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Aircraft Measurements of Electrified Clouds at Kennedy Space Center

Final Report: Part III

1989 Flights Sponsored by the National Aeronautics and Space Administration and the United States Air Force under NASA Grant NAG8-751

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August 21, 1990

(NASA-CR-186964) AIRCRAFT MEASUREMENTS OF ELECTRIFIED CLOUDS AT KENNEDY SPACE CENTER, PART 3 Final Report (New Mexico Inst. of Mining and Technology) 207 p CSCL 04B

N91-13039

Unclas G3/47 0303422

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1 Introduction

The space-vehicle launch commit criteria for weather and atmospheric electrical conditions in use at Cape Canaveral Air Force Station (CCAFS) and Kennedy Space Center (KSC) have been made quite restrictive because of the past difficulties that have arisen when space vehicles have triggered lightning discharges after their launch during cloudy weather. With the present ground-based instrumentation and our limited knowledge of cloud electrification processes over this region of Florida, it has not been possible to provide a quantitative index of safe launching conditions. The very conservative restrictions placed on space vehicle launchs, stated in Part I of this report, are the result of this limited knowledge.

While these restrictions appear to eliminate any significant hazards arising from lightning strikes, they also reduce greatly the opportunities for launches. Atmospheric electrical hazards do not always exist during the weather conditions specified in the launch criteria but when they do occur, the charges that cause them may be difficult to detect from the ground due to their localized nature, rapid growth and to screening by other distributions of charge. If better knowledge of the electrical conditions aloft over the launch area were available on a timely basis to the meteorologist advising the launch director, more launches could be made during periods with cloudy weather containing no electrical hazards. Airborne measurements of the electricity in clouds are therefore desirable so that an evaluation can be made of the hazards associated with the various weather conditions now prohibited in the launch commit criteria. The necessary measurements can be made with the use of a suitably instrumented airplane.

Part I of this report describes the initial phase of a program to study clouds that might pose a threat to space vehicles launched through them. It describes flights made over Kennedy Space Center during the fall of 1988 using an airplane equipped to measure electric field and other meteorological parameters. It also describes this airplane, the New Mexico Institute of Mining and Technology / Office of Navel Research (NMIMT / ONR) Special Purpose Test Vehicle for Atmospheric Research, or SPTVAR, and the real-time data display developed during the project.

Part II of the report is a case study of a situation when the electric field mills in the surface array at KSC indicated field strengths greater than 3 kV/m while SPTVAR flying directly over them at an altitude of 3.4 km measured field strengths less that 1.6 kV/m.

This report, Part III of the larger report, summarizes flights made by SPTVAR during a second deployment to Florida during the summer of 1989. It also presents the findings based on the data gathered and discusses the progress made during the second year of the project. The summer 1989 study was carried out with the support and guidance of Col. John Madura, Commander of Detachment 11, 2nd Weather Squadron, USAF, at

Patrick Air Force Base (PAFB) and Cape Canaveral Air Force Station. The research group included our Air Force liaison, Capt. T. Strange, and National Aeronautics and Space Administration (NASA) personnel Launa Maier and John McBrearty at Kennedy Space Center, plus Mark Wheeler of Computer Science Raytheon. Operational support provided by Air Force and NASA personnel and Mr. Wheeler included weather forecasts, weather and surface electric field information, and copies of radar displays and satellite photographs of the clouds. Universal format tapes of data from the McGill WSR74 radar at PAFB were supplied by Doug Mach at Marshall Space Flight Center. The principal geographical area of interest for the study was the same as that in the fall of 1988 and is shown in Fig. 1, which is reproduced from Part I of this report. The numbers used at KSC to identify field mill sites have been added to the map and are used throughout this report when referring to specific mills.

In much of this report numerical quantities are quoted in SI units. In cases pertaining to operational procedures which commonly use only conventional units the SI values are either omitted or appear between parentheses following the conventional units. Throughout this report when quoting electric field values measured with SPTVAR the sign convention used is that the direction of an electric field vector at some point in space is the direction of the electric force that would be experienced by a small positive test charge located there. Thus a negative charge aloft produces an upward directed or "positive" electric field at the surface of the earth. The KSC contour plots use another parameter, the (electric) potential gradient (∇V), in place of electric field (E). The two are related by $\nabla V = -E$.

A list of acronyms used in this report is included in Appendix A.

2 Project Goals

- Develop and demonstrate techniques for measuring the electric field aloft and locating regions of charge during flight.
- Within and near clouds, characterize the electric conditions that are presently identified as a threat to space launch vehicles.
- Study the correlation between the electric field aloft and that at Kennedy Space Center's ground-based field mill array for a variety of electrified clouds.

3 Summary of Flights

Table 1 is a summary of the 22 flights made by SPTVAR during the summer of 1989, arranged in chronological order. The table shows the take-off and touch-down times and

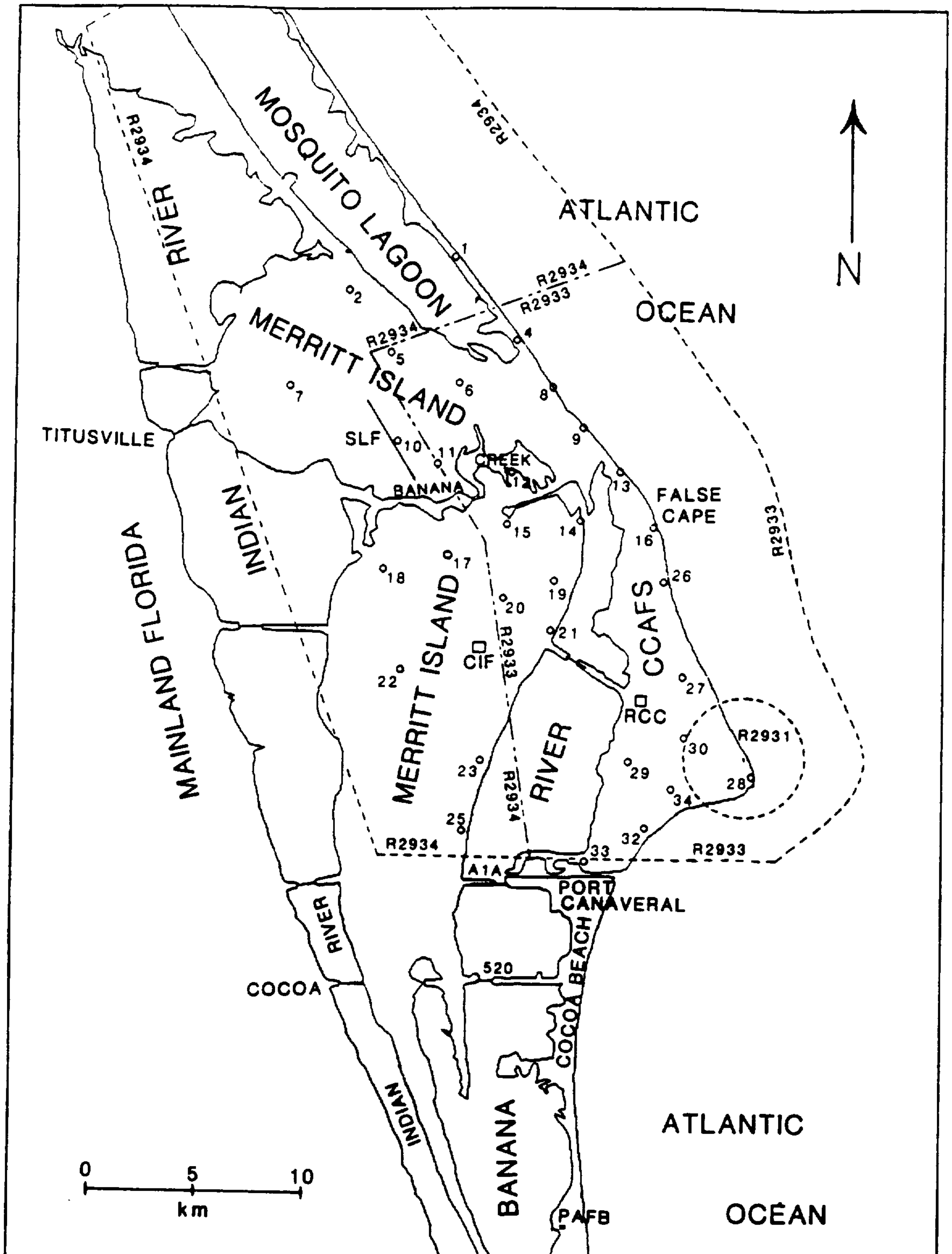


Figure 1: Map of Kennedy Space Center and surroundings showing geographic features, field mill sites (○) and relevant restricted airspace boundaries, such as those of R2934. Throughout this report the field mills are referred to by their site numbers, shown adjacent to the site symbols in this map.

primary flight altitudes for each flight. Brief comments summarize the highlights of each flight and the presence or absence of any significant electric field.

Table 2 arranges the 16 flights of meteorological interest according to whether studied clouds were electrified or not and lists local time (EDT) at take-off, flight duration, cloud top heights, and the 0 °C, −10 °C and −20 °C temperature levels. Cloud top heights with a "P" suffix are visual estimates reported by the SPTVAR pilot, whereas those with an "R" suffix are radar echo tops determined by the McGill WSR74 radar at Patrick Air Force Base. Cloud top heights are not stated in the table when they were not visible to the pilot and when radar heights are not available. Brief comments summarize the highlights of each flight. In both tables "No E" means $|E| < 200$ V/m was determined from a strip chart recording of electric field components which was made during the flight.

Detailed summaries of the individual flights listed in Table 2 appear in Appendix A.

4 Results

4.1 Unelectrified clouds

During the first three flights listed in Table 2, the clouds over KSC that were investigated by SPTVAR all failed to show any indication of electrification, either in the SPTVAR data, or in that recorded by the surface field mill array at KSC. On the fourth day listed, 13 August, SPTVAR measured electric field over the north end of the Indian River due to a cloud to the west and northwest. The contour plot of the KSC surface field mill array data also showed an electric field over the north end of Merritt Island due to the cloud to the north-northwest. The clouds over KSC, however, were unelectrified. Since the clouds on all four of these days had tops above the +5 °C level, launch commit criteria weather rule B(1) would have been violated had a rocket been launched through them. On the other hand, the highest cloud top altitude over KSC for any clouds during these SPTVAR flights was about 17,000 ft (5.5 km) on 13 August. The corresponding cloud top temperature was about −5 °C and thus no other launch criteria were violated. On the last three days in this category the tops of the clouds studied by SPTVAR did not exceed the +5 °C level and the clouds were unelectrified.

4.2 Electrified clouds

For the remainder of the flights, SPTVAR measured electric fields during at least part of each flight. Near the beginning of the flight on 19 August SPTVAR flew around a cloud as it first became electrified. All the other electrified clouds were already electrified when

Table 1: Chronological Summary, SPTVAR flights, KSC–Patrick AFB, 1989.

Take-off and touch-down times in this table are Universal Coordinated Time (Z).

DATE	DAY	T-O (Z)	T-D (Z)	ΔT (H:MM)	ALTITUDE (kft)	COMMENTS
21 Jul.	89202	1934	2102	1:28	–	Test flight, no clouds.
22 Jul.	89203	1906	2006	1:00	–	Test flight, no clouds.
25 Jul.	89206	1638	1753	1:15	–	No clouds, all instruments operational.
29 Jul.	89210	1848	2204	3:16	12–19	$\vec{E}$ from anvil and cumulus clouds.
30 Jul.	89211	1855	2148	2:53	13-21	Electrified cloud north-northwest of PAFB, $E_Y \sim 100$ V/m under anvil cloud.
4 Aug.	89216			0:05	–	Test flight.
8 Aug.	89220	1812	2006	1:54	12	Cloud tops to ~ 15,000 ft, no $\vec{E}$.
9 Aug.	89221	1720	1913	1:53	12-14	$\vec{E}$ from strongly electrified cloud.
10 Aug.	89222	1638	1854	2:16	12	Clouds tops never exceeded 14,000 ft, no $\vec{E}$.
11 Aug.	89223	1829	2101	2:32	12	Cloud tops to ~ 17,000 ft, no $\vec{E}$.
13 Aug.	89225	1711	1853	1:42	6-12	Some cloud tops to ~ 17,000 ft, no $\vec{E}$.
14 Aug.	89226	1811	2057	2:46	6, 17	$\vec{E}$ from cloud over ocean, very localized $\vec{E}$ in cloud near mills 16 and 26, and $\vec{E}$ from large electrified cloud over SLF and Mosquito Lagoon.
18 Aug.	89230	1708	2006	2:58	11	$\vec{E}$ from clouds west of Indian River, ΔE due to triggered lightning.
19 Aug.	89231	1553	1849	2:56	12	Electrified cloud over Merritt Island, E_{XY} plot used to guide study of cloud charge, SPTVAR flew by field mills on balloon teather.
20 Aug.	89232	1405	1626	2:21	12	$\vec{E}$ from clouds moving onshore from Atlantic Ocean.
22 Aug.	89234	1742	1859	1:17	–	Engine test.
25 Aug.	89237	1819	1826	0:07	–	Flight aborted due to engine problem.
26 Aug.	89238	1811	2035	2:24	12	$\vec{E}$ from electrified cloud over mills 23 and 25 and from a second cloud that was west of mill 18.
27 Aug.	89239	1621	1734	1:13	12	Low cumulus, no $\vec{E}$.
29 Aug.	89241	1748	1900	1:12	8	Practiced side-by-side flight with Aeromet Lear Jet, but there was no $\vec{E}$.
30 Aug.	89242	1630	1816	1:46	12	Max cloud tops to ~ 20,000 ft, no $\vec{E}$.
1 Sep.	89244	1700	2008	3:08	12	Weak $\vec{E}$ in cloud to 30,000 ft over mill 7.

Table 2: Meteorological Summary, SPTVAR flights, Kennedy Space Center, 1989.

Eastern Daylight Time (EDT) is 6 hours less than Universal Coordinated Time (Z).

DATE	T/O TIME (EDT)	CLOUD TOPS (kft)	0, -10, -20 °C LEVELS (kft)	COMMENTS
				Clouds with no associated Electric Field
8 Aug.	1212	15 (P)	17, 20, –	No $\vec{E}$.
10 Aug.	1038	14 (P)	15, 21, 26	No $\vec{E}$.
11 Aug.	1229	17 (P)	14, 20.5, –	No $\vec{E}$.
13 Aug.	1111	~ 17 (P)	15, 20, 25	No $\vec{E}$ from clouds over KSC. SPTVAR measured $\vec{E}$ of clouds to west.
27 Aug.	1021	8 (P)	15, 22, 27.5	No $\vec{E}$.
29 Aug.	1148	–	17, 23, 27	No $\vec{E}$.
30 Aug.	1030	12 (P)	18, 22.5, –	No $\vec{E}$.
				Cloud moving onshore from the Atlantic Ocean
20 Aug.	0805	29 (R)	15.5, 21, –	SPTVAR measured $\vec{E}$ in a cloud that came onshore over Port Canaveral and moved northwest.
				Clouds that grew over land
29 Jul.	1248	–	16, 20, 26	SPTVAR performed roll, yaw and pitch manuvers in the E field of an anvil cloud. SPTVAR flew along sides of electrified cloud and was hit by lightning.
30 Jul.	1255	–	15, 20.5, 26	The study cloud was west of the Indian River. Late in flight SPTVAR flew under anvil cloud over KSC and measured $E_Y \sim 100$ V/m.
9 Aug.	1120	–	15, 20.5, 26	SPTVAR flew around sides of strongly electrified cloud over Merritt Island.
14 Aug.	1211	35 (R)	15, 21, –	SPTVAR measured $\vec{E}$ from cloud several miles off-shore, several times in small clouds near mill 16 with tops to 35,000 ft, and along edges of large electrified cloud which developed over the Shuttle Landing Facillity and then moved over Mosquito Lagoon and out over the Atlantic Ocean.
18 Aug.	1108	–	15, 21, –	SPTVAR measured $\vec{E}$ of anvil clouds, and ΔE due to a rocket-triggered lightning flash. SPTVAR struck by lightning during a cloud penetration.
19 Aug.	0953	28 (R)	28,000	1. SPTVAR Measured $\vec{E}$ of cloud as it electrified and later decayed. The E_{XY} plot was used to guide SPTVAR for repeted observations of positive charge in the cloud. 2. SPTVAR flew past field mills on balloon tether.
26 Aug.	1611	– – 13	15, 22, 27.5	SPTVAR studied two electrified clouds: 1st cloud was southwest of mill 25; many lightning flashes. 2nd cloud was west of mill 18.
1 Sep.	1100	30 (P)	17, 22, 27 –	1. SPTVAR recorded lightning signatures of cloud west of mill 7. 2. SPTVAR studied decaying slightly electrified cloud over mill 7.

SPTVAR began studying them. Many were so large and dynamic that SPTVAR avoided penetrating them, concentrating instead on measuring the characteristics of their external electric field.

4.2.1 Marginally electrified clouds and cloud charge persistence

Some understanding of the persistence and fate of electric charge in marginally electrified clouds was gained from clouds studied using SPTVAR on 19 and 20 August. The 19 August cloud was monitored through its full electrification cycle, lasting one hour. The cloud on 20 August was studied, also for one hour, as it came onshore over Port Canaveral subsequent to its initial electrification. Neither cloud made lightning, and negative charge in both clouds appears to have been removed as it fell to the ground on precipitation after the active electrification of the cloud ceased. The fallout of negative charge from the 19 August cloud occurred over a period of about 20 minutes. The decay of the negative charge was readily apparent in the strip chart and contour plots of the electric field data from the surface field mill array at KSC.

After the negative charge was removed, positive charge persisted in the 19 August cloud for at least another five minutes. This positive charge was above the negative charge and appears to have also fallen on precipitation as the cloud expired. The presence of positive charge detected by the airplane on this occasion was not evident in the data from the surface field mill array.

On 1 September SPTVAR measured weak electric fields near mill 7 which were due to a cloud which SPTVAR's pilot described at 1918 Z as having reached 30,000 ft (9.1 km) and gone soft on top. SPTVAR data for 1934 to 1938 Z indicate that there was a weak positive charge north-northwest of mill 7 and an even smaller negative charge south of mill 7. The pilot's comments indicate that the cloud over mill 7 was decaying during the time that it was studied by SPTVAR, 1920–1951 Z. It appears that this cloud experienced a brief period of electrification just before its dynamic growth stage came to an end.

Stronger electric fields were measured in a compact cloud that reached as high as 35,000 ft (10.6 km) over the Titan complex on 14 August. The radar reflectivity of this cloud reached 48 dBZ. Another more vigorous cloud grew over the Shuttle Landing Facility as the cloud over the Titan complex declined. This vigorous cloud became electrified by about the time it reached 30,000 ft (9.1 km) and continued to grow in height and area while becoming highly electrified.

4.2.2 Strongly electrified clouds

Anvil cloud electric fields

On three flights, 29 and 30 July and 18 August, SPTVAR measured electric fields due to anvil clouds. roll, yaw and pitch maneuvers conducted in an anvil electric field on 29 July provided data which partially confirm the calibration of the SPTVAR measurement of electric field components. Some anvil clouds had extensive fields which changed only slowly with time and position, such as the one early in the 29 July flight, while others, such as the one late in that flight when there were other clouds at lower levels, had much more complex electric fields.

Spatial variation of the electric field outside clouds

At a sufficient distance from a distributed charge within a cloud, the electric field of that charge should approximate the $1/r^2$ variation with distance of the electric field of a point charge of the same size located at the position of the distributed charge. On the flights of 13, 14, 18 and 19 August the spatial variation of the measured electric field with distance from the side of an electrified cloud was in qualitative agreement with this sort of expected behavior of the electric field of charge in the cloud. Although this behavior of the electric field does not rule out the presence of screening layers on the sides of clouds, it does indicate that screening layers, if they existed, were insufficient to fully screen the electric field of the charge within the clouds we studied.

Electric fields were measured several km away from strongly electrified clouds on 30 July and 13, 14 and 20 August 1989. For example, on several occasions while flying over the western most mills in the KSC surface field mill array (mills 7, 18, 22 and 25), SPTVAR measured electric field due to clouds west of the Indian River.

Rocket-triggered lightning

On 18 August, SPTVAR measured the change in the ambient $\vec{E}$ due to a lightning flash triggered by a rocket fired from the rocket-triggered-lightning site on the southwest shore of Mosquito Lagoon. From ΔE measured by SPTVAR we have estimated that this flash removed a total of about 60 coulombs of negative charge from the cloud.

4.2.3 Small unexplained cloud charge

On 14 August SPTVAR measured a small electric field variation, superimposed on the smoothly varying electric field of a cloud offshore, which appears to have been due to a small charge in a cloud near field mill 26. Five minutes earlier, at 1825 Z, the SPTVAR pilot had described the cloud over mill 26 as having an 8,000 to 10,000 ft top and that it was producing rain. The KSC field mill array contour plot for 1815 Z indicated a positive charge over mill 26 while the contour plot for 1830 Z indicated a weaker positive charge over mill 16. Thus the surface field mills indicated that the positive charge apparent from the SPTVAR data was present in the vicinity of mills 16 and 26 from 1815 to 1830 Z during which time the SPTVAR pilot had noted that the top of the cloud was only about 10,000 ft. Due to its low cloud top altitude this cloud was not a likely candidate for being electrified.

4.3 Real-time electric vector display used to guide airplane flight

On 19 August we used the real-time display of SPTVAR's track with E_{XY} barbs, described in Part I of this report, to guide SPTVAR's flight so as to sample the electric field of a region of positive charge several times in a short period of time. This study was presented in a poster session at the Fall Meeting of the American Geophysical Union in San Francisco, December 4, 1989.

4.4 Comparison of SPTVAR and KSC field mill array measurements

On two SPTVAR flights, 9 and 13 August 1989, the KSC display of constant surface ∇V contours gave a false indication of negative charge aloft. The apparent presence of charge aloft was suggested or implied by the presence of closed contours drawn by the contouring routine. See Figs. 49 and 13. In each case a closed contour was drawn around one or more of the westernmost KSC field mills despite there being no data to indicate that the electric field actually decreased to the west of the array. However, measurements of $\vec{E}$ made by SPTVAR revealed that there was no negative charge aloft over the mills around which the closed contours were drawn and that ∇V measured at the surface was due to an electrified cloud to the west of the Indian River.

This type of unjustified contour closing beyond outermost mills of the field mill array occurred for mills 33 and 34 on the Atlantic Coast between 1446 and 1506 Z on 20 August 1989. See Figs. 31 and 32. In this case, however, there was indeed a charge of the indicated polarity aloft. The closed contours were not justified since there was no evidence for the electric field decreasing south of mill 33 or offshore from mill 34. Indeed, the SPTVAR measurements show that the electric field extended farther to the southeast than implied by the closed contours and was due to charge in a cloud moving onshore from that direction.

On 14 August ∇V contours which closed over the ocean east of mills 13, 16 and 26 partly masked the presence of negative charge in a cloud over the ocean several km east of these field mills. In this case, however, there was a very localized charge near these same mills on several occasions.

One particular contour, namely the one for $\nabla V = 0$, was properly drawn in the plots. Apparently separate criteria are applied when the $\nabla V = 0$ contour is calculated.

4.5 Instrumentation checks

Roll, yaw and pitch maneuvers in an anvil electric field on 29 July and various turns in small quasi-steady fields on 30 July, 13, 14, and 18 August and 1 September demonstrated the adequacy of the SPTVAR determination of the electric field components relative to each other.

Late in the 19 August flight, SPTVAR flew past four field mills strung along the tether cable of a large balloon above the rocket-triggered-lightning site. E_Z measured by SPTVAR was a fair-weather field of −50 to −70 V/m with an uncertainty of ±100 V/m, in disagreement with the −1 kV/m measured by the two mills (on the tether) closest to the balloon, but compatible with the 0 kV/m measured by a field mill lower on the tether and another one on the ground.

On 29 August, the Aeromet Lear Jet practiced flying past SPTVAR for the purpose of comparing the electric field calibrations of the two airplanes. There was no significant electric field at the time and an opportunity to repeat the fly-bys with a strong electric field present did not occur.

4.6 Airplane effects

4.6.1 Severe electrical charging of the airplane

Limitations of airplane measurements of electric field inside clouds, especially electrified ones, are a major concern due to the net charge that the airplane may acquire and due to plumes of electric charge that may be emitted from the airplane since in either case an associated electric field is imposed at the faces of the field mills on the airplane. On two days, 19 and 20 August, SPTVAR experienced severe electrical charging, first negative then positive, when it approached and receded from negative cloud charge while flying through precipitation. The charges acquired by SPTVAR were so great that the electric field at the face of the mills mounted on the fuselage was as large as for a cloud electric field of 60 to 80 kV/m. However, the deduced E_Y and E_Z values were only about 5 to 10 kV/m. We are skeptical of the correctness of the electric field measurement in cases such as these for which the field due to charge on the airplane is large compared with the ambient field. On the other hand, we have determined that during the severe charging experienced on these two days, the electric field due to plumes of charge behind the airplane became the dominant electric field at the face of the aft mill with the result that the deduced X component of the cloud electric field was inverted and severely distorted.

4.6.2 Lightning strikes sustained by SPTVAR

SPTVAR was twice struck by lightning during the 1989 flight operations. The first strike, with attachment points at each wing tip, occurred on 29 July at a time when the ambient electric field was small. Thus the lightning strike was probably due to a nearby channel which was already developing rather than having been triggered by SPTVAR.

The second strike, on 18 August, resulted in SPTVAR being left with a net charge of about 500 μC, which increased the field at the top and bottom mills by about 300 kV/m and that at the aft mill by about 500 kV/m. (Fields this strong at the mills correspond to an ambient atmospheric field strength of about 60 kV/m.) Intense plumes of positive charge developed instantly and removed this excess charge in about four seconds.

5 Conclusions

The following conclusions combine those presented in Part I of this report with those drawn from the 1989 flight operations and data discussed herein. 1988 flights referenced in the following are described in Part I of this report.

1. An airplane instrumented to measure the electric field vector in the atmosphere has been shown to be an effective vehicle for assessing electrical conditions in clouds over KSC. Such a vehicle has been shown to have the following advantages:

    - An airplane flies above the screening layer that normally forms above the earth's surface when there is an electrified cloud aloft. Thus an airplane is better able to study the electric field aloft than are field mills confined to the surface.
    - An airplane flies in a realm where the atmospheric electric field often has horizontal components. The continuous motion of an airplane changes its position with respect to the clouds and any associated electric field so that, for example, a plot of the horizontal component of the electric vector at frequent intervals along the track of the airplane can provide a way to show the variation of the electric field, in both magnitude and direction, and thereby locate the charged regions of a cloud.
    - An airplane's freedom of movement allows it to travel to and investigate clouds of specific interest anywhere over or near the Space Center including the Atlantic Ocean and various waterways in the vicinity of KSC. Thus, cloud charges beyond the boundaries of KSC may be located and monitored as the clouds approach or retreat from the KSC area.

2. An airplane can be in only one place at a time and can remain aloft for relatively short periods of time. Thus the capabilities of the KSC field mill array on the earth's surface complement those of an airplane since it monitors the surface electric field continuously, 24 hours a day, to provide a comprehensive picture of the electric field over the KSC area.

3. A real-time display of electric vectors plotted along the track of an airplane has been shown to be a powerful tool for monitoring cloud electric fields, for guiding airplanes to regions of electric charge in clouds, and for interpreting the results of the measurements (see for example 31 October 1988 and 19 August 1989). From the real-time vector displays the locations of regions of cloud charge can be quickly identified. The display should be visible to controllers on the ground who guide the airplane and make decisions about electrical hazards to operations at KSC.

4. Airborne electric field measurements can be calibrated by comparing electric field changes at the ground with those at the airborne platform as, for example, the flight on 26 September 1988.

5. For most of the clouds studied by SPTVAR during fall 1988 and summer 1989 it appears that dynamic growth to above the −20 °C level was required for cumulus clouds over KSC to become electrified. However, on 14 August 1989 SPTVAR measured very localized electric field which appears to have been associated with a small cloud whose top was at only 8,000 to 10,000 ft.

    - During 14 flights into cumulus clouds whose tops were lower than the 0 °C level, no significant electrification was encountered. Nor was any electrification encountered during two other flights (11 and 13 August 1989) into cumulus clouds whose tops were between the 0 °C and −5 °C levels.
    - Three marginally electrified clouds (on 19 and 20 August and 1 September 1989) had 5 dBZ reflectivity tops to about the −20 °C level, while another cloud whose radar top reached the −25 °C level (on 14 August 1989) became somewhat more electrified. Well electrified clouds typically had 5 dBZ tops that were considerably higher than the −20 °C level.

6. Clouds over KSC may be only weakly electrified and persist for as long as an hour in an electrified state without ever making lightning. In such cases the cloud charge apparently falls out of the cloud with precipitation after electrification processes cease and the cloud begins to dissipate (19 and 20 August 1989).

7. The contour plot of surface ∇V gave misleading visualizations of charge locations due to unjustified closing of contours of constant ∇V when the cloud charge was not actually over the array of field mills (on 9, 13, 14 and 20 August 1989).

8. On one occasion (on 18 September 1988) when there was a widespread cloud layer, the electric field disturbances coincided with embedded convective cells.

9. Screening layers on the sides of clouds, if they existed, were insufficient to conceal the presence of charge within clouds when the airplane was flying outside the clouds (13, 14, 18 and 19 August 1989).

10. In the vicinity of electrified clouds, usually the electric field aloft is much stronger than that at the ground, but we encountered one interesting exception (on 4 November 1988) when the electric field at the aircraft's altitude of 11,500 ft (3.5 km) was weaker than that at the ground.

6 Recommendations

6.1 Use an airplane to monitor electrical conditions in clouds

We highly recommend that an airplane instrumented to measure the atmospheric electric vector in cloudy skies be used just prior to launch of space vehicles. In the course of this project such a vehicle has been shown to provide an effective way to detect atmospheric electric fields in a localized region of the atmosphere. The real-time display of the horizontal component of the electric vector plotted along the airplane track, developed for this project, provides a way to monitor the extent of an electric field once detected and to indicate the location of the charge responsible for the electric field. The information obtainable with an airplane is a valuable complement to that obtained with the surface field mill array at KSC.

6.2 Improve the surface electric field contour plots

The electric field contour plot is an effective visualization device. However, it is important that the user not be misled by false representation of the actual data from which it is developed. In order to remove some difficulties inherent in the present contour routine we recommend the following actions:

1. Modify the contour routine so that it does not draw closed contours unless there are sufficient data to support doing so, i.e., there should be no contours that are closed west of mills 7, 18, 22 or 25; north of mills 7, 2 or 1; east of the mills along the Atlantic shore; or south of mills 28, 34, 32, 33 and 25.

2. Show the mill locations in the display.

3. Represent each mill by a symbol whose area or linear dimension is proportional to the measured electric field—perhaps circles if the field is negative and triangles if the field is positive. This type of display would quickly reveal spurious readings by individual mills due to malfunction or local interference.

4. Note that presently the strip charts for the KSC surface field mill array record electric field, but that ∇V is used as the parameter for the contour plots. We recommend that the parameter used be standardized, with the electric field being the preferred choice.

6.3 Conduct further studies of cloud charge persistence

Although some understanding of cloud charge persistence in marginally electrified clouds was gained in this project, the vigorous clouds that make lightning need further study. Specifically, the question of what happens to charge remaining in expiring and debris clouds after lightning activity ceases needs to be pursued.

Electric charge may persist longer in anvil clouds than in low level debris clouds. This possibility needs study, using airplanes capable of high altitude flight into anvil clouds.

6.4 Continue to develop displays of the aircraft track and electric vectors

Our present displays show only two of the three components of $\vec{E}$ simultaneously. Color displays have the potential of showing all three. The track of the aircraft with data should be displayed against a background display of radar echoes in addition to the present map showing significant landmarks and boundaries of restricted areas.

6.5 Develop real-time methods for deducing cloud charge parameters

When the electric field pattern measured at the aircraft is not too complex, it should be possible to find a simple model of charge to fit the measurements in real-time. The locations and magnitudes of the charges deduced in this way could be checked by new flight tracks in the vicinity of the charges.

6.6 Improve estimate of reliability of measured electric vector

The reliability of aircraft measurements of electric vectors is degraded when the electric field at the face of the field mills due to the ambient cloud electric field is a small fraction of the actual field present. This situation occurrs whenever there is a proportionately large net electric charge on the airplane and/or in charge plumes released from the airplane by corona. We need a better understanding of these phenomena and better methods for estimating the reliability of the measurements.

6.7 Test the above techniques in field programs

Since the number and types of clouds available for study during the 1988 and 1989 field program were limited and since electrified clouds vary widely in anatomy and behavior, further field programs of airborne electrical measurements will be required. We specifically recommend the following investigations:

1. Study the development of electrification in cumulus clouds as they ascend above the −10 °C level and as their tops descend back below −10 °C to determine what factors must be present for electrification to appear.
2. Make airborne measurements around anvil clouds and other layered clouds to determine under what conditions they become electrified and to learn whether there are ever any cases in which the electrification cannot be identified by measurements of electric field at the ground.
3. Study clouds with rain whose tops are at any altitude below the −20 °C level to determine under what circumstances they might become electrified.
4. Continue to study the variation of electric field strength with distance away from electrified cumulus at various altitudes. Penetrate these clouds to ascertain the presence or absence of significant screening layers.
5. Airborne electrical measurements around winter frontal storms are either rare or non-existent. It is a good time to get a measurement program started.

6.8 Two recommendations of a more general nature

1. Aircraft measurements around electrified clouds would be greatly enhanced by data from a high resolution Doppler cloud physics radar located within the boundaries of KSC. We recommend now, as we have in the past, that KSC acquire such a radar with capabilities for vertical scanning. We also recommend that the aircraft display

mentioned above be combined with the radar display to enhance the capabilities for real-time guidance of the aircraft.

2. An airborne electric field system with the capabilities we are developing will be a unique state-of-the-art facility for characterizing electrified clouds. While we have stressed the importance of real-time techniques for interpreting the data, much of the value in the data will appear only in later analysis when they are viewed in the context of other information about the clouds. Thus we recommend that all the electric field and cloud physics data collected by the airborne field mill system be available to a broad scientific community and that strong liaisons be developed with some investigators for the purpose of promoting the understanding of electrified clouds.

7 Acknowledgments

Many people of NASA and USAF contributed to the success of this project by their enthusiastic and energetic support. Col. John Madura and Dr. Hugh Christian organized the effort and made the study possible. We thank Captains Tom Strange and Ann Hollis, Launa Maier and Mark Wheeler for coordinating the day-to-day operations, gathering and interpreting data, and solving a myriad of problems. Staff of the 2nd Weather Squadron, Detachment 11, USAF, provided invaluable weather forecasts for deciding when to mobilize the SPTVAR aircraft; we particularly appreciate the efforts of Msgt. Richard Bailey, and Sgts. Juan Tenicela and Larry Rodgers for the many briefings they gave us throughout the day. We are grateful for the contributions of John McBrearty, Doug Mach, Jim Nicholson, and Bill Jafferis of NASA and Maj. Norman Buss, Lt. Col. Condon, Lt. Col. Lutz and Msgt. Pucel of the USAF. We thank Bill Jafferis for sending us the data in Table 3. Many other people at NASA and the USAF contributed in ways not evident to us.

We thank the Miami Controllers of the Federal Aviation Administration and the Miami ARTCC Military Mission Coordinators for making it possible to fly unusual flight patterns.

We thank Ken Eack for his assistance with the daily operations of the telemetry station and Sandy Kieft, Langmuir Laboratory's Field Program Coordinator, for cheerfully fulfilling an endless stream of requests from Florida. We also thank Robert Hignight for outfitting the telemetry trailer, Sonny Edwards for hauling it to and from Patrick AFB, and Dave Raymond for collecting upper air soundings.

A Individual Flight Summaries

In this appendix the indented portions of the discussions which give a weather synopsis are condensations of daily synoptic summaries jointly prepared by Launa Maier of KSC and Mark Wheeler of CSR. Notice that the KSC field mill array contour plots, and thus the discussion provided by Ms. Maier and Mr. Wheeler for each flight, follow the potential gradient convention for the sign of the electric field: $\nabla V = -E$ is positive when positive charge overhead dominates. As noted in the introduction, we use the opposite convention so that, for example, E_Z is positive when it exerts an upward force on a positive charge (i.e., when negative charge overhead dominates) for all SPTVAR data.

A number of conventions have been used in the individual flight summaries that follow. The telemetry system on board SPTVAR sends all the data obtained to a receiving station on the ground as described in Part I of this report. The electric field data sent via telemetry consist of three signals from each field mill which represent the electric field at the face of the mill. They differ in gain and thereby provide a wide dynamic range of sensitivity.

On the ground the signals are converted to the electric field strength (in kV/m) at the individual mill faces. These field values are combined and scaled to determine the components of the ambient electric field at the SPTVAR location as described in Part I of this report. The ambient electric field components are expressed first in the Airplane Coordinate System (ACS) in which the X axis is directed forward along the axis of the airplane fuselage, the Y axis is directed to the left in the plane of the wigs and the Z axis is directed upward and perpendicular to the XY plane.

The plots drawn on the PC monitor in real time during a flight by the program "SPT," described in Part I, were made using the electric field components expressed in the ACS. The plots in this appendix which show the flight track for a complete flight were made using SPT and a screen print routine. The barbs drawn at intervals along the SPTVAR track represent either E_Z (shown with positive E_Z directed to the right, or up) or $\vec{E}_{XY}$ $(=(E_X, E_Y, 0))$ in the ACS.

Post-flight analysis provided the option of expressing the components in two other coordinate systems. The first is obtained by successive rotations about the roll and pitch axes whereby all three components are transformed from the ACS to the Level-flight Coordinate System (LCS). In the LCS the $+Z$ axis is vertical, i.e., perpendicular to the surface of the earth, and directed upward, while the XY plane is horizontal with the X axis directed in the heading direction of the airplane. The final coordinate system, the Geographic Coordinate System (GCS), is obtained by a rotation about the vertical Z axis whereby E_Y and E_X in the LCS are transformed into E_N and E_E in the GCS, where N is the direction of magnetic north and E is the direction of magnetic east.

Plots which show the horizontal electric field vector at intervals along the SPTVAR track for limited time intervals were made with a Sun Workstation using $\vec{E}_{NE} = (E_E, E_N, 0)$ in the GCS. Similarly, plots of the electric field vector in the XZ plane at intervals along the SPTVAR track (the "altitude profile") were made using $\vec{E}_{XZ} = (E_X, 0, E_Z)$ in the LCS. These plots made with the Sun Workstation show more detail than the real-time E_{XY} plots made with the PC using SPT since the PC was supplied with only a subset of the data recorded during a flight.

The interpretation of PC plots of the horizontal electric field, E_{XY} in the ACS, was explained in Part I of this report. In the following, we apply that interpretation to the E_{NE} plots and introduce the corresponding interpretation of the altitude profile plots. The barbs plotted along the airplane track in the E_{NE} plots represent the electric field vector projected onto the horizontal (NE) plane in the GCS while the E_{XZ} plots represent $\vec{E}$ projected onto the vertical XZ plane in the LCS. In both cases the two-dimensional vectors are drawn with their tails at the SPTVAR track so that the free ends point in the direction of the electric vector. Thus they represent, at the location of the airplane, the direction of the force on a positive charge due to the ambient atmospheric electric field. Convergence of the vectors toward a point indicates negative charge near the point of convergence. Conversely, divergence of the vectors away from a common point indicates positive charge near the point of divergence. Of course, due to the $1/r^2$ dependence of the electric force this is only an approximation to the more complex reality of extended distribution of charge in clouds. Nevertheless, it provides a good starting point for identifying charge locations in clouds.

In some plots showing individual electric field components a plot showing the airplane charge is included. The parameter plotted is actually the "airplane charge field"—the average electric field at the mill faces due to, and thus proportional to, the net charge on the airplane. Furthermore, this parameter has been scaled to the corresponding E_Z so that the relative magnitude of the electric field at the faces of the mills due to the airplane charge may be compared to that due to the ambient field being measured. In this way, times when E_Z was very small compared to the airplane charge field, and thus less reliably determined, are easily identified.

Isolated spikes in some of the plots of individual electric field components, such as for the 29 July flight, were usually due to radio interference on the telemetry frequency. The telemetry reception was generally good during the 1989 operations from Patrick AFB, but at times the signal was overlaid by voice transmissions between military aircraft.

A.1 Clouds With No Associated Electric Field

A.1.1 Summary: 8 August 1989 (89220)

Highlight:
- Cumulus with tops to about 15,000 ft violated the launch constraint requiring that clouds be below the +5 °C level. The clouds, however, were not electrified.

> At 1400 Z on 8 August a line of thunderstorms was located to the southwest and stretched from there into the Gulf of Mexico. By 1646 Z there were good outflow boundaries, due to the earlier convection, with cumulus building near Tampa. The low level flow was southwesterly at 10 to 13 knots and the steering flow was west-southwesterly at 12 to 14 knots. Troughing was evident from the surface up to 200 mb with its axis extending from North Carolina and Georgia into northwestern Florida at 850 mb.

The 1200 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 2.

A flight was initiated at 1812 Z with the intention of studying initial electrification since scattered cumulus were expected to develop over the KSC area around 1900 Z. However, the lower humidity above 14,000 ft prevented any of the clouds going above 15,000 ft and a wind sheer resulted in the tops of the clouds being carried to the east. Only fair weather electric field was measured by SPTVAR during this flight which was terminated at 2006 Z. Inland, some clouds grew to greater heights. Late in the afternoon a thunderstorm moved into the PAFB area from the west, producing extensive light rains and numerous lightning flashes.

The track of SPTVAR during this day's flight is shown in Fig. 3.

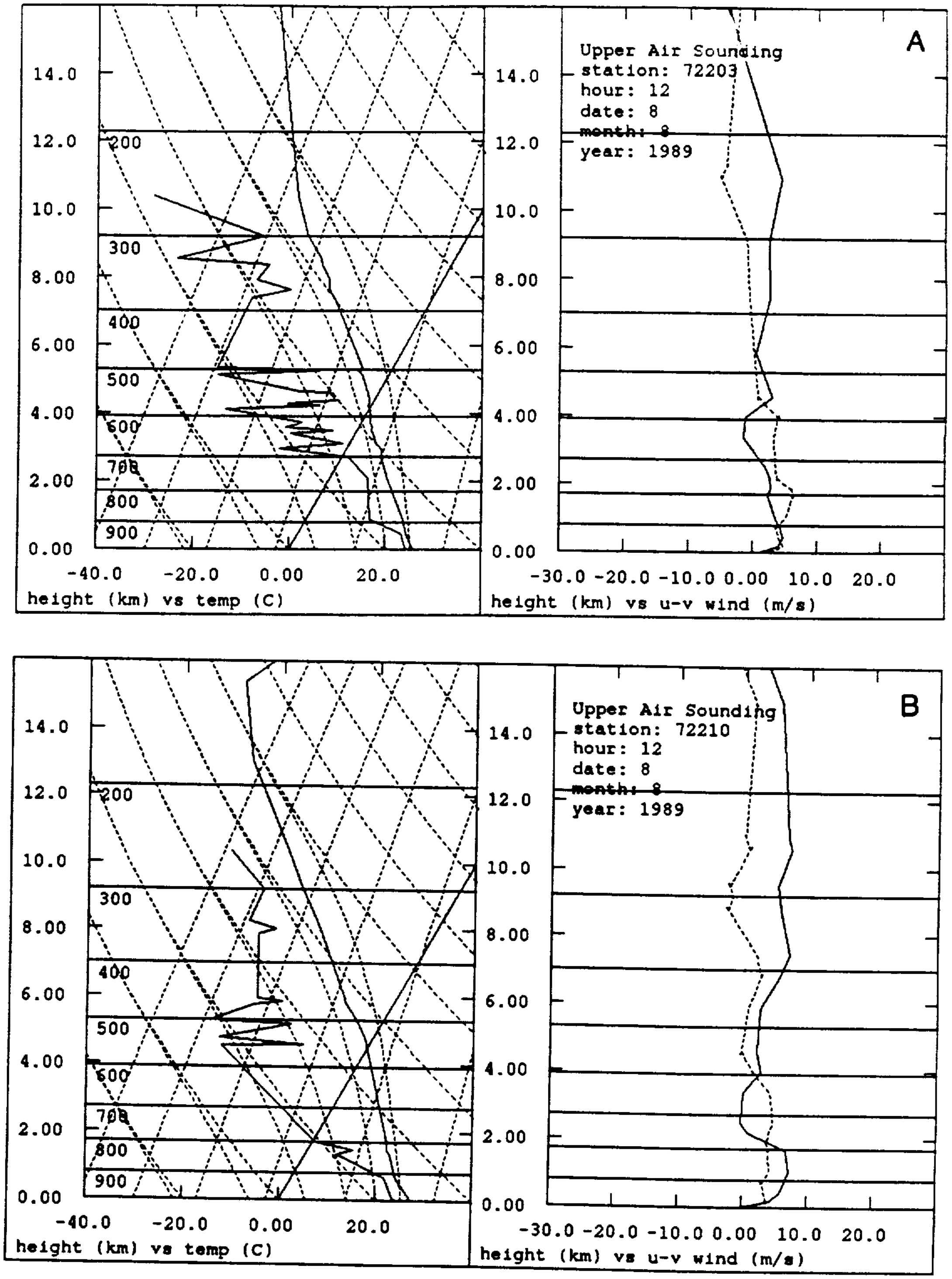


Figure 2: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 8 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, **u**, is the solid line and the north component, **v**, is the dashed line.

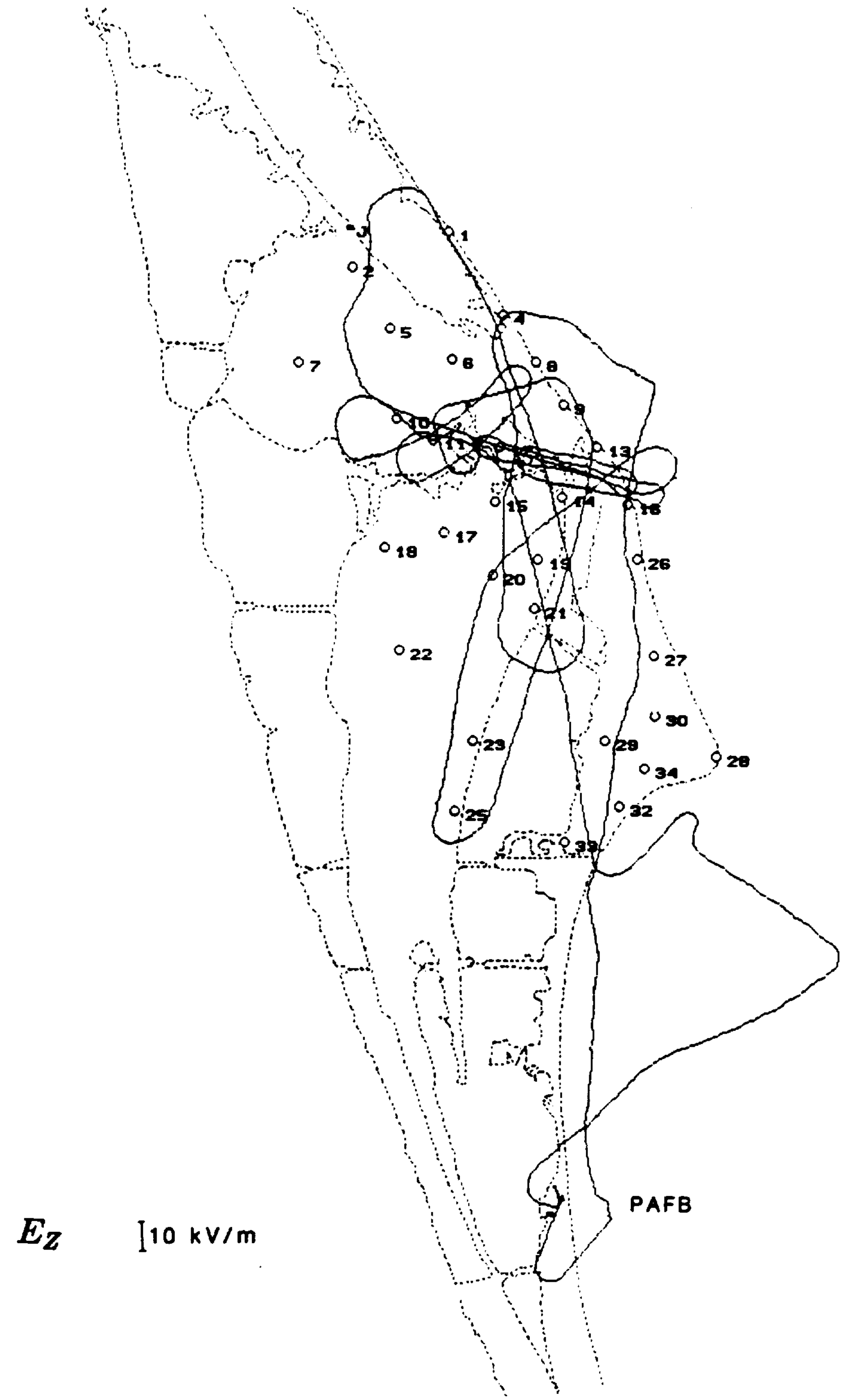


Figure 3: The flight track of SPTVAR on 8 August 1989. E_Z barbs would be seen in this figure if E_Z at SPTVAR had ever exceeded 0.5 kV/m during this flight.

A.1.2 Summary: 10 August 1989 (89222)

Highlight:
- Cumulus with tops to about 14,000 ft violated the launch constraint requiring that clouds tops be below the +5 °C level, but the clouds were not electrified.

On 10 August a frontal boundary extended from Daytona Beach through Orlando and Tampa into the Gulf of Mexico. The 200 mb southwest flow indicated divergence between Orlando and south Georgia. The KSC sounding showed good moisture (RH > 80%) all the way up except around 19,000 ft (5.8 km). The lifted index was −7.0 and the forecast was for thunderstorms beginning about 1900 Z.

The 1200 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 4.

A flight was initiated at 1638 Z to study initial electrification. The track of SPTVAR during this day's flight is shown in Fig. 5

Despite the favorable forecast and optimistic predictions for thunderstorms, the clouds could not make a thunderstorm. The SPTVAR pilot estimated the clouds were growing to 14,000 ft (4.3 km) and then disintegrating. Building cumulus formed during the early part of the flight. SPTVAR flew in and out of a cloud over field mill 22 from about 1715 Z until the cloud fell apart at about 1830 Z. The pilot estimated that this cloud had a maximum top of about 13,000 ft (4.0 km), just above the +5 °C flight level of 12,000 ft (3.7 km). Although this cloud would thus violate the launch constraint requiring clouds be below the +5 °C level, the electric field measured by SPTVAR never exceeded about 200 V/m. Surface field mills 18 and 22 measured fair-weather field values at all times under this cloud. After the last cloud penetration over the KSC area all the clouds disintegrated and vanished in a few minutes. The flight was terminated at 1854 Z.

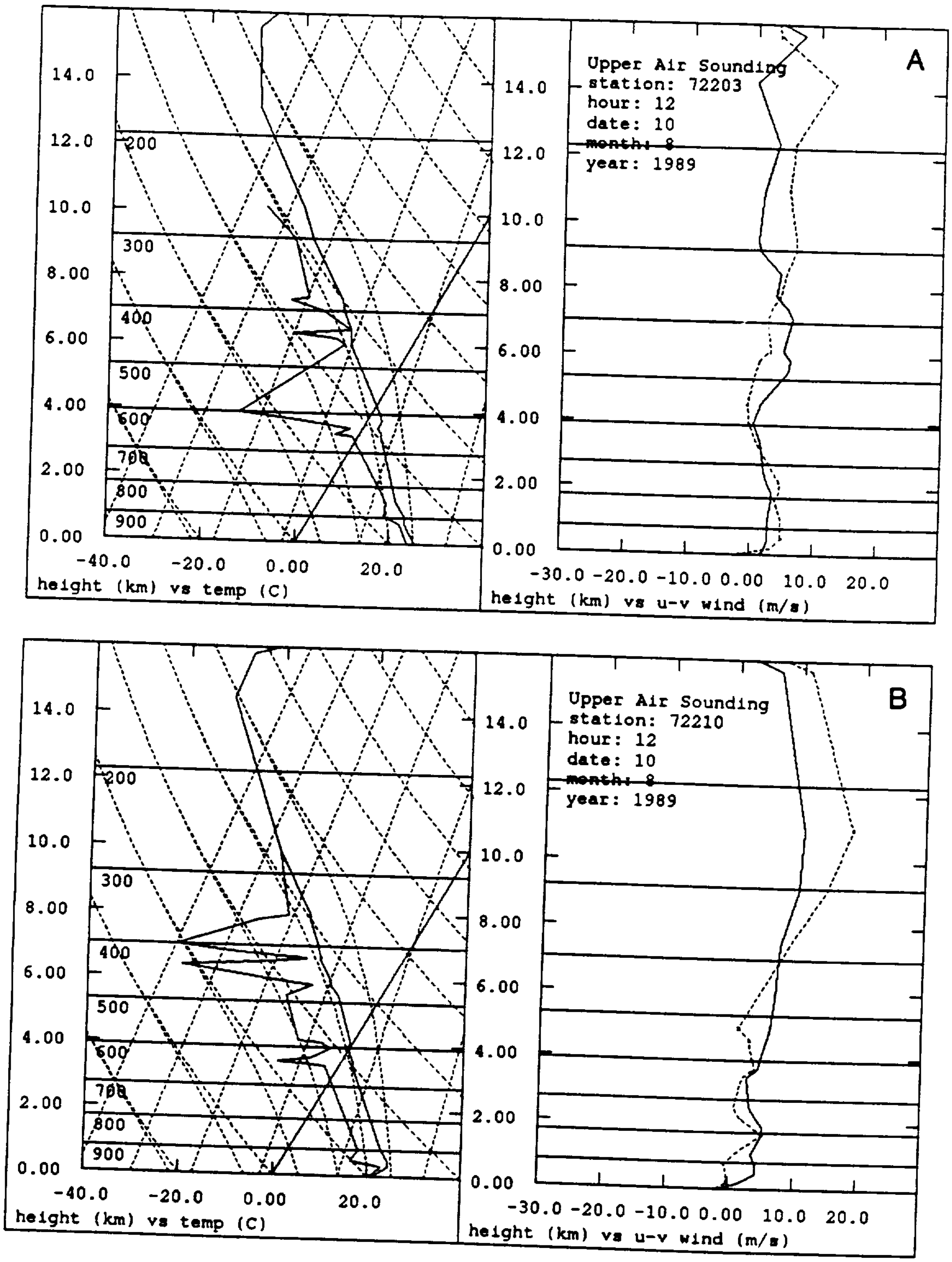


Figure 4: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 10 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

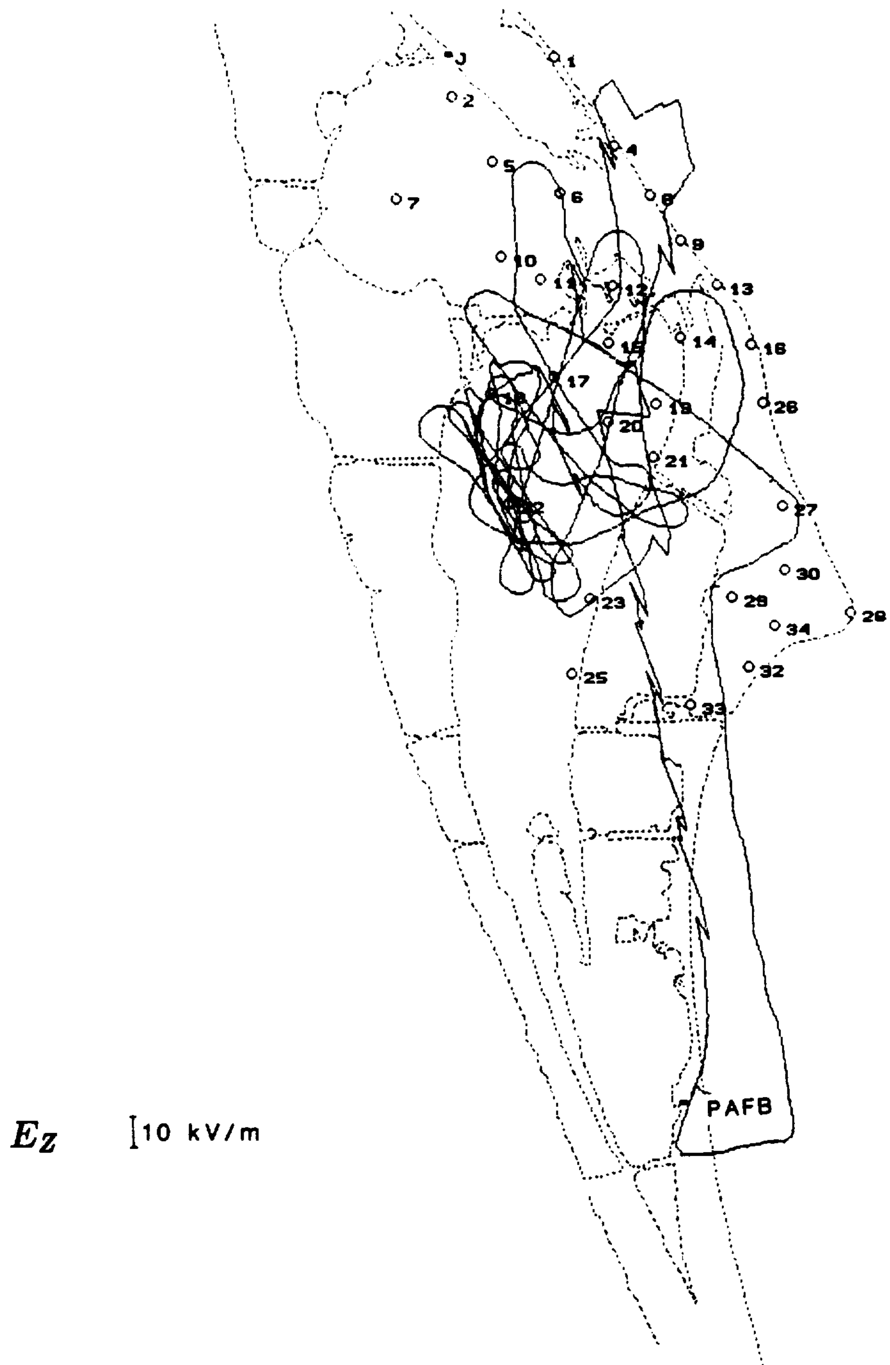


Figure 5: The flight track of SPTVAR on 10 August 1989. E_Z barbs do not appear in this figure since $|E_Z|$ at SPTVAR never exceeded 200 V/m during this flight.

A.1.3 Summary: 11 August 1989 (89223)

Highlight:

- Although cumulus tops to about 17,000 ft were above the +5 °C level and thus violated launch constraints, the clouds were not electrified.

On 11 August the surface wind and humidity pattern indicated a stationary front right over KSC at 1500 Z. A short wave had passed through the area during the evening hours. The morning sounding depicted westerly flow at all levels, becoming south-southwesterly above 500 mb. Above 700 mb there was significant drying and the satellite images indicated that it was relatively dry between two short waves located east and west of the east coast of Florida. The lifted and K indices were −7 and 37.9 respectively and the Patrick forecast was for thunderstorms to form in the vicinity between 1800 and 1900 Z after the onset of the seabreeze which was forecast for 1700 Z.

The 1200 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 6.

A flight was initiated at 1829 Z with the objective of studying initial electrification. The track of SPTVAR during this day's flight is shown in Fig. 7.

Cumulus clouds were present over the area during the first part of the flight and SPTVAR made several cloud penetrations at 12,000 ft (3.7 km). The pilot estimated cloud tops to 14,000 ft (4.3 km) and the airplane measured only fair-weather fields for the entire flight. The KSC field mill array measured only fair-weather fields except for a six-minute interval when mill 7 reversed polarity to −72 V/m. During the last hour of the flight the cumulus development was over the port and south of CCAFS. There was also development just north of Titusville, where a cell reached at least 30,000 ft (9.1 km) and produced one cloud-to-ground lightning flash according to Ms. Maier's notes on weather during the flight. SPTVAR flew west to a point over highway 95 just south of Titusville before returning to Patrick AFB at 2101 Z, but failed to encounter any electric field from the cloud.

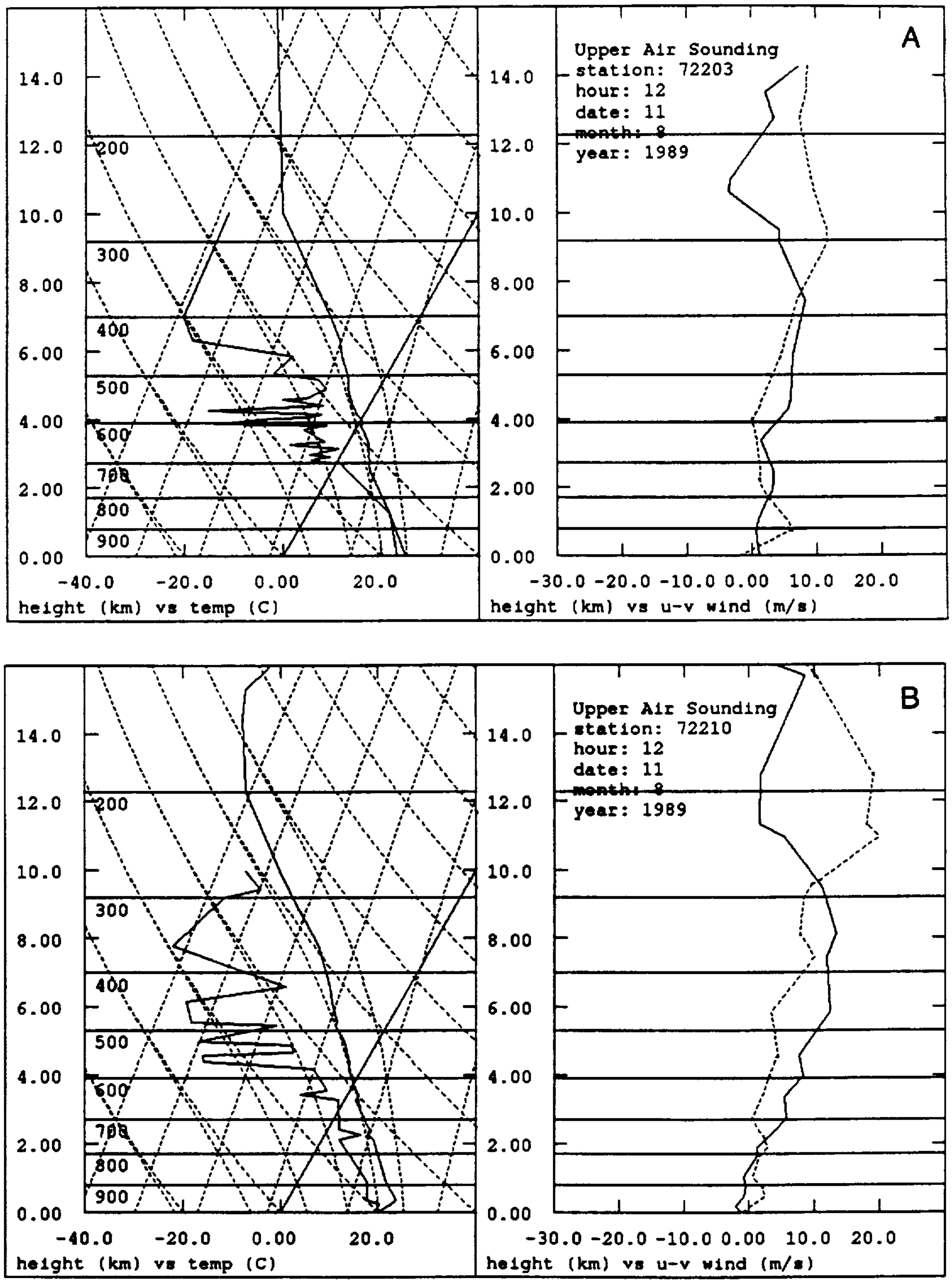


Figure 6: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 11 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

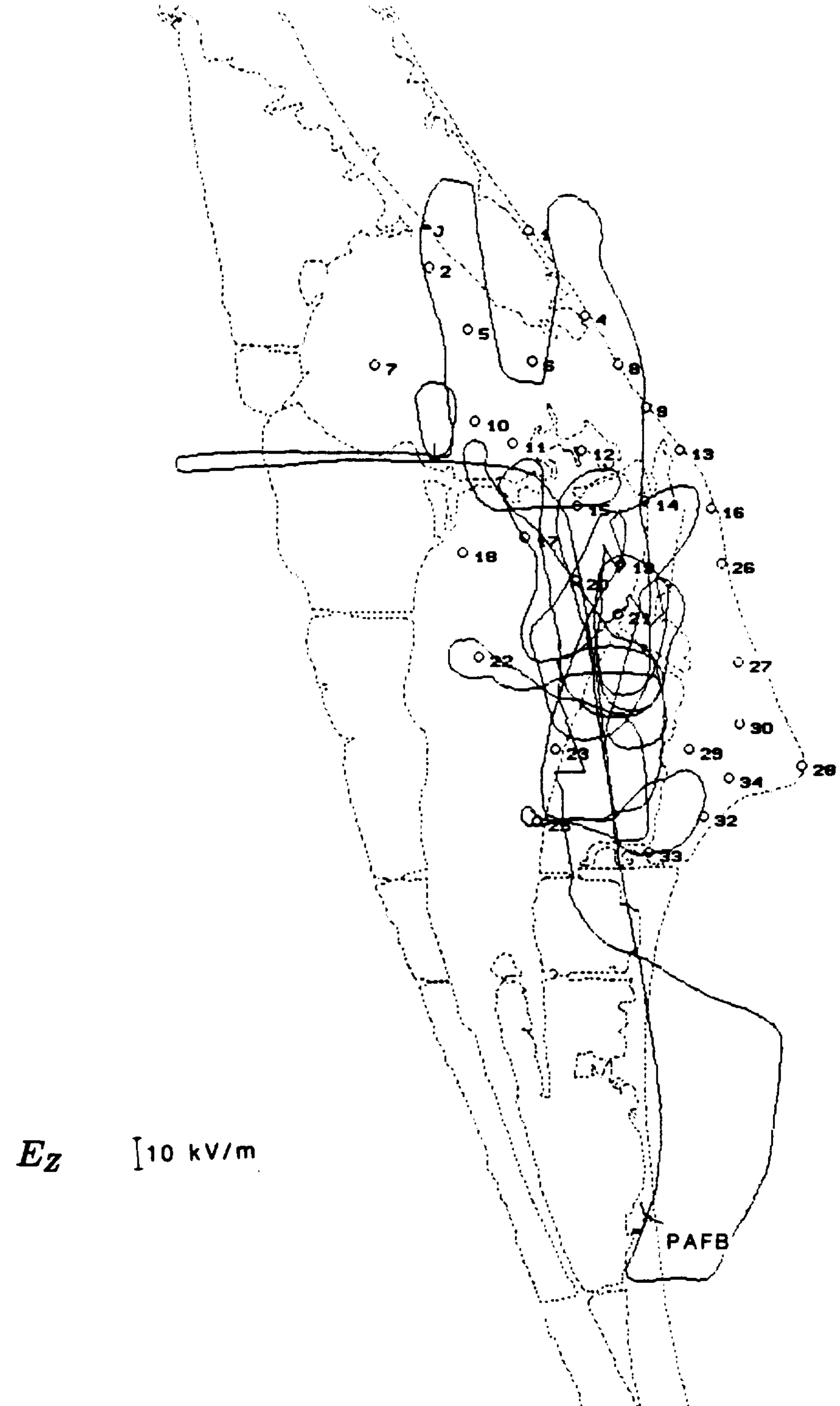


Figure 7: The flight track of SPTVAR on 11 August 1989. E_Z barbs would be seen in this figure if $|E_Z|$ at SPTVAR had ever exceeded 0.5 kV/m during this flight.

