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Investigation of HF Propagation Conditions Associated with the Third High Energy Astrophysical Observatory Launch

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INVESTIGATION OF HF PROPAGATION CONDITIONS ASSOCIATED WITH THE THIRD HIGH ENERGY ASTROPHYSICAL OBSERVATORY LAUNCH

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The burning of an Atlas-Centaur rocket in the ionospheric F-region was used to determine the extent of HF propagation anomalies associated with the resultant drop in ionospheric electron content. This "ionospheric hole" grew to encompass the control points of many Caribbean to North American high frequency paths soon after the 0528 GMT launch from Kennedy Space Center, Cape Canaveral, Florida, on September 20, 1979. Short-wave listeners, who collectively monitored 86 paths after launch, volunteered signal strength and fade quality data concerning special broadcasts on 15295 kHz from Bonaire and on 17815 kHz from Antigua. Although these frequencies were closer to the predicted maximum usable frequency than what were normally used, the expected blackout of radio circuits did not occur; in fact, computer analysis revealed that the large number of minor fadeouts that followed the launch were not related to the location of the control points. The burning thus appeared to have negligible effect on HF signals that crossed the rocket path.

Key words: ionospheric depletions; propagation blackout; short-wave broadcasting

1. INTRODUCTION

The increased demand for renewable domestic energy sources had prompted the Department of Energy to consider a Satellite Power System (SPS) to provide energy for the nation in the early twenty-first century (Koomanoff and Sandahl, 1980). As part of this project, Heavy-Lift Launch Vehicles (HLLVs) would be used to place extensive amounts of hardware into earth orbit, from which giant solar collectors would be constructed. The engine exhaust from large rockets, such as those associated with the launch of the Skylab vehicle, could react with the ionosphere, creating an area of electron-depleted plasma known as an "ionospheric hole" (Mendillo et al 1979). Further, it had been theorized (Bernhardt et al 1980) that this ionospheric hole could cause a distortion of short-wave radio transmissions since these signals use the ionosphere as the medium for propagation.

The purpose of this report is to describe the results of an experiment to deduce how extensively short-wave radio broadcasts can be affected by the firing of a rocket into the ionosphere. Since most satellite boosters in current use do not burn for extended periods at ionospheric altitudes (100-800 km), the launch of the third High Energy Astrophysical Observatory (HEAO-C) provided a special opportunity to observe possible ionospheric depletion effects on the performance of HF propagation systems. The HEAO-C satellite was placed into orbit by an Atlas-Centaur

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booster, which burned throughout the F-layer of the ionosphere (200-500 km). Though the resultant ionospheric hole or electron density depletion was less extensive than that anticipated from an HLLV, the HEAO-C launch provided an inexpensive "experiment of opportunity" to monitor the relatively unobserved radio effects of an ionospheric depletion without having to finance a special launch.

Prior to discussing the results obtained from the experimental observations, a brief background concerning the experiment is given. The launch preparations and equipment descriptions are presented in the following section, after which a review of the results is given. It is concluded that no disturbances in HF propagation performance could be attributed to the ionospheric depletion associated with the HEAO-C launch.

2. BACKGROUND

The Saturn V booster used to launch NASA's Skylab workshop from the Kennedy Space Center at 1230 EST on May 14, 1973, produced a significant depletion in the ionospheric total electron content (TEC) over an area of two to three million square kilometers (Mendillo et al., 1975). By analyzing the polarization of VHF signals sent from geostationary satellites and monitored continuously by receivers near the Saturn V trajectory path, it was determined that the depletion was due to effluents from the Saturn V booster. Such an effect had not been observed previously because 1) virtually all rockets launched since the early 1960's added only minute amounts of exhaust to the atmosphere, 2) the few large rockets that were launched rarely burned above 200 km, and 3) most American launches originating at NASA's Kennedy Space Center had trajectories well over the Atlantic Ocean and away from ionospheric monitoring equipment (Mendillo et al., 1979). Most of the ionosonde data taken at stations near the Skylab launch trajectory were severely impacted by a solar flare that had commenced twenty minutes before launch. Many of these data had to be discarded since the solar flare-associated disturbance made it impossible to separate solar- from rocket-induced ionospheric disturbances.

Though it was expected to form a depletion ninety times smaller than an HLLV burn (Rote, 1980), the launch of the HEAO-C satellite provided a rare opportunity to observe the effects of an F-region rocket firing (Mendillo et al., 1979). This launch was particularly interesting for three reasons:

1. The Centaur stage of the Atlas-Centaur booster rocket was scheduled to burn at altitudes between 209 km and 466 km--well into the ionospheric F-region.

2. This stage was to begin firing at about 28°North latitude and 78°West longitude, and after heading due east, the rocket was to drop south and terminate its burn at roughly 23°North and 58°West. This trajectory was near the expected control points of many Caribbean-to-North American HF broadcast paths; thus, a network of monitors might be able to detect any propagation anomalies resulting from the launch. The placement of such a network might also provide details on the intensity of specific disturbances at particular reception sites, from which the horizontal extent of the ionospheric hole might be estimated.
3. After the rocket passed through the ionosphere, the electron density of the affected area would likely remain unchanged for many hours. This was because the rocket was to be launched at 0528 GMT, about four and one-half hours before ionospheric sunrise, after which time direct solar radiation would produce ionization to counteract the depletion.

3. PRE-LAUNCH EXPERIMENTAL PREPARATIONS

Three basic tasks were performed prior to launch. First, predictions of HF broadcast performance were developed to provide an estimate of what might occur. Second, commercial broadcasters whose transmitters beamed signals near the anticipated rocket path were requested to transmit special frequencies on the night of the launch. Finally, groups of short-wave listeners were requested to monitor the special frequencies.

Simple geometric models of the projected HEAO-C burn region were developed to determine the most likely radio paths to be disturbed by the HEAO-C launch. It was decided that the best transmitter sites to be monitored in North America would be Antigua (17.15°N,61.82°W) and Bonaire (12.25°N,68.45°W). Hypothetical monitoring sites were placed at every five degrees latitude and ten degrees longitude for most of the United States. Using a ionospheric computer prediction program developed by ITS (IONCAP, John Lloyd, private communication, 1979), monthly median maximum usable frequencies (MUFs) were calculated for the paths between the Caribbean transmitters and the hypothetical sites.

This computer program was also used to calculate the number of ionospheric hops necessary for transmission on each hypothetical radio path at the MUF. The ionospheric control points of each such path were then calculated using the number of hops and the transmitter and hypothetical receiver coordinates. Since it was uncertain how large the ionospheric hole would be, depletion diameters of 2, 5, and 10 longitudinal degrees were used. The Caribbean control point of each path was then compared with the trajectory-centered depletion models to determine if any rocket-induced effects were possible on that path. For example, if the control point of a certain path was located 1 1/2 degrees from the rocket trajectory, that path might experience a radio disturbance if the depletion was 5 or 10 degrees in width, but not if the depletion were only 2 degrees wide. The subsequent disturbance possibilities are given in the Appendix, which was prepared for the volunteer monitors.

