

STUDY OF THE DYNAMICS AND IONIZATION OF THE UPPER ATMOSPHERE

L. G. Smith

J. F. Bedinger

E. Constantinides

CASE FILE
COPY



Bedford, Massachusetts

FINAL REPORT
CONTRACT NO. NASw-1881

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HEADQUARTERS
Washington, D. C.

July 1970

GCA-TR-70-3-N

STUDY OF THE DYNAMICS AND IONIZATION OF
THE UPPER ATMOSPHERE

L. G. Smith

J. Bedinger

E. Constantinides

GCA CORPORATION
GCA TECHNOLOGY DIVISION
Bedford, Massachusetts

FINAL REPORT
Contract No. NASw-1881

July 1970

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HEADQUARTERS
WASHINGTON, D. C.

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
	SUMMARY	1
I	INTRODUCTION	1
II	A SEQUENCE OF ROCKET OBSERVATIONS OF NIGHTTIME SPORADIC E	3
	A. Introduction	3
	B. Equipment	3
	C. Observations	
	D. Discussion	
	E. Conclusions	
	REFERENCES	19
III	OBSERVED REDISTRIBUTION OF E REGION IONIZATION BY NEUTRAL WINDS	22
	A. Introduction	22
	B. General Theory	23
	C. Results and Discussion	27
	D. Recombination Coefficients and Pro- duction Rates	30
	E. Conclusions	33
IV	MEASUREMENT OF WINDS ABOVE 200 km	42
V	CONCLUSIONS AND RECOMMENDATIONS	51

STUDY OF THE DYNAMICS AND IONIZATION OF THE UPPER ATMOSPHERE

By L. G. Smith, J. Bedinger, and E. Constantinides
GCA Corporation, Bedford, Massachusetts 01730

SUMMARY

Simultaneous measurements of electron density profiles obtained with rocket borne Langmuir probes and wind profiles determined from vapor trails released from the same rocket were made at Wallops Island, Va. during the early morning of 22 February 1968. In addition to the usual features of the nighttime E region, a layer of enhanced electron density was observed to descend from 140 to 110 km during the six-hour period between midnight and sunrise. It is concluded that this layer probably occurs regularly in the E region at night, but is often blanketed by underlying layers and thus not recorded on ionograms. A simple theory of redistribution of ionization by horizontal winds accurately describes the motion of this layer. Application of the theory allowed determination of consistent values of the effective recombination coefficient and also revealed that the effects of electric fields were small during the observing period. In the lower E region, the winds produced relatively small ion drift velocities and layers of enhanced electron density were observed to persist for several hours.

I. INTRODUCTION

The purpose of this contract is to continue the study of the relationship of the ionized and neutral portions of the atmosphere. A primary objective is the detailed analysis of measurements of electron density and winds in the E-region obtained from probes and vapor trails released from the same rocket. Some preliminary results of this analysis were presented at the annual meeting of the American Geophysical Union in Washington, D.C. during April and at the COSPAR meeting in May 1969. The analysis is now completed and is being submitted for publication in a technical journal.

The most complete data available at the present time were obtained from a series of Nike Apache rockets launched at intervals of 90 minutes between midnight and sunrise on 22 February 1968 at Wallops Island. A prominent feature of the electron density profile during these observations was a layer of enhanced electron density which descended from 140 to 110 km in the six-hour period. The significance of this phenomena and the relation of rocket-borne probe measurements

to those obtained with ground based ionosondes are discussed in Section II of this report which has been accepted for publication in the Journal of Atmospheric and Terrestrial Physics as a paper entitled, "A Sequence of Rocket Observations of Nighttime Sporadic E," by L. G. Smith. The winds, observed from vapor trails throughout the period were used to compute the expected vertical drift velocity of ions. The computed drift velocities adequately describe the temporal variations in the upper layer but no satisfactory relation was found for the lower region. These results and deductions concerning vertical winds, electric fields, ionization production rates and recombination coefficients are discussed in Section III of this report which is also being submitted to the above-mentioned journal as a paper entitled, "Observed Redistribution of E-region Ionization by Neutral Winds," by E. Constantinides and J. F. Bedinger.

Another objective of this contract was the measurement of winds above 200 km in order to investigate the proposal made by King-Hele that part of the observed variation in the orbital inclination of certain satellites is due to a mean west to east wind above 200 km. During February 1969, a Nike-Tomahawk rocket system was used to form a vapor trail from 50 to 260 km over Wallops Island. The resulting wind measurements are discussed in Section IV which has been published in the Journal of Geophysics Research as a paper entitled, "Measurement of Winds Above 200 km," by J. F. Bedinger.

The results are summarized and suggestions are made for future programs in Section V.

SECTION II

A SEQUENCE OF ROCKET OBSERVATIONS OF NIGHTTIME SPORADIC E

The variation of the structure of the nighttime E region has been observed in a series of five rocket flights from Wallops Island, Virginia, on 22 February 1968. The launch times were 0009, 0130, 0300, 0430, and 0602 EST. Electron density profiles were obtained by Langmuir probe during rocket ascent. A sporadic-E layer, identified as the intermediate or E2 layer of radio observations, is found in the upper E region. It is observed at 140 km in the first two profiles and subsequently descends until finally merging with the lower, irregular, region. The layer is initially blanketed by the underlying layers but later appears in ionograms as sequential sporadic E. Long persistence of layers in the lower E region is also noted.

A. Introduction

The main features of the nighttime E region have been demonstrated in previous rocket observations (Smith, 1966a). The lower part of the region, between about 90 and 120 km, has a complex structure of thin layers of enhanced electron density (sporadic E). The thickness is of the order of 1 km and the horizontal extent may be 100 km or more. At higher altitudes a smoother profile is seen, often with low values of electron density. The detailed structure shows great variability from night to night.

The series of rocket flights described here was planned as an investigation of sporadic-E layers at altitudes between 90 and 120 km. The experiment had two objectives. The first was to observe the change in the electron density profile over a period of several hours in order to examine the formation and dissipation of the layers. The second objective was to evaluate the role of the neutral wind in the development of the structure. The launch site was Wallops Island, Virginia, (37.84° N, 75.48° W). The night chosen for the experiment was to be one with sporadic-E echoes on the ionograms and one which had clear visibility for photography of vapor trails used for the wind determination. The first night to meet both of these requirements was that of 21-22 February 1968. The electron density profiles obtained from the rocket-borne instrumentation are the subject of this paper.

B. Experiment

Five Nike Apache rockets were launched at intervals of about 90 minutes between midnight and sunrise, Table 1. Each payload carried a vapor cannister (of trimethylaluminum or sodium) and a Langmuir probe. The probe uses the nose tip of the rocket as the electrode (Smith, 1969) and alternates between a voltage sweep of 0.5 sec duration and a fixed voltage of 1.5 sec duration. The probe potential for these and subsequent flights is 4.05 V; for previous flights it had been 2.70 V. The sweep is primarily used to obtain electron temperature and vehicle potential. The fixed voltage mode is used to obtain the electron density profile with a height

TABLE 1

WALLOPS ISLAND, 22 FEBRUARY 1968

Rocket	Launch (EST)	Apogee (km)	Vapor
14.364	0009	156	TMA
14.365	0130	176	TMA
14.366	0300	181	TMA
14.367	0430	190	TMA
14.208	0602	168	Sodium

resolution of about 10 m. It has been found that the current to the probe is proportional to electron density over a wide range of electron density and of altitude. The constant of proportionality, obtained from subsequent daytime flights using the same probe potential, is 1.0×10^{-10} amp for an electron density of 1 cm^{-3} in the E region. The small values of electron density indicated in the profiles at altitudes below 90 km represent a considerable extrapolation of this proportionality and these parts of the profiles should be taken as an indication of the structure rather than as definitive values.

The electron density profiles terminate with the release of vapor for the wind measurement. The release of trimethylaluminum produces a decrease in probe current and a modulation at the spin frequency of the rocket (about 6 rps). It is still possible to identify the major features of the profile during descent of the rocket and to establish that peaks of electron density indicate sporadic E layers. Sodium vapor, used in the last flight of the series, short-circuits the probe, probably by deposition on the ceramic insulator, and no data are obtained following the release. On the basis of the preceding observations the peaks in the final profile can be confidently interpreted as layers.

The J-5 ionosphere sounder at Wallops Island was operated in support of this experiment. The frequency is swept from 0.25 to 20 MHz on a logarithmic scale. Soundings were made at five-minute intervals during the night with additional soundings at one-minute during the rocket flights. The ionograms shown in Fig. 1 were made two minutes after each launch when the rocket is at an altitude of about 130 km. The horizontal separation of rocket and sounder at this time is about 40 km.

The values of virtual height and blanketing frequency quoted in the following section have been scaled from the ionograms by Mr. R. Gray, Environmental Science Services Administration, without prior knowledge of the rocket observations. The determination of blanketing frequency is difficult as these values fall within the broadcast band where the ionograms exhibit considerable interference from radio stations. The electron concentration (N, cm^{-3}) corresponding to the blanketing frequency (f, MHz) is calculated using $N = 1.24 \times 10^4 f^2$.

C. Observations

The five profiles of electron density obtained from the rocket-borne probes are shown in Fig. 2. Individual profiles have been displaced by one decade in electron density and the scales are shown for the first and last profiles. Features of the profiles on a vertical scale of 0.5 km have been reproduced. The characteristics of the nighttime E region are clearly seen. Unexpectedly a sporadic E layer appears initially in the upper part of the region. This layer subsequently descends and merges with the lower, irregular, region.

The first rocket was launched at 0009 EST. The ionogram for 0011 EST, Fig. 1, indicates the presence of sporadic E at a virtual height of 105 km

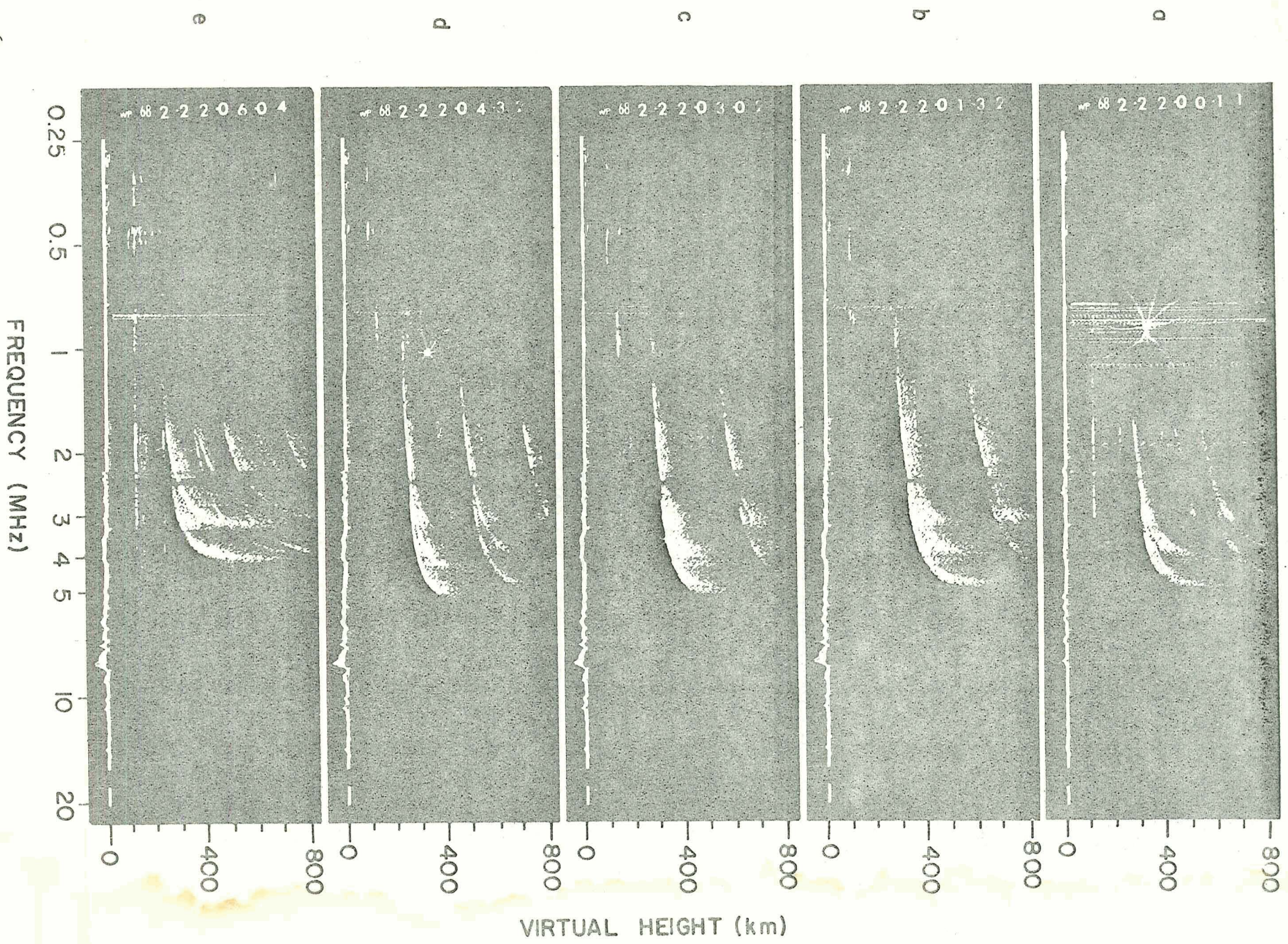


Figure 1. Vertical incidence ionograms taken at Wallops Island on 22 February 1968. The times are (a) 0011 EST, (b) 0132 EST, (c) 0302 EST, (d) 0432 EST and (e) 0604 EST. The star-like images in (a), (c) and (d) are film defects.

