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A SEARCH OF ARCHIVED DATA SOURCES FOR ROCKET EXHAUST-INDUCED MODIFICATIONS OF THE IONOSPHERE

by

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I. AN ATMOSPHERIC ASSESSEMENT STUDY

I.1. Introduction

The emergence of the Satellite Power System (SPS) concept (Glaser, 1968, 1980) as a way of augmenting the dwindling energy sources available for commercial power useage involved such a large and unprecendented technological program that detailed "assessment" and "feasibility" studies were undertaken in an attempt to specify the true impact such a program would have (Koomanoff and Sandahl, 1980). As part of the issues addressed, a comprehensive environmental impact study was initiated that involved an unprecedented scope of concerns ranging from ground-level noise and weather modifications to possible planetary-scale perturbations caused by SPS activity in distant Earth orbits (Rote, 1980). This report describes results of a study of an intermediate region of the Earth's environment (the ionosphere) where large-scale perturbations are caused by routine rocket activity. The SPS program calls for vast transportation demands into and out from the ionosphere (h≈200 to 1000 km), and thus the well-known effect of chemical depletions of the ionosphere (so-called "ionospheric holes") caused by rocket exhaust (Mendillo, 1980) signaled a concern over the possible large-scale and long-term consequences of the induced effects.

It should be stressed that many of the environmental issues involved in the SPS assessments deal with well known processes. For the "ionospheric hole" effect, in particular, most of the topics examined were related to the unprecedented scale of the potential effects, rather than to new physical or chemical processes uniquely associated with the SPS design.

I.2. Background.

Concerns about possible "unknown" effects endangering the earth's environment as a result of the expanding U.S. space program in the early sixties subsided towards the middle of the decade with the publication of a reassuring review by Kellogg (1964). Such fears were further reduced by the failure to observe any dramatic impact on the lower atmosphere and the ionosphere following tests of large (Saturn) rockets. Until recently, the literature contained only a handful of accounts dealing with rocket-induced atmospheric/ionospheric perturbations (see Table 1). Most of the early reports represented seemingly inadvertent or semi-routine observations using existing ionosonde stations located in the general vicinity of NASA launch sites. Two later developments helped rekindle interest in the subject. One was the description by Mendillo et al. (1975a, b), using data gathered on the large-scale ionospheric hole created by the Saturn-V rocket that launched Skylab, of the chemical basis of the plasma depletion process. The other was the growing interest in programs calling for active plasma experiments in the near-earth environment using Space Shuttle capabilities. The renewed activity in this field includes theoretical investigations (e.g., Bernhardt, 1976; Anderson and Bernhardt, 1978; Mendillo and Forbes, 1978), active experiments (Pongratz and Smith, 1978), and so-called "experiments of opportunity" using temporary observing networks to monitor pre-shuttle satellite launch effects (Mendillo et al., 1979; Mendillo et al., 1980).

Early in the SPS atmospheric assessment formulation, it became clear that in addition to theoretical and experimental initiatives specifically connected with SPS concerns, a parallel effort to uncover "retro-active" experiments-of-opportunity could be carried out using the vast archives of ionospheric data

TABLE 1

OBSERVATIONS OF IONOSPHERIC DISTURBANCES CAUSED BY ROCKET LAUNCHINGS.

Rocket	Date	Altitude of Engine Shut-off (km)	Effect	Observation Technique	Observer
Vanguard 2	1959	F-region	F-region depletion	Vertical sounding	Booker (1961)
Scout	1961	320	F-region depletion; E-region enhancement	Vertical sounding Faraday rotation	Jackson et al., (1962)
Atlas	1961	350	F-region depletion; E-region enhancement	Faraday rotation	Stone et al., (1964)
Saturn SA-9/ Pegasus	1965	500	F-region depletion; E-region enhancement	Vertical sounding	Felker & Roberts (1966)
Black Brant	1970	35	F-region depletion	Vertical sounding	Reinisch (1973)
Saturn 5 (Apollo 14)	1971	190	TID	Vertical sounding	Arendt (1971)
Saturn 5 (Apollo 15)	1971	190	TID	Vertical sounding	Arendt (1972)
Saturn 5	1973	442	Large-scale F-region depletion ('ionospheric hole')	TEC measurement	Mendillo et al., (1975)
Saturn I-b (Apollo-Soyuz)	1975	200	TID; E-region enhancement	Vertical sounding	Bakai et al., (1977)

collected at the World Data Centers and at individual observatories. The hope of such a tedious and time-consuming study was that the possibility existed of increasing significantly the number of known ionospheric hole events available for analysis. Thus, the aim of this report is to identify instances of plasma depletion effects found from archived data sources. The fact that the number of cases showing unambiguous rocket effects was very small allowed us to perform a preliminary analysis of a few events. The main emphasis of the report, however, is to document that the vast majority of past rocket launches had exhaust emissions that were too small or at inappropriate altitudes to provoke observable effects at the very limited network of geophysical observatories located in the vicinity of NASA launch sites.

I.3. Areas of Study.

In Section II, a summary is given of an extensive search of ionosonde records kept at the World Data Center A in Boulder. Section III deals with a smaller search of satellite beacon observations of the ionospheric total electron content from observatories capable of detecting effects from large rockets launched from the Kennedy Space Center. The general conclusions from the study are given in Section IV, followed by appropriate Acknowledgements (Section V) and References (Section VI).

II. USE OF WORLD DATA CENTER IONOSONDE RECORDS TO SEARCH FOR ROCKET-INDUCED PERTURBATIONS

II.1 Archived Ionograms and Past Rocket Launches

NASA has compiled a list of over 400 major rocket launches carried out by the agency between November 1958 and August 1978 (NASA, 1978). Table 2 provides a breakdown of these missions by launch sites, while Figure 1 gives a histogram showing the distribution by year. This NASA compilation of rocket activity formed the basis for combing the vast body of ionosonde records stored at the World Data Center A (Boulder, Colorado) in search of rocket-caused ionospheric changes. Most of the larger rockets contained in Figure 1 were launched from the Kennedy Space Center, Florida, and the ionospheric stations at Cape Kennedy and Grand Bahama Island were the primary sources of ionograms for these launchings. Table 3 lists the rocket launchings examined and brief comments on the associated ionograms. The notation N/E stands for the observation that no ionospheric effect attributable to the rocket was evident on the ionograms. The asterisk denotes the appearance of some feature on the ionogram that cannot be clearly identified as either an artificial or natural perturbation when compared to the same periods on the days before and after the launch. The other entries in Table 3 are:

(a) No test coverage--only routine coverage of the ionosphere (usually, one sounding every fifteen minutes) was available. "Test coverage" refers to a station being alerted to a pending launch so that rapid-run ionograms could be made.

(b) Poor records--quality of available ionograms so poor as to render them largely useless; may be due to sounder problems or poor photographics.

(c) Missing records--either ionograms for the whole day unavailable or

TABLE 2

TOTAL NUMBER OF NASA MAJOR ROCKET LAUNCHINGS FROM 1958 TO 1977.

Launch Site	Number of Launchings
KSFC	299
WI	38
WSMR	5
WTR	60

KSFC (Kennedy Space Flight Center, Florida)
WI (Wallops Island, Virginia)
WSMR (White Sands Missile Range, New Mexico)
WTR (Western Test Range, California)

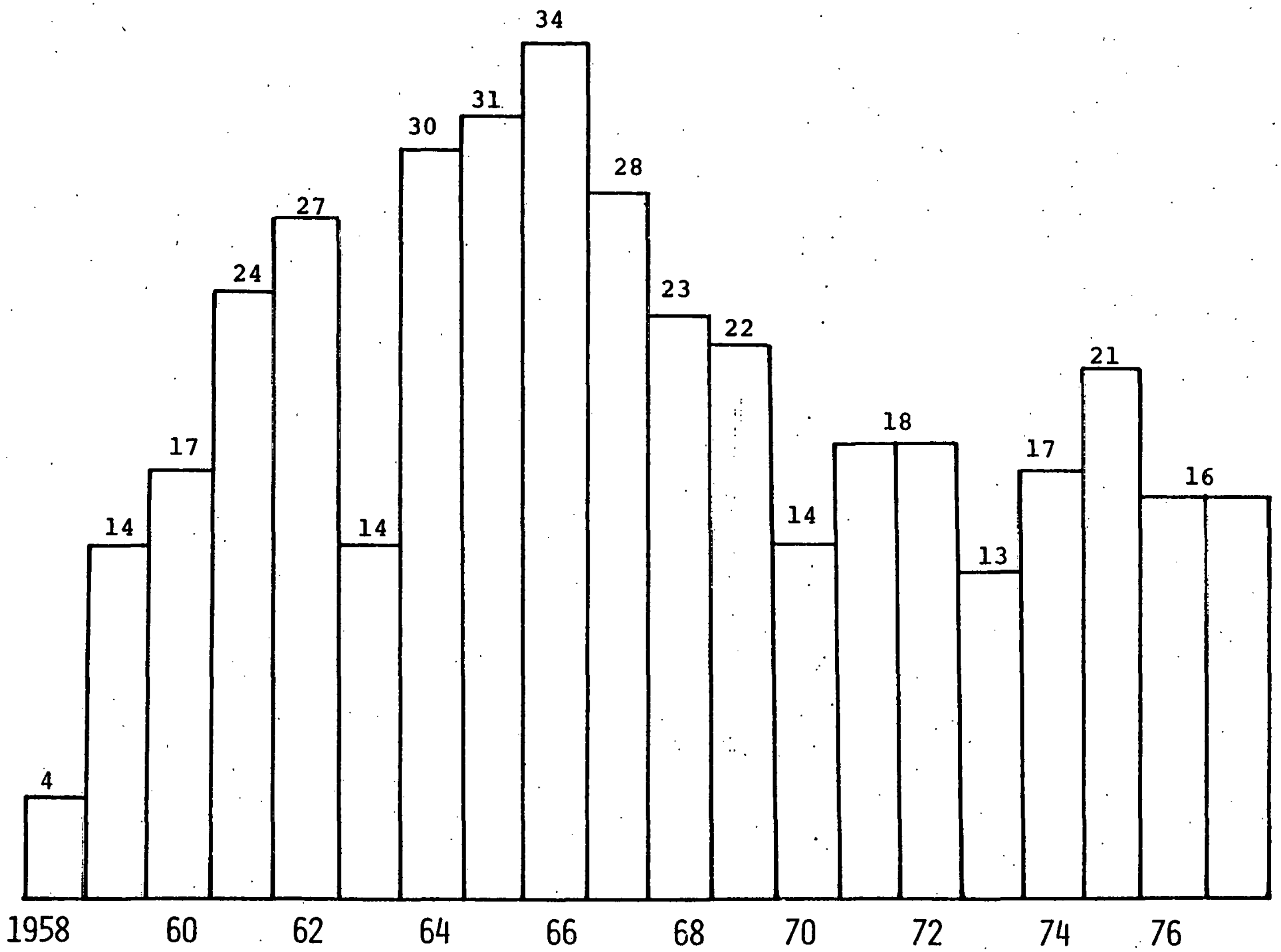


Figure 1. NASA major rocket launches from 1958 to 1977

Table 3.