A.1.4 Summary: 13 August 1989 (89225)

Highlights:

- Cumulus over KSC ascended to about the 0 °C level and thus violated the launch commit criteria forbidding launch through clouds with tops higher than the +5 °C level. The clouds, however, were not electrified.
- The only electric field measured by SPTVAR was over the north end of the Indian River and was caused by a cloud to the west.
- Closure of a $\nabla V = -1$ kV/m contour around mill 7 made ∇V measured by mill 7 give the appearance of charge overhead whereas the charge responsible was actually in the electrified cloud west of the Indian River. We recommend a change in the contouring algorithm.

On 13 August a ridge was building in from the Atlantic and was already established off the coast of North Carolina and south into Georgia. There was an easterly surface wave just off the coast of Florida. Initial cloud activity was expected in the early afternoon with stronger activity later.

The 1200 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 8.

Around noon the McGill radar showed clouds with good development moving north along the coast, so a flight was initiated to study initial electrification. The track of SPTVAR during this flight with barbs proportional to E_Z drawn at intervals along the track is shown in Fig. 9. By SPTVAR's take-off time (1711 Z) the cumulus moving toward the northwest and approaching the Cape had tops at 20,000 to 22,000 ft (6.1 to 6.7 km). However, as the cells came onshore near the Cape ten minutes later they began to dissipate. At 1733 Z SPTVAR investigated a cloud over the KSC Headquarters area with echo tops at 15,000 to 16,000 ft (the 0 °C level) and rain present below cloud base, which was at about 2,500 ft. At this time most of the clouds had tops sufficiently high to violate the launch commit criteria disallowing flight through a cloud with top above the +5 °C level or of flight within five nautical miles of a cloud extending above the 0 °C level. Other launch criteria would have been violated due to the presence of anvil and mid-level debris clouds. Nevertheless, these clouds were not electrified.

After investigating the cloud over the Headquarters area, SPTVAR flew north toward Mosquito Lagoon. North of mill 5 SPTVAR diverted to the west in the direction of active clouds west of the Indian River. After about two minutes SPTVAR reversed course and flew back east. Fig. 10 shows the E_{NE} plot for one minute on each side of the course reversal and shows a weak field directed toward the west-northwest. This indicates the presence of a net negative charge in the cloud ahead.

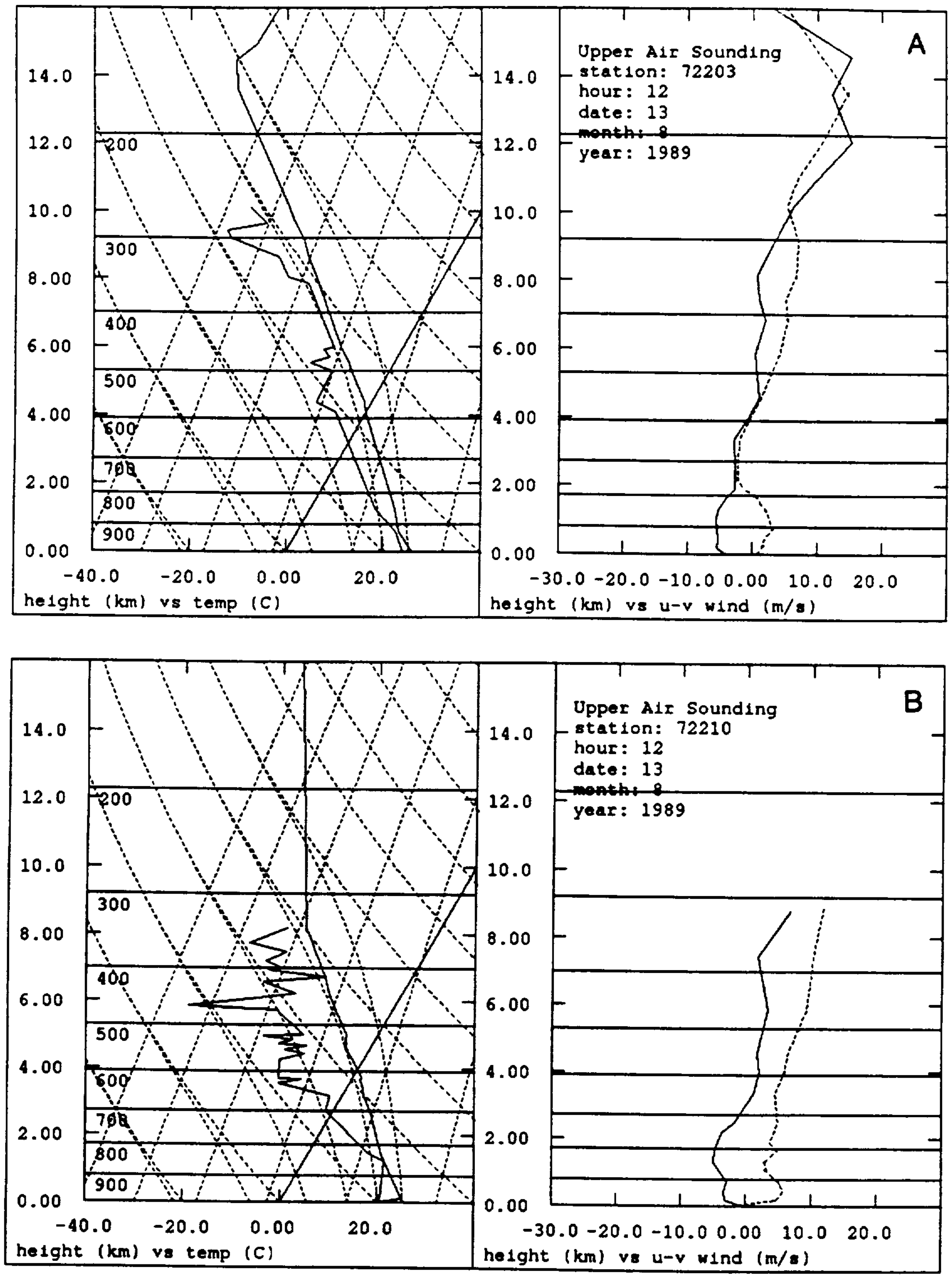


Figure 8: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 13 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

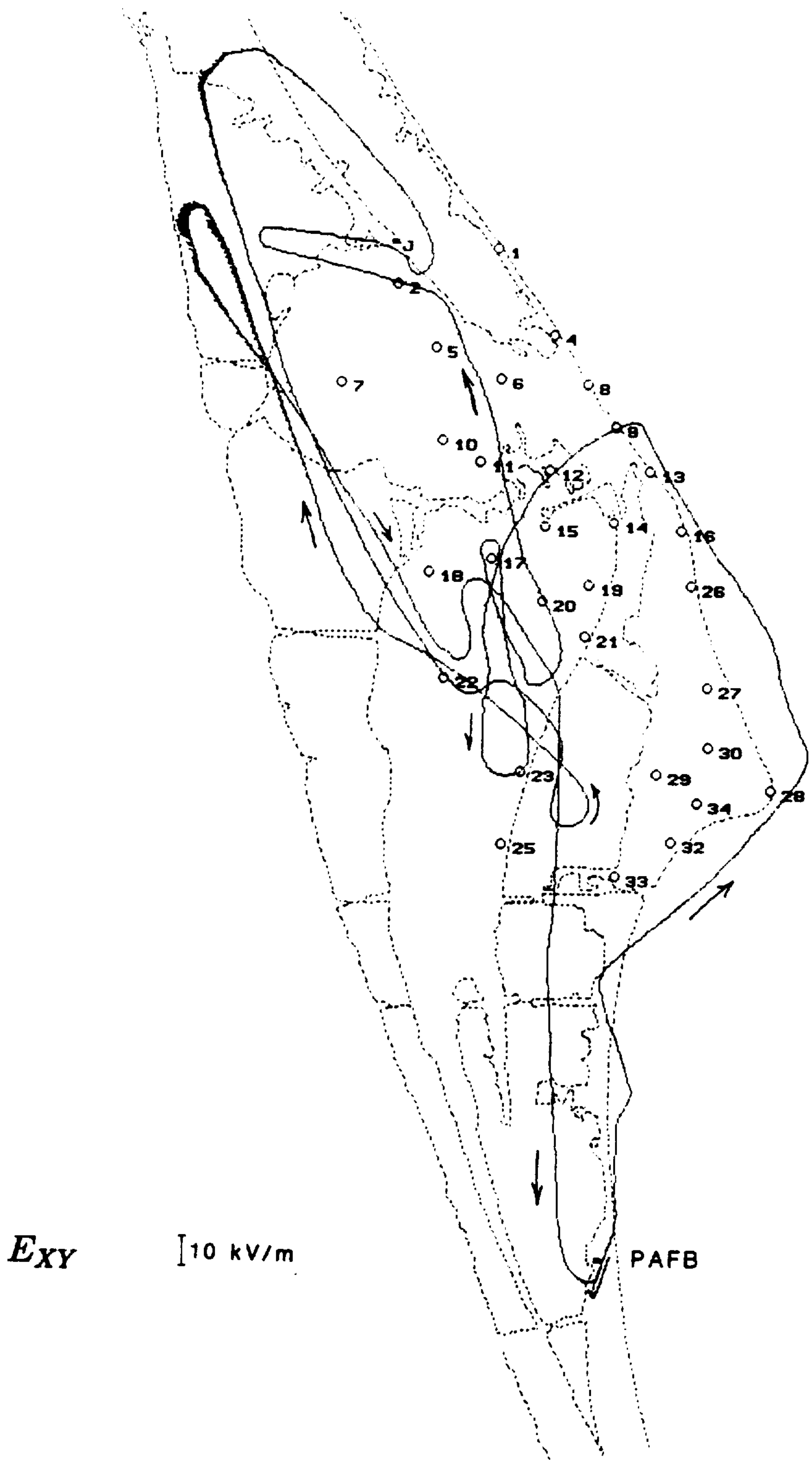


Figure 9: The flight track of SPTVAR on 13 August 1989. E_Z barbs drawn at intervals along the track point to the right (or up) when E_Z is positive and are seen only over the north end of the Indian River since $|E_Z|$ at SPTVAR nowhere else exceeded 0.5 kV/m. A scale of electric field magnitude is shown in the figure.

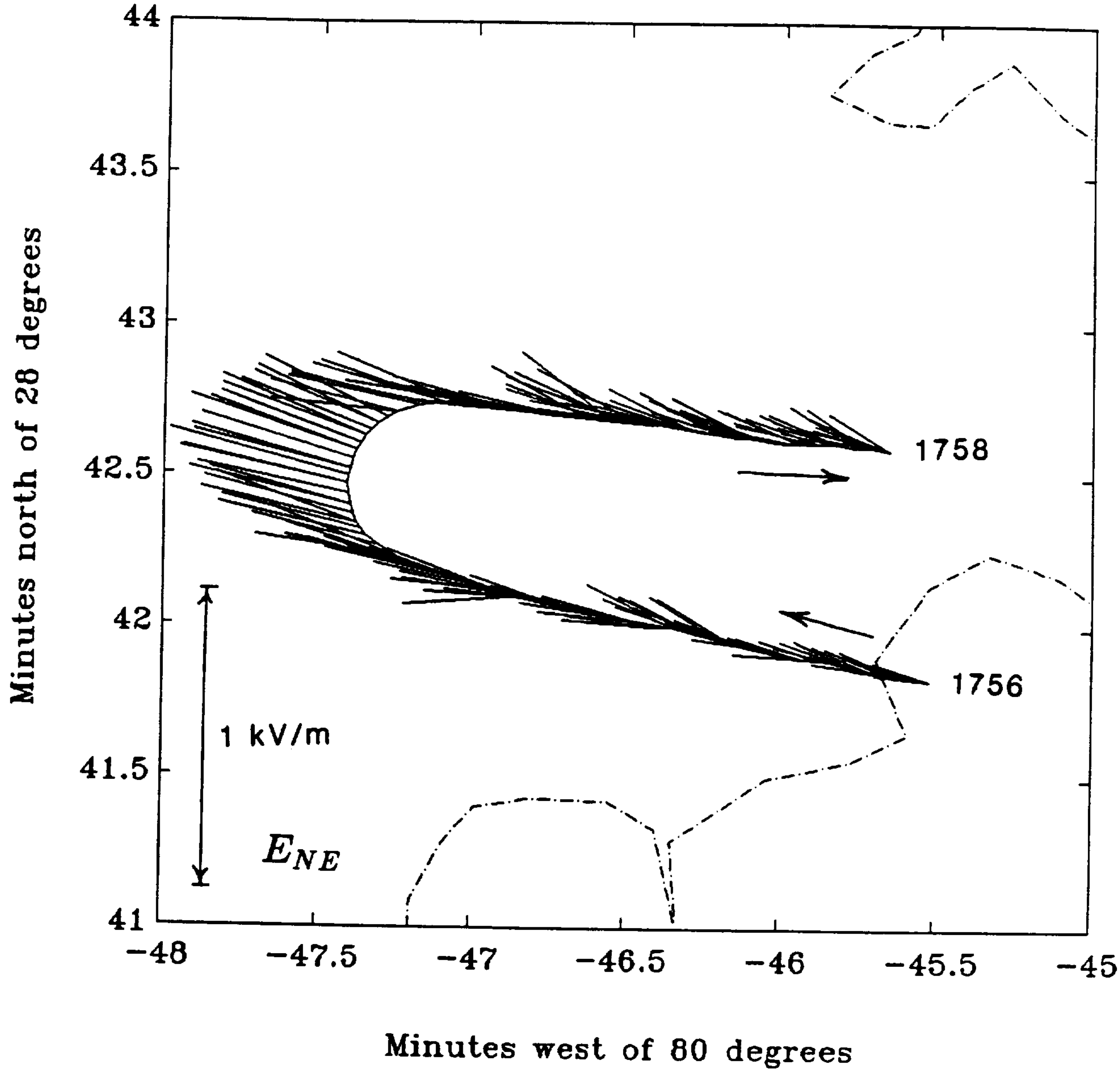


Figure 10: E_{NE} vectors plotted along the SPTVAR flight track from 1756 to 1758 Z on 13 August 1989. A scale of electric field magnitude is shown in the figure.

SPTVAR then flew north-northwest, turning first to the west and then to the south over the north end of the Indian River. The E_{NE} plot for the eight minutes of flight between 1801 and 1809 Z is presented in Fig. 11 and clearly shows that the electric field measured by SPTVAR was due to a cloud to the west-northwest of the SPTVAR track.

SPTVAR continued on a southerly course to the vicinity of mill 23, where it turned around, and from 1822 to 1830:30, flew back to the north end of the Indian River. The track of SPTVAR during this northerly flight during which SPTVAR flew west of mill 7 is shown in Fig. 12. The parallel and progressively longer E_{NE} vectors in this plot clearly indicate that the source of the electric field was a cloud north of Titusville and west of the north end of the Indian River. During this time the 1824 Z contour plot of surface electric field showed a closed -1 kV/m contour around mill 7, for which the one-minute average ∇V was -1450 kV/m, as shown in Fig. 13. A closed contour west of mill 7 persisted in the 1828, 1832 and 1836 Z contour plots. These contour plots thus indicated a negative charge overhead, in contradiction to the SPTVAR measurements. However, the one- minute average ∇V values for mills 2, 5, 6, 10, 11, 17 and 18 listed in Fig. 13 were also negative at 1824 Z. The $\nabla V = 0$ contour accurately reflects this situation. Since mill 7 is the westernmost of the mills that measured negative ∇V and the electric field gradient was largest at mill 7, the surface field mill array data indeed indicate the source of the electric field to be west of mill 7. The closure of the -1 kV/m contour west of mill 7 contradicts this simple interpretation of the overall pattern of the electric field gradients measured by all eight operational field mills in the northwest end of the KSC field mill array. Note that the $\nabla V = 0$ contour accurately indicates a negative cloud charge north-northwest of mill 7.

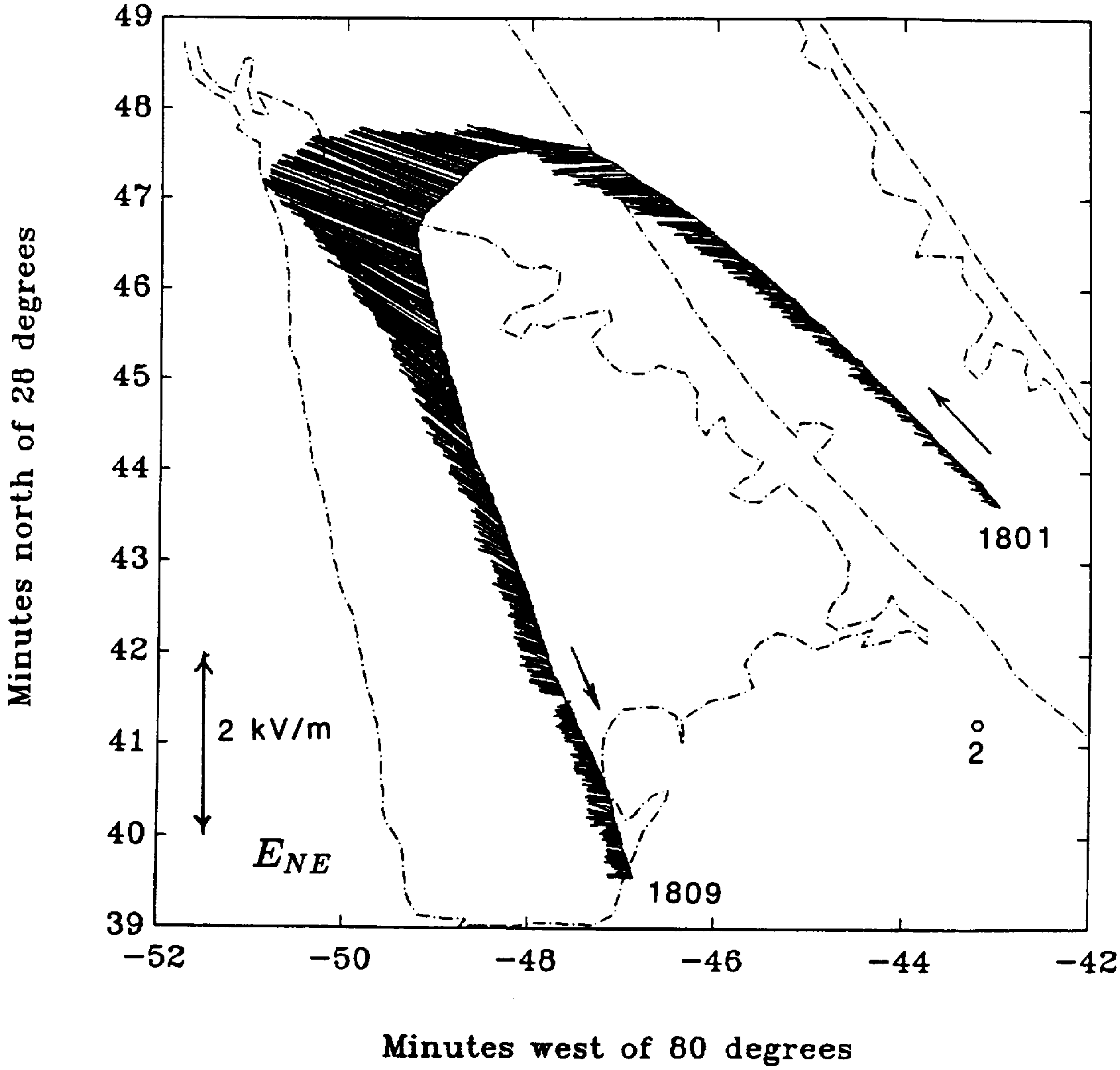


Figure 11: E_{NE} vectors plotted along the SPTVAR flight track from 1801 to 1809 Z on 13 August 1989.

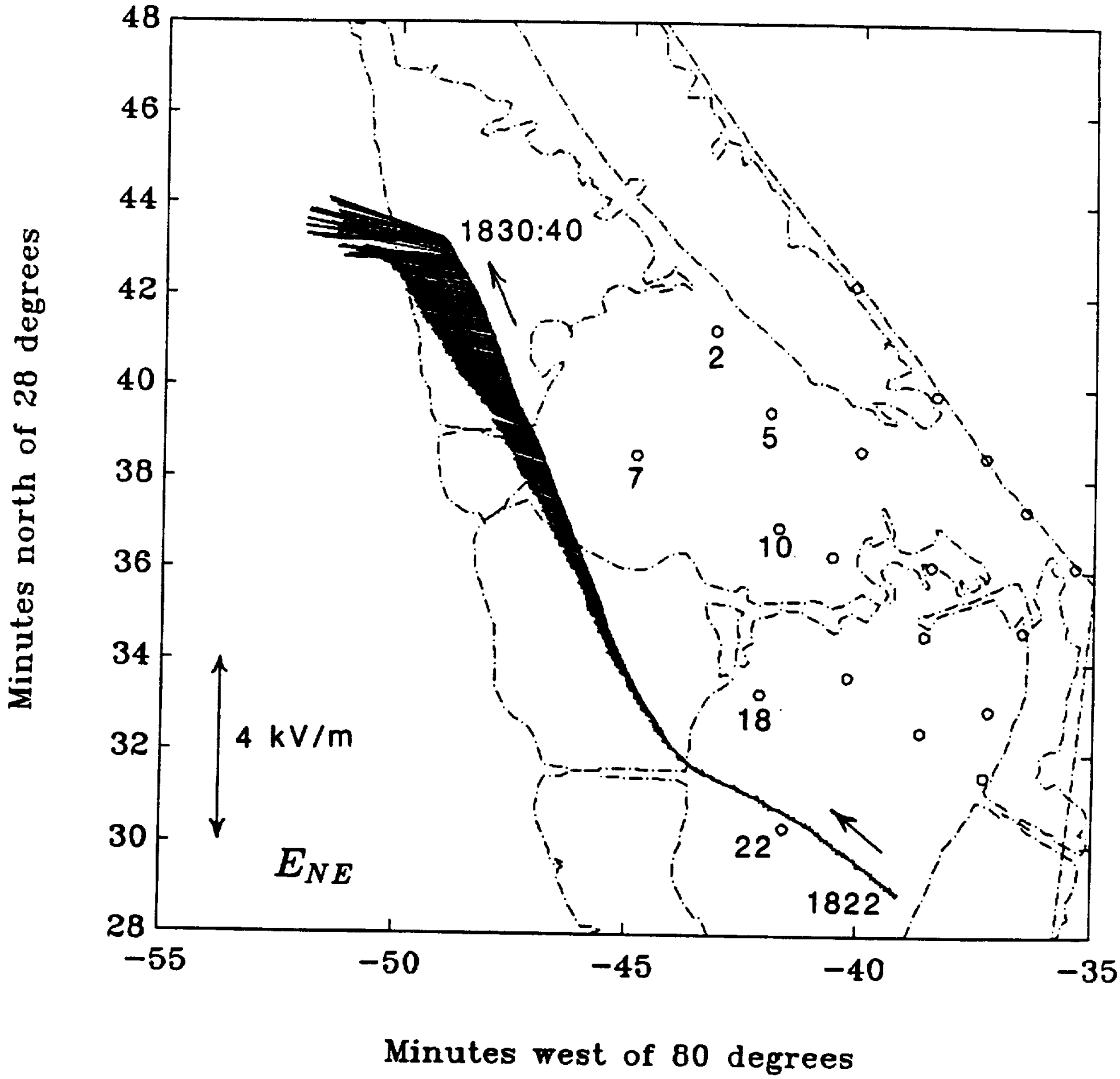


Figure 12: E_{NE} vectors plotted along the SPTVAR flight track from 1822 to 1830:40 Z on 13 August 1989.

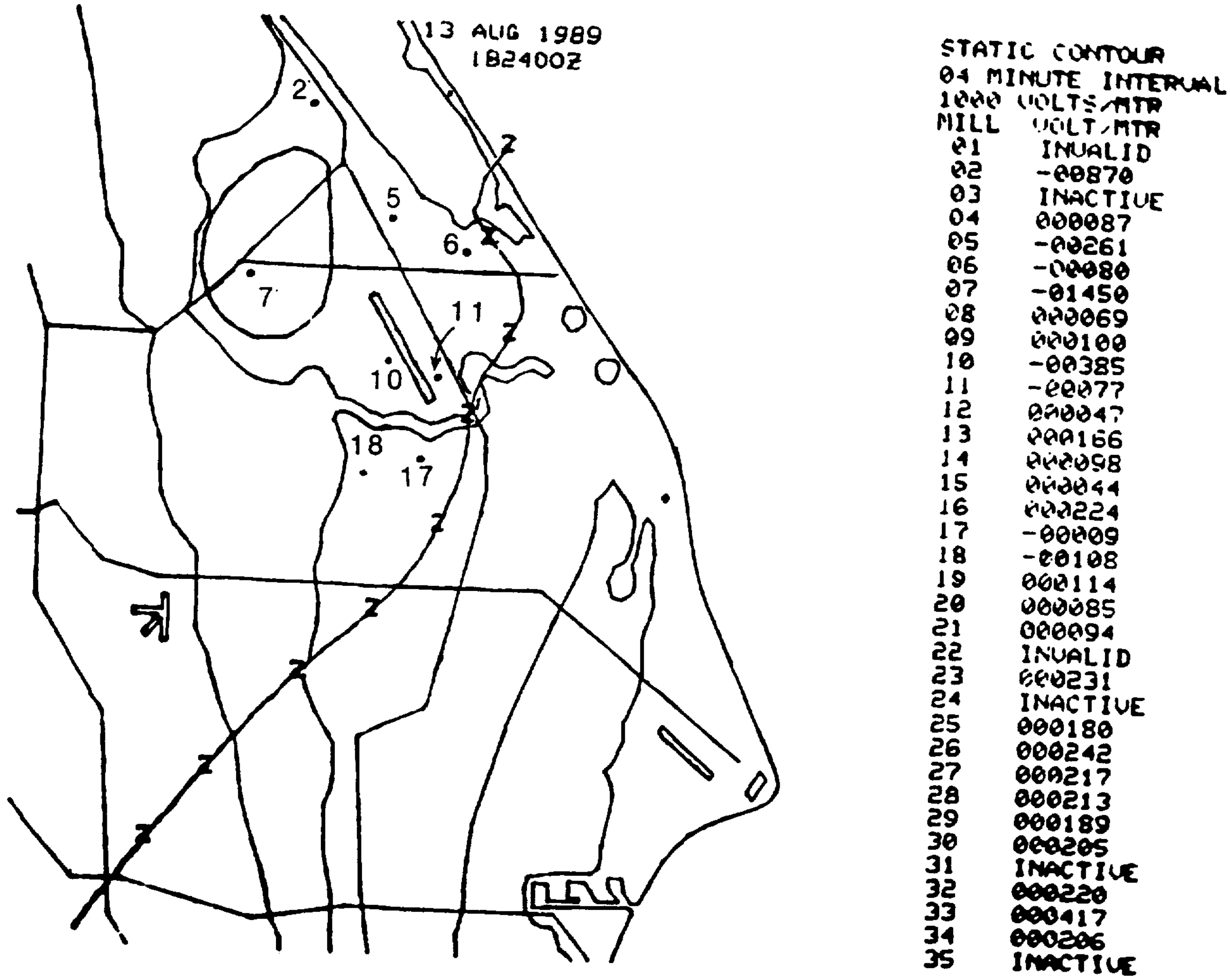


Figure 13: KSC surface electric field contour plot for 1824 Z on 13 August 1989. Approximate locations of field mills 2, 5, 6, 7, 10, 11, 17 and 18 are indicated by the dots. Note the closed contour around mill 7 which gives the impression of a negative charge aloft over that mill. This false representation of the electric field situation at the time of the display is explained in the text.

A.1.5 Summary: 27 August 1989 (89239)

Highlight: • All clouds over KSC had tops less than 8,000 ft and were not electrified. No launch commit criteria were violated.

> High pressure continued to dominate the eastern United States. The sounding was relatively moist. Below 7,000 ft, the winds were westerly with wind speeds of up to 11 knots. Above 7,000 ft the winds were easterly, gradually increasing to about 25 knots at the tropopause. The steering level flow was north-northeasterly at 5 to 10 knots. Activity was expected to form along the sea breeze and move inland.

The zero Z West Palm Beach and 1200 Z Tampa, Florida, soundings are shown in Fig. 14.

When SPTVAR took off at 1621 Z low clouds were formed along a line parallel to the Banana River and were drifting east-northeast. The Loran system onboard SPTVAR was malfunctioning on this day so that there is no record of the SPTVAR track during all except the first few minutes of this flight. Only fair-weather electric field was measured on this flight during which the cloud tops never exceeded 8,000 ft. The flight terminated at 1734 Z.

A.1.6 Summary: 29 August 1989 (89241)

Highlight: • The Aeromet Lear Jet practiced flying past SPTVAR for the purpose of comparing electric field measurements; however there was not a strong enough electric field for the comparison to be useful.

> High pressure continued to dominate the southeastern United States. The sounding was dry. At all levels the winds were easterly. The steering level flow was northeasterly at 10 to 15 knots. Not much activity was expected. A convergence line offshore was expected to advect in and bring isolated showers.

The sounding for this day showed that there was dry air above 700 mb, with winds from the east at all altitudes. There were two inversions, one between 700 and 660 mb, and the other between 500 and 480 mb. The 1200 Z West Palm Beach, Florida, sounding is shown in Fig. 15.

Due to Loran system problems there is no record of the track of SPTVAR for this flight. There were no clouds of any consequence. The main purpose of the flight was to practice in-flight comparisons of the SPTVAR and the Aeromet Lear Jet sensors and field mill

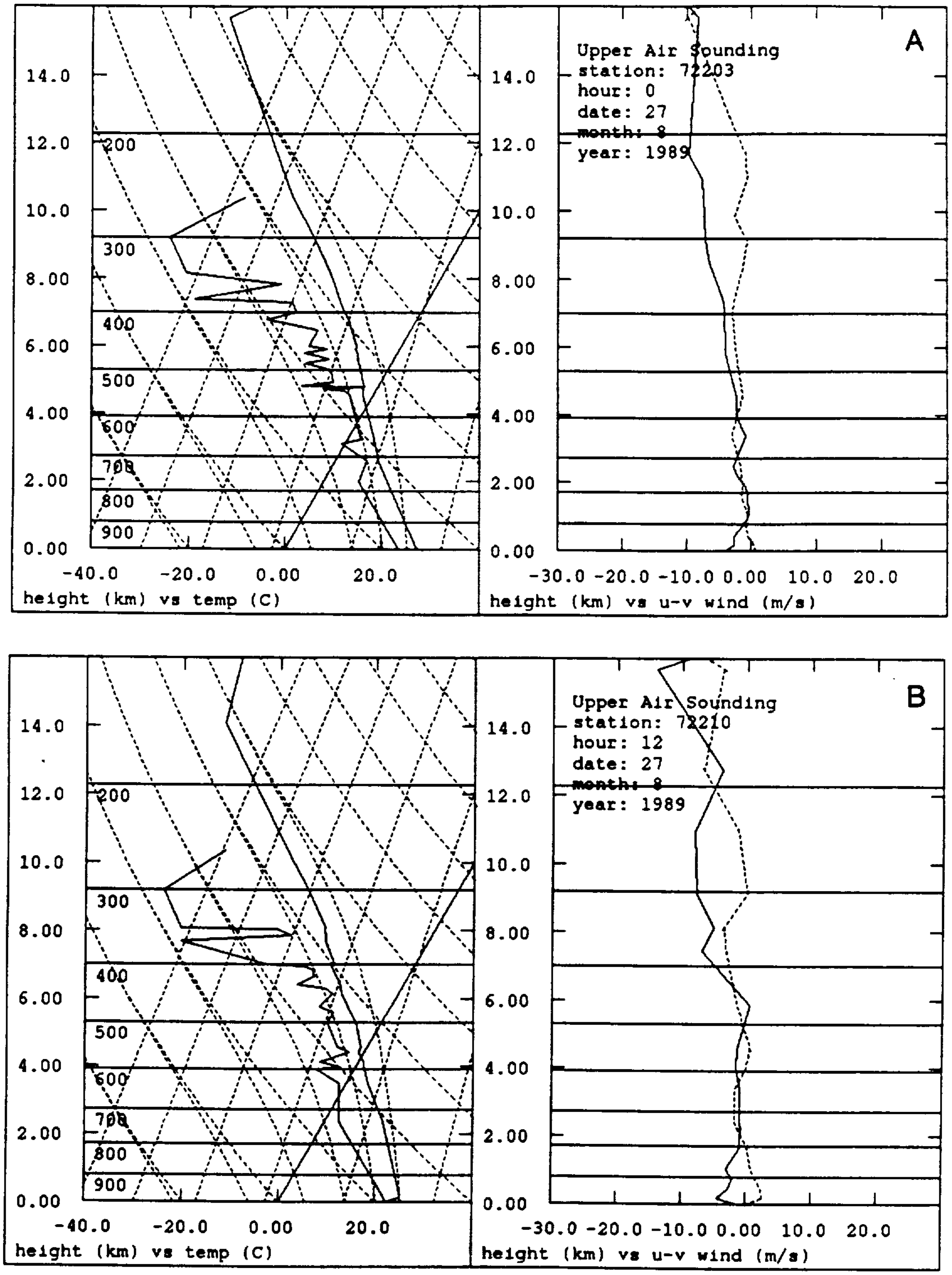


Figure 14: Skew T diagrams for the zero Z West Palm Beach (A) and 12 Z Tampa (B), Florida, soundings on 27 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

systems. SPTVAR flew a narrow racetrack pattern parallel to, and just south of, the railroad line through Wilson (just north of the Titusville beach road). The Lear flew a wider racetrack pattern around SPTVAR, which flew at 80 knots while the Lear flew at about 180 knots. The Lear had trouble reaching SPTVAR before SPTVAR came to the edge of the restricted area. This problem was overcome by SPTVAR making its turn-around when the Lear was half way around its turn. Due to the lack of any significant atmospheric electric field an actual comparison of the SPTVAR and Lear Jet electric field calibrations was not possible.

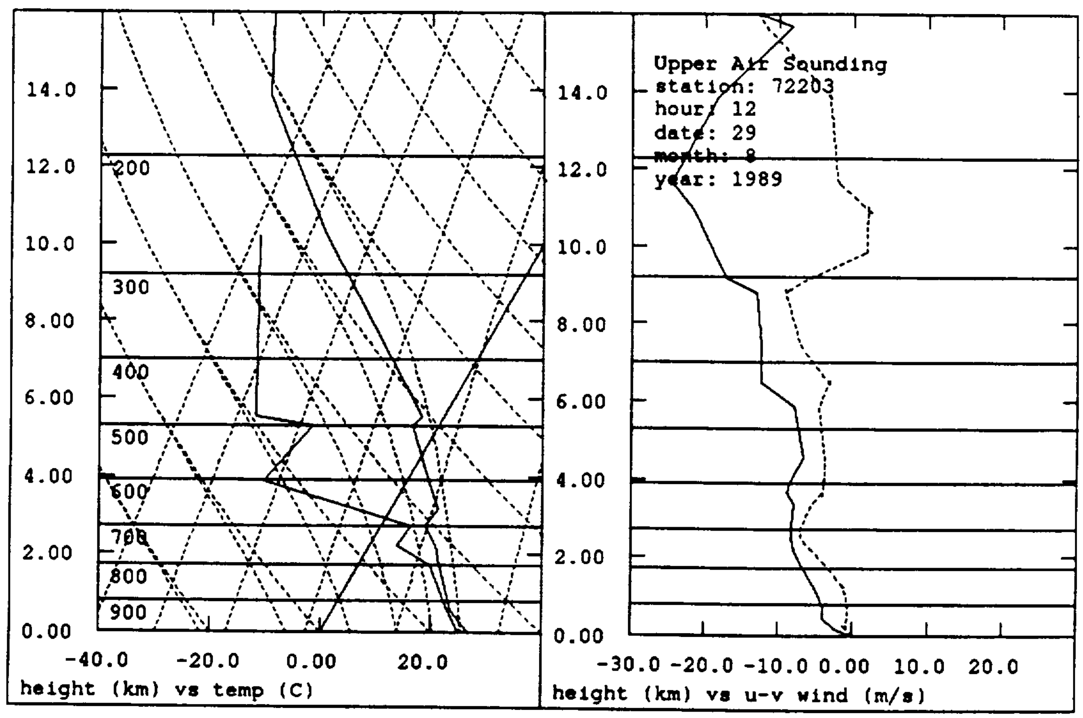


Figure 15: Skew T diagram for the 12 Z West Palm Beach, Florida, sounding on 29 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

A.1.7 Summary: 30 August 1989 (89242)

Highlight: • The cloud tops never exceeded 12,000 ft (3.7 km) over KSC during this flight. No launch commit criteria were violated and the clouds were not electrified.

The weather this day was dominated by a ridge running east to west with a high over Georgia. The sounding showed moist air (RH $\geq$ 65%) up to 13,000 ft (4.0 km) and dry air (RH $\leq$ 15%) above. At all levels the winds were easterly. The steering level flow was northeasterly at 10 knots. Not much activity was expected, but there was a slight chance of showers with the onset of the sea breeze.

The 1200 Z West Palm Beach and 1300 Z Tampa, Florida, soundings are shown in Fig. 16.

SPTVAR took off at 1630 Z and flew at 12,000 ft (3.7 km) over Merritt Island for most of the flight. The pilot reported no clouds taller than 12,000 ft (3.7 km) over KSC and no clouds taller than 20,000 ft (6.1 km) all the way from Daytona Beach to Melborne during the flight. Only fair-weather electric field was measured over KSC by SPTVAR. The clouds deteriorated and the flight was terminated at 1816 Z. The track of SPTVAR is shown in Fig. 17.

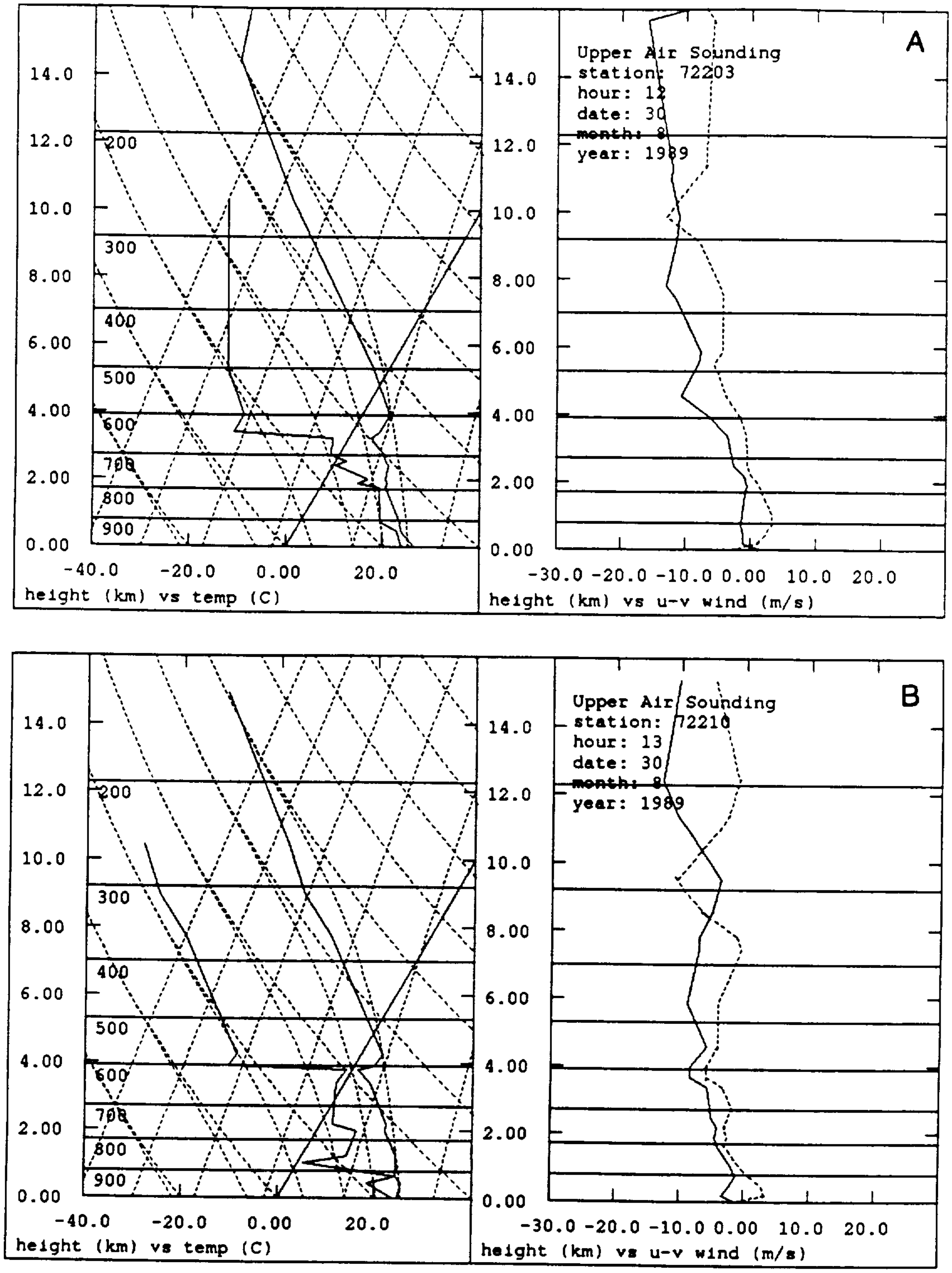
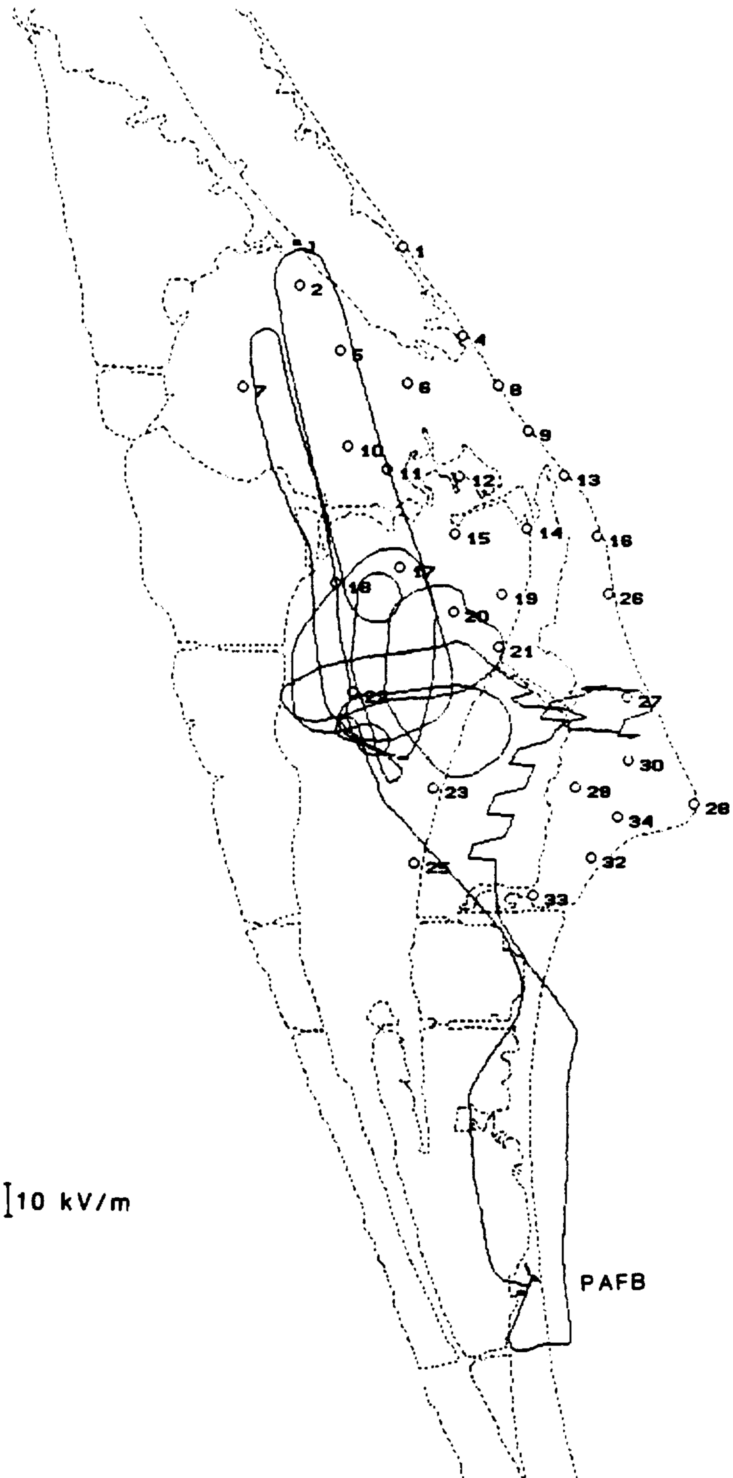


Figure 16: Skew T diagrams for the 12 Z West Palm Beach (A) and 13 Z Tampa (B), Florida, soundings on 30 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, **u**, is the solid line and the north component, **v**, is the dashed line.



E_Z]10 kV/m

Figure 17: PC plot of the SPTVAR flight track on 30 August 1989. Only fair-weather electric field was measured on this flight. Faulty LORAN positions caused the sawtooth pattern in part of the flight path.

A.2 Cloud That Moved Onshore From The Atlantic Ocean

A.2.1 Summary: 20 August 1989 (89232)

Highlights:

- SPTVAR measured $\vec{E}$ from a cloud that came onshore over Port Canaveral and finally dissipated over the southern part of Merritt Island without ever producing a lightning flash, despite the surface ∇V having reached -8 kV/m. Launch commit criteria weather rules B(3) and C would have forbidden launch through this cloud.
- A second cloud was followed toward the west and inland after a lightning flash removed negative charge in its eastern fringe over the Indian River.
- False ∇V contour closures in the KSC surface electric field contour display occurred both as the first cloud came onshore and as it dissipated over Merritt Island.

> The long wave trough at 200 mb was still evident from the Great Lakes into northern Florida, but it was weaker. The airmass had easterly flow up to 400 mb at approximately 7 knots, clearly depicting the tropical influence. The airmass was extremely moist and unstable. The preflight satellite imagery indicated that convection would be present all day.

The 1200 Z West Palm Beach and Tampa, Florida, soundings for this day are shown in Fig. 18.

The object of this day's flight was to investigate clouds which came onshore as part of the activity associated with a tropical wave. An intense rain shower had moved onshore over Patrick AFB after 1300 Z and very quickly passed to the west. There was a rapidly developing cloud just east of Patrick AFB when SPTVAR took off at 1405 Z. This cloud had a maximum radar reflectivity of 48 dBZ at 1411 Z. Two minutes later the Aeromet Lear Jet reported from a flight altitude of 36,000 ft (10.9 km) that the top of this cloud was above that altitude. SPTVAR flew north along the west side of this cloud and then back and forth across its north end which was then just east of the town of Cape Canaveral. Figure 19 shows a PC plot of the SPTVAR flight track and E_{XY} vectors for the first hour and 25 minutes of this flight (1405 to 1530 Z), while Fig. 20 shows a Sun Workstation plot of the interesting segment from 1420 to 1440 Z with E_{NE} vectors plotted at intervals along the track. At the points labeled **A**, **B** and **C**, SPTVAR flew through small regions of cloud. The resultant charging of the airplane caused spurious electric field component measurements, seen as unorganized E_{NE} vectors in the figure. This effect can also be seen

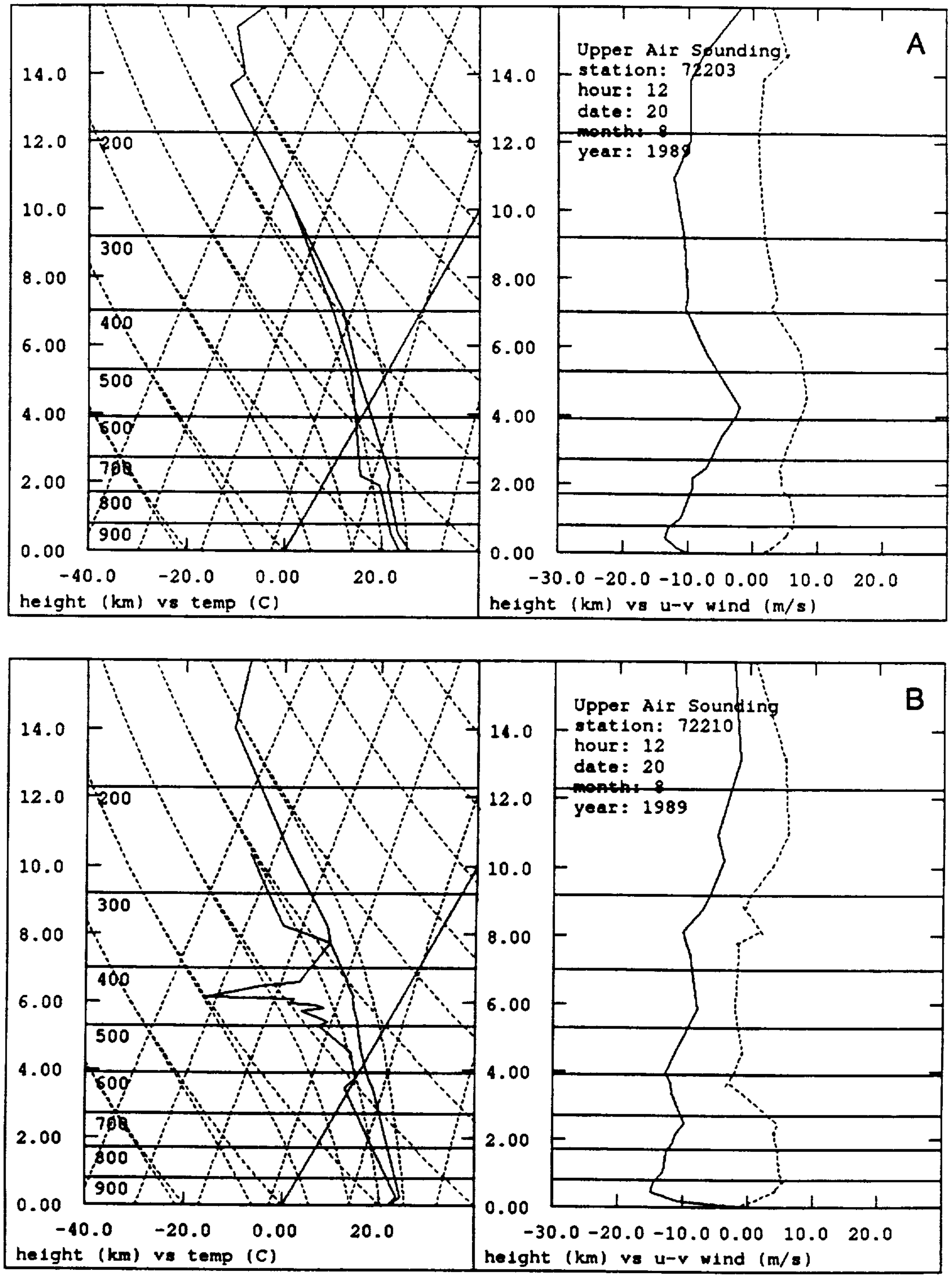


Figure 18: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 20 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

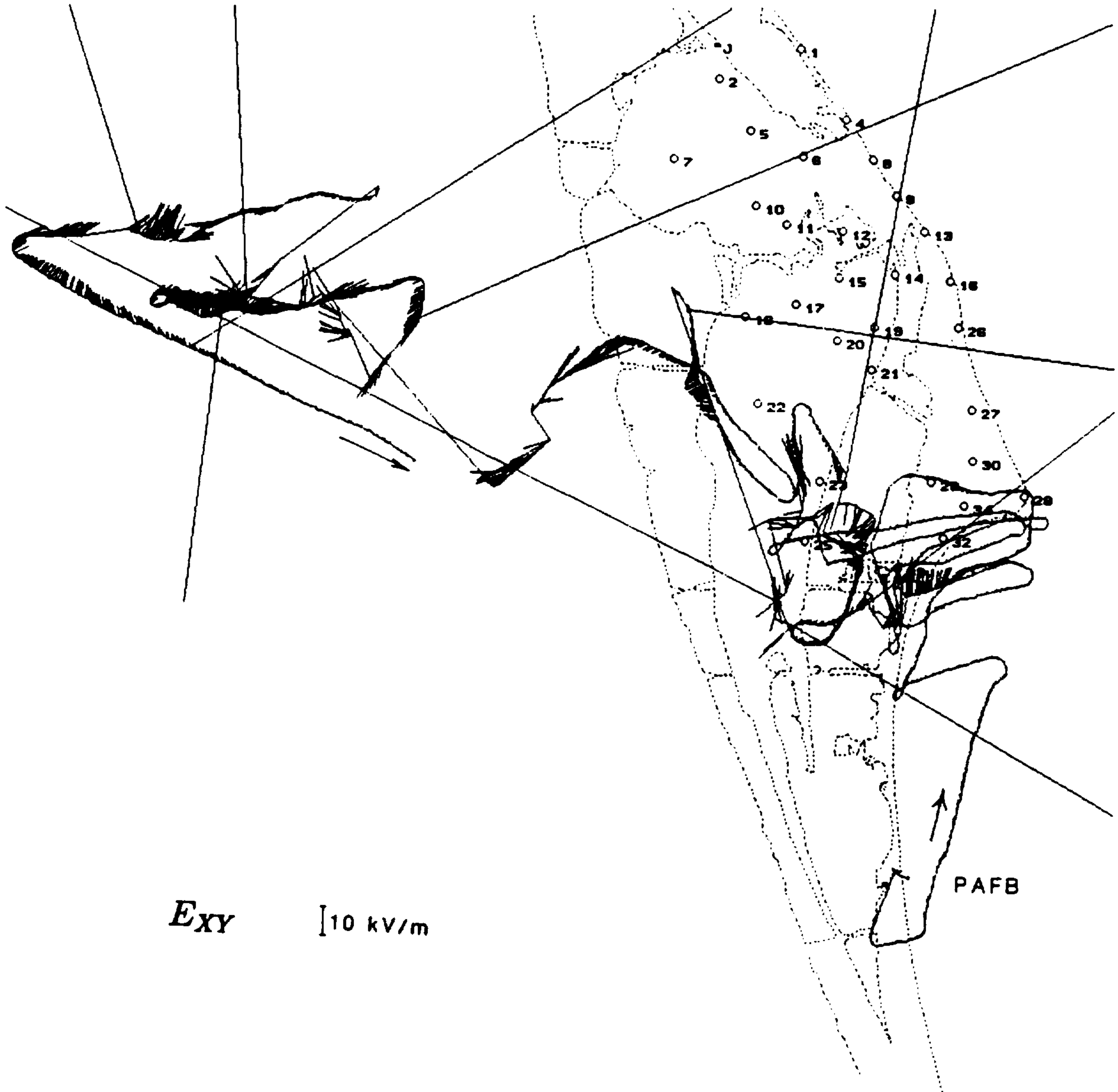


Figure 19: PC plot of E_{XY} vectors along the SPTVAR flight track from 1405 to 1530 Z on 20 August 1989. As we mentioned earlier the spikes in the record resulted from interference in the telemetry signal.

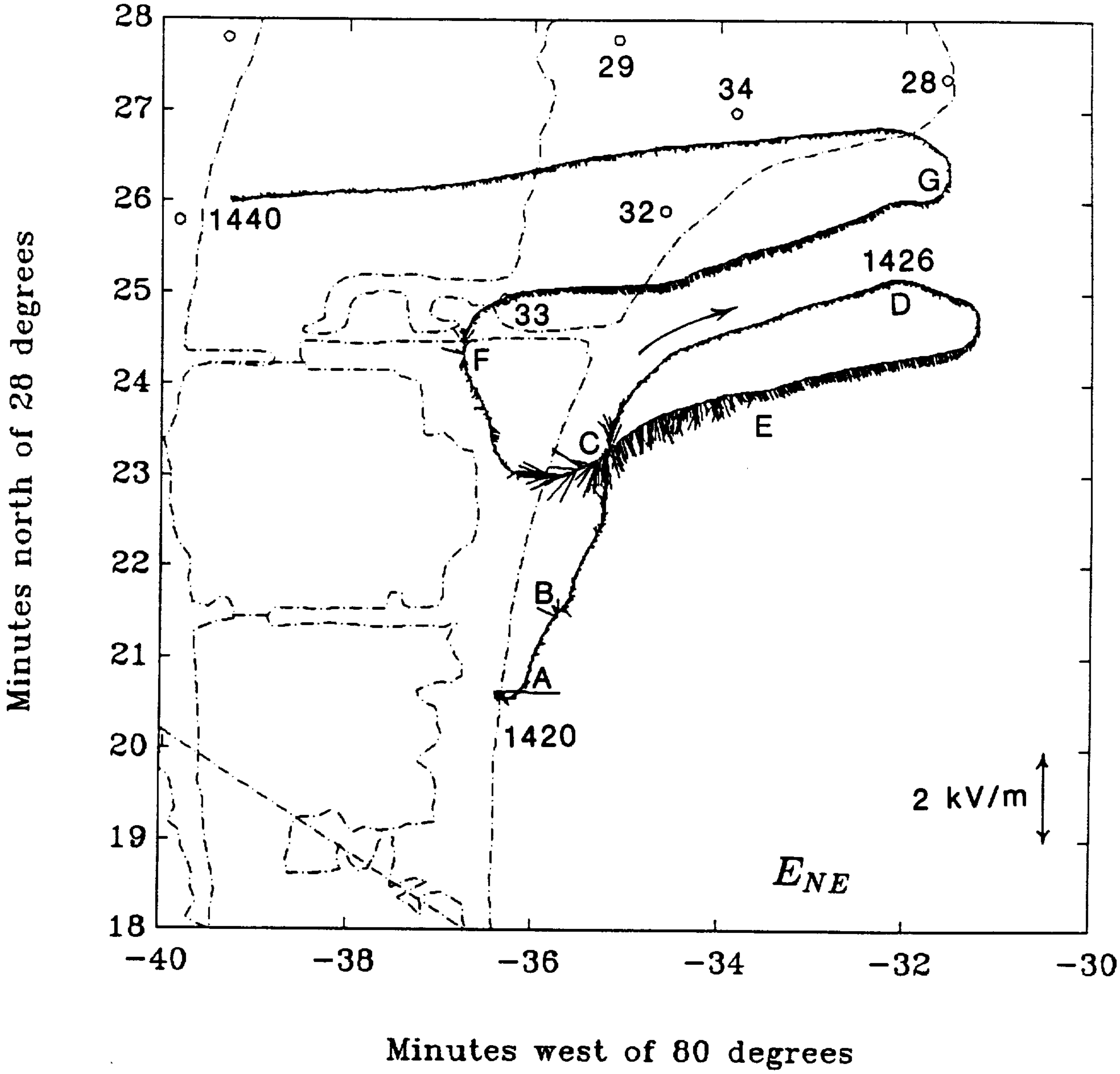


Figure 20: E_{NE} vectors plotted along the SPTVAR flight track from 1420 to 1440 Z on 20 August 1989.

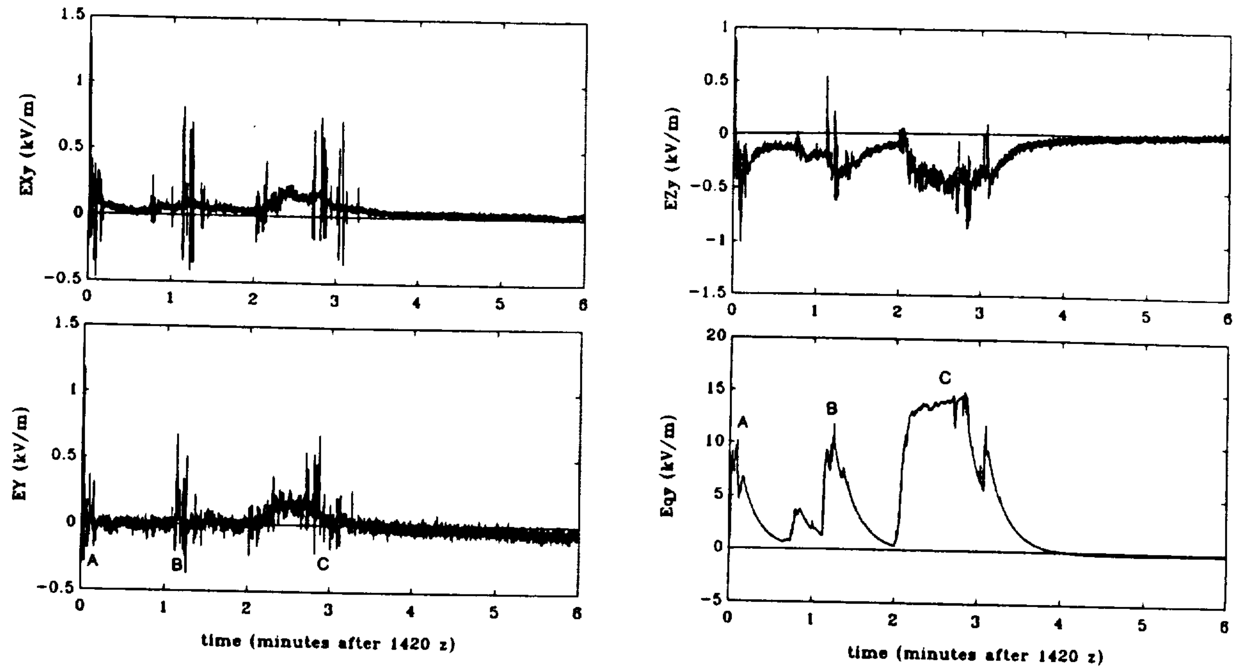


Figure 21: E_X, E_Y, E_Z and the field E_q due to the net charge on the airplane from 1420 to 1426 Z on 20 August 1989.

in the plots of individual electric field components for the first six minutes of this time interval shown in Fig. 21. This figure also shows the electric field due to the charge on SPTVAR and that E_Y became slightly negative after 1424 Z. Although this trend in E_Y appeared to be insignificant and had a magnitude only slightly larger than the noise in the data, it was actually the first indication that the cloud to the south was electrified. After 1426 Z, **D** in Fig. 20, where this slight field was just barely discernible as $E_Y \simeq -75$ V/m, SPTVAR turned to the right and flew back across the north end of the cloud. E_{NE} vectors again pointed south and with a larger and more convincing magnitude ($E_Y \simeq +200$ V/m). Half way along this east-to-west pass SPTVAR encountered a cloud and became mildly charged, the cause for the spurious E_{NE} vectors from there (**E**) to the turn from north to east heading over Port Canaveral at **F**. From there to **G**, SPTVAR flew toward the east with E_Y peaking at about -150 V/m before SPTVAR turned around to the left and flew back west. During the earlier part of this westward flight segment E_Y was about $+100$ V/m. This sequence of electric field measurements suggests a negative cloud charge was somewhere offshore of Cocoa Beach.

The next 19 minutes of flight are shown in Fig. 22. Just after 1440 Z, SPTVAR turned around and flew toward the east, measuring the strongest electric field over the western basin of Port Canaveral at 1444 Z, indicating a negative charge SSE of there. After turning around just SE of Cape Canaveral SPTVAR flew over Port Canaveral while turning toward the south, only to double back over Cocoa Beach and fly north and then east toward the Cape. Both the north-to-south and south-to-north flight segments over the town of Cape Canaveral show a convergence of E_{NE} vectors to the east of SPTVAR (just before and after 1453 Z), verifying the presence of a negative cloud charge offshore of the town of Cape Canaveral. The convergence of the E_{NE} vectors as SPTVAR subsequently flew just north of mill 34 indicates that the negative charge was close to shore at that time (1458 Z).

At 1459 Z SPTVAR turned south over the Cape and, shortly thereafter, toward the Port at which time SPTVAR was headed directly for negative charge in the cloud, as evidenced by the E_{NE} vectors being drawn forward along the flight track. While still offshore SPTVAR apparently entered a region of negative charge and flew past more negative charge above and extending to the right of the flight track. See Figs. 23 and 24.

Between 1505 and 1510 Z SPTVAR flew north over the western basin of the Port where it experienced severe electrical charging. The situation was similar to that on the day before (please see the discussion of severe airplane charging in the account of the 19 August flight). Although the electric field components were not properly determined when the airplane was highly charged, there was a brief time when the charge was small and changing polarity. The value of $E_Z = +27$ kV/m measured at that time is probably correct. The deduced electric field components for this flight segment are shown in Fig. 25.

