1z} \\
H_{1z} &= 0 \\
\sigma_t \operatorname{div}' \underset{\sim}{E}_1 &= -\frac{\partial J_{1z}}{\partial_z} \\
\operatorname{curl}' \underset{\sim}{E}_1 &= 0 \\
\operatorname{div}' \underset{\sim}{H}_1 &= 0 \\
\operatorname{curl}' \underset{\sim}{H}_1 &= J_{1z}
\end{aligned}\right\} \quad (A.12)$$

and

$$\left.\begin{aligned}
\nabla^2 H_{2z} &= -\frac{\omega^2}{\nu_A^2} H_{2z} \\
J_{2z} &= 0 \\
\operatorname{div}' \underset{\sim}{E}_2 &= 0 \\
\operatorname{curl}' \underset{\sim}{E}_2 &= -i\omega\mu_0 H_{2z} \\
\operatorname{div}' \underset{\sim}{H}_2 &= -\frac{\partial H_{2z}}{\partial_z} \\
\operatorname{curl}' \underset{\sim}{H}_2 &= 0
\end{aligned}\right\} \quad (A.13)$$

Each of these two parts represents one mode of propagation. The total field is the sum of the two fields.

The velocity of the electrons and ions is derived from the approximative equation of motion:

$$\underset{\sim}{E} = -\mu_0 \underset{\sim}{\nu} \times \underset{\sim}{H}_0 \tag{A.14}$$

$\underset{\sim}{H}_0$ is the constant magnetic field. Equation A.14 yields:

$$\left.\begin{aligned}
\operatorname{div}' \underset{\sim}{E} &= -\mu_0 H_0 \operatorname{curl}' \underset{\sim}{\nu} \\
\operatorname{curl}' \underset{\sim}{E} &= \mu_0 H_0 \operatorname{div}' \underset{\sim}{\nu}
\end{aligned}\right\} \quad (A.15)$$

Formulations related to Equations A.12, A.13, and A.15 are given in References 38 through 40.

The two sets of equations, Equations A.12 and A.13, describe two different propagation modes. The wave equation of the first mode, top equation of Equation A.12, contains ∂^2/∂_z^2 as only partial derivative. This indicates perfect guidance of the waves along the z-axis, i.e., in the direction of the magnetic force lines. The waves in this case are Alfven waves. The wave equation of the second mode, top equation of Equation A.13, contains the Laplacian operator ∇^2, thus expressing an omnidirectional propagation, which corresponds to the second hydromagnetic mode.

According to Equations A.12 and A.15, the nondisappearing quantities in case of Alfven waves are J_z, $\operatorname{div}' \underset{\sim}{E}$, $\operatorname{curl}' \underset{\sim}{E}$, and $\operatorname{curl}' \underset{\sim}{\nu}$. Local processes producing primarily a curl of some vector quantity can hardly be imagined. It is therefore expected that Alfven waves are produced by oscillatory longitudinal currents corresponding to a current density J_z or by an initial $\operatorname{div}' \underset{\sim}{E}$, which will originate from a separation of positive and negative charges.

In case of the other mode of hydromagnetic waves, Equation A.13 with Equation A.15, the quantities H_z, $\operatorname{curl}' \underset{\sim}{E}$, $\operatorname{div}' \underset{\sim}{H}$, and $\operatorname{div}' \underset{\sim}{\nu}$ do not disappear. The emission of the waves thus may result from an initial velocity of the ionized matter with div$'\, \underset{\sim}{\nu} \neq 0$, which may be due, for example, to an artificial explosion.

An atomic explosion in the ionosphere will generate the two propagation modes. The velocity field produced will lead to the omnidirectional mode. A charge separation arising from the emission of charged particles will cause a div$'\, \underset{\sim}{E}$ with a radiation of Alfven waves. The processes in the vicinity of the explosion surely are nonlinear, and this theory will not apply there. But the fact that a velocity field leads to the nonguided waves and a charge separation to Alfven waves is expected to remain.

There may be other means for separating the charges in order to obtain Alfven wave emission. The velocity field required for the omnidirectional radiation (of the second mode), however, may hardly be produced by any other artificial effect but an explosion. An initial curl$'\, \underset{\sim}{E}$ would also lead to this second mode. Whether a curl$'\, \underset{\sim}{E}$ can be produced primarily is not known.

A.3 WHISTLER MODE

Whistler propagation has been extensively treated in the literature. At the frequencies at which whistlers are observed, roughly from 1 to 30 kc, only one mode (conventionally called the extraordinary) is propagated freely. Therefore, any source will emit only this mode. The other mode can exist only in the near field.

The hydromagnetic waves dealt with in the preceding section had linear polarization; a definite direction of $\underset{\sim}{E}$ and $\underset{\sim}{H}$ was found at every location. The polarization in whistler propagation, however, is circular. Consequently, a two-dimensional divergence of $\underset{\sim}{E}$ or $\underset{\sim}{H}$ appears only in combination with a two-dimensional curl of the same quantity and vice versa. Any source leading to a div$'\, \underset{\sim}{E}$ or to a div$'\, \underset{\sim}{\nu}$ will, consequently, emit the two modes—the freely propagated whistler mode and the attenuated ordinary mode. A limitation to one mode is attained only if the source emits a circular polarization of a particular sense of rotation.

Whistler propagation may be expected from any source radiating in the corresponding frequency range. A process (pulse or transient) that is shorter than roughly 100 μsec has a continuous spectrum extending well into the range of whistler frequencies.

Whistler propagation is known to be a propagation with imperfect guidance along the terrestrial magnetic force lines. It thus seems to be intermediate between the perfectly guided Alfven waves and the omnidirectional second type of hydromagnetic waves.

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