A. STATION: POINT ARGUELLO

DATE	ROCKET	IONOGRAMS
25 Jan 64	THOR AGENA	No test coverage
28 Aug 64	THOR AGENA	No test coverage
10 Oct 64	SCOUT	Missing records
29 Nov 65	THOR AGENA	N/E
29 Nov 65	THOR AGENA	N/E
4 Feb 70	THOR AGENA	N/E
31 Mar 71	DELTA	N/E
21 Oct 71	DELTA	No test coverage
23 Jul 72	DELTA	No test coverage
6 Nov 73	DELTA	N/E
16 Jul 74	SCOUT	Poor records
30 Aug 74	SCOUT	No records
15 Nov 74	DELTA	No records
22 Jan 75	DELTA	Poor records
9 Apr 75	DELTA	No records
12 Jun 75	DELTA	No test coverage
8 Aug 75	DELTA	No test coverage
6 Oct 75	DELTA	No test coverage
12 Oct 75	SCOUT	No test coverage

B. STATION: WHITE SANDS

DATE	ROCKET	IONOGRAMS
28 Aug 63	Little Joe II	No records
13 May 64	Little Joe II	No test coverage
8 Dec 64	Little Joe II	No test coverage
19 May 65	Little Joe II	No test coverage
20 Jan 66	Little Joe II	No records

C. STATION: WALLOPS ISLAND

DATE	ROCKET	IONOGRAMS
27 Mar 64	SCOUT	N/E
20 Jul 64	SCOUT	N/E
18 Aug 64	SCOUT	No test coverage
6 Nov 64	SCOUT	No test coverage
15 Dec 64	SCOUT	No test coverage
29 Apr 65	SCOUT	No test coverage
8 Aug 65	NIKE - CAJUN	N/E
10 Aug 65	SCOUT	N/E
19 Nov 65	SCOUT	No test coverage
8 Jul 71	SCOUT	No test coverage
16 Aug 71	SCOUT	No test coverage
13 Aug 72	SCOUT	No test coverage
18 Jun 76	SCOUT	No test coverage

D. STATION: GRAND BAHAMA ISLAND

DATE	ROCKET	IONOGRAMS	
9 Sep 59	ATLAS	Poor records	
11 Mar 60	THOR ABLE	Poor records	
1 Apr 60	THOR ABLE	N/E	
25 Sep 60	ATLAS ABLE	N/E	
21 Feb 61	ATLAS	Poor records	
5 May 61	REDSTONE	N/E	
21 Jul 61	REDSTONE	Poor records	
23 Aug 61	ATLAS AGENA	Poor records	
27 Oct 61	SATURN	N/E	*
18 Nov 61	ATLAS AGENA	N/E	
29 Nov 61	ATLAS	N/E	
15 Jan 62	THOR	N/E	
29 Jan 62	ATLAS AGENA	N/E	
20 Feb 62	ATLAS	N/E	
7 Mar 62	THOR DELTA	N/E	
23 Apr 62	ATLAS AGENA	N/E	
25 Apr 62	SATURN	N/E	*
24 May 62	ATLAS	N/E	
18 Jul 62	THOR	Poor records	
22 Jul 62	ATLAS AGENA	Poor records	
27 Aug 62	ATLAS AGENA	N/E	
16 Nov 62	SATURN	N/E	

28 Mar 63	SATURN	N/E
15 May 63	ATLAS	N/E
27 Nov 63	DELTA	N/E
27 Nov 63	ATLAS CENTAUR	N/E
29 Jan 64	SATURN	N/E
30 Jan 64	ATLAS AGENA	N/E
8 Apr 64	TITAN	N/E
28 May 64	SATURN	N/E
30 Jun 64	ATLAS CENTAUR	N/E *
5 Sep 64	ATLAS AGENA	N/E
18 Sep 64	SATURN	N/E
28 Nov 64	ATLAS AGENA	foF2 changes from 3.7 to 3.0 following launch. *
19 Jan 65	TITAN II	N/E
22 Jan 65	DELTA	No test coverage
16 Feb 65	SATURN I	Ionograms show severe rocket-caused changes.
17 Feb 65	ATLAS AGENA	Some foF2 changes; rocket-caused or not remains to be determined.
21 Mar 65	ATLAS AGENA	N/E
23 Mar 65	TITAN II	N/E
22 May 65	ATLAS X259	N/E
25 May 65	SATURN I	Perturbed ionosphere, possibly rocket-caused effects.
29 May 65	DELTA	No test coverage
3 Jun 65	TITAN II	No test coverage
30 Jul 65	SATURN I	Perturbed F-region, possibly rocket-caused effects.
11 Aug 65	ATLAS CENTAUR	N/E

21 Aug 65	TITAN II	N/E	
25 Aug 65	ATLAS AGENA	N/E	
4 Dec 65	TITAN II	N/E	
15 Dec 65	TITAN II	N/E	
3 Feb 66	DELTA	N/E	
26 Feb 66	SATURN IB	N/E	
28 Feb 66	DELTA	N/E	
16 Mar 66	TITAN II	Missing records	
8 Apr 66	ATLAS CENTAUR	N/E	
8 Apr 66	ATLAS AGENA	N/E	
25 May 66	DELTA	N/E	*
30 May 66	ATLAS CENTAUR	N/E	*
1 Jun 66	ATLAS AGENA	N/E	*
3 Jun 66	TITAN II	N/E	*
7 Jun 66	ATLAS AGENA B	N/E	
24 Jun 66	THOR AGENA	Missing records	
1 Jul 66	THOR DELTA	N/E	
5 Jul 66	SATURN IB	N/E	*
18 Jul 66	TITAN II	N/E	
18 Jul 66	ATLAS AGENA	N/E	
25 Aug 66	SATURN IB	N/E	
12 Sep 66	TITAN II	N/E	
12 Sep 66	ATLAS AGENA	N/E	
20 Sep 66	ATLAS CENTAUR	N/E	
6 Nov 66	ATLAS AGENA	Missing records	
11 Nov 66	TITAN II	Missing records	
11 Nov 66	ATLAS AGENA	Missing records	

25 Aug 66	SATURN IB	N/E	
12 Sep 66	TITAN II	N/E	
12 Sep 66	ATLAS AGENA	N/E	
20 Sep 66	ATLAS CENTAUR	N/E	
6 Nov 66	ATLAS AGENA	Missing records	
11 Nov 66	TITAN II	Missing records	
11 Nov 66	ATLAS AGENA	Missing records	
7 Dec 66	ATLAS AGENA	N/E	
14 Dec 66	DELTA	N/E	*
11 Jan 67	THOR DELTA	N/E	
18 Jan 67	TITAN IIIC	N/E	*
4 Feb 67	ATLAS AGENA	N/E	
8 Mar 67	DELTA	N/E	
22 Mar 67	DELTA	N/E	
6 Apr 67	ATLAS AGENA	N/E	
17 Apr 67	ATLAS CENTAUR	N/E	
28 Apr 67	TITAN IIIC	N/E	
4 May 67	ATLAS AGENA	Missing records	
14 Jun 67	ATLAS AGENA	N/E	
1 Jul 67	TITAN IIIC	N/E	
14 Jul 67	ATLAS AGENA	N/E	
19 Jul 67	DELTA	N/E	
1 Aug 67	ATLAS AGENA	N/E	
7 Sep 67	DELTA	N/E	
8 Sep 67	ATLAS CENTAUR	N/E	
28 Sep 67	DELTA	N/E	
18 Oct 67	DELTA	Poor records	

5 Nov 67	ATLAS AGENA	Poor records	
7 Nov 67	ATLAS CENTAUR	N/E	*
9 Nov 67	SATURN V	Missing records	
13 Dec 67	DELTA	N/E	
7 Jan 68	ATLAS CENTAUR	Poor records	
22 Jan 68	SATURN IB	N/E	*
4 Mar 68	ATLAS AGENA D	N/E	
4 Apr 68	SATURN V	N/E	*
13 Jun 68	TITAN IIIC	N/E	
6 Aug 68	ATLAS AGENA	Poor records	
10 Aug 68	ATLAS CENTAUR	Poor records	
18 Sep 68		Poor records	
26 Sep 68		Poor records	
11 Oct 68	SATURN IB	Missing records	
8 Nov 68	DELTA	Poor records	
5 Dec 68	DELTA	Poor records	
7 Dec 68	ATLAS CENTAUR	Missing records	
18 Dec 68	DELTA	Poor records	
21 Dec 68	SATURN V	Poor records	
22 Jan 69	DELTA	N/E	*
5 Feb 69	DELTA	Missing records	
9 Feb 69	TITAN IIIC	Poor records	
25 Feb 69	ATLAS CENTAUR	Poor records	
26 Feb 69	DELTA	Poor records	
3 Mar 69	SATURN V	N/E	*
27 Mar 69	ATLAS CENTAUR	Poor records	
13 Apr 69	ATLAS AGENA	Missing records	

18 May 69	SATURN V	Poor records	
22 May 69	THOR DELTA	Poor records	
23 May 69	TITAN IIIC	Poor records	
29 Jun 69	DELTA	Poor records	
16 Jul 69	SATURN V	N/E	
26 Jul 69	THOR DELTA	Missing records	
9 Aug 69	DELTA	Poor records	
12 Aug 69	ATLAS CENTAUR	N/E	*
27 Aug 69	DELTA	Poor records	
14 Nov 69	SATURN V	Missing records	
22 Nov 69	DELTA	Missing records	
14 Jan 70	DELTA	Missing records	
20 Mar 70	DELTA	Poor records	
8 Apr 70	THOR AGENA	N/E	
11 Apr 70	SATURN V	N/E	*
22 Apr 70	DELTA	N/E	
19 Jun 70	THOR DELTA	Missing records	
23 Jul 70	DELTA	N/E	
19 Aug 70	DELTA	N/E	
1 Sep 70	ATLAS AGENA	N/E	
6 Nov 70	TITAN IIIC	N/E	
30 Nov 70	ATLAS CENTAUR	N/E	
25 Jan 71	ATLAS CENTAUR	N/E	
31 Jan 71	SATURN V	N/E	
3 Feb 71	THOR DELTA	Missing records	
13 Mar 71	DELTA	Missing records	
5 May 71	TITAN IIIC	N/E	
8 May 71	ATLAS CENTAUR	Missing records	
30 May 71	ATLAS CENTAUR	Missing records	

a series of ionograms missing from an otherwise continuous set of records for the day.

The following further comments about the search summarized in Table 3 are needed to keep the conclusions of the study in perspective:

(d) All the sounding stations except Cuba were operated by or on behalf of the U.S. Air Force and in most instances the stations were notified prior to rocket launchings. This enabled the stations to switch to the rapid-run mode: two soundings per minute in contrast to the normal rate of one sounding every fifteen minutes. Usually the operation in the rapid-run mode started a few minutes before lift-off and continued for at least one hour after lift-off, generating more than 120 ionograms per station during this period alone. Due to the sheer volume of data thus collected and to the wealth of detail normally available on each ionogram, it became necessary to restrict the search to those launchings that were judged to be most likely to cause ionospheric changes large enough to be readily seen on ionograms. In the absence of knowledge about the trajectory and exhaust characteristics of the individual rockets, size alone was used as the criterion for this selection.

(c) With the closing of the Grand Bahama Island Station in July, 1971, the last ionosonde capable of readily monitoring Cape Kennedy launchings disappeared, leaving all later tests without any sounder coverage. Note also that owing to the relatively small number of tests involved in the White Sands, Wallops Island and Western Test range cases, all available launch-related ionograms were searched.

(f) The availability of rapid-run coverage is essential for identifying rocket-caused changes seen on ionograms unless the ionospheric disturbances happen to be so massive as to appear unambiguously on 15-minute records. In most instances rapid-run coverage of the rocket launches were available. Still, the identification of the changes seen on the ionograms as rocket-caused is a difficult task given the normal variability and complexity of ionograms. Changes in the critical frequency of the F2-layer are the most obvious effects and it was on these that we concentrated during the screening of the records.

(g) When a rocket-caused effect was tentatively identified on Cape Kennedy or Grand Bahama Island ionograms, available records from San Salvador, Cuba, Jamaica and Wallops Island were also examined to establish the extent and temporal behavior of the event. Figure 2 shows the network of vertical soundings stations thus utilized to monitor rocket launchings from the Kennedy Space Center.

(h) It now becomes clear that the few rocket-related ionospheric effects documented in the literature were not the result of inadvertent discoveries but rather of anticipated observations because of USAF ionosondes located in the vicinity of the four test ranges being alerted prior to rocket launchings; in the vast majority of instances the ionosphere was thus actively monitored during and following tests (e.g. Felker and Roberts, 1966).

Table 3 lists 193 rocket tests. No ionospheric changes attributable in an obvious manner to rocket launchings were found at the Western Test Range (Point Arguello/Vandenberg ionosonde), Wallops Island or White Sands. Three events have been identified on the Grand Bahama Island/Cape Kennedy records as involving rocket-caused ionospheric changes. One of these (February 16, 1965), which has received limited attention previously, might have affected a wider region of the ionosphere than previously thought. Records at Cuba and Jamaica show some weak changes which could have been the result of the plasma depletion process spreading to the vicinity of those stations.