SPTVAR then turned south and was approaching negative charge somewhat to the right of its track when, just west of mill 23 at 1512 Z, it experienced even more severe charging than at 1501–1503 with the result that E_X and E_Y could be correctly determined for only part of the pass. Nevertheless, at 1513 Z as the charge on SPTVAR was near zero and changing from negative to positive, E_Z was measured as about +29 kV/m. Since the airplane charge was small this is a good estimate of the true vertical field component at that time. The SPTVAR track with E_{NE} vectors is shown in Fig. 26, while the individual electric field components are shown in Fig. 27.

SPTVAR then turned back north, Fig. 28, and once again experienced severe charging west of mill 25. Although the electric field measurement was again compromised between 1514 and 1516 Z, it appears that E_Z reached at least 10 kV/m at 1515 Z. The data shown in Fig. 29 indicate that after 1516 Z the airplane charge was small and hence the electric field component determination was correct. Between 1516 and 1517 Z E_X and E_Z indicate that SPTVAR was then flying away from negative charge located below the SPTVAR altitude. As SPTVAR continued to the northwest after 1516 Z, the E_{NE} vectors pointed to the southwest, apparently due to another cloud in that direction rather than the one followed up to that time.

Indeed, after SPTVAR turned back toward the southeast at 1520 Z, the pattern of the E_{NE} vectors shown in Fig. 30 confirms this picture, indicating negative charge was over the Indian River south of the NASA–Titusville causeway. Then, at 1523:13, the vectors

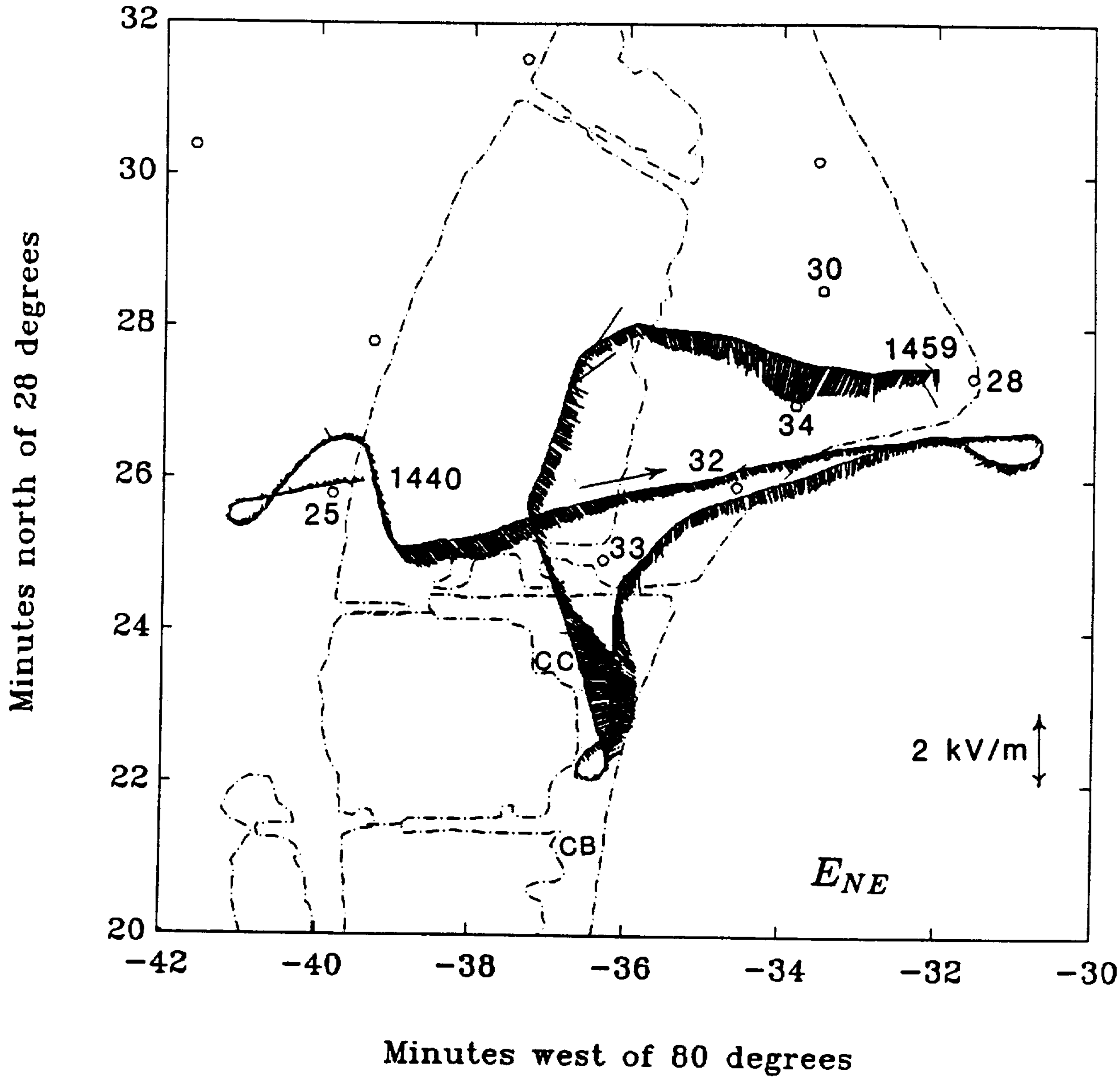


Figure 22: E_{NE} vectors plotted along the SPTVAR flight track from 1440 to 1459 Z on 20 August 1989. CC and CB denote the towns of Cape Canaveral and Cocoa Beach.

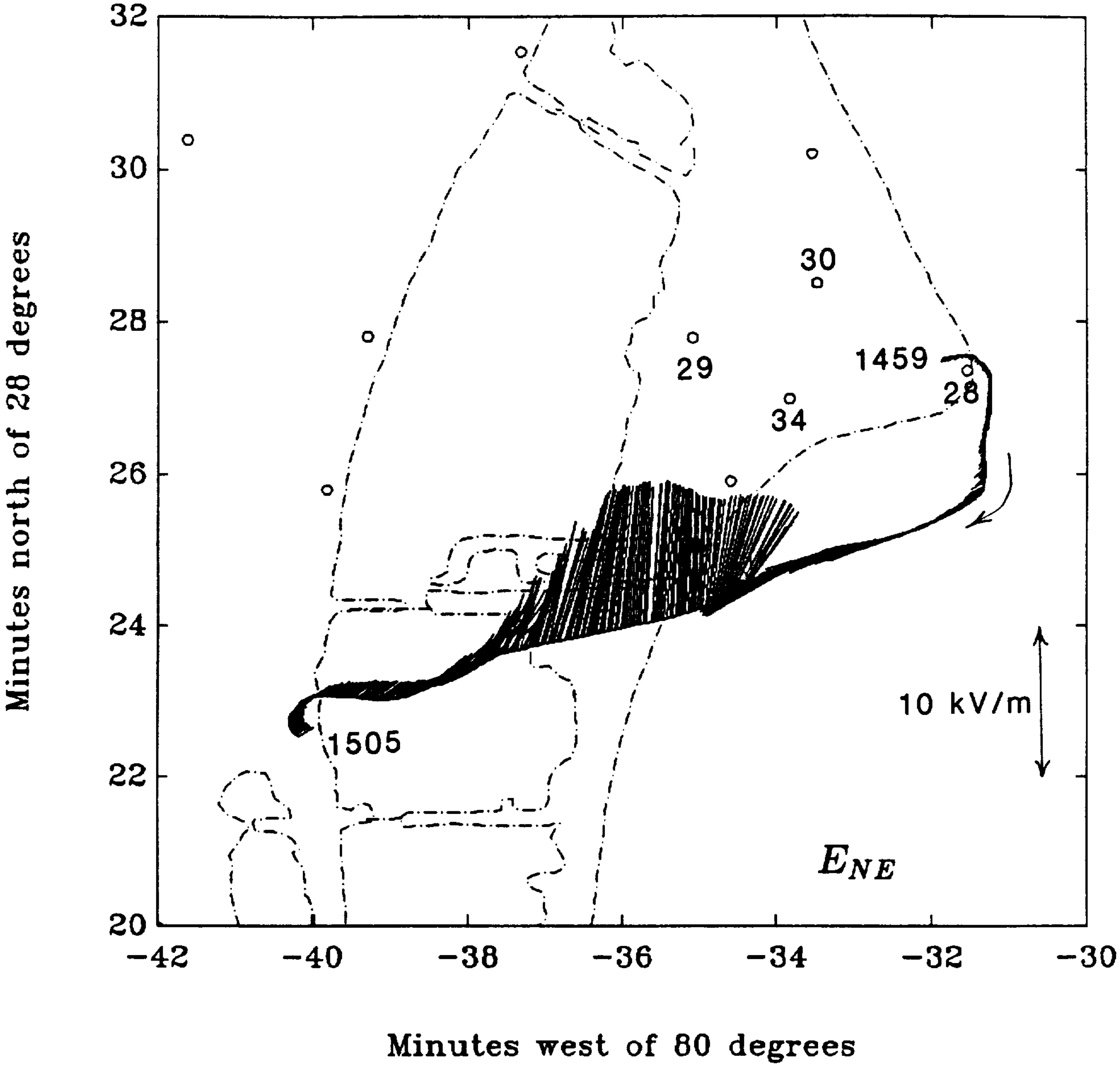


Figure 23: E_{NE} vectors plotted along the SPTVAR flight track from 1459 to 1505 Z on 20 August 1989.

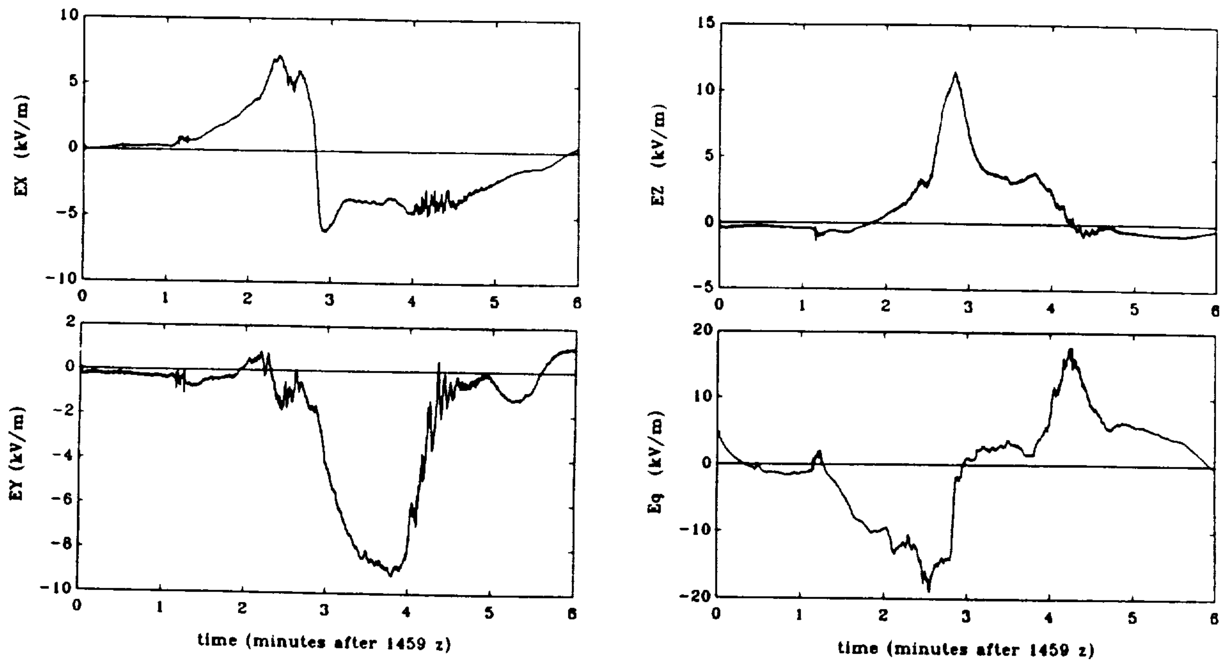


Figure 24: E_X, E_Y, E_Z and the field E_q due to the net charge on the airplane from 1459 to 1505 Z on 20 August 1989.

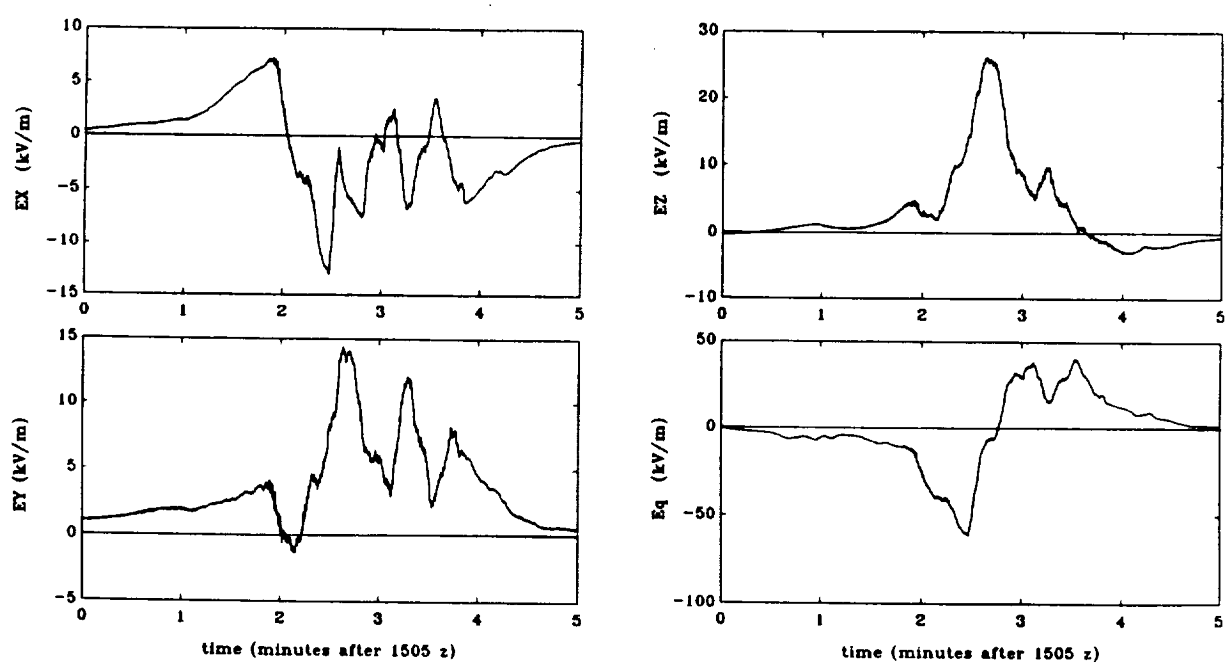


Figure 25: E_X, E_Y, E_Z and the field E_q due to the net charge on the airplane from 1505 to 1510 Z on 20 August 1989.

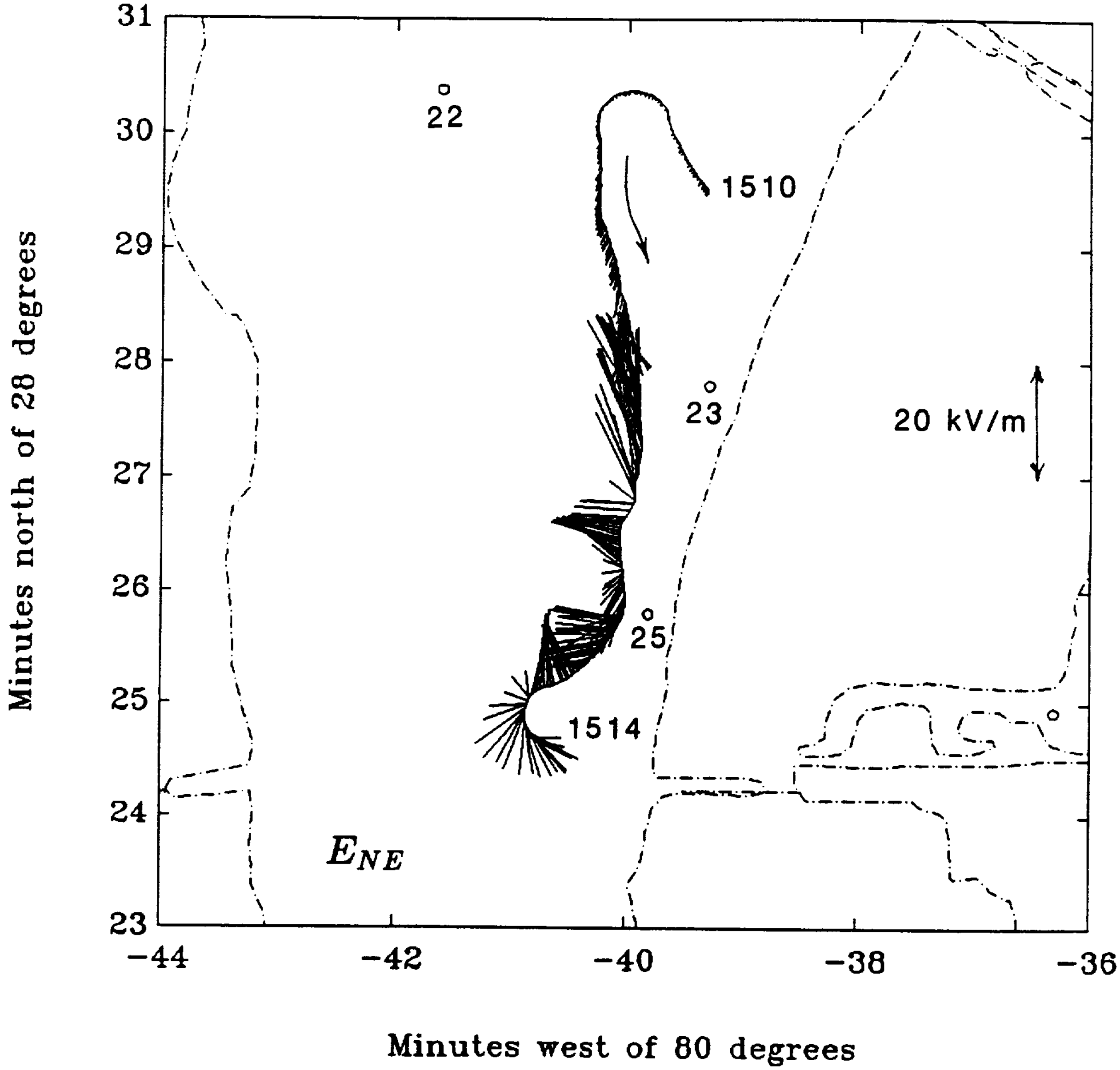


Figure 26: E_{NE} vectors plotted along the SPTVAR flight track from 1510 to 1514 Z on 20 August 1989.

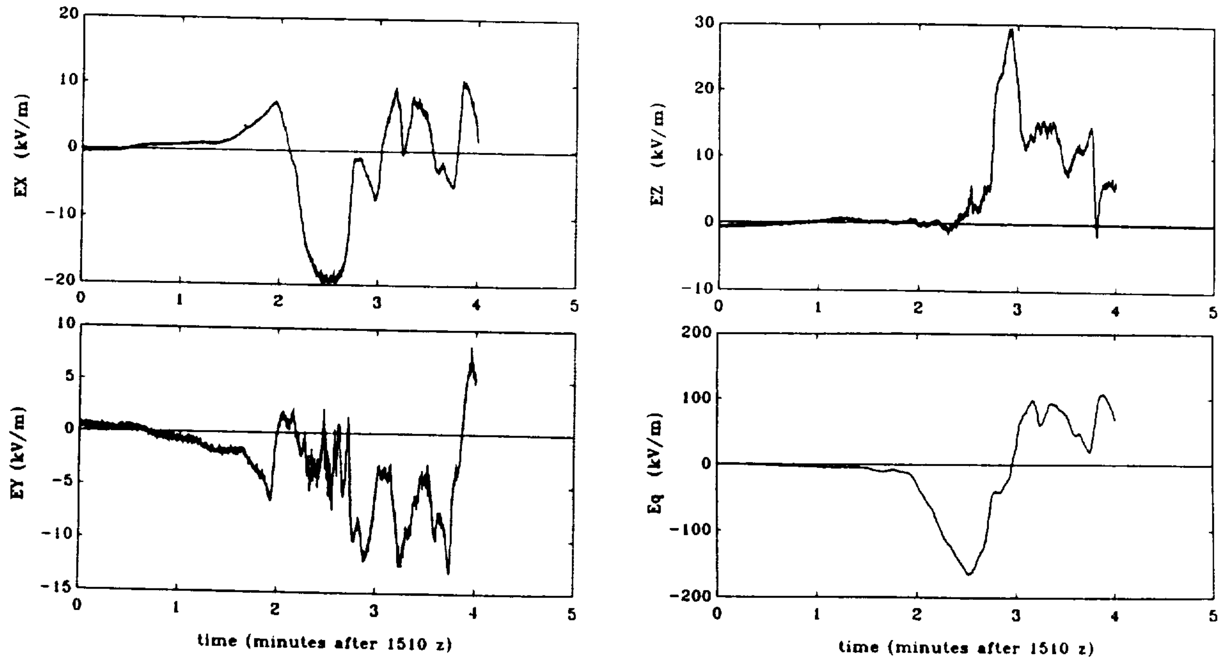


Figure 27: E_X, E_Y, E_Z and the field E_q due to the net charge on the airplane from 1510 to 1514 Z on 20 August 1989.

suddenly decreased in length with but little change in direction indicating that the charge just to the west was depleted by a lightning flash. SPTVAR turned around west of mill 23 and flew toward Titusville. The charge previously noted over the Indian River was no longer there due to its having been removed by the lightning flash. However, SPTVAR did measure electric field which was apparently due to negative charge farther to the west over the Florida mainland. Note also that as SPTVAR turned around west of mill 23 at about 1525 Z there was no sign of the electric field measured there only ten minutes earlier. The charge responsible for the E_Z of -29 kV/m measured by SPTVAR at 1513 Z near mill 23 had disappeared, perhaps having been carried to the ground on rain.

SPTVAR followed the second cloud on to the west out of restricted area R2934 until it was 20 mi west of the Indian River. During the later part of this time and while well west of the Indian River, SPTVAR made several surveys along the south end of the cloud and experienced repeated strong electrical charging. The pattern was fairly consistent, with first negative mill readings followed by positive readings, much like the episodes of strong charging earlier during this flight and early in the flight of the previous day (19 August). The flight was terminated at 1626 Z.

The KSC surface electric field mill array first indicated the presence of an electrified cloud when the one-minute average ∇V at mill 33 became more negative than -100 V/m at 1442 Z, by about which time the electric field measured by SPTVAR was beginning to

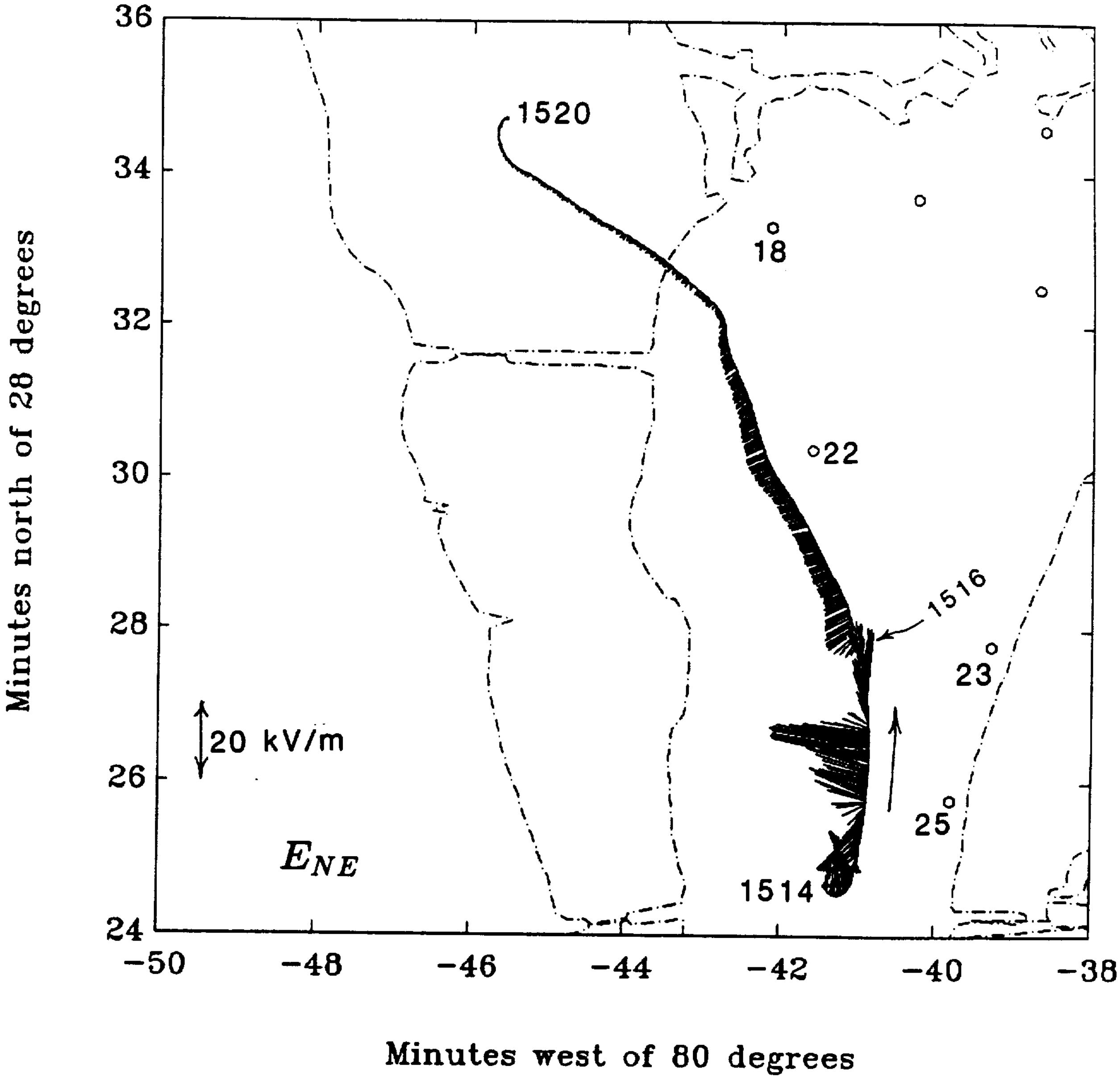


Figure 28: E_{NE} vectors plotted along the SPTVAR flight track from 1514 to 1520 Z on 20 August 1989.

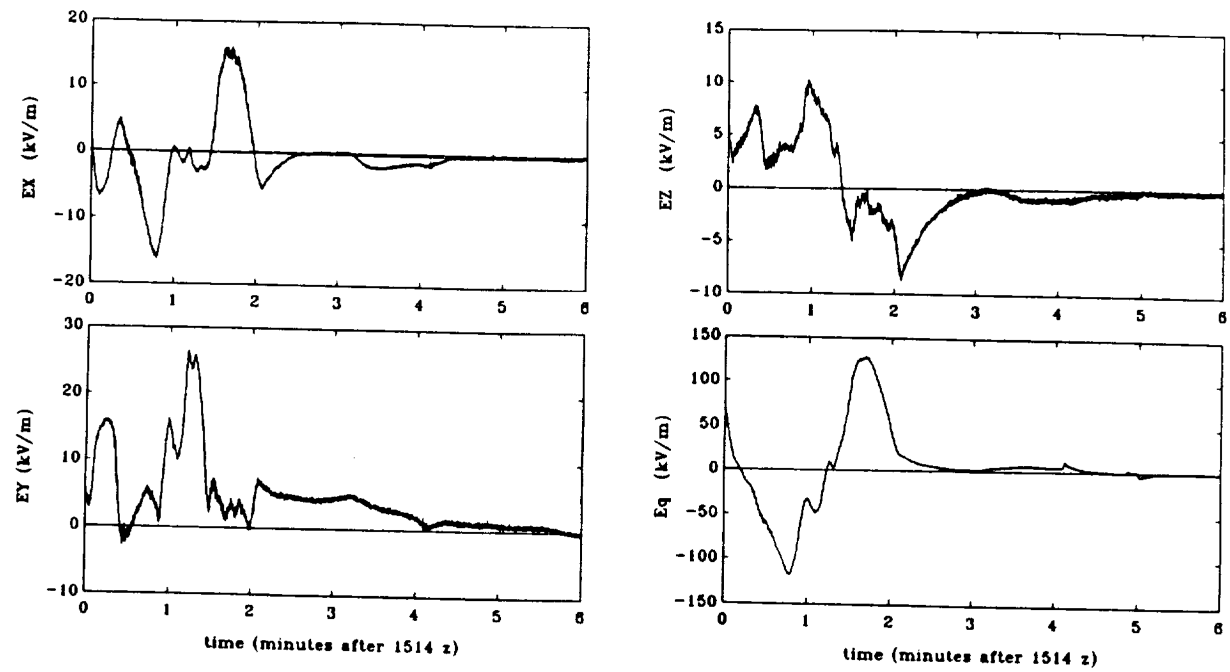


Figure 29: E_X, E_Y, E_Z and the field E_q due to the net charge on the airplane from 1514 to 1520 Z on 20 August 1989.

indicate that an electrified cloud was coming onshore over Port Canaveral. From 1240 to 1440 Z the surface ∇V measured by all the surface field mills had been between +500 and −100 V/m. The first contour plot to show the zero ∇V contour was also that for 1442 Z. The surface ∇V contour plots at two-minute intervals for 1442 to 1540 Z are shown in Figs. 31 to Fig. 35.

Between 1446 and 1506 Z the contour plot displays showed closed negative ∇V contours in the vicinity of Port Canaveral and that the field intensity was increasing, suggesting the development of an electrified cloud aloft. After 1506 Z the electric field over the southeast corner of the surface field mill array began shifting toward the west. At 1510 Z mill 25 measured $\nabla V = -8.0$ kV/m, the maximum field intensity measured under the cloud. Thereafter, the surface ∇V declined and the strongest ∇V shifted north to over mill 22. By 1542 Z, ∇V at mill 22 had declined to −200 V/m. The strip chart recordings of surface electric field measured by mills 22, 23, 25, 34, 32 and 33 (arranged north to south) are reproduced in Fig. 36. At about 1523 Z there was a sudden decrease in the electric field measured by mill 22 indicating a lightning flash. Of the other mills in the KSC surface field mill array only mill 23 recorded this flash, an indication that the affected charge was nearest to and west of mill 22, in agreement with the interpretation of the lightning signature in the SPTVAR data at that time. Only one lightning location was recorded by the LLP system during the SPTVAR flight. The time of the strike was 1523:12 Z with a

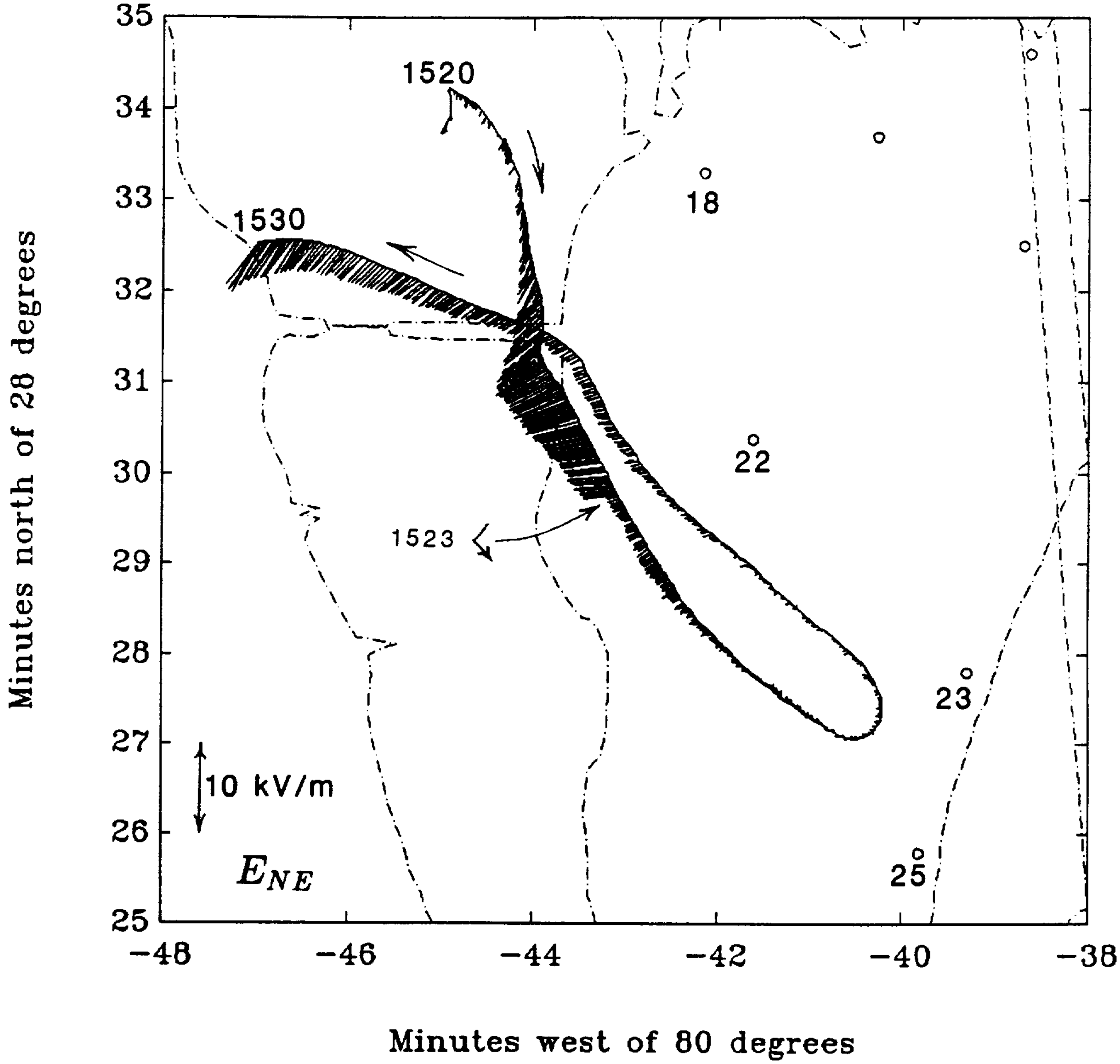


Figure 30: E_{NE} vectors plotted along the SPTVAR flight track from 1520 to 1530 Z on 20 August 1989.

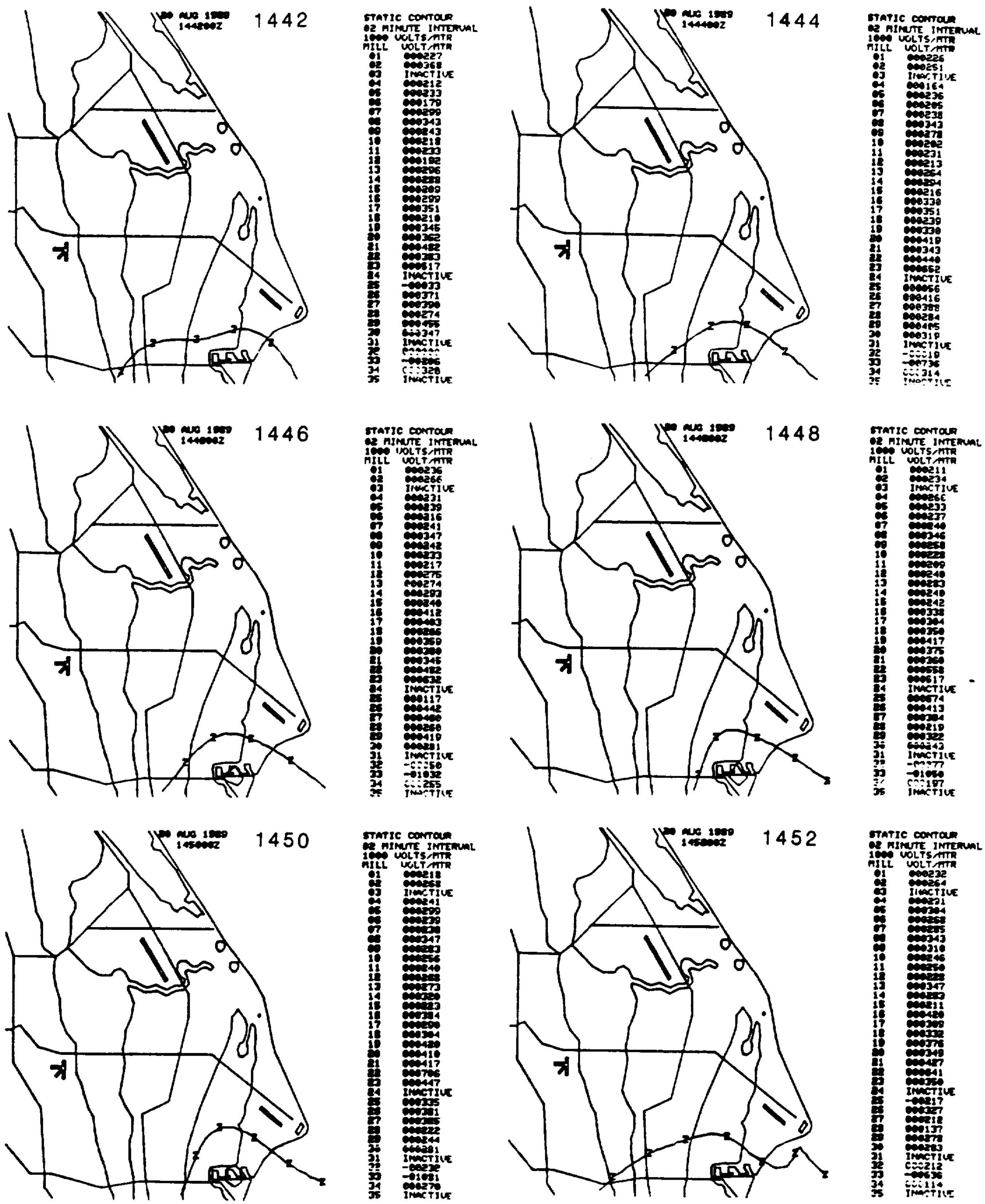


Figure 31: KSC surface ∇V contour plots for 1442 to 1552 Z on 20 August 1989.

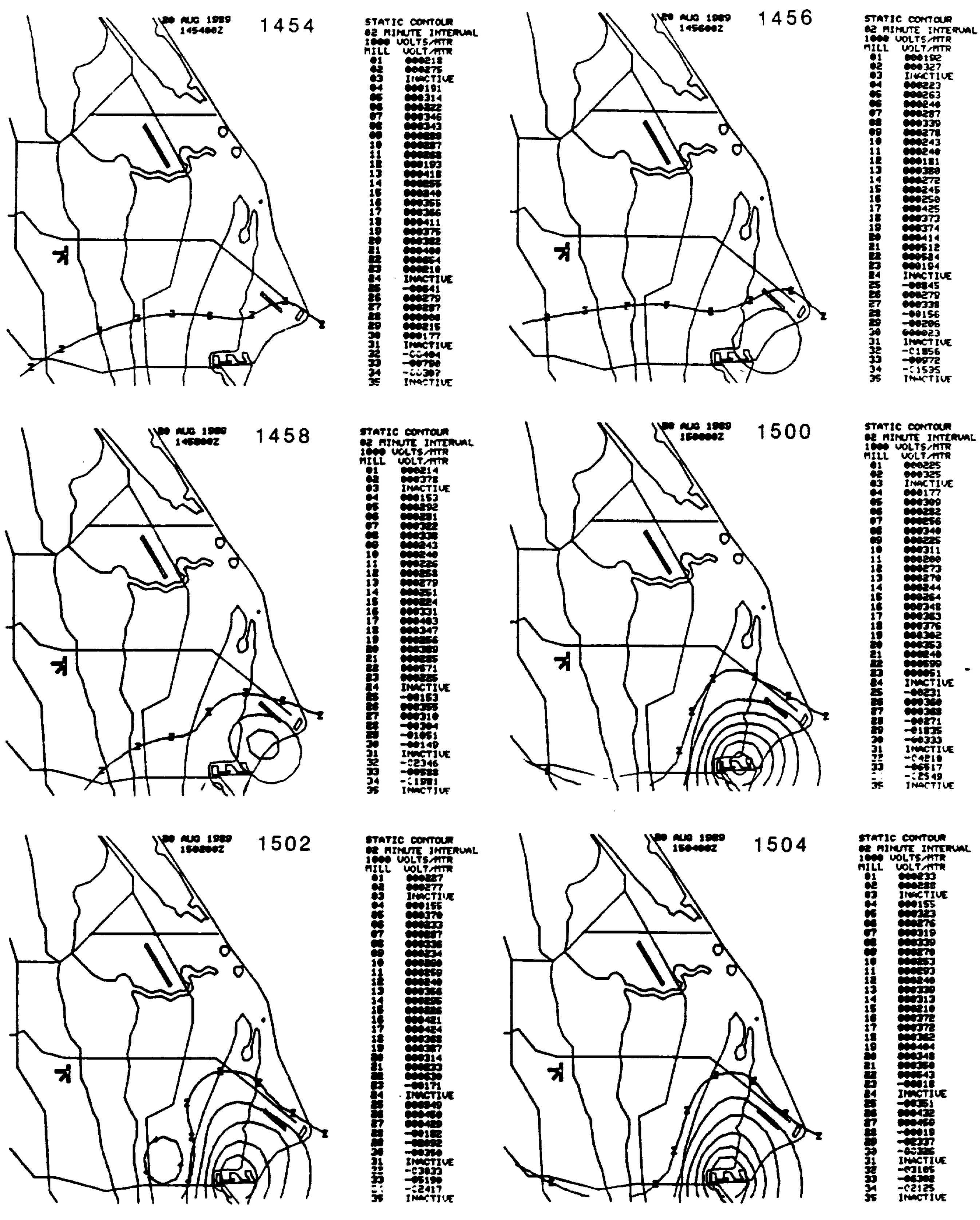


Figure 32: KSC surface ∇V contour plots for 1454 to 1504 Z on 20 August 1989.

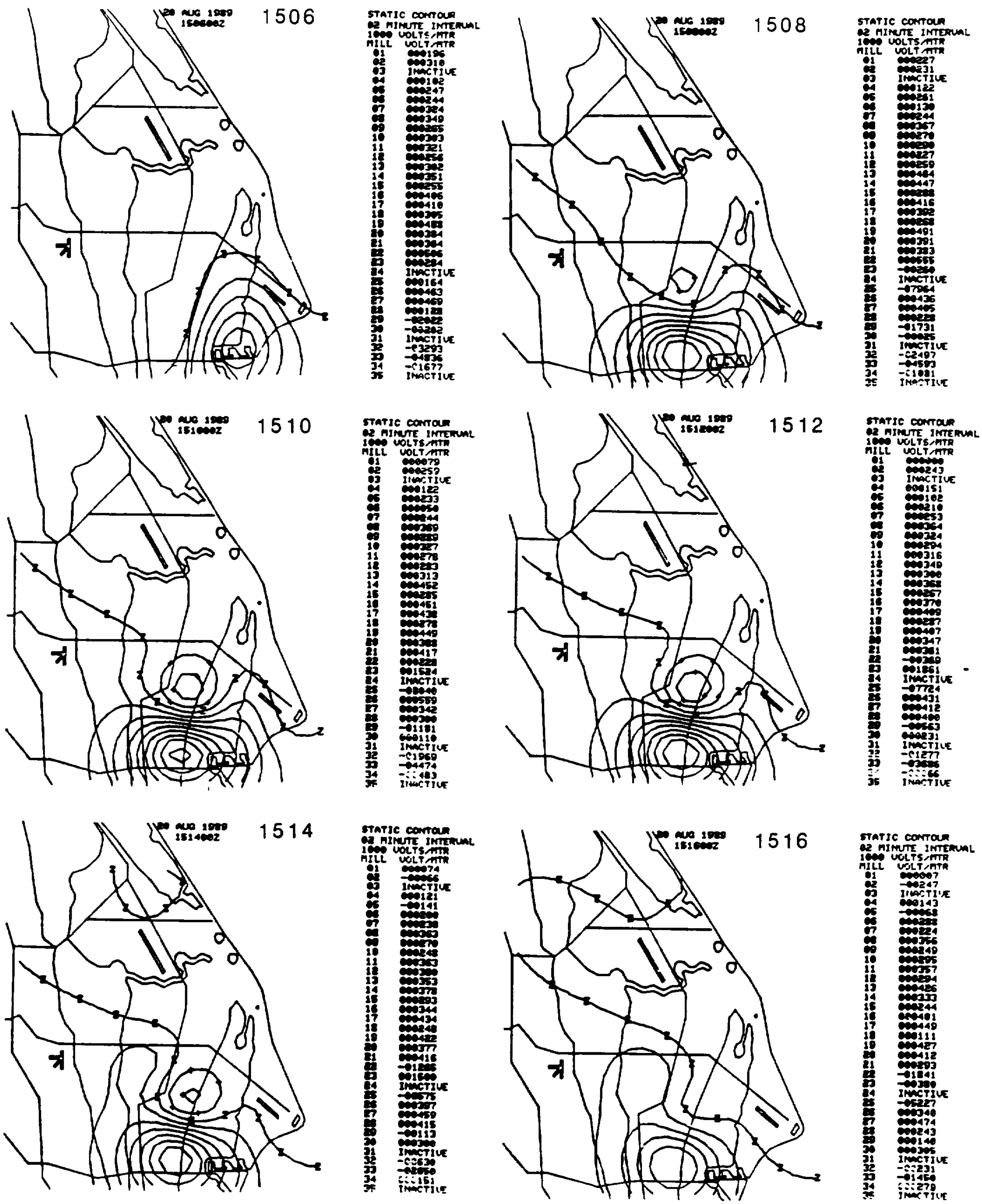


Figure 33: KSC surface ∇V contour plots for 1506 to 1516 Z on 20 August 1989.

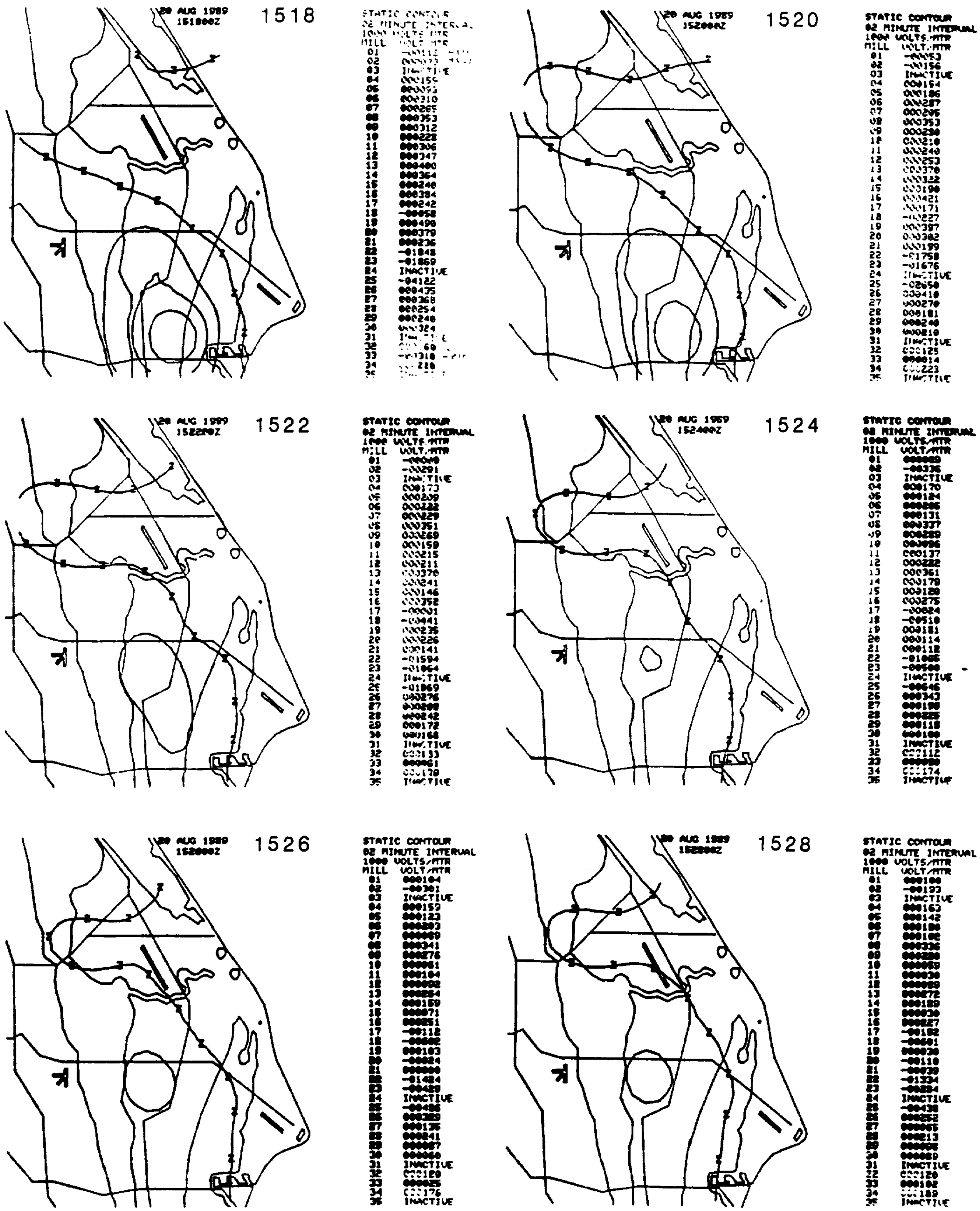


Figure 34: KSC surface ∇V contour plots for 1518 to 1528 Z on 20 August 1989.

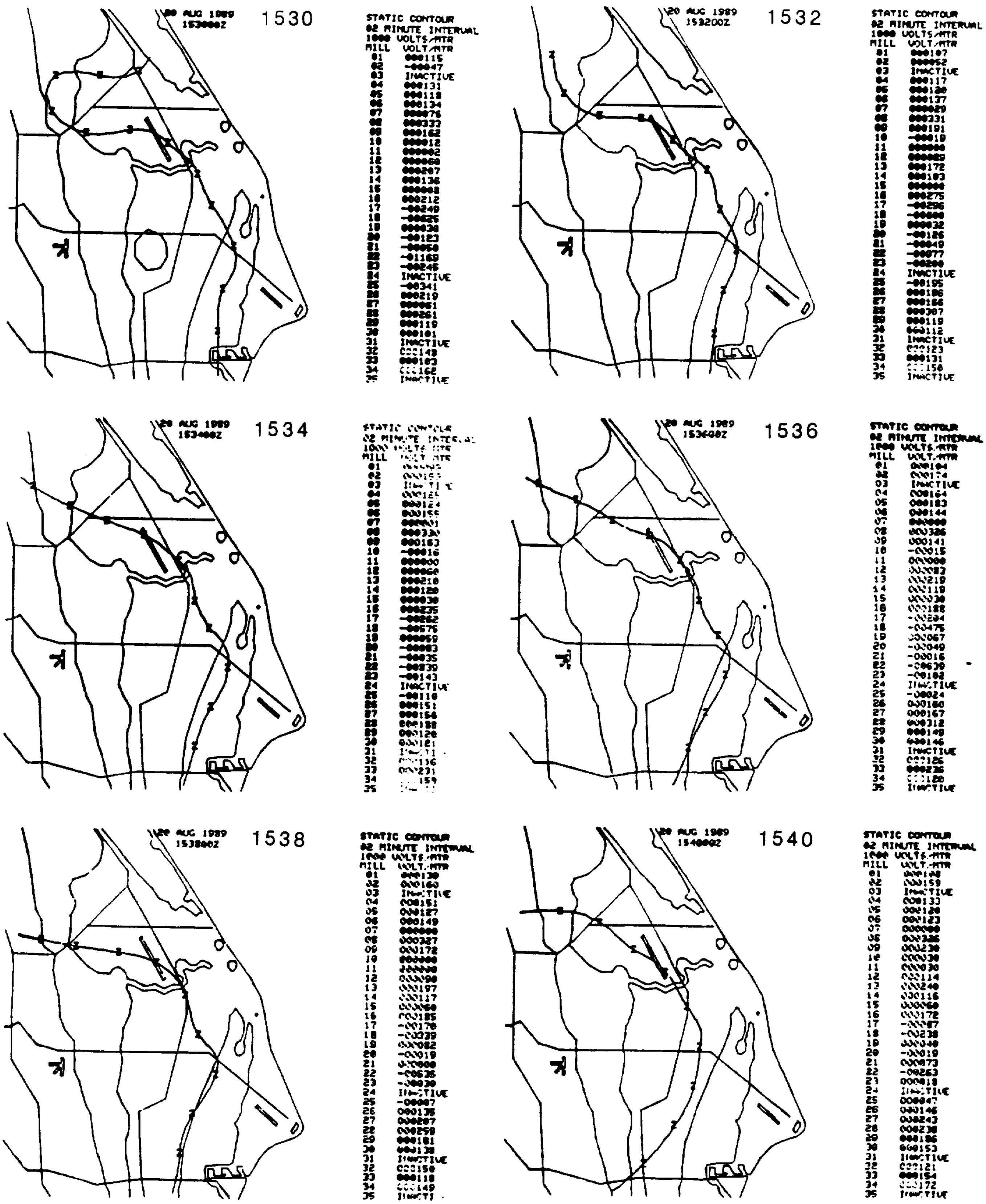


Figure 35: KSC surface ∇V contour plots for 1530 to 1540 Z on 20 August 1989.

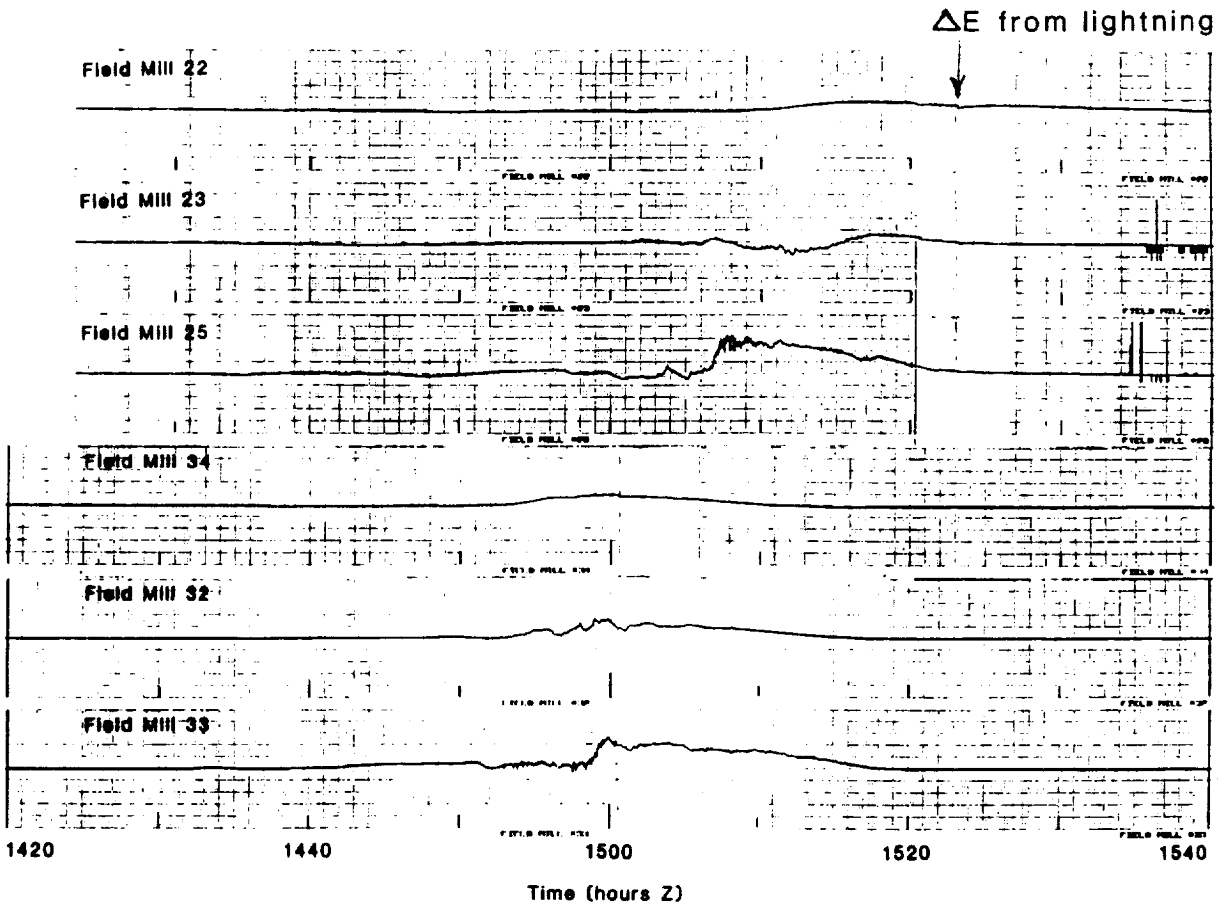


Figure 36: Strip chart recordings of the surface electric field at KSC mills 22, 23, 25, 34, 32 and 25 (arranged north to south according to their locations) on 20 August 1989.

location of 335° and 21.6 nautical miles from COF (Patrick AFB). Although this location places the strike just off the top of Fig. 30 at latitude 28° 35.39' and longitude 80° 46.44', the time agrees with that determined from the SPTVAR data.

Thus, although the cloud that came onshore over Port Canaveral was electrified for more than 42 minutes, 1442 to 1524 Z, there is no indication of its having produced a lightning flash. The one lightning signature at 1523:12 recorded by SPTVAR and KSC mill 22 was due to a second cloud over the Indian River and the mainland which SPTVAR studied after 1525 Z.

During this flight the surface electric field contour display again exhibited its shortcomings. The closed contours drawn to the south of mill 33 and and to the east of mills 32 and 34 between 1446 and 1506 Z suggest that the cloud first electrified over the Port Canaveral area, whereas the SPTVAR measurements show that the cloud was electrified as early as 1425 Z and thus was already electrified when it came onshore. Also, the SPTVAR data for 1510 to 1530 Z indicate that the cloud that had been studied over the south end of Merritt Island was declining by 1514 and was gone ten minutes later at about 1525 Z when SPTVAR turned around just west of mills 23 and 25. The contour plots for 1518 to 1524 Z show a steady decline of ∇V at mill 22, followed by a renewal of ∇V there from 1526 to 1530 Z. The contours which were closed to the west of mill 22 from 1522 through 1530 Z suggest a charge aloft, contrary to the interpretation derived from the SPTVAR data which show the ∇V at mill 22 was due to the cloud to the west. In both of these cases only the zero ∇V contour was consistent with the measurements obtained aloft by SPTVAR. At 1442 the zero field contour suggests a charged cloud somewhere south of Port Canaveral. Later, from 1524 to 1542 Z, the zero field contour suggests a charged cloud somewhere west of mills 22 and 25. Both of these interpretations are consistent with the SPTVAR data.

A.3 Clouds That Grew Over Land

A.3.1 Summary: 29 July 1989 (89210)

Highlights:

- Data from roll, yaw and pitch maneuvers in the electric field of an anvil cloud confirmed some of the calibration constants for deducing $\vec{E}$.
- SPTVAR was hit by lightning while flying beside a strongly electrified cloud.
- SPTVAR encountered strong electric fields. Various of the launch commit criteria weather rules would not have permitted launch under the conditions prevailing during this flight.

On 29 July a ridge that had been centered over the eastern United States had weakened significantly so that the flow over Florida was weak at all levels. Although the morning sounding at KSC was much drier than those at both Tampa and West Palm Beach, the satellite images revealed that moister air had advected into the KSC area by late morning. The 500 mb chart depicted a small cool pocket over central Florida and the 200 mb chart indicated slight difluence aloft.

Thunderstorm activity was expected to begin in the area about 2000 Z with storm movement predicted to be toward the east-northeast at 5 to 10 knots. The 1200 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 37

SPTVAR took off at 1848 Z after towering cumulus had begun forming in the area at about 1800 Z. A plot of the entire SPTVAR path for this flight is not shown since there were periods when the Loran data were garbled. As SPTVAR entered restricted area R2934, ∇V in excess of +1 kV/m was being measured at the north end of the KSC field mill array. Cells first formed along an east-west line, extending onto the northern part of Merritt Island. SPTVAR made three passes through these clouds between 1910 and 1950 Z. The pilot reported observing lightning toward Titusville at 1910 Z, and E_Z values up to +45 kV/m were measured during the second and third of these cloud penetrations. Figure 38 shows E_Z during and after the third penetration (1943 to 1953 Z). During the last four minutes of this time (1949 to 1953 Z, as SPTVAR was flying toward the north and out from beneath an anvil cloud) roll, yaw and pitch variations were executed in order to check the calibration of the electric field measurement.

The SPTVAR heading, roll and pitch angles during that time are shown in Fig. 39. These variations of the aircraft attitude angles affect the deduced components of $\vec{E}$ in the airplane

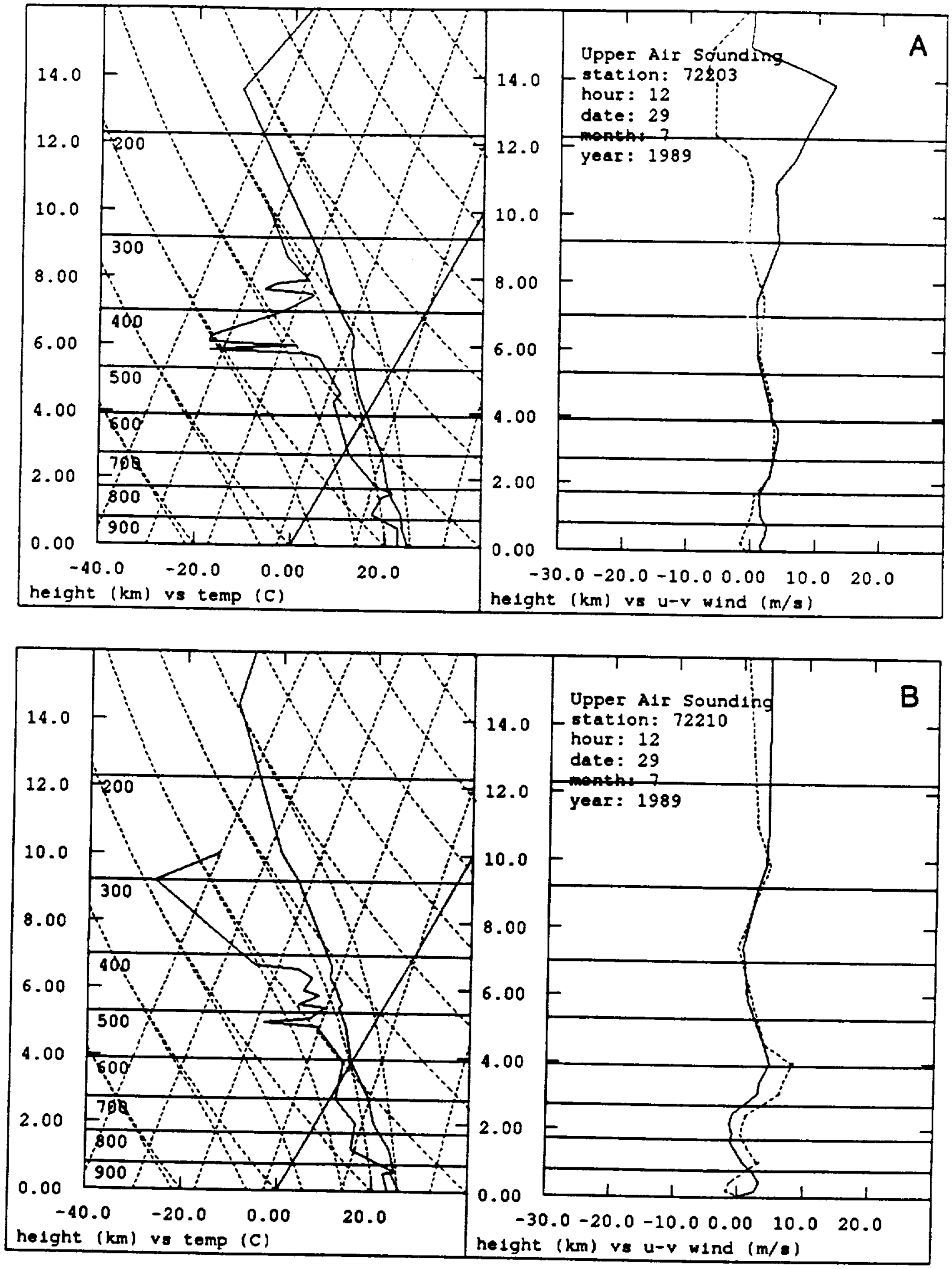


Figure 37: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 29 July 1989. In the graph of horizontal air velocity vs. altitude, the east component, **u**, is the solid line and the north component, **v**, is the dashed line.