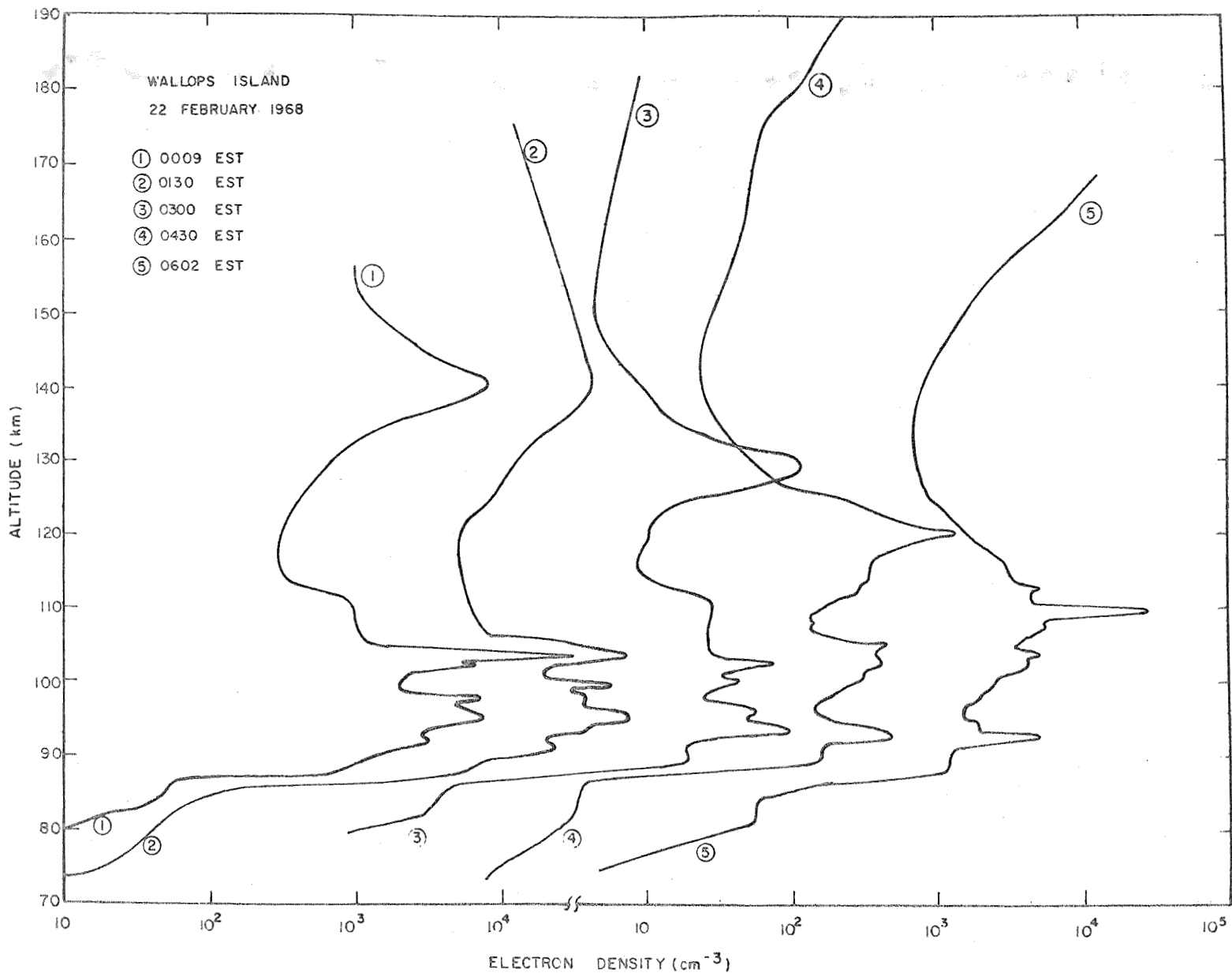


Figure 2. Electron density profiles from the probes on rockets launched from Wallops Island on 22 February 1968. The profiles are each displaced by one decade. The electron density scales for the first and last profiles are given. The part of the profiles below 90 km should be regarded as indicating the structure, rather than as absolute values.

and with a blanketing frequency not greater than 0.98 MHz, corresponding to an electron density of $1.2 \times 10^4 \text{ cm}^{-3}$. There is also evidence of an additional layer at 120 km. The electron density profile from the rocket-borne probe is shown in Fig. 2. The principal layer occurs at 103 km in agreement with the ionogram. The altitude (to the nearest 0.5 km) and the electron density at the peak of the principal layers in this profile are: 140 km, $9.0 \times 10^3 \text{ cm}^{-3}$; 103 km, $3.5 \times 10^4 \text{ cm}^{-3}$; 97.5 km, $7.5 \times 10^3 \text{ cm}^{-3}$; and 94.5 km, $7.5 \times 10^3 \text{ cm}^{-3}$. The upper layer is separated from the lower layers by a valley having a minimum electron density of 300 cm^{-3} at an altitude of 117 km. The thickness of the layer at 103 km, measured at one-half the peak electron density (as are other values of thickness quoted below), is 1 km. The thickness of the layer at 140 km is 6 km. This upper layer is blanketed by the underlying layers. There is no feature on the probe profile to produce the echo at a virtual height of 120 km.

The next profile, from the rocket launched at 0130 EST, shows that the layer at 140 km has decreased in electron density to $4.5 \times 10^3 \text{ cm}^{-3}$ and the thickness has increased to 27 km. The other principal layers in this profile are: 103.5 km, $7.5 \times 10^3 \text{ cm}^{-3}$; 100 km, $6.0 \times 10^3 \text{ cm}^{-3}$; and 95.5 km, $8.0 \times 10^3 \text{ cm}^{-3}$. The layer at 95.5 km thus blankets the higher layers. In the corresponding ionogram, 0132 EST, the virtual height of the sporadic E is 95 km and the blanketing frequency is 0.76 MHz ($7 \times 10^3 \text{ cm}^{-3}$) both in good agreement with the probe data. The electron density in the valley between the upper and lower layers has increased. The minimum value is 500 cm^{-3} at 118 km.

The upper layer is first evident in the ionogram recorded at 0200 EST. The virtual height at this time is about 200 km but it subsequently decreases and multiple echoes appear. The ionogram at 0302 EST shows layers at virtual heights of 91, 129, 152 and 179 km. The blanketing frequency is 0.83 MHz ($8.5 \times 10^3 \text{ cm}^{-3}$). The probe profile shows the upper layer now at 128 km, with a thickness of 5 km and a peak electron density of $1.2 \times 10^4 \text{ cm}^{-3}$. The principal layers of the lower region are: 102.5 km, $7.5 \times 10^3 \text{ cm}^{-3}$; and 93.5 km, $9.0 \times 10^3 \text{ cm}^{-3}$. The 91 and 129 km echoes are accounted for by the probe profile, as in the absence of an echo from the layer at 102.5 km. There are, however, no features on the probe profile at heights of 152 and 179 km. The electron density in the valley has again increased. The minimum value is 900 cm^{-3} at 116 km. The electron density in the upper part of the E region has a minimum value of 450 cm^{-3} at 150 km.

The electron density profile from the fourth rocket, launched at 0430 EST, shows that the upper layer has again descended. It is now seen at 119.5 km and is no longer clearly separated from the lower, irregular, region. The thickness of this layer is 3 km and the peak electron density is $1.3 \times 10^4 \text{ cm}^{-3}$. The principal lower layers are: 104.5 km, $4.5 \times 10^3 \text{ cm}^{-3}$; and 92 km, $5.0 \times 10^3 \text{ cm}^{-3}$. The corresponding ionogram, 0432 EST, shows layers at virtual heights of 93 and 122 km in agreement with the rocket data, as in the blanketing frequency of 0.90 MHz ($1.0 \times 10^4 \text{ cm}^{-3}$). No echo is seen from the layer at 104.5 km because of blanketing by the layer at 92 km. The electron density of the upper part of the profile has again decreased. The minimum value is 250 cm^{-3} at 143 km.

The final profile of the sequence was obtained from the rocket launched at 0602 EST. At this time the solar zenith angle is 98 degrees and the upper part of the region is being ionized by solar Lyman- α radiation (Smith, 1966b). The minimum electron density in the E region has increased to a value of 700 cm^{-3} at an altitude of 135 km. The upper layer, now at 109 km, has merged into the lower, irregular, region. The electron density at the peak of this layer is $3.3 \times 10^4 \text{ cm}^{-3}$ and the thickness is 0.9 km. Other principal layers are: 103.5 km, $5.0 \times 10^3 \text{ cm}^{-3}$; and 92 km, $6.0 \times 10^3 \text{ cm}^{-3}$. Layers are identifiable on the ionogram, 0604 EST, at virtual heights of 94 and 108 km in agreement with the rocket data. There are additional echoes at 100, 140 and 192 km on this ionogram with no features at these heights on the probe profile. The blanketing frequency is 1.28 MHz ($2.0 \times 10^4 \text{ cm}^{-3}$).

D. Discussion

The upper layer.- The first direct measurement of a layer in the upper E region at night was made by Cartwright (1964) using a propagation experiment at 10.2 kHz on a rocket launched from Wallops Island at 0030 EST on 12 April 1963. The profile, which extends to an altitude of 200 km, shows a layer with a peak electron density of $3.5 \times 10^3 \text{ cm}^{-3}$ at 142 km and a thickness of 10 km. The lower region has a peak electron density of 1.7×10^3 at 105 km. Between the two layers a minimum electron density of about 150 cm^{-3} occurs at an altitude of 120 km, and in the valley above the upper layer the minimum electron density is about 250 cm^{-3} at 180 km.

The upper layer is present in the electron density profile from a rocket-borne probe on 22 June 1965, although it was not previously recognized as such. Nike Apache 14.201 was launched from Wallops Island at 2300 EST and reached an apogee of 167 km. The profile, Fig. 3, shows the layer with a peak electron density of 800 cm^{-3} at an altitude of 152 km. The thickness of the layer is 30 km and it is separated from the lower, irregular, region by a valley in which the minimum electron density is 170 cm^{-3} at 125 km.

Data from a recent rocket flight also show the presence of the upper layer. Nike Apache 14.394, which included a probe in the payload, was launched from Wallops Island at 2306 EST on 11 September 1969. Based on a preliminary analysis the layer has a peak electron density of $3.0 \times 10^3 \text{ cm}^{-3}$ at an altitude of 147 km. It has a thickness of 23 km and is blanketed by a layer at 100 km having a peak electron density of $3.5 \times 10^3 \text{ cm}^{-3}$. The minimum electron density in the valley between the layers is 150 cm^{-3} at an altitude of 114 km.

The four rocket observations of the upper layer near midnight are summarized in Table 2. The electron density and altitude are measured at the peak of the layer. The thickness is measured at an electron density of one-half of the value at the peak. The thickness of the layer varies inversely with the electron density at the peak so that the columnar electron densities of the four layers are nearly equal. It is also seen

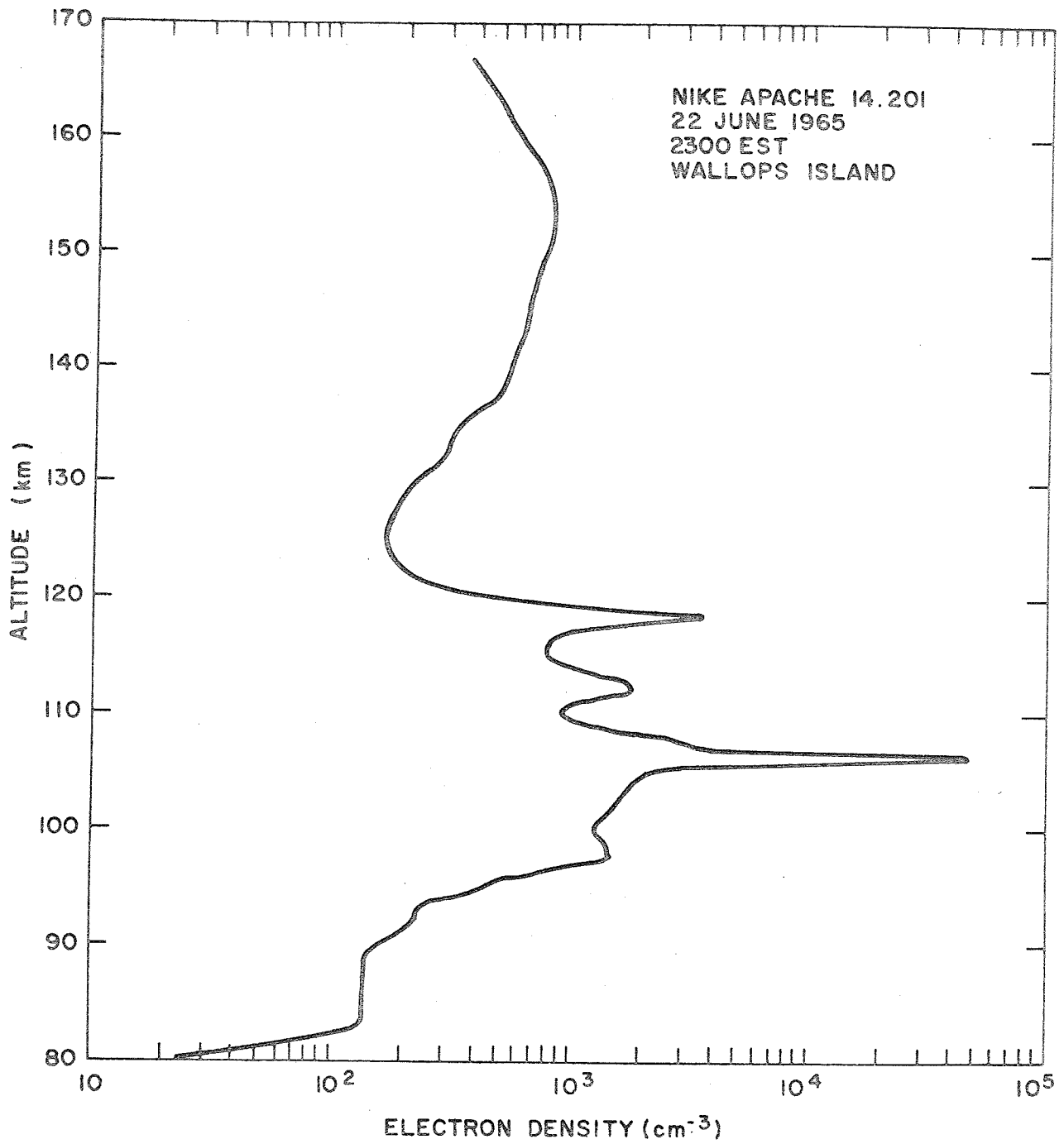


Figure 3. Electron density profile, 2300 EST 22 June 1965.