The statistical message of Table 3 is that significant alterations in

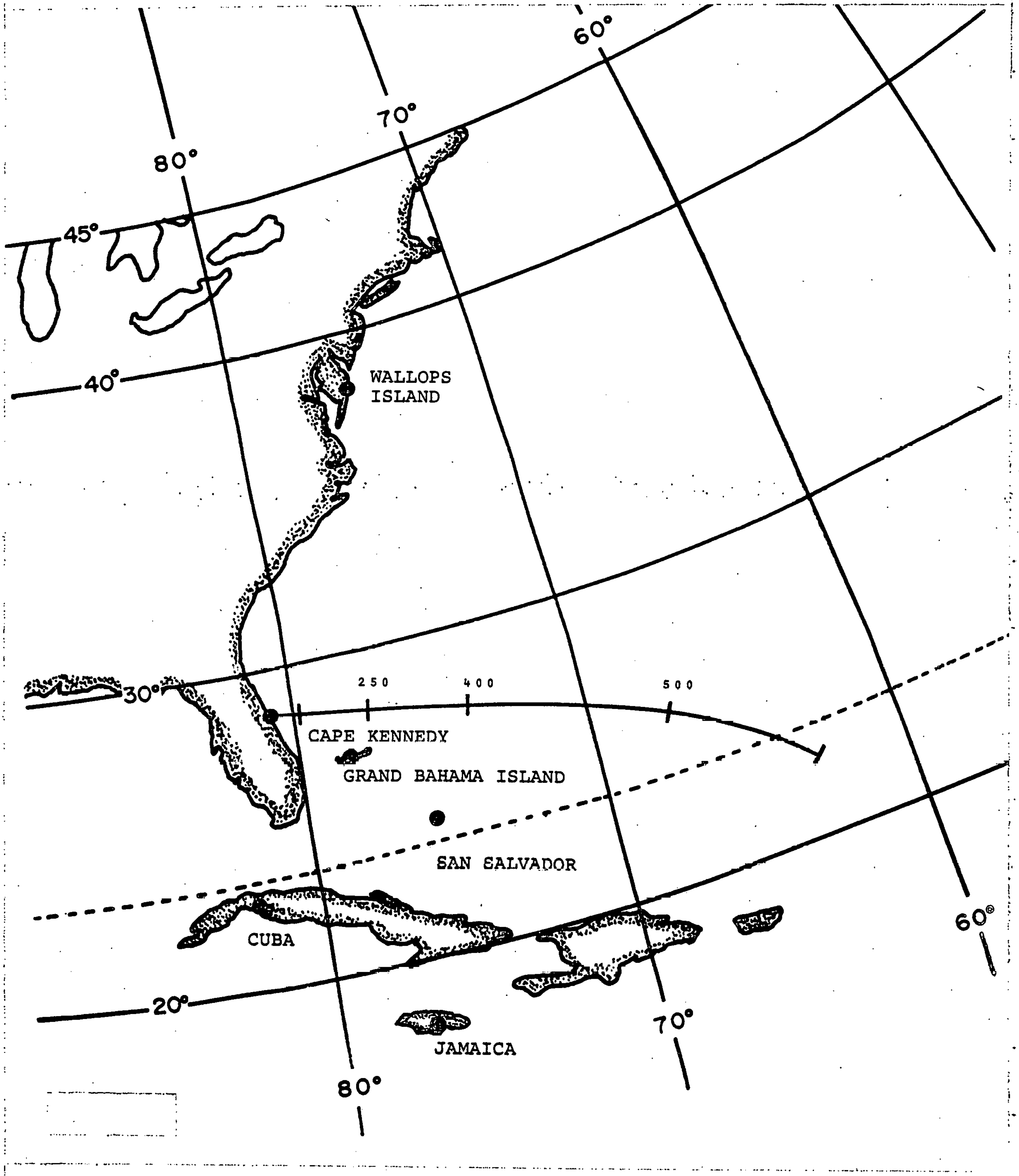


Figure 2. Ground track for Pegasus I launch (with times from lift-off given in seconds). Ionosonde stations operating at that time are also indicated.

the ambient conditions of the ionosphere resulting from previous rocket launchings have been very infrequent. In the case of rocket tests conducted at Cape Kennedy before May 1971, the frequency of probable ionospheric modifications has been about one in thirty-three.

The Pegasus Series

The Pegasus series consisted of three rocket tests carried out from Cape Kennedy in 1965. The booster rockets were powered by Saturn-I engines and the second stage cut off occurred, typically, at 500 km altitude. Figure 2 shows the trajectory of the February 16, 1965, launch and the locations of ionosonde stations used to examine this and all other Cape Kennedy rocket launchings for rocket-caused ionospheric modifications. The two later Pegasus tests (May 25, 1965, and July 30, 1965) also had comparable trajectories and other flight characteristics. The distinguishing feature of the Pegasus series is that in all three instances the large Saturn-I engines (1,500,000 pounds of thrust) deposited vast quantities of rocket effluents at F-region altitudes up to 500 km.

Pegasus-I

The launch occurred at 0937 EST on February 16, 1965, and the trajectory is sketched in Figure 2. The flight profile is shown in Figure 3. Felker and Roberts (1966) described an "ionospheric rarefaction" following the launch test. Figure 4a shows the behavior of the critical frequency (foF2) at Cape Kennedy (28^{o}N, 279^{o}E) from 0900 EST to 1300 EST on February 15 (dashed curve) and February 16 (solid curve). There were no rocket tests at Cape Kennedy on February 15 and the dashed curve may be taken to represent the undisturbed ionosphere at Cape Kennedy during the time period indicated. On February 16, between 0930 and 1020 EST, the critical frequency suffers a decline of 2.6 MHz. It is clear that

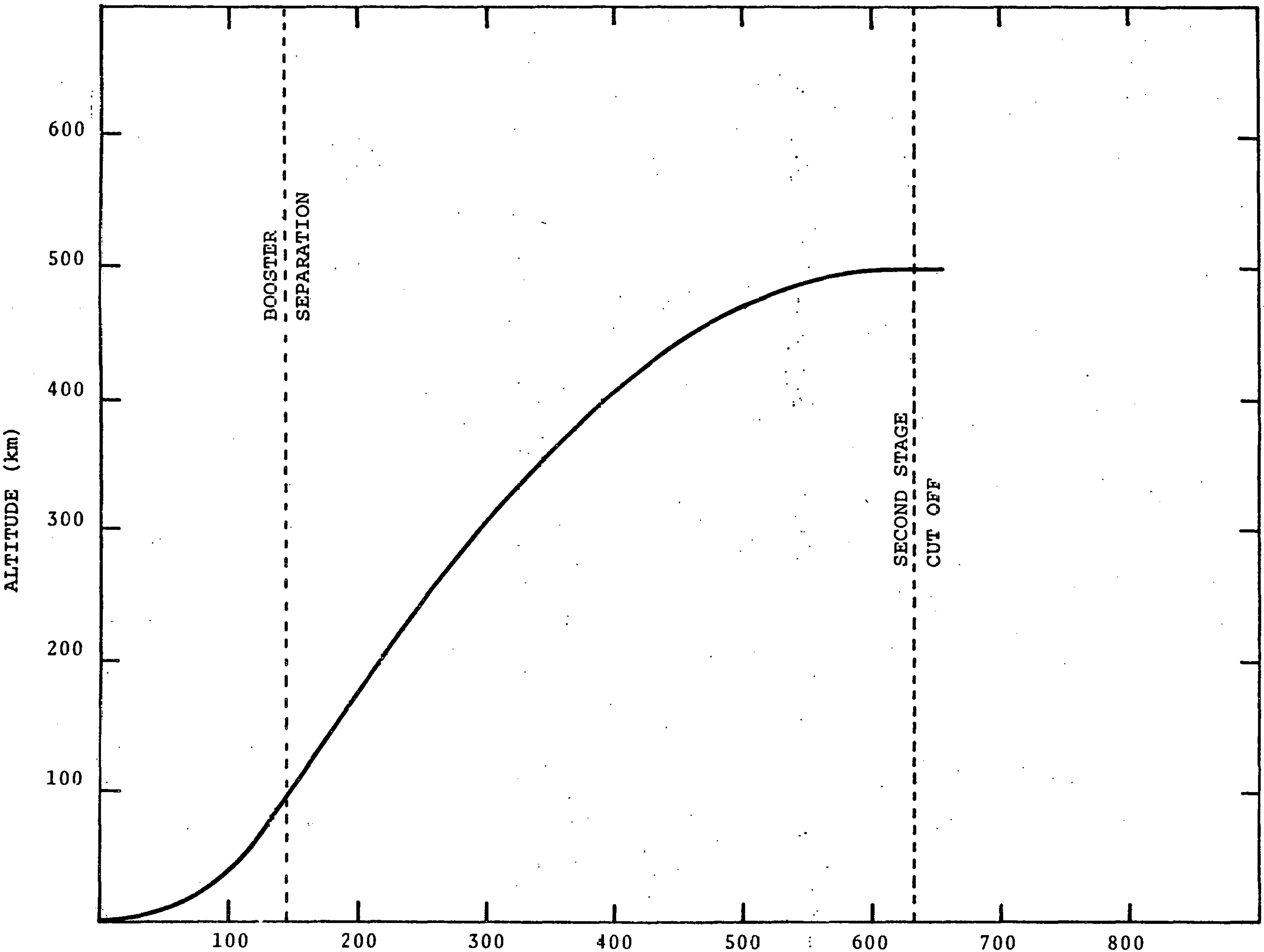


Figure 3. Flight profile of Pegasus I

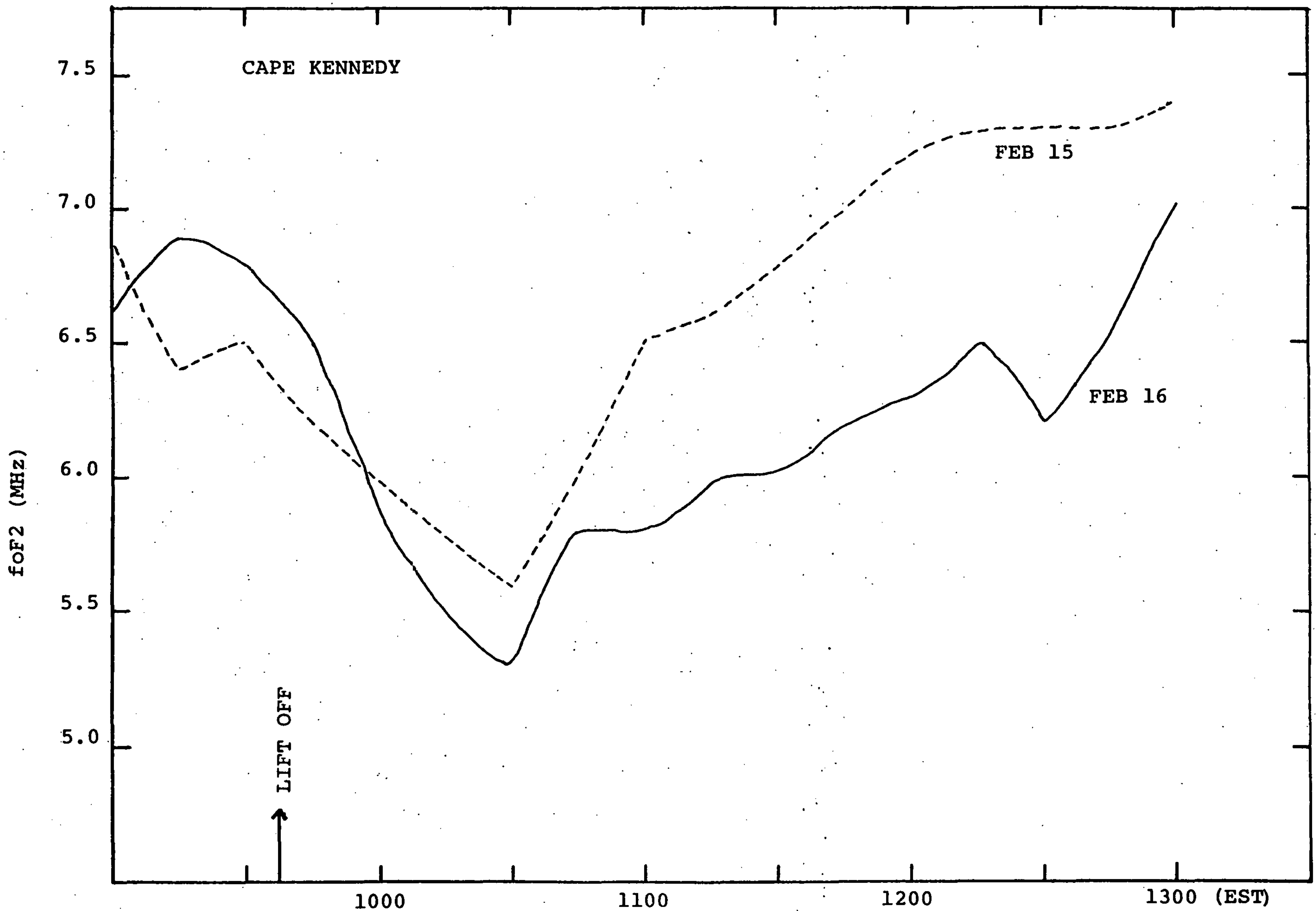


Figure 4a. Pegasus I. Critical frequencies scaled from ionograms recorded at Cape Kennedy vertical sounding station on February 15 and 16, 1965.

all of this decline cannot be attributed to the passage of the rocket (as Felker and Roberts did in their preliminary report in 1966) for the February 15 curve also shows significant erosion of the F2 peak until 1030 EST. It is, however, also clear that at least part of the foF2 decline on February 16 is rocket-induced: the decline starts between 0930 and 0945 EST and it is sharper and somewhat deeper. The strongest support for this conclusion comes from the similarity the Cape Kennedy curve bears to the Grand Bahama Island and San Salvador curves (see Figures 4b and 4c) which show rocket effects more dramatically.