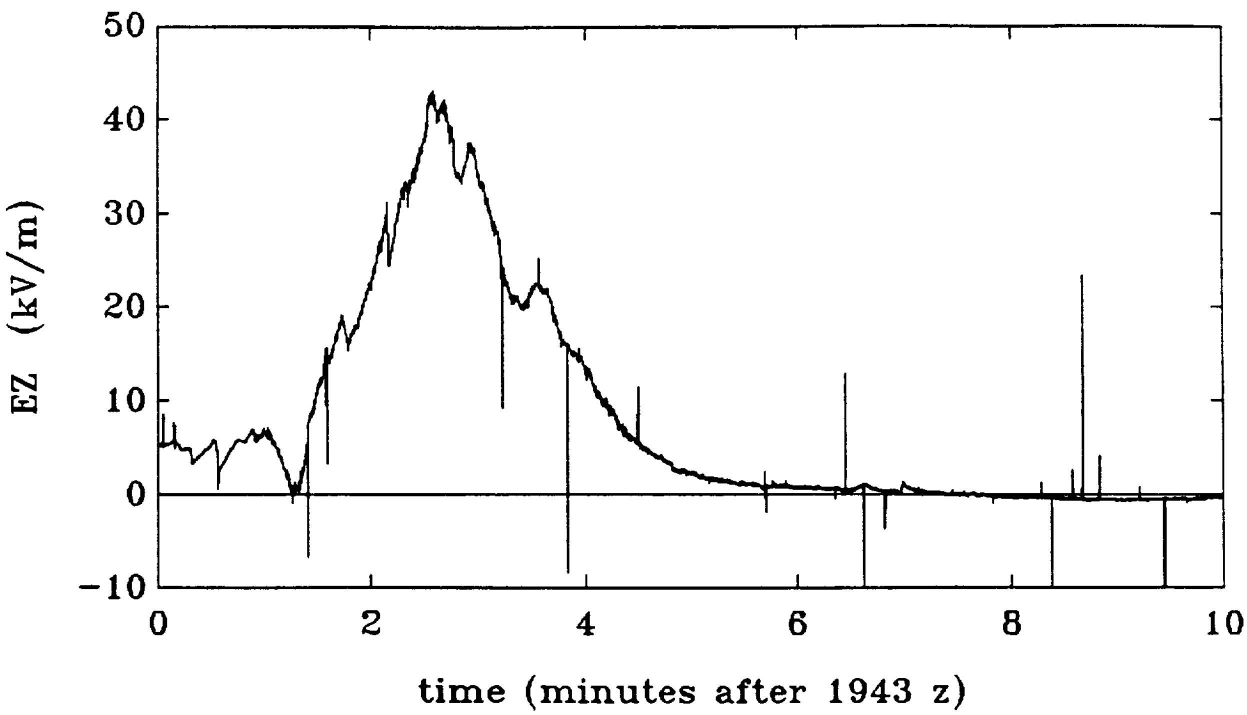


Figure 38: E_Z from 1943 to 1953 Z on 29 July 1989.

coordinate system (ACS) in a predictable way, as shown in Fig. 40. Transformation of the components of the electric field from the ACS to the level flight coordinate system (LCS) by means of successive roll and pitch angle transformations resulted in the electric field components shown in Figure 41. The intervals of the attitude angle variations are indicated in the figures.

The insensitivity to pitch variations of E_X and E_Z in the LCS indicates that the SPTVAR calibration coefficient C_X (see Part I), which scales the X component to the Z component in the ACS, is well determined.

Further transformation of the horizontal components of the electric field from the LCS to the geographic coordinate system (GCS) by means of a heading angle transformation results in the electric field components in the north and west directions shown in Fig. 42.

Although the electric field components in the GCS should not be affected by the attitude angle variations, the figure shows that there are small effects in the E_N and E_W components and a larger effect in E_Z.

Unfortunately, it is not possible to vary the roll angle greatly without changing the airplane heading since the airplane naturally turns when the wings are rolled severely. We know that E_Z in the ACS has some sensitivity to E_X (our simple method of determining the electric

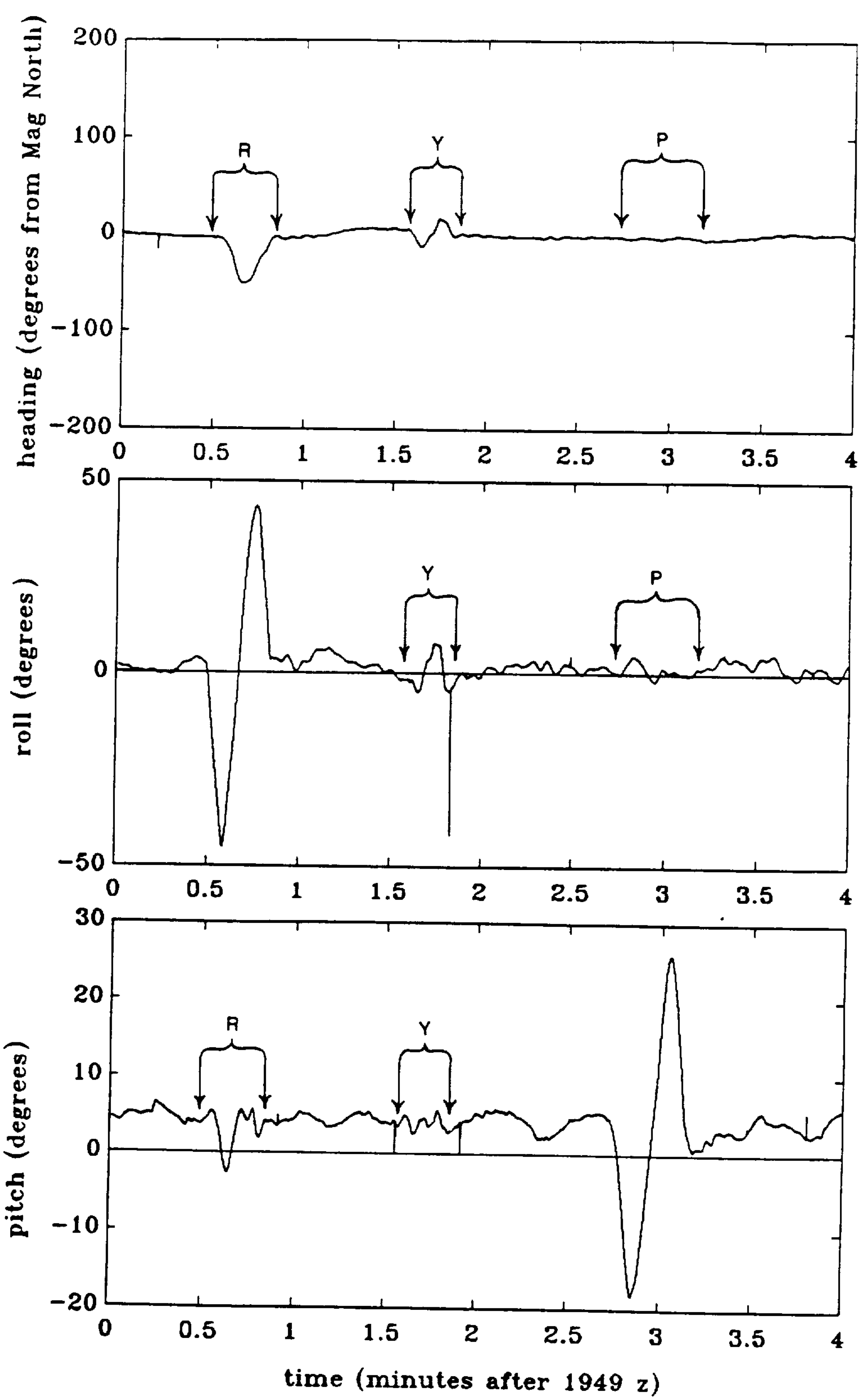


Figure 39: Plots of SPTVAR heading, roll and pitch angles during the roll (R), yaw (Y) and pitch (P) exercises between 1949 and 1953 Z on 29 July 1989.

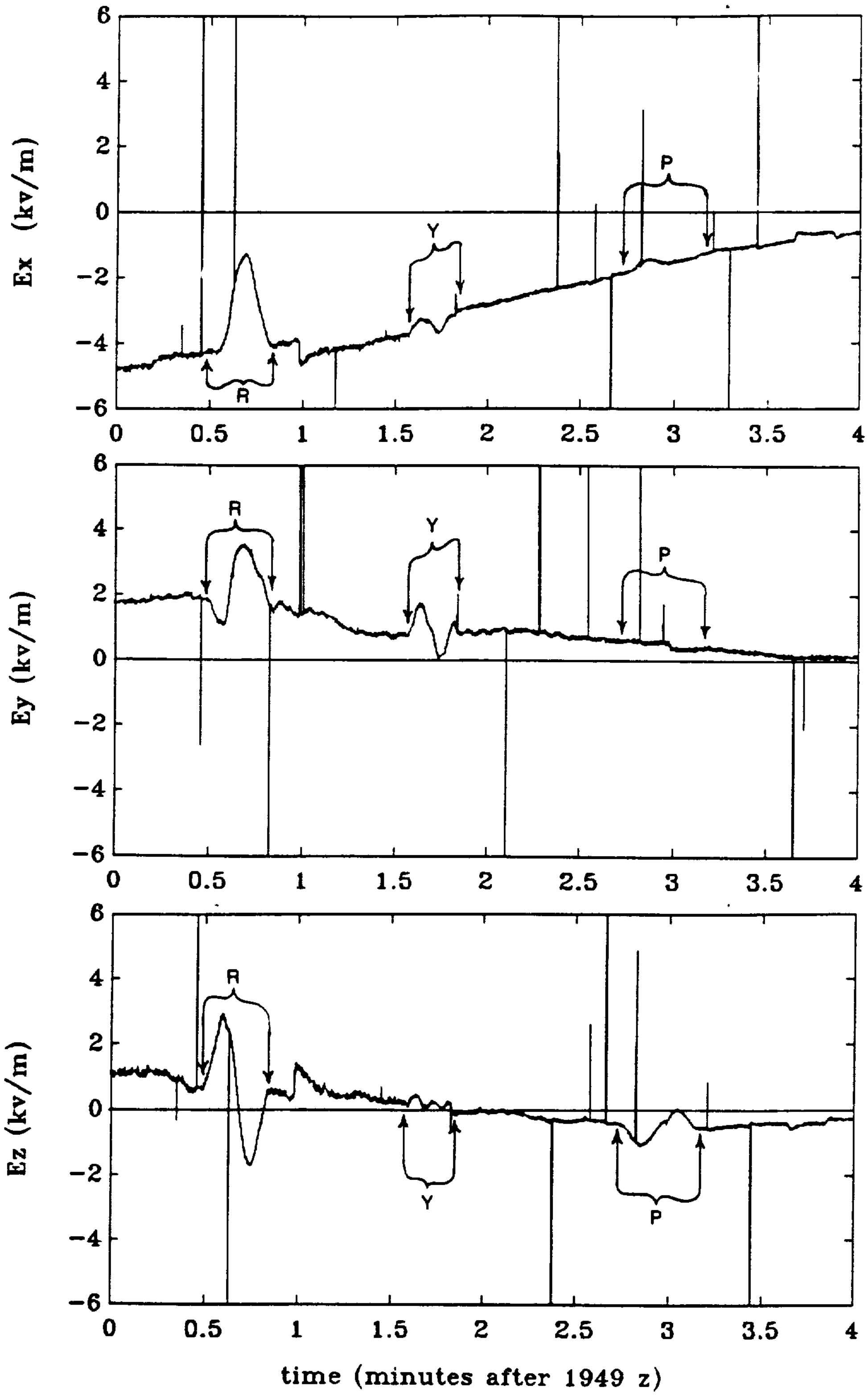


Figure 40: Components of $\vec{E}$ along the X, Y and Z directions in the airplane coordinate system during the roll (R), yaw (Y) and pitch (P) between 1949 and 1953 Z on 29 July 1989. The spikes in the data are due to the interference in the telemetry signal mentioned earlier.

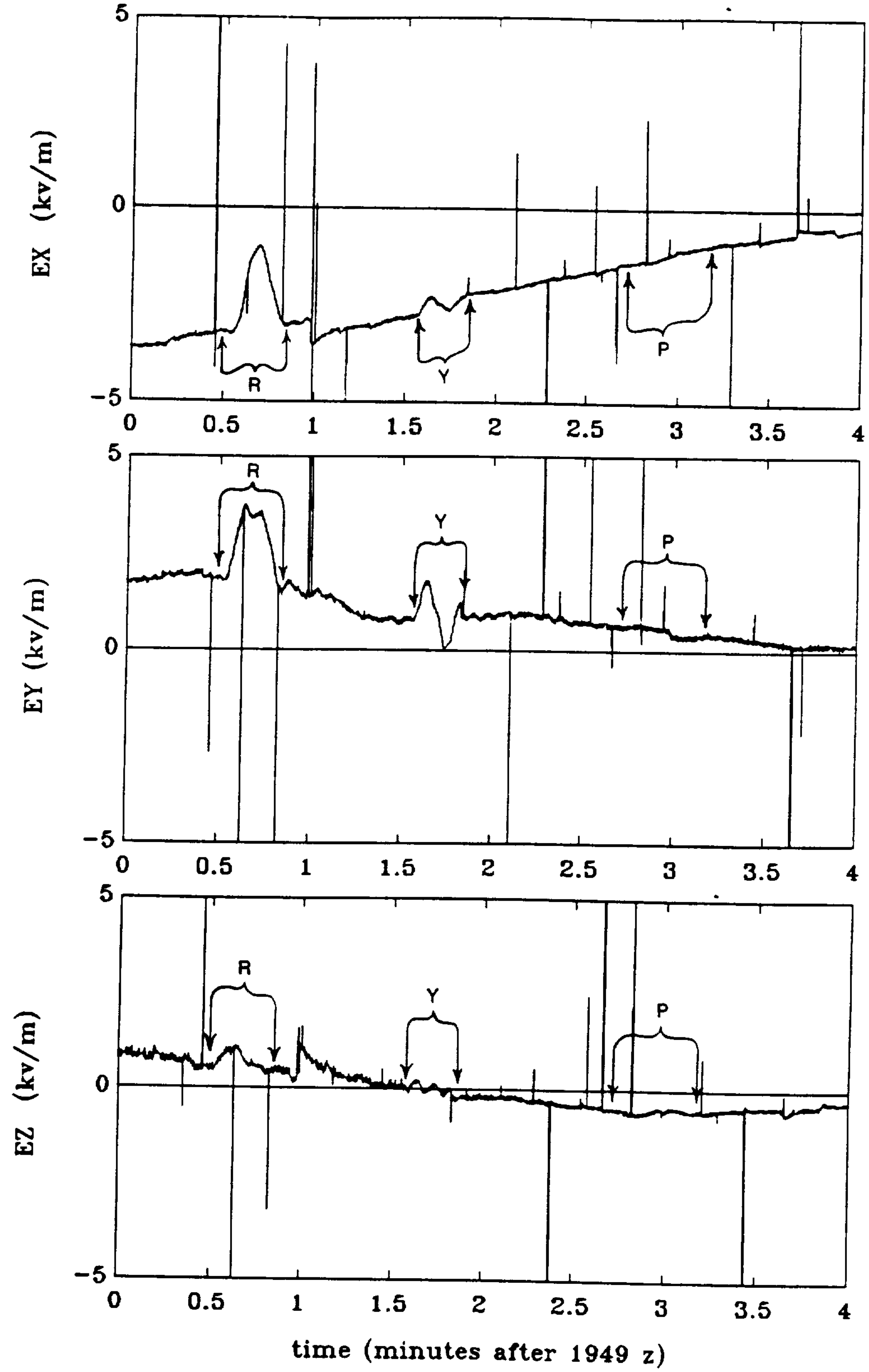


Figure 41: Components of $\vec{E}$ along the X, Y and Z directions in the level flight coordinate system during the roll (R), yaw (Y) and pitch (P) exercises between 1949 and 1953 Z on 29 July 1989. The spikes in the data are due to the interference in the telemetry signal mentioned earlier.

field components in the ACS is in this regard not perfect) so that when E_Z is small, as here, there may be a noticeable contribution to E_Z due to E_X. After the transformation to the GCS, this small error in E_Z becomes apparent in the other components as well. Note, however, that the effect shown here is the result of a severe roll angle excursion from 0° to −45° to +45° to 0°. The plot of E_{NE} vectors along the SPTVAR track for 1949 to 1955 Z during the first four minutes of which the attitude angles were varied, shown in Fig. 43, indicates that in practice the small errors in the electric field components do not significantly distort the vector pattern. The E_{NE} vectors maintain nearly constant direction during the left/right turn sequence consequent to the roll maneuver and continue to indicate that the source of the electric field measured by SPTVAR was negative charge at some distance to the southwest.

For the following 50 minutes SPTVAR investigated a complex and vigorous cloud complex over KSC which at 2024:40 Z was reported to have a radar echo top at 46,000 ft (11 km) over the Banana Creek bridge. Shortly thereafter, from 2027 to 2028:30 Z, E_Z measured by SPTVAR was large and negative as SPTVAR flew toward the south over the west lobe of the northern part of Merritt Island. This persistence of E_Z values more negative than −40 kV/m for one and one half minutes, Fig. 44, indicates that SPTVAR flew below a region of positive charge (or possibly above a region of negative charge) having a horizontal extent of some 4 km (note the difference in the time variation of E_Z in this figure and that shown in Fig. 38).

At 2031:11 Z, as SPTVAR continued on the same southerly heading, it was struck by lightning and the pilot reported experiencing an electrical shock (post flight inspection of the airplane revealed attachment scars on both wing tip static wicks). Plots of the electric field components in the level flight coordinate system from 2030 to 2036 Z, Fig. 45, show that all electric field components were small at the time of the lightning flash (labeled **c**). About ten seconds later E_Z rapidly increased to about +45 kV/m. Since $\vec{E}$ at SPTVAR was small at the time of the flash it is not likely that the flash was initiated by the airplane, but rather that SPTVAR just happened to be in the path of the flash. The storm was very active electrically at this time as may be seen from the prevalence of lightning flashes, **a** through **k**, in this six-minute period.

As the first storm declined, a second storm developed and covered the southern part of KSC, extending to the west side of the Indian River. During the last hour of the flight all storm cores were west of the Indian River with anvil clouds and some stratus over the KSC area. Most of the clouds were too high for SPTVAR to penetrate during this time. For nearly half an hour, from 2057 to 2120 Z, SPTVAR flew beneath an anvil, Ez being consistently negative (positive charge aloft) and at times reaching −50 kV/m, until a brief excursion to about +50 kV/m for 30 seconds at 2119 Z. E_Z for this time interval is shown in Fig. 46. The flight was concluded at 2204 Z.

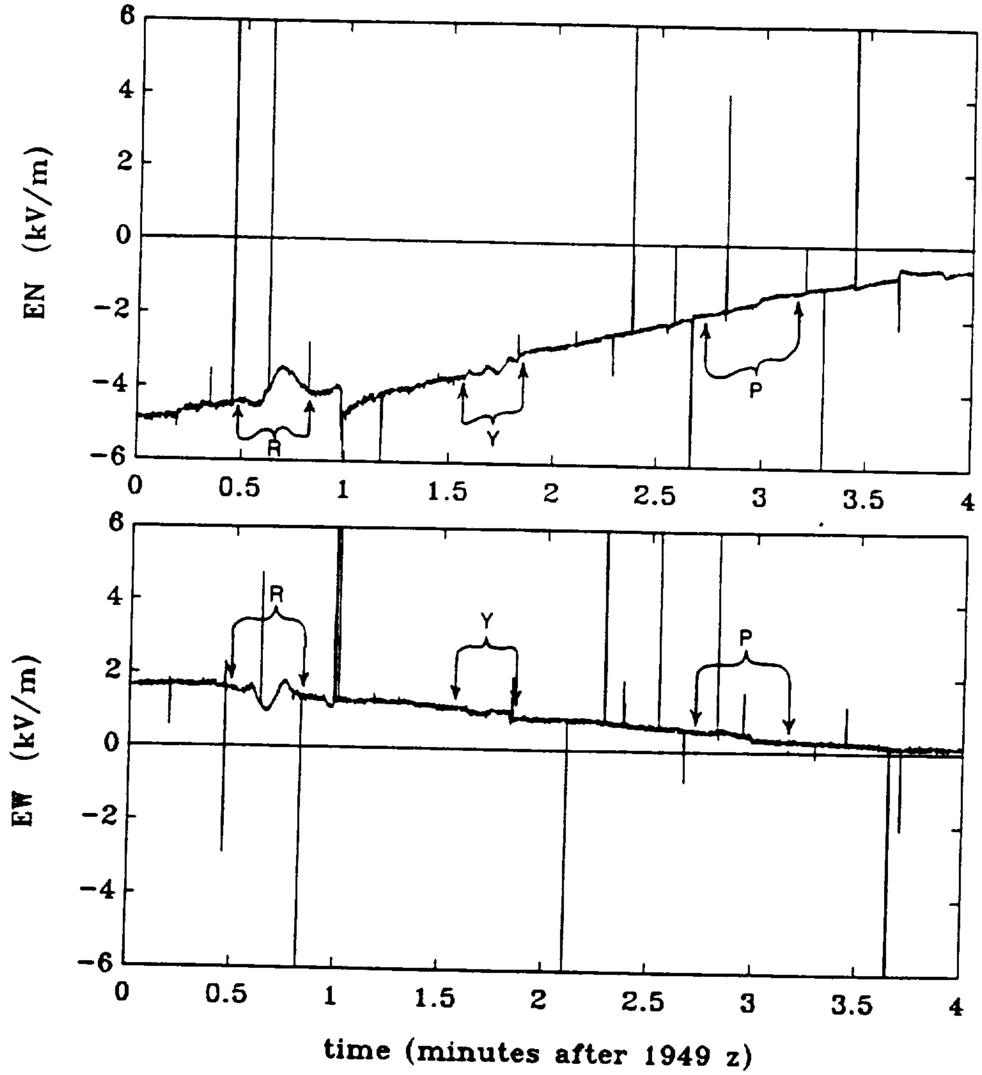


Figure 42: Horizontal components of $\vec{E}$ along the N, W and Z directions in the geographic coordinate system during the roll (R), yaw (Y) and pitch (P) exercises between 1949 and 1953 Z on 29 July 1989. The spikes in the data are due to the interference in the telemetry signal mentioned earlier.

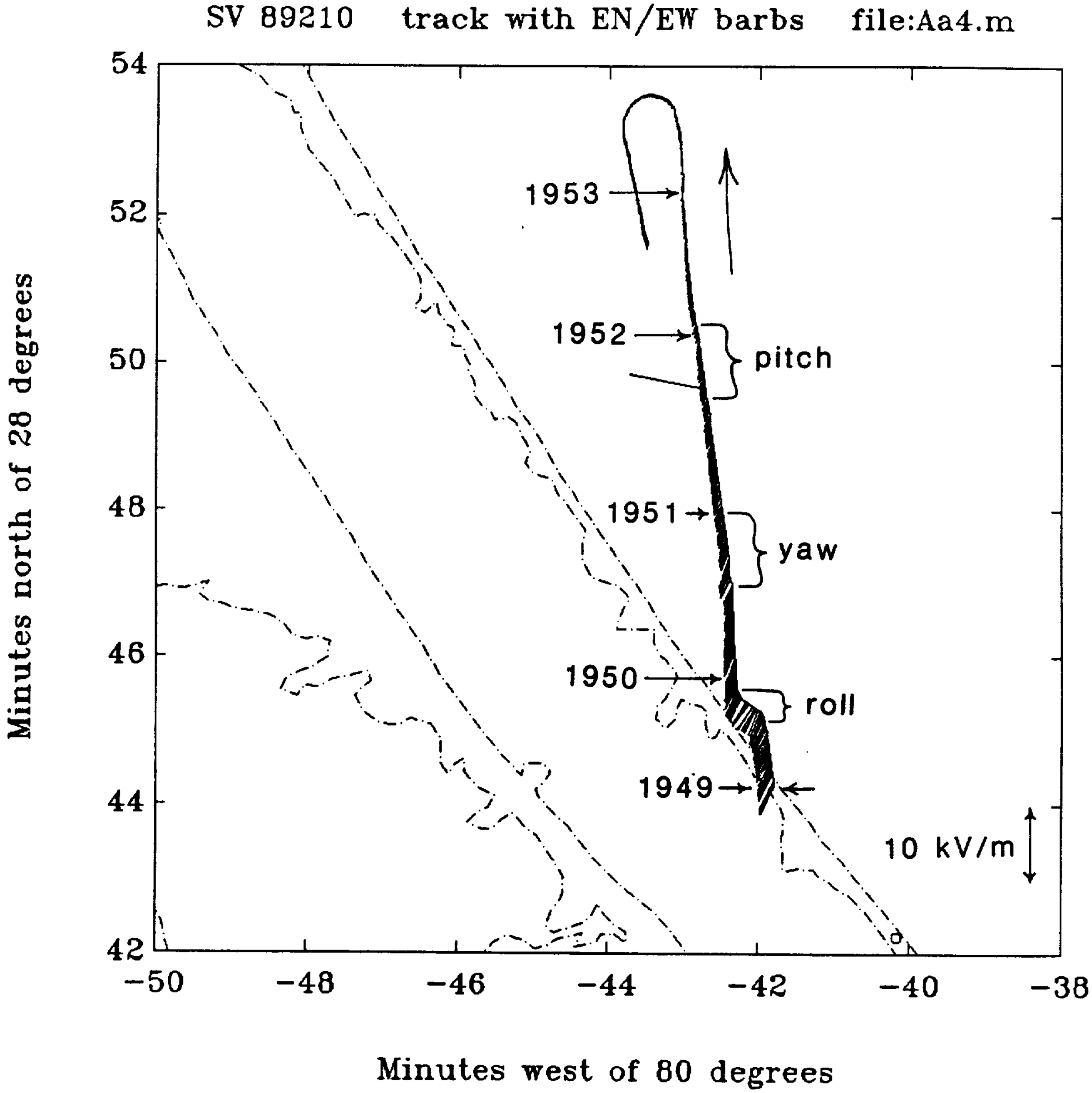


Figure 43: E_{NE} vectors plotted along the SPTVAR flight track from 1949 to 1955 Z on 29 July 1989.

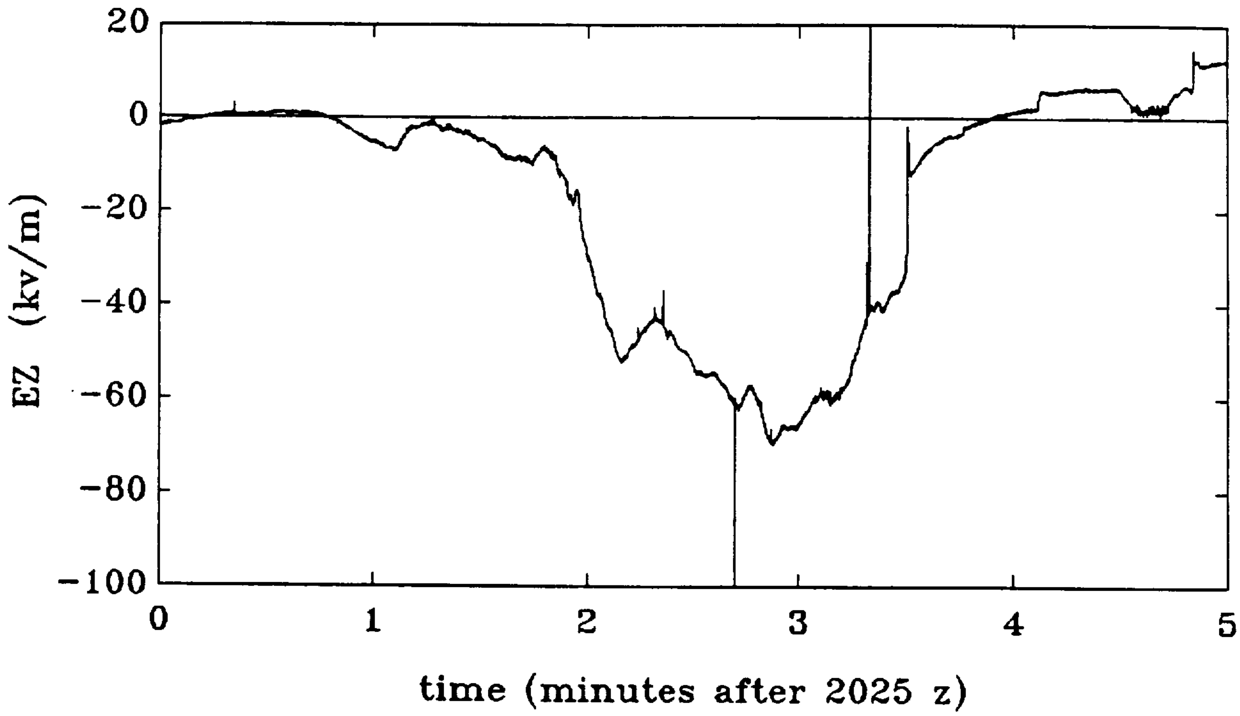


Figure 44: E_Z from 2025 to 2030 Z on 29 July 1989.

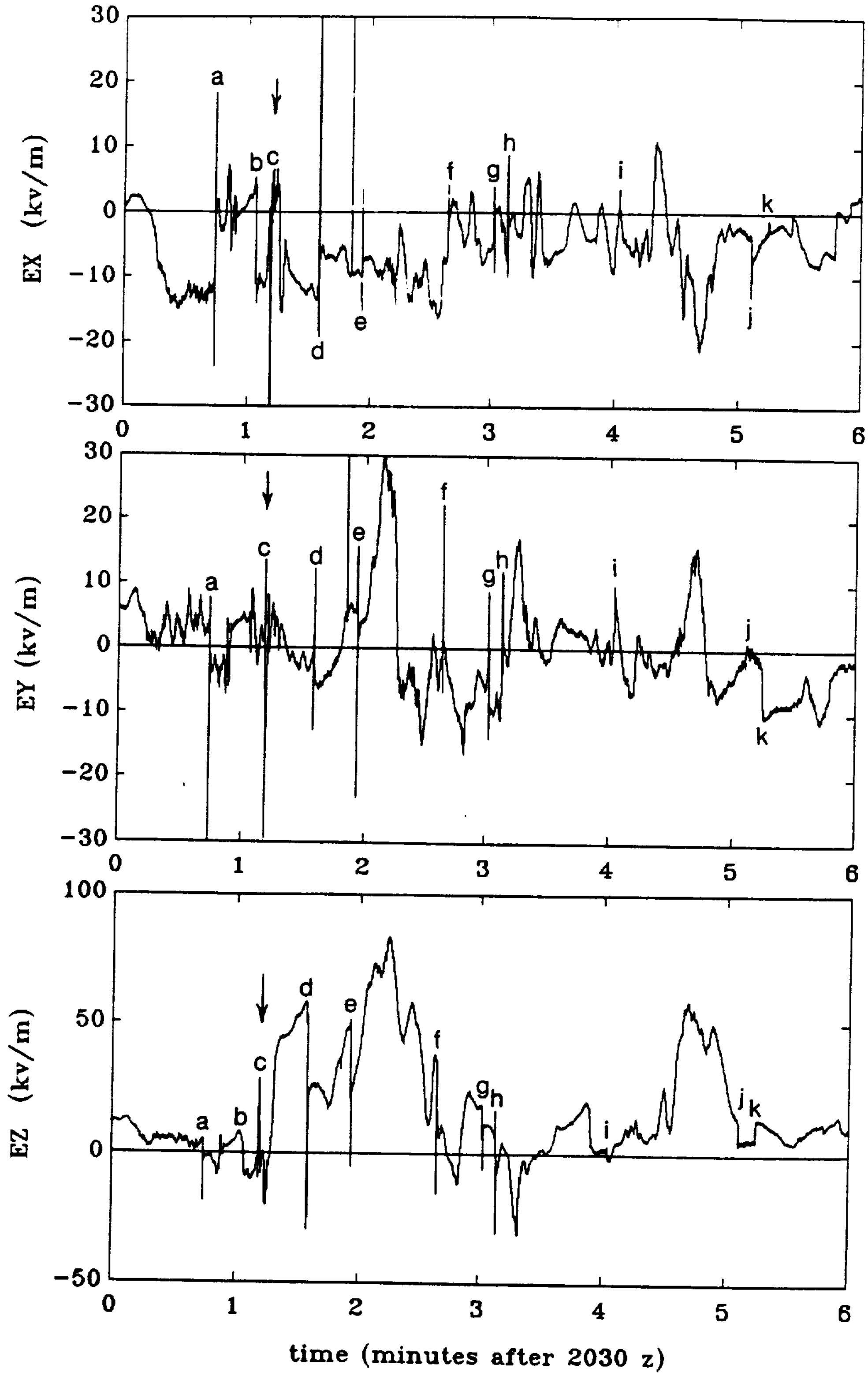


Figure 45: Electric field components in the level flight coordinate system for 2030 to 2036 Z on 29 July 1989. The letters **a-k** denote times that lightning flashes affected the measured electric field. SPTVAR was struck by lightning at the point labeled **c**.

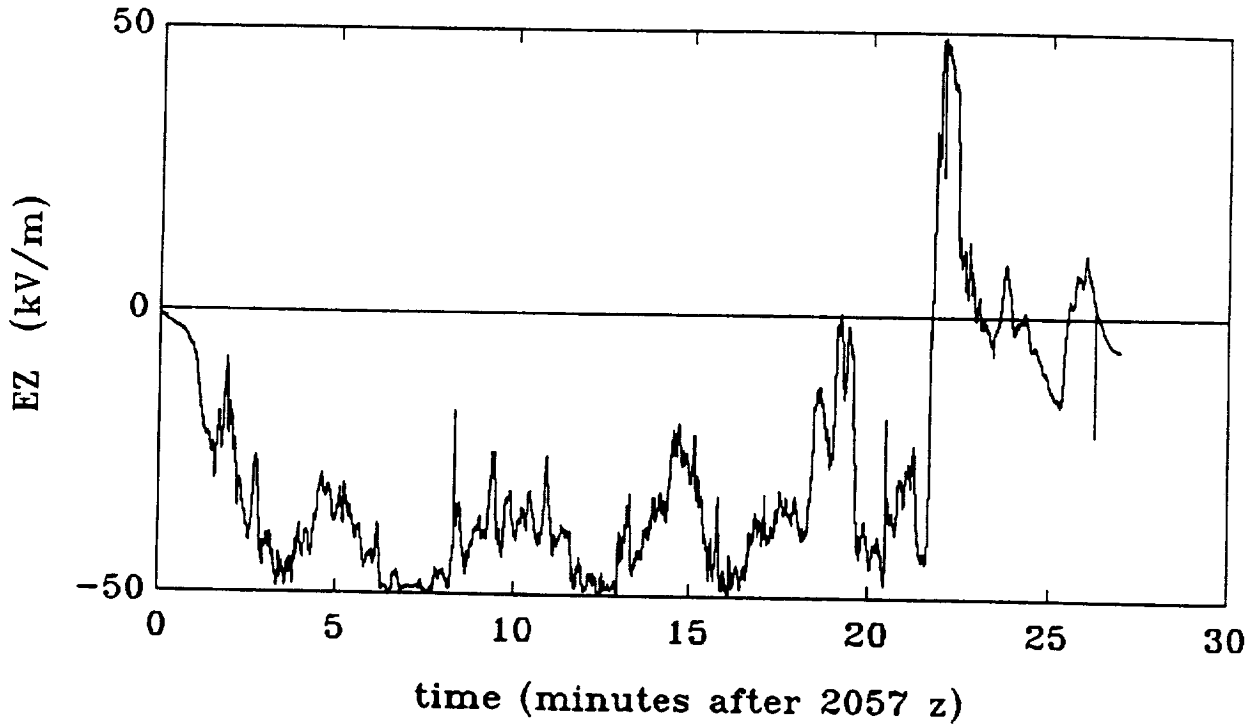


Figure 46: E_Z from 2057 to 2124 Z on 29 July 1989 while SPTVAR flew under an anvil cloud.

A.3.2 Summary: 30 July 1989 (89211)

Highlights:
- SPTVAR studied an electrified cloud west of the Indian River.
- $E_Y \sim 100$ V/m due to a cloud to the west was measured over KSC by SPTVAR at a time when the surface ∇V contour plot indicated charge aloft above mills 18, 22 and 25.

On 30 July there was a weak ridge at 500 mb extending along the eastern coast with its axis through northern Florida. The winds at 500 and 700 mb were southwesterly at 6 to 8 knots, becoming westerly at 850 mb. Overall the steering flow was weak from the southeast with good available moisture (RH > 80%) up to 19,000 ft. The computed lifted index was −8, primarily due to a cold pocket at 500 mb (−9 °C) and the good moisture. The lack of widespread activity was apparently due to a speed confluence at 200 mb along the east coast of Florida from Viro Beach northward. The daytime differential heating produced a seabreeze around 1700 Z which overcame the weak southwest flow and migrated inland west of Titusville by 2000 Z. A few cumulus tried to grow as the seabreeze migrated across the Cape but failed to surpass 15,000 ft.

The 1200 Z West Palm Beach and 1300 Z Tampa, Florida, soundings are shown in Fig. 47.

The mission objective was to investigate initial electrification. Since nothing was happening over the KSC area it was decided to fly the cells forming west of Patrick AFB and Merritt Island. Following an 1855 Z takeoff SPTVAR flew to the west-northwest of PAFB. A plot of SPTVAR's flight track with E_{XY} vectors along the track is shown in Fig. 48.

From 1915 to 1955 Z SPTVAR probed the edges of the developing storm. Cloud top heights and maximum reflectivities determined with the McGill radar were reported as 20,000 ft and 50 dBZ at 1907; 25,000 ft at 1929; > 50 dBZ at 1933; and 25,000 to 35,000 ft at 1943 Z. After the first penetration SPTVAR resorted to probing only the edges of the cloud since it was vigorous and developing rapidly with heavy rain, hail, sleet and updrafts as much as 5,000 ft/min. Some of these probings of the cloud margins resulted in a rough ride for the pilot even though he reversed course only about 20 seconds after entering the cloud from the west. After 1951 Z, as the individual clouds merged into a unified cloud mass, SPTVAR remained outside the cloud while moving around its north end to fly down and up the east side of the storm. By 1950 Z the storm's electrification was well underway and SPTVAR measured electric field all along the east side of the storm from 1953 to 2045 Z.

The storm had produced an anvil over KSC by 2100 Z. At about that time the contour display for the KSC field mill array indicated negative charge over mills 18, 22 and 25

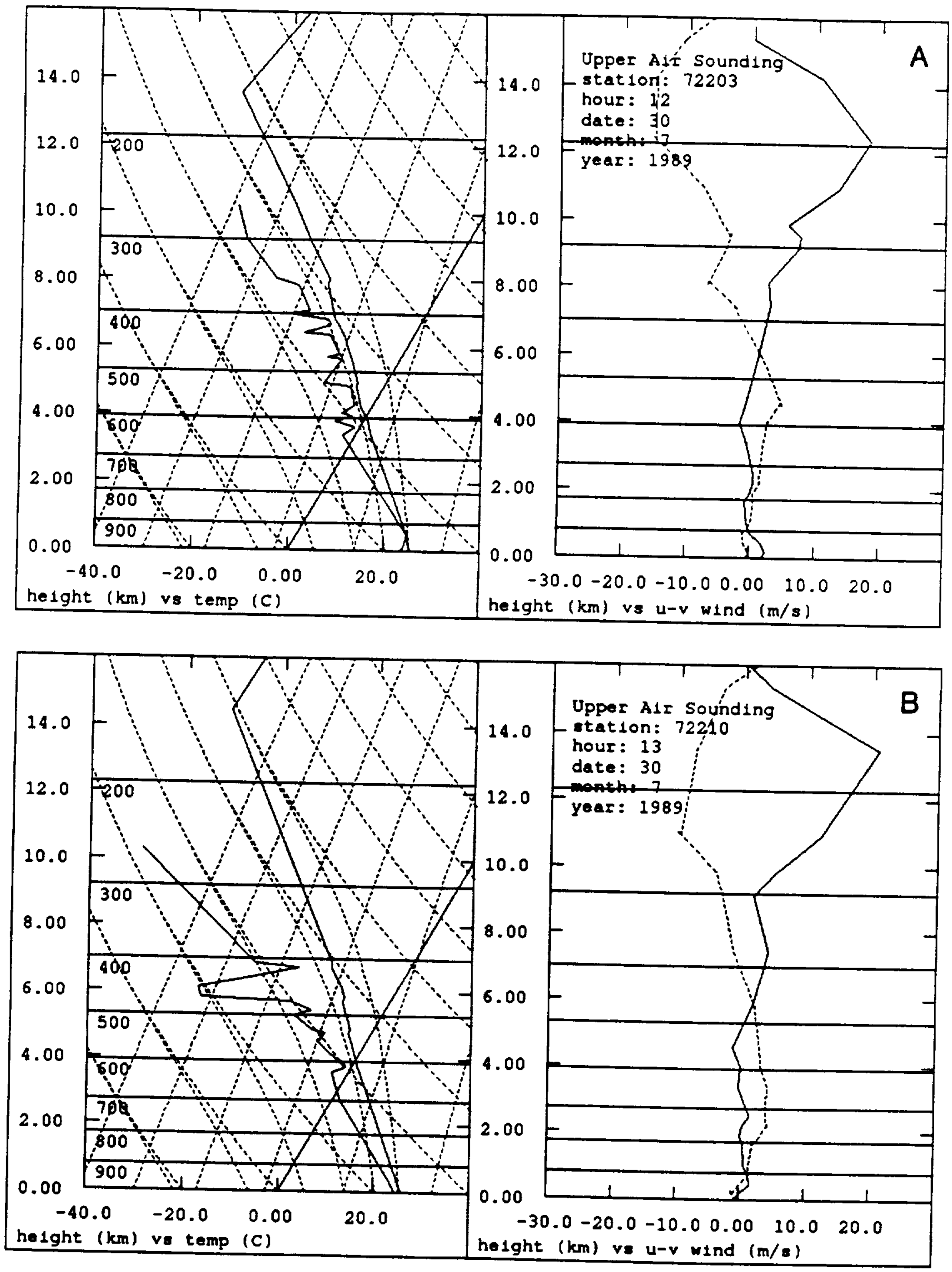


Figure 47: Skew T diagrams for the 12 Z West Palm Beach (A) and 13 Z Tampa (B), Florida, soundings on 30 July 1989. In the graph of horizontal air velocity vs. altitude, the east component, **u**, is the solid line and the north component, **v**, is the dashed line.

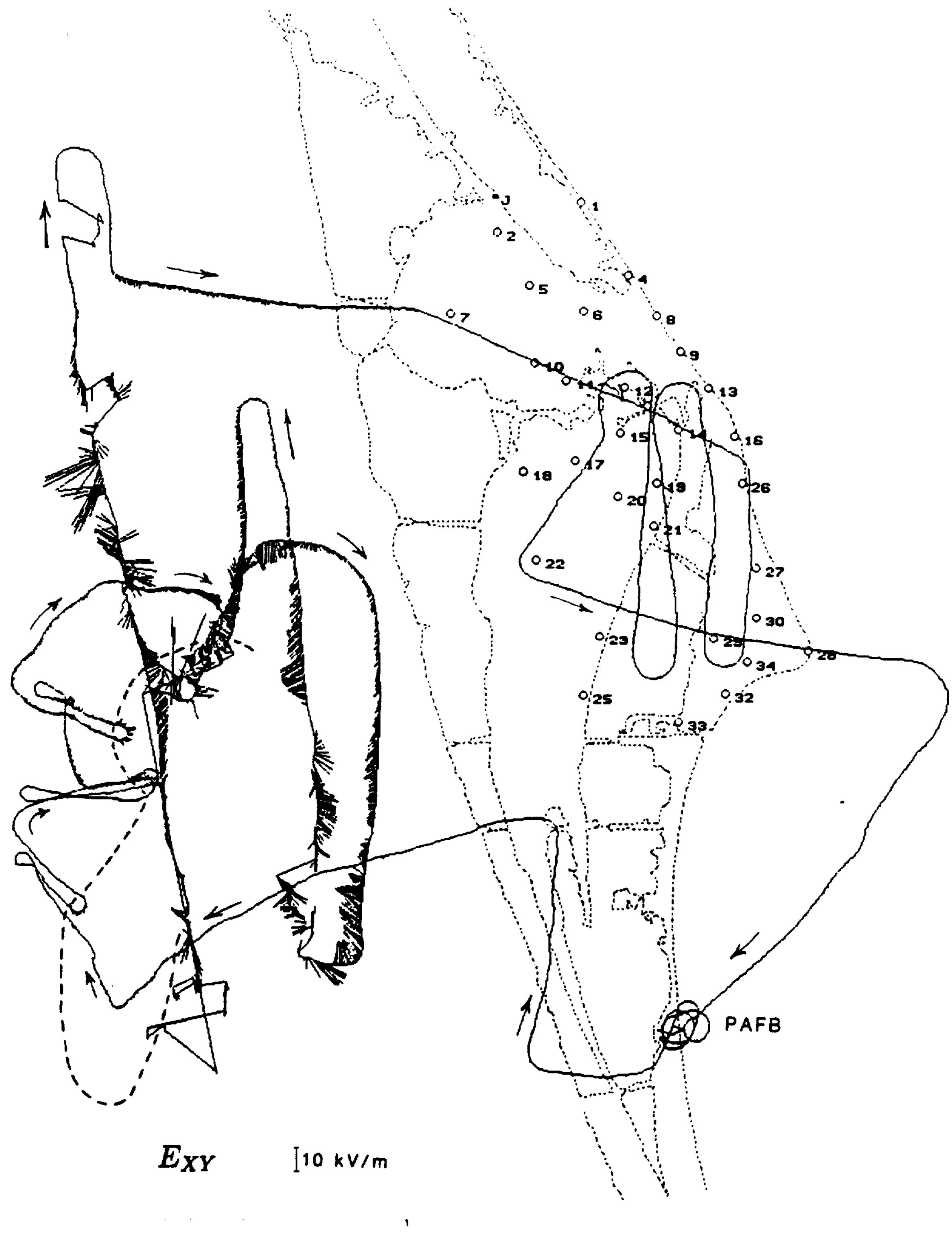


Figure 48: PC plot of E_{XY} vectors along the SPTVAR flight track of 30 July 1989. The dashed line is a sketch of the cloud's edge during the early investigations along its western side. A few glitches from the Loran positioning system are evident in the flight track.

along the western edge of the field mill array (note the $\nabla V = -1$ kV/m contour around these mills and the $\nabla V = -2$ kV/m contour around mill 22 at 2110 Z in the top panel of Fig. 49).

In response to this display a request was made for SPTVAR to investigate the apparent charge over KSC. After abandoning its study of the large electrified cloud west of the Indian River SPTVAR entered restricted area R2934 at 13,000 ft (4.0 km) and the pilot reported an anvil overhead at approximately 20,000 ft (6.1 km). While SPTVAR made four north-south passes over the NASA causeway area it climbed steadily in an attempt to enter the bottom of the anvil (Fig. 48). Although SPTVAR reached 21,000 ft (6.4 km), the bottom of the anvil itself moved up so that SPTVAR never entered it. During this time SPTVAR detected only a very weak electric field. Although too small to show on the PC display, it was just discernible as shifts of about 200 V/m in the real-time strip- chart record of E_Y when SPTVAR reversed course at 2106:40 and 2120 Z and when it turned 100° toward the east while over mill 22 at 2130:30 Z. The shift in E_Y at 2120 Z indicates an E_Y magnitude of about 100 V/m. These measurements of the electric field aloft do not agree well with the measurements on the surface since ∇V more negative than -1 kV/m was measured by mills 22 and 25 at 2120 and 2125 Z as shown by the $\nabla V = -1$ kV/m contour in the two lower panels of Fig. 49.

At the time of this flight the discrepancy between the electric field at the ground and that aloft was perplexing. We may resolve this enigma with a simple analysis of the airplane data. A plot of E_Z for the time interval 2113-2125 Z is shown in Fig. 50, while $\vec{E}_{NE}$ along the SPTVAR track for the same interval is shown in Fig. 51.

E_Z was zero (to within ± 50 V/m) for this entire time period, indicating that there was no charge in the anvil cloud anywhere overhead along the SPTVAR flight path. In Fig. 51 the $\vec{E}_{NE}$ vectors uniformly point to the west and have an approximately constant length both before and after the 180° turn at 2120 Z. The apparent lack of convergence or divergence of the barbs together with their small size and insensitivity to SPTVAR latitude indicate that the observed field was due to negative charge many kilometers to the west where we know that SPTVAR had just been studying a large electrified storm. Consequently, we conclude that the electric field that SPTVAR measured over KSC and CCAFS was due to that large storm to the west. After a final pass over mills 17 and 22, SPTVAR flew over mills 29 and 28 and concluded its flight at 2148 Z.

We now compare the SPTVAR data and the KSC surface field mill array contour display. The contour display shown in Fig. 49 shows the 1 kV/m contour closed around mills 18, 22 and 25. The resultant contour pattern was interpreted as due to a charge overhead, presumed to be in the anvil present over KSC at the time. The SPTVAR data show that this was not the case, but rather that there was a negative charge at a considerable distance to the west. Since there were no data from mills on the ground that could justify the closing of the contours to the west of the field mill array, we conclude that the closing was unjustified, resulting in a misleading interpretation of the field mill array data.

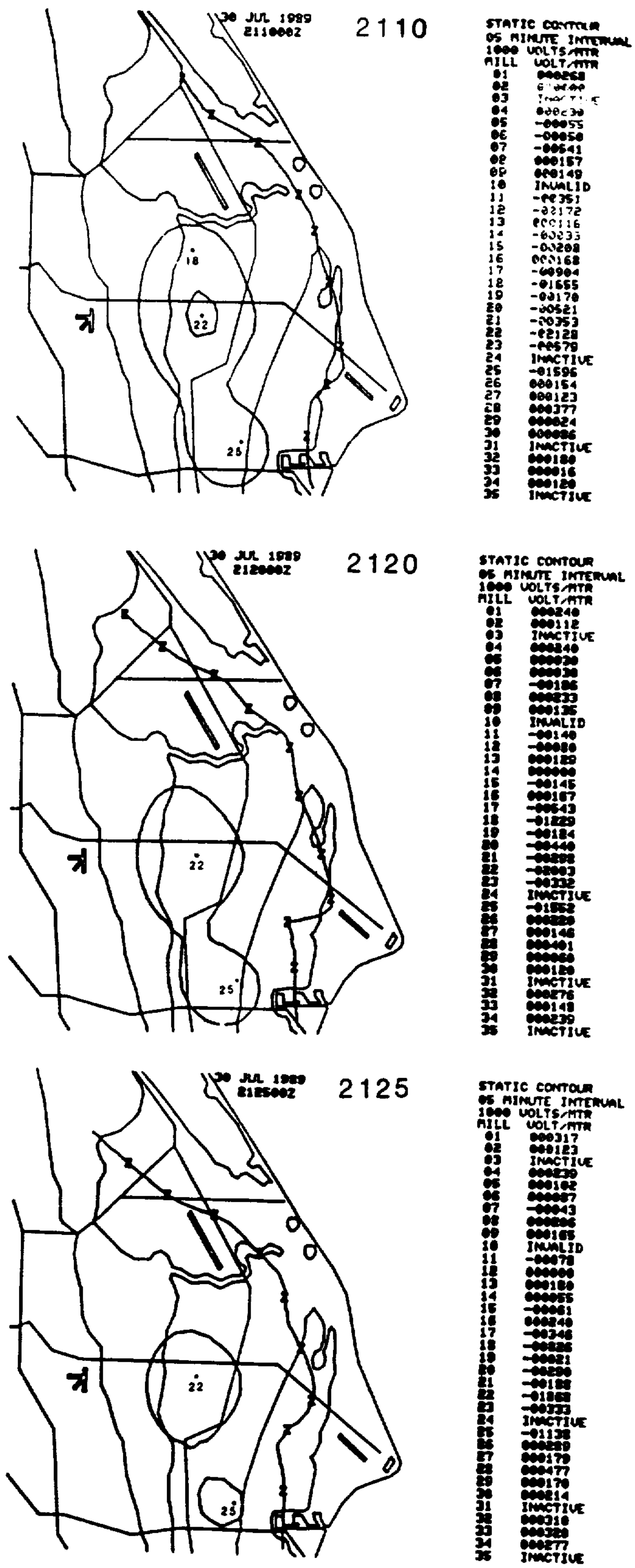


Figure 49: KSC surface ∇V contour plots for 2110, 2120 and 2125 Z on 30 July 1989. Note the closed contours to the west of the western most KSC field mills.

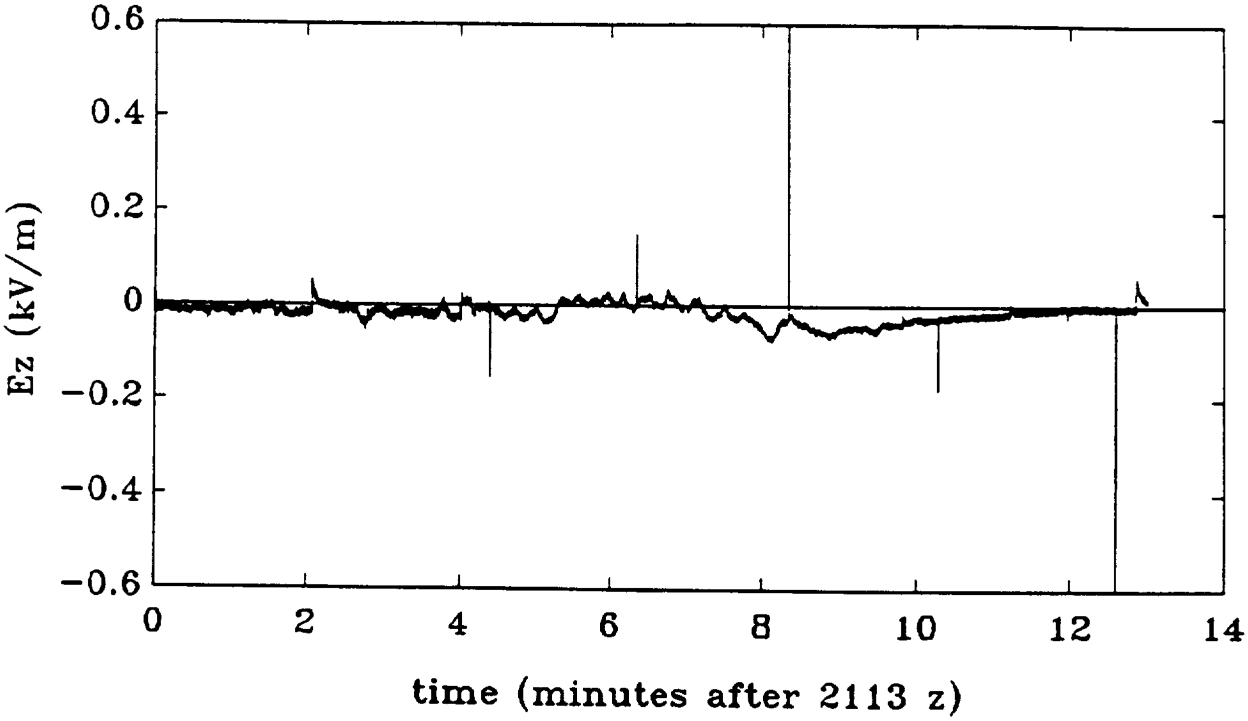


Figure 50: E_Z measured by SPTVAR from 2113 to 2125 Z on 30 July 1989.

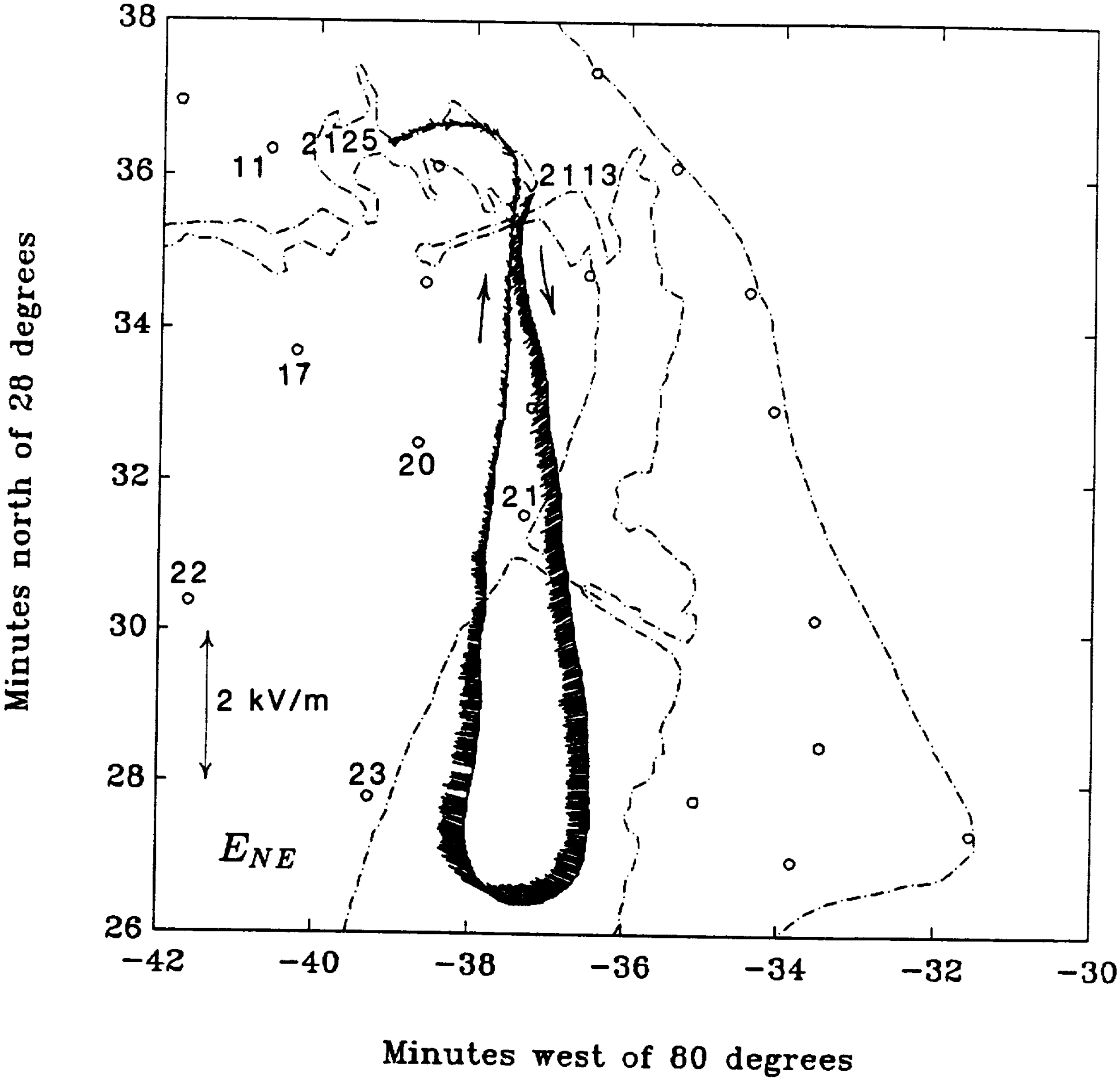


Figure 51: E_{NE} vectors plotted along the SPTVAR flight track from 2113 to 2125 Z on 30 July 1989. A scale of electric field magnitude is shown in the figure.

A.3.3 Summary: 9 August 1989 (89221)

Highlight: • SPTVAR flew along the edges of a strongly electrified cloud over Merritt Island.

On 9 August a weak front was located from the east coast in northern Florida across Tampa and out into the Gulf of Mexico. A strong upper-air trough dominated the Eastern United States and was accompanied by troughing at all levels. The morning KSC sounding was moist from the surface through 750 mb with a dry layer above 750 mb and more moisture between 450 and 300 mb. The steering flow was southwesterly at 12 to 15 knots.

The 1200 Z West Palm Beach and 1300 Z Tampa, Florida, soundings are shown in Fig. 52.

During the late morning there were storms north of Daytona Beach which were building toward the south. Thunderstorm activity was expected to develop over the KSC area no later than 1900 Z, so a flight was initiated at 1720 Z with the objective of studying initial electrification. A plot of E_{XY} vectors along the SPTVAR track is shown in Fig. 53.

As SPTVAR approached the KSC airspace there was already a rapidly growing cloud over the northwest part of Merritt Island, which extended many km north and west. SPTVAR flew up the coastline and across the south end of the storm which was over the rocket-triggered-lightning site. Due to the large extent of the cloud no attempt was made to penetrate it. However, after skirting the south end of the cloud, now near the Cape, the pilot found an alley along the west side of the cloud through which he flew SPTVAR. Just north of the of the Haulover Canal between the Indian River and Mosquito Lagoon he turned back, retracing the alley, and then flew around the south end of the cloud once again and along its east side which now extended out over the Atlantic Ocean. Since storms were closing in on Patrick AFB the flight was terminated at 1913 Z and the SPTVAR was hangared, just before a storm moved over the airfield.

Although the storm studied was extensive, SPTVAR encountered strong fields only while flying through the alley along its west side. The E_{NE} vectors plotted along the track in Fig. 54 indicate negative charge east of the track (and west of mill 2). The strongest potential gradient measured by the KSC field mill array during this SPTVAR flight was -7.4 kV/m at mill 8 on the coastline north of pad 39 B at 1820 Z. At this time SPTVAR was headed north about midway through the alley and west of mill 2 in Fig. 54. The ∇V contour plot for 1820 Z, with the SPTVAR track sketched in, is shown in Fig. 55. It shows a maximum negative ∇V just east of SPTVAR's track, consistent with the interpretation of the SPTVAR data in Fig. 54.

Small fields were also seen along the southeast side of the storm over the Atlantic on the last leg of the flight before SPTVAR returned to Patrick. The contour plots of surface ∇V

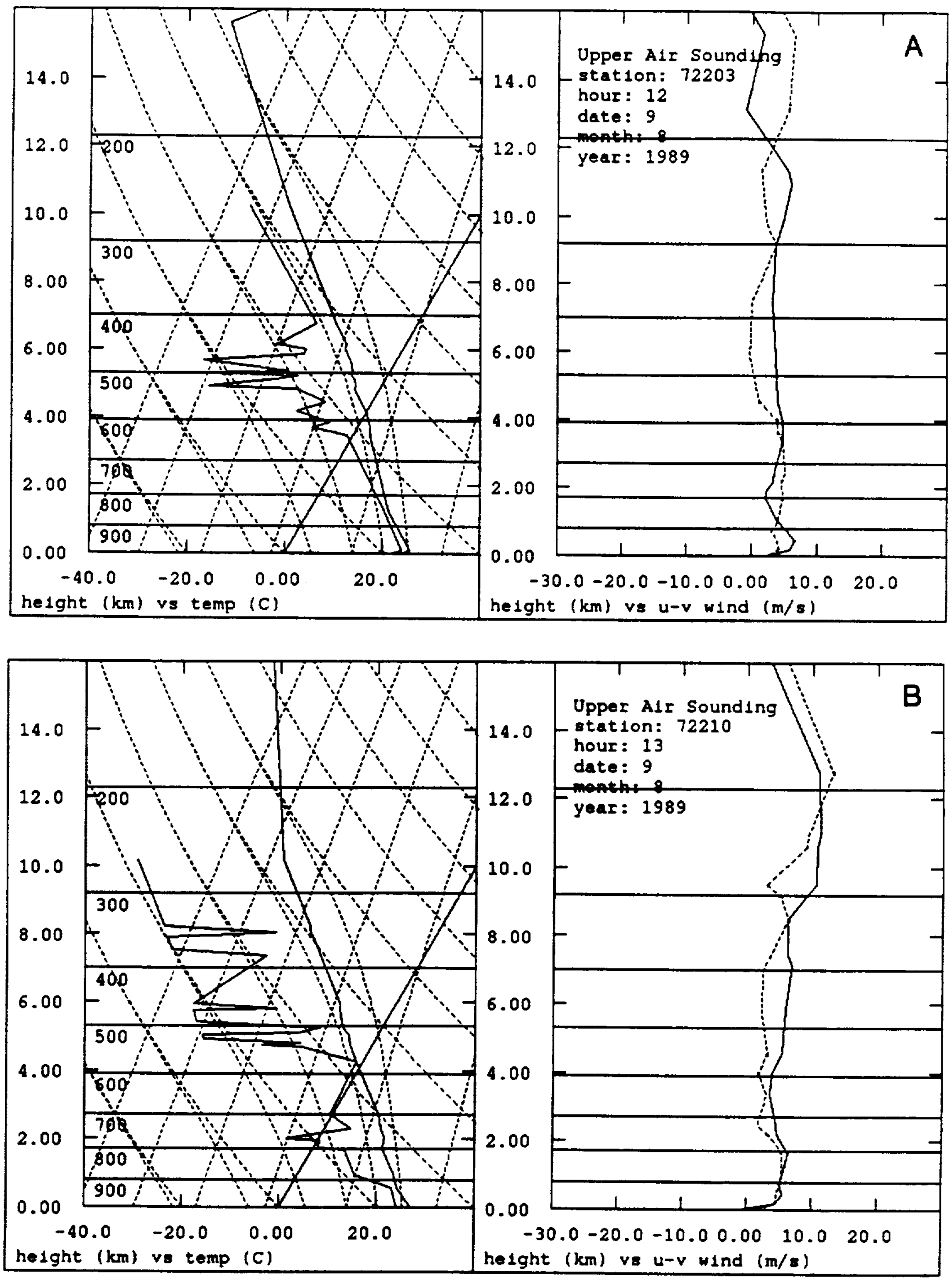


Figure 52: Skew T diagrams for the 12 Z West Palm Beach (A) and 13 Z Tampa (B), Florida, soundings on 9 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

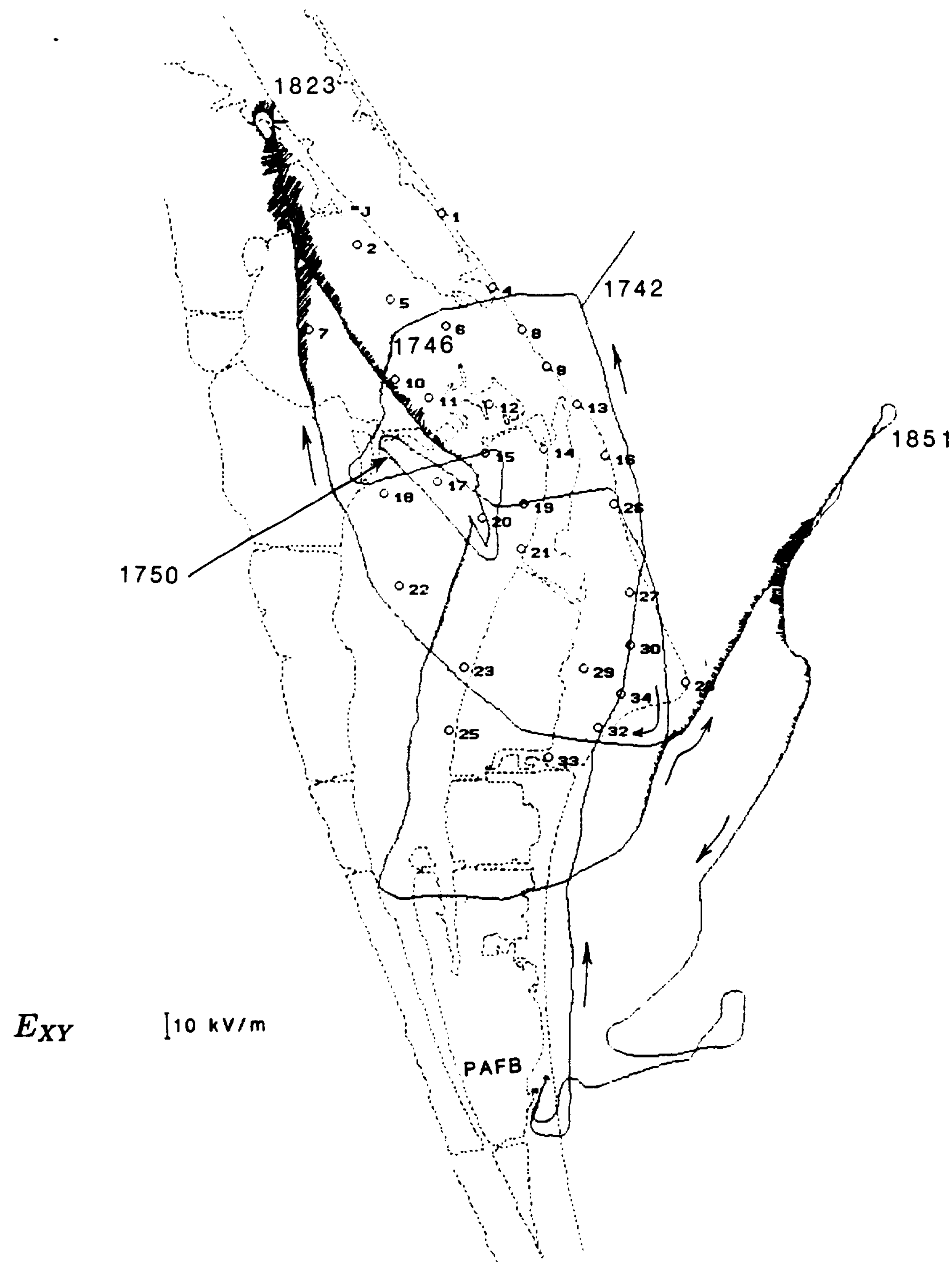


Figure 53: PC plot of E_{XY} vectors along the SPTVAR flight track of 9 August 1989.