TABLE 2

ROCKET OBSERVATIONS OF THE UPPER LAYER NEAR MIDNIGHT

Date	Time (EST)	Electron Density (cm ⁻³)	Altitude (km)	Thickness (km)
12 April 1963	0030	3.5×10^3	142	10
22 June 1965	2300	0.8×10^3	152	30
22 February 1968	0009	9.0×10^3	140	6
11 September 1969	2306	3.0×10^3	147	23

that the two layers observed about one hour before midnight have smaller values of peak electron density and greater altitudes than the other two layers observed in the half-hour following midnight.

The same tendency to constant columnar electron density is seen in the sequence of observations of 22 February 1968. As the layer descends the value of electron density at the peak increases and there is a corresponding decrease in the thickness of the layer.

The tilt of the upper layer has been determined for the third and fourth profile. As shown in Table 3 the tilt is not significantly different from zero. The same result has been obtained for other sporadic-E layers (Smith, 1966a).

The fourth profile (0430 EST) shows a striking similarity in structure with the only other profile recorded about two hours before ground sunrise. The profile from Nike Apache 14.144 launched at 0300 EST on 15 July 1964 (Smith, 1966b) shows sporadic-E layers at 95 and 118.5 km with a possible additional layer at 103.5 km, seen only on rocket descent. Above the upper layer the electron density decreases to a minimum of about 150 cm^{-3} at an altitude of 145 km.

Comparison with ionograms.- The occasional indication of a layer at a virtual height of about 150 km is well established by ionosphere sounders. In this context it is known as the E2 layer (Becker and Dieminger, 1950) and the intermediate layer (Watts and Brown, 1954), the former being generally used for daytime and the latter for nighttime observations. Elling (1960) reports a frequency of occurrence of 7 percent at Tsumeb ($19^{\circ}\text{S}, 17^{\circ}\text{E}$). Wakai (1967) finds that the layer at night, when it occurs, forms in the two hours before midnight and disappears by 0300 hr, local time.

The observation of a layer in the upper E region is sometimes followed, as on 22 February 1968, by a decrease in virtual height over a period of several hours. This is a feature of both daytime and nighttime observations by ionosphere sounders and is identified as sequential sporadic E (McNicol and Gipps, 1951; Matsushita, 1955; Thomas, 1956a).

The layers indicated by the probe profiles are recorded in the corresponding ionograms at virtual heights within 2 km of the true height. The discrepancy probably represents the limit of accuracy of scaling the ionogram. Additional echoes occur in the ionograms at virtual heights for which there are no corresponding features in the probe profiles. It is believed that these are multiple echoes involving two sporadic-E layers (Thomas, 1956b).

Previous studies of daytime sporadic E at middle and low latitudes (Mukunda Rao and Smith, 1968) and of the nighttime auroral E region (Reddy et al., 1969) have shown good agreement between the electron density corresponding to the blanketing frequency and that observed by a probe at the peak of the layer. In the series of observations from 22 February 1968

TABLE 3
 ALTITUDE AND TILT OF THE UPPER LAYER
 ON 22 FEBRUARY 1968

Time (EST)	Ascent (km)	Descent (km)	Separation (km)	Tilt (deg.)
0300	128.2 ± 0.1	128.4 ± 0.5	77.9	0.15 ± 0.45
0430	119.7 ± 0.1	119.5 ± 0.3	78.8	-0.15 ± 0.30

the blanketing frequencies deduced from the peak electron density of the five profiles are, respectively, 1.68, 0.80, 0.85, 1.02, and 1.63 MHz. The corresponding values obtained by scaling the ionograms are ≤ 0.98 , 0.76, 0.83, 0.90, and 1.28 MHz. The pairs of values from the second, third, and fourth observations are in good agreement. The discrepancy for the first and fifth pairs of values is attributed to an error in scaling the ionograms. Reexamination of the ionograms, knowing the blanketing frequency derived from the probe, shows that the difficulty arises from interference, and in the last case, from a multiple echo of the sporadic E layer. Thus the data tend to support the earlier conclusion that the blanketing frequency corresponds with the peak electron density in the layer.

Bowhill (1966), also comparing ionograms and probe profiles, has shown that the transparent part of the sporadic E echo is, in the cases investigated, produced by small-scale irregularities in the electron density profile. The upper layer does not show these irregularities and the transparent part of the echo must be attributed to partial reflection at the steep gradient of the lower boundary.

Geomagnetic activity.- A correlation of the intermediate layer with geomagnetic activity has been established by radio observations. Haubert (1959) reports that the appearance of the layer in ionograms at night is related to an increase in magnetic activity; the layer is almost certain to be observed when $K_p > 5$. Wakai and Sawada (1964) find an increase in the electron density of the intermediate layer with an increase in K_p . Wakai (1967) has analyzed in detail three representative nights. For quiet conditions (K_p : 0 and 1) he finds a deep valley between 100 and 200 km with no evidence of an intermediate layer. On a moderately disturbed night (K_p : 3 and 4) a layer developed at midnight with a peak electron density of $6 \times 10^3 \text{ cm}^{-3}$ at 155 km. On a severely disturbed night (K_p : 5 and 6) the intermediate layer formed about one hour before midnight but at a lower altitude, 140 km, and with a larger value of peak electron density of $2 \times 10^4 \text{ cm}^{-3}$.

The K_p indices for the four nights for which rocket observations of the intermediate layer are available are given in Table 4. The night of 21-22 February 1968 is the most disturbed of this group. The two nights of 11-12 April 1963 and 11-12 September 1969 are roughly comparable with each other and are intermediate in activity between the February 1968 case and the relatively quiet night of 22-23 June 1965. Reference to the data on the upper layer given in Table 3 shows that there is a clear correlation between electron density at the peak of the layer and the K_p indices, supporting the radio observations.

The lower layers.- The continuity of the sporadic E layers in the lower region is seen when the five profiles are superimposed, Fig. 4. The layer at 103.5 ± 1.0 km is present in all profiles. The peak electron density decreases in two steps through the sequence: 0009 EST, $3.5 \times 10^4 \text{ cm}^{-3}$;

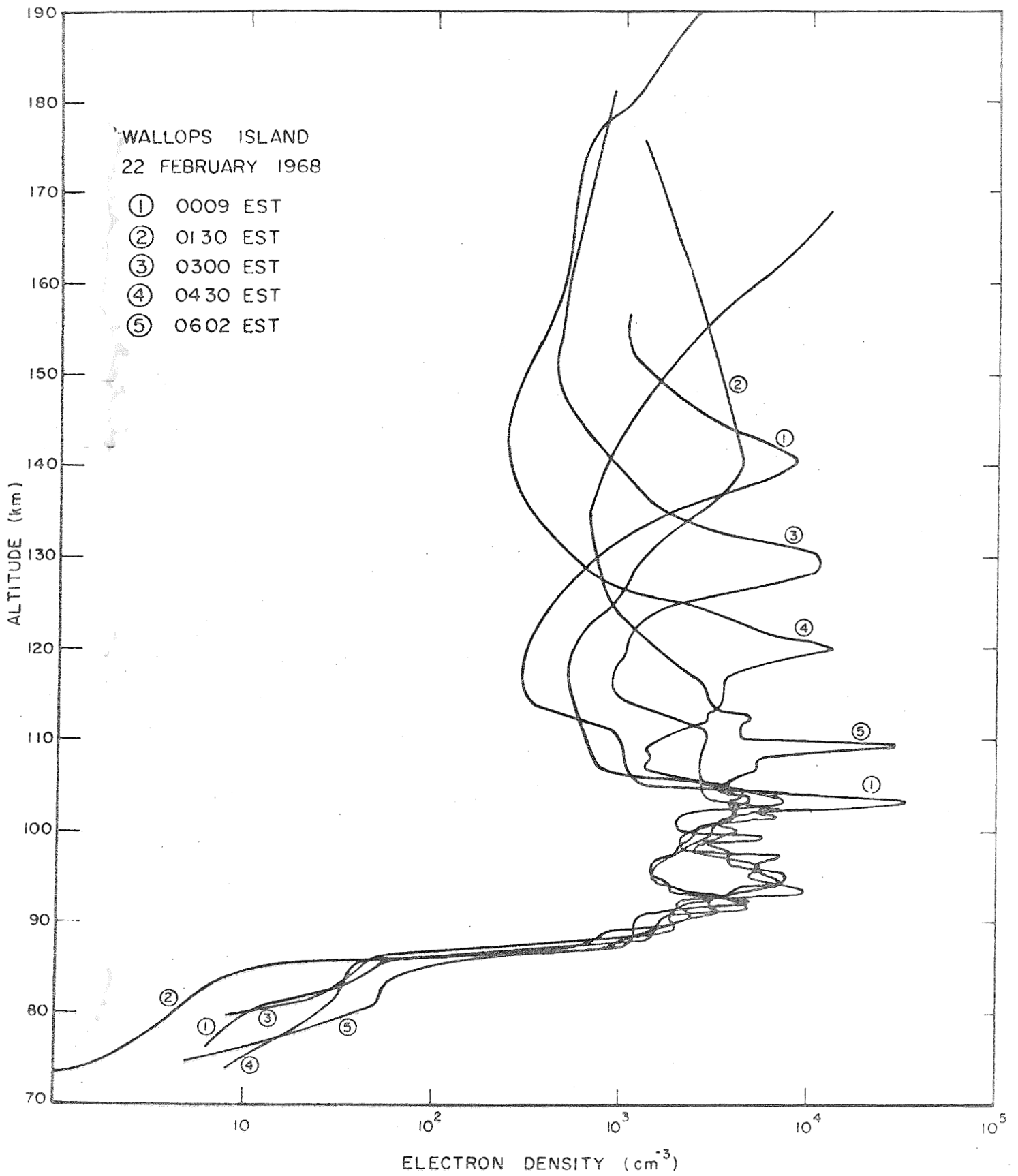


Figure 4. Electron density profiles of 22 February 1968 superimposed.

TABLE 4
 Kp THREE-HOUR RANGE INDICES

Time (EST)	1600 - 1900 - 2200 - 0100 - 0400 - 0700				
11-12 April 1963	1o	3-	1o	2o	3-
22-23 June 1965	1+	2-	0+	0+	1-
21-22 February 1968	4o	3-	3+	3o	3o
11-12 September 1969	1o	2-	2+	1+	2o

0130 EST, $7.5 \times 10^3 \text{ cm}^{-3}$; 0300 EST, $7.5 \times 10^3 \text{ cm}^{-3}$; and 0602 EST, $5.0 \times 10^3 \text{ cm}^{-3}$. This layer should have been detected on the probe profile from the descent of the first rocket during the TMA release. Its absence is taken as evidence of limited extent; the horizontal separation of rocket penetration of this altitude is 83 km.

The layer at 94.5 ± 1.0 km persists for the first three observations, with a peak electron density of about $8 \times 10^3 \text{ cm}^{-3}$. In the fourth and fifth profiles the layer is replaced by a valley with minimum electron density of $1.5 \times 10^3 \text{ cm}^{-3}$. The principal lower layer is now at 92.0 km in both profiles and the peak electron density is $5.5 \times 10^3 \text{ cm}^{-3}$.

The lower boundary of the region is sharply defined. The electron density increases by an order of magnitude within 2 km. The altitude at which the electron density is 300 cm^{-3} , which occurs in the middle of the ledge, is found to remain at a constant altitude of 87.0 ± 0.5 km during the sequence. Below the ledge a small layer appears at the altitude of the daytime D-layer.

E. Conclusions

The sequence of rocket observations of sporadic-E in the nighttime ionosphere shows the descent of a layer from the upper part of the E region into the lower, irregular, part. Comparison of the data from the rocket-borne probe with that from the ionosphere sounder shows that the delayed appearance of the upper layer is caused by blanketing by underlying layers. Agreement between the blanketing frequency scaled from the ionogram and that deduced from the peak value of electron density determined by the probe is satisfactory.

The upper layer is identified as the intermediate or E2 layer of radio observations. The descent into the lower region is an example of sequential sporadic-E. Neither phenomenon is a common occurrence in ionograms. The available rocket data lead us to suggest that the layer is present on most nights near midnight. Except on geomagnetically disturbed night the layer is blanketed by underlying layers and does not produce an echo in ionograms.

The rise in the upper boundary of the nighttime E layer observed on this and other nights provides evidence that the descent of the layer is also a regular feature of the E region at night.

The increase of the intermediate layer with geomagnetic activity, represented by the index Kp, has been established by ionosphere sounder observations. The rocket observations are consistent with this relationship.