Figure 4b shows, in the same format as Figure 4a, the behavior of the critical frequency monitored at the vertical sounding station Grand Bahama Island (27°N, 282°E) on February 15 and February 16. The undisturbed ionosphere over Grand Bahama Island is virtually indistinguishable from that over Cape Kennedy. The February 16 curve in Figure 4b, however, shows vastly altered conditions. The small decline in foF2 that appears to start at 0915 EST should be viewed as part of the normal fluctuations seen on ionograms representing the undisturbed ionosphere. The precipitous drop in foF2 from 6.8 MHz at 0945 EST to 4.4 MHz at 1015 EST is attributed to the passage of the rocket. Note that although the recovery rates on both days are roughly comparable, the February 16 critical frequencies remain below the previous day's values until at least 1300 EST, in spite of the fact that during the pre-launch period foF2 remains generally above the February 15 levels.

Figure 4c shows the variation of the F2 peak over San Salvador (24°N, 284°E) on February 15 and February 16 in the same format as the previous two figures. Of the three stations examined, the records from San Salvador show the most drastic decrease of F-region plasma frequency, from 7.4 MHz at 0945 EST to 4.4 MHz at 1015 EST. This is consistent with the exhaust deposition profile shown in Figures 2 and 3 in that the plume at 400 seconds occurs near 400 km,

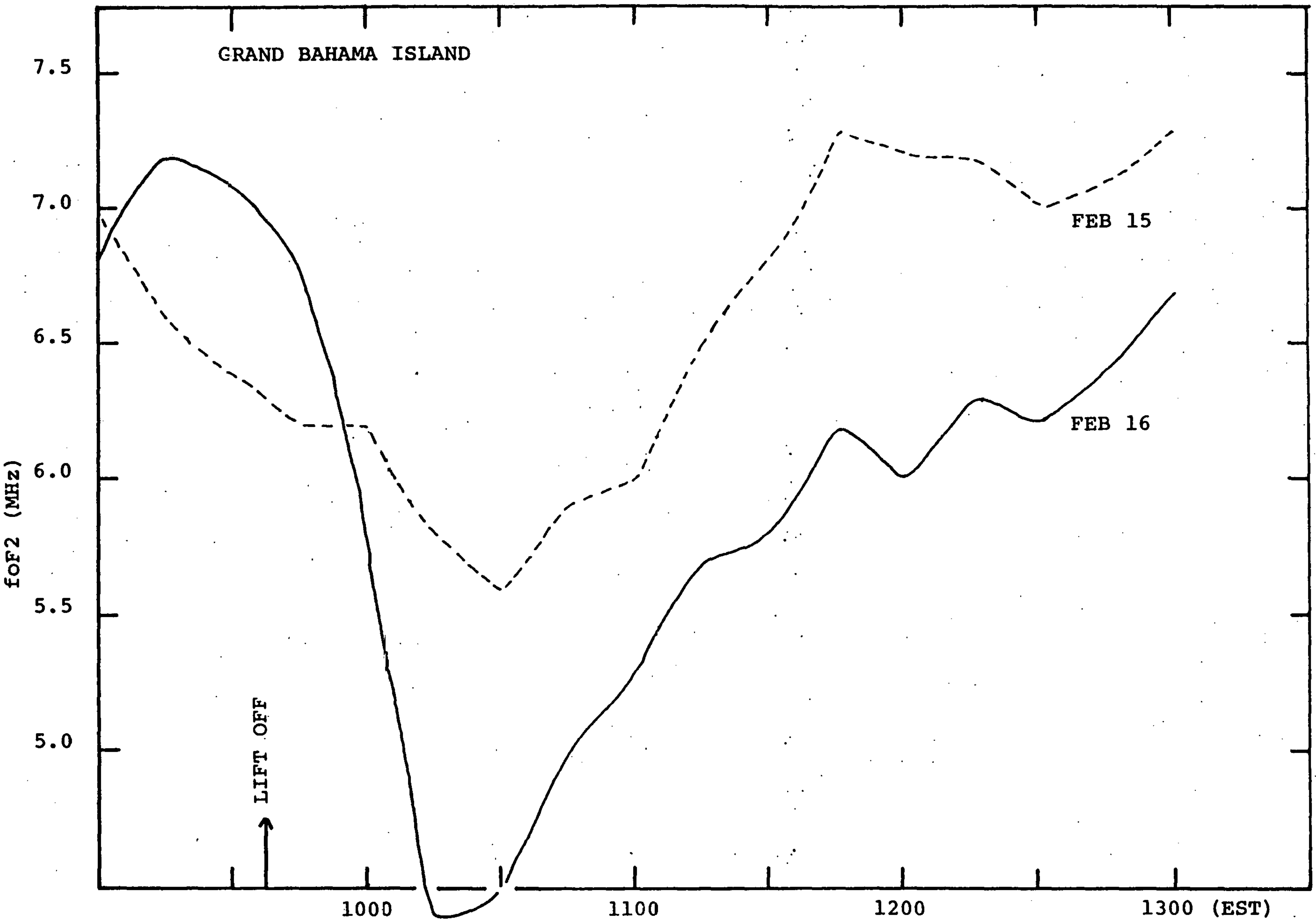


Figure 4b. Pegasus I. Critical frequencies scaled from ionograms recorded at the Grand Bahama Island vertical sounding station on February 15 and 16, 1965.

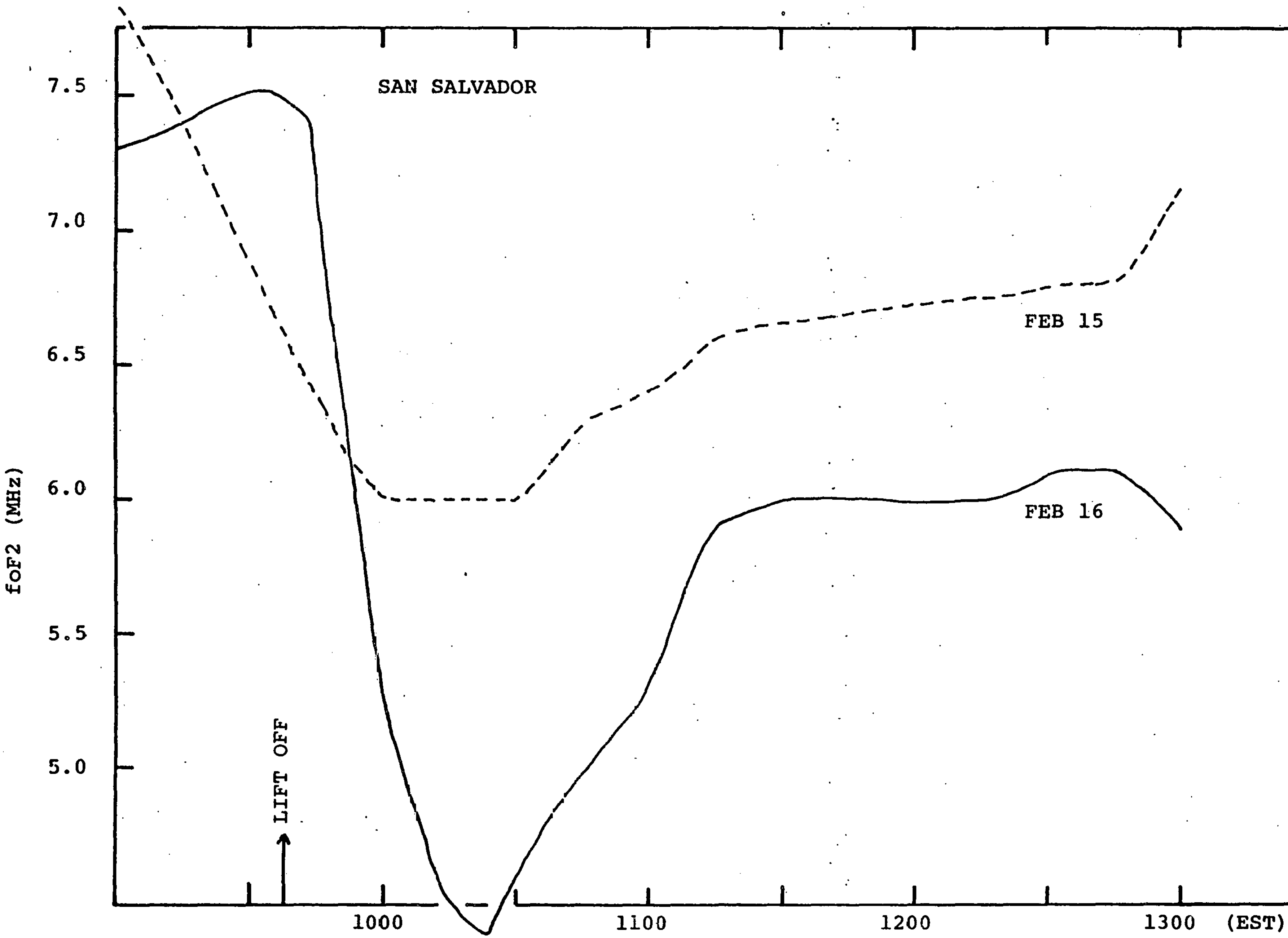


Figure 4c. Pegasus I. Critical frequencies scaled from ionograms recorded at the San Salvador vertical sounding station on February 15 and 16, 1965.

due north of San Salvador. Recovery of ionization appears to follow the rate of growth seen on February 15, indicating that it is solar production which controls the re-filling of the hole. Indeed, much the same trend is seen at Grand Bahama Island and Cape Kennedy also.

Felker and Roberts (1966) do not consider the natural lowering of critical frequency seen to occur at the three stations before 1030 EST. Hence their calculation of the intensity of the plasma depletion attributable to the rocket transit (e.g., from 7.0 x 10^5 el/cm^3 to 2.3 x 10^5 el/cm^3 at San Salvador) involves an over-estimate. Table 4 lists the depletion found at the three sites as a percentage of the pre-launch value after allowing for the anticipated decrease in foF2 given by the control curve.

TABLE 4: Changes in the Peak Density of the F-Region Derived from foF2 Observations During the Pegasus I Launch.

STATION	Nmax (%) DEPLETION
San Salvador	49
Grand Bahama Island	41
Cape Kennedy	10

There are some indications that the spreading exhaust cloud could have affected sites beyond the three stations considered above. Figure 4d shows the Cuba observations. An ionospheric hole of the type found in the records of Cape Kennedy, Grand Bahama Island and San Salvador clearly did not develop over Cuba. The increasing divergence between the two curves after 1130 EST is an interesting point to consider. Effects with such a long time delay have not been seen in F-region hole behavior. Computer simulation studies, as recently carried out by Zinn et al. (1980) for the Skylab effect, might be able to examine if such plume transport effects are possible.