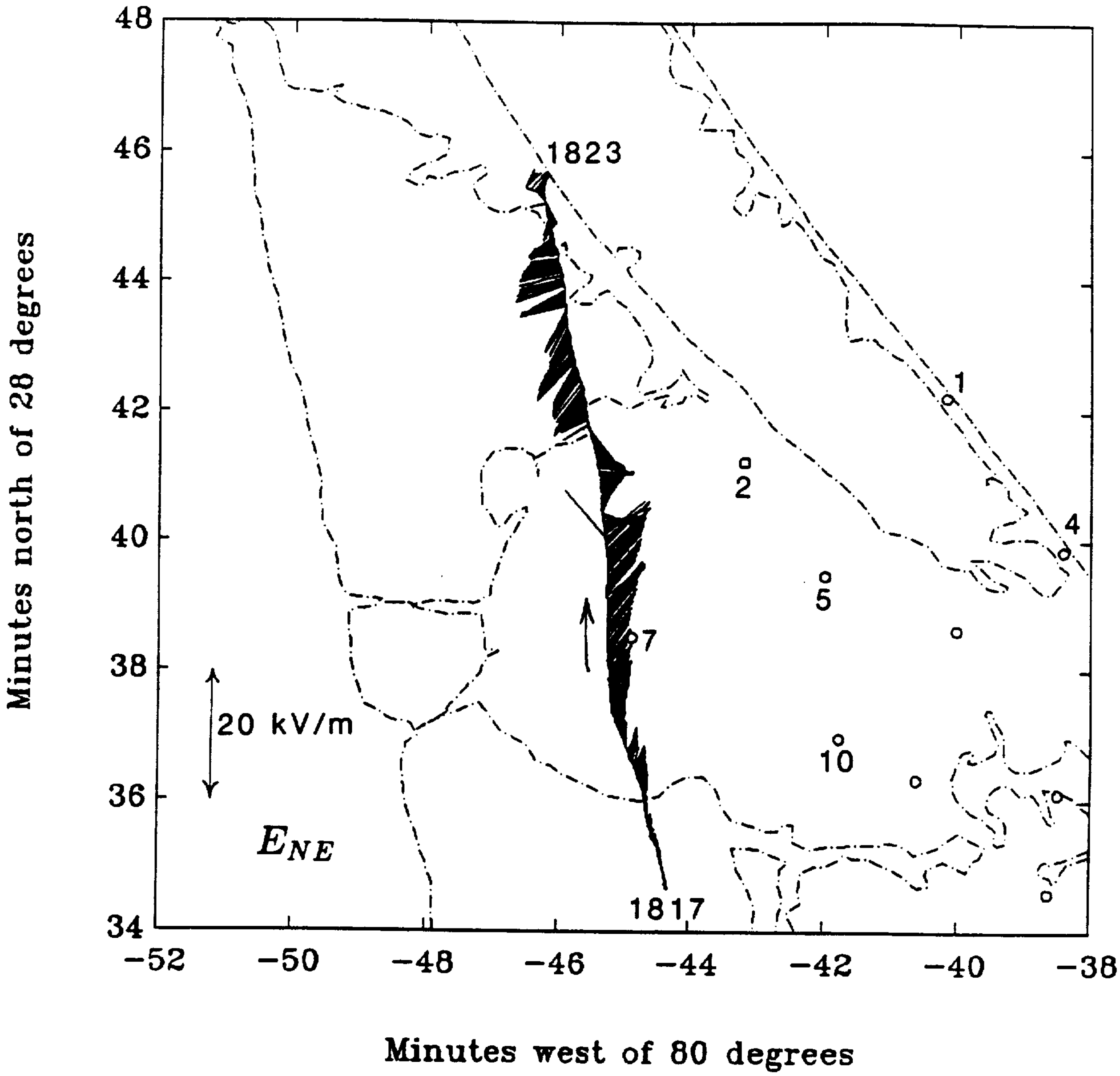


Figure 54: E_{NE} vectors plotted along the SPTVAR flight track from 1817 to 1823 Z on 9 August 1989.

agree with the SPTVAR measurements along the cloud boundaries and show further that the cloud rapidly developed a very complicated ∇V pattern at the surface as the cloud expanded. By 1905 Z all of the Space Center was under electrified clouds.

During the hour immediately after the SPTVAR flight numerous lightning strikes were recorded by the LLP system, both on the north end of Merritt Island and around Cape Canaveral proper.

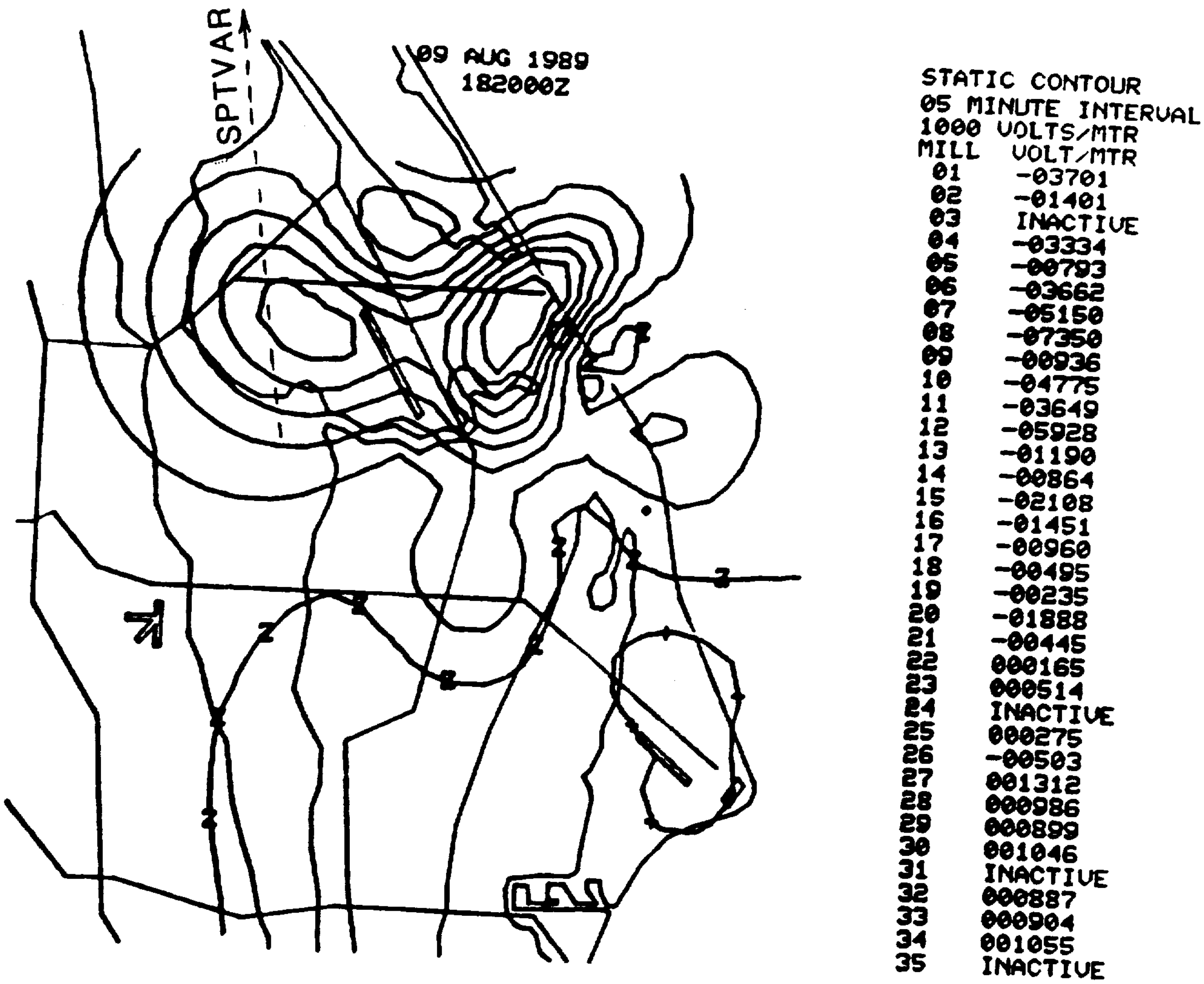


Figure 55: KSC surface ∇V contour plot for 1820 Z on 9 August 1989.

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A.3.4 Summary: 14 August 1989 (89226)

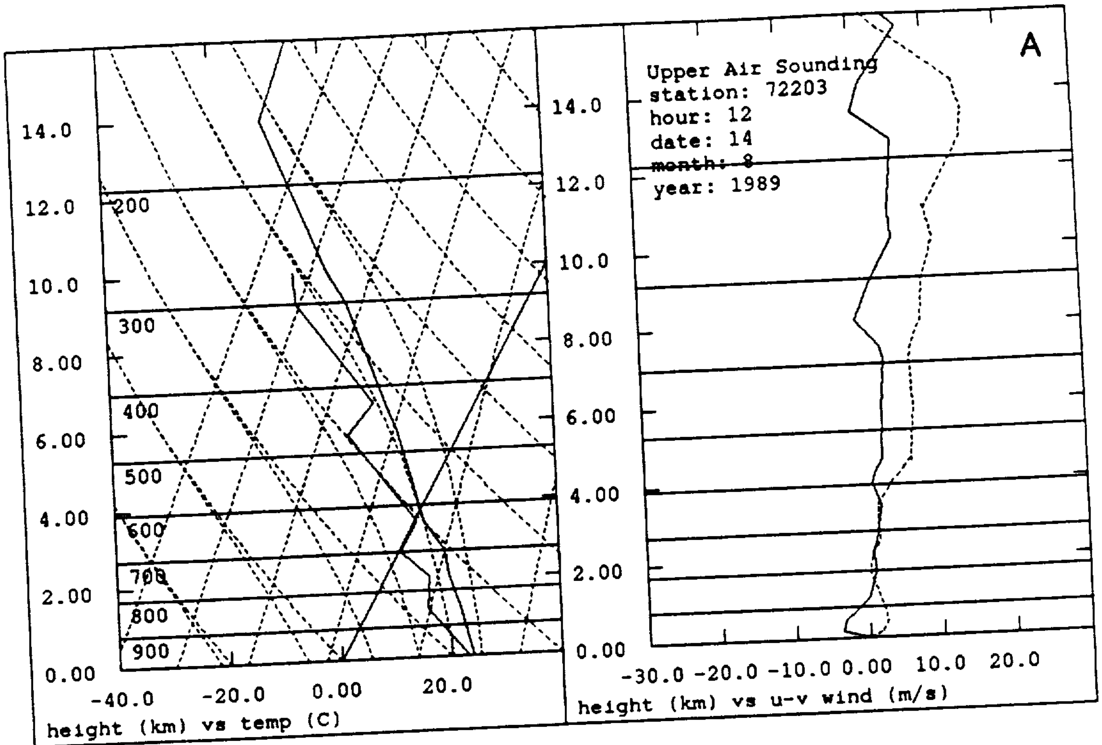
Highlights:

- SPTVAR investigated briefly electrified clouds over the False Cape and measured the electric field of a large cloud several miles from shore over the ocean. Various of the launch commit criteria weather rules would not have permitted launch within 10 nautical miles of the briefly electrified clouds over the False Cape.
- SPTVAR flew along the edges of a large electrified cloud over the north end of KSC.

On 14 August a weak easterly wave was approaching Florida and a cyclonic curvature was over central Florida at 700 to 850 mb accompanied by a slight difluence at 200 mb. The 1300 Z KSC sounding indicated good moisture up to the 500 mb level with a small dry pocket between 750 and 650 mb. The winds were light and southwesterly above 600 mb and light and easterly below. Debris clouds were abundant in the early morning due to thunderstorms the previous night. The lifted and K indices were −5 and 33 respectively.

The 1200 Z West Palm Beach and 1300 Z Tampa, Florida, soundings are shown in Fig. 56.

At about 1700 Z the KSC field mill array measured a small electric field excursion under a cloud moving onshore over the False Cape. Expecting a repeat of this behavior, a SPTVAR flight was initiated at 1811 Z. While SPTVAR was being readied for take-off a strong surface electric field developed over the Banana River and along the Atlantic shore line as may be seen from the KSC contour plots of surface electric field for 1740 to 1810 Z shown in Figs. 57 and 58. Unfortunately, the field mill locations and identifying site numbers are not shown in the contour displays. In order to facilitate the following discussion we show them in these figures for selected field mills. According to these contour plots ∇V had became more negative than −1 kV/m at mill 29 by 1745 Z. This depression in ∇V deepened and moved toward the north-northwest until it was centered between mills 20 and 21 at 1800 Z, at which time a second depression in ∇V, centered at mill 26, had developed. The second depression then became the dominant one as it deepened, reaching −8.35 kV/m at mill 26 at 1810 Z just before the SPTVAR take-off. Only five minutes later, at 1815 Z, a positive ∇V pattern had appeared around mill 26, which measured $\nabla V = +3.32$ kV/m, and the center of the negative ∇V pattern had shifted to the False Cape, between mills 13 and 16. Five minutes later, at 1820 Z, the positive ∇V contours were centered on mill 16 and the negative ∇V pattern was much weaker. Figures 58 through 60 show that from 1815 to 1845 Z both patterns had continued to weaken with the positive ∇V pattern remaining centered on mill 16 and the negative one centered on



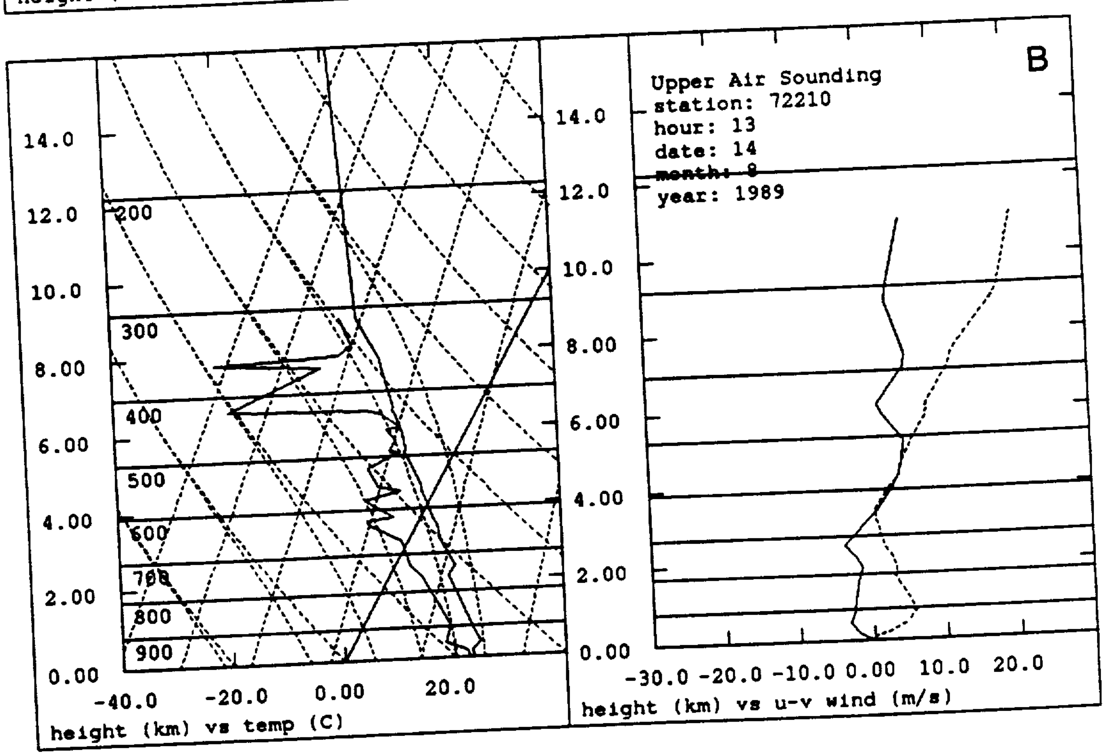


Figure 56: Skew T diagrams for the 12 Z West Palm Beach (A) and 13 Z Tampa (B), Florida, soundings on 14 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

mill 13. Although both positive and negative ∇V contours were no longer shown in the 1850 Z plot, the zero ∇V contour persisted until 1915 Z much as it had been at 1845 Z.

The surface ∇V contour plots shown in Figs. 57 through 60 are in some ways puzzling. The positive ∇V contour pattern appeared suddenly at 1815 Z and with its maximum strength despite there having been no sign of it just five minutes earlier. Only mills 26 and 19 were affected while all surrounding mills measured negative ∇V. Indeed, at 1815 Z the most intense ∇V was -7.7 kV/m measured by mill 16, the next mill to the north of mill 26. However, the negative ∇V contour pattern for that time is centered over the False Cape, between mills 13 and 16, while the site of mill 16, just south of the False Cape, is hidden under negative ∇V contours. Although the positive ∇V contour pattern persisted until 1845 Z, it never involved mills other than mills 16, 26 and, to a slight extent, mill 19.

An understanding of this behavior of the surface electric field is provided by the electric field measurements made by SPTVAR on this day's flight for which a plot of E_{XY} vectors drawn at intervals along the SPTVAR track is shown in Fig. 61.

When SPTVAR arrived over KSC the cloud of interest was over the north end of the Banana River and the False Cape. At 1825 Z, while approaching this area from the south, the SPTVAR pilot described the cloud over the Banana River as a little cloud making rain and having a hard-looking top at about 8,000 to 10,000 ft. Two minutes later (1827 Z), while still approaching the False Cape from the south, he noted that there was also a large cloud making rain about five to ten miles offshore over the Atlantic Ocean. Continuing on a northerly heading, SPTVAR flew over the False Cape at 6,000 ft at 1831 Z. The E_{NE} and E_{XZ} vector patterns along the SPTVAR track for that time are shown in Fig. 62.

The SPTVAR measurements of E_{XZ} show positive E_Z as SPTVAR approached mill 16 (which measured $\nabla V = +1948$ kV/m at 1830 Z) and negative E_Z thereafter as SPTVAR passed mill 13 (which measured $\nabla V = -1528$ kV/m just north of mill 16 at 1830 Z). Although the SPTVAR measurement of E_Z thus seems to match the surface ∇V contour pattern, the two measurements disagree in sign since, despite E_Z and ∇V being the same in magnitude, they differ in algebraic sign. Midway through the flight segment shown SPTVAR flew through a small cloud (1830:40 to 1831 Z) which was over the Banana River, north of the KSC–CCAFS causeway. Although the SPTVAR-measured pattern of E_{XZ} vectors suggests negative charge about two km overhead in the small cloud penetrated at 1830:40, the E_{NE} vector pattern appears to have been due to the large cloud over the ocean. This interpretation is based on the observation that the E_{NE} vectors varied only slowly in direction and magnitude over many kilometers of flight path and also that the E_{NE} vectors are much longer than the E_{XZ} vectors. As SPTVAR passed through the small cloud just offshore of mills 26 and 16 the otherwise smooth variation of the direction and length of the E_{NE} vectors was modified by the electric field of the small cloud. During the time that SPTVAR was in the cloud these vectors became somewhat longer and exhibited two brief periods when they diverged slightly. Thus, it appears that there were two small

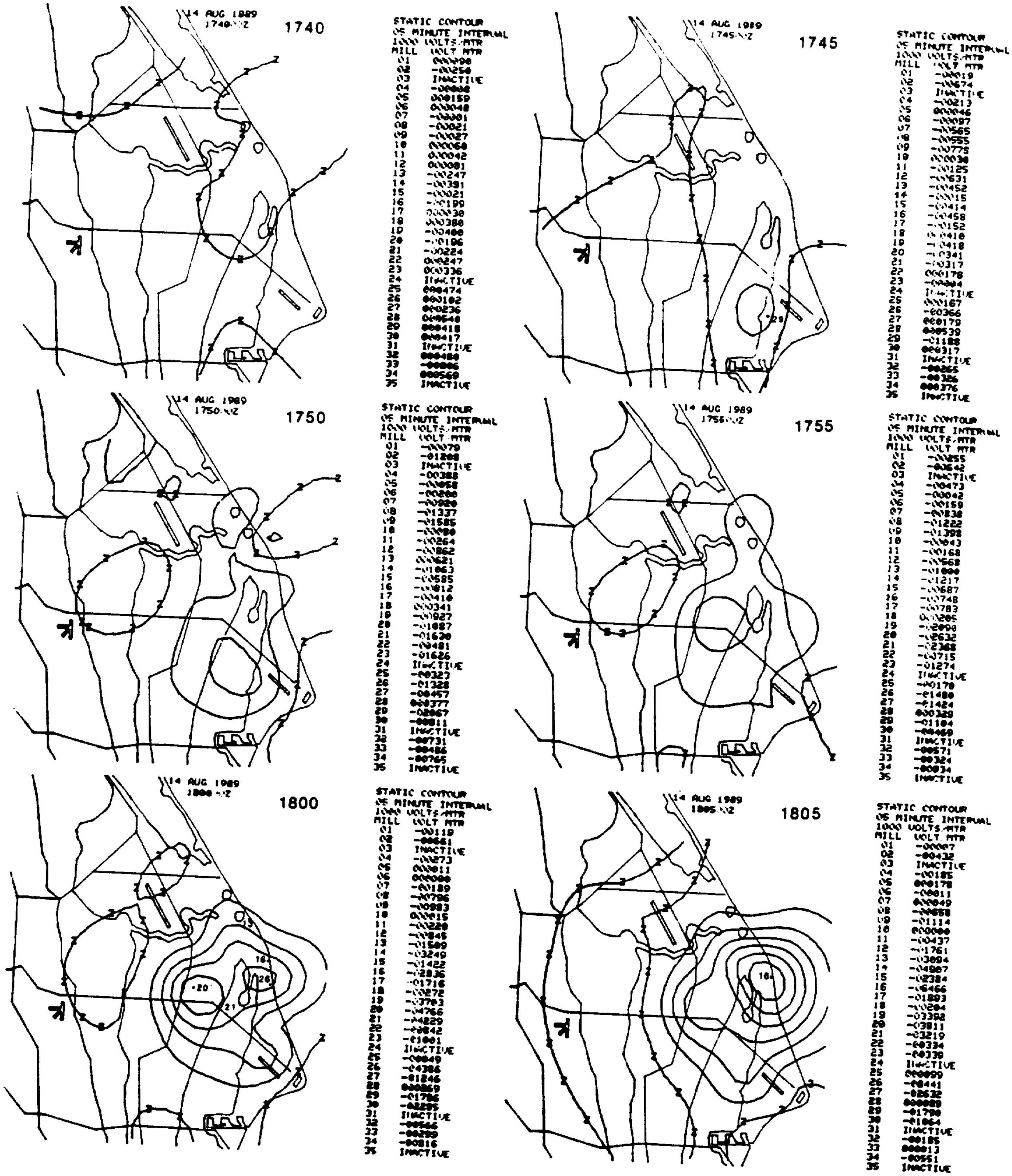


Figure 57: KSC surface ∇V contour plots for 1740 to 1805 Z on 14 August 1989.

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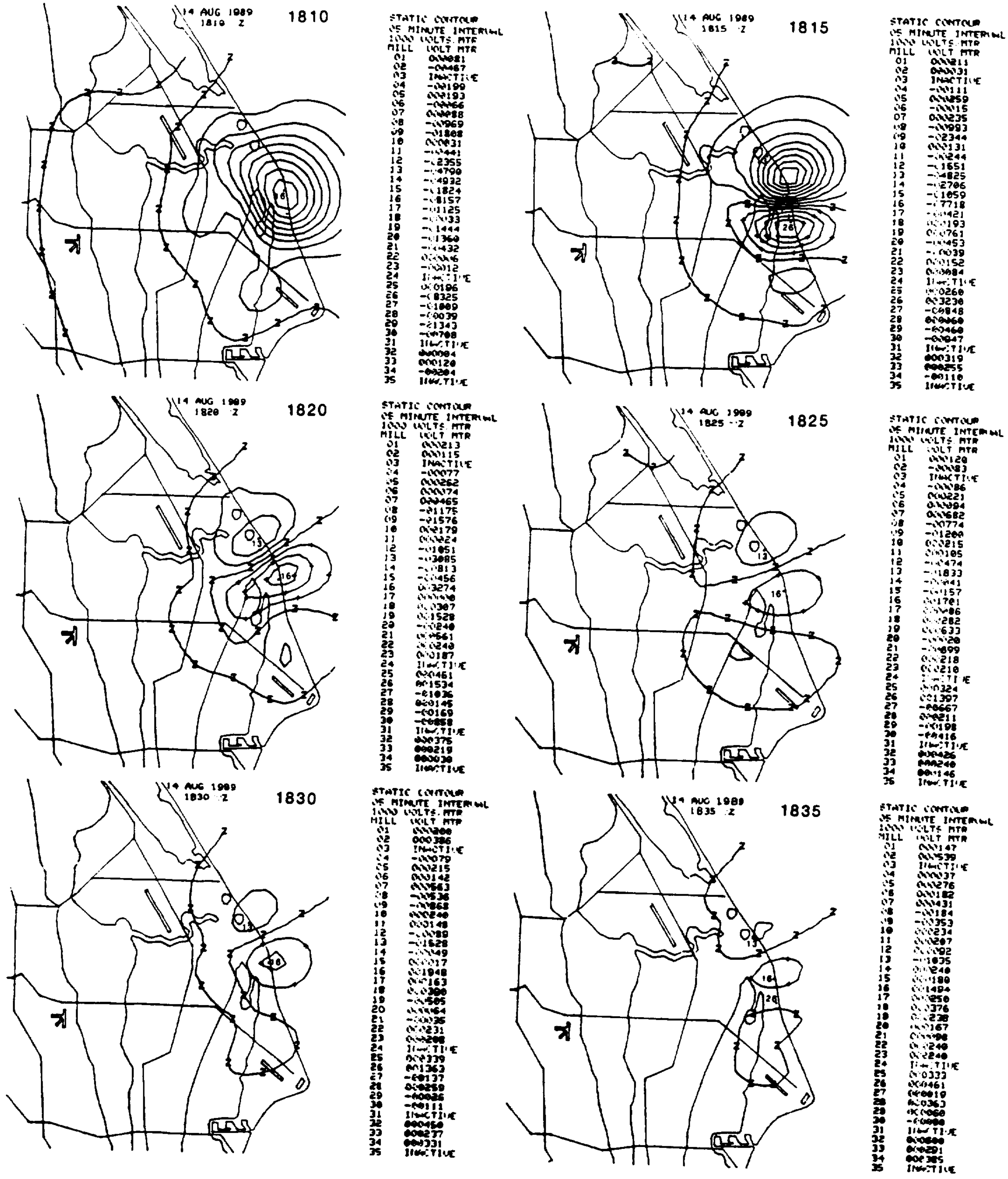


Figure 58: KSC surface ∇V contour plots for 1810 to 1835 Z on 14 August 1989.

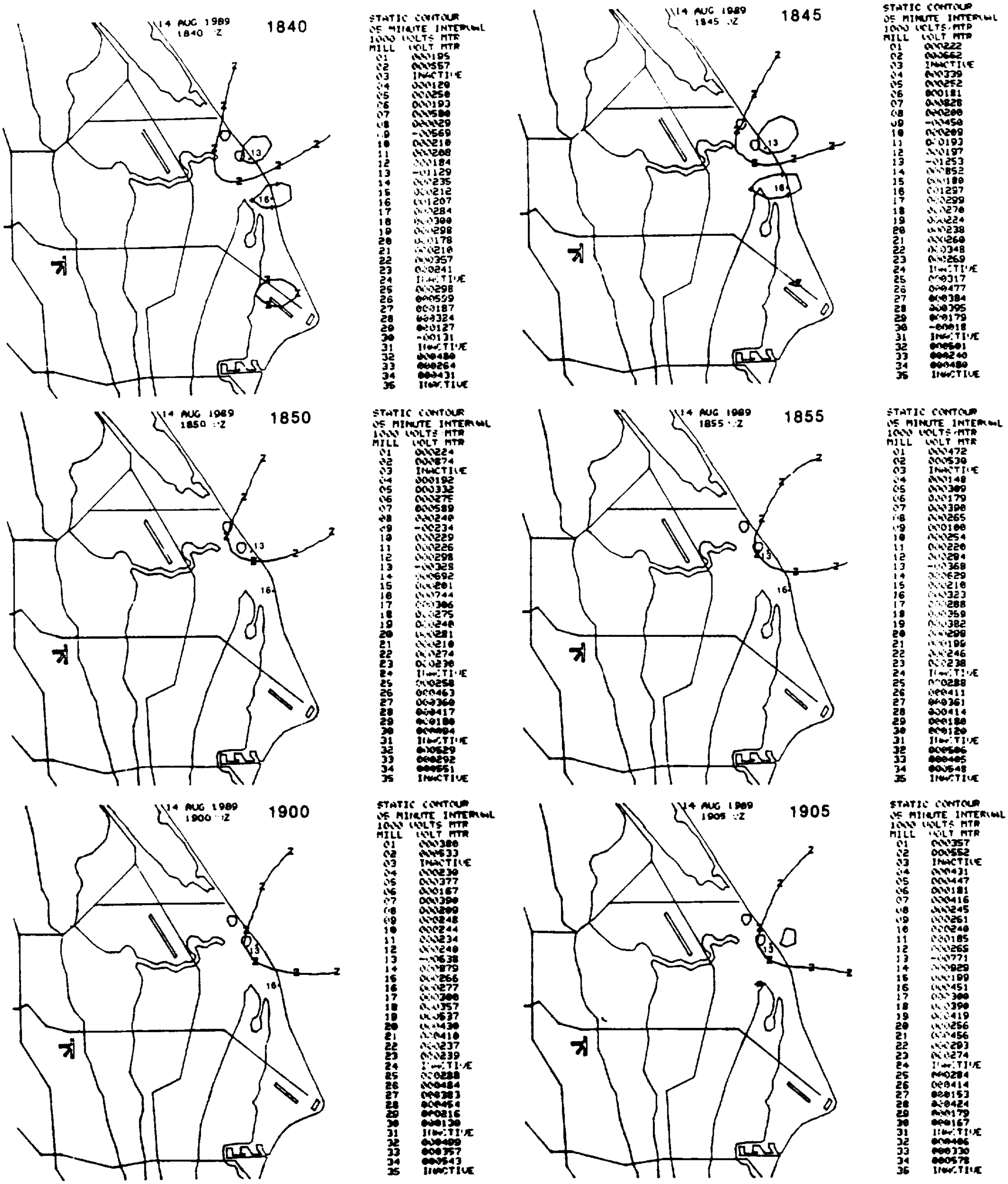


Figure 59: KSC surface ∇V contour plots for 1840 to 1905 Z on 14 August 1989.

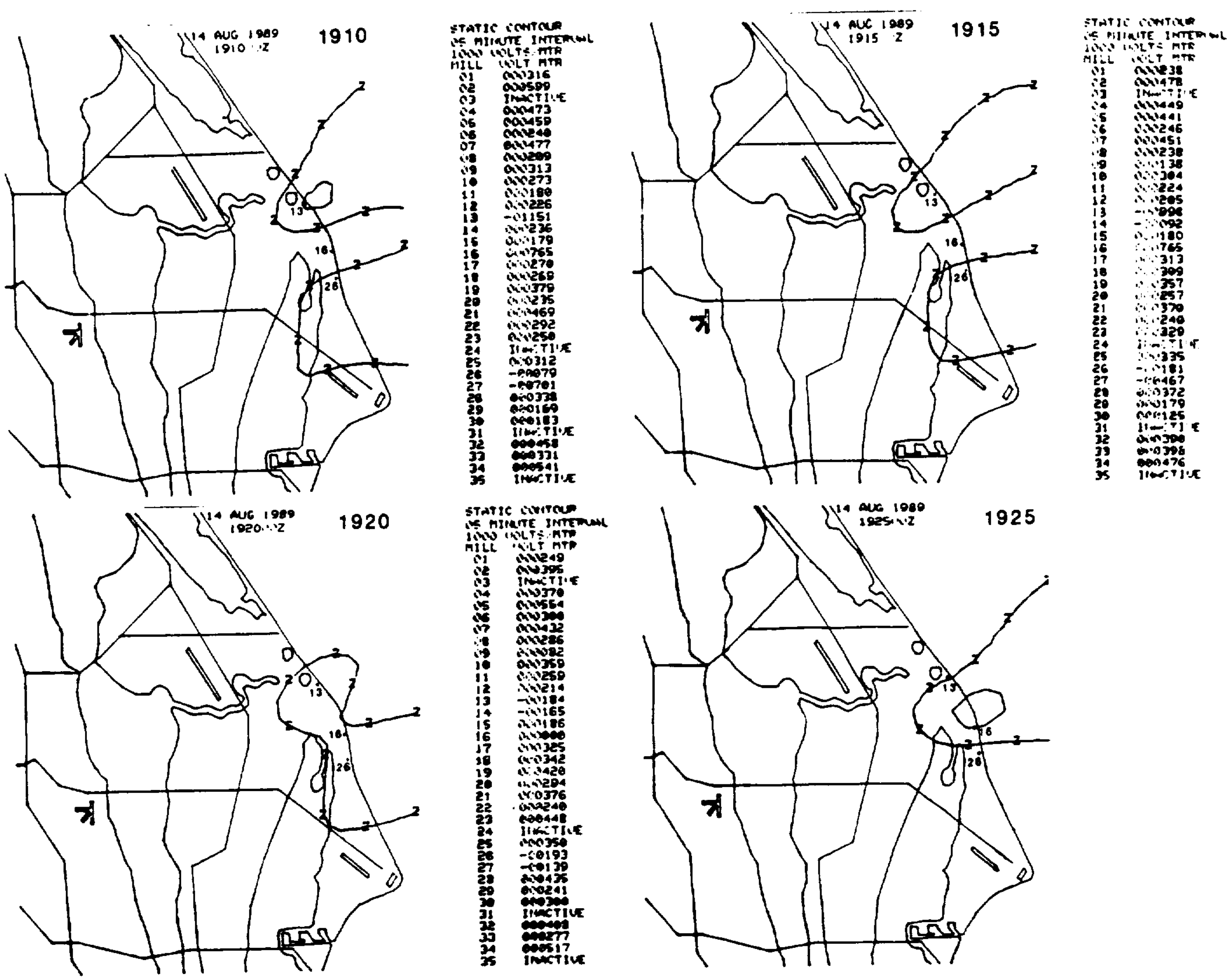


Figure 60: KSC surface ∇V contour plots for 1910 to 1925 Z on 14 August 1989.

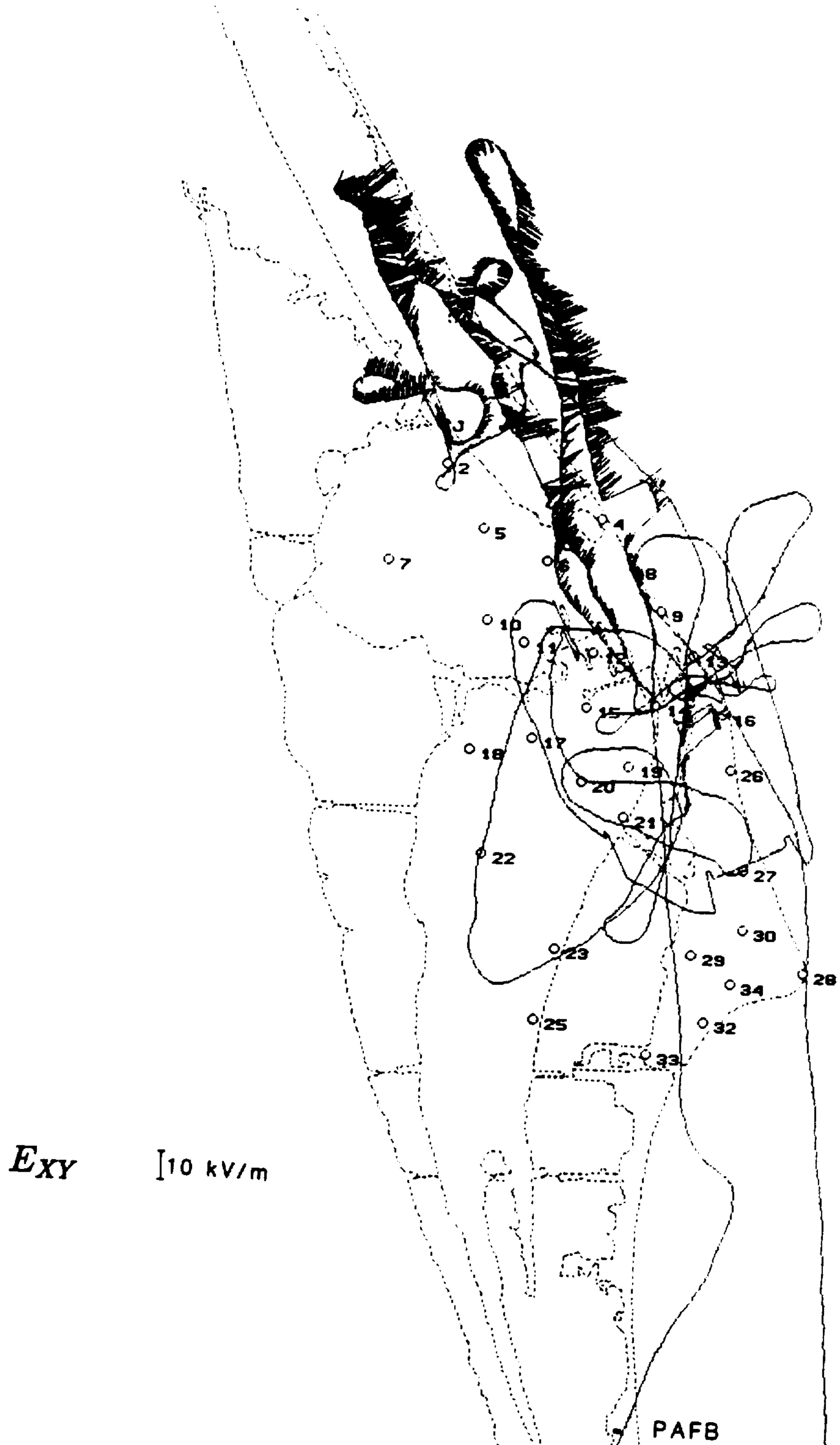


Figure 61: PC plot of E_{XY} vectors along the SPTVAR flight track of 14 August 1989.

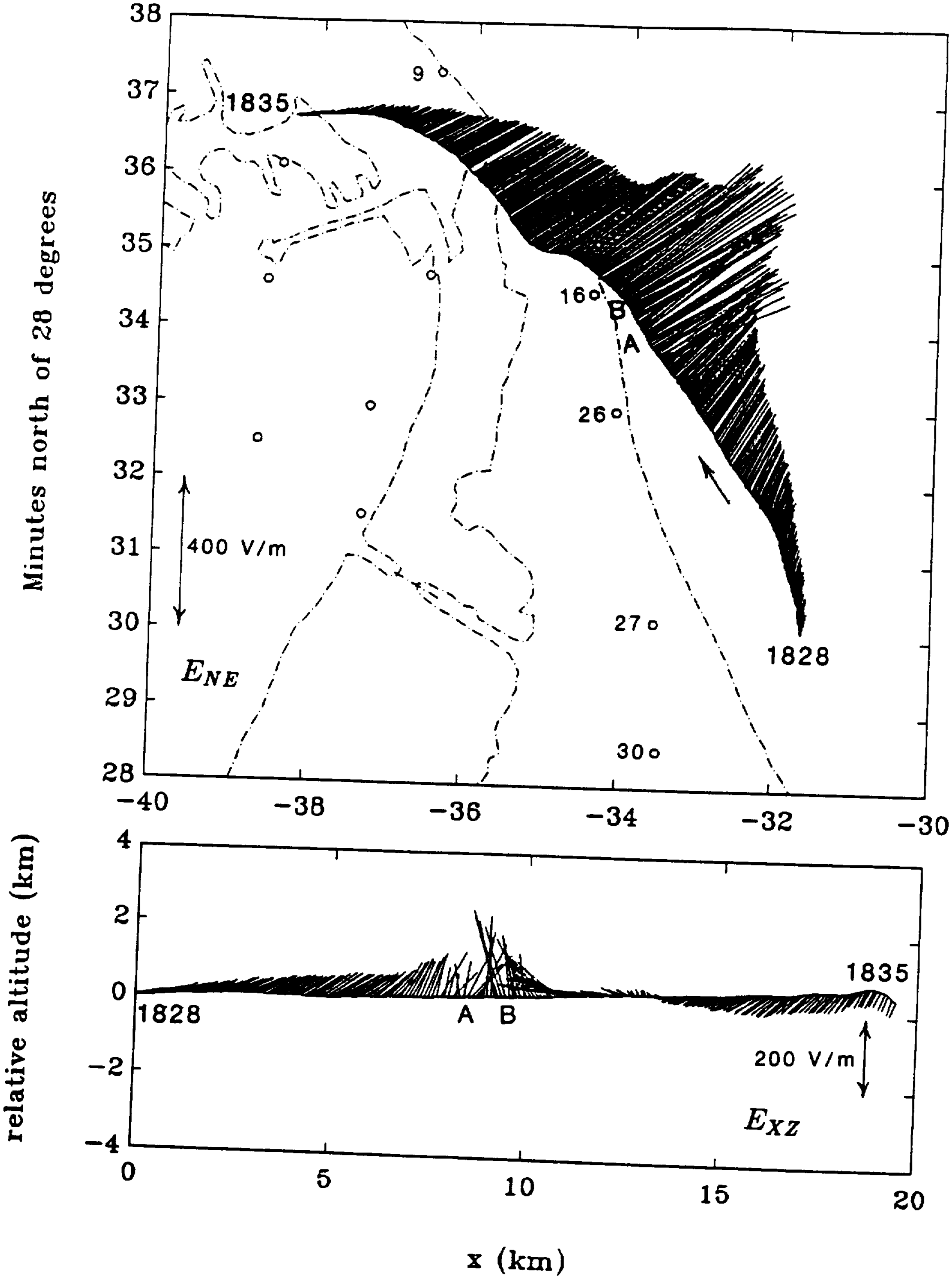


Figure 62: E_{NE} vectors along the SPTVAR track (upper panel) and E_{XZ} vectors along the SPTVAR altitude profile (lower panel) for 1828 to 1835 Z on 14 August 1989.

positive charges, at **A** and **B** in Fig. 62, associated with the small cloud over the False Cape, but that the dominant electric field was due to negative charge in the large cloud over the Atlantic Ocean. The apparent convergence of the E_{XZ} vectors above the altitude profile between **A** and **B** then may be reinterpreted as due to divergence due to positive charge below the SPTVAR at **A** and **B**. This analysis is supported by the plot of one-minute averages of ∇V measured by the nine mills along the Atlantic shore line from 1740 to 1920 Z shown in Fig. 63. All the mills show a wide- spread, persistent and weak negative ∇V due to the cloud over the ocean. ∇V measured by mills 26 and 16 are anomalous since both show an exaggerated negative excursion followed by a unique positive excursion not detected by the other mills. There is also a notable delay between the times that mills 26 and 16 measured the enhanced negative ∇V and subsequent polarity reversal, suggesting that the disturbance may have begun nearer mill 26.

The ∇V contour plots for 1800 to 1845 Z present a misleading view of the surface electric field gradient since they show the negative ∇V contours as closed curves over the Atlantic Ocean east of the surface field mill array. Without electric field data from offshore sites there is no justification for the contours to be shown as closed curves. If the offshore portions of the contours are ignored, the contour plots are consistent with a negatively charged cloud over the Atlantic Ocean to the east of the False Cape. Adopting this overall view, the contour plots for 1815 and 1820 Z may be viewed as the ∇V pattern of a very compact localized positive charge superimposed on the ∇V pattern of the negative cloud charge offshore.

By 1840 Z, the tops of the cumulus along the north end of the Banana River were between 12,000 and 14,000 ft (4.3 km), still too low to account for the observed positive ∇V at the surface. Indeed, a little later a cloud developed over the southern part of CCAFS with tops to 17,000 ft (5.2 km), below which mills 21–32 measured only fair-weather fields.

Somewhat later, however, clouds over the Titan complex area near mill 16, although limited in area, developed vigorously. At 1914 Z the cloud in that area had a core radar reflectivity of 43 dBZ. At 1934 Z its radar top was at 35,000 ft. By 1941:30 Z its radar reflectivity reached 48 dBZ. At 1948 Z, SPTVAR's pilot reported that the cloud looked soft on top and was now below 35,000 ft.

At about 1923 Z, SPTVAR penetrated a towering cumulus with top just above the flight altitude of 17,000 ft (5.2 km) and a rain shaft below. It was not electrified. Shortly thereafter, at about 1930 Z, SPTVAR penetrated the nearby cloud over the Titan complex (whose radar top reached 35,000 ft at 1934 Z as noted above) while on a heading of about 210°. The E_{NE} and E_{XZ} vectors along the SPTVAR track, shown in Fig. 64, indicate a very localized negative charge slightly above the flight altitude and just northwest of mill 16. Plots of the electric field components are shown in Fig. 65. The ∇V contour plot for 1925 Z, five minutes earlier, included in Fig. 60, indicates negative charge above mills 13 and 16 at that time.

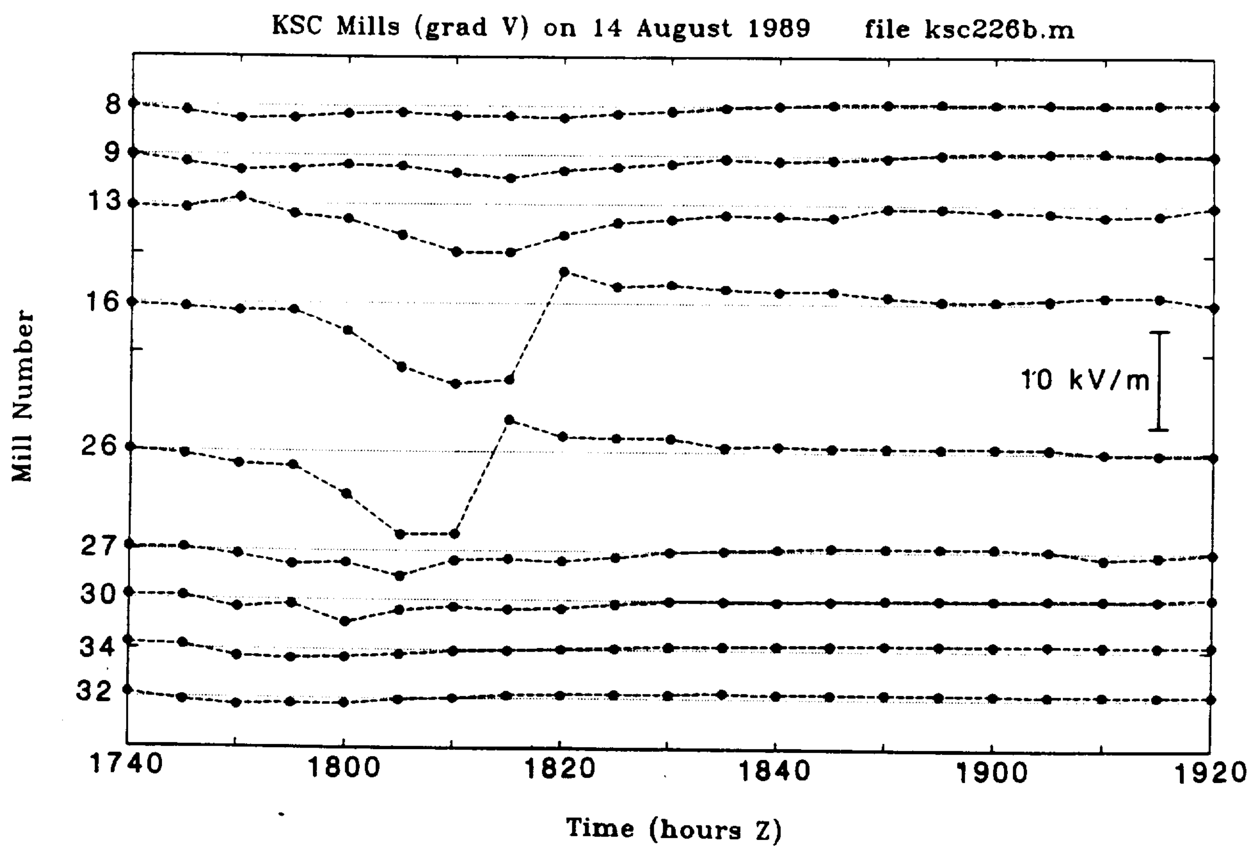


Figure 63: One minute average ∇V values at five minute intervals measured by field mills along the Atlantic coastline from 1740 to 1920 Z on 14 August 1989.

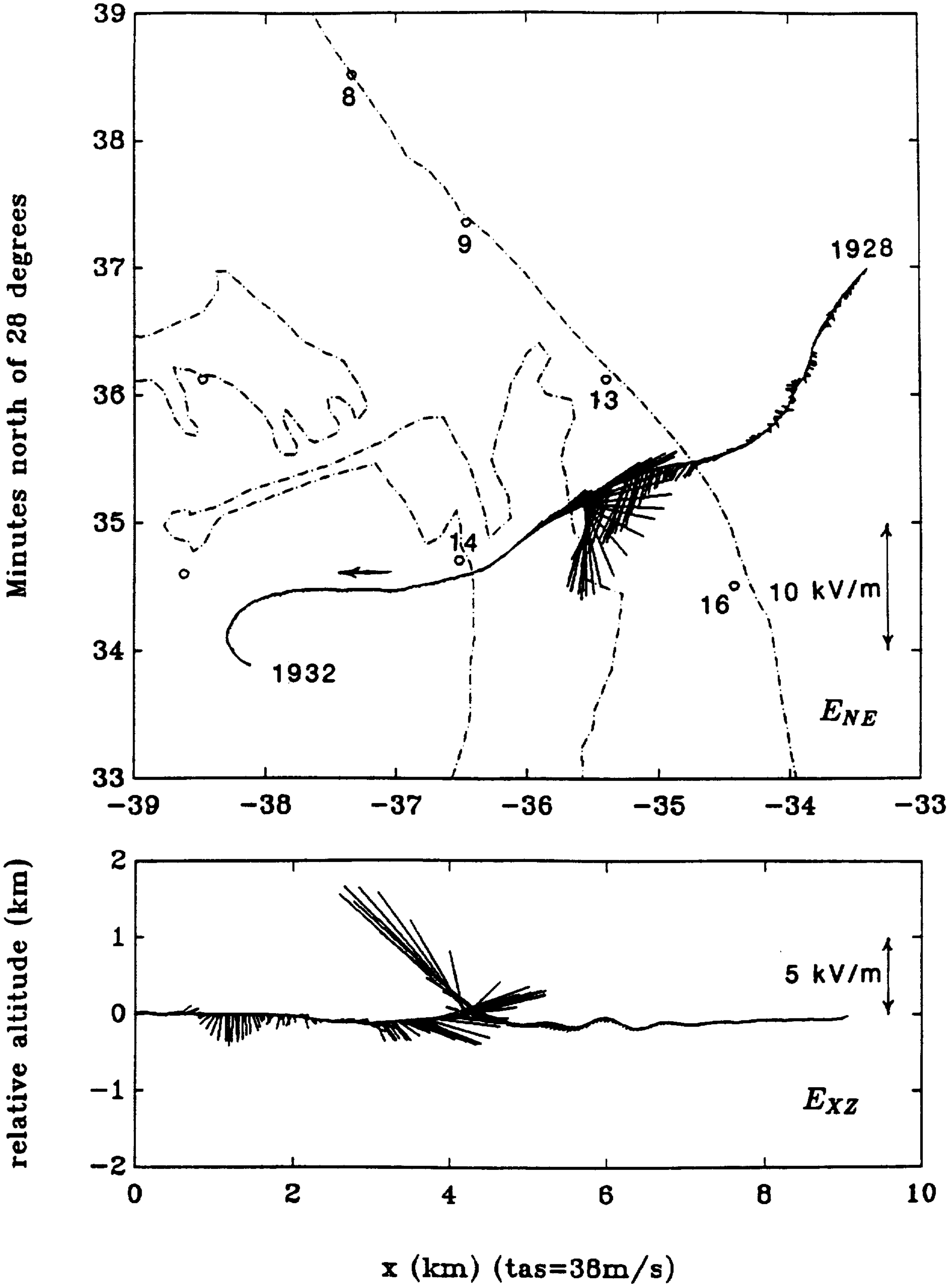


Figure 64: E_{NE} vectors along the SPTVAR track (upper panel) and E_{XZ} vectors along the SPTVAR altitude profile (lower panel) for 1928 to 1932 Z on 14 August 1989.

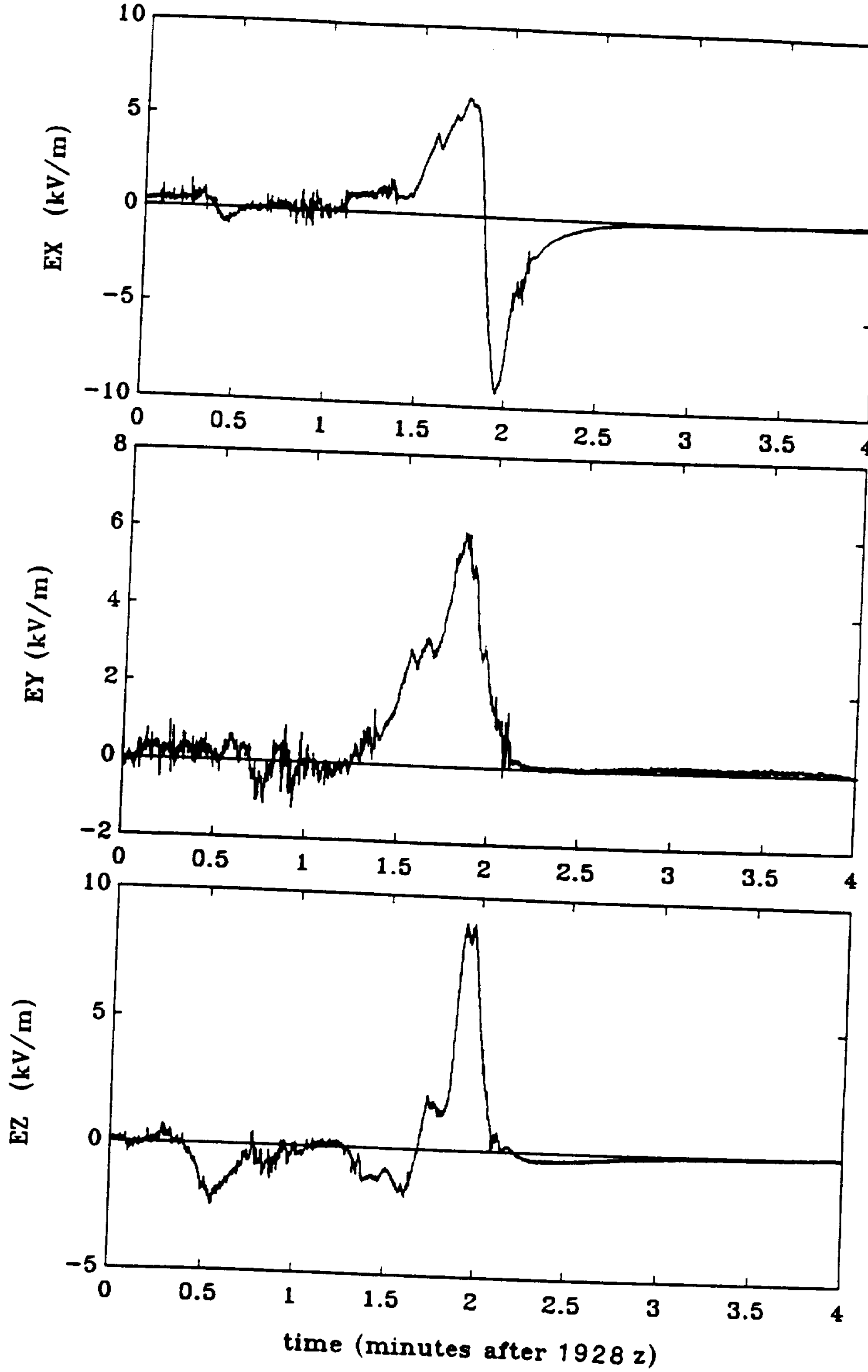


Figure 65: E_X E_Y and E_Z from 1928 to 1932 Z on 14 August1989.

At 1944 Z while on a southerly course and above the east shore of the Banana River to the west of mill 26, SPTVAR measurements indicated localized negative charge somewhat east of the flight track. Seven minutes later while on a north bound course, also over the east shore of the Banana River, SPTVAR obtained measurements that indicate negative charge in a cloud penetrated from 1951 to 1952 Z. The electric field due to the negative charge is partially masked by that due to charge plumes resulting from airplane charging caused by the LWC of the cloud. Nevertheless, negative charge somewhat to the east of and below SPTVAR may be inferred. The E_{NE} and E_{XZ} vectors along the flight track are shown in Fig. 66, while the individual electric field components are shown in Fig. 67.

Although SPTVAR flew in and out of clouds in the vicinity of the False Cape from 1830 to 1954 Z, the only significant electric fields measured were either due to the cloud over the ocean or in the very local area of mill 16. The apparent localized position of positive charge below the 6,000 ft SPTVAR altitude at 1830 Z near mill 16 and the Titan complex suggests that the charge was not a normal cloud charge since positive charge is usually found much higher in clouds. Perhaps this anomalous charge was related to human activity on the surface.

The later observation of electric field of negative charges at about 17,000 ft in the cloud which reached 35,000 ft near mill 16 indicates that the cloud experienced a brief period of electrification and that the charge persisted for at least 20 minutes.

Meanwhile, a cloud which had begun over the Shuttle Landing Facility had a radar top about 30,000 ft (9.1 km) at 1948:40 Z. By 1954:20 this cloud had a maximum radar reflectivity of 45 dBZ and had made four lightning flashes. SPTVAR moved to this cloud and flew along its eastern side as it moved toward the northeast. As the cloud moved out to sea from Mosquito Lagoon SPTVAR flew around to the west side and continued to fly back and forth along the edge of the cloud as it continued to expand rapidly, growing at 4,000 ft/min everywhere according to the SPTVAR pilot. It was soon a very big cloud with high reflectivity cores and radar echo tops of 40,000 ft (12.2 km). SPTVAR made a few very brief probings of the cloud edges, but avoided any possibly long penetrations since it had picked up ice on the few short penetrations at 17,000 ft (5.2 km) in the clouds studied earlier over CCAFS. Electric fields in excess of 20 kV/m were measured while SPTVAR was flying just outside the edges of this cloud. The flight was terminated at 2057 Z.

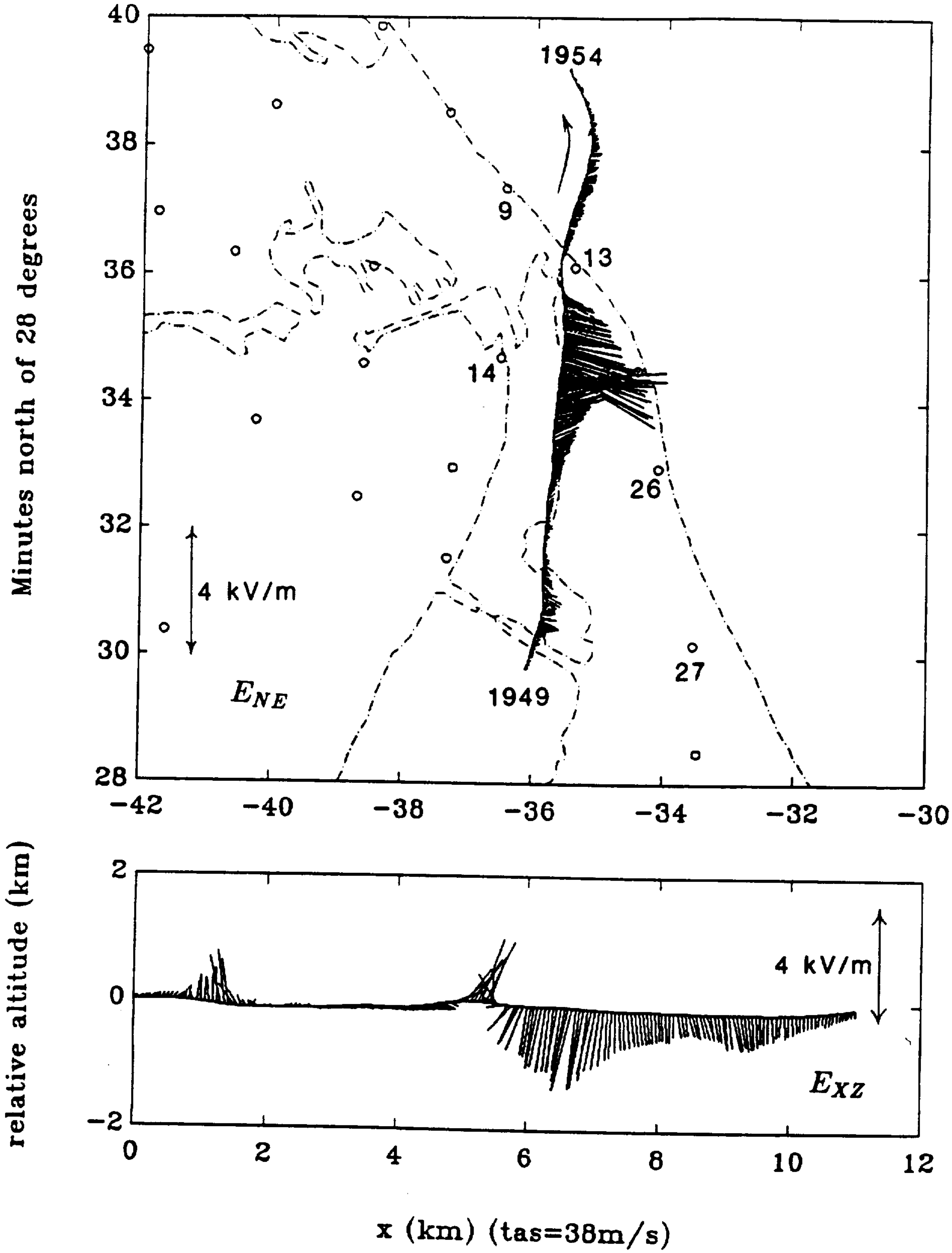


Figure 66: E_{NE} vectors along the SPTVAR track (upper panel) and E_{XZ} vectors along the SPTVAR altitude profile (lower panel) for 1949 to 1954 Z on 14 August 1989.

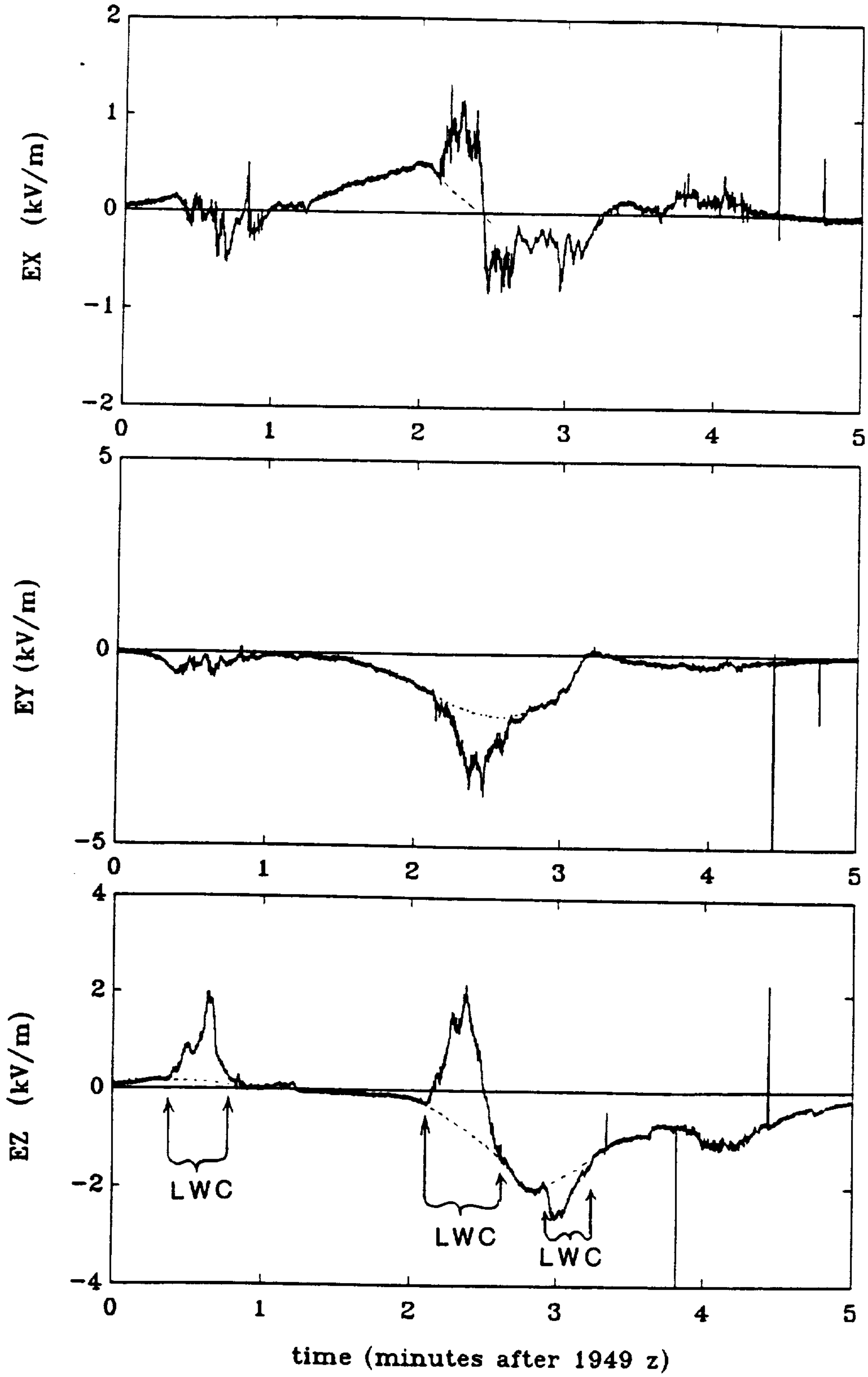


Figure 67: E_X E_Y and E_Z from 1949 to 1954 Z on 14 August 1989. Periods when the airplane was charged by liquid water are indicated. During these times the measured field components were not reliable; the dotted lines show our guesses at the true values.