As the operation of certain Caribbean and North American transmitters was essential to the project, major international broadcasters were approached for assistance. Because the average MUF for a one-hop Caribbean-to-North American point at 0600 GMT was predicted to be about 20 MHz, the transmission of special frequencies close to this MUF was requested for the launch date and time. Such frequencies would likely propagate at higher levels in the ionosphere where the rocket-induced perturbations were more likely to occur. The details concerning these special broadcasts appear in Table 1. All of these transmissions began around launch time and lasted at least one hour. The international broadcasters provided another form of assistance: staff personnel stationed at the relay sites on Antigua and Bonaire monitored Caribbean-targeted broadcasts from North America.

The majority of monitors were volunteer shortwave listeners who listen to commercial HF broadcasts as a hobby. A request for monitors was made by notifying various short-wave listener clubs, who then published notices in their monthly bulletins. Listeners who responded to this request were sent a guide to the launch, which included general details of the launch and the computer predictions in the Appendix. A standard report form was included with the guide, along with a request for strip chart and/or audio cassette recordings. Monitors were encouraged to give signal strength readings in decibels over one microvolt per meter, if possible, and to note any phase disturbances. Canadian listeners were informed that monitoring transmission from stations in northern South America might be useful, since these paths might encounter the rocket path. But it was expected that most of the monitors would be in the eastern United States, especially in New England, as this was the predicted prime area to detect anomalies in transmissions from Antigua. An additional letter detailing the special broadcast information was sent to the monitors about one week before the launch. By special arrangement, radio station WWV transmitted the latest launch date and time information each hour prior to launch, since the launch window often changed.

Table 1. Special Broadcasts for HEAO-C Launch

Station	Transmitter site	Frequency (kHz)	Power (kW)	Target area
Deutsche Welle	Antigua (17.15°N,61.82°W)	17815	500	E. North America
Radio Nederland	Bonaire (12.25°N,68.45°W)	15295	300	W. North America
Voice of America	Greenville (35.60°N,77.38°W)	17715	250	Caribbean
	Bethany (39.35°N,84.35°W)	21495	175	Caribbean
Radio Canada Int.	Sackville (45.88°N,64.32°W)	15125	100	Caribbean

4. TRANSMISSION AND MONITORING PROCEDURES

The equipment used by the international broadcasters to effect transmission is quite extensive. The transmitting powers of the stations monitored in this experiment range from 100 kW to 500 kW, which is adequate to beam strong signals into the target areas. The frequencies and operating times used by the broadcasters generally change seasonally, thus allowing for daily reception of many stations. Multi-element curtain antennas occupying several acres are used to help to achieve the desired signal coverage.

In contrast, the transmitting set-up of the amateur radio operator is more basic, since amateur transmissions are not intended for the public. Though the maximum allowed transmitter power is 2 kilowatts, it is often less in practice. The frequencies and operating times may change from moment to moment, so long as the operator stays within specified radio bands. The transmitting antenna is frequently a single dipole or vertical element. However, the receiving equipment used by both short-wave listeners and amateurs is quite similar. Receivers can range from single-stage sets to digital-synthesized units. Antennas may vary from top-of-the-set whips to extensive long-wire versions. Though many listeners used multi-tube or simple superheterodyne transistor receivers in this experiment, about half of the monitors used the newer Wadley-loop units. Most of the antennas employed were long-wire types ranging from 10 to 50 meters long.

A total of 47 listeners collectively monitored 86 paths on the night of the HEAO-C launch. This was actually better than expected, since most of the monitors had to stay up past 1:00 A.M., local time, on a week-night to effect the monitoring. A summary of the numbers and types of paths monitored appears in Table 2. Reports from the paths listed as positively out of the HEAO-C effect range were used as control data.

Each listener provided a written report of his or her observations. Most used the standard form supplied in the monitor's guide. An example of how one listener used this form is given in Figure 1. Some monitors noted changes in reception strength as they occurred, though many others reported signal values on a minute-by-minute basis. As none of the monitors used field-strength meters in the experiment, other means of reporting signal strength were used rather than decibels over one microvolt-per-meter. Readings from an S-meter on the receiver were sometimes employed, but the majority of the listeners used the SINPO scale in their reports, which assigned a number from "1" (poor grade) to "5" (excellent grade) for signal strength, interference, atmospheric noise propagation (fading), and overall signal quality. Though neither the meter readings nor the SINPO grades provided a measure

Table 2. Paths Monitored on the Night of the HEAO-C Rocket Launch

Path	Total number monitored	Number of paths positively out of HEAO-C effect range
Antigua to North America	27	13
Bonaire to North America	27	7
Other Caribbean sites to North America	17	14
Other Worldwide sites to North America	5	5
North America to Caribbean	4	0
All Other Paths	6	4
TOTALS	86	43

Name WILLIAM BUTUK

Address 149 HARRISON STREET

THUNDER BAY, ONTARIO, P7A 7A5 CANADA

RX LAT, RX LON - 48.40 N, 89.32 W

REGISTERED PROFESSIONAL ENGINEER
WM. BUTUK
29 OCT '79
PROVINCE OF ONTARIO

RECEIVERS USED:

1. YAESU MUSEN FRG-7 MK II
2.
3.
4.

ANTENNAS USED:

A. HYBRID LONGWIRE - TAPPED WOUND COIL
B.
C.
D.

NUMBER	DATE	TIME (GMT)	RA	SITE (BONAIRE)	FREQUENCY	STRENGTH	FADE RATE (SEC'S PER FADE)
1	SEPT 20/79	04:45	1,1	12.25N, 68.45W	15.295MHz	S 20/9	NIL (NO FADES)
2	"	05:05	"	"	"	S 20/9	" "
3	"	05:12	"	"	"	S 20/9	1.6 SECS / FADE
4	"	05:13	"	"	"	S 20/9	NO FADES
5	"	05:23	"	"	"	S 20/9	NO FADES
6	"	05:28	"	"	"	S 20/9	NO FADES
7	"	05:32	"	"	"	S 20/9	NO FADES
8	"	05:34	"	"	"	S 20/9	NO FADES
9	"	05:35	"	"	"	S 4	ABRUPT SHORT FADE - NOTICEABLE CHANGE IN AUDIO TONE
10	"	05:37:20	"	"	"	S 4	"
11	"	05:38:15	"	"	"	S 4	"
12	"	05:41	"	"	"	S 20/9	NO FADES
13	"	05:47:33	"	"	"	S 3+	VERY ABRUPT FADE 1 SEC / FADE
14	"	05:48	"	"	"	S 3+	2 SHORT FADES
15	"	05:49	"	"	"	S 20/9	
16	"	05:49:30	"	"	"	S 9	1 FADE IN 1 SEC. SLIGHT RINGING IN AUDIO NOT OBSERVED PREVIOUSLY

WB

Figure 1. Example of a completed report form.

of absolute signal strength, they were useful for determining relative strengths throughout a monitoring session. Fading was often reported in fades per second.