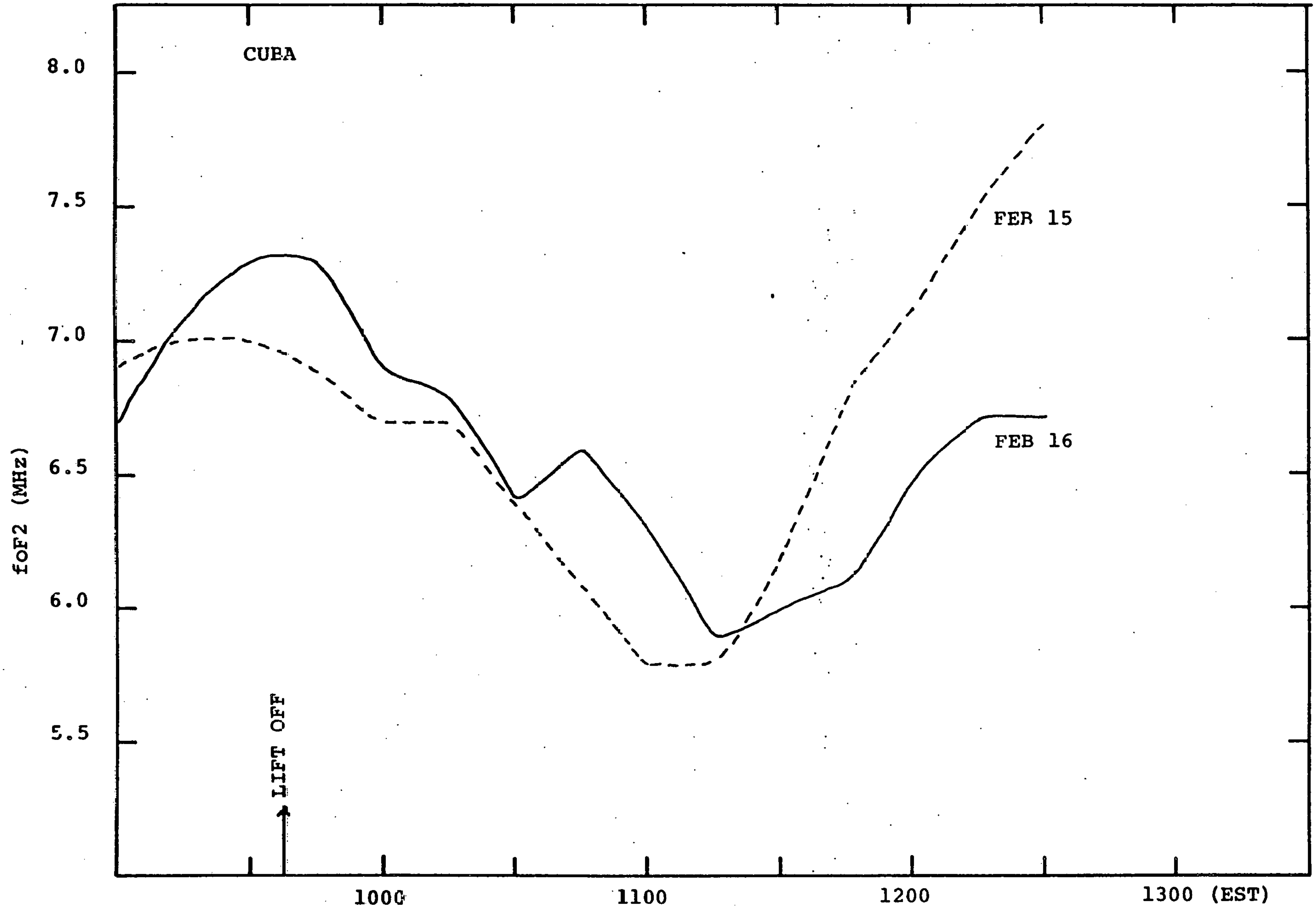


Figure 4d. Pegasus I. Critical frequencies scaled from ionograms recorded at the Cuba vertical sounding station on February 15 and 16, 1965.

A significant lowering of the virtual height of the peak is observed at San Salvador and Grand Bahama Island following the rocket launching (Figures 4e and 4f). The control day for the comparision of virtual heights is taken to be February 17 because the available ionograms for the 15th were not readily scalable for virtual heights. Figures 4e and 4f are remarkably similar in shape. The abrupt decline in virtual height might have started at San Salvador a few minutes earlier. The recovery at San Salvador takes place about twenty minutes earlier than at Grand Bahama Island. The decline of foF2 with simultaneous lowering of h'F2 seen at these two stations shows that the plasma hole develops as a result of the top of the F-region being depleted by the rocket's exhaust molecules. Figure 4g shows the virtual height variation at Cape Kennedy until 1035 EST on February 16. (Records for the subsequent period are not scalable for h'F2). There is no lowering of virtual height seen in Figure 4g. It is likely that the relatively mild peak density loss (10%) seen at Cape Kennedy did not proceed via a preferential erosion of the top-side because, as may be inferred from Figures 2 and 3, Cape Kennedy received the bulk of its share of rocket effluents at or below the F2 peak.

<u>Pegasus II and Pegasus III</u>

Pegasus II was launched from Cape Kennedy at 0235 EST on May 25, 1965. The San Salvador vertical sounding station had gone out of operation by this time. Records from Cape Kennedy and Grand Bahama Island are, however, available and they show substantial peak density erosion (Figures 5a and 5b). The percentage depletions of the electron density at the F2 peak, computed according to the previous scheme, are shown in Table 5.

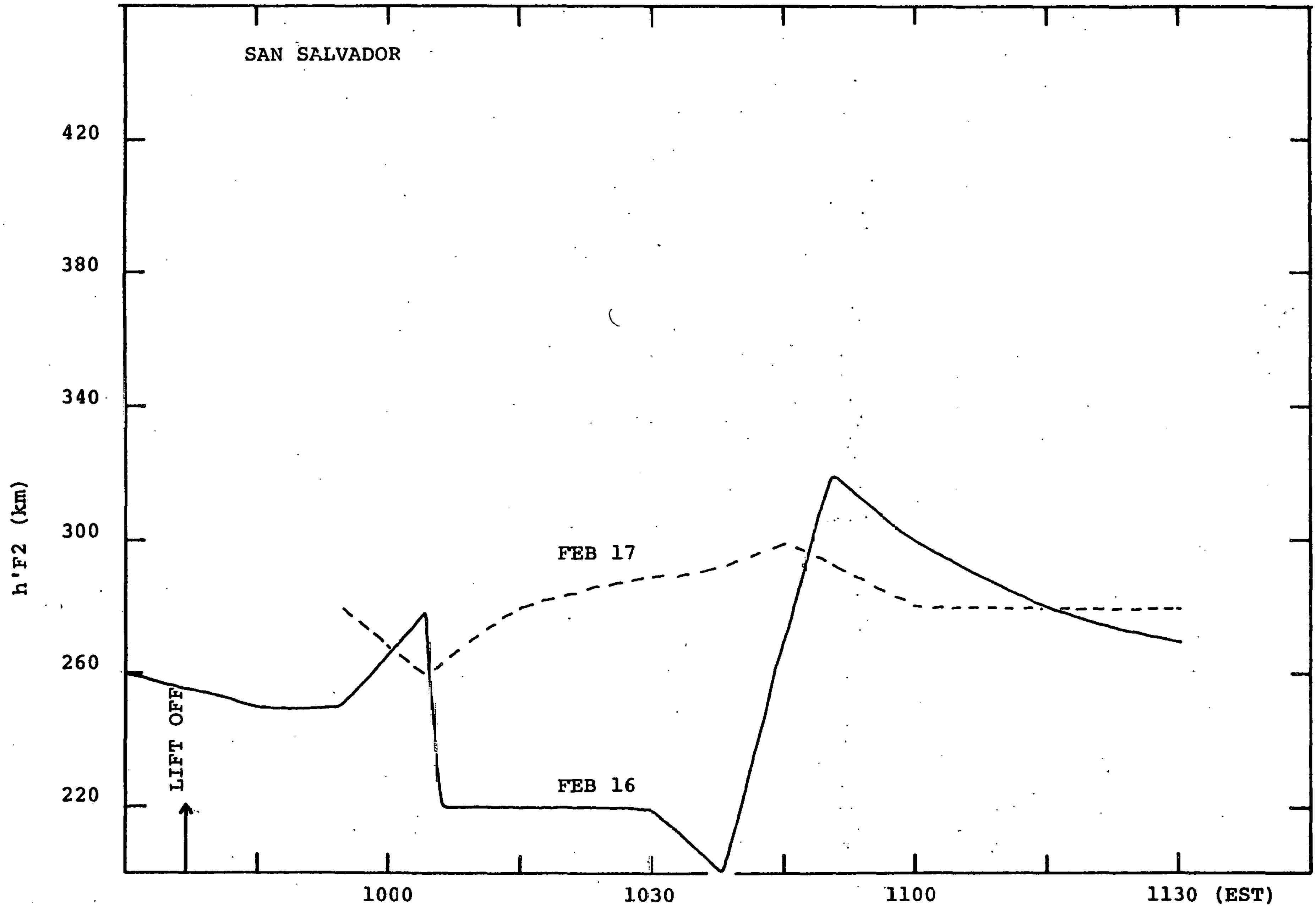


Figure 4e. Pegasus I. Virtual heights scaled from ionograms recorded at the San Salvador vertical sounding station on February 16 and 17, 1965.

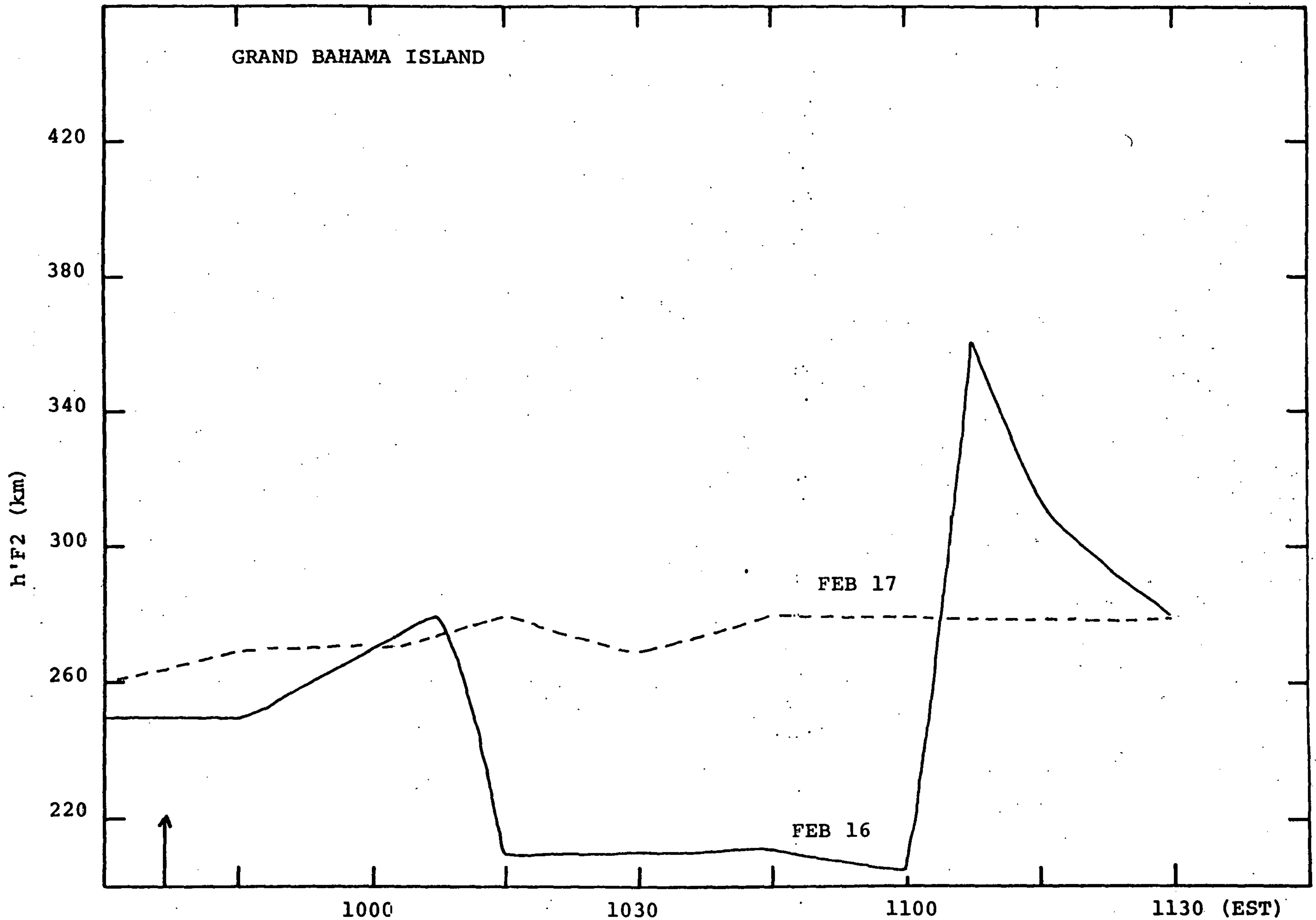


Figure 4f. Pegasus I. Virtual heights scaled from ionograms recorded at the Grand Bahama Island vertical sounding station on February 16 and 17, 1965.