A.3.5 Summary: 18 August 1989 (89230)

Highlights:

- SPTVAR measured the variation of E_X outside an electrified cloud as SPTVAR flew toward and away from the cloud.
- Several cloud charges were located despite effects of lightning on the measured electric field components.
- SPTVAR was struck by lightning; the resultant large net charge of about 500 μC was shed in about 3 seconds.
- SPTVAR measured $\Delta\vec{E}$ due to lightning triggered by a small rocket fired from the rocket-triggered-lightning site. From the SPTVAR data we estimate that the lightning removed about -60 coulombs of charge from the cloud.
- For much of the flight the electric field measured by SPTVAR was due to anvil clouds.
- Various of the launch commit criteria weather rules would not have permitted a launch under the conditions prevailing during this flight.

A 200 mb trough extended from Michigan into the Gulf of Mexico south of Alabama. The weather pattern was dominated by tropical features at lower levels. The winds were easterly from the surface through 8,000 ft. The local air mass was moist throughout the troposphere. The surface ridge was centered over KSC and extended eastward. The 700 mb flow was from 70° at 3 to 6 knots. Because of the light easterly flow, activity was expected at the initial onset of the sea breeze.

The 1200 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 68.

This day's flight was initiated at 1708 Z. The flight track with E_{XY} vectors drawn at intervals along it is shown in Fig. 69.

Most clouds this day were large ones that grew just west of the Indian River. The winds aloft blew their anvils over the KSC area. As a result, for much of the flight the electric field measured by SPTVAR was due to these anvil clouds. During the first part of the flight the strongest field was at the north end of R2934. Later, SPTVAR went south to study the electric field due to a storm to the west of mill 7. Frequently the electric field vectors were constant over relatively large distances and maintained a constant direction (relative to the earth) as SPTVAR turned. Late in the flight we heard that the French Group had triggered lightning at a time that SPTVAR was again over the northern part of

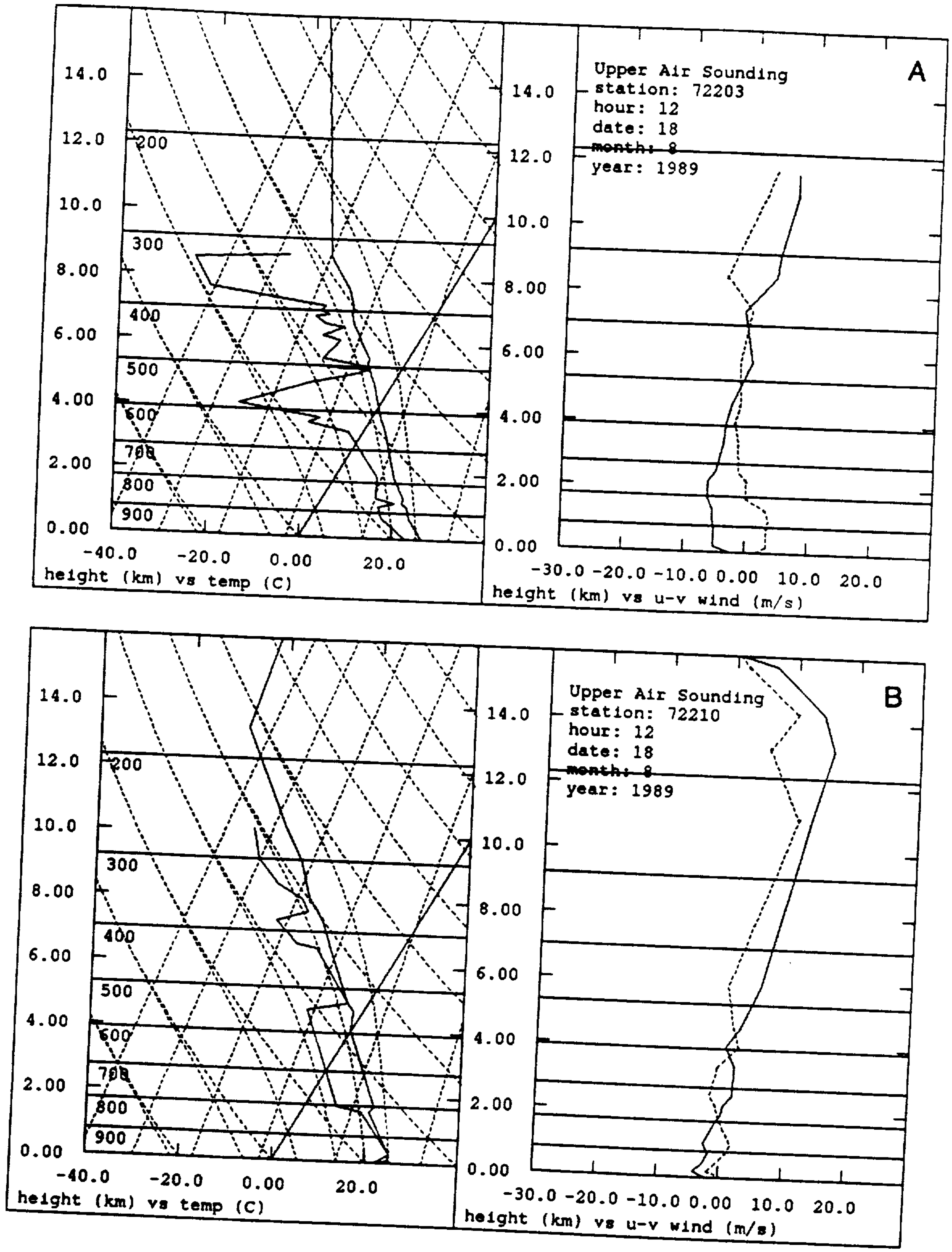


Figure 68: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 18 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

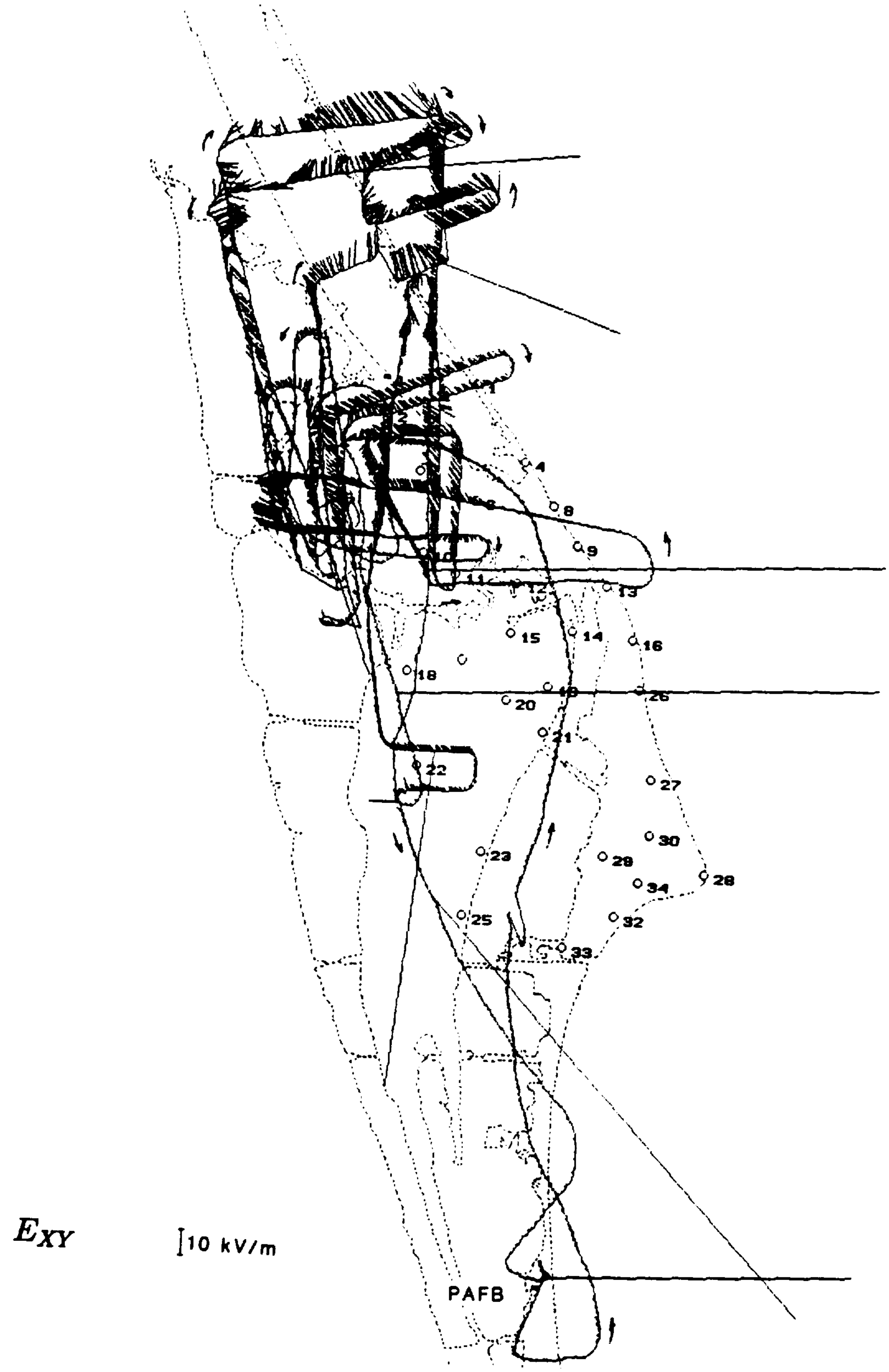


Figure 69: PC plot of E_{XY} vectors along the SPTVAR flight track of 18 August 1989. The spurious spikes resulted from radio interference on the telemetry frequency. SPTVAR was at 11,000 ft during this flight.

KSC, near the rocket-triggered-lightning site. One interesting field change at SPTVAR, in which all three components changed sign, was the result of a triggered lightning flash. At the time of this flash SPTVAR was about 3 km to the SE of the rocket-triggered-lightning site. For all of this flight, except the climb and descent stages, SPTVAR flew at 11,000 ft (3.4 km).

A number of interesting observations may be gleaned from the data collected on this flight, and some of these lead to interesting conclusions.

The first flight segment of interest was that from 1905 to 1913 Z. The E_{NE} plot for this time interval is shown in Fig. 70. The pilot's comments indicate that the 180° turn at 1909 was made just before SPTVAR entered a large cloud to the north.

Plots of E_X, E_Y, E_Z and the LWC for this flight segment are shown in Fig. 71.

The first part of the E_X curve shows that E_X increased toward more positive values indicating that SPTVAR was approaching a negative charge to the north. However, before entering the cloud that apparently contained this charge SPTVAR turned back toward the south. As it did so, E_X rapidly reversed sign as the relative position of the negative charge swung around from in-front-of to behind SPTVAR. E_X then decreased as SPTVAR retreated from the charge in the cloud. These data demonstrates that the cloud's electric field is clearly observable outside the cloud. It is also clear that the strength of the electric field varied with distance from the charge in a nonlinear fashion as we expect it to since Coulomb's law states that the electric field of a spherically symmetric charge distribution decreases as $1/r^2$ outside the region of charge.

Upon comparing this E_X variation due to flying toward and away from negative charge with the variation of E_X in Fig. 65 due to flying past negative charge, we see that this characteristic bipolar E_X pattern can arise from either situation. If the charge in these two examples had been positive then E_X would initially have increased toward negative values and then reversed quickly to positive values as the airplane flew past, or turned away from, the charge. In the example described here the charge apparently was directly ahead of SPTVAR since both E_Z and E_Y remained effectively zero until just before SPTVAR turned away from the cloud ahead (Fig. 71).

After turning south at 1909 Z, SPTVAR flew through a cloud at 1912 Z. As SPTVAR passed through this cloud, the time between the two vertical lines in Fig. 71, the E_X, E_Y and E_Z signals all became noticeably noisier. This was due to the charging of SPTVAR by the LWC of the cloud which resulted in plumes of discharge ions which affected the electric field measurement. Note that although the general trend of E_X and E_Z does not appear to have been seriously distorted while SPTVAR was in the cloud, E_Y appears to have been as much as 2 kV/m more positive than would be expected from the adjacent values. Characteristically, E_Y is the component most susceptible to being corrupted by LWC charging effects on SPTVAR.

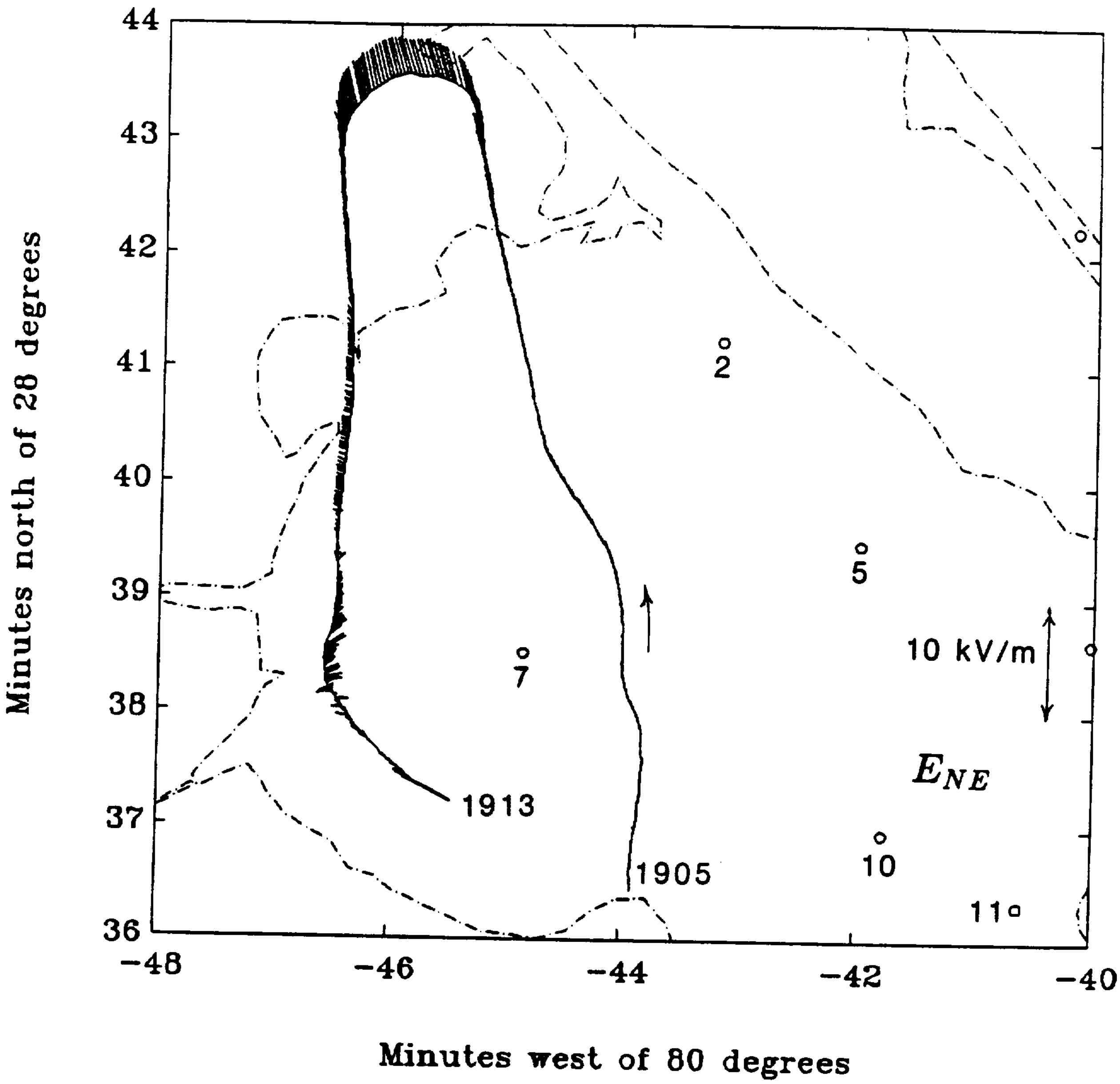


Figure 70: E_{NE} vectors plotted along the SPTVAR flight track from 1905 to 1913 Z on 18 August 1989.

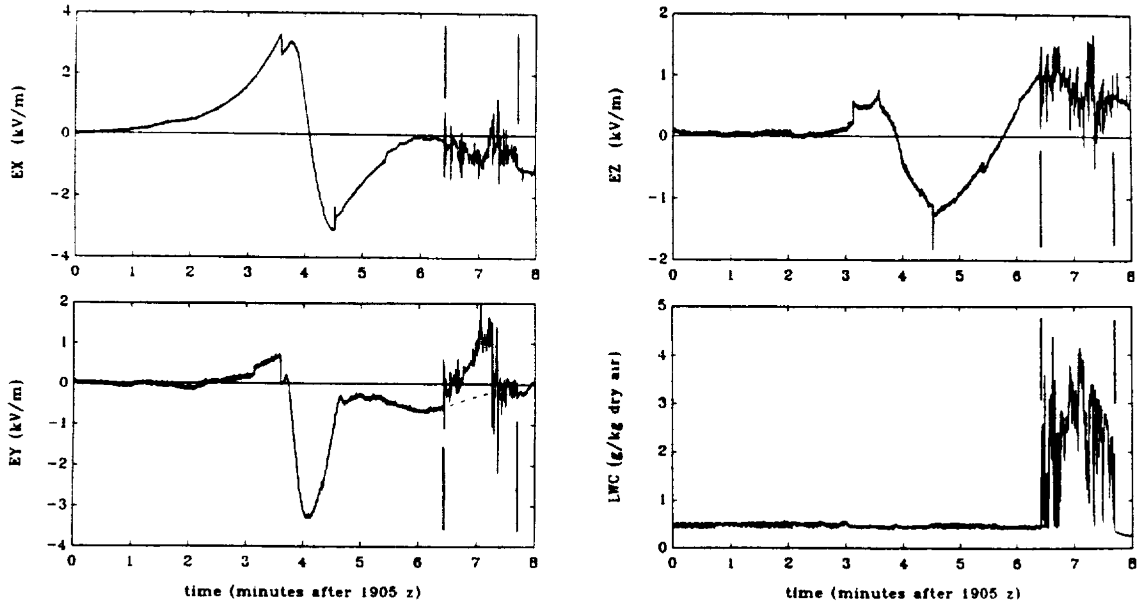


Figure 71: Plots of E_X, E_Y, E_Z and LWC for 1905 to 1913 Z on 18 August 1989.

After the time shown in Fig. 70, SPTVAR flew around to the east and returned south on a course about 1.5 km to the east of the southbound path in Fig. 70. During this time, 1918 to 1921 Z, SPTVAR flew through cloud and measured the electric field patterns shown in Fig. 72. Plots of the individual electric field components and cloud LWC for this time interval are shown in Fig. 73. Although at least 14 lightning flashes are discernible in the plots of the individual components for these three minutes, Fig. 72 still reveals a positive charge just east of the SPTVAR flight path at **A** (note the positive going change in E_X at time **A**). There followed an apparent negative charge perhaps 2 km west of point **B** on the SPTVAR track. The positive charge was about at the SPTVAR altitude, whereas the negative charge was well above the SPTVAR altitude. Note that interpretation of the measured field between **C** and **D** just after the lightning flash labeled 1 is less certain since the cloud LWC encountered just after the time of the lightning flash appears to have biased E_X and E_Y. The period of the LWC encounter and airplane charging therefrom is indicated in Fig. 73. Although E_Y appears to have been decreased in magnitude beyond the decrease due to the lightning flash, E_Z does not appear to have been particularly affected. The dashed lines in the figure indicate the probable variation of the electric field components had there been no LWC.

Another interesting observation derived from the plots of E_Y and E_Z in Fig. 73 is that, for the first half of the time interval shown, both of these components of $\vec{E}$ increased approximately linearly in the brief intervals, averaging 10 s, between lightning flashes. Since SPTVAR was flying at about 50 m/s it typically traveled only 500 m during each

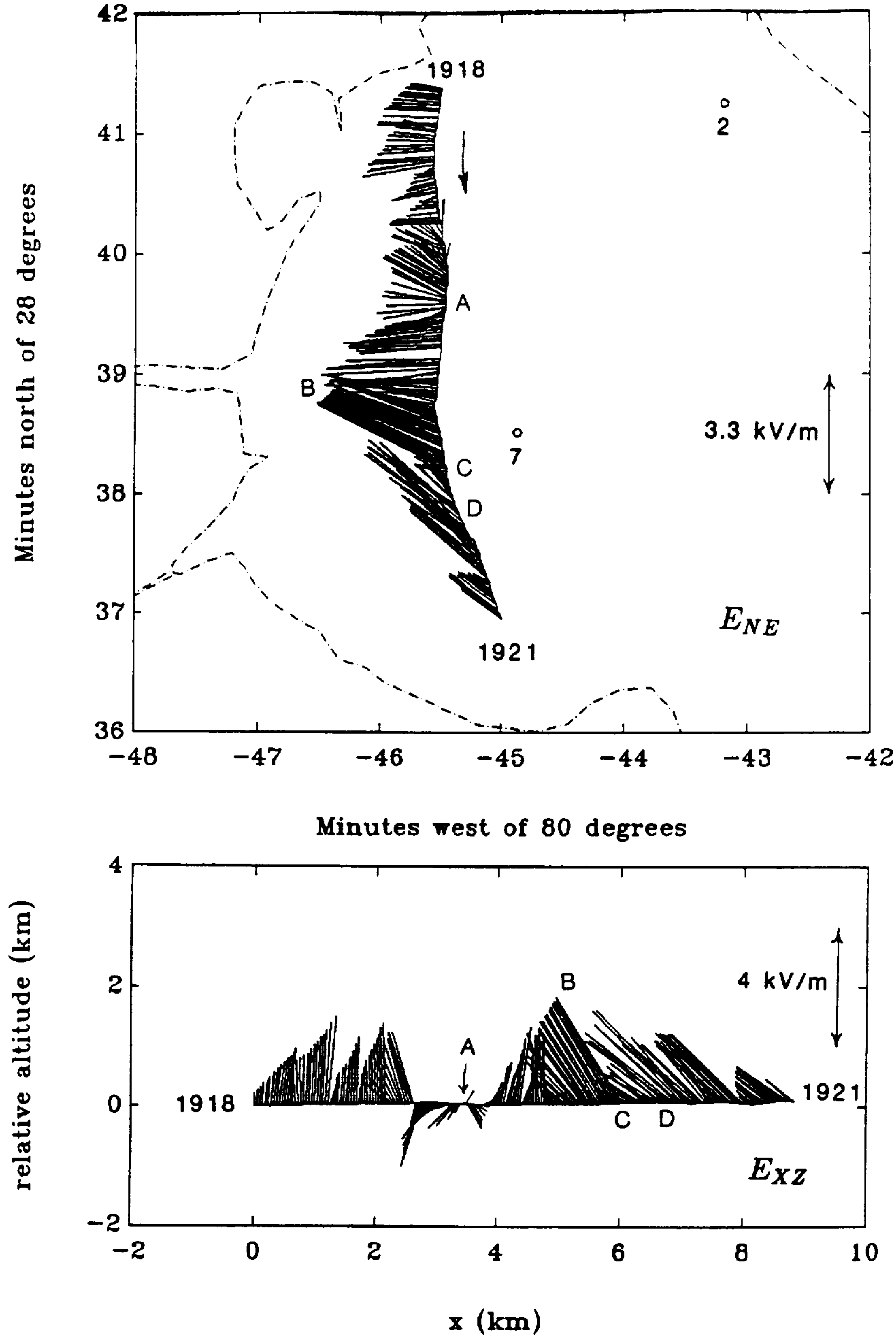


Figure 72: E_{NE} vectors plotted along the SPTVAR flight track and E_{XZ} vectors plotted along the SPTVAR altitude profile from 1918 to 1921 Z on 18 August 1989.

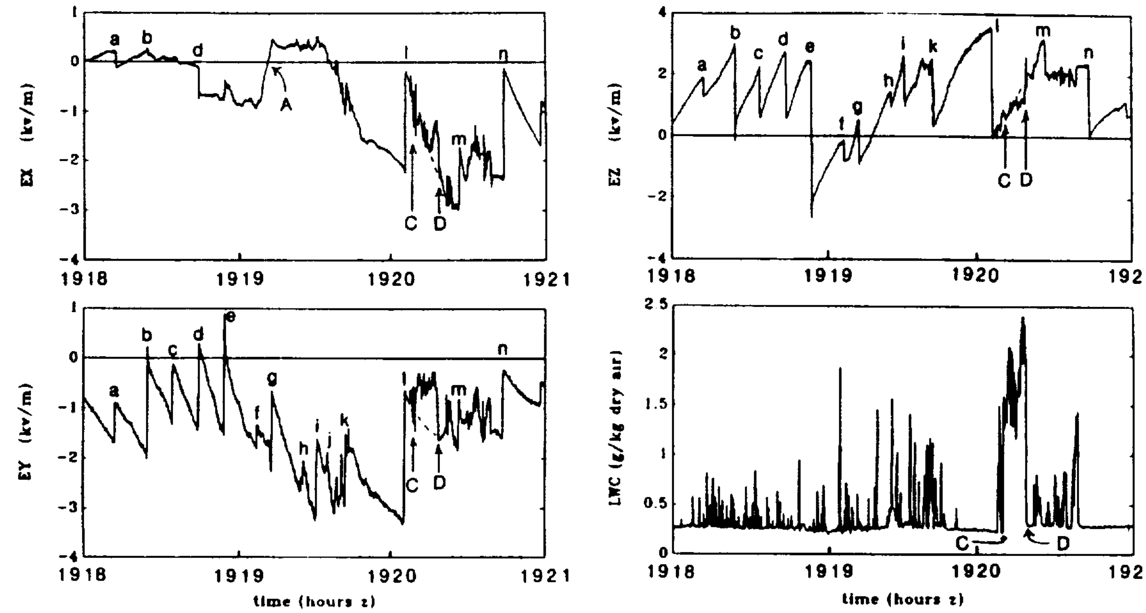


Figure 73: Plot of E_X, E_Y, E_Z and LWC for 1918 to 1921 Z on 18 August 1989.

of these linear segments of electric field growth. If we assume that the charges affected by the lightning were negative and located approximately 45° above and to the right of SPTVAR, and at least 2 km away, then these electric field increases were probably due to changes in the cloud charge rather than the motion of SPTVAR relative to the clouds. This indicates that the electrical generator operating in the clouds was separating electric charge at a nearly constant rate. This observation is consistent with the findings of Winn and Byerley (1975) made with balloon borne-field mills above the space charge layer near the earth's surface.

Following the flight segment shown in the previous figures SPTVAR flew toward the north and then made a 180° turn to the left. This subsequent flight segment is shown in Fig. 74. During this four-minute time interval there were some eight lightning flashes. Nevertheless, a positive charge just left of the SPTVAR path is clearly evident at **A** in Fig. 74. Shortly after SPTVAR passed this positive charge the fourth lightning flash to occur during this flight segment, at **d**, resulted in an increase in the magnitude of the horizontal component of the electric field.

Some understanding of this behavior may be gained from the plot of E_{XZ} shown in Fig. 74. When SPTVAR was nearest the charge the E_{XZ} vectors diverged from a point just below SPTVAR. However, after passing the charge location the vectors became longer and diverge from a point farther below SPTVAR's altitude. After the lightning flash, **d**, the E_{XZ} vectors diverge down and to the right from an apparent positive charge just above

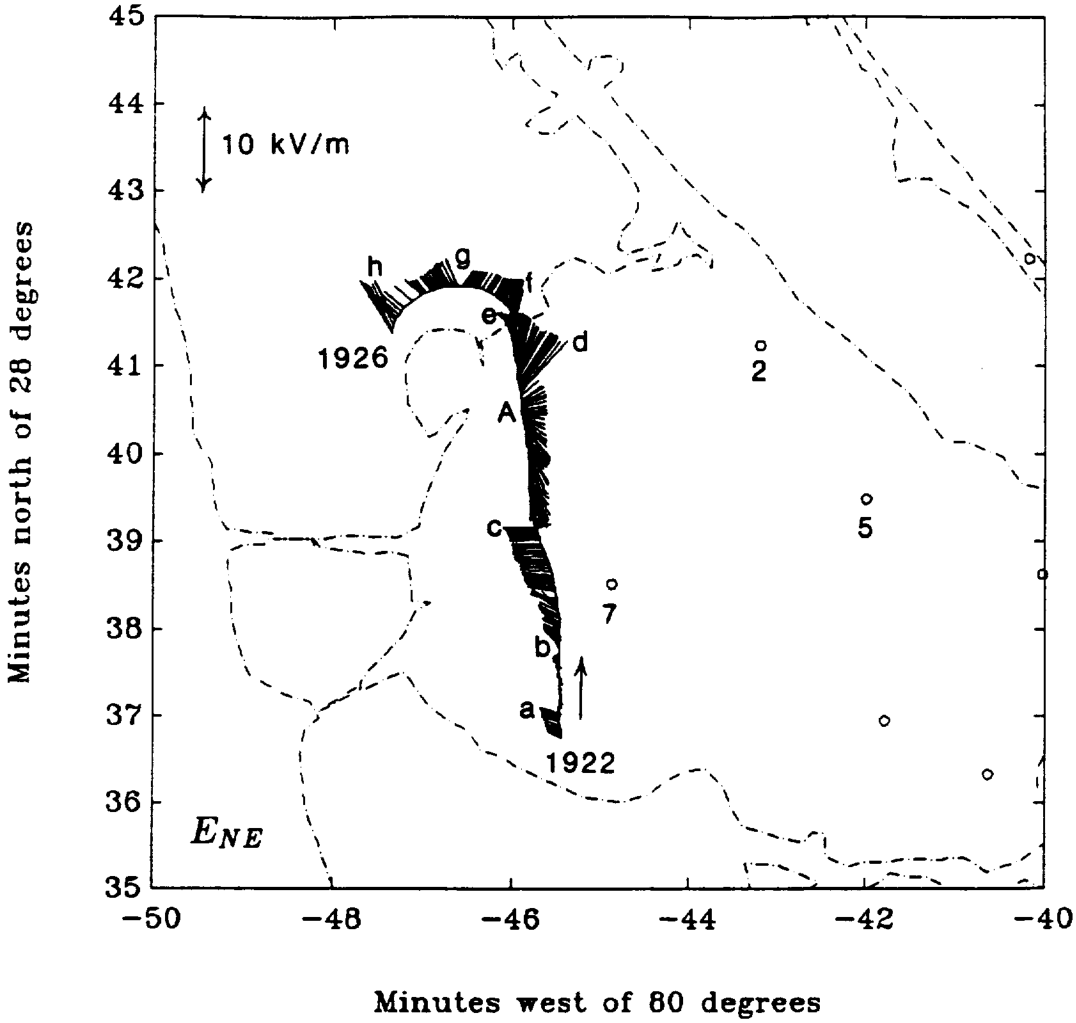
SPTVAR's altitude. A possible explanation for this behavior is that SPTVAR flew through a region containing positive charge extending above and below SPTVAR's altitude. Before the lightning flash there was more charge below SPTVAR than above so that the charge immediately below had the greatest influence when SPTVAR was directly over it, while the charge even lower came into dominance once SPTVAR was farther from the smaller charge just below its altitude. The increase in the magnitude of E_{XZ} and the sudden change in sign of E_Z may be explained by the lightning having removed the portion of the positive charge below SPTVAR, leaving mainly the charge above the SPTVAR altitude. Before the lightning flash, the electric field from the charge above SPTVAR was opposed by that from the charge below. After the flash the charge above in effect became more visible.

Note that the later part of the E_{XZ} plot should be disregarded, i.e., after lightning flash **f**, since SPTVAR began a turn at that time and the variation of E_X with time was due to the turn. Thus the E_{XZ} display cannot be used to determine charge locations when the airplane heading is changing in a turn.

The next flight interval, 1926 to 1929 Z, is shown in Fig. 75. Although the electric field encountered by SPTVAR during this time was very complicated, some sense can yet be made of the data. The E_{NE} and E_{XZ} plots indicate that lightning flashes occurred when SPTVAR was at the points labeled **a**, **b**, **c** and **d**, and that SPTVAR passed near positive charges at **A**, **B**, **C** and **D**. The four lightning flashes are clearly discernible in the individual field component plots shown in Fig. 76. These plots were derived from the medium gain signals from the field mills and have an anomaly after the flash labeled **c**. As can be seen in Fig. 76 the derivative with respect to time of all three field components was zero for a brief time after the flash. The value of E_X was about 17 kV/m when this occurred, or approximately the maximum field value determinable from the medium sensitivity signals, indicating that the medium gain signals were saturated.

This conclusion is confirmed by the plots of low sensitivity top, bottom and aft mill signals shown in Fig. 77. All three show a sudden increase in the electric field at the face of the mills to very large values, and indeed the corresponding plots (not shown here) for the medium sensitivity mill signals show that they all were saturated (clipped) at about 270 kV/m (these signals are the electric field at the face of the mills and are enhanced by the curvature of the airplane, hence the large magnitudes). From the average of the top and bottom mill signals, "*eq*," which is a measure of the airplane charge (also shown in Fig. 77) we determined (Jones, 1990) that the electric charge on the airplane increased by about 500 μC at the time of flash **c**. Only lightning striking SPTVAR could have deposited such a large charge in the short time indicated in the figures.

The plot of *eq* shows that the charge on SPTVAR decayed away in about 4 seconds. Figure 78 shows the three components of $\vec{E}$ determined from the low sensitivity signals for about one minute around the time of flash **c**. Although SPTVAR's determination of



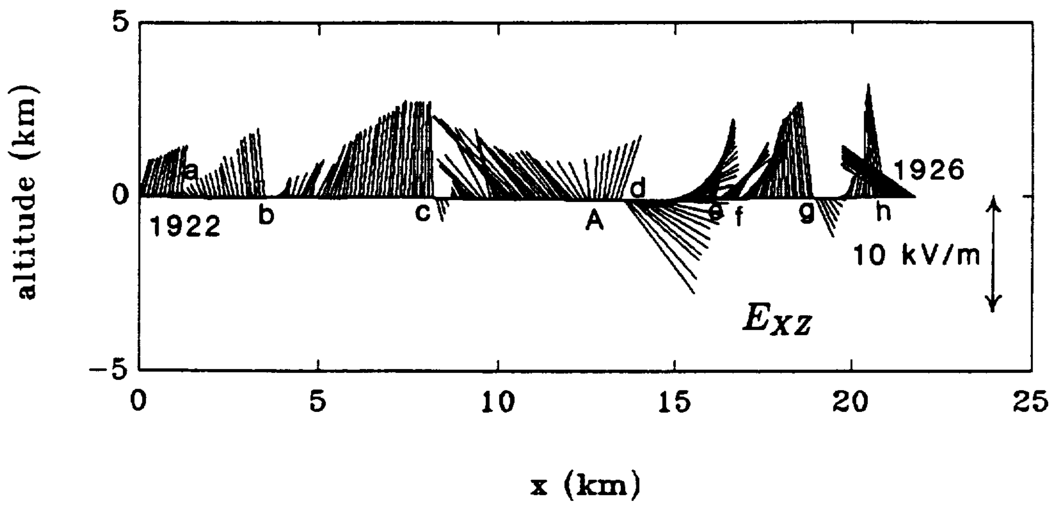


Figure 74: E_{NE} vectors plotted along the SPTVAR flight track (upper panel) and E_{XZ} vectors plotted along the SPTVAR altitude profile (lower panel) from 1922 to 1926 Z on 18 August 1989. Times of lightning flashes are denoted by the letters **a** through **h** and the position of positive charge by **A**.

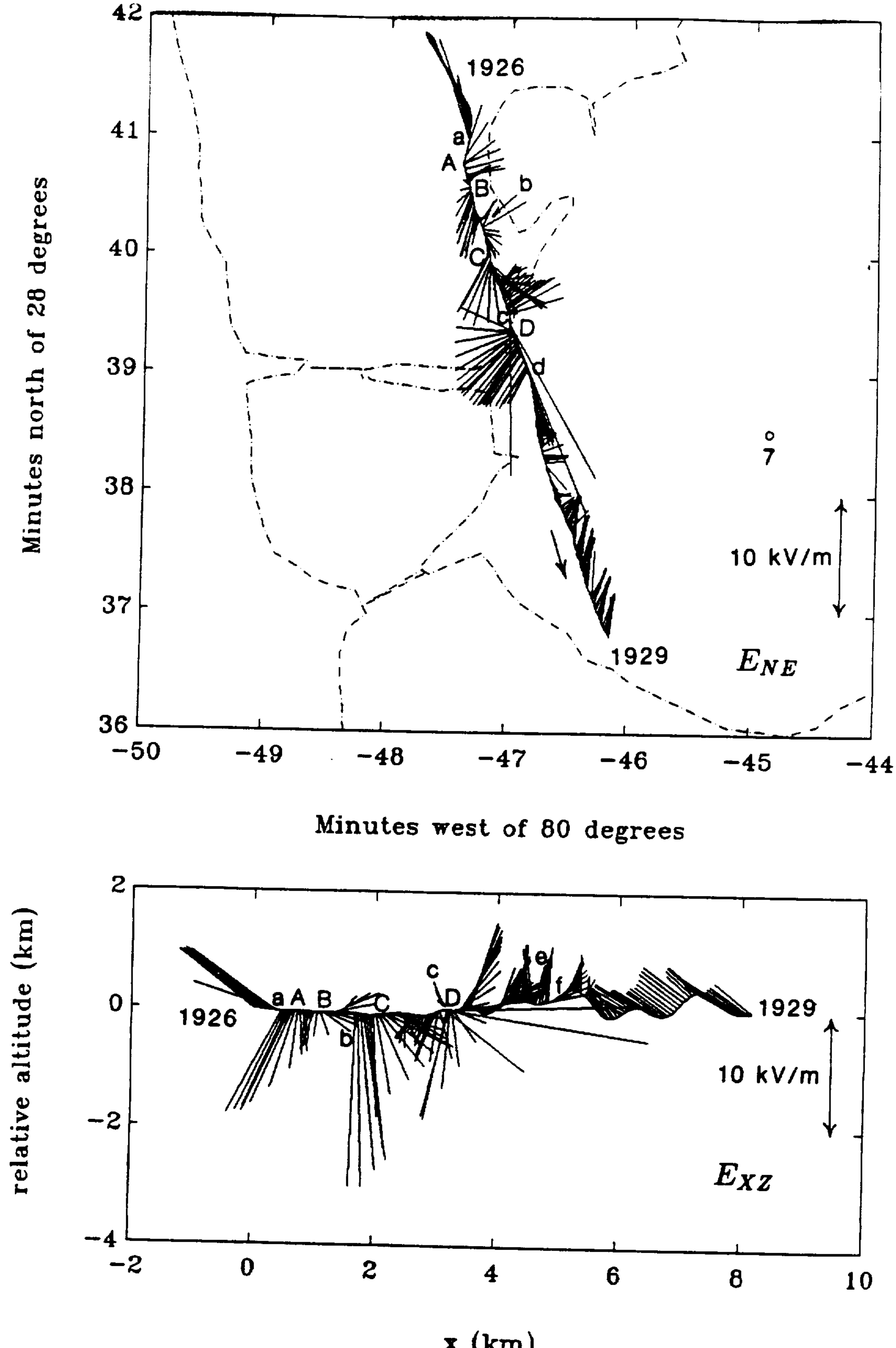


Figure 75: E_{NE} vectors plotted along the SPTVAR flight track (upper panel) and E_{XZ} vectors plotted along the SPTVAR altitude profile (lower panel) from 1926 to 1929 Z on 18 August 1989. Times of lightning flashes are denoted by the letters a through d and apparent positions of positive charge by **A** through **D**.

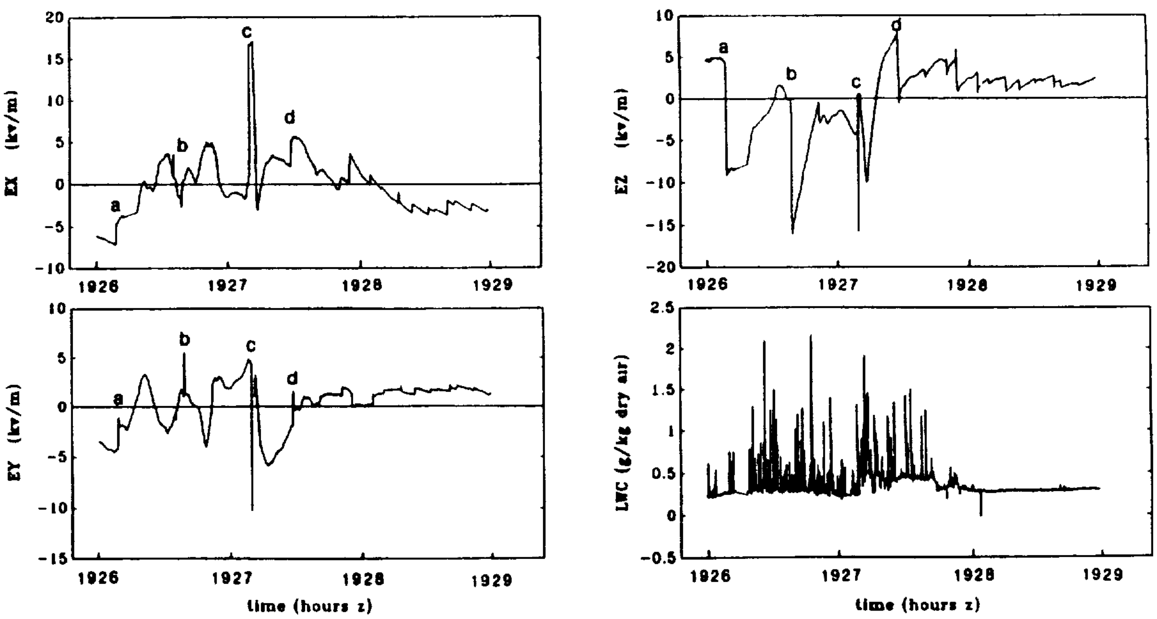


Figure 76: Medium sensitivity E_X, E_Y and E_Z plus LWC for 1926 to 1929 Z on 18 August 1989. Note that there is a baseline shift of about +0.3 g/kg in the LWC plot and that the LWC was actually zero from 1928 to 1929 Z.

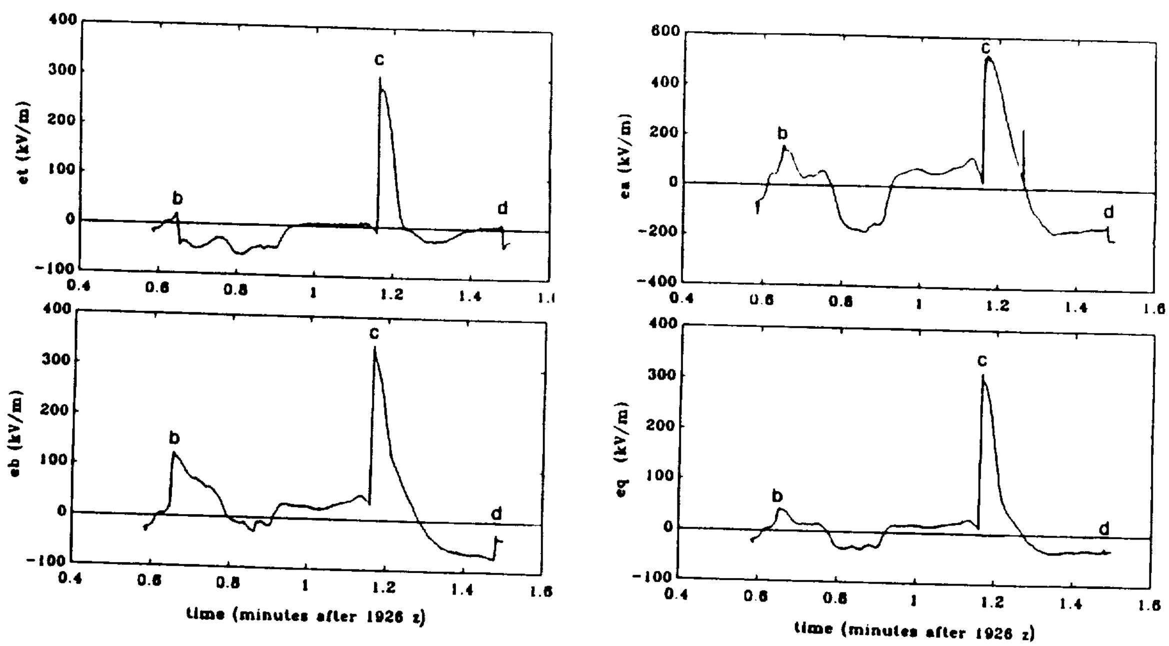


Figure 77: Electric field at the face of the top, bottom and aft mills plus *eq*, the mill face field due to the airplane charge, determined from the low sensitivity mill signals for 1926:35 to 1927:30 Z on 18 August 1989.

E_Z was only slightly affected by the sudden charging of SPTVAR and the determination of E_Y only mildly affected, there is an anomalous peak in the E_X plot subsequent to the flash (labeled **P** in Fig. 78). From Fig. 77, SPTVAR is seen to have acquired a positive charge from the flash, so that during the subsequent 4-s discharge period SPTVAR must have been emitting plumes of positive charge. The electric field of positive plumes behind the airplane should appear as a positive E_X, just as is seen in Fig. 78.

During the last minute of the flight interval shown in Fig. 75 SPTVAR was out of cloud (LWC=0 as shown in Fig. 76), yet there is a series of apparent E_{NE} vector convergences just left of SPTVAR's track. The plot of E_X in Fig. 76 shows that E_X suffered repeated offsets due to lightning flashes during this time and that between flashes E_X always increased toward more negative values. Although less obvious, E_Y was slightly increased toward positive values by most of the same flashes. These shifts in E_X and E_Y combine to produce the apparent convergences seen in the E_{NE} vectors. Since the offsets in field components due to lightning are small, it is probable that the affected regions of charge are at some distance from SPTVAR. If we mentally remove the lightning-caused offsets in E_X, E_Y and E_Z it appears E_X would have crossed zero at about the time of flash **e** and remained negative while E_Y would have remained small. This merely suggests that there may have been a negative charge somewhere in the cloud and to the left shortly before SPTVAR exited the cloud.

The E_{NE} and E_{XZ} plots for the time interval 1931 to 1934 Z are shown in Fig. 79. SPTVAR had just exited a cloud at 1931 Z and turned to the east just after 1933 Z in response to a report of ∇V values of about -4 kV/m at mills 5, 6, and 10. Despite some 16 lightning flashes during this time, the vector patterns indicate that SPTVAR was approaching negative charge overhead for most of this time interval, passing beneath the charge somewhere near the SPTVAR position labeled **A**. This was just before SPTVAR started the turn to the right shown in the figure. Note that the E_{NE} vectors indicate a negative charge slightly to the left of SPTVAR from 1931 Z to the point labeled **A**, then to the right of SPTVAR during the turn and then once again to the left after the turn. Such a pattern suggests an extended negative charge overhead along the line **A** to **B**. The sudden changes in the E_{XZ} vectors are due to lightning flashes. Despite the enhanced convergence of the E_{XZ} vectors between flashes, there is an overall convergence of these vectors which indicates negative charge was as much as three to five km above SPTVAR. Since the the lengths of the E_{XZ} vectors were often noticeably changed by the lightning flashes while their directions were but little affected it appears that the flashes repeatedly depleted charge overhead (lightning flashes labeled **d**, **e**, **f**, **i**, **j** and **k**). Between the flashes the lengths of the E_{XZ} vectors steadily increased, indicating that the charge was actively growing between flashes. E_X, E_Y and E_Z for this flight segment are shown in Figure 80. Until the beginning of the turn (just after flash **l**) E_Y and E_Z grew linearly between flashes, indicating that the charge overhead was growing linearly (the curvature in E_X between flashes is due to the high sensitivity of this component of the electric field to the change in airplane position).

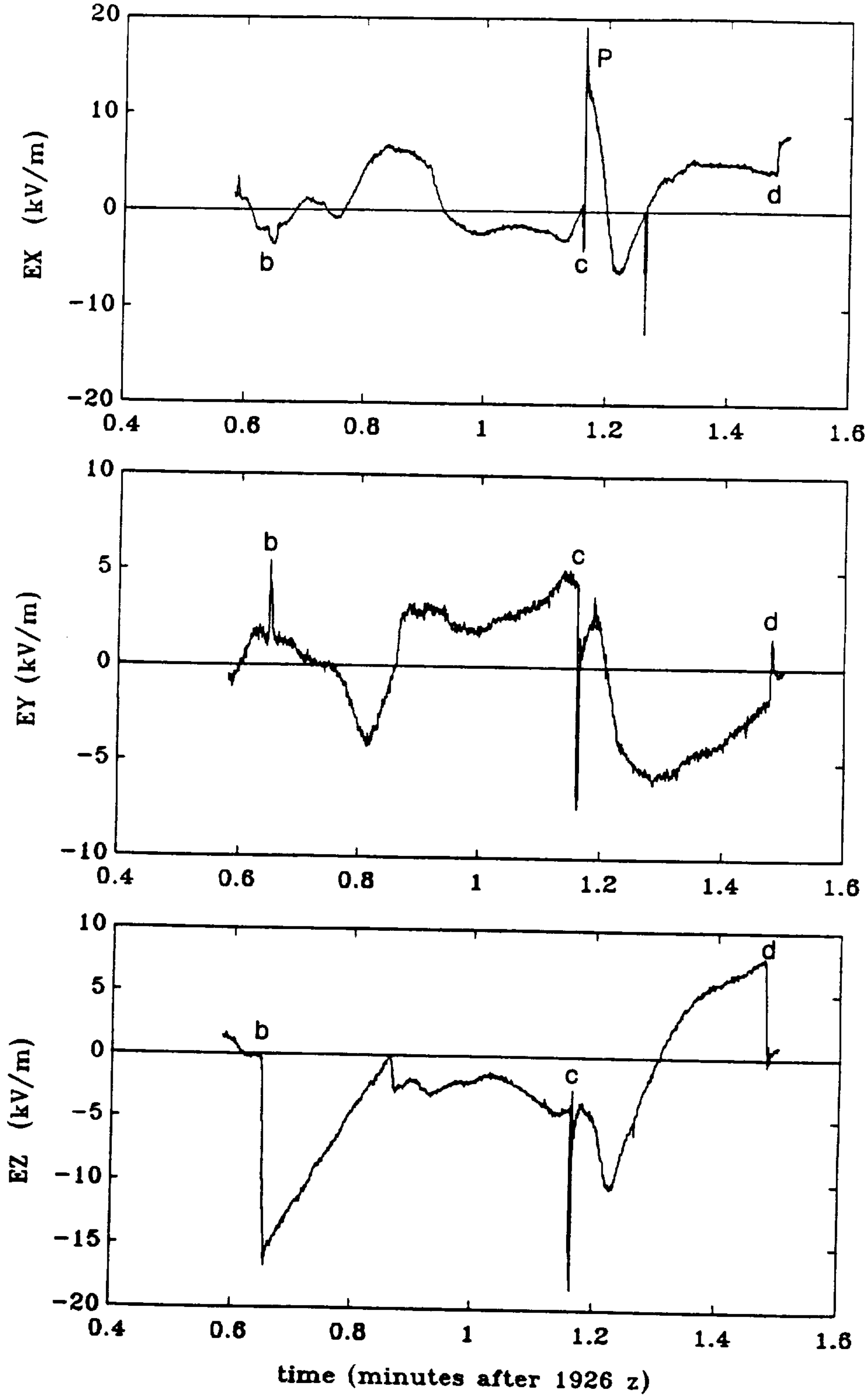


Figure 78: Low sensitivity E_X, E_Y and E_Z for 1926:35 to 1927:30 Z on 18 August 1989.

Both before and after this time the pilot reported the existence of anvil and other layered clouds associated with the rapidly growing cumulus over Merritt Island. The 1931–1934 Z data appear to indicate an active and vigorous growth of negative charge in overhead clouds at a time when SPTVAR was flying in clear air. Since the cloud overhead may have been an anvil, this is an unexpected electrification scenario. Note, however, that the cloud overhead was closely associated with at least some of the clouds over Merritt Island and may actually have been the upper portion of the cloud penetrated from 1930:33 to 1931:10 Z. The linearity of the charge growth, as in the 1918–1921 Z time interval, is again an interesting result.

A verification of the correctness of some of the calibration coefficients for $\vec{E}$ is provided by the next two-minute interval during this flight. Figure 81 shows the E_{NE} plot for the time interval 1934–1936 Z. The constancy of both the length and direction of the E_{NE} vector in the GCS for the straight-line flight between lightning flashes at **a** and **b** indicates that SPTVAR was at a large distance from the charge responsible for the measured electric field, since if a charge is at a large distance the direction of E_{NE} should not change very much over a short distance. After the flash labeled **b**, E_{NE} was constant in both magnitude and direction before, during and after the 90° turn shown. Since such a turn mixes all three components of the electric field, this example indicates that the ratios between the calibration coefficients for the three components of $\vec{E}$ as measured in the airplane coordinate system have been well determined.

During the later part of this flight, at 1941:06 Z, lightning was triggered by a rocket fired from the rocket-triggered-lightning site on the west shore of the south end of Mosquito Lagoon. At that time SPTVAR was about 3 km southeast of the rocket site and recorded the effects of a lightning flash on $\vec{E}$. This flash reversed both the X and Y components of $\vec{E}$ and changed the Z component from +8.5 to −6 kV/m. These changes are clearly shown at **A** in the E_{NE} plot for the time interval 1939–1951 Z and the E_{XZ} plot for the northbound half of this time interval shown in Fig. 82. In both plots the two-dimensional vectors just before and after the flash are antiparallel, so that they point in the exactly opposite direction just after the flash. This indicates that just prior to the flash these vectors were pointing directly toward charge that was removed from the cloud by the flash. The plot of E_{NE} vectors indicates that the affected charge was on a line passing about 1.5 km south of the rocket-triggered-lightning site, while the plot of E_{XZ} vectors indicates that it was at about 5 km above SPTVAR, or at an altitude of approximately 29,000 ft (8.7 km) where the temperature was less than −20 °C. From the changes in the electric field components and the estimated position of the affected charge we estimate that the lightning removed about −60 coulombs of charge from the cloud.

About one minute after the prominent flash triggered by the rocket, the plot of E_{XZ} vectors indicates that SPTVAR passed negative charge about 7,000 ft (2.5 km) above its altitude. Although the horizontal position of the charge is not so clearly shown by the E_{NE} vectors

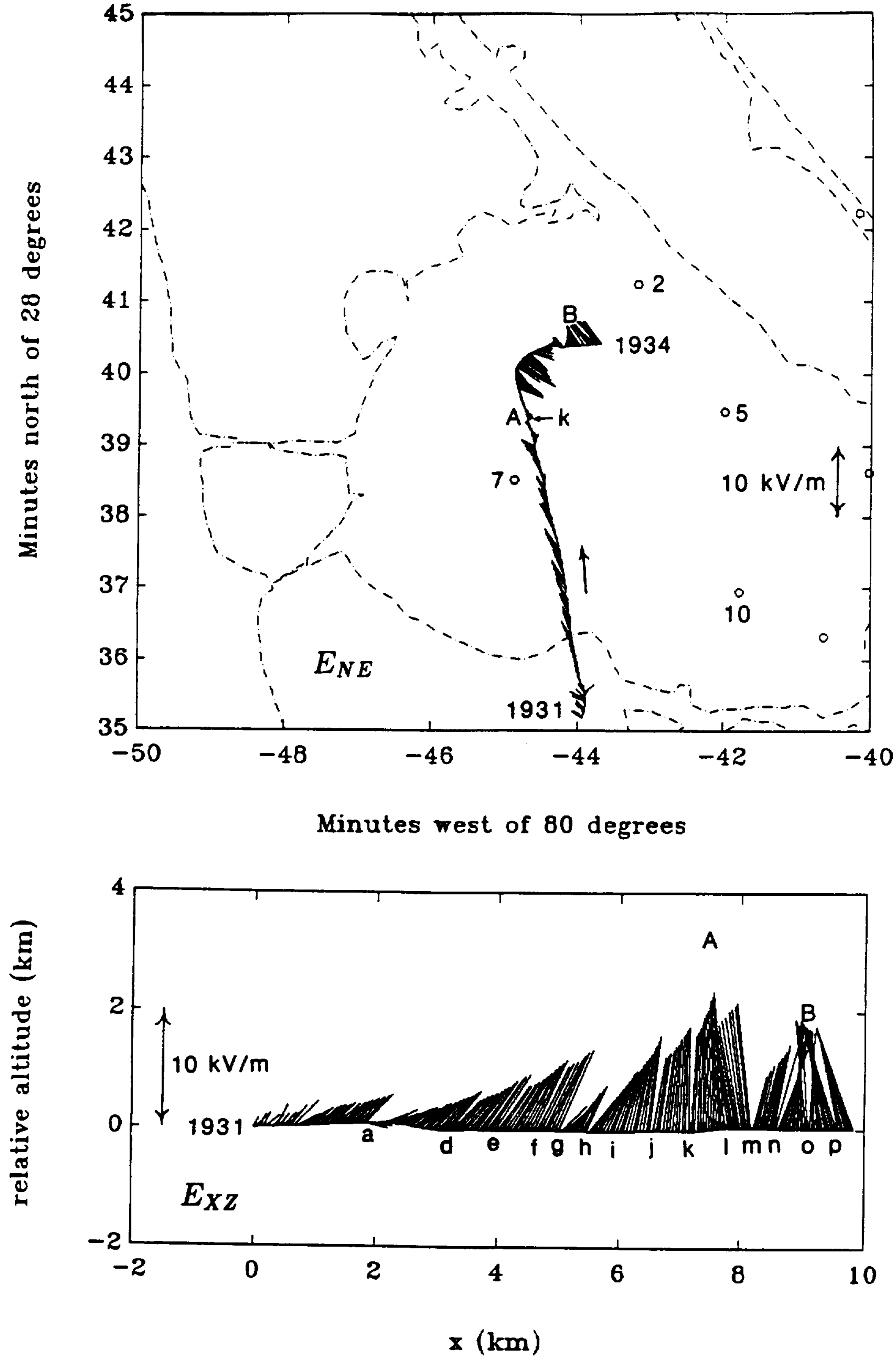


Figure 79: E_{NE} vectors plotted along the SPTVAR flight track (upper panel) and E_{XZ} plotted along the SPTVAR altitude profile (lower panel) from 1931 to 1934 Z on 18 August 1989. Times of lightning flashes are indicated by the letters a through p. The location of positive charge overhead is indicated by the letter A, while that of positive charge left of the track is indicated by the letter B.

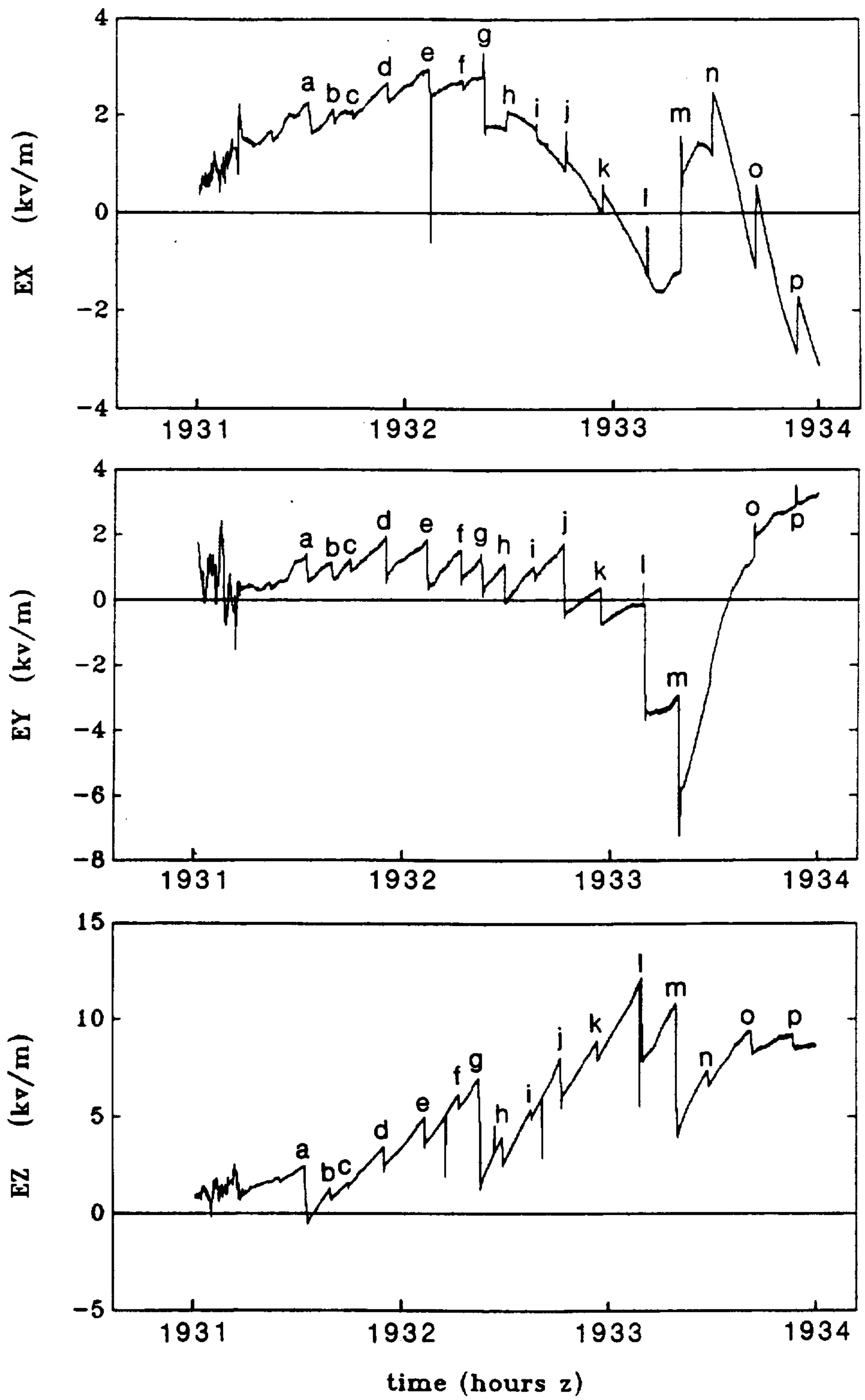


Figure 80: Plots of E_X, E_Y and E_Z for 1931 to 1934 Z on 18 August 1989.

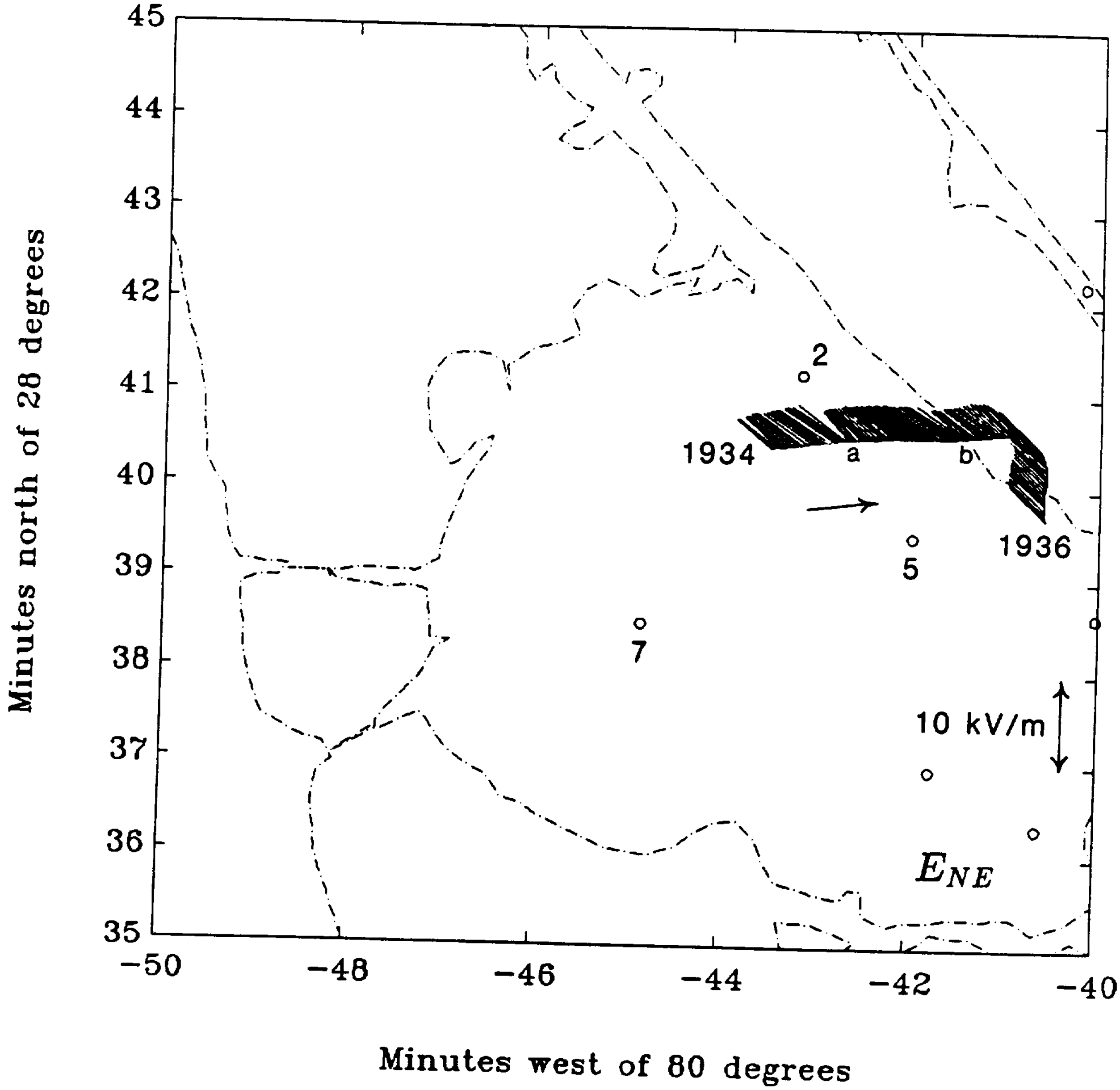


Figure 81: E_{NE} vectors plotted along the SPTVAR flight track from 1934 to 1936 Z on 18 August 1989.