A total of 15 audio cassettes representing 22 different paths were received from the monitors. Ten strip charts from ten different paths were also obtained. Though strip charts were preferred because of their more detailed information, audio cassettes were also greatly appreciated, since they too provided actual data. Both strip chart data and audio data were used to detect the precise onset times, durations, and relative importances of individual disturbances.

5. RESULTS

The launch of the HEAO-C satellite from the Kennedy Space Center, Cape Canaveral, Florida (28.40°N,80.60°W), took place as planned on September 20, 1979, at 0528:00 GMT. The Atlas-Centaur booster subsequently produced an ionospheric hole covering one to three million square kilometers, according to preliminary studies of deduced TEC levels, airglow measurements, and incoherent scatter radar surveys (Mendillo et al., 1980). However, the predicted four- to five-hour long blackout of certain radio circuits between North America and the Caribbean did not occur. Except for random fadeouts lasting no more than thirty seconds each, the the signal strengths along these circuits were generally constant from 0520 until 0620 GMT. It was thus theorized that the rise in short-term disturbances noted soon after launch might have been caused by the sudden decrease in ionospheric electron content caused by the adiabatic expansion of the rocket exhaust cloud. The emphasis of the data analysis therefore shifted to a search for patterns in the data that might support this hypothesis. However, an analysis of the Antigua and Bonaire special broadcast data conducted with respect to earliest possible rocket effect times and hypothetical regions of election depletion proved that, to within the limitations of the data, the launch had no effect upon short-wave signals that crossed the path of the rocket. An analysis of data from other radio circuits that were monitored support this conclusion.

A general overview of the short-wave reception conditions around launch time on the days before, during, and after the takeoff date is displayed in Figure 2, which shows strip charts of Deutsche Welle's signal on 17845 kHz from Wertachtal, Germany, as monitored by a listener in Elkton, Virginia. Poor signal quality was observed on September 19: hourly ionospheric sounding data for Wallops Island, Virginia (37.80°N,75.00°W), obtained from the World Data Center A, indicate that spread-F conditions existed on September 19 at time concurrent with those in Figures 2a. Such conditions, along with depressed critical frequencies noted prior

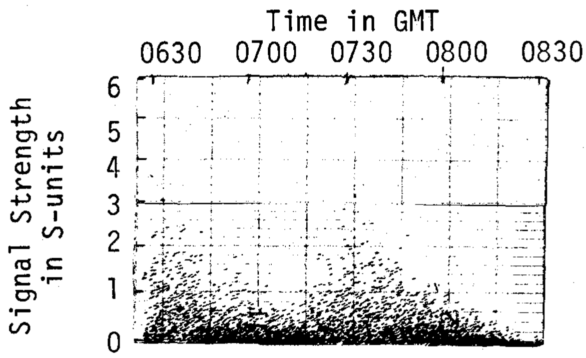

Figure 2a. Strip chart for September 19, 1979.

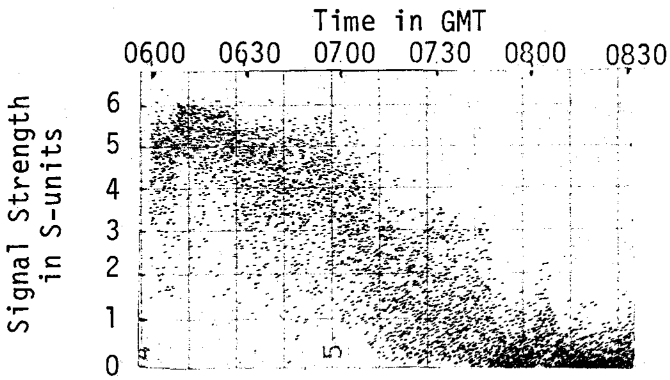

Figure 2b. Strip chart for September 20, 1979.

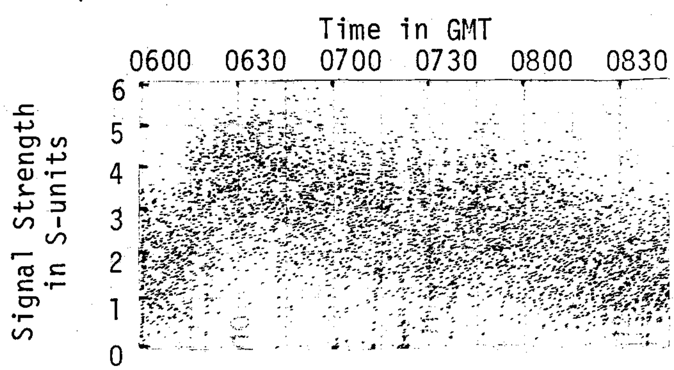

Figure 2c. Strip chart for September 21, 1979.

Figure 2. Strip charts of Deutsche Welle from Wertachtal, Germany, on 17845 kHz, as monitored in Elkton, Virginia, on the days before, during, and after the launch. Strikebar frequency was one strike every two seconds.

to the spread F, suggest that a magnetic storm took place throughout that day. Nevertheless, normal signal strengths were seen early on September 20, but conditions decayed gradually between 0600 and 0800 GMT, after which poor conditions settled in. The following day, September 21, saw the return of normal levels without the decay seen on September 20. Reception conditions on other circuits generally agree with these observations over the three-day period.

5.1 Analysis of Data Concerning the Bonaire Broadcast on 15295 kHz

The best set of monitoring data for use in determining the effect of the HEAO-C launch on short-wave broadcasts was collected by listeners who observed Radio Nederland's special transmission from Bonaire. The English portion of this broadcast from Bonaire on 15295 kHz ran from 0530 to 0625 GMT on September 20, 1979. A list of monitoring sites for this broadcast is given in Table 3. Though a similar number of monitors observed Deutsche Welle's special transmission from Antigua on the night of the launch, many listeners first monitored Bonaire and switched to Antigua at 0625 when Bonaire signed off. The Radio Nederland data set thus provided a significantly greater number of observations than the Deutsche Welle group in the crucial minutes immediately after launch.