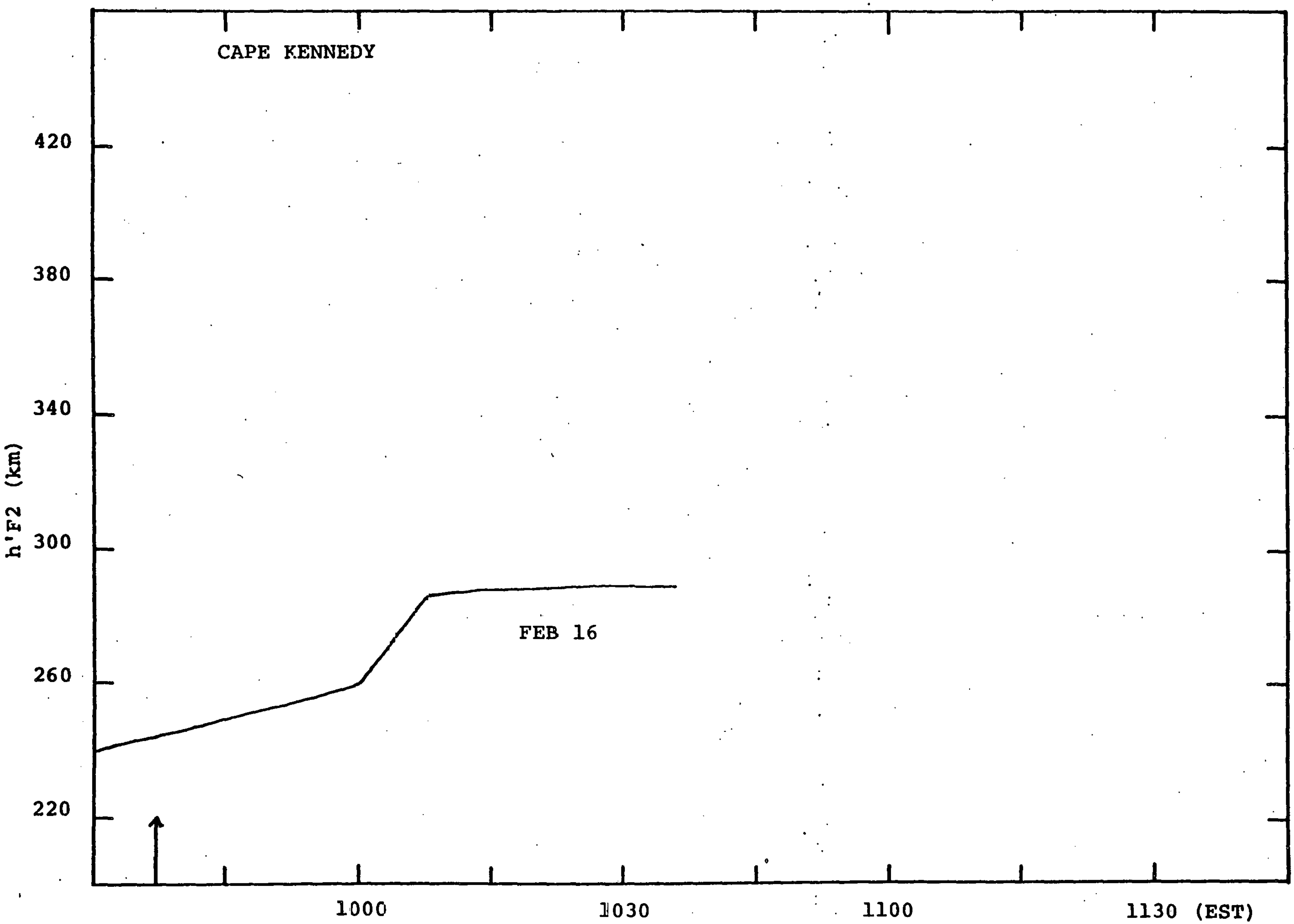


Figure 4g. Pegasus I. Virtual heights scaled from ionograms recorded at the Cape Kennedy vertical sounding station on February 16, 1965.

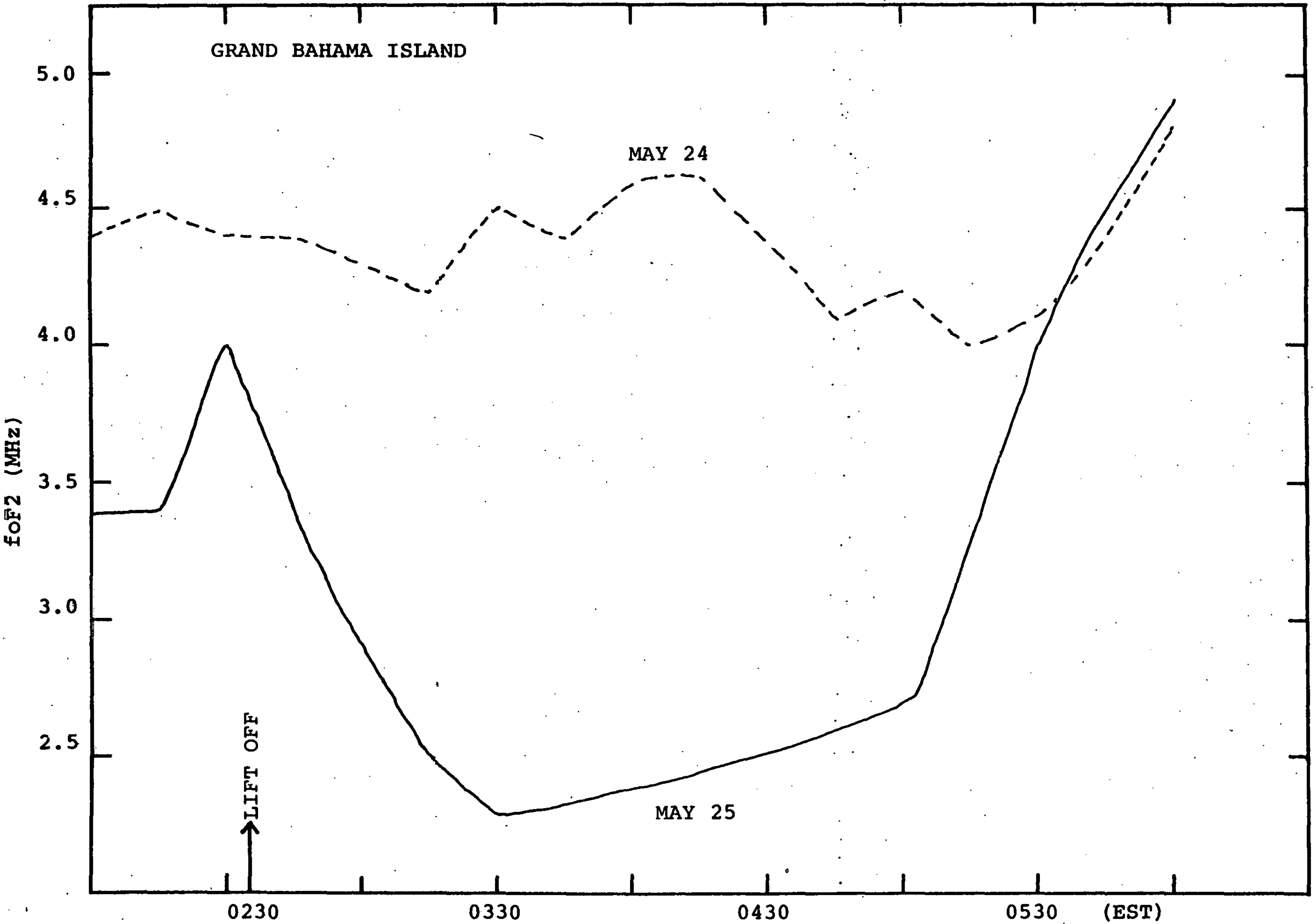
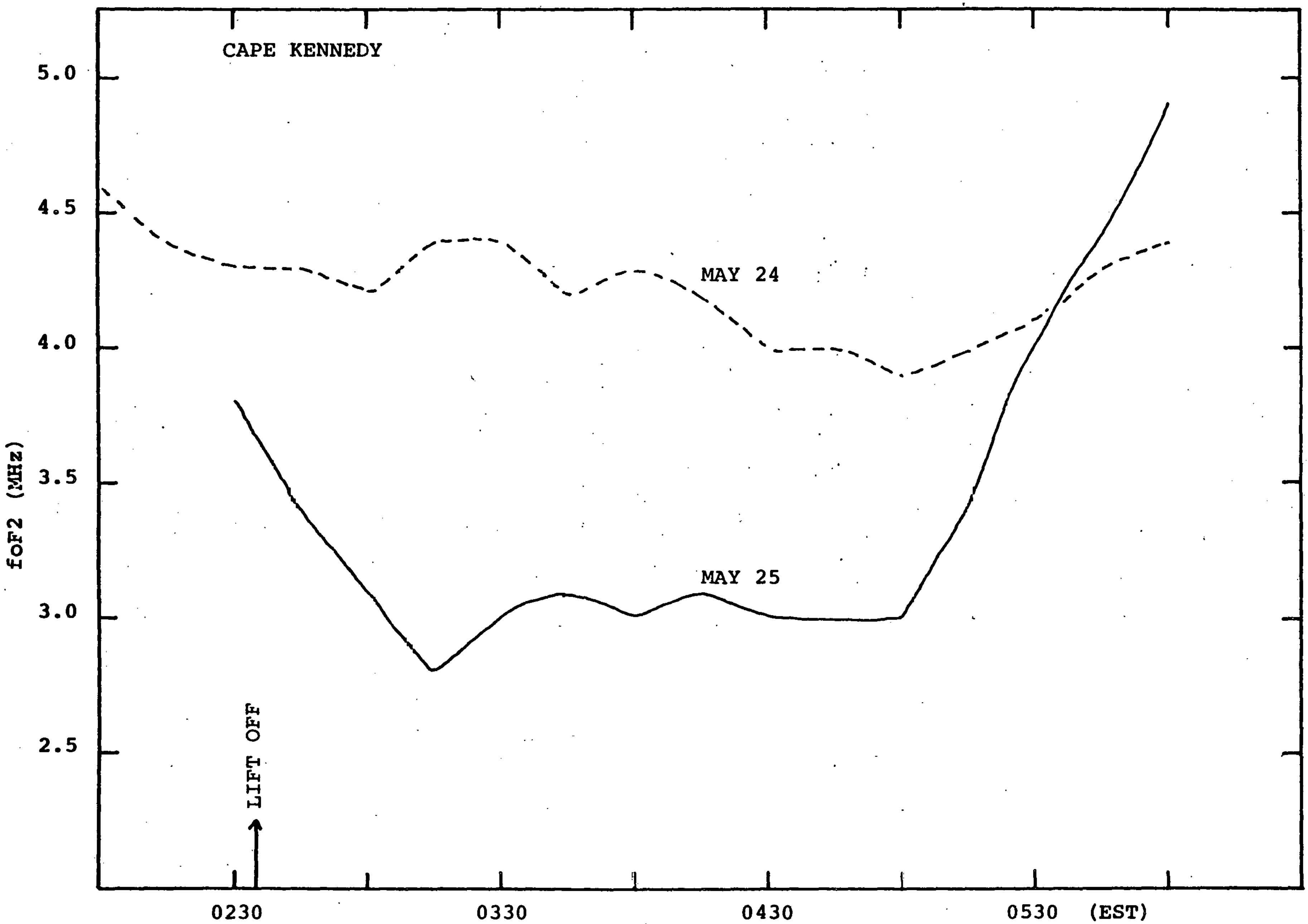


Figure 5a. Pegasus II. Critical frequencies scaled from ionograms recorded at the Grand Bahama Island vertical sounding station on May 24 and 25, 1965.