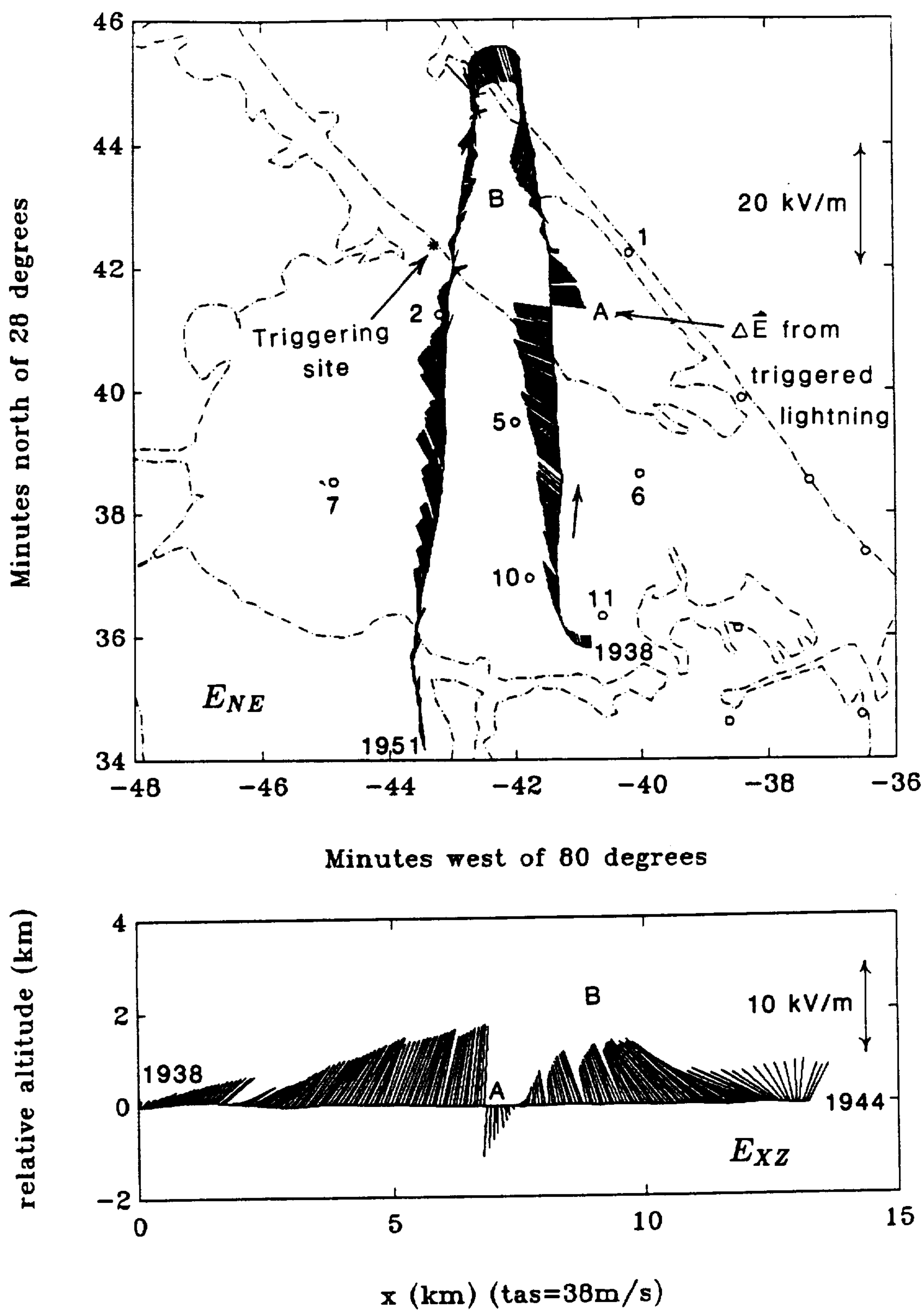


Figure 82: E_{NE} vectors plotted along the SPTVAR flight track from 1938 to 1951 Z (upper panel) and E_{XZ} vectors along the altitude profile from 1938 to 1944 Z (lower panel) on 18 August 1989.

it appears to have been over Mosquito Lagoon between SPTVAR and the rocket site at the approximate position indicated by **B**. As this figure shows, SPTVAR then turned around toward the west and flew south almost over the rocket site. During this southbound flight segment SPTVAR recorded at least 33 lightning signatures. The E_{XZ} plot for this flight segment is shown in Fig. 83 and indicates that SPTVAR passed below a negative charge at the point labeled **C**. The altitude of the charge with respect to SPTVAR is about the same as in the northbound pass, and Fig. 82 is compatible with the charge having about the same horizontal position labeled **B** as the charge detected on the northbound pass. For the remainder of the time shown, both figures indicate negative charge above and to the northwest of SPTVAR.

A video tape made by Vince Idone (The State University of New York at Albany) on 18 August 1989 shows a rocket-triggered flash at 1941:05.9 Z. This was a "classical" grounded rocket launch from the "water pad," 70 m from the shore of Mosquito Lagoon. At the time this rocket was launched the electric field measured over land was -7 kV/m, while that over water was -29 kV/m. Data collected by a group led by Andre Eybert-Berard of the Centre d'Etudes Nucleaires de Grenoble, France, identified six strokes in this flash. Some characteristics of the flash, measured by the French, are shown in Table 3.

Table 3: Characteristics of triggered lightning flash at 1941:06 Z on 18 August 1989.

Stroke	Max Current (kA)	Max dI/dt (kA/μ sec)
1	23	103
2	6	28
3	15	47
4	31	37
5	10	50
6	23	72

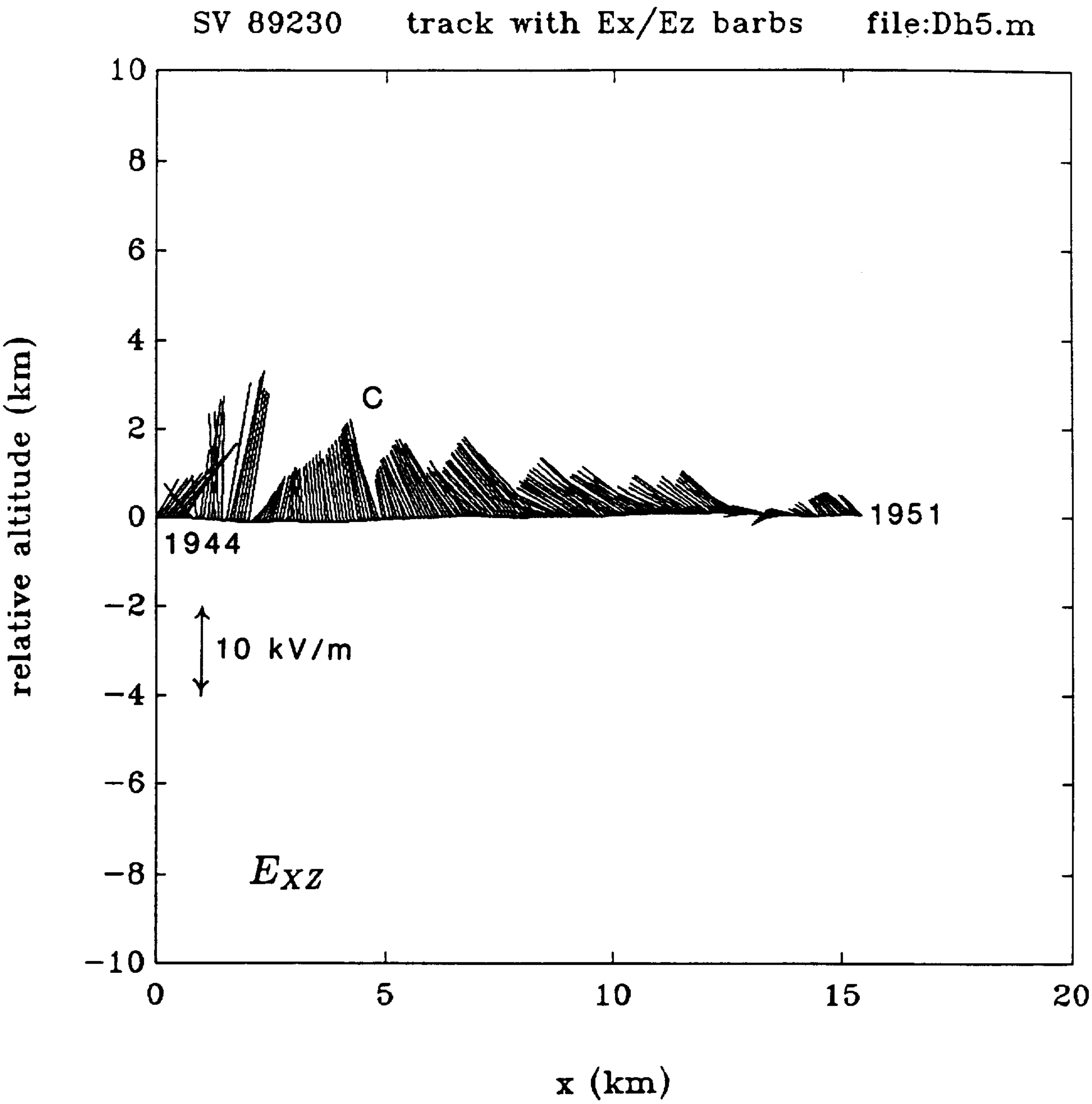


Figure 83: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1944 to 1951 Z on 18 August 1989.

A.3.6 Summary: 19 August 1989 (89231)

Highlights:

- SPTVAR studied the initial electrification and life story of a cloud that electrified over mill 20 but never made lightning.
- Various launch commit criteria weather rules would not have permitted a launch through or near this cloud.
- We develop a quantity for evaluating the reliability of SPTVAR measurement of $\vec{E}$ in the presence of severe airplane charging.
- A real-time display of SPTVAR's path with electric field barbs was used to guide the airplane toward a region of cloud charge.
- E_Z measured by SPTVAR did not agree with that measured by mills suspended from a balloon at the triggered-lightning site.

A long wave trough at 200 mb dominated the eastern seaboard, extending from Indiana into the Gulf of Mexico. The trough was present in the form of a cut-off low over Indiana. The influence at 500 mb was evident into northern Florida. Below 500 mb, central and south Florida were under a typical tropical pattern, moist and barotropic. With easterly flow, the best activity was expected early, before mid-afternoon. Activity was present during the early morning hours, but cleared up around 1200 Z.

The 1200 Z West Palm Beach and Tampa, Florida, soundings for this day are shown in Fig. 84.

There were rain showers along the coast about 1300 Z the morning of this flight. At about 1645 Z a cloud a short distance offshore from PAFB grew rapidly, broke up, and was followed by new growth in the same air mass. The plan for the day was to study and monitor clouds moving onshore from the south-southeast in a region of cloudy air. After take-off at 1553 Z, the SPTVAR pilot reported a cloud over the Port Canaveral area and another one farther to the west. The cloud over the Port was developing into a series of three clouds extending north-northwest from the Port to over the west end of the NASA causeway. The decision to study these clouds resulted in SPTVAR being able to record the onset of electrification in the northernmost cell. The SPTVAR flight track with E_{XY} vectors drawn at intervals along it is shown in Fig. 85.

Initial electrification of small marginal cloud over KSC Headquarters.

Beginning at 1610 Z, SPTVAR flew around the northern cell in a counterclockwise direction. On the second circuit a weak electric field was detected at the north side of the

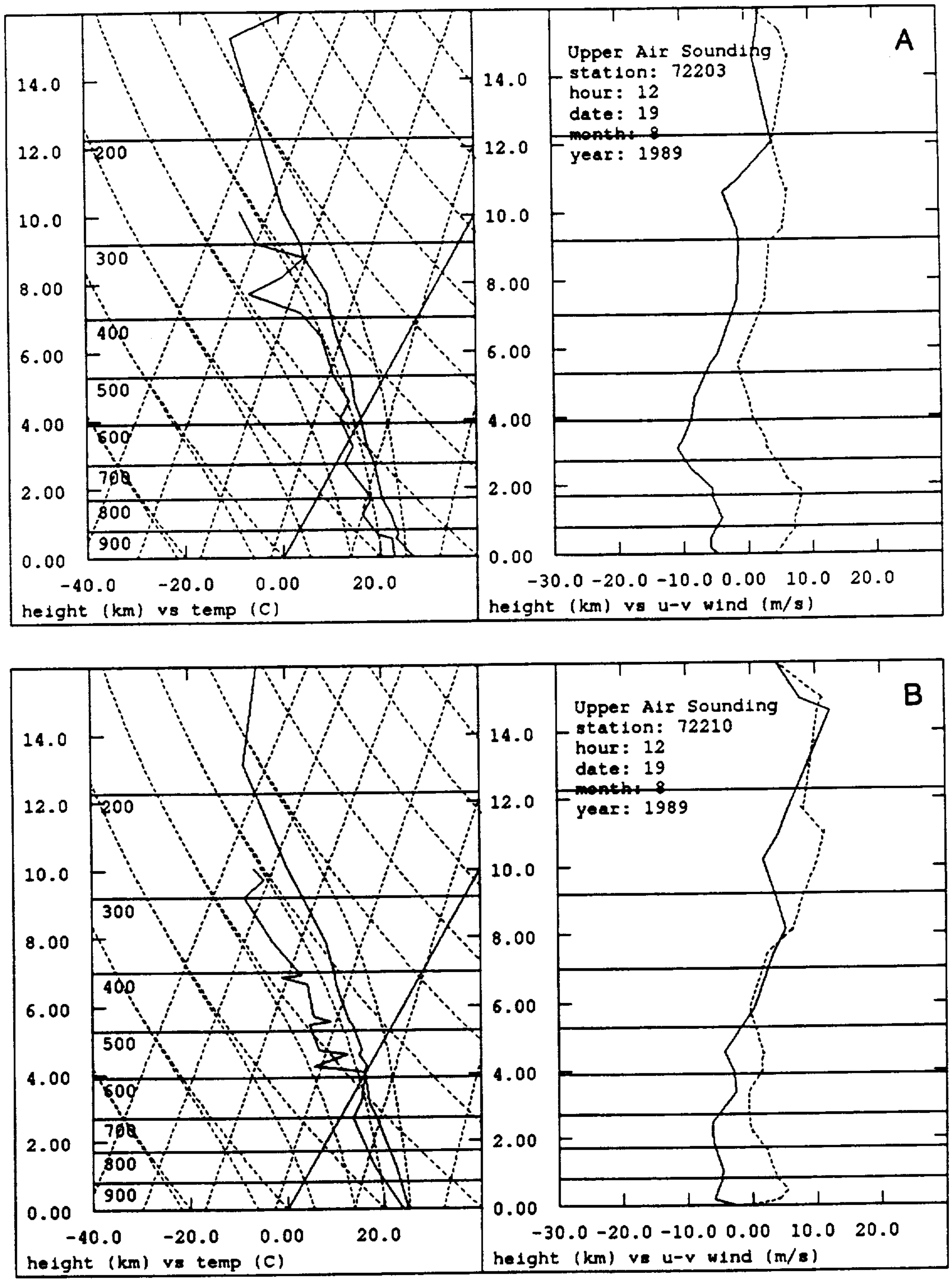


Figure 84: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 19 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, **u**, is the solid line and the north component, **v**, is the dashed line.

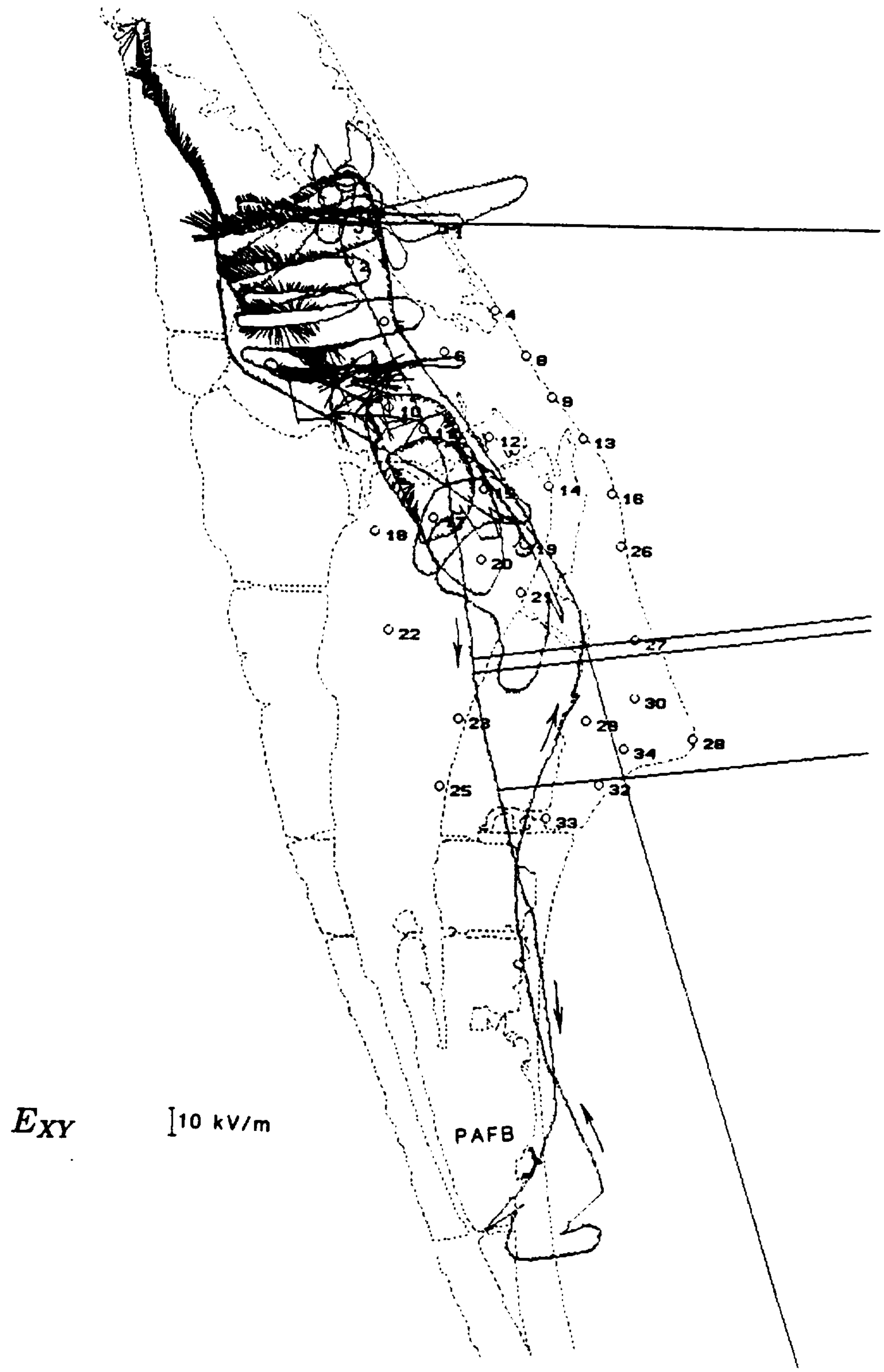


Figure 85: PC plot of E_{XY} vectors along the SPTVAR flight track of 19 August 1989. The five spurious spikes resulted from radio interference on the telemetry frequency.

cell. The best field was at the north-northwest side of the cloud (almost directly over KSC mill 17) and just in front of the cloud in the direction in which the cloud was moving. SPTVAR turned back across the north side of the cloud and upon reaching its east side turned back again (near KSC mill 19) and flew once again across the north side of the cloud, this time continuing on a counterclockwise circumnavigation of the cell. The development of the electric field as measured by SPTVAR during this time interval, 1610–1648 Z, is shown by the E_{NE} plots in Figs. 86 through 91. These figures, made using a Sun Workstation, show more detail than the real-time E_{XY} plots produced by the PC and better indicate the rapidly growing negative charge in the northwest side of the cloud. The growth of the cloud's electric field as measured by SPTVAR is summarized by the plot of the magnitude of $\vec{E}$ vs. time in Fig. 92.

The growth of this cloud's electric field as measured by SPTVAR may be compared to that measured by the KSC field mill array on the earth's surface. Figure 93 reproduces the strip-chart recordings for mills 20, 17, 10 and 7, while Figs. 94 to 97 show the ∇V contour plots for 1624 to 1745 Z. The initial growth of the electric field was over mill 20, which first measured a positive ∇V at about 1624 Z. The first contour plot display to show the presence of a negative charge overhead was the one for 1626 Z shown in Fig. 94. The five previous ones, 1610–1624 Z, were blank. Note that both SPTVAR and the KSC field mills first detected the electrification of this cloud at the same time, and that the contour plot display indicated its presence just two minutes later. Note also that the SPTVAR measurements, unlike those of the surface field mill array, clearly show an exponential-like intensification of the maximum measured electric field over a time span of 25 minutes.

As the cloud's electrification evolved it moved toward the north-northwest and passed over mills 17, 10 and then 7. This motion of the cloud and its spatial development are illustrated in Fig. 98 which shows the outline of 5 dBZ or greater radar reflectivity in the 5.8° elevation scan of the McGill radar, superimposed over a map of KSC, for four times during the study of the cloud. At 1620 Z, just before the cloud began to electrify, it was over mills 20 and 21. By 1640 Z, as the cloud's electrification was well underway, the cloud had grown in area and extended from over mill 20 to almost over mill 10 (see also Fig. 90). At 1655 Z the original cloud extended from over mill 17 to almost over mill 7, and was becoming merged with a new cloud growing just west of mill 18. There were also two other clouds growing nearby, one just northwest of the small cloud merging with the southwest corner of the original cloud and another one farther to the north-northeast. Fifteen minutes later, at 1710 Z, all four clouds had merged into a single cloud mass.

Severe electrical charging experienced by aircraft in precipitation from cloud.

After 1648 Z SPTVAR continued to study this cloud, and from 1651 to 1701 Z experienced four episodes of severe electrical charging. In each case SPTVAR first experienced very strong negative charging followed by very strong positive charging. The periods of charging were well defined, with sudden onset of the initial negative charging and abrupt termination

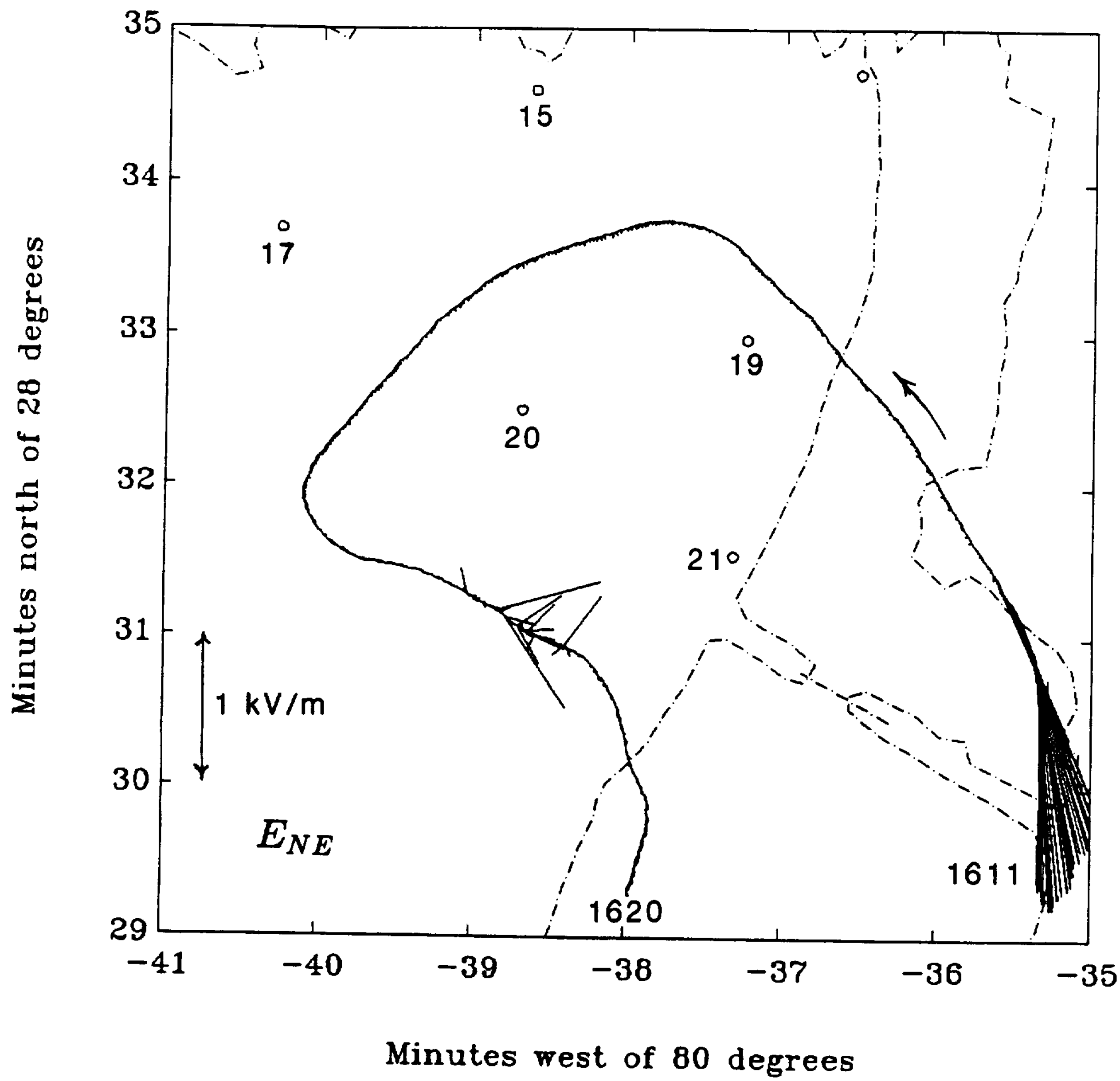


Figure 86: E_{NE} vectors plotted along the SPTVAR flight track from 1611 to 1620 Z on 19 August 1989. The vectors drawn along the track at the start represent the electric field of charge released from the airplane while it was being artificially charged.

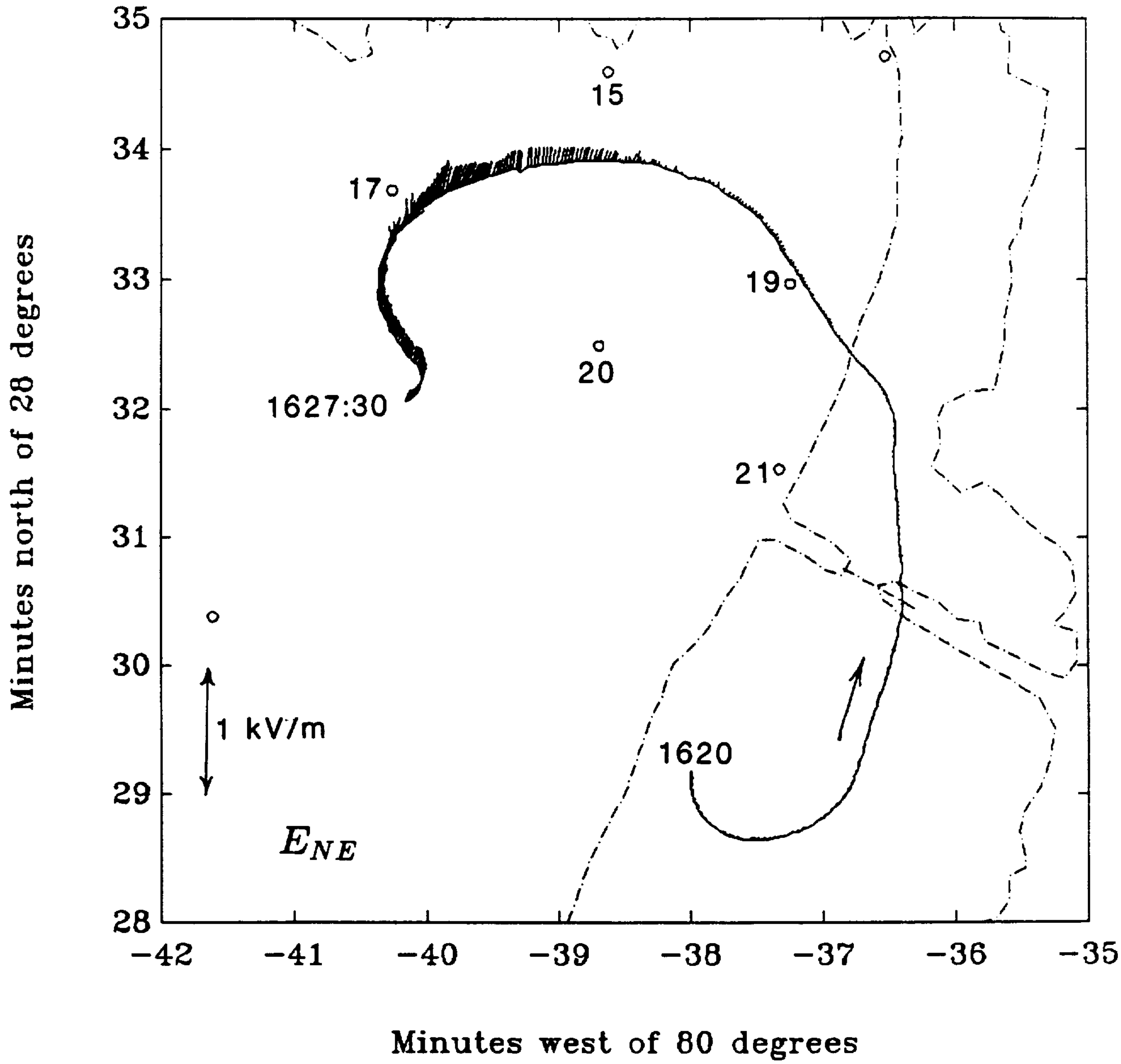


Figure 87: E_{NE} vectors plotted along the SPTVAR flight track from 1620 to 1627:30 Z on 19 August 1989.

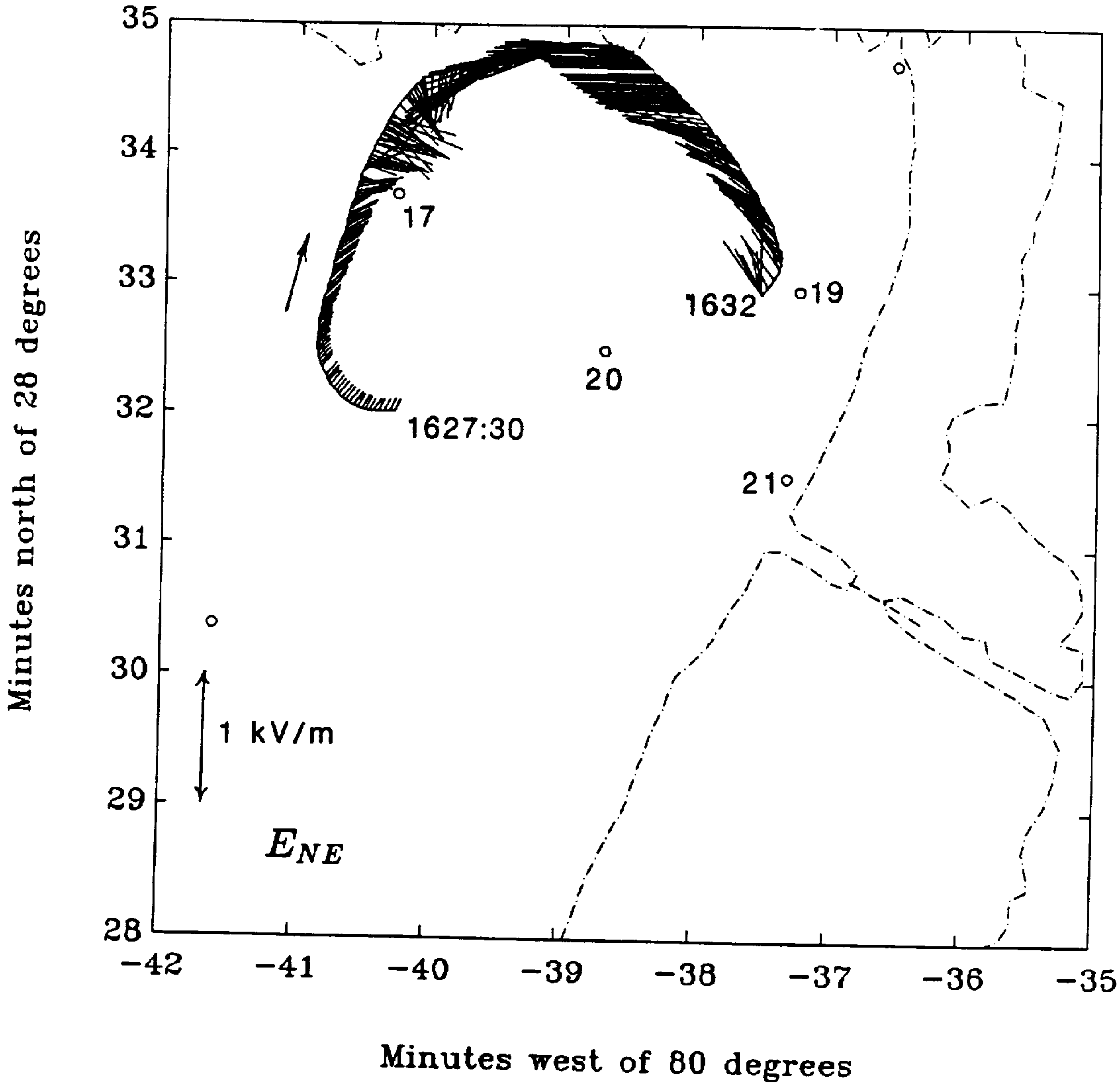


Figure 88: E_{NE} vectors plotted along the SPTVAR flight track from 1627:30 to 1632 Z on 19 August 1989.

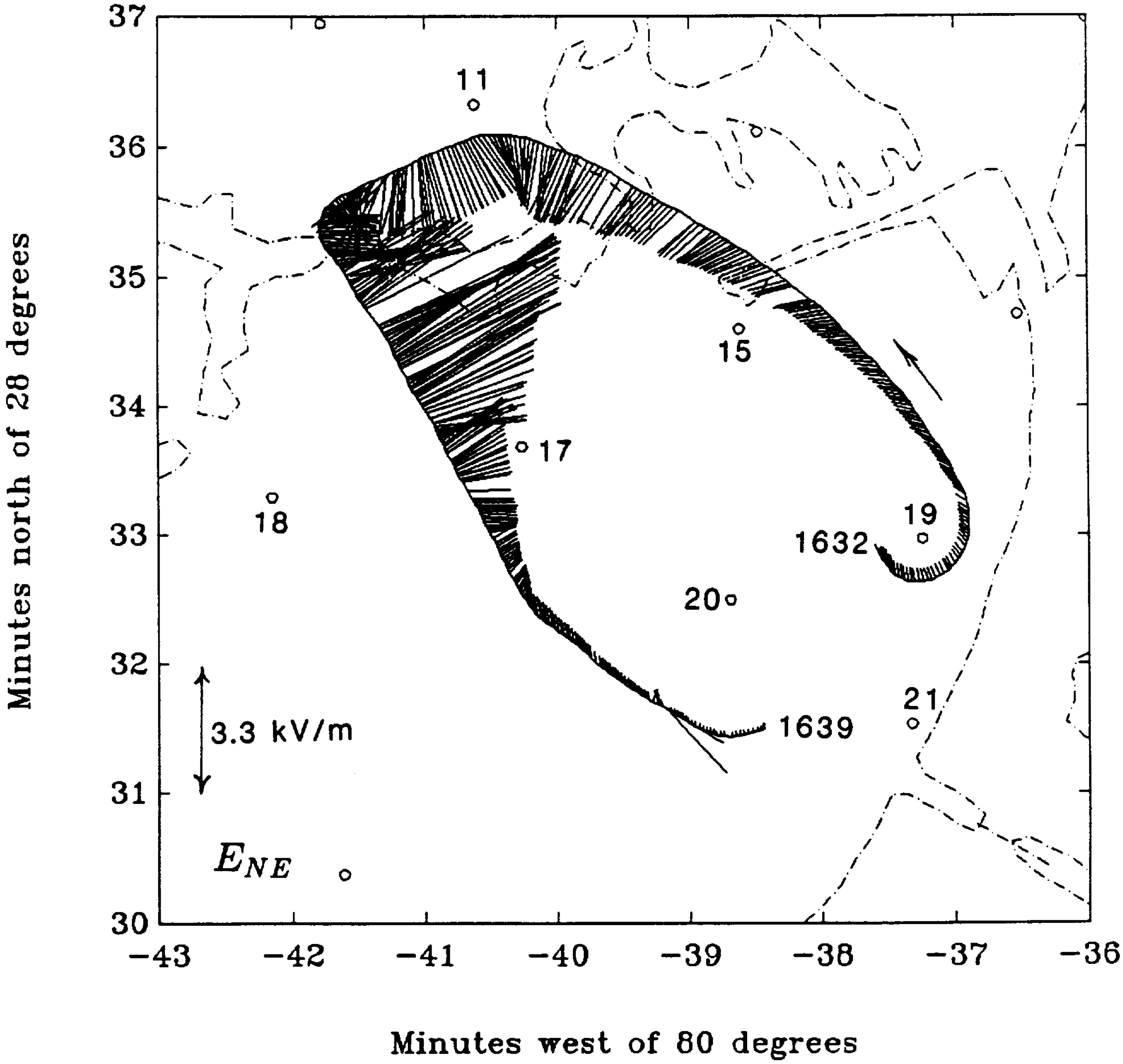


Figure 89: E_{NE} vectors plotted along the SPTVAR flight track from 1632 to 1639 Z on 19 August 1989.

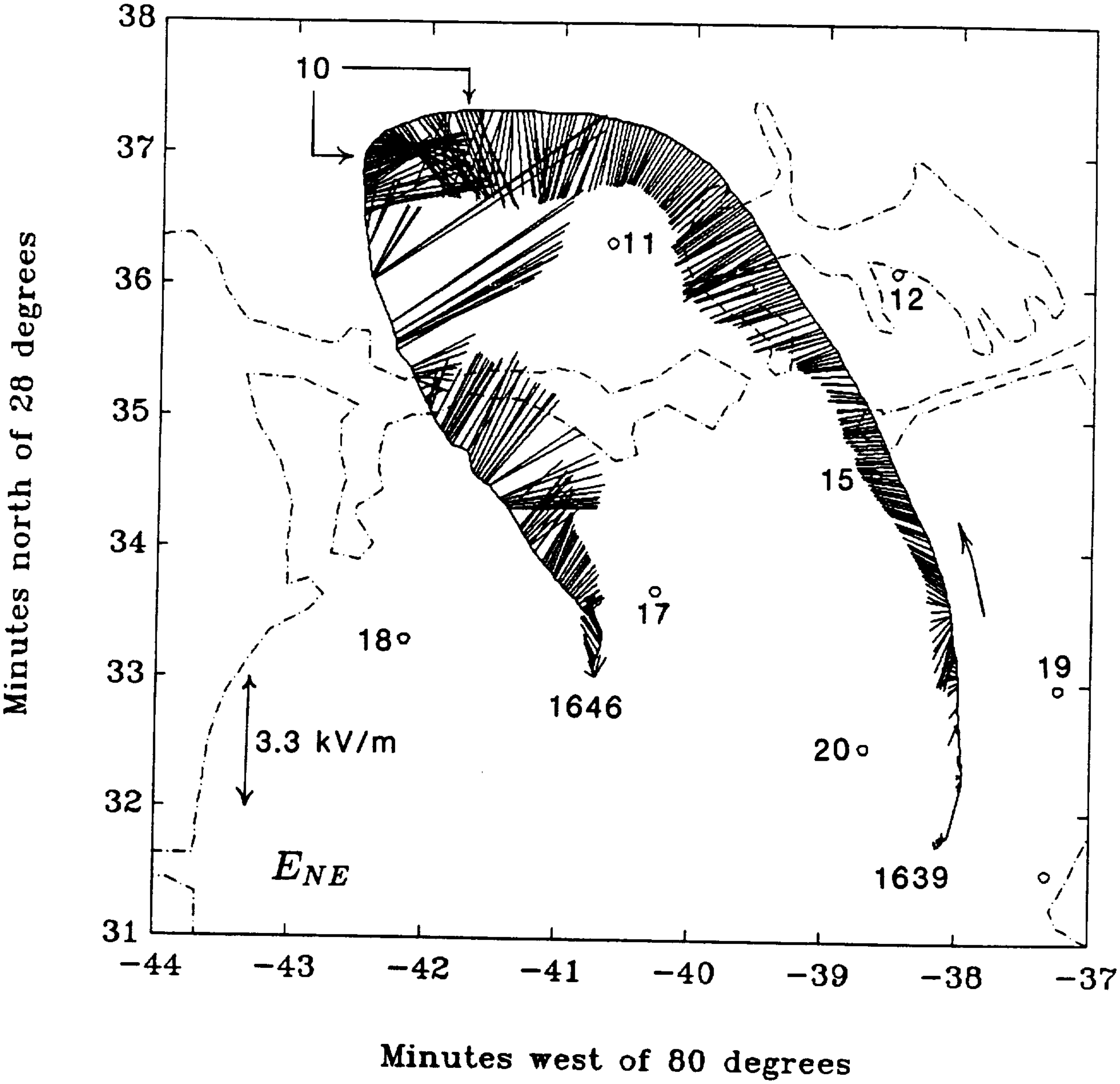


Figure 90: E_{NE} vectors plotted along the SPTVAR flight track from 1939 to 1646 Z on 19 August 1989.

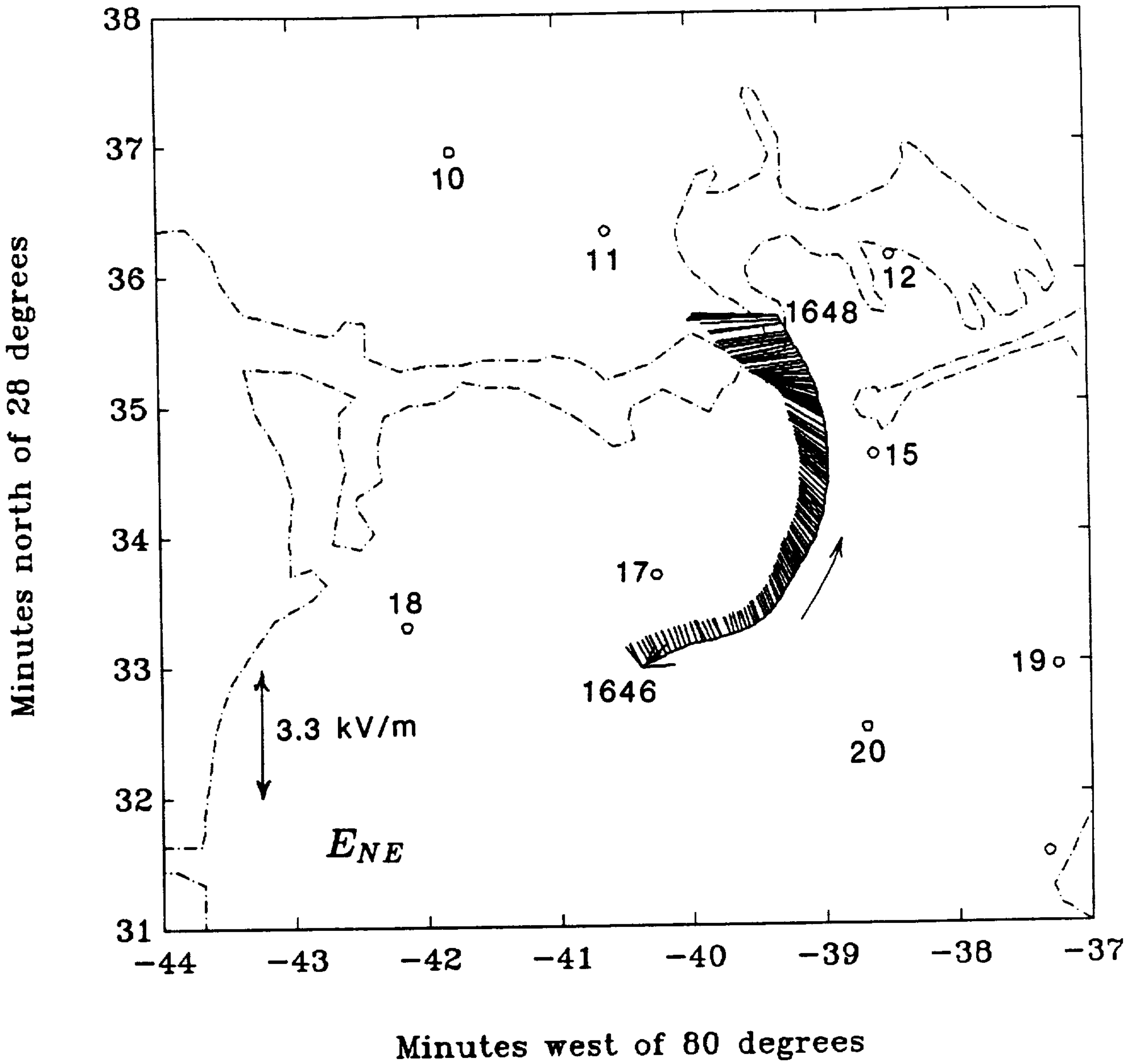


Figure 91: E_{NE} vectors plotted along the SPTVAR flight track from 1946 to 1648 Z on 19 August 1989.

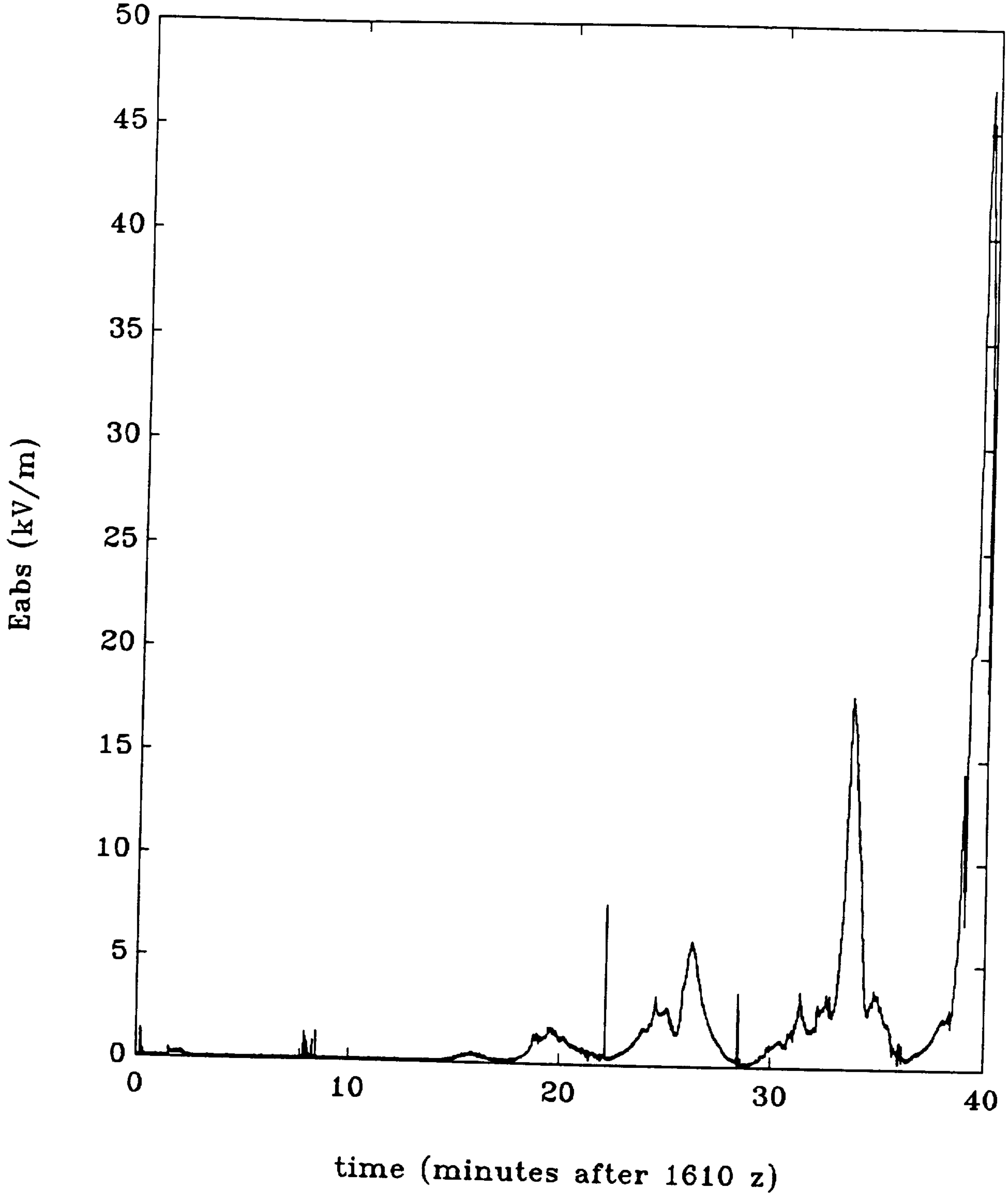


Figure 92: Magnitude of $\vec{E}$ measured by SPTVAR for 1610 to 1648 Z on 19 August 1989.

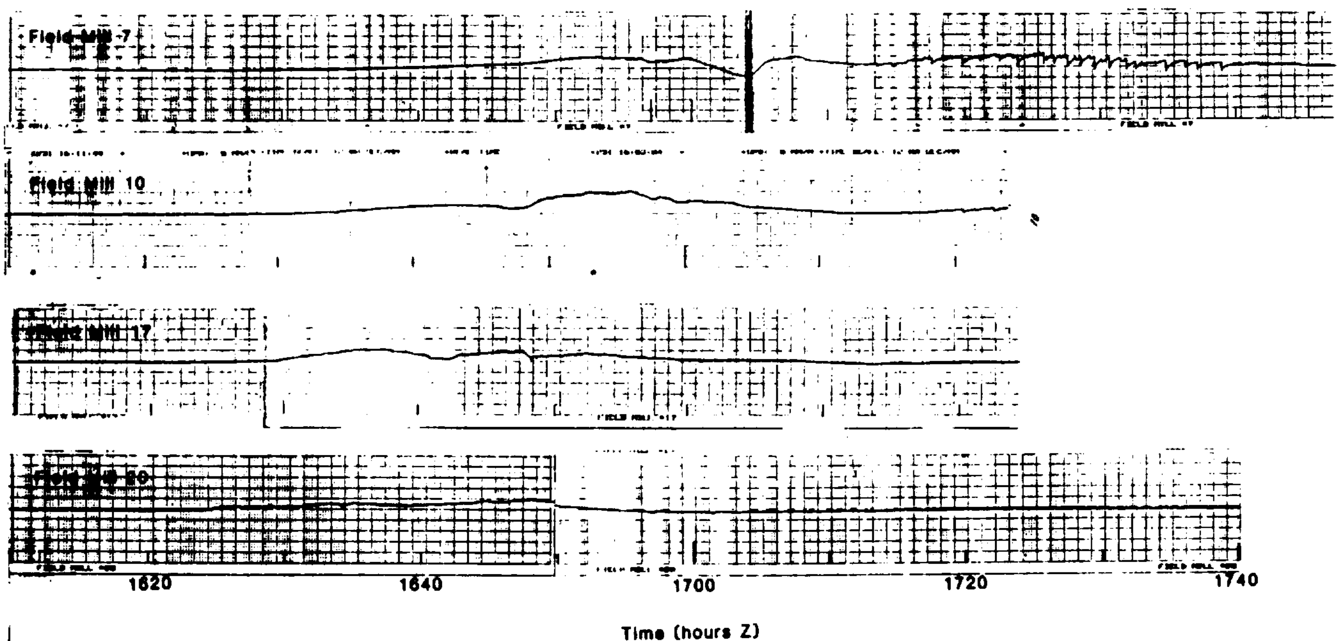


Figure 93: Strip chart recordings for mills 7, 10, 17 and 20 on 19 August 1989, showing the development of negative charge in a cloud above mill 20 and its subsequent motion to the north-northeast over mills 17, 10 and 7.

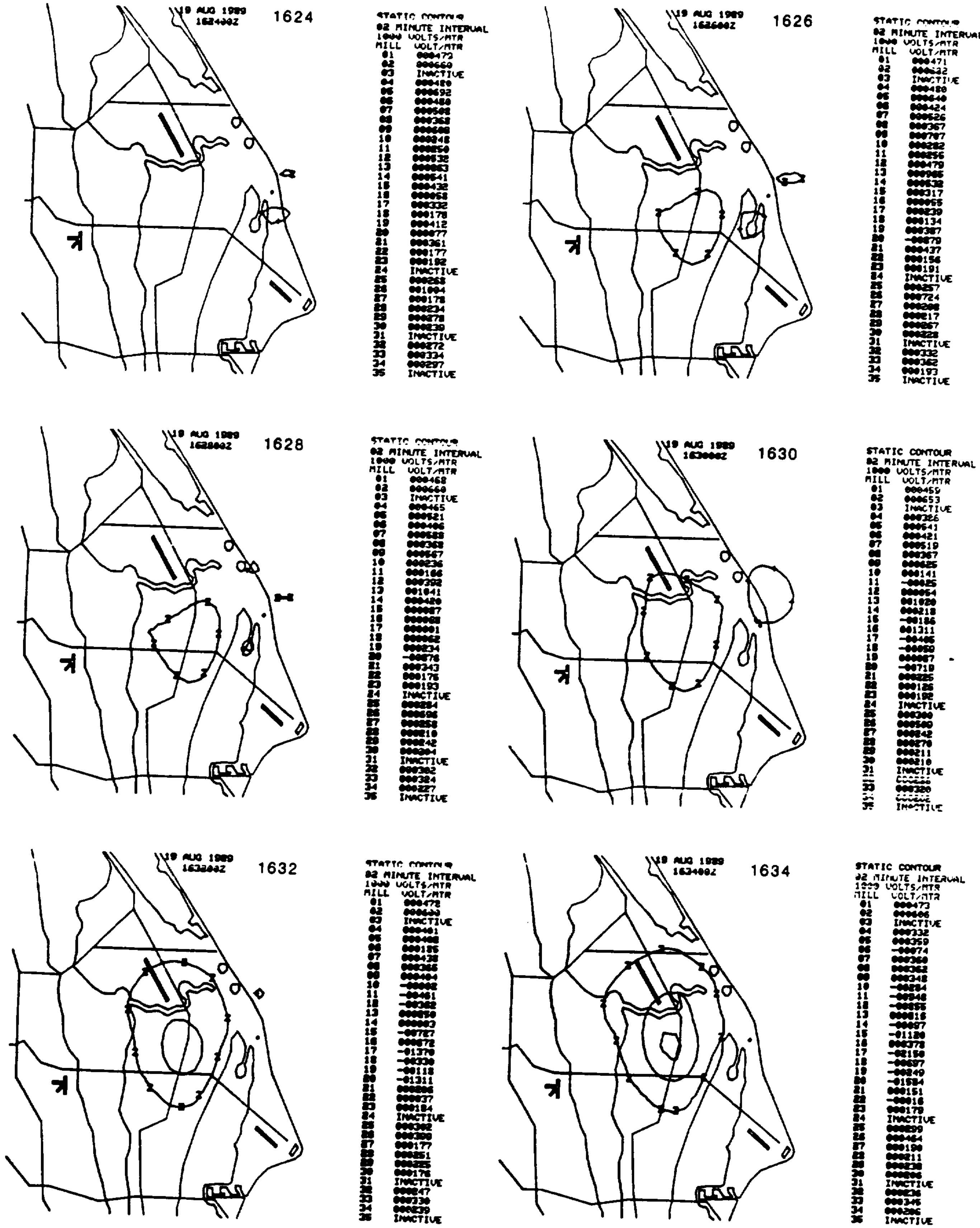


Figure 94: KSC surface ∇V contour plots for 1624 to 1634 Z on 19 August 1989.

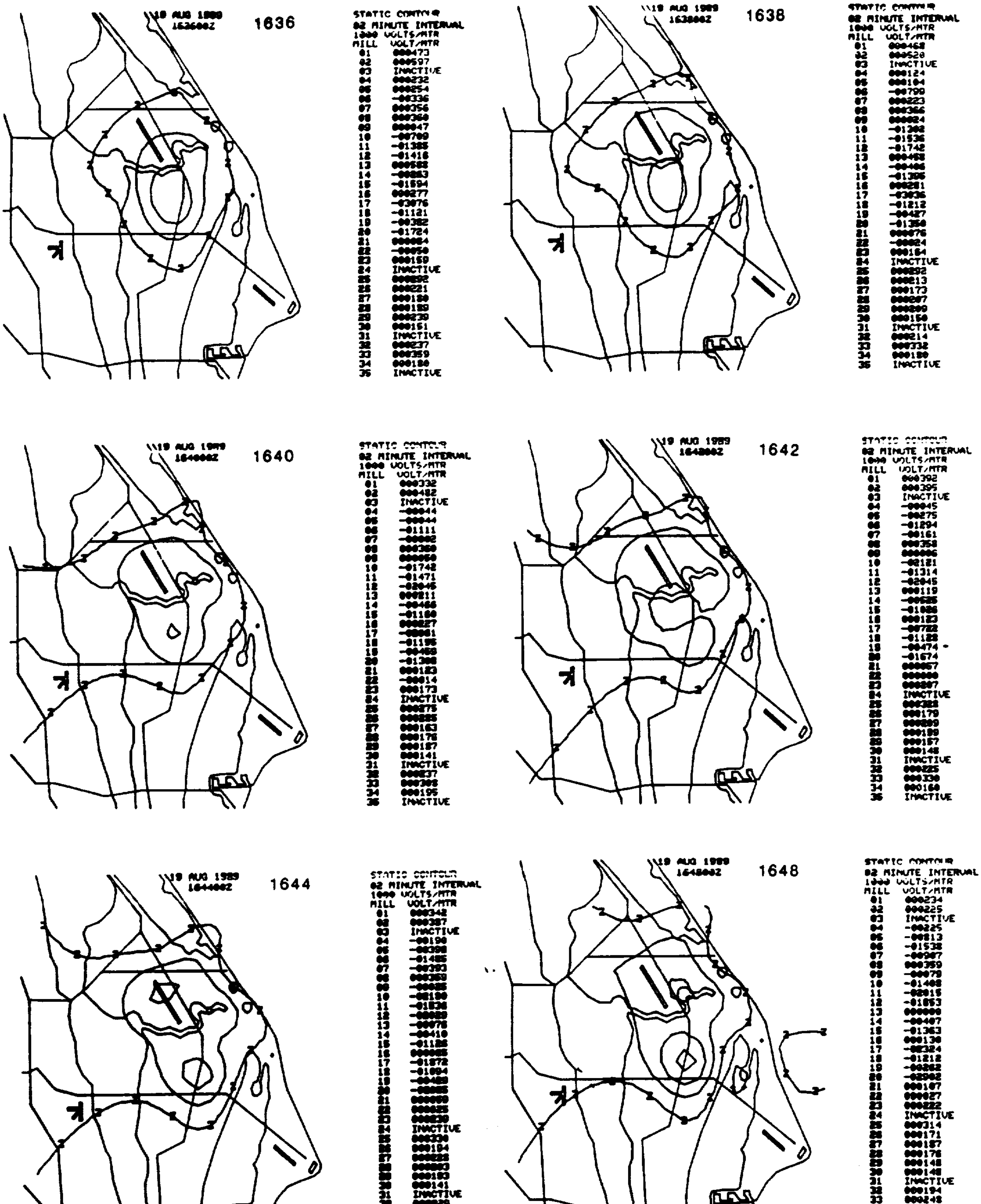


Figure 95: KSC surface ∇V contour plots for 1636 to 1648 Z on 19 August 1989.

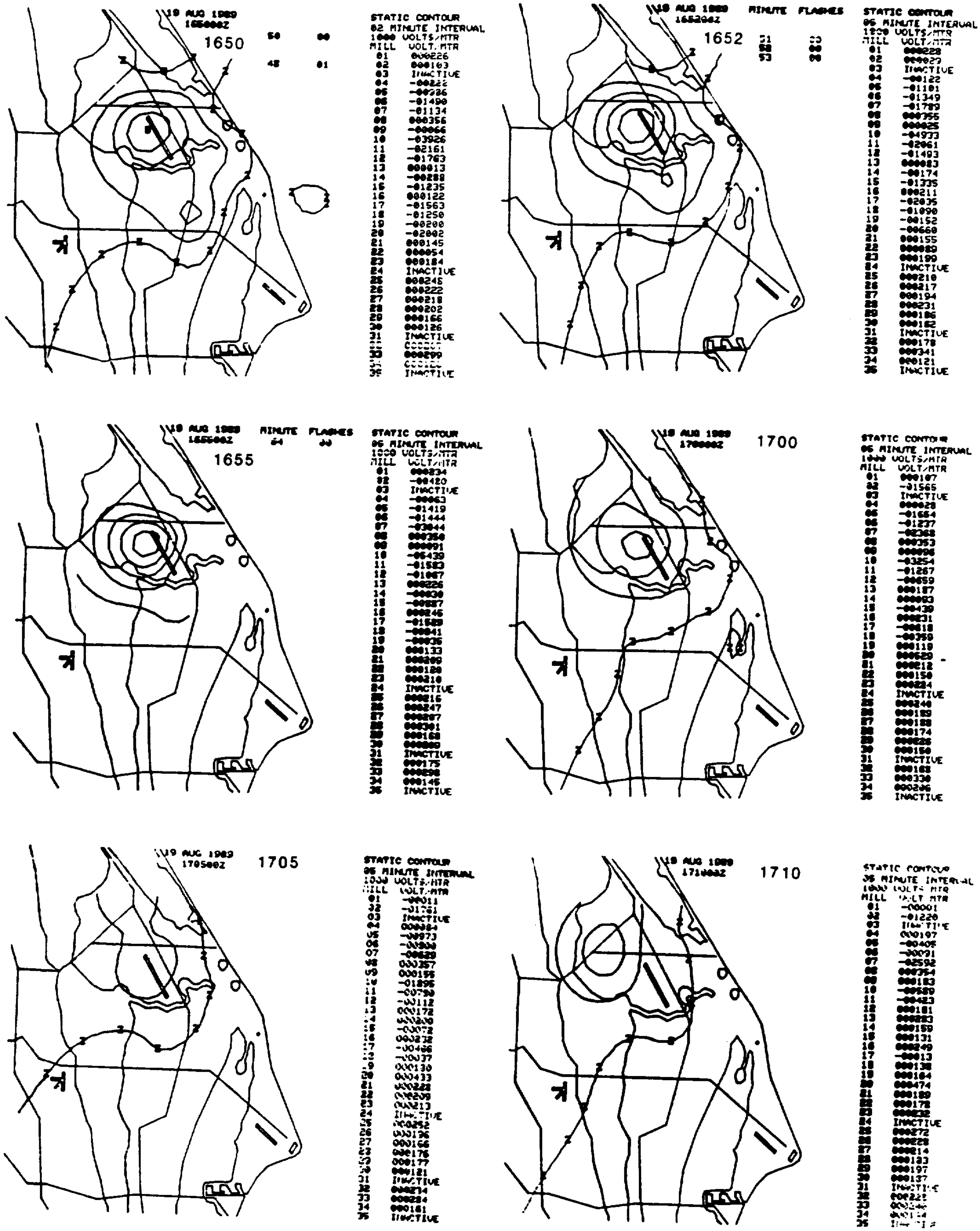


Figure 96: KSC surface ∇V contour plots for 1650 to 1710 Z on 19 August 1989.