The Bonaire data, when tabulated according to minutes after launch, did not exhibit any regularity with respect to fluctuations in strength and fading characteristics. An attempt to better correlate these changes was based on a simple observation: if monitors throughout North America simultaneously reported disturbances in propagation conditions within the first ten minutes after launch, these disruptions could not have been rocket-induced, because the rocket swept across the various radio paths at different times. For example, if listeners in Chicago, Illinois, and Portland, Maine, each noticed a fade-out in Bonaire's signal eight minutes after takeoff, both disturbances could not have been due to the launch, since the rocket had not yet crossed the path between Bonaire and Portland. Yet the anomaly noted in Chicago might have been rocket-induced, as the Bonaire-Chicago path had been traversed. Thus, the position of the rocket is an important factor in analyzing disturbances noted soon after launch.

This concept was used to determine times of earliest possible effect (EPE times) for each monitor site. Given a fixed transmitter location and the rocket position at a particular time, rays separating the possible and impossible radio effect regions for that time were produced. The EPE time map containing these rays for Bonaire transmissions appears in Figure 3. As an example, the line labeled "0534" is a segment of the great circle through Bonaire and the rocket's

Table 3. Locations and Earliest Possible Effect Times of North American Monitors who Observed Radio Nederland from Bonaire on 15295 kHz at Least Twice on the Night of the Launch

Site	Degrees North latitude	Degrees West longitude	Earliest possible effect time for Bonaire in GMT
Sacramento, California	38.53	121.50	none
Lawton, Oklahoma	34.60	98.42	none
Port Arthur, Texas	29.98	94.00	none
Eunice, Louisiana	30.50	92.43	none
Panama City, Florida	30.17	85.68	none
Casselberry, Florida	28.55	81.35	none
Sanford, Florida	28.82	81.28	none
Decatur, Georgia	33.75	84.28	0533
Suquamish, Washington	47.57	122.67	0533
Knoxville, Tennessee	36.00	83.95	0534
South Bend, Indiana	40.67	86.25	0535
Duluth, Minnesota	46.75	92.17	0535
Greenville, North Carolina	35.60	77.38	0535
Winnipeg, Manitoba, Canada	49.88	97.17	0536
Bernic Lake, Manitoba, Canada	50.42	95.42	0536
Thunder Bay, Ontario, Canada	48.45	89.20	0536
Washington, D. C.	38.92	77.00	0536
Toronto, Ontario, Canada	43.70	79.75	0536
Norristown, Pennsylvania	40.12	75.33	0537
Broomall, Pennsylvania	39.98	75.37	0537
Reading, Pennsylvania	40.33	75.92	0537
Brick, New Jersey	40.10	74.03	0537
Wayne, New Jersey	40.93	74.26	0537
Brooklyn, New York	40.67	73.97	0537
Wilbraham, Massachusetts	42.13	72.43	0537

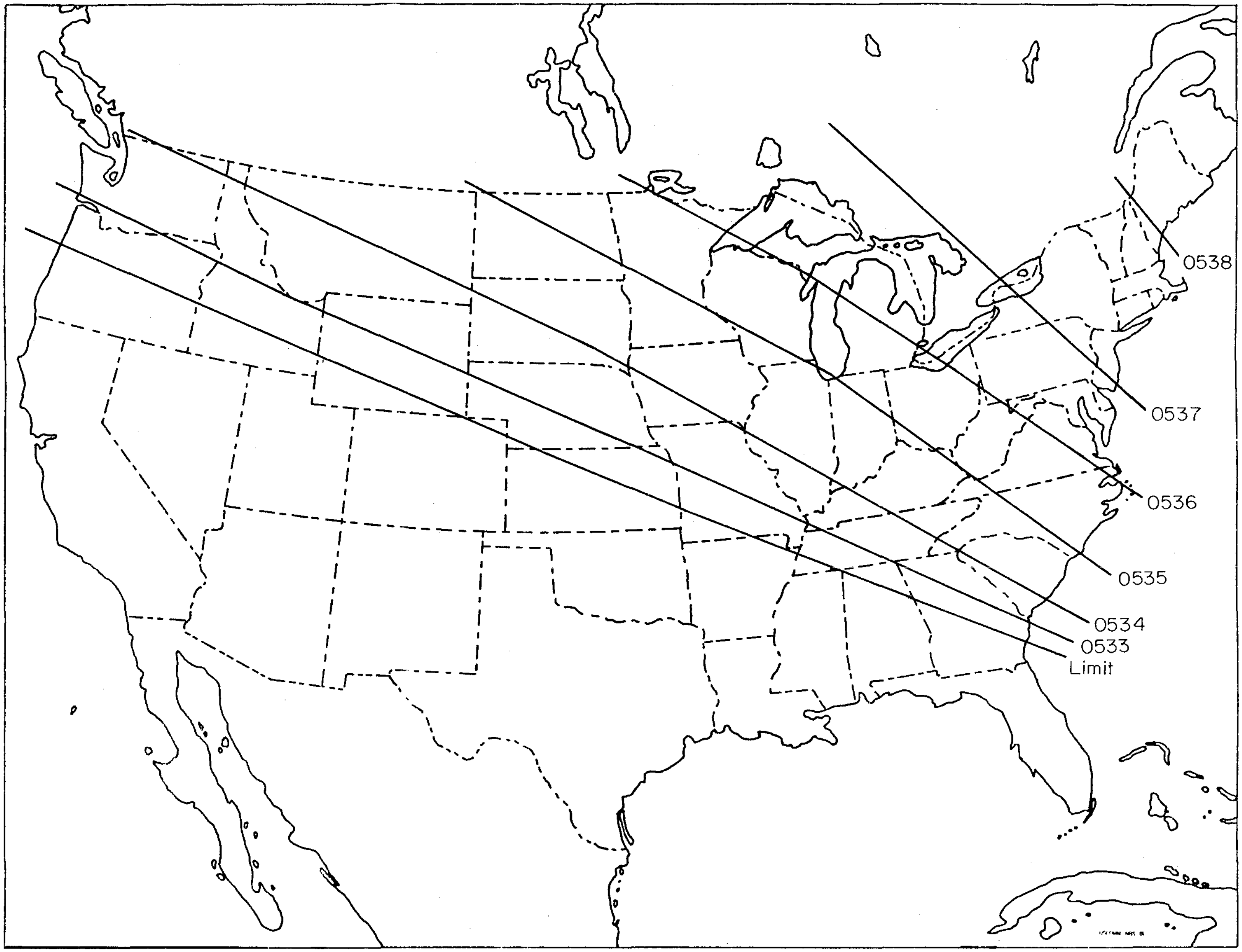

Figure 3. Map detailing the earliest possible times that broadcasts from Bonaire could be affected by the launch (times are in GMT).

location at 0534:00 GMT, which was 28.48°N, 73.76°W. Thus, any listener east of this ray could not have detected any launch-induced effects before 0534 GMT. The ray labeled "limit" defines the EPE ray for 0532:20, which is when the Centaur rocket first began firing: if a monitor was located west of this line, that listener could never detect any rocket-induced effects.