The long persistence of the structure of the below 105 km has been noted. The changes in the principal features in this region are relatively discontinuous, suggesting that the sporadic-E layers have well-defined horizontal extent.

The formation of the upper layer and its subsequent downward movement and change in shape have been interpreted by Bedinger and Constantinides (1969) in terms of the redistribution of ionization by the vertical shear of the horizontal wind. Further discussion of the role of the winds in the structure of the nighttime E region will be given in a separate paper.

REFERENCES

- Becker W. and Dieminger W. Naturwiss. 37, 90 (1950)
- Bedinger J. F. and Constantinides E. R. COSPAR, Prague (1969)
- Bowhill S. A. Radio Sci. 1 (New Series), 187 (1969)
- Cartwright D. G. J. Geophys. Res. 69, 4031 (1964)
- Elling W. Some Ionospheric Results Obtained during the IGY (edited by W. J. G. Beynon) p. 252, Elsevier, Amsterdam (1960)
- Haubert A. J. Atmos. Terr. Phys. 15, 84 (1959)
- Matsushita S. J. Geomag. Geoelect. (Kyoto) 7, 91 (1955)
- McNicol R. W. E. and Gipps G. de V. J. Geophys. Res. 56, 17 (1951)
- Mukunda Rao M. and Smith L. G. J. Atmos. Terr. Phys. 30, 645 (1968)
- Reddy C. A., Mukunda Rao M., Matsushita S. and Smith L. G. Planet. Space Sci. 17, 617 (1969)
- Smith L. G. Radio Sci. 1 (New Series), 178 (1966a)
- Smith L. G. J. Atmos. Terr. Phys. 28, 1195 (1966b)
- Smith L. G. Small Rocket Instrumentation Techniques (edited by K.-I. Maeda) p. 1, North Holland, Amsterdam (1969)
- Thomas J. A. Aust. J. Phys. 9, 228 (1956a)
- Thomas J. A. Aust. J. Phys. 9, 574 (1956b)
- Wakai N. J. Geophys. Res. 72, 4507
- Wakai N. and Sawada K. J. Radio Res. Lab. (Japan) 11, 1 (1964)
- Watts J. M. and Brown J. N. J. Geophys. Res. 59, 71 (1954)

SECTION III

OBSERVED REDISTRIBUTION OF E REGION IONIZATION BY NEUTRAL WINDS

Sequential measurements of electron density profiles are compared with the ionization drift velocities derived from simultaneously obtained neutral wind velocities. The measurements resulted from a series of five rocket flights launched at Wallops Island during a six-hour period in the morning of 22 February 1968. The electron density profiles were measured with a Langmuir probe during rocket ascent and the wind profiles were determined from vapor trails released during descent. The computed ion drift velocities describe accurately the upper portion of the electron density profiles which are characterized by a slowly descending layer of enhanced electron density. The small and slowly varying drift velocities in the lower E region cannot be so simply related to the complex structure observed in the electron density. The data from the upper portion of the electron density profiles are used to calculate the value of the recombination coefficient. This value compares well with laboratory measurements.

A. Introduction

The purpose of the observations reported in this paper was to determine the influence of neutral winds on the distribution of ionization in the E region. Measurements of the electron density profile and of the vertical profile of the horizontal wind were made at Wallops Island, Virginia, during the morning of 22 February 1968. Five Nike-Apache rockets were launched at one and one-half hour intervals over a six-hour period from midnight to dawn. The launch times were 0009, 0130, 0300, 0430, and 0602 EST. Each payload contained a Langmuir probe which recorded the electron density profile, and a canister which released a vapor trail during the descent. The first four trails were TMA, whereas the last trail contained a mixture of both sodium and lithium vapors which were sunlit at the release altitude. Winds were obtained from triangulation photography of the wind-driven vapor trails. The ionosonde at Wallops Station indicated the presence of sporadic E throughout the observing period.

The results of the electron density measurements have been previously reported (Smith, 1970). A prominent feature of the electron density profile during these observations was a layer of enhanced electron density which descended from 140 to 110 km in the six-hour period. It was concluded that this layer probably occurs regularly in the E region at night, but is often blanketed by underlying layers and thus

not recorded on ionograms. The complicated structure of the lower E region exhibits remarkable continuity during the six-hour period of observation. A layer at 103.5 ± 1.0 km is present in all profiles. In addition, a lower layer is present at 94.5 ± 1.0 km during the first three observations, and at 92.0 km during the last two. The persistence of these features is discussed in Section B.

In this paper, it is shown that a simple theory of redistribution of ionization by horizontal winds describes the observed variations in the upper layer but is not so simply applied to the complex structure in the lower region. Section B gives a brief account of the theory of formation of sporadic E layers, and of the method of computation of the ionization drift velocities from neutral wind velocities. Section C compares the theoretical predictions with the measured electron density profiles and Section D describes the method used to compute the effective recombination coefficients in the upper layer.

B. General Theory

Regions of enhanced ionization are frequently observed in the E region. Because the vertical dimension (a fraction of a kilometer up to a few kilometers) of these regions is much smaller than the horizontal dimensions (several hundred kilometers), these regions are effectively horizontal layers, and because they do not occur systematically are called sporadic E layers. These layers are formed and controlled by the dynamics and chemistry of the region. The dynamics are described by the equation of continuity and the equation of motion for each charged species. These are, respectively,

$$\frac{\partial N_k}{\partial t} = - \nabla \cdot (\tilde{u}_k N_k) + P_k - L_k \quad (1)$$

and

$$N_k m_k \left(\frac{\partial \tilde{u}_k}{\partial t} + \tilde{u}_k \cdot \nabla \tilde{u}_k \right) = N_k q_k (\tilde{E} + \tilde{u}_k \times \tilde{B}/c) \quad (2)$$

$$+ N_k m_k \nu_k (\tilde{U} - \tilde{u}_k) - \nabla P_k + N_k m_k \tilde{g}$$

where

N = number density

\tilde{u} = velocity vector

\tilde{P} = rate of production

L = rate of loss

m = mass

q = charge

\tilde{E} = electric field vector

\tilde{B} = magnetic field vector

c = speed of light
 ν = collision frequency between charged particles and neutrals
 \vec{U} = neutral wind velocity vector
 p = partial pressure
 \vec{g} = gravitational acceleration vector

and the subscript k refers to the k th charged species. The effects of ion-ion and ion-electron collisions are not important in the altitude range considered. The formulation used in this paper follows, essentially, the model of Axford, Cunnold and Gleeson (1966).

Equations (1) and (2) are simplified by the following considerations:

- (1) The terms on the left side of equation (2) are at least an order of magnitude smaller than the terms on the right. Hence, equation (2) reduces to a set of algebraic equations.
- (2) Only one species of positive ions is assumed to be present. Even though this assumption is not strictly justified, it results in small errors if the recombination coefficients and masses of the dominant ions are roughly equal.
- (3) Local neutrality obtains, i.e., the ion and electron densities are equal.
- (4) The vertical component of the drift velocity of ions and electrons is the same. If this were not very nearly so, vertical polarization fields would be set up and, owing to the high value of the vertical component of the conductivity, local neutrality would tend to be established.
- (5) Because of the large horizontal extent of sporadic E layers, the dependence of all quantities on the horizontal coordinates may be neglected.
- (6) The rate of loss is due entirely to dissociative recombination. Electron attachment processes are not important in the E region.

Under the preceding assumptions, which are valid for mid-latitudes, equation (2) can be solved for the drift velocity and equation (1) may be written in the form

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial z} (wN) = P - \alpha N^2 + \frac{\partial}{\partial z} \left(D \frac{\partial N}{\partial z} \right) \quad (3)$$

where

N = number density of electrons
 P = rate of electron production
 α = coefficient of dissociative recombination
 D = coefficient of diffusion
 w = effective drift velocity

D and w are explicitly defined by the following equations:

$$D = \frac{kc}{eBG} (T_i + T_e)$$

$$w = Ax U_x + Uy + Az Uz + F_x Ex + F_y Ey - \frac{1}{G} \left[g \left(\frac{1}{w_i} + \frac{1}{w_e} \right) + \frac{kc}{eB} \frac{\partial}{\partial z} (T_i + T_e) \right]$$

where

U_x, U_y, U_z = eastward, northward, and upward, respectively, components
 of the neutral wind velocity

E_x, E_y = eastward and northward, respectively, components of the
 electric field.

$$G = R_i (1 + R_i^2) (Z^2 + R_i^2)^{-1} + R_e (1 + R_e^2) (Z^2 + R_e^2)^{-1}$$

$$A_x = Z (XC_2 + YZC_1) / G$$

$$A_y = Z (YC_2 - XZC_1) / G$$

$$A_z = (R_i + R_e) / G$$

$$C_1 = (Z^2 + R_e^2)^{-1} - (Z^2 + R_i^2)^{-1}$$

$$C_2 = R_i (Z^2 + R_i^2)^{-1} + R_e (Z^2 + R_e^2)^{-1}$$

$$F_x = (c/B) (YC_2 - XZC_1) / G$$

$$F_y = (c/B) (-XC_2 - YZC_1) / G$$

$$R_i = v_i / \omega_i$$

$$R_e = v_e / \omega_e$$

$$\omega_i = eB / m_i c$$

$$\omega_e = eB / m_e c$$

c = speed of light

B = magnitude of terrestrial magnetic field

X, Y, Z = eastward, northward, and upward, respectively, direction
 cosines of the magnetic field vector

M_i, M_e = mass of positive ion and electron, respectively

ν_i, ν_e = collision frequency with neutrals for ions and electrons,
 respectively

T_i, T_e = temperature of ions and electrons, respectively

e = electronic charge (absolute value)
 k = Boltzman constant
 g = gravitational acceleration constant
 z = vertical coordinate

Directions are specified with respect to geographic coordinates. The evaluation of the collision frequencies were based on the results of Banks (1966). All dimensional quantities are in Gaussian units.

The occurrence of Sporadic E layers must ultimately result from the variation with height of one or more of the quantities w , P , and α . Any theory that attributes the formation of these layers primarily to the vertical variation of the drift velocity w may be reasonably called a "redistribution theory." If it is assumed that the electron density profile adjusts immediately to the instantaneous value of the drift velocity profile, then the time derivative may be omitted from equation (3), which reduces to the "steady-state" equation

$$\frac{\partial}{\partial z} (wN) = P - \alpha N^2 + \frac{\partial}{\partial z} \left(D \frac{\partial N}{\partial z} \right) \quad (4)$$

The mechanics of the formation of Sporadic E layers, based on an equation equivalent to equation (4) were first investigated by Whitehead (1961) and Axford (1963). (Their theory is referred to as the "wind-shear theory," because the variation of w is determined by the variation of the neutral winds with height. This is not strictly true of course since the presence of electric fields affects the drift velocity w as well. It seems preferable, therefore, to use the term "redistribution theory" which is not as restrictive as the term "wind shear theory"). The steady-state theory predicts the formation of a Sporadic E layer at a height z_p such that

$$w(z_p) = 0 \quad \text{and} \quad \partial w / \partial z |_{z = z_p} \equiv -\delta < 0. \quad (5)$$

These statements express mathematically the fact that ionization is drifting towards the height z_p from above and below this height. There are, of course, other conditions under which ionization peaks can occur, but peaks at heights that satisfy (5) are the simplest to investigate theoretically and to compare with observations.

The predictions of the time-dependent theory, based on equation (3), are essentially the same with two significant exceptions which can be summarized as follows: (1) An initially uniform electron density profile will tend to the profile predicted by the steady-state theory only after a time t_{\min} . In particular, the height of the peak will essentially coincide with the height predicted by (5) for times $t \geq t_{\min}$. A measure of the time t_{\min} is given by the reciprocal of the gradient at the height z_p defined by (5):

$$t_{\min} \approx \tau \equiv \left[\partial w / \partial z |_{z = z_p} \right]^{-1} \quad (6)$$

(2) An initially non-uniform electron density profile will tend to the profile predicted by the steady-state theory after a time which exceeds t_{\min} , as defined by equation (6), but which also depends on the detailed characteristics of the initial profile. Both of these general characteristics limit the validity of the assumption that the electron density profile adjusts immediately to the instantaneous value of the drift velocity profile. For the slowly descending peak of the upper E region, the time constant τ of equation (6) ranges between 12 and 45 minutes, whereas for the lower E region (below 105 km) a typical value of τ is several hours. Hence, agreement between observation and the predictions of the steady-state theory cannot be expected, in general, in the lower E region. In this region the past history of both the ionization and drift velocity profiles are necessary to determine the instantaneous ionization profile. The observed persistence of distinctive features on the lower part of the profiles in Figures 1-5 verifies this conclusion.

The complete determination of the effective drift velocity w requires knowledge of the horizontal electric fields E_x and E_y , as well as of the vertical component of the neutral wind, U_z . None of these quantities were observable during the rocket launchings described in this report. The vertical wind U_z , has been found to be too small to be measured by the vapor trail method. However, an upper limit of 1-3 m/sec can be inferred from the known accuracy of the method (Manring and Bedinger, 1968). Thus, its contribution to the drift velocity is small, although not entirely negligible. The effects of horizontal electric fields are briefly discussed in the next section.