Pegasus II. Critical frequencies scaled from ionograms recorded at the Cape Kennedy vertical sounding station on May 24 and 25, 1965.

(Figur b)

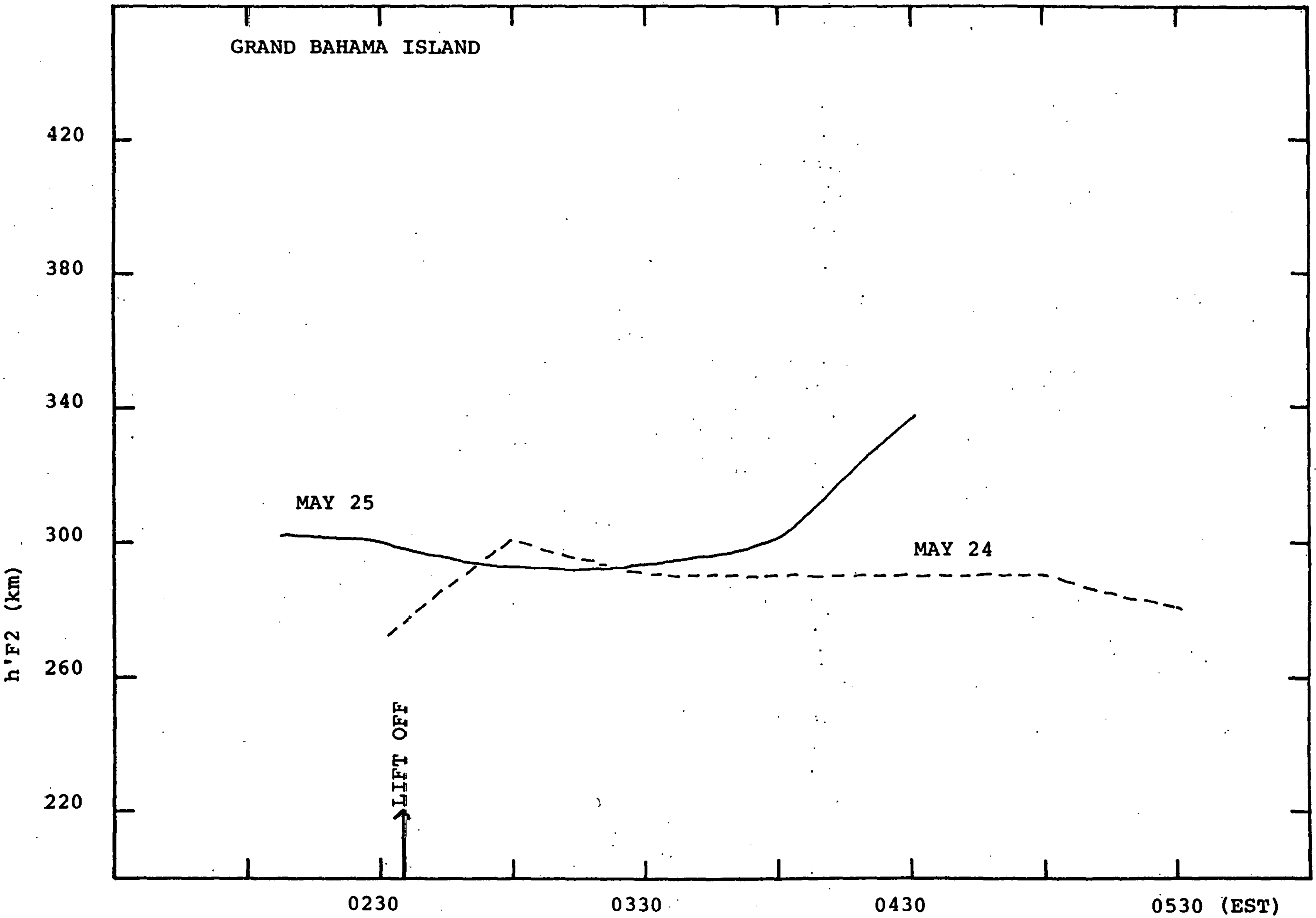


Figure 5c. Pegasus II. Virtual heights scaled from ionograms recorded at the Grand Bahama Island vertical sounding station on May 24 and 25, 1965.

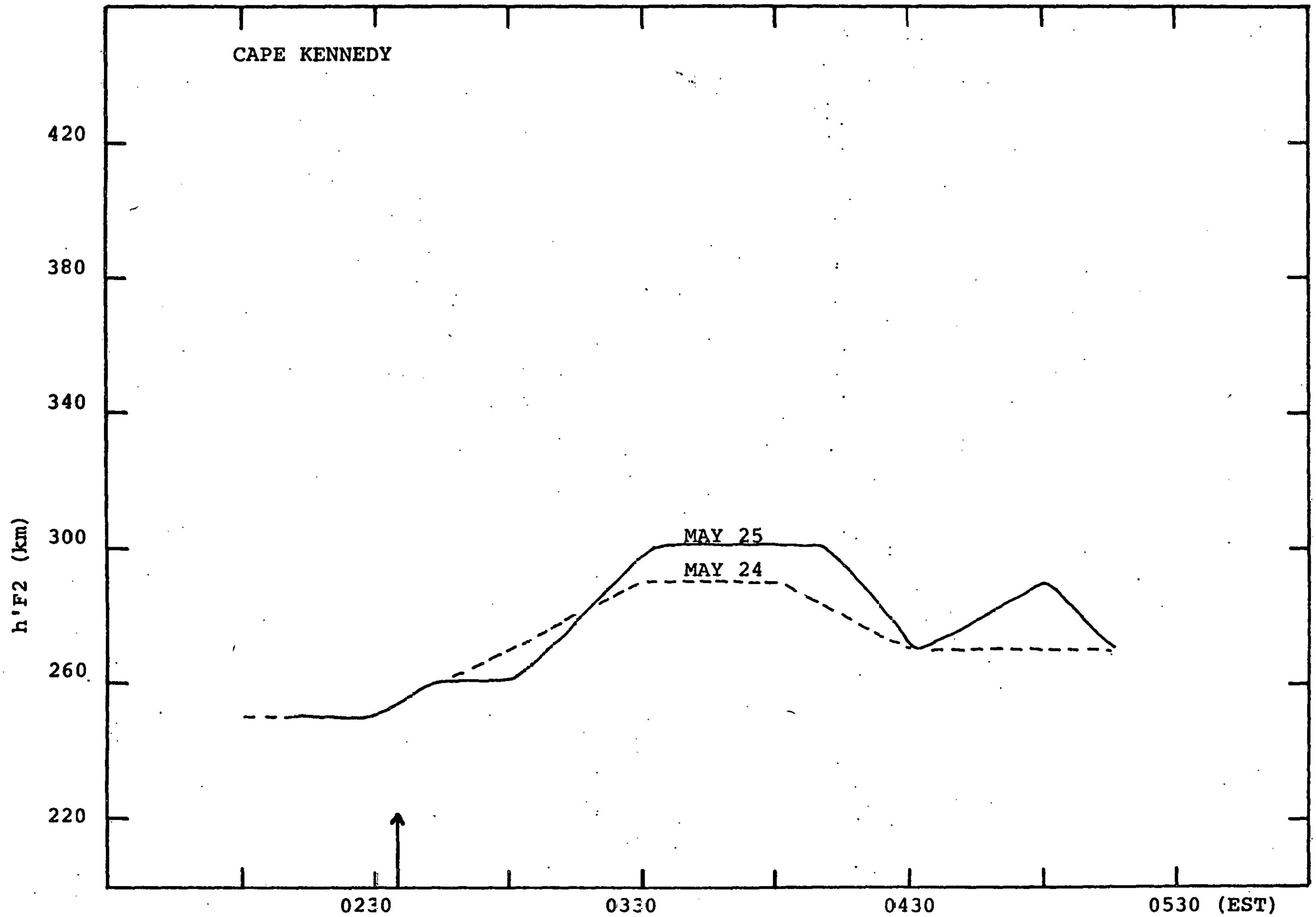


Figure 5d. Pegasus II. Virtual heights scaled from ionograms recorded at the Cape Kennedy vertical sounding station on May 24 and 25, 1965.

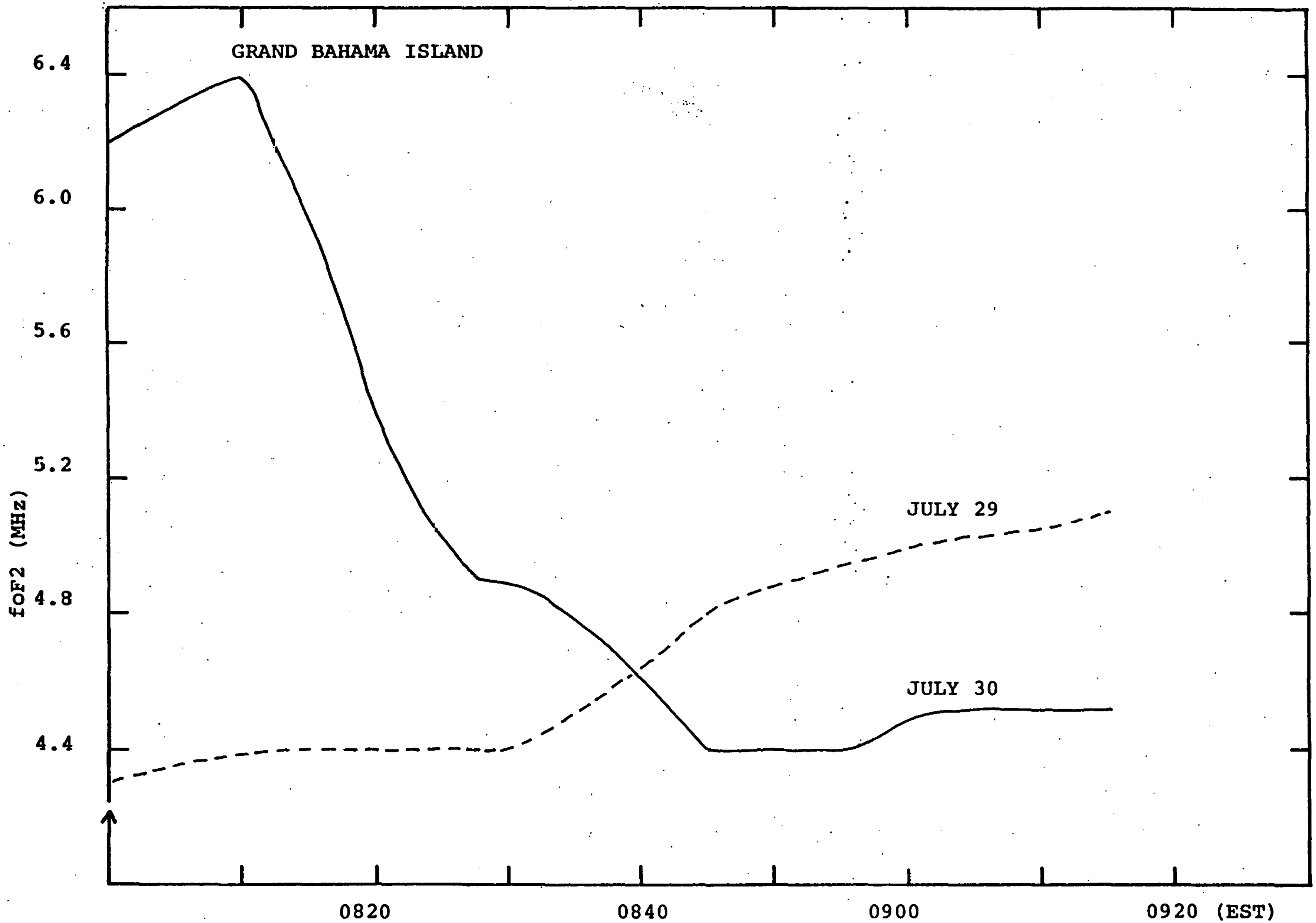


Figure 6a. Pegasus III. Critical frequencies scaled from ionograms recorded at the Grand Bahama Island vertical sounding station on July 29 and 30, 1965.