From this map, the EPE time for each listening site was determined. Because virtually all of the listeners reported changes in reception conditions to the nearest minute, the EPE times were rounded accordingly. The Bonaire data were then rearranged according to minutes after EPE time, and although this introduced some rounding error, it was hoped that rocket effects requiring a few minutes to develop, such as the expansion of the exhaust cloud, could be detected by this procedure. A significant result deduced from the EPE tabulation was that four listeners detected a drop in signal strength and/or fade quality at two minutes after EPE time, as can be seen in Table 4. The tabulated relative values each describe the difference between the current and previous SINPO quality figures.

In analyzing the results, the control points of each Bonaire-to-North America monitor path were first determined. It was then deduced whether or not these points lay within regions centered on the rocket path having electron density depletions with hypothetical widths of 2, 5, and 9 degrees of latitude. These widths were chosen because preliminary TEC, airglow, and radar studies estimated the final width of electron density depletion region resulting from the HEAO-C launch was between 600 and 1000 km (5 and 9 degrees) wide (Mendillo et al., 1980). Total electron content measurements suggest an ionospheric depletion with a 2-degree width was achieved by one and a half minutes after EPE time (Bernhardt et al., 1980).

Returning to Table 4, the symbols to the left of the monitoring sites give the results of the determinations: an asterisk indicates that the control point of that path fell within the hypothetical 2-degree hole, a blank implies that it was within 5 degrees, an "N" denotes within 9 degrees, and an "R" implies that this path's control point fell outside the 9-degree hole. Keeping these conventions in mind, it can be shown that the degradations in signal quality noted by four of the monitors at two minutes after EPE time were not rocket-induced: first, the listener who had the greatest probability of noting a disturbance within one and a half minutes after EPE time--namely, the listener in Toronto, Ontario--noticed nothing unusual in this period. The sites requiring a 5-degree hole width for signal disruption also detected no perturbations. Furthermore, although a 5- to 9-degree hole width may have been achieved, this size was certainly not formed within two minutes after EPE time; so the three "N" monitors who detected disturbances were

Table 4. Relative Signal Strength and Fading Data Taken Two Minutes After Earliest Possible Effect Time by Monitors of Bonaire on 15295 kHz

	Location of monitor	Relative strength	Relative fading	Minutes since last report
R	Suquamish, Washington	0	-1	2
N	Knoxville, Tennessee	-1	-1	1
	South Bend, Indiana	0	0	1
N	Duluth, Minnesota	0	0	1
N	Greenville, North Carolina	0	-	1
N	Winnipeg, Manitoba, Canada	-1	-1	1
N	Bernic Lake, Manitoba, Canada	-1	0	1
N	Thunder Bay, Ontario, Canada	0	0	1
*	Toronto, Ontario, Canada	0	0	1
	Wayne, New Jersey	0	0	2

not hearing rocket-induced effects, as was true for the control monitor in Suquamish, Washington.

5.2 Analysis of Other Radio Circuits

The earliest-possible-effect (EPE) time procedure was also applied to the data collected by North American listeners of Deutsche Welle's special broadcast from Antigua on 17815 kHz. A listing of monitors for this program appears in Table 5. As stated previously, relatively few listeners monitored this station in the hour following launch. In addition, the EPE time map for Antigua given in Figure 4 shows that a sizable portion of the continent was outside of Antigua's region of possible effect, thus eliminating a large part of monitoring information. Further breakdown of the Antigua data set was therefore unwarranted, since the EPE analysis itself yielded a poor sample size.

Nevertheless, thirteen monitors observed Antigua's special broadcast between 0600 and 0700 GMT on the launch date. During this period, a significant decay in signal strength was detected simultaneously with an increase in fade frequency and depth by eight of these listeners. This is vividly displayed in Figure 5, which follows the signal decay from 0619:35 until 0637:32, as monitored in South Bend, Indiana. However, considerable evidence suggests that this effect was not rocket-induced because three of the eight listeners who reported this disturbance were located outside of Antigua's region of possible effect and, secondly, no unusual fadeouts were noted during this time period by Bonaire monitors.

Similarly, the transmissions from North America collected by the professional monitors stationed on Antigua and Bonaire was consistent with the Bonaire data mentioned previously: signal strengths remained constant in the first half hour after launch, though a few minor disturbances were detected. The Bethany, Ohio, transmission on 21495 kHz monitored in Antigua is an example of a radio circuit that had its control point within two degrees of the rocket path. Although this path was one of the best to detect launch-induced effects, this circuit had virtually unperturbed signal strengths throughout the first half hour after lift-off. This further demonstrates how the launch had no discernible effect on signals that traversed the rocket path.

At the same time, six North American monitors observed signals from Bonaire and Antigua that were transmitted on their usual frequencies in the 6 and 9 MHz bands. Since relatively few anomalies were noticed at higher frequencies, even fewer disturbances were expected at the lower ones, because lower-frequency signals were reflected at lower ionospheric heights, where the rocket produced only a minor

Table 5. Locations and Earliest Possible Effect Times of North American Monitors Who Observed Deutsche Welle from Antigua on 17815 kHz at Least twice on the Night of the Launch

Site	Degrees North latitude	Degrees West longitude	Earliest possible effect time for Antigua in GMT
Sacramento, California	38.53	121.50	none
Lawton, Oklahoma	34.60	98.42	none
Port Arthur, Texas	29.98	94.00	none
Eunice, Louisiana	30.50	92.43	none
Port Richy, Florida	28.25	82.74	none
Casselberry, Florida	28.55	81.35	none
Sanford, Florida	28.82	81.28	none
Decatur, Georgia	33.75	84.28	none
South Bend, Indiana	40.67	86.25	0533
Greenville, N. Carolina	35.60	77.38	0533
Winnipeg, Manitoba, Canada	49.88	97.17	0533
Thunder Bay, Ontario, Canada	48.45	89.20	0533
Conway, Pennsylvania	40.68	80.28	0533
Herndon, Pennsylvania	40.72	76.83	0534
Philadelphia, Pennsylvania	40.00	75.17	0535
Norristown, Pennsylvania	40.12	75.33	0535
Broomall, Pennsylvania	39.98	75.37	0535
Reading, Pennsylvania	40.33	75.92	0535
Brick, New Jersey	40.10	74.03	0535
Wayne, New Jersey	40.93	74.26	0535
Newtown, Connecticut	41.42	73.32	0535