C. Results and Discussion

The electron density profiles and the drift velocity profiles are plotted together in Figures 1 through 5. The electron density profiles were measured with Langmuir probes, as described elsewhere (Smith, 1970). The plotted drift velocity, w' , does not include the contribution from the horizontal electric fields or from the vertical neutral wind, as mentioned in the preceding section. Table 1 summarizes one aspect of the comparison between observations and theoretical predictions. The first two columns list the NASA vehicle number and the launch time. The next two columns list the height of the electron density peak as observed by the Langmuir probes and as predicted from the plotted ionization drift velocity profile. For rocket flight 14.367 the conditions (5), mentioned as sufficient for the formation of an ionization peak, do not occur. Instead the drift velocity profile exhibits a broad and shallow minimum centered at 119.5 km. The existence of a minimum in the absolute value of the ionization drift velocity is also conducive to the formation of an ionization peak (Constantinides, 1968). Because this minimum is very broad and shallow for flight 14.367, the predicted height is somewhat uncertain. Hence, its value has been enclosed in parentheses in Table 1. The fifth column lists the difference between the observed and predicted heights of the upper peak. This difference is to be compared with the observed half-width of the peak which is listed in the last column. In the first four cases the height differences are less than the observed

TABLE 1

COMPARISON OF OBSERVED AND PREDICTED PEAK HEIGHTS

NASA Rocket No.	Launch Time (EST)	Height of Observed (Km)	Upper Peak Predicted (Km)	Height Difference (Km)	Peak Half-Width (Km)
14.364	0009	140.0	136.2	3.8	6.0
14.365	0130	140.0	142.5	-2.5	24.0
14.366	0300	128.0	128.8	-0.8	5.4
14.367	0430	119.5	(119.5)	(0.0)	3.0
14.208	0602	109.0	107.5	1.5	1.2

half-widths. Since the upper peak is relatively isolated, and since the half-width of the peak exceeds the discrepancy between observed and predicted peak heights, the agreement between observations and predictions cannot be regarded as fortuitous.

The uncertainties in the predicted values are due primarily to the following sources: (1) In the height region considered, the photographic triangulation method contains an uncertainty of one kilometer in the determination of the absolute height of a measurement of the neutral wind. (2) The computation of collision frequencies, and hence of the ionization drift velocity profile was based on the 1962 U.S. Standard Atmosphere, which may be significantly different from the actual atmosphere on the night of the observations. (3) As stated in section 2, a comparison of the instantaneous electron density profile with the instantaneous ionization drift velocity profile will not in general lead to exact agreement. (4) the plotted drift velocity profile does not contain the contributions of the horizontal electric field and of the vertical neutral wind.

Given these uncertainties, the agreement between observed and predicted heights exhibited in Table 1 must be considered good. In fact, the good agreement encourages the speculation that the horizontal electric field and the vertical neutral wind contribute little to the drift velocity, at least in the vicinity of the observed electron peaks. That vertical neutral winds play a minor role is not surprising because these winds are known to be small. On the other hand, a horizontal electric field of one volt per kilometer would contribute about 15 meters per second to the drift velocity in the upper E region. The effects of a contribution of this magnitude would certainly have been evident on the electron density profile. That they are not implies either that electric fields were small on the night of the observations or that the contributions of the two horizontal components cancelled each other. The second explanation is quite plausible because the two horizontal components of the electric field contribute with about equal weight to the ionization drift velocity in the region of the observed peaks.

Other simultaneous measurements of winds and ionospheric structure have been previously reported. (SMITH, 1966, BEDINGER and KNAFLICH, 1966). Often peaks above 110 km on the electron density profiles appeared at heights which are consistent with the expected distribution by horizontal winds. The heights of some of these layers were 122 km on the morning of 7 November 1962, 114 km on the morning of 15 July 1964, 150 km on the morning of 8 October 1964, and 132 km on the evening of 7 October 1964.

Another series of wind measurements were made during the night of 13-14 February 1969. There were no rocket-borne probes but ground based ionosondes furnished extensive coverage. In contrast to the 1968 data, the ionosondes observed very little ionization in the E region throughout the night and at no time recorded layers of the magnitude observed in 1968. The vertical drifts computed from the observed winds indicated that ionization was moving upward and out of the region above 120 km during the entire night.

In the lower E region no clearcut relation exists between the drift velocity profiles and the corresponding electron density profiles. Because of the long time constants involved in the evolution of an electron density profile from a given drift velocity profile, as mentioned in Section C, no attempt has been made to analyze the data from this region. Theoretical discussions of the complex structure of the lower region have been given by Chimonas and Axford (1968) and Layzer (1969).

D. Recombination Coefficients and Production Rates

It is possible to obtain a good estimate of the recombination coefficient α of equation (4). Two methods have been used to obtain this estimate. The first assumes the production rate P is known. The second method assumes only that the production rate is known to within a constant.

Method 1

In the vicinity of a peak that satisfies equation (5) it is assumed that

$$w(z) = -\delta(z - z_p)$$

and

$$N(z,t) = N_p(t) \exp \left\{ -\ln 2 \left[\frac{z-z_p}{h} \right]^2 \right\}$$

where z_p is the height of the peak, N_p is the peak density at the time t , and h is the half-width of the peak. The parameters z_p and h are in general time-dependent. Evaluating equation (3) at $z = z_p$ yields the result

$$\frac{\partial N_p}{\partial t} = (\delta - 2 \ln 2 D/h^2) N_p + P - \alpha N_p^2 \quad (7)$$

The five sequential measurements of the electron density profile permit the calculation of the time derivative $\partial N_p / \partial t$. The gradient α of the drift velocity profile at the peak, the half-width h , and the peak density N_p are obtained from the data. The diffusion coefficient D is known. Hence equation (7) provides a relation between the recombination coefficient α and the production rate P . If the latter is known, α can be computed from equation (7).

Method 2

In this method, equation (7) is supplemented by a second equation derived as follows. Assume that the electron production rate is proportional to the theoretical value, the proportionality factor being a constant independent of height. For each observation, equation (3) is integrated with respect to height between z_0 and z_p , where z_p is the height of the upper E region peak and z_0 is the first null in the drift velocity profile below z_p . If account is taken of the fact that w vanishes at z_p and at z_0 , and that $\partial N / \partial z$ vanishes at the peak, the following equation is obtained:

$$\frac{d}{dt} \int_{z_0}^{z_p} dz N(z,t) + N(z_0,t) \frac{dz_0}{dt} - N(z_p,t) \frac{dz_p}{dt} + D(z_0) \left. \frac{\partial N}{\partial z} \right|_{z=z_0}$$

$$= \lambda \int_{z_0}^{z_p} dz P(z) - \int_{z_0}^{z_p} dz \alpha(z) N(z,t)^2 \quad (8)$$

The left side of this equation can be calculated from the data. The first integral on the right is calculated from the theoretical production rates. (OGAWA AND TOHMATCU, 1966). The proportionality factor λ is an unknown parameter. The second integral involves the recombination coefficient under the integral sign. However, because α varies slowly with height compared to the square of the density, and because the integral is essentially determined by contributions from the vicinity of the peak, α may be taken outside the integral and replaced by its value at the peak. Equation (8) in conjunction with equation (7), in which P is replaced by λP , constitute two equations in the unknowns α and λ . This second method provides, in a sense, a test of the redistribution theory over a height range in excess of 20 kilometers for the observations reported here.

Table 2 gives the results of the calculations. The first line lists the NASA vehicle identification number. The second and third lines list the observed values of the recombination coefficient as calculated by the first and second methods, respectively. The fourth line contains published laboratory values of the recombination coefficient, (Ogawa and Tohmatsu, 1966) adjusted for the temperature at the observed peak heights on the basis of the 1962 U.S. Standard Atmosphere. It has been assumed that the dominant ion is NO^+ . The fifth line gives the ratio of the observed (by Method 1) recombination coefficient to the laboratory value. The last line gives the ratio of the observed production rate, as calculated by Method 2, to the theoretical value.

For the first three cases, the ratio of observed to laboratory value for the recombination coefficient ranges between 0.54 and 0.74 (average value = 0.6). The agreement between observations and theory must be considered good in view of the uncertainties listed in Section 3. For the last case (flight 14.208) the observed value of the recombination coefficient is only 2% of the laboratory value. At the time of the observation, the solar zenith angle was 98° , and the electron density profile still had the characteristic nighttime minimum above 120 km and the irregular lower structure. On the basis of equation (7) it would require a production rate of 200 electrons/cm³/sec to sustain an NO^+ peak at this height. This value is much too high (Tomatsu, et al, 1965) for the conditions, and it appears that the low value of the recombination coefficient should be attributed to the dominance of a slowly recombining ionic species. Metallic ions with such characteristics have been observed in the region with mass spectrometers (Narcissi, 1968). However, no sporadic E layers at heights as great as 110 km have been reported to be composed of metallic ions. It is also thought that the total number of metallic ions present in the atmosphere is too small to be the primary source of the dense daytime sporadic E. Thus the composition of some lower nighttime layers and the dense daytime layers remain uncertain.

TABLE 2
 COMPARISON OF OBSERVED AND LABORATORY VALUES OF THE
 RECOMBINATION COEFFICIENT

NASA Rocket No.	14.364	14.365	14.366	14.208
$10^7 * \alpha_{\text{obs}} (\text{cm}^3 \text{s}^{-1})$ Method 1	0.73	0.82	1.47	0.06
$10^7 * \alpha_{\text{obs}} (\text{cm}^3 \text{s}^{-1})$ Method 2	0.72	0.78	1.51	0.06
$10^7 * \alpha_{\text{lab}} (\text{cm}^3 \text{s}^{-1})$	1.34	1.34	1.98	3.76
$\alpha_{\text{obs}} / \alpha_{\text{lab}}$	0.54	0.61	0.74	0.02
$\lambda = P_{\text{obs}} / P_{\text{theory}}$	0.78	0.50	2.58	1.07

The ratio of observed to theoretical production rates ranges between 0.5 and 2.6 (average value 1.2). The observed agreement lends further support to the validity of the redistribution theory and confirms the theoretical calculations.

E. Conclusions

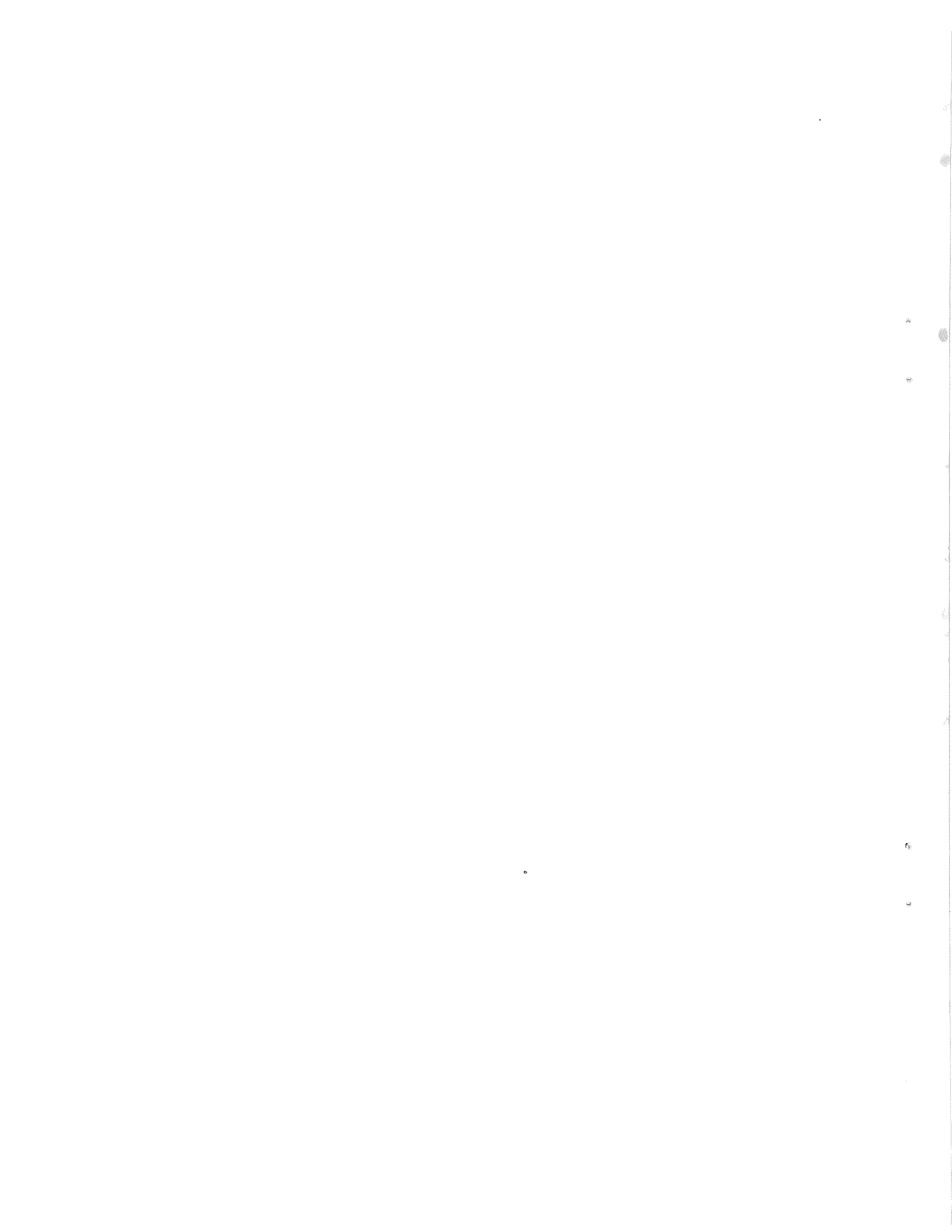
The analysis of the sequential observations of electron density profiles and neutral winds in the E region suggests the following conclusions:

- (1) In the upper E region (above 110 km) the structure of the electron density profile is governed by the vertical profile of the horizontal neutral winds. In general, the effect of the neutral winds is to redistribute the region's ionization. Specifically, the neutral winds determine the vertical profile of the ionization drift velocity, from which the location of the peak electron densities can be determined. Further, the peak electron density can be determined if the recombination coefficient of the dominant ion is known. The numerical results cited in Section 4 suggest that the dominant ion at night is NO^+ . The electron production rates deduced from the data are in good agreement with the theoretical estimates of Ogawa and Tohmatsu (1966). Finally, the analysis of the data indicates that the effects of horizontal electric fields were small. At present it is not possible to decide whether this result was due to the presence of very small electric fields during this particular observation, or whether the (algebraically) combined contribution of the two horizontal components of the electric field was small.
- (2) In the lower E region (below 110 km) the neutral winds produce relatively small drift velocities (generally less than 1 m/s). As a consequence, the redistribution mechanism requires a period of several hours to produce or to alter the observed structure of the electron density profile. This result probably explains the persistence of peaks and other features of the electron density profile in this region.