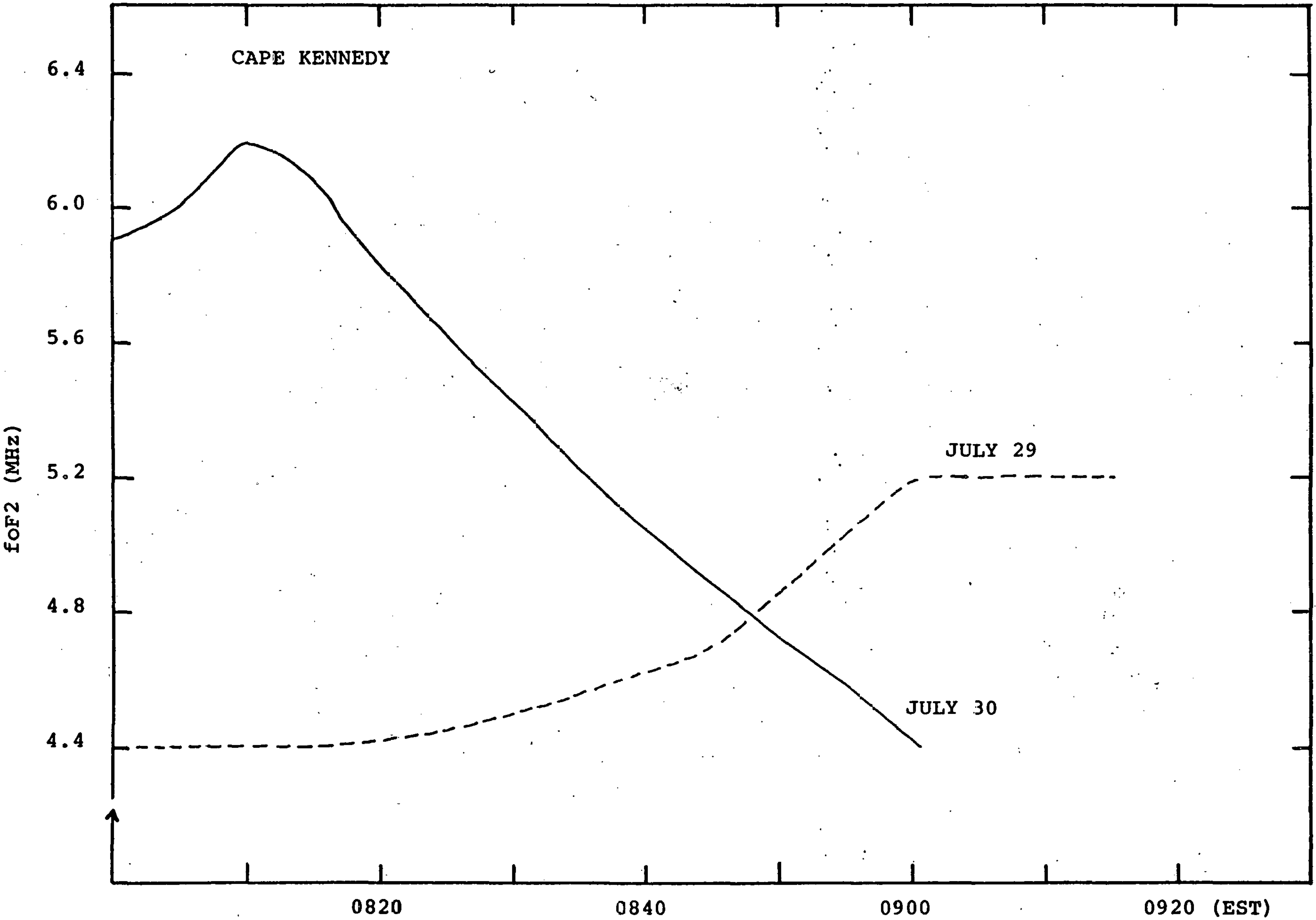


Figure 6b. Pegasus III. Critical frequencies scaled from ionograms recorded at the Cape Kennedy vertical sounding station on July 29 and 30, 1965.

TABLE 5: Changes in the Peak Density of the F-Region Derived From foF2 Observations During the Pegasus II Launch.

STATION	N_{max} (%) DEPLETION
Grand Bahama Island	72
Cape Kennedy	50

The relatively large percentage depletions seen here stem from the circumstance that at 0235 EST the pre-launch electron density values (May 24) are already depleted by natural night side recombination (by approximately 40% and 20% respectively). Both Figures 5a and 5b reveal that there is very little recovery taking place prior to the time solar production begins to fill in the hole rapidly at 0500 EST.

Figures 5c and 5d show the variation of virtual height on May 24 and May 25 at Grand Bahama Island and Cape Kennedy, respectively, and reveal that plasma depletion in this instance proceeds without affecting the virtual height of the F2 peak.

Pegasus III was launched at 0800 EST on July 30, 1965. Figures 6a and 6b depict the behavior of the critical frequency at Grand Bahama Island and Cape Kennedy. The corresponding curves in both figures are quite similar in shape with a slightly steeper decline seen at Grand Bahama Island following the rocket transit on July 30. Both stations show the formation of a plasma hole on July 30 with a decline in the F2 peak electron density reaching roughly the 50 percent level.

II.2. Conclusion

Among the 193 rocket launchings we studied three were found to have caused large-scale electron density depletions in the ionosphere. Table 3 implies that, on a percentage basis, a few events could have gone unnoticed because ionosonde data on 35% of the rocket launchings listed there are either unavailable or too poor in quality for analysis. No electron depletions were detected following rocket launchings at the White Sands Missile range, the Western Test Range or at Wallops Island.

III. USE OF ROUTINE TOTAL ELECTRON CONTENT OBSERVATIONS TO DETECT ROCKET-INDUCED DISTURBANCES

III.1. Total Electron Content (TEC) Data During Rocket Launches from the Kennedy Space Center.

The Skylab hole was discovered when geostationary satellite VHF signals along slanted ray paths revealed an ionospheric region with severely depleted plasma densities. We have searched Faraday rotation records for the twelve other Saturn V launchings without encountering any rocket-related changes, including large-scale holes or traveling ionospheric disturbances (TID's). The reason for the unique nature of the Skylab event becomes obvious when the flight profiles of the other Saturn V rockets are studied. The Skylab launch on May 14, 1973, was alone among the thirteen Saturn V launches to have a flight profile that resulted in the engines burning well into the F-region; for Skylab, engine shutdown occurred at 442 km while the other rockets ceased burning at altitudes below 190 km.

In addition to altitude injection requirements, there is the obvious necessity that the satellite radio beacon signals used to derive TEC data must pass close to the rocket plume location. The positions of geostationary satellites carrying suitable VHF beacons are relatively few in number, and thus the east coast sites making such measurements rarely monitor paths crossed by burning rockets. TEC observations made during the Atlas-Centaur launchings of the satellites HEAO-A, B and C serve to illustrate this point. HEAO-A was launched at 0130 EST on August 12, 1977, and HEAO-B lift off occurred at 0024 EST on November 13, 1978. TEC records obtained at Cape Kennedy and Puerto Rico, looking due south towards the beacons on the geostationary satellites ATS-3 and ATS-5, failed to reveal any features attributable to rocket-induced electron density changes. In contrast, the HEAO-C event (0535 EST, September 20, 1979) did show characteristic signatures attributable to severe electron density depletions in much the same manner as the Skylab event. In the case of HEAO-C, the SIRIO beacon (located far to the east) passed directly through the depleted region. The clear implication of these results is that for even large-scale effects it is essential to position the observer in relatively stringent locations determined by the rocket trajectory and VHF ray paths.

III.2. TEC For West Coast Rocket Launches

Rocket launches from the Vandenberg Air Force Base have not produced any instances of large-scale ionospheric holes in routine satellite beacon observations. The Stanford University Radio Science Laboratory has recorded TEC data from several sites in California during various periods from the early 1960's to the present. A preliminary search of this data base during many of the rocket launches contained in Table 3 has not revealed any clear cases of rocket-induced perturbations (Bernhardt, private communication, 1979). The recent launch of the satellite NOAA-B by an Atlas-F rocket in May 1980 has resulted in the first clear case of a large-scale hole from a Vandenberg launch (Bernhardt, Baumgardner, private communications, 1980). This "experiment of opportunity" was similar to the HEAO-Hole study in that special networks of TEC observatories were set up to monitor the anticipated effects. A full analysis of the NOAA-B effects has not yet been carried out.

IV. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A comprehensive study of archived ionospheric data was undertaken to search for F-region perturbations associated with rocket launches into the upper atmosphere. The study spanned two decades of space flight activity and involved many station-years of ionosonde and electron content data. That no more than a handful of plasma depletion events were uncovered in this search resulted from several coupled factors:

(1) The vast amount of rocket launches considered pertained to relatively small vehicles and thus the exhaust clouds would have created plasma depletions over too small a region to be detected by the distribution of available observing stations.

(2) Even when the rockets themselves were large (Saturns, Atlas-Centaurs, etc), the engine burns almost invariably terminated at too low an altitude ($h < 200$ km) for the exhaust molecules to cause noticeable chemical depletion effects.

(3) That so few plasma depletions were found in the large available ionosonde data base was due in part to the complexity and extreme variability of "normal" ionograms. Even when a rocket effect is conspicuous, as with the 15 February 1965 event, it was difficult to separate the precise nature of the anticipated undisturbed behavior from the artificially-induced variations.

(4) All of the Cape Kennedy launchings after May 1971 were not capable of being analyzed using archived ionosonde data simply due to the fact that the observing stations at San Salvador, Grand Bahama Island and Cape Kennedy had all closed by that date.

(5) During the two decades of KSC rocket activity examined in this study, routine Faraday rotation measurements of the ionospheric total electron content (TEC) made from several Atlantic area observatories (Sagamore Hill (MA), Fort Monmouth (NJ), Rosman (NC), Cape Kennedy (FL), Richmond (FL), and Arecibo (PR)) were made using the satellites ATS-1, 3, 5 and 6 -- all having line-of-sight observing paths to the south or west of the typical eastward launch tracks from the Cape.

It should be recalled that the emphasis throughout our search has been on identifying and documenting large-scale electron depletion events. It is from this perspective that we recorded "no effect" (N/E) against the entries in Table 3. This is not meant to inhibit investigators in the future from looking for relatively subtle rocket-related ionospheric effects which they may have reason to expect in connection with a given rocket launch. In this context, one should note that several of the reports listed in Table 1 suggested that rocket plumes caused enhancements in E-Region ($h \approx 150$ km) densities. In those reports, it was suggested that the ionized component of a rocket exhaust cloud could exceed ambient ionospheric densities at low altitudes where the plume would be confined in space by the very dense neutral atmosphere. This type of mechanism has received little or no attention in recent years due to greater interest in the chemical depletion processes operating at much higher altitudes. Further theoretical or experimental work on short-term E-Region modifications could address this issue in more detail.

Another consideration not addressed in this study was the possibility of moving an ionospheric disturbance away from regions monitored by ionosonde or TEC observing stations. Recent computer simulation results of Zinn and Sutherland (1980) show that neutral winds can displace a rocket's exhaust cloud to the point of having the hole "blow away" from an observing site. Diurnal and semi-diurnal winds capable of affecting ionospheric processes between 30^{o}- 45^{o} latitude have strong local time, seasonal and solar cycle components. A follow-up study could address this issue by examining the relationship between the local time of launch, the anticipated wind pattern and the locations of operating monitoring sites.

Finally, in light of the few ionosonde-based events found in this study, and in consideration of the success of recent "experiments of opportunity" associated with the HEAO-C launch, it is possible to suggest where "all-purpose" monitoring sites might be established for future observations. From the perspective of ionosonde facilities, the present study suggests that the re-installation of an ionosonde on either Grand Bahama Island or San Salvador would be very useful in monitoring future launch activity from the Kennedy Space Center. Perhaps a less costly and more worthwhile option would be to install a quasi-permanent TEC observing station on Bermuda. Given the prevalence for geostationary satellite beacons to be located near the 70^{o}W meridian, a TEC observatory on Bermuda (north of the Cape) would be capable of making electron content observations along ray paths that would pass close to most KSC launches with high-altitude burn profiles. Observations made by the Naval Research Laboratory from Bermuda during the HEAO-C event illustrated the usefulness of such a scheme (Reilly, 1980).

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