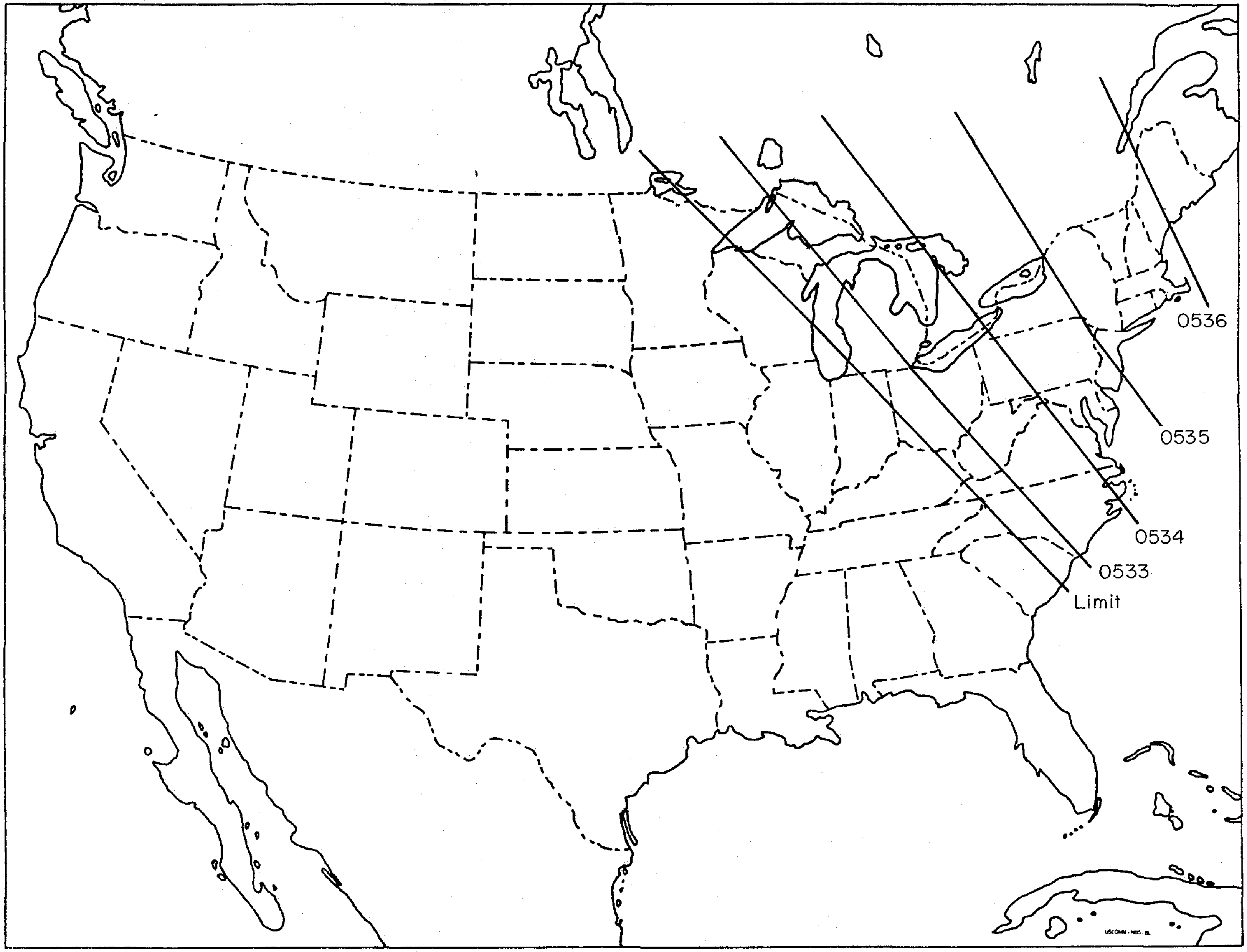

Figure 4. Map detailing the earliest possible times that broadcasts from Antigua could be affected by the launch (times are in GMT).