The successful application of the redistribution theory in relating the observed variations in winds and electron density increases the value of coordinated measurements of different parameters. Similar observations with the inclusion of mass spectrometers would verify the indicated variation of ion composition with height. Additional observations would also strengthen the inference concerning electric fields and vertical winds which are difficult to measure directly. Finally, coordinated observations would aid greatly in the interpretation and thus increase the usefulness of the large quantity of ionospheric drift data that is becoming available.

REFERENCES

- | | | |
|---|------|---|
| Axford, W. I., Cunnold, D. M.
and Gleeson, L. J. | 1966 | Planet. Space Sci. <u>14</u> , 909 |
| Axford, W. I. | 1963 | J. Geophys. Res. <u>68</u> , 769 |
| Banks P. | 1966 | Planet. Space Sci. <u>14</u> , 1085 |
| Bedinger, J. F. and Knaflich,
H. B. | 1966 | Radio Sci. <u>1</u> , No. 2, 156 |
| Chimonas, G. and Axford, W. I. | 1968 | J. Geophys. Res. <u>73</u> , 111 |
| Layzer, D. | 1969 | Nature <u>223</u> , 794 |
| Manring, E. R. and Bedinger,
J. F. | 1968 | Meteorological Monographs <u>9</u> ,
No. 31, 196 |
| Narcisi, R. S. | 1968 | Space Research VIII, 360 |
| Ogawa, T. and Tohmatsu, T. | 1966 | Rept. Ionos. Space Res. Japan,
<u>20</u> , 395 |
| Smith, L. G. | 1966 | Radio Sci. <u>1</u> , No. 2, 178 |
| Smith, L. G. | 1970 | J. Atmosph. Terr. Phys. |
| Tohmatsu, T., T. Ogawa, and H.
Tsuruta | 1965 | Rept. Ionos. Space Res. Japan,
<u>19</u> , 482 |
| Whitehead, J. D. | 1961 | J. Geophys. Res. <u>64</u> , 2188 |
| Reference is also made to the following unpublished material: | | |
| Constantinides, E. | 1968 | GCA-TR-68-14-N
Final Report on Contract No.
NASw-1676 |



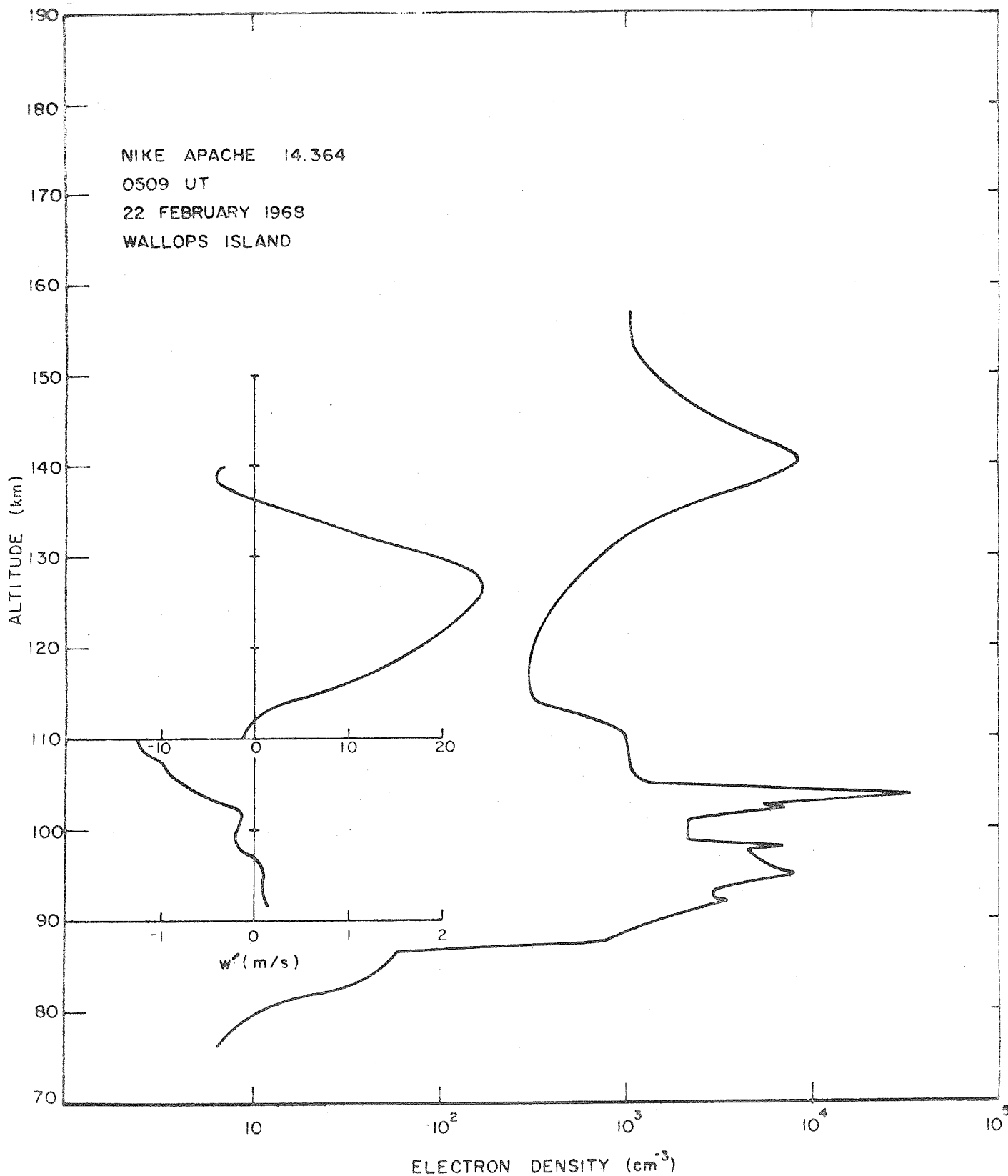


Figure 1. Observed electron density profile compared to vertical ion drift velocities computed from observed horizontal winds. Note the expanded scale at the lower altitudes where the drift velocities are small.

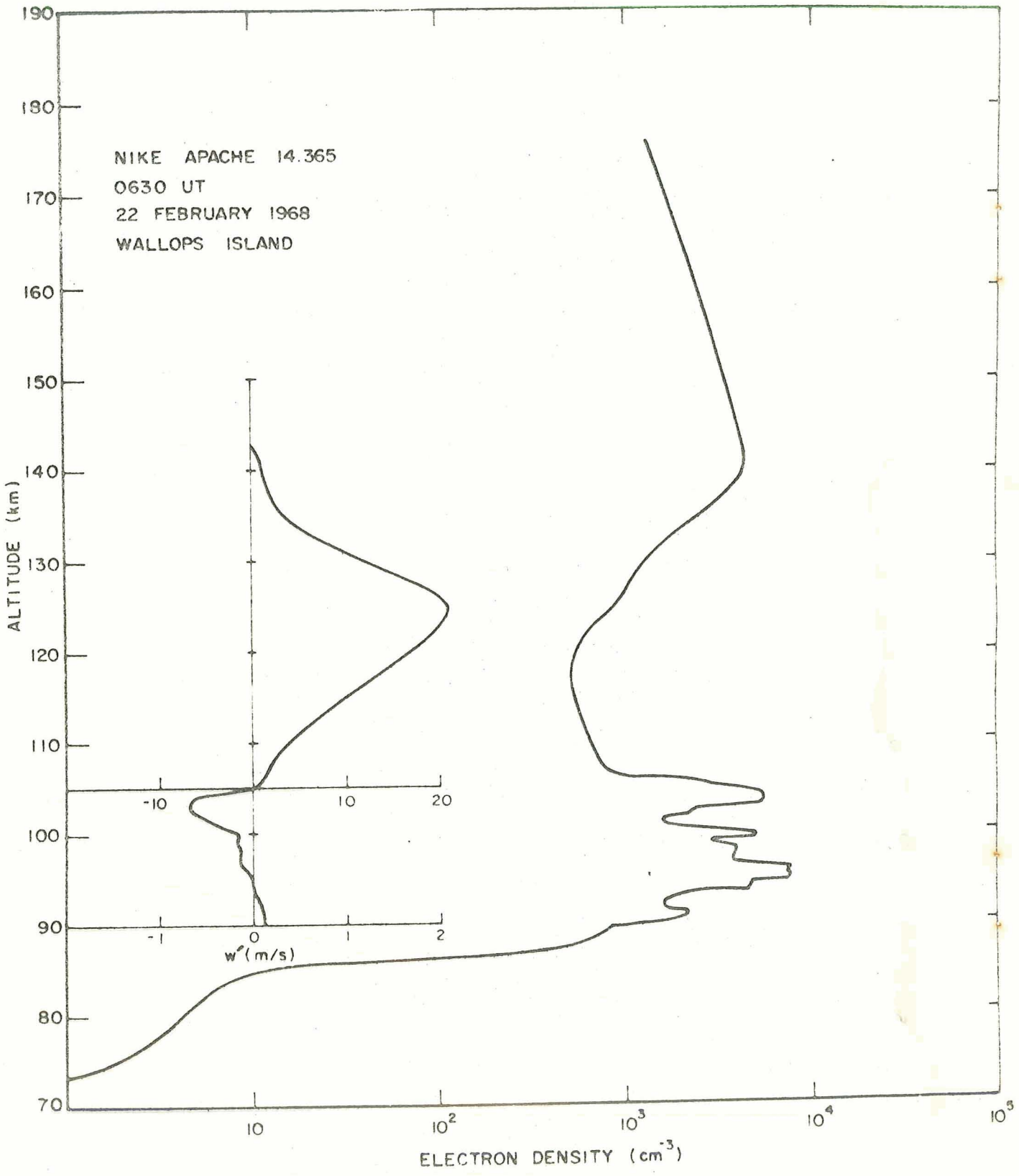


Figure 2. Observed electron density profile compared to vertical ion drift velocities computed from observed horizontal winds. Note the expanded scale at the lower altitudes where the drift velocities are small.

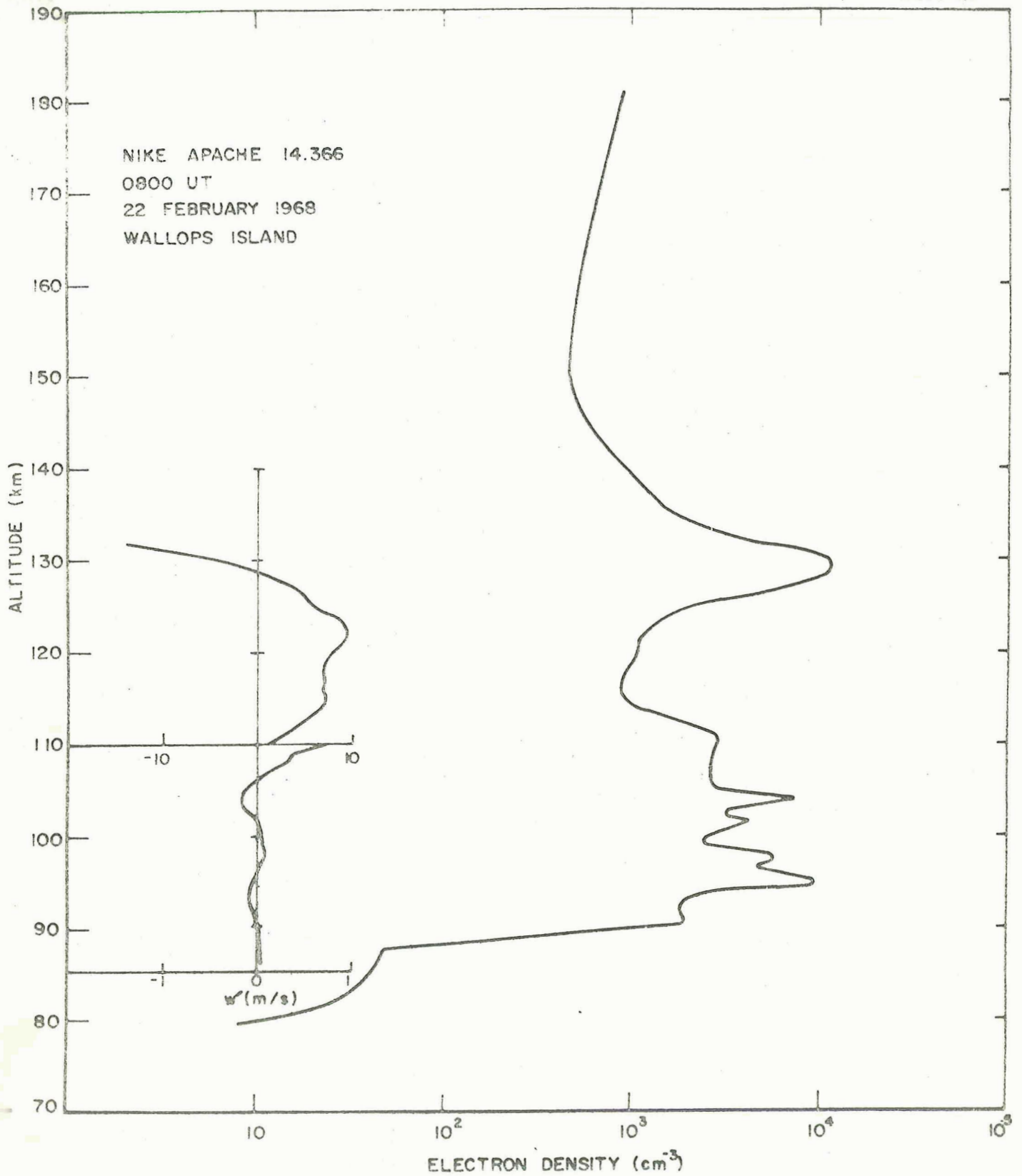


Figure 3. Observed electron density profile compared to vertical ion drift velocities computed from observed horizontal winds. Note the expanded scale at the lower altitudes where the drift velocities are small.