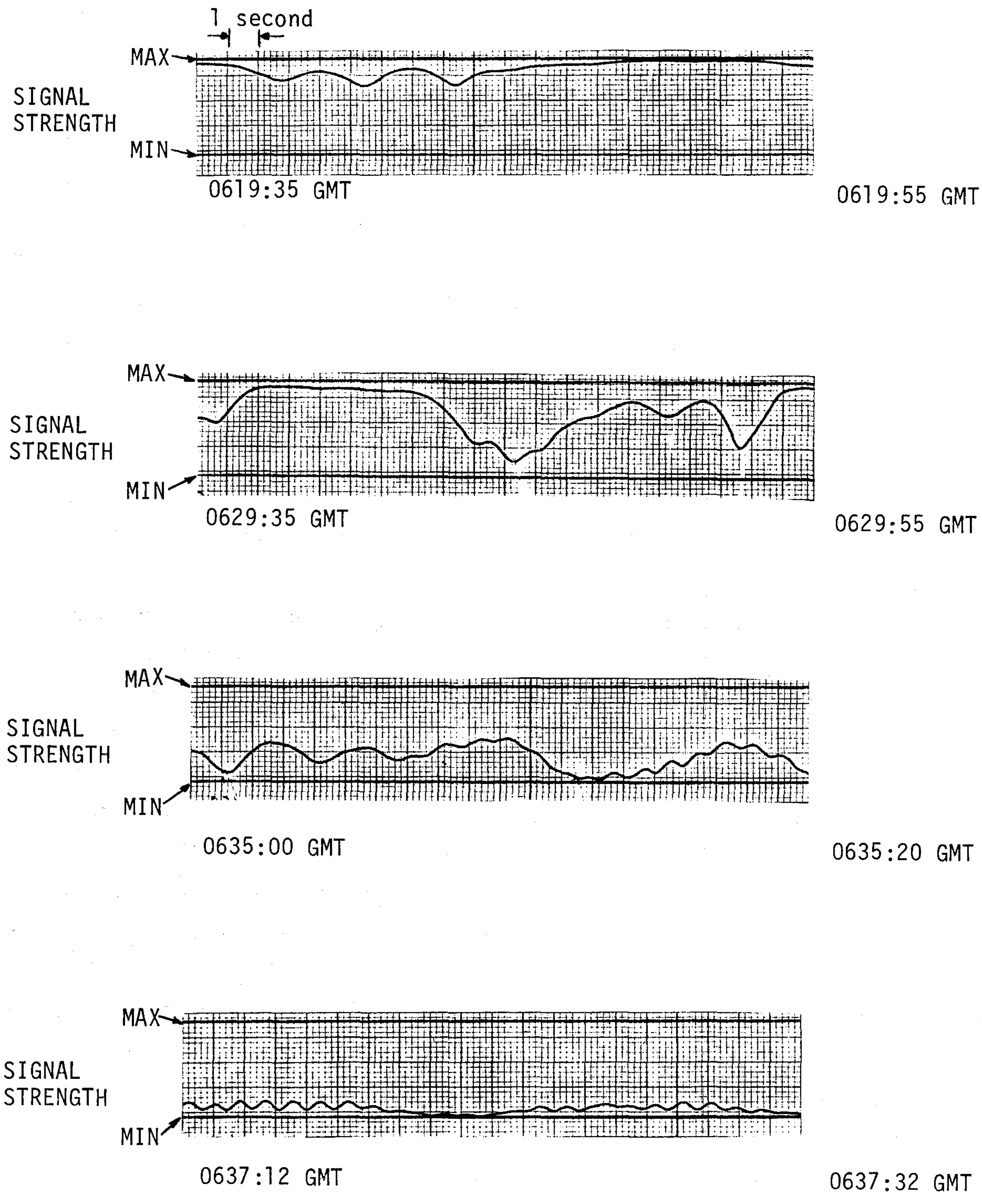

Figure 5. Examples of signal strength values on four intervals between 0619:35 and 0637:32 GMT of Deutsche Welle on 17815 kHz as monitored in South Bend, Indiana, on September 20, 1979.

change in ambient conditions. Consequently, many lower-frequency listeners received disturbance-free signals from 0530 until 0700 GMT, and those who did notice signal variations were located outside of any region of possible effect. Lower-frequency observations thus matched what was expected.

Three reports were received concerning transmissions from other Caribbean locations. In response to a special request, listeners in Winnipeg, Manitoba, monitored broadcasts from utility transmitters in Puerto Rico, Martinique, and Surinam, on frequencies of 12710, 8478.4, and 8652.5 kHz, respectively, all of which fell within possible effect regions. However, no signal fluctuations were observed on the 8 MHz paths, and the Puerto Rico data suffered too much interference and transmitter failure to be of value. As with the lower-frequency data above, no effects were expected and none were detected.

6. DISCUSSION AND CONCLUSIONS

The ionospheric depletion created by the HEAO-C launch had no discernible effect on short-wave signals that crossed the rocket trajectory. Even though a rise in minor fadeouts occurred soon after launch, a major blackout did not develop. It had been originally theorized that high-frequency disturbances might occur on circuits that propagated anywhere near the path of the Centaur-state burn, which took place at heights between 209 and 466 km. More recently, however, it has been estimated that the majority of ionospheric reflection for paths from the Caribbean to North America near the rocket trajectory occurred between 250 and 300 km (Klobuchar et al., 1980). This would limit the blackout possibility regions to those areas that had EPE times between 0532:55 and 0533:45 GMT. The Antigua-to-Southeastern United States paths were the only one-hop circuits that had EPE times within this fifty-second interval. Unfortunately, the reception reports for these paths did not contain enough information to validate any effects due to the rocket launch. No radio disturbances were detected on any of these paths in the half-hour following launch. A somewhat larger depletion, encompassing a much greater portion of these transmission paths, would have been necessary to create noticeable HF disturbances.

The objective of this study was to determine the effects on short-wave radio propagation resulting from the firing of a rocket into the ionosphere. Although it was anticipated that the size of the subsequent depletion could be determined by noting which radio circuits experienced signal distortions, it appears that this was not possible. Due to the obscurity of such disturbances, one must rely on morphological data to deduce which paths had any possibility of noticing an effect, and then determine which of these circuits had disturbances at times that could be related to the development of the depletion. As stated above, no disturbances in propagation correlation could be related to the ionospheric depletion.

A few recommendations can be made for those who may wish to organize the short-wave community to monitor rocket launch effects in the future. Since it appears that rocket-induced effects on HF broadcast performance are subtle at best, one must minimize the listener-dependent variations to achieve greater uniformity in the data: Wadley-loop receivers (or those with equivalent sophistication) should be used to provide greater stability and noise rejection, while antenna systems must be properly grounded and directed. Furthermore, the monitors should be required to make strip chart and/or cassette recordings during the first twenty or so minutes after launch. Such recordings would yield a large quantity of objective and time-synchronized data unavailable when only discrete signal checks are used. When such measurements are made, one must be certain that the continuous data recorder monitors the radio signal at a point preceding the automatic gain control (AGC) stage in the receiver. This would prevent distortion of the readings by the subsequent audio stages. In order to properly synchronize the audio data, a stereo recorder might be used: one channel could record the monitored transmission, while the other could carry a simultaneous time station broadcast, such as WWV. This synchronization would be necessary to accurately match radio signal information to the rocket hole morphology.

Finally, a general model of the expected depletion should be developed well before launch. This would allow time to optimize operating frequencies and transmitter/receiver locations, and would permit better monitor notification of exact listening times and frequencies. A large number of monitors should be used in the possible effect region to further account for localized disturbances. A few listeners outside the region of possible effect should simultaneously observe the same frequencies to provide control data.

Although the formation of ionospheric electron density depletions comparable in size to that created by the Atlas-Centaur engine burn would likely go undetected by normally-equipped short-wave listeners, one cannot conclude that HLLV launches would produce similar effects, since the depletion associated with such launches would be significantly larger than those produced during the HEAO-C launch.

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APPENDIX: Summary of pre-launch computer predictions sent to the volunteer monitors

KEY FOR TABLES A-1 AND A-2

TX LAT, TX LON	Transmitter latitude and longitude 17.15N 61.82W is Antigua 12.25N 68.45W is Bonaire
RX LAT, RX LON	Hypothetical receiver latitude and longitude
MAXIMUM USABLE FREQUENCIES	Monthly median values calculated using an expected Zurich sunspot number of 151.2. The five time periods given are in GMT.
HOPS	Number of hops necessary for transmitting on the MUF at 0600 GMT.
LAYER	Ionospheric layer used when broadcasting at the MUF.
EFFECT AT GIVEN HOLE WIDTH	Whether or not any propagation disturbance could possibly be attributed to the ionospheric hole, if the hole was 2, 5, or 10 degrees of latitude wide.