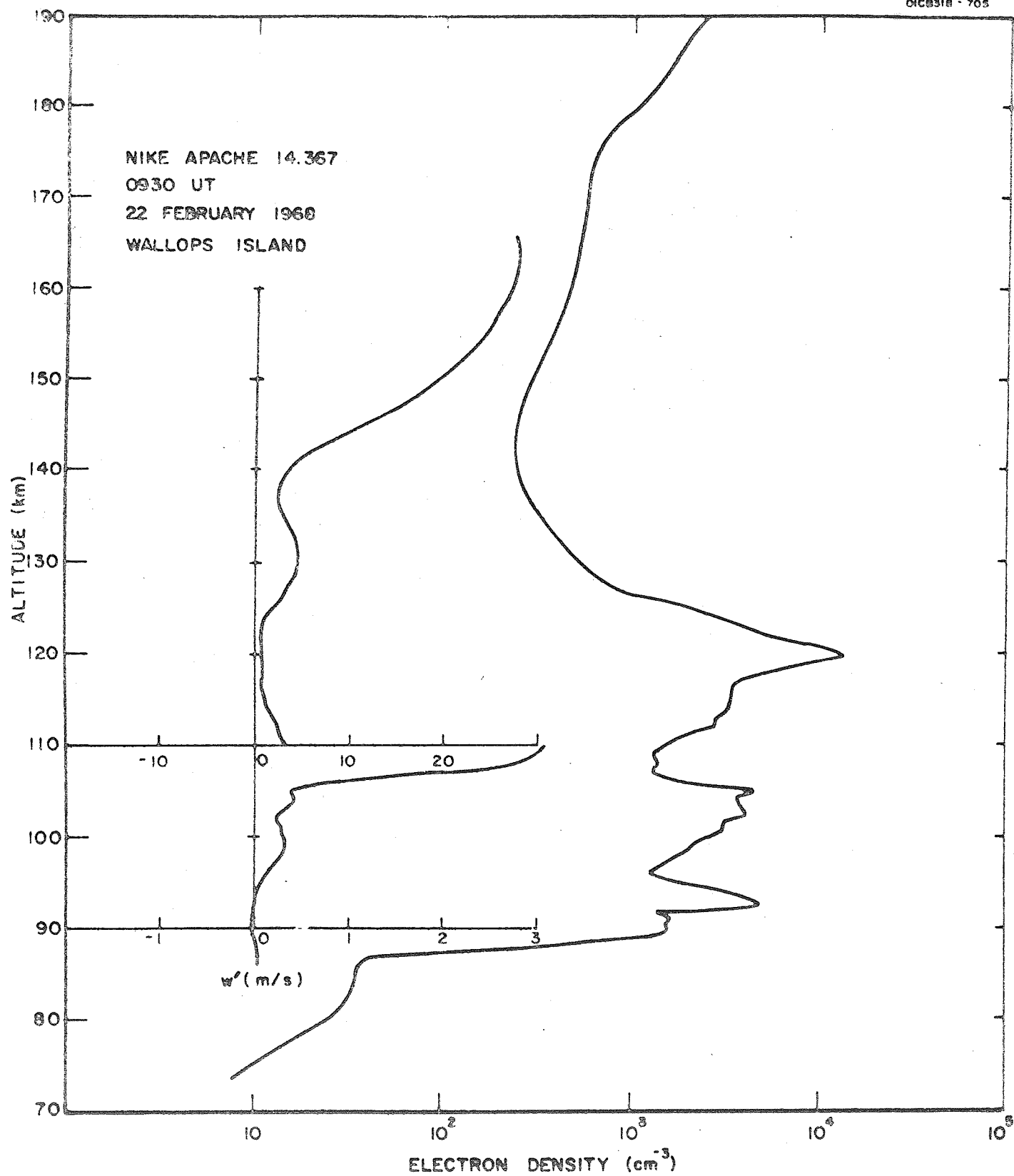


Figure 4. Observed electron density profile compared to vertical ion drift velocities computed from observed horizontal winds. Note the expanded scale at the lower altitudes where the drift velocities are small.

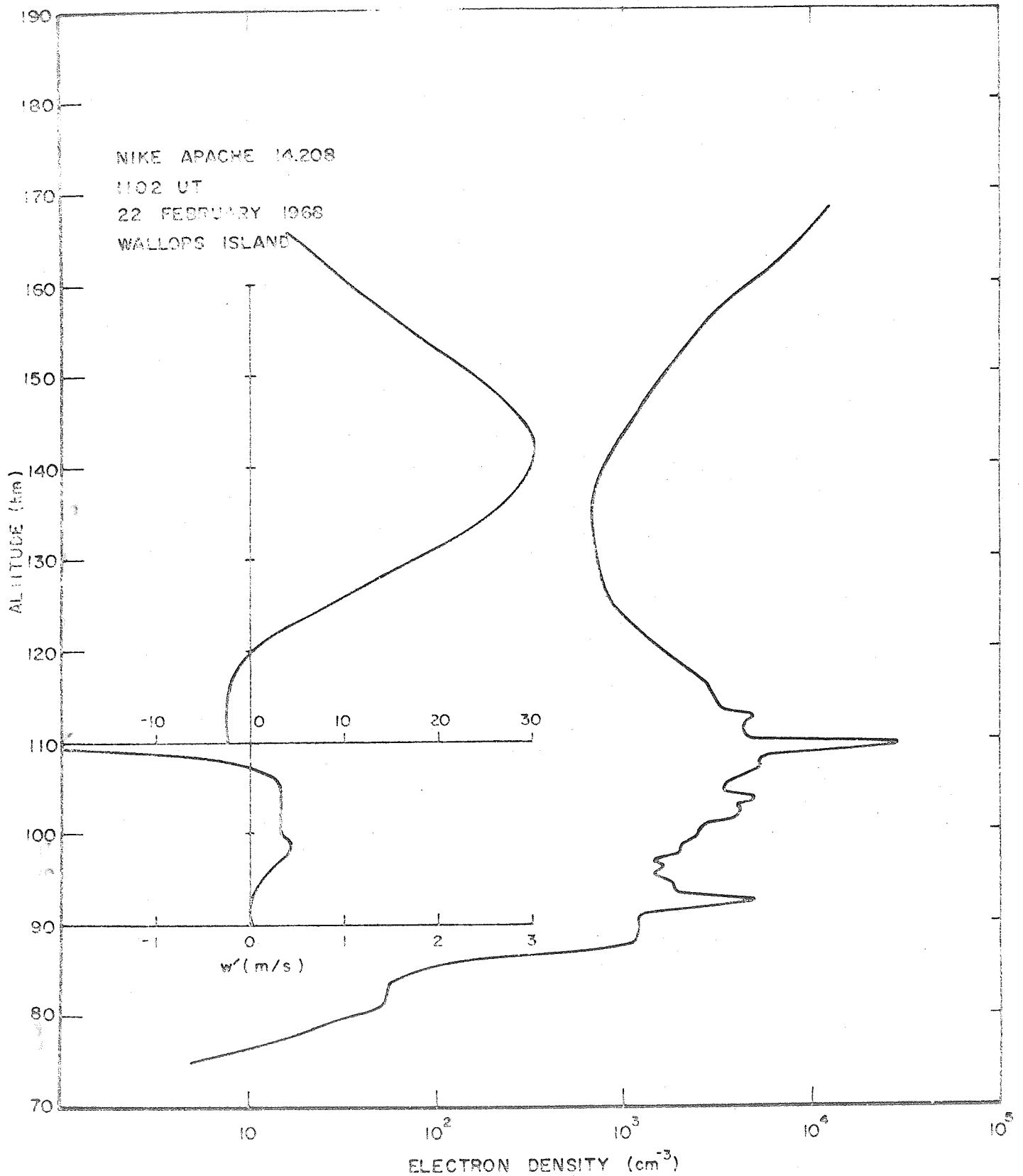


Figure 5. Observed electron density profile compared to vertical ion drift velocities computed from observed horizontal winds. Note the expanded scale at the lower altitudes where the drift velocities are small.

SECTION IV

MEASUREMENT OF WINDS ABOVE 200 KM

King-Hele (1964) has attributed part of the observed variation in the orbital inclination of certain satellites to a mean west to east wind above 200 km. The proposal is based on the analysis of the orbits of a large number of satellites which revealed consistent differences between the observed and predicted variations in orbital inclination. These differences have been interpreted by King-Hele as evidence that the angular velocity of the Earth's atmosphere is greater than that of the Earth. This interpretation requires that the ratio (atmospheric angular velocity)/(Earth's angular velocity) must increase with height from about 1.1 at 210 km to about 1.4 at 250 km which should be evidenced by an apparent mean west to east wind of 30 m/sec at 210 km, increasing to 130 m/sec at 260 km. It was also suggested that the west to east winds may be strongest in the late afternoon or evening and may become westward in the morning. This letter describes the results of an experiment designed to measure the winds above 200 km.

A Nike Tomahawk rocket system was used to form a trail of alkali metal vapor from 80 to 260 km over Wallops Island, Virginia, during the evening twilight of 13 February 1969. The hodograph of the observed winds is shown in Figure 1. At the higher altitudes the wind direction was very close to the direction of the rocket trajectory. This fact caused uncertainty in the correspondence of successive points determined by triangulation near apogee where the trail is nearly horizontal and expands rapidly. Good triangulation for determination of winds was attained up to 225 km, and since no evidence of shear above this height is apparent on the trail photographs, it is certain that the winds remained nearly constant at a speed of 100 m.sec to the east up to the top of the trail at 260 km.

The wind speed of 100 m/sec to the east around 250 km is very close to the prediction of King-Hele. However, the constant speed down to 165 km is not consistent with the super-rotating atmosphere hypotheses which predicts much smaller speeds at lower heights. Most of the previous wind measurements from motion of vapor trails are limited to altitudes below 180 km by the range of the small sounding rockets from which the vapor is released. However, there have been nine other observations of winds above 180 km from Wallops Island since 1959 including one up to 225 km. The speed and direction in which the trails were moving at the highest observed altitude are given in Table 1. Some measurements from other launch sites are listed also. All of the data have been previously reported (Bedinger, 1966) except the two most recent firings from Wallops Island. The 1961 measurements from Australia were reported elsewhere. (Jarrett et al, 1963.) Three of the five evening measurements from Wallops Island have an easterly component as does one of four from Italy and one of two from India. Results from two other trails during both twilights on 31 May 1968 in Australia were reported by Rees (1969) as being consistent with the King-Hele proposal.

TABLE I

Launch Site	No.	Observations Date/Time	Alt. (km)	Windspeed (m/sec)	Direction of Motion (Deg. from North)
Wallops Island (38°N, 75.5°W)	1	8/17/59 A.M.	225	110	225
	2	4/17/62 A.M.	190	110	270
	3	5/23/63 P.M.	200	60	260
	4	1/16/64 A.M.	190	230	240
	5	7/14/64 P.M.	180	80	240
	6	7/15/64 A.M.	190	120	230
	7	11/10/64 P.M.	185	70	70
	8	11/11/64 P.M.	195	70	20
	9	1/18/66 A.M.	180	50	270
	10	2/13/69 P.M.	260	100	90
New Mexico (32.5°N, 106.5°W)	11	11/26/57 A.M.	200	40	240
Italy (39.6°N, 9.5°E)	12	4/19/61 P.M.	185	145	180
	13	4/20/61 A.M.	190	135	230
	14	9/07/61 P.M.	200	100	140
	15	5/20/61 P.M.	195	80	180
	16	5/21/61 P.M.	190	90	180
Pakistan (26°N, 67°E)	17	12/01/64 A.M.	205	40	240
India (8.5°N, 77°E)	18	11/21/63 P.M.	180	250	345
	19	1/08/64 P.M.	190	75	45
Australia (31°S, 137°E)	20	3/06/61	180	130	300
	21	11/28/62	200	110	345