Table A-1. Pre-launch Predictions for Antigua

TX LAT	TX LONG	RX LAT	RX LONG	MAXIMUM USABLE FREQUENCIES 0400	0600	0800	1000	1200	HOPS	LAYER	EFFECT AT GIVEN HOLE WIDTH 2 DEG	5 DEG	10 DEG
17.15N	61.82W	50.00N	60.00W	21.8	20.1	17.8	22.7	23.4	1	F2	NO	NO	NO
17.15N	61.82W	50.00N	70.00W	21.6	20.0	17.5	20.9	22.8	1	F2	YES	YES	YES
17.15N	61.82W	50.00N	80.00W	15.6	14.4	17.6	14.1	22.6	2	F2	YES	YES	YES
17.15N	61.82W	50.00N	90.00W	15.9	14.6	13.0	13.4	21.6	2	F2	YES	YES	YES
17.15N	61.82W	50.00N	100.00W	16.3	15.0	13.5	12.8	20.1	2	F2	YES	YES	YES
17.15N	61.82W	50.00N	110.00W	17.0	15.6	14.1	12.7	18.1	2	F2	NO	YES	YES
17.15N	61.82W	50.00N	120.00W	18.1	16.1	14.5	12.9	16.2	2	F2	NO	YES	YES
17.15N	61.82W	45.00N	60.00W	21.1	19.5	17.1	21.9	32.4	1	F2	NO	NO	NO
17.15N	61.82W	45.00N	70.00W	21.0	19.4	16.9	20.2	31.4	1	F2	NO	NO	YES
17.15N	61.82W	45.00N	80.00W	21.4	19.8	17.4	19.2	30.9	1	F2	NO	NO	YES
17.15N	61.82W	45.00N	90.00W	15.6	14.5	12.9	13.3	21.8	2	F2	NO	YES	YES
17.15N	61.82W	45.00N	100.00W	16.2	15.1	13.7	13.0	20.5	2	F2	NO	YES	YES
17.15N	61.82W	45.00W	110.00W	17.0	15.8	14.5	13.1	18.6	2	F2	YES	YES	YES
17.15N	61.82W	40.00N	70.00W	19.8	18.3	15.8	18.9	29.6	1	F2	NO	YES	YES
17.15N	61.82W	40.00N	80.00W	20.8	19.2	16.8	18.5	30.1	1	F2	YES	YES	YES
17.15N	61.82W	40.00N	90.00W	21.7	20.1	17.9	18.2	21.2	1	F2	YES	YES	YES
17.15N	61.82W	40.00N	100.00W	16.2	15.1	13.8	20.8	20.8	2	F2	NO	NO	YES
17.15N	61.82W	40.00N	110.00W	17.2	16.1	15.0	13.5	19.1	2	F2	NO	YES	YES
17.15N	61.82W	35.00N	70.00W	18.1	16.6	14.2	16.9	26.7	1	F2	YES	YES	YES
17.15N	61.82W	35.00N	80.00W	19.9	18.3	15.9	17.4	28.6	1	F2	NO	YES	YES
17.15N	61.82W	35.00N	90.00W	21.6	20.0	17.7	17.8	29.6	1	F2	NO	YES	YES
17.15N	61.82W	35.00N	100.00W	16.3	15.2	13.9	13.0	20.9	2	F2	NO	NO	YES

Table A-2. Pre-launch Predictions for Bonaire

				MAXIMUM USABLE FREQUENCIES							EFFECT AT GIVEN HOLE WIDTH		
TX LAT	TX LONG	RX LAT	RX LONG	0400	0600	0800	1000	1200	HOPS	LAYER	2 DEG	5 DEG	10 DEG
12.25N	68.45W	50.00N	60.00W	16.8	15.5	13.5	16.3	25.2	2	F2	NO	YES	YES
12.25N	68.45W	50.00N	70.00W	16.4	15.1	13.2	14.8	23.9	2	F2	NO	NO	YES
12.25N	68.45W	50.00N	80.00W	16.2	15.0	13.3	13.8	22.7	2	F2	NO	NO	YES
12.25N	68.45W	50.00N	90.00W	16.3	15.1	13.6	13.2	21.3	2	F2	NO	NO	YES
12.25N	68.45W	50.00N	100.00W	16.6	15.5	14.1	13.0	19.7	2	F2	NO	NO	YES
12.25N	68.45W	50.00N	110.00W	17.3	16.0	14.6	13.1	17.9	2	F2	NO	NO	YES
12.25N	68.45W	50.00N	120.00W	18.4	16.5	14.9	13.5	16.3	2	F2	NO	NO	YES
12.25N	68.45W	45.00N	60.00W	23.0	21.2	18.4	22.0	24.2	1	F2	NO	YES	YES
12.25N	68.45W	45.00N	70.00W	22.3	20.6	18.0	20.0	22.7	1	F2	YES	YES	YES
12.25N	68.45W	45.00N	80.00W	22.1	20.5	18.1	18.7	21.9	1	F2	YES	YES	YES
12.25N	68.45W	45.00N	90.00W	16.0	14.9	13.4	13.0	21.3	2	F2	NO	NO	NO
12.25N	68.45W	45.00N	100.00W	16.4	15.4	14.2	13.0	20.0	2	F2	NO	NO	YES
12.25N	68.45W	45.00N	110.00W	17.2	16.2	15.0	13.5	18.4	2	F2	NO	NO	YES
12.25N	68.45W	40.00N	70.00W	21.6	19.8	17.1	19.0	31.1	1	F2	NO	YES	YES
12.25N	68.45W	40.00N	80.00W	21.5	19.9	17.5	18.0	29.9	1	F2	NO	NO	YES
12.25N	68.45W	40.00N	90.00W	22.0	20.4	18.4	17.6	20.5	1	F2	NO	YES	YES
12.25N	68.45W	40.00N	100.00W	16.3	15.4	14.1	12.9	20.0	2	F2	NO	NO	NO
12.25N	68.45W	40.00N	110.00W	17.3	16.5	15.3	13.7	18.6	2	F2	NO	NO	NO
12.25N	68.45W	35.00N	70.00W	20.2	18.4	15.6	17.3	28.6	1	F2	NO	NO	YES
12.25N	68.45W	35.00N	80.00W	20.6	18.8	16.4	16.7	28.0	1	F2	NO	NO	NO
12.25N	68.45W	35.00N	90.00W	21.8	20.1	17.9	16.9	28.0	1	F2	NO	NO	YES
12.25N	68.45W	35.00N	100.00W	16.3	15.3	14.0	12.5	19.7	2	F2	NO	NO	NO

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The burning of an Atlas-Centaur rocket in the ionospheric F-region was used to determine the extent of HF propagation anomalies associated with the resultant drop in total electron content. This "ionospheric hole" grew to encompass the control points of many Caribbean to North American high frequency (HF) paths soon after the 0528 GMT launch from Kennedy Space Center, Cap Canaveral, Florida (28.40°N, 80.60°W) on September 20, 1979. Short-wave listeners, who collectively monitored 86 paths after launch, volunteered signal strength and fade quality data concerning special broadcasts on 15295 kHz from Bonaire (12.25°N, 68.45°W) and on 17815 kHz from Antigua (17.15°N, 61.82°W). Although these frequencies were closer to the predicted maximum usable frequency (MUF) than what were normally used, the expected blackout of radio circuits did not occur; in fact, computer analysis revealed that the large number of minor fadeouts that followed the launch were not related to the location of the control points. The burning thus appeared to have negligible effect on HF signals that crossed the rocket path.

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