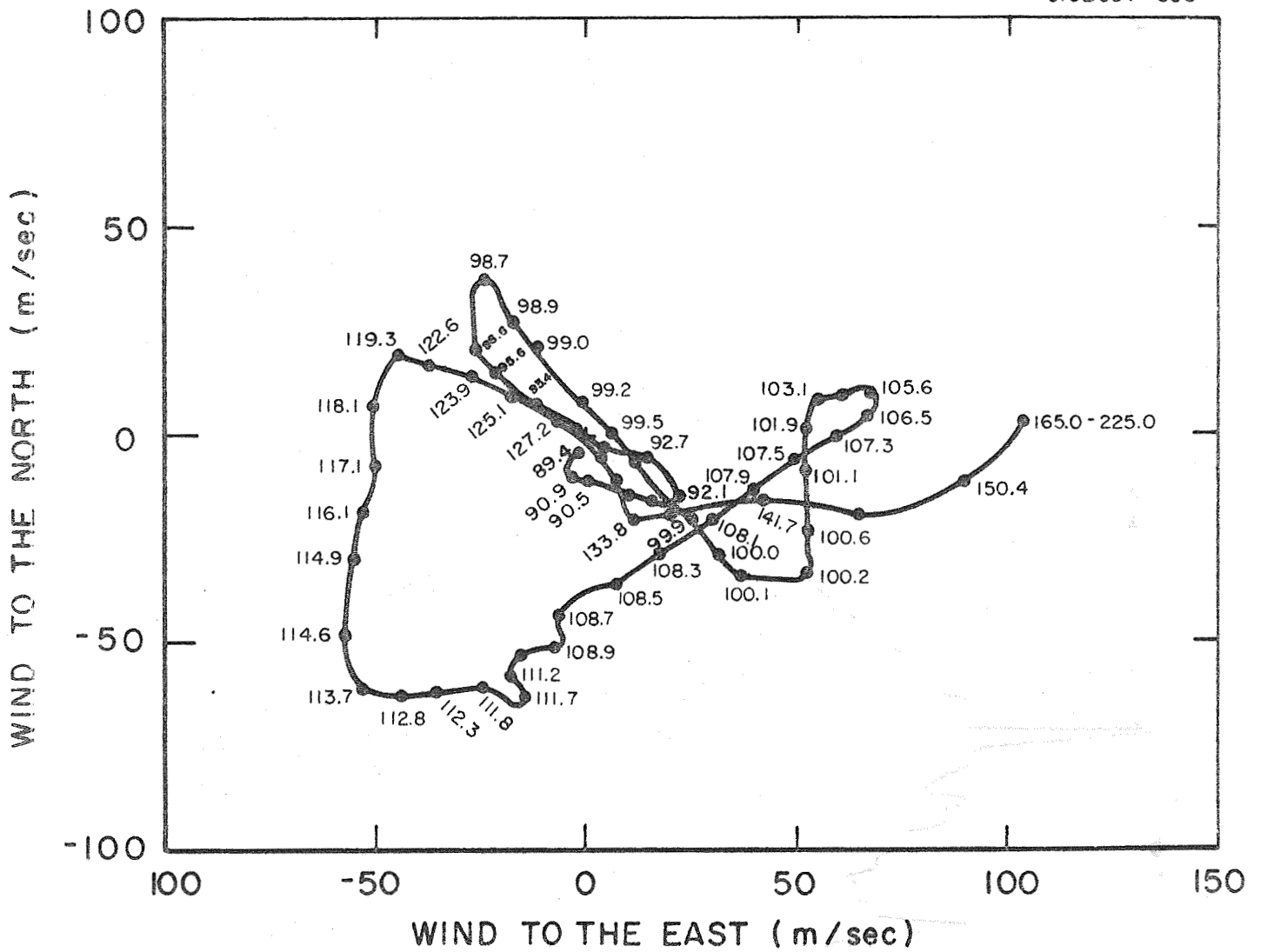


Figure 1. Hodograph of wind derived from a vapor trail over Wallops Island, Virginia, during evening twilight of 13 February 1969. Heights of data points are marked in kilometers.

The vapor trail measurements are shown in hodograph form in Figures 2 and 3. The winds in the evening are variable and show no obvious preferential direction. However, the morning winds are all toward the southwest.

Many authors have considered various aspects of the source and structure of a high altitude wind system. Most recently, Challinor (1969) computed the winds resulting from an asymmetric global pressure system and hydromagnetic forces. In the mid-latitudes, the predicted flow is eastward during evening twilight in accordance with King-Hele's experimental results, but is not strongly supported by the vapor trail data in Figure 2. The model predicts winds toward the southwest in the morning twilight at mid-latitudes in the northern hemisphere and the data in Figure 3 are in complete accord.

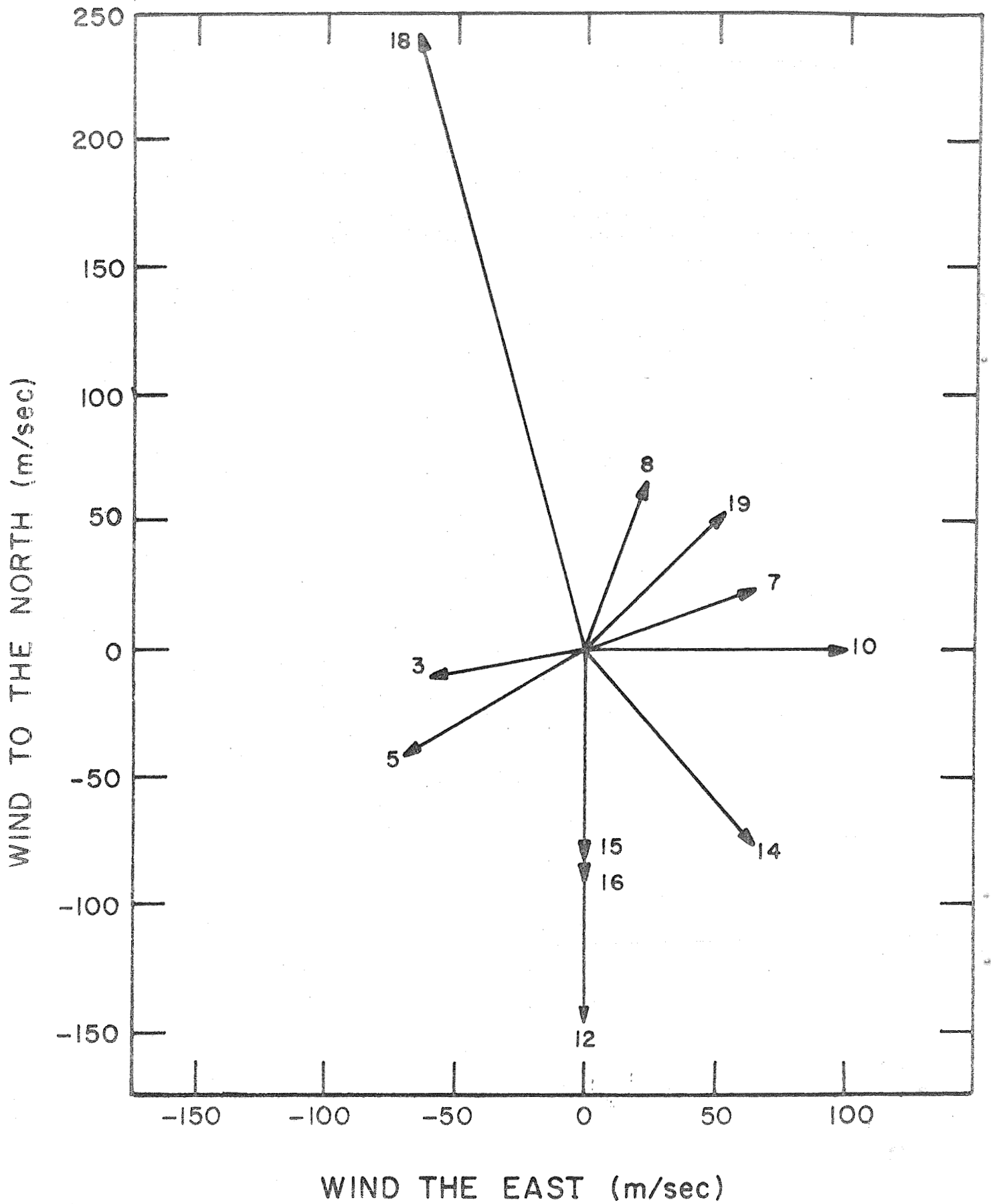


Figure 2. Hodograph of wind measurements during evening twilight from Table 1.

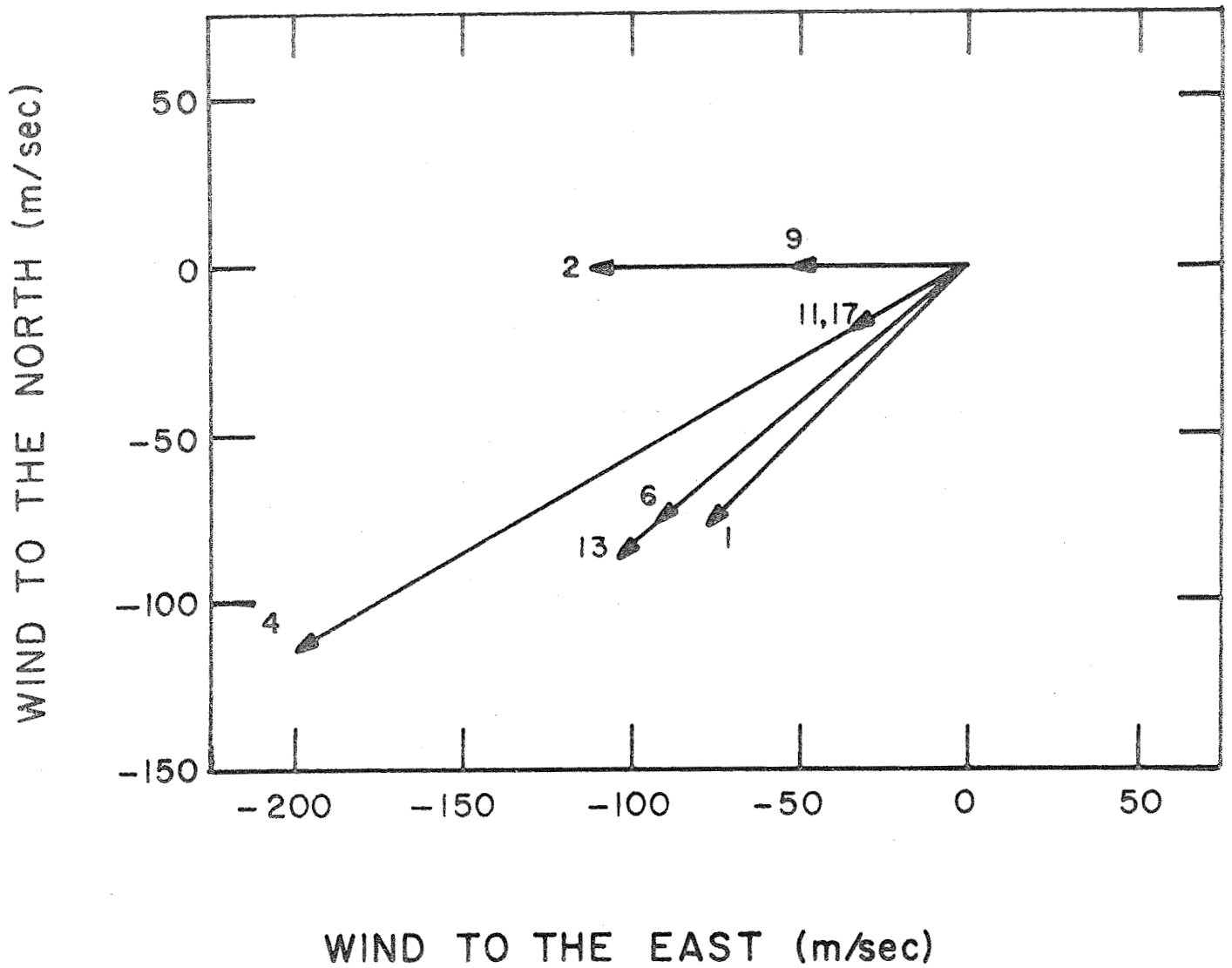


Figure 3. Hodograph of wind measurements during morning twilight from Table 1.

REFERENCES

- Bedinger, J. F., "Compendium of Wind Data From the Vapor Trail Technique," GCA Tech. Rept. 66-7-N, NASA Contract NASw-1083, March 1966.
- Challinor, R. A., "Neutral-Air Winds in the Ionospheric F Region for an Asymmetric Global Pressure System," Planet. Space Sci., 17, 1097, 1969.
- Jarrett, A. H., G. J. McGrattan and F. J. Smith, "The Measurement of High Altitude Wind Velocities From Vapor Releases - III," Planet. Space Sci., 11, 1319, 1963.
- King-Hele, D. G., "The Rotational Speed at the Upper Atmosphere Determined From Changes in Satellite Orbits," Planet. Space Sci., 12, 835, 1964.
- Rees, D., "High Altitude Profiles of Wind Velocity, Temperature and Density," Presented at the Twelfth Meeting of COSPAR in Prague, Czechoslovakia, May 1969.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Detailed summaries of results are included at the end of the preceding sections. A general assessment of the program and recommendations for future programs are presented here.

The simultaneous measurements of winds and electron density profiles and the subsequent analysis of the data have produced two major results concerning the lower E region. First, a simple theory of redistribution of charge by horizontal winds is applicable in the region above about 110 km, and secondly, the descent of the upper layer is probably a regular occurrence in the E region at night furnishing a source of electrons to the lower levels.

The simple theory relates the two sets of observations so precisely that consistent values of recombination rates and production rates were obtained. It is also evident that the effects of vertical winds and electric fields were small during this period which suggests that this method may allow an indirect determination of these parameters which are difficult to measure directly at the present time.

The positive results from the coordinated measurements indicate that more observations should be made in order to investigate the effects of magnetic activity, latitude, and various wind patterns. It is also suggested that other parameters such as composition and temperature should be included. The successful application of the theory will be helpful in understanding other observations such as the various types of drift measurements which result from radio probing of the ionosphere. A large amount of such data is presently becoming available.

Finally, it should be noted that these results are from nighttime observations only, although daytime measurements are equally important. However, daytime winds with the required resolution and over the necessary height range are not being measured at this time. It is strongly recommended that such a program be initiated. It has been demonstrated that the vapor trail method can be adopted for daytime use and a proposal to do so has been submitted.