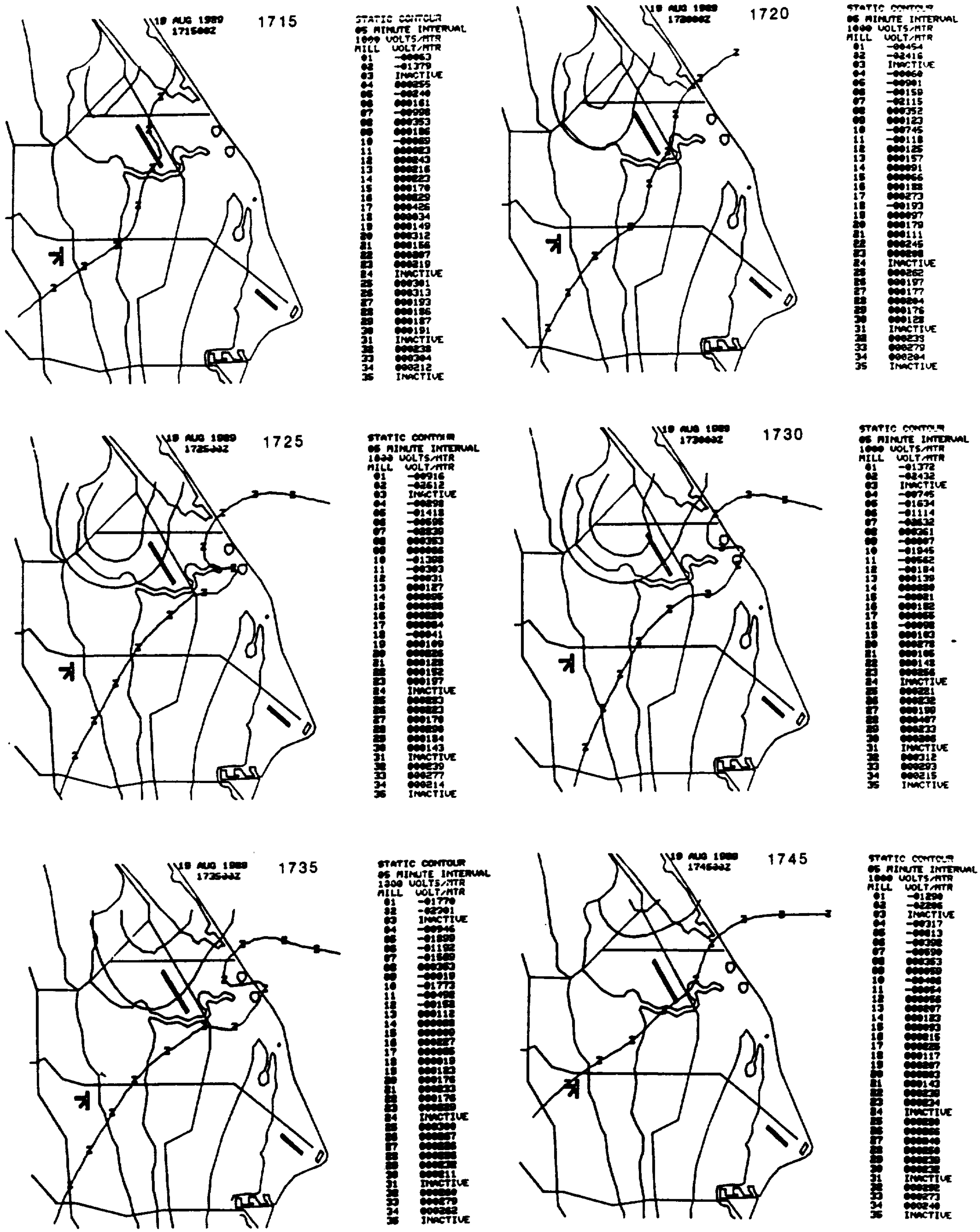


Figure 97: KSC surface ∇V contour plots for 1715 to 1745 Z on 19 August 1989.

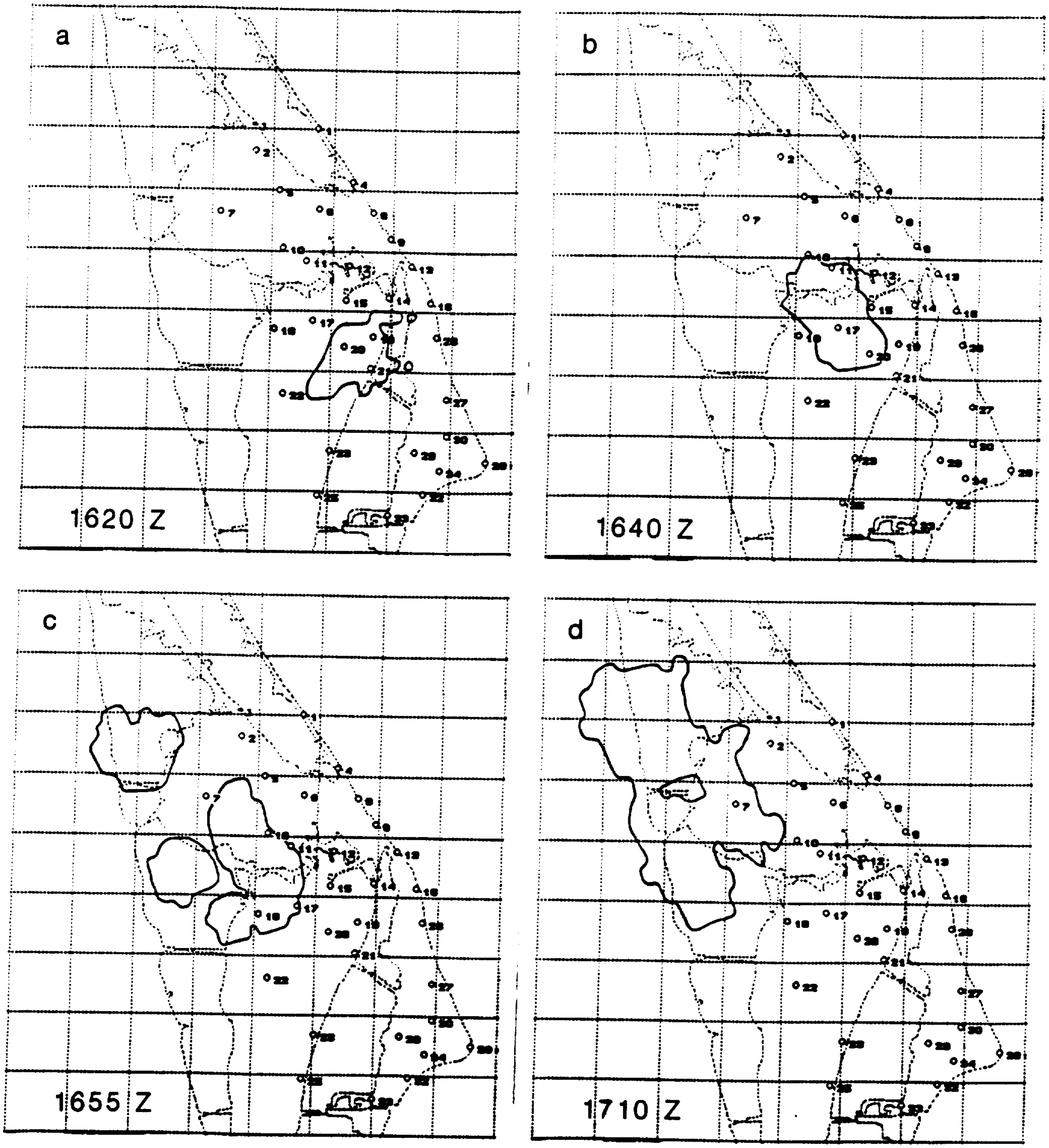


Figure 98: Outlines of 5 dBZ or greater radar reflectivity in the 5.8° elevation scans of the McGill radar at 1620, 1640, 1655 and 1710 Z on 19 August 1989.

of the subsequent positive charging. The third incidence of this severe charging, between 1654 and 1657 Z, is the clearest example of the phenomenon. Plots of E_X and "E_Q" (the average of the electric field, due to the charge on the airplane, at the faces of the top and bottom mills) and E_A (the total electric field at the face of the aft mill) are shown in Fig. 99. Note, however, that both E_Q and E_A have been scaled to E_X using the same scale denominator used for determining E_X and thus the values indicated are much smaller than actual electric field values measured at the mill faces.

Note that the charge on SPTVAR was nearly zero from 1654 to 1655 Z (**A** to **B** in the figure) and from 1656.3 to 1657 Z (**E** to **F**). During these time intervals there should have been little or no release of charge from the airplane by corona processes and thus no plumes of charge in the air behind the airplane that could have corrupted the ambient electric field . This observation, coupled with the fact that the deduced E_X is significantly larger than E_Q, leads us to believe that the deduced electric field components are true representations of the ambient electric field of the cloud during these initial and final time periods in the figure.

The non-linear increase of E_X from zero to positive values between **A** and **B** is the behavior expected when an airplane is approaching a negative charge. Similarly, the non-linear decrease of E_X from negative values to zero between **E** and **F** is the behavior expected when an airplane is flying away from a negative charge. Similar behavior was seen on 18 August when SPTVAR flew toward an electrified cloud and then turned around and flew away from the cloud (Fig. 71). These observations form the basis for a model of the behavior of the SPTVAR measurement of the electric field during this and similar cases of severe airplane charging which are unlike any of the airplane charging scenarios discussed by Jones (1990). The model is developed from the data obtained during the time interval shown in Fig. 99.

The essence of the model is that SPTVAR, while in precipitation, flew through, or very near to, a region of negative electric charge in the cloud (the charge having resided precipitation drops since cloud LWC encountered by SPTVAR was very small or negligible) and was charged inductively as it collided with the precipitation drops. As SPTVAR approached the negative cloud charge both SPTVAR and the precipitation drops were electrically polarized by the strong positive E_X in the cloud. Each time that a leading surface of SPTVAR collided with a precipitation drop, the positive polarization charge on the leading surface of the airplane attracted the negative polarization charge on the side of the drop facing the airplane and repelled the positive charge on the far side of the drop. Consequently, positive charge was carried away in the splash from the airplane-drop collision, leaving negative charge on the airplane. As negative charge accumulated on SPTVAR this process eventually would have ceased when the negative field at the leading surfaces of the airplane due to the net negative charge on the airplane equaled the positive E_X in the cloud. However, as SPTVAR approached the charge in the cloud, we expect E_X to have increased

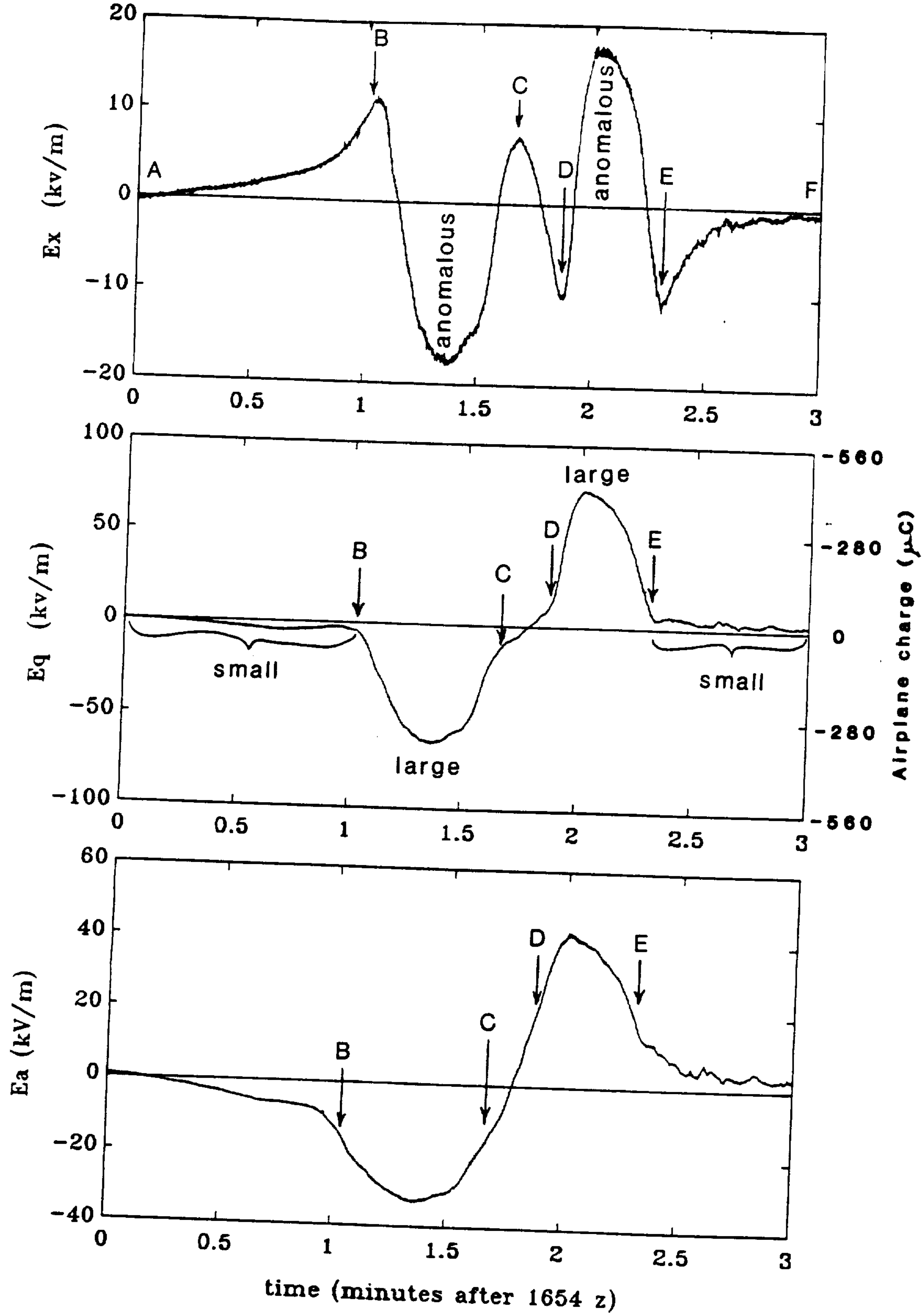
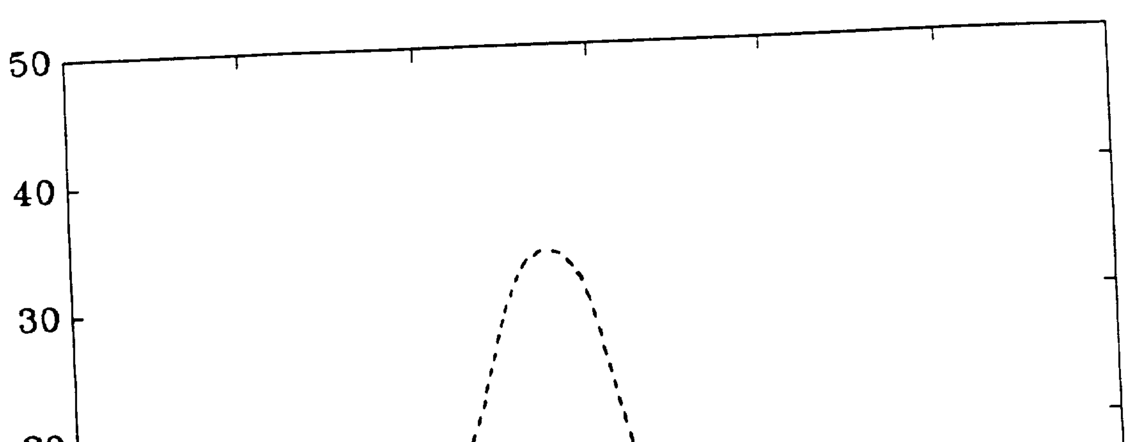


Figure 99: E_X, E_Q (the average of the electric field, due to charge on SPTVAR, at the top and bottom mill faces) and E_A (the field at the face of the aft mill) for 1654 to 1657 Z on 19 August 1989. Both E_Q and E_A are scaled to E_X. The labeled arrows delineate the times of onset or cessation of severe electrical charging experienced by SPTVAR.

approximately as $\simeq 1/r^2$ so that the E_X in the cloud continually exceeded the contribution to E_X at the leading surfaces due to airplane charge until E_X in the cloud began to fall off as SPTVAR began to pass through or past the cloud charge. Thus the SPTVAR charge was able to grow rapidly by induction charging as the airplane approached the cloud charge, so that the net charge acquired by the airplane was approximately proportional to the magnitude of E_X. Conversely, as SPTVAR flew away from the negative charge ($E_X < 0$), all charge polarities reversed and SPTVAR acquired a positive charge.

Another possibility is that when E_X was sufficiently strong and positive the enhanced field at trailing surfaces may have become large enough that corona developed. When E_X was positive the corona would have been negative, so that negative charge would have been removed from the airplane and the airplane would have become positively charged. Since a *negative* airplane charge developed when E_X was positive this process does not appear to have played a significant role in the charging. However, as negative charge accumulated on SPTVAR the field at points with large curvature eventually became sufficiently strong that corona developed and the negative charge began to escape from trailing edges of the airplane. The escaping charge formed plumes of charge behind SPTVAR, the charge polarity of the plumes being the same as that of the net charge on SPTVAR. Thus, there were plumes of negative charge behind SPTVAR as it approached the negative cloud charge. The electric field at the rear of SPTVAR due to these negative charge plumes appeared as a superimposed negative contribution to E_X. This negative contribution to E_X reduced the field at rear surfaces of the airplane due to the net charge on the airplane and so acted to limit corona emission and the removal of negative charge. But, as the airplane charge increased, the plumes also increased so that the charge density in the plumes and thus the field at the rear of SPTVAR due to the plumes increased in proportion to the charge on SPTVAR.

The electric field at the face of the aft mill is the superposition of three separate electric fields: the ambient field (due to charge in the cloud), the field due to the net charge on the airplane, and the field due to charge plumes. To determine the X component of the ambient electric field from the SPTVAR field mill data we first subtract from the aft mill signal a signal due to the net charge on the aircraft, scaled so that the result is independent of the airplane charge. Then, since the aft mill is mounted behind the tail and faces in the negative X direction, the algebraic sign of this quantity is reversed to yield E_X. Thus the deduced E_X is actually a superposition of the cloud and charge plume fields. N



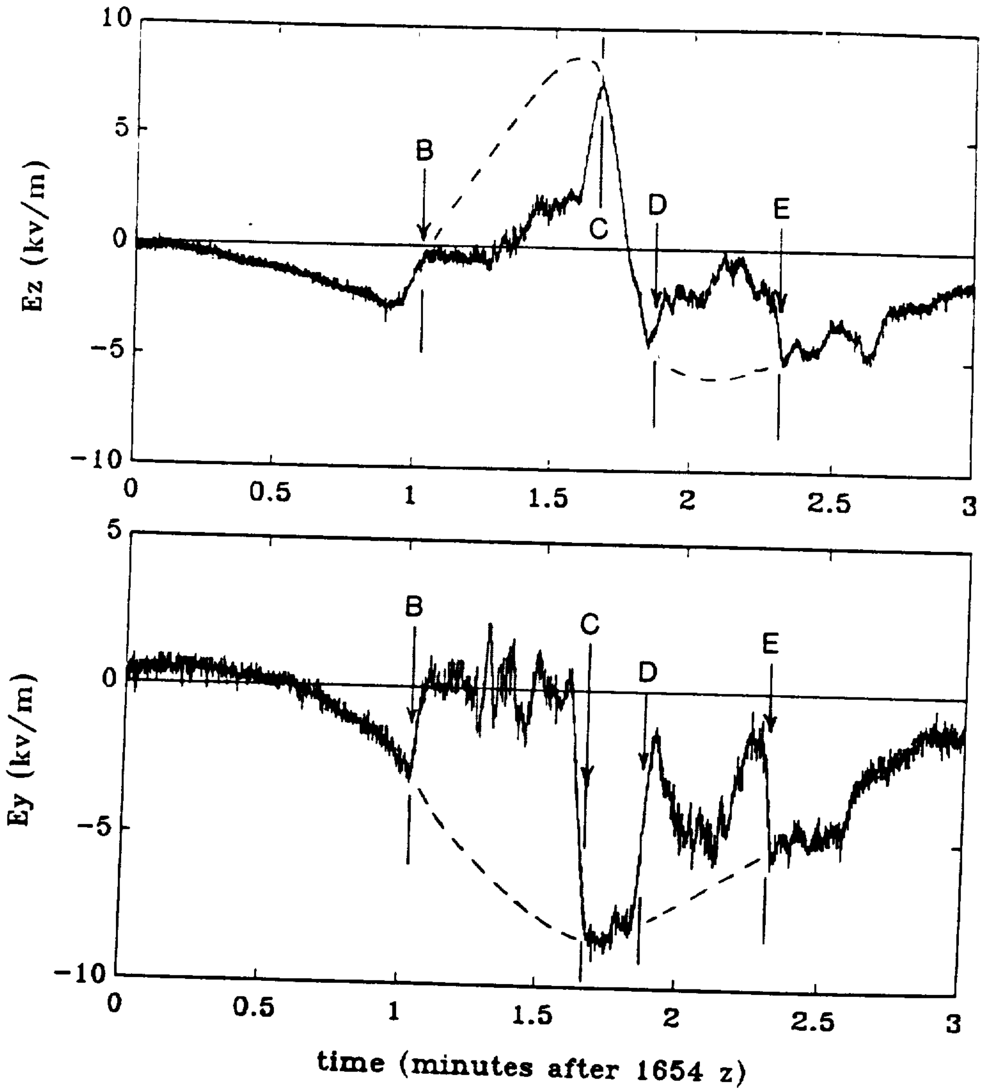


Figure 101: E_Y and E_Z for 1654 to 1657 Z on 19 August 1989. The vertical lines are at the same times as those in Fig. 99. The dotted lines are an estimation of the true variation of the electric field components with time.

C and the positive one between **D** and **E** in the E_X curve of Fig. 100 are the field of charge plumes superimposed on and overwhelming the ambient electric field at the aft mill. As a result the deduced E_X, the solid curve, is totally different from the expected true E_X of the cloud approximated by the dotted line in the figure.

Thus, when there are charge plumes streaming from the airplane the electric field components determined from the field mill data are corrupted. One way to identify unreliable data is to determine that charge plumes were present. In the electrical situation discussed here, the field at the aft mill due to the plumes and the field due to the charge on the airplane were opposite in polarity. Since the deduced E_X is mostly that of the plumes when they are strong, a possible way to determine the presence of plumes is to form the product $E_X E_Q$. When there were plumes, whose charge polarity was the same as that of the airplane charge as discussed here, this product should have been positive and large. Fig. 102 shows this product for the 1654 to 1657 Z time interval discussed above. Although the large positive peaks in this figure alert us to the presence of plumes, we must refer to the E_X and E_Q plots to determine more precisely when the plumes corrupted the data (since, for example, E_X was positive at **B** when the plumes first corrupted the SPTVAR determined E_X – Fig. 99).

Although the electric field components determined from the SPTVAR data were incorrect during the times that SPTVAR experienced the severe charging, there are still sufficient data of reasonable reliability to give a picture of the electric charge in the cloud. The top panel in Fig. 103 shows the plot of E_{NE} vectors along the SPTVAR track for the time period of the data shown in Fig. 99, while the bottom panel shows the same picture, after suppressing data obtained during times when there were charge plumes. Although the picture in the top panel is rather confusing, that in the bottom panel shows clearly that SPTVAR passed a negative charge a short distance to the right of its path on this flight segment. The corresponding plot of E_{XZ} vectors along the SPTVAR altitude profile (Fig. 104) indicates that the negative charge was centered roughly 0.5 km below the SPTVAR altitude. By ignoring the slight vertical and horizontal offsets of the charge center from the SPTVAR track we may calculate the approximate size of the cloud charge. E_X in Fig. 99 was +10 kV/m just before **B** and −10 kV/m just after **E**. These two points are 78 seconds apart or, at an approximate SPTVAR airspeed of 45 m/s, about 3.5 km. Assuming a point charge at 1.75 km midway between these two points where $|E_X|$ was 10 kV/m we find that the amount of charge in the cloud was approximately −3.4 coulombs.

Plots of E_{NE} vectors along the SPTVAR track and E_{XZ} vectors along the SPTVAR altitude profile for the three other flight segments during which severe charging occurred, two previous to and one subsequent to the one just discussed, are shown in Figs. 105 through 108. In each case a negative charge was centered just to the side of the airplane path. The vertical position of the negative charge may be inferred from the E_{XZ} plots. At the times of the four encounters between 1648 and 1701 Z the altitude of the negative

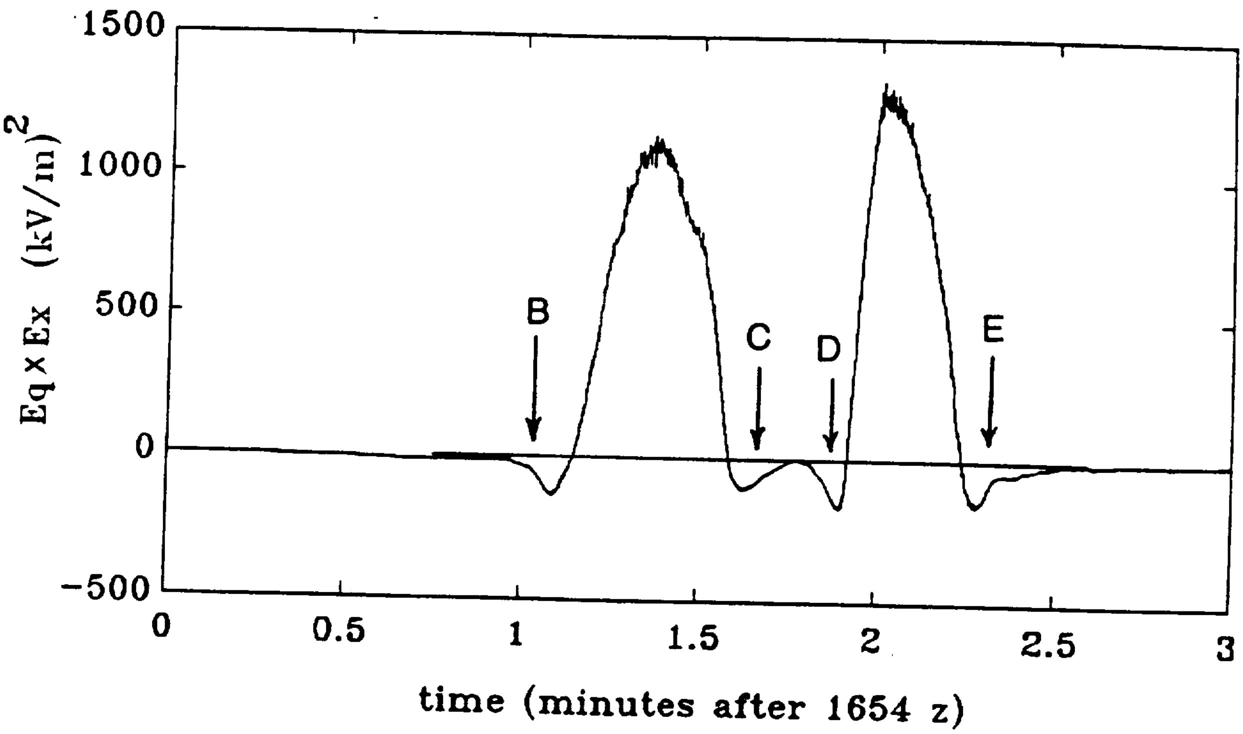


Figure 102: The product $E_Q E_X$ for 1654 to 1657 Z on 19 August 1989. The large positive values of this product indicate the presence of plumes of charge behind SPTVAR. The electric field components (and especially E_X) measured by SPTVAR during such times are incorrect.

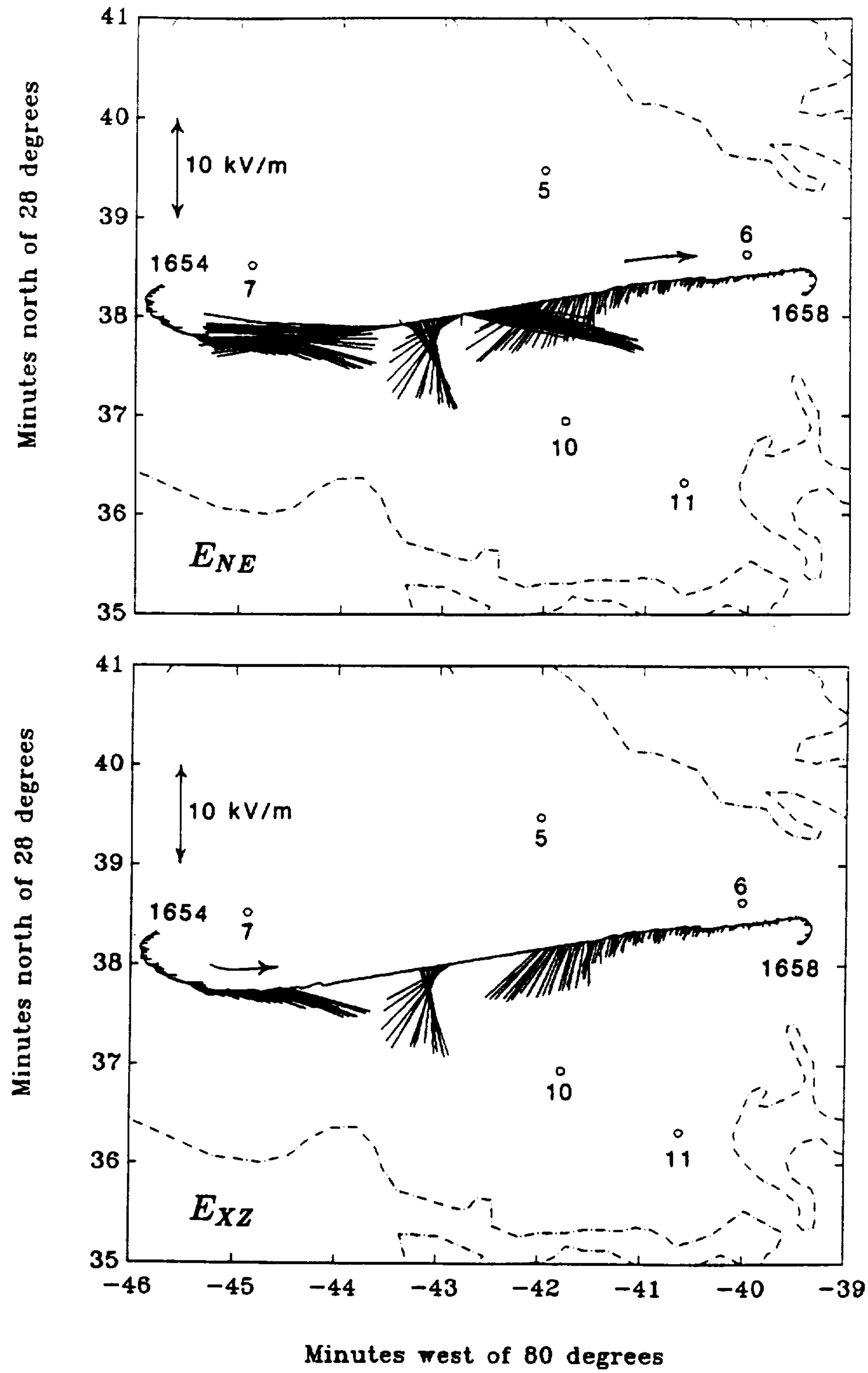


Figure 103: E_{NE} vectors plotted along the SPTVAR flight track from 1654 to 1658 Z on 19 August 1989. The bottom panel is the same as the top panel except that the E_{NE} vectors have been suppressed during the two periods when there were charge plumes behind SPTVAR.

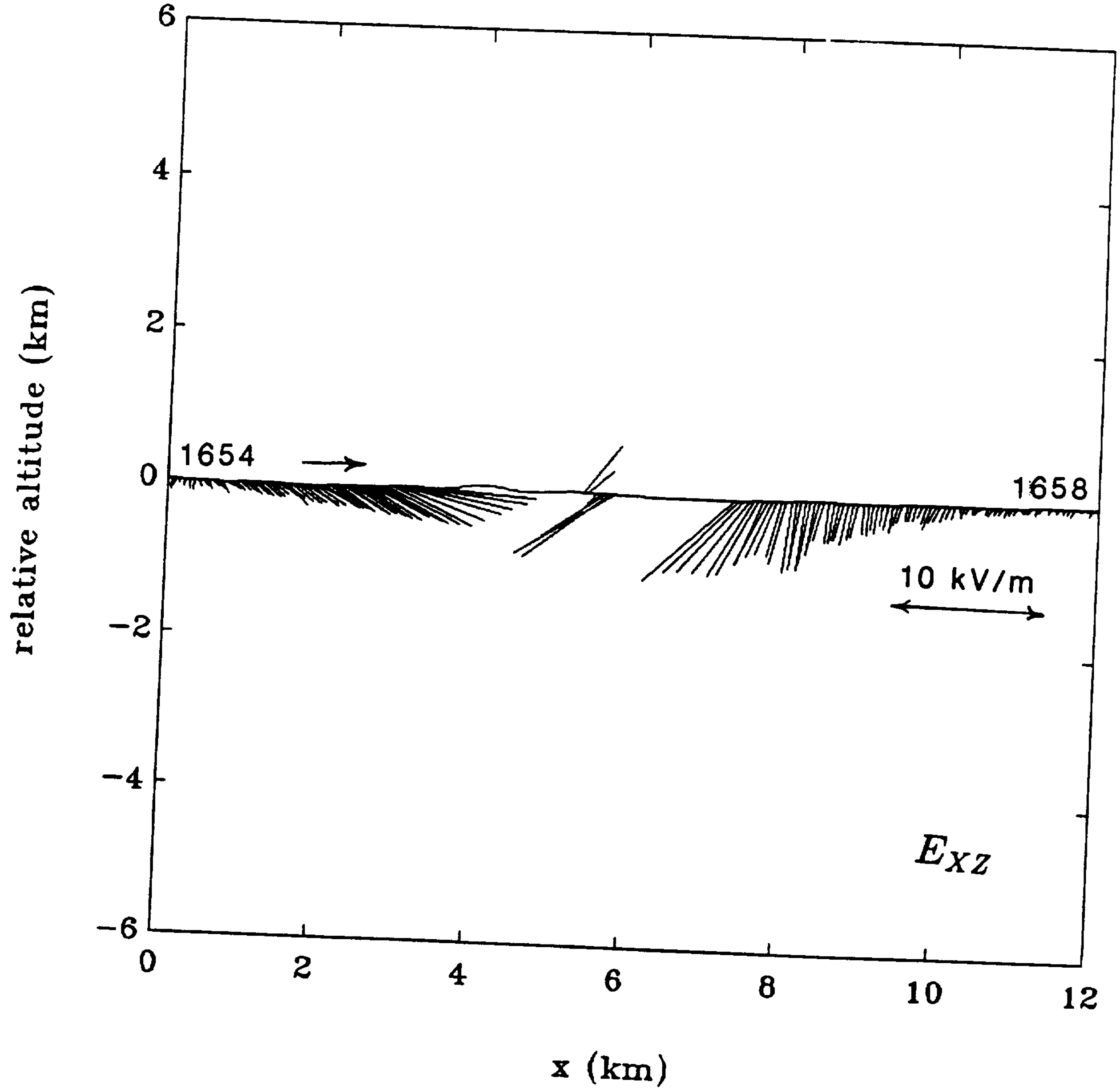


Figure 104: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1654 to 1658 Z on 19 August 1989. The E_{XZ} vectors have been suppressed during the two periods when there were charge plumes behind SPTVAR.

charge with respect to the 12,000 ft altitude of SPTVAR was approximately +2, +1, −0.5 and −1.5 km. From these approximate charge altitudes we calculate that the negative charge was descending at least as fast as 5 m/s. Since this is consistent with the fall speed of smaller rain drops it appears that the negative charge was falling out of the cloud on the rain drops. Thus, although the charge plumes resulting from the severe charging of SPTVAR corrupted some of the electric field data, we have been able to eliminate the bad data and reveal an interesting aspect of this particular cloud's electrical behavior.

PC display of horizontal electric vector used to guide airplane investigation of positive cloud charge.

After the four encounters with severe charging previously discussed, SPTVAR made a series of east–west flight legs at 12,000 ft as the lower reaches of the cloud below the flight altitude rapidly disintegrated. After the first of these passes (1701 to 1705 Z) the real-time PC display of the E_{XY} vectors along the airplane track was used to guide the pilot so that repeated measurement of the positive charge in the cloud was accomplished. This procedure was reported on at the Fall Meeting of the American Geophysical Union in San Francisco on 4 December 1989. A somewhat more complete description of the data obtained is presented in the following paragraphs.

The first of these flight legs, 1701 to 1705 Z, was from west to east. Charging of SPTVAR was much less than on the previous four flight legs. E_X and E_Y appear to make sense and suggest negative cloud charge observed on the previous passes was now below the SPTVAR flight altitude and just to the right of SPTVAR, as shown by the plots of E_{NE} and E_{XZ} vectors in Fig. 109. The $E_Q E_X$ product for this time interval, Fig. 110, never exceeded about 40 $(\text{kV/m})^2$, implying that plumes of charge behind the airplane (although possibly present) were not nearly as serious a problem as they were during the previous four flight legs.

On the next pass below the cloud from east to west, 1705 to 1708 Z, the PC display of the SPTVAR track with superimposed E_{XY} vectors (in the telemetry trailer at Patrick AFB) indicated a positive charge just to the south of the SPTVAR path and north of mill 7. For the next three passes the scientist in the telemetry trailer used the PC's real-time display of SPTVAR track with E_{XY} vectors to repeatedly guide the pilot back to this region of positive charge. A replica of the PC display for five passes covering the time interval 1701 to 1714:30 Z, is shown in Fig. 111. Near the end of the pass that began at 1705 Z, the pilot was asked to turn 180° to the left and fly back toward the east. On this pass, 1708 to 1710 Z, a more definitive pattern of vectors indicated a positive charge just to the north of the SPTVAR track. The pilot was then asked to turn back to the left and fly back west, this time making a more gradual turn. After he did so, the display, 1710 to 1712 Z, showed that the positive charge was again south of the airplane track. The pilot was asked to turn back to the left sharply and fly to the east. Upon his doing so, the E_{XY} vectors were aligned more or less along the track line, indicating that SPTVAR had flown above, through or under the charge responsible for the measured electric field.

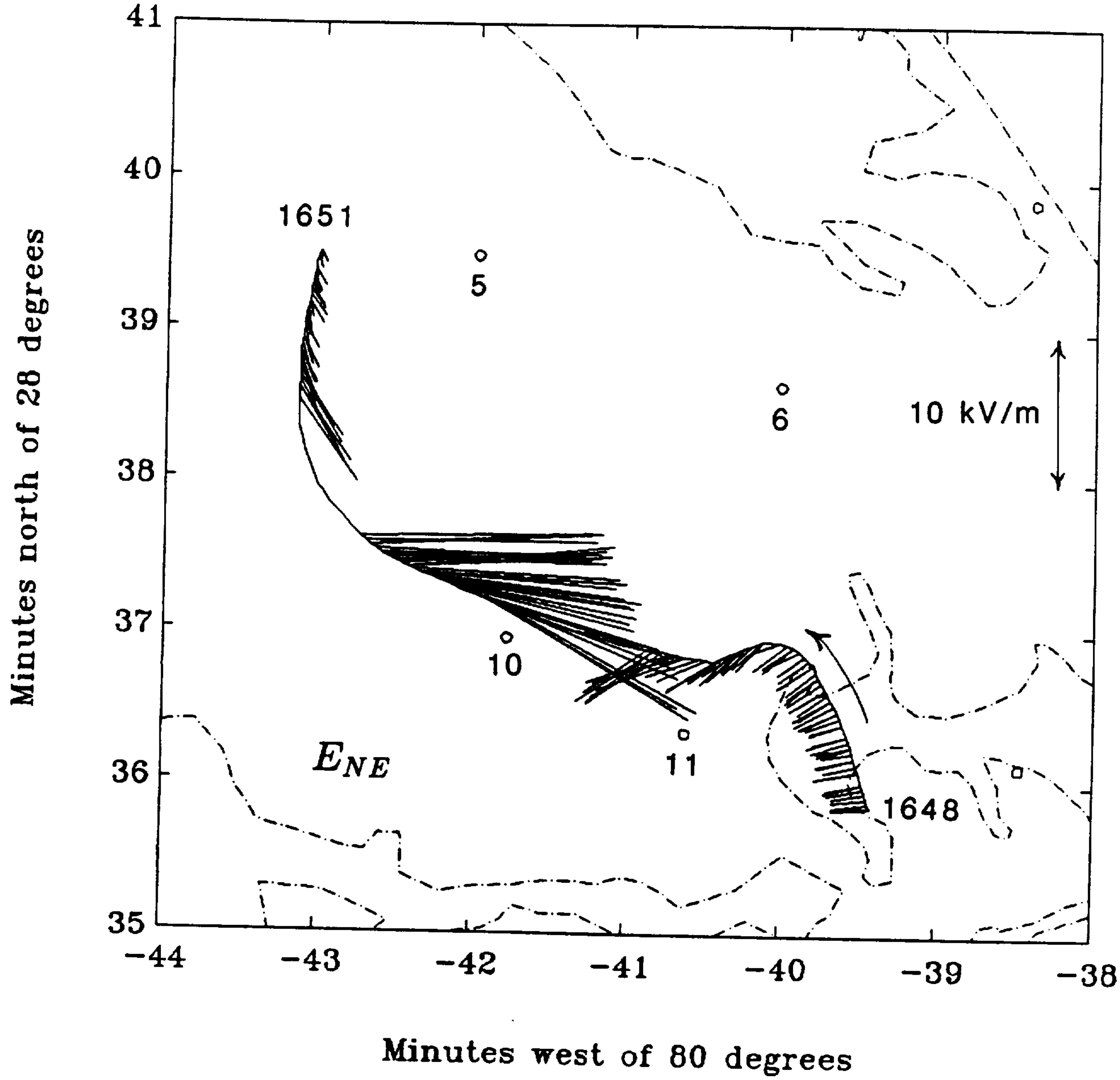


Figure 105: E_{NE} vectors plotted along the SPTVAR flight track from 1648 to 1651 Z on 19 August 1989.

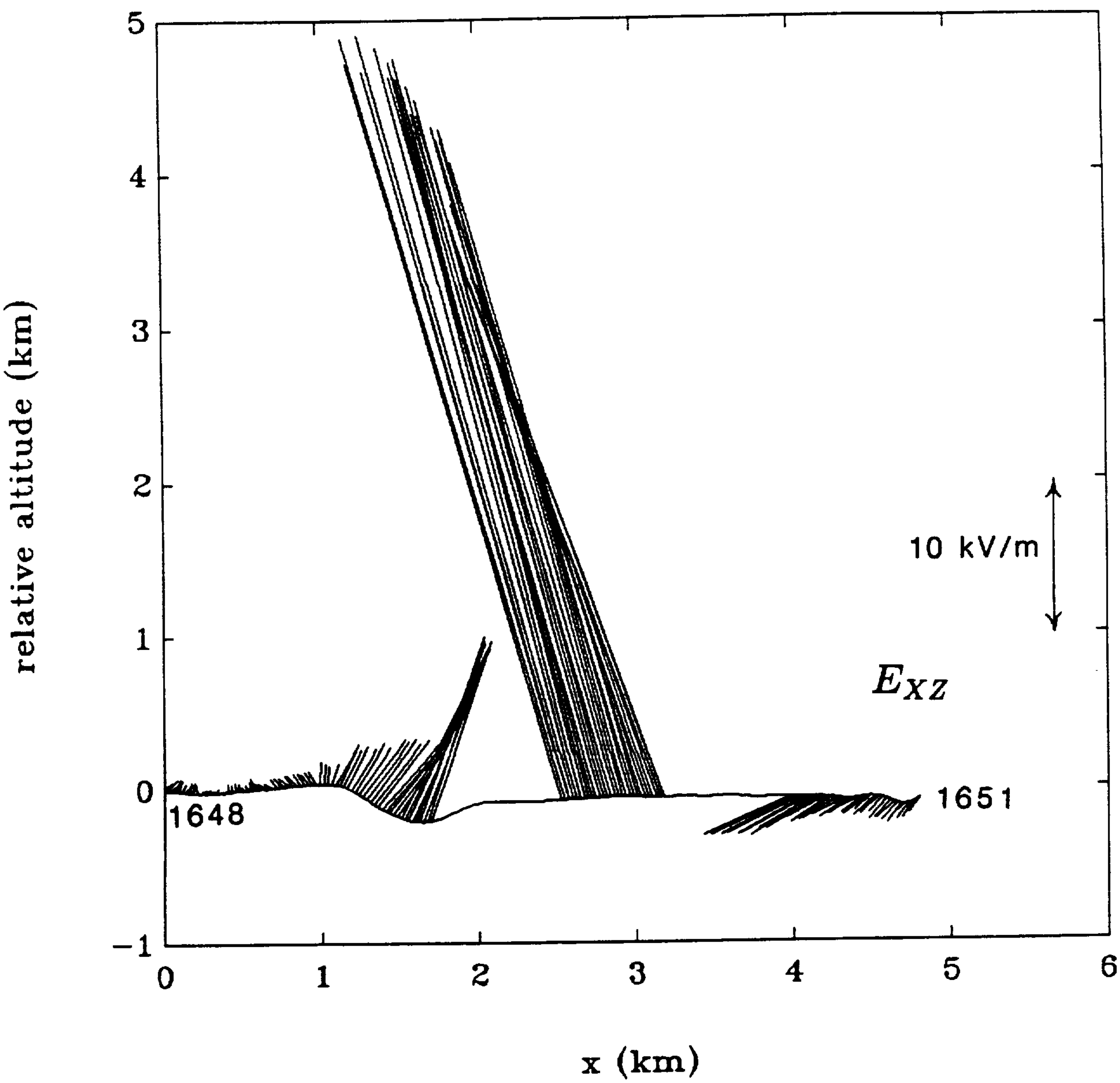
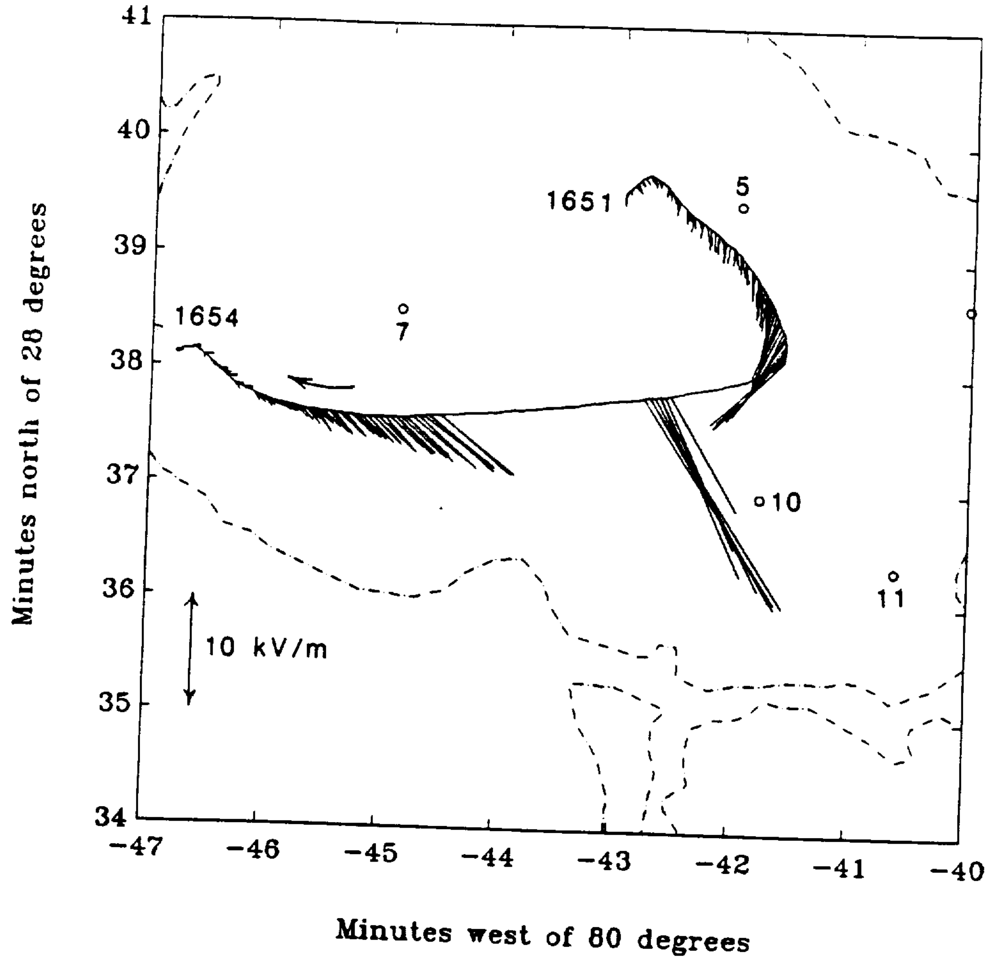


Figure 106: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1648 to 1651 Z on 19 August 1989.



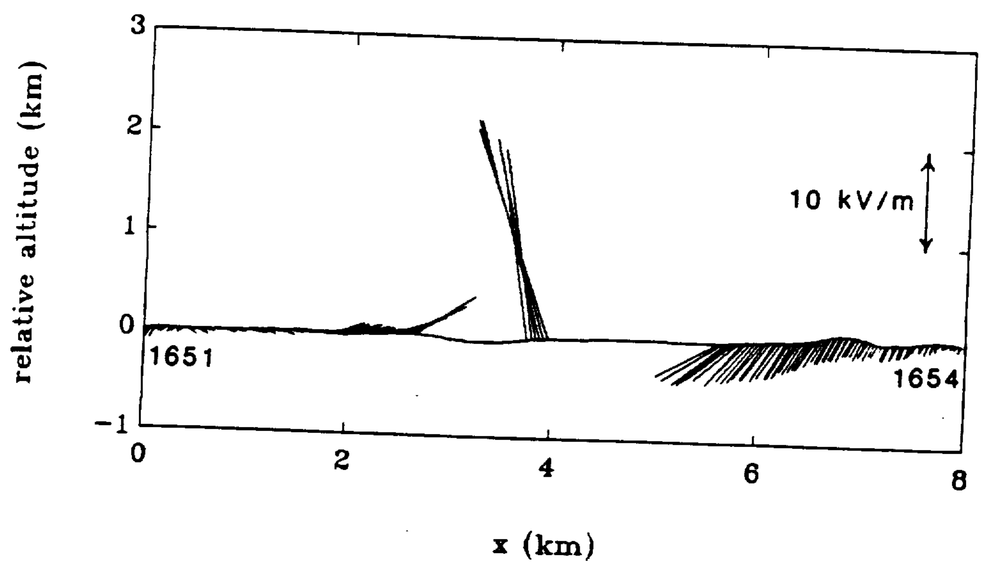


Figure 107: E_{NE} vectors plotted along the SPTVAR flight track (top panel) and E_{XZ} vectors along the altitude profile (bottom panel) from 1651 to 1654 Z on 19 August 1989.

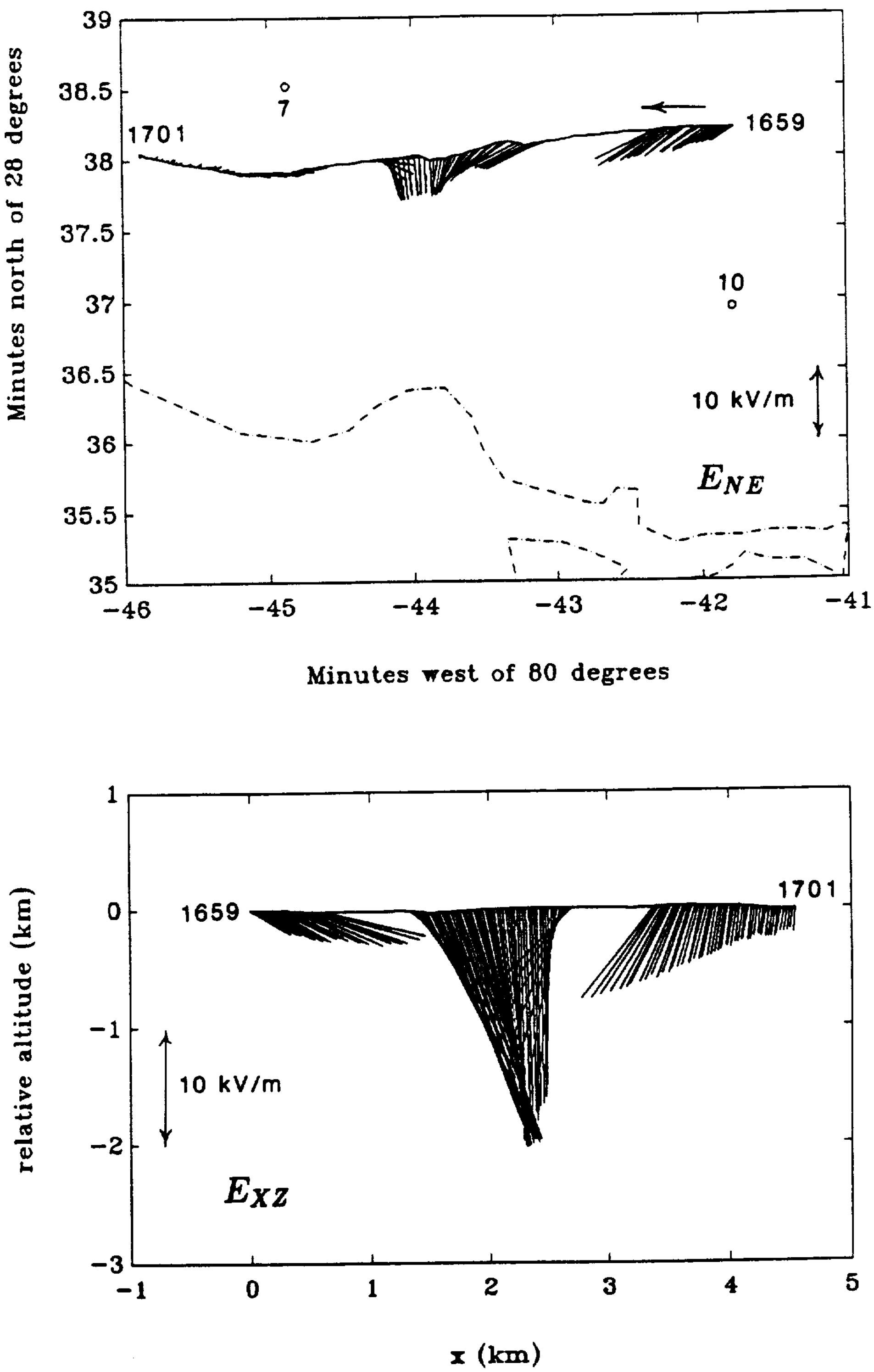


Figure 108: E_{NE} vectors plotted along the SPTVAR flight track (top panel) and E_{XZ} vectors along the altitude profile (bottom panel) from 1659 to 1701 Z on 19 August 1989.

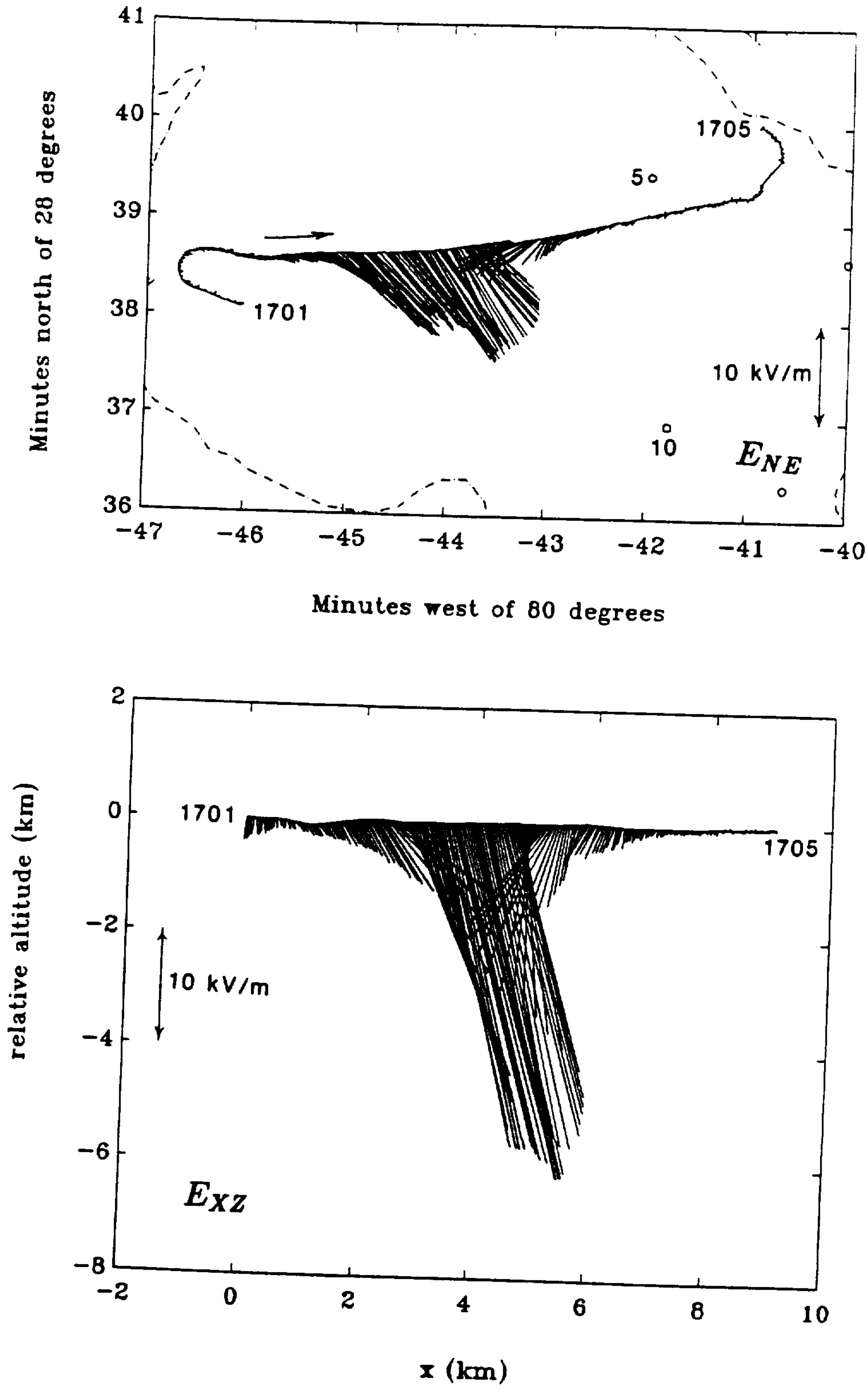


Figure 109: E_{NE} vectors plotted along the SPTVAR flight track (top panel) and E_{XZ} vectors along the altitude profile (bottom panel) from 1701 to 1705 Z on 19 August 1989.

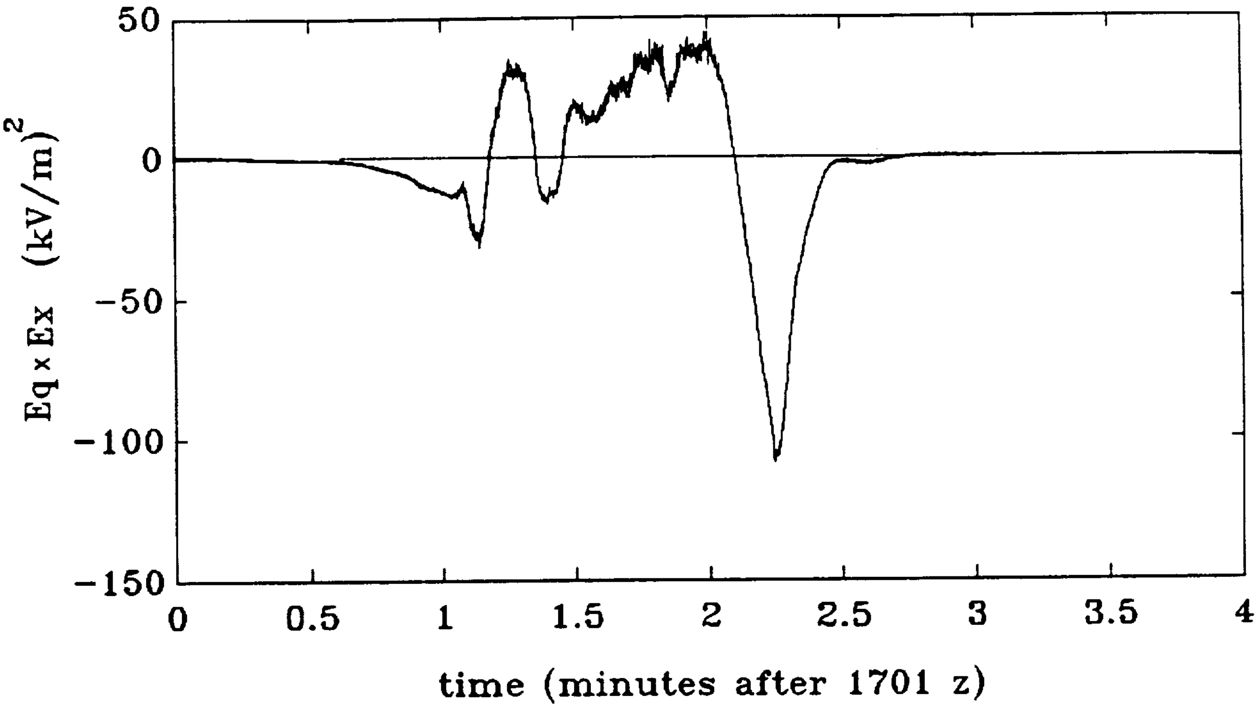


Figure 110: The product $E_Q E_X$ for 1701 to 1705 Z on 19 August 1989. Large positive values of this product, such as in Fig. 102, would indicate the presence of plumes of charge behind SPTVAR and that the electric field components measured by SPTVAR during such times were incorrect.

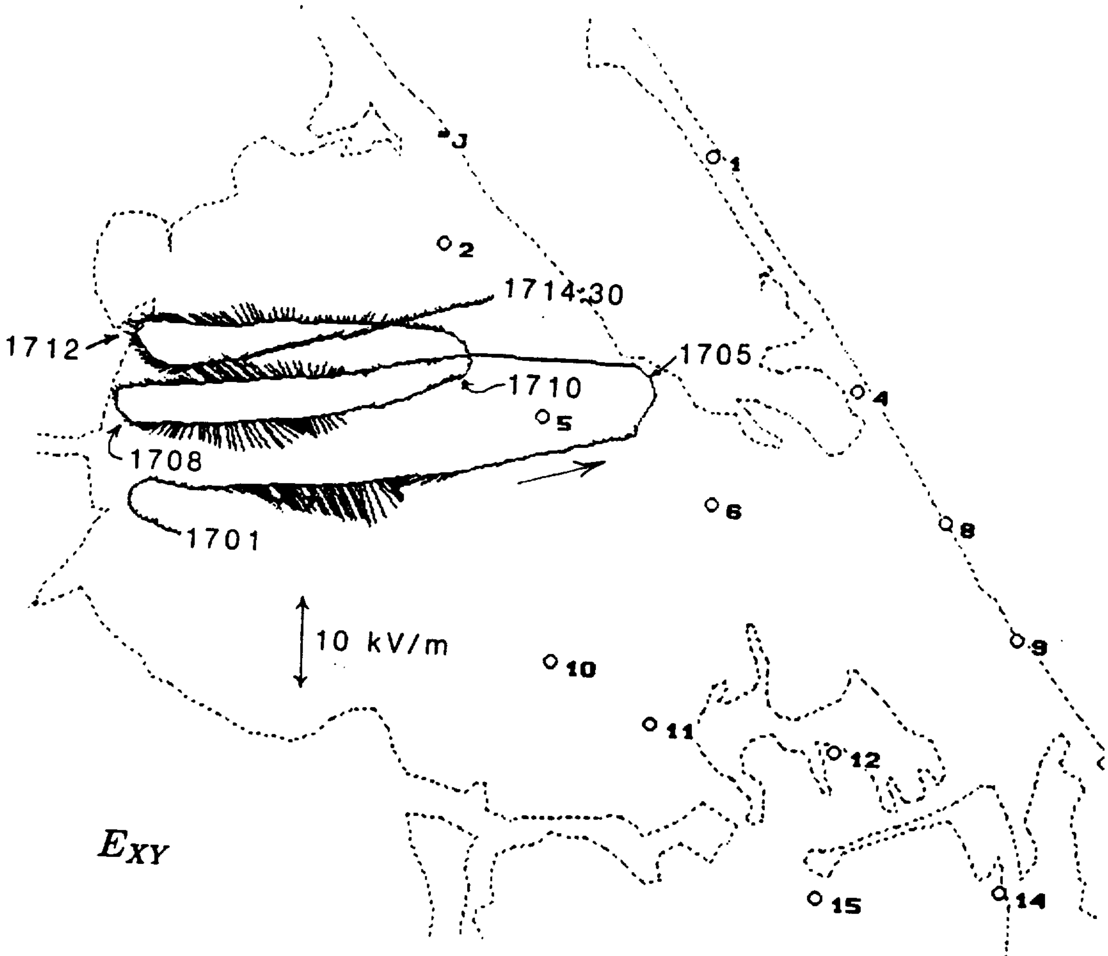


Figure 111: The flight track of SPTVAR plotted by the PC for 1701 to 1714:30 Z on 19 August 1989. E_{XY} barbs are drawn along the track to show the direction and magnitude of the horizontal electric vector.

More can be learned about the region of positive charge investigated during the interval 1705 to 1714:30 Z from plots of the E_{NE} vectors along the SPTVAR path and E_{XZ} vectors along the SPTVAR altitude profile which were made as part of our subsequent analysis. These plots for the four passes during this time interval are shown in Figs. 112 to 119. They were made using a Sun Workstation and show more detail than the real-time E_{XY} plots produced by the PC. The E_{NE} plots allow us to visualize the horizontal position of the positive charge in the cloud overhead. While the E_{XZ} plots clearly show that the positive cloud charge was well above the SPTVAR flight altitude, the first few also show the continued descent of negative cloud charge below the SPTVAR flight altitude. The electric field patterns in Figs. 112 and 113 may be interpreted as due to negative charge about 2 km below SPTVAR just to the east of positive charge which was about 2 km above SPTVAR. Similarly, the vector patterns in Figs. 114 and 115 may be interpreted as due to positive charge some 2 km above SPTVAR and about 2 km west of negative charge some 2.5 km below SPTVAR. Figures 116 and 117 show the E_{XZ} vectors diverging to either side of a set of vertical vectors. Thus there may have been negative charge below the positive charge overhead at this time, but the charge altitudes cannot be determined from the pattern of the vectors. In Figs. 118 and 119 there is no longer any sign of the lower negative charge. The positive charge approximately 1.5 km above SPTVAR is, however, clearly indicated. From this figure the positive charge directly overhead in the cloud has been calculated to have been +5.4 coulombs. The data for this pass are believed to be quite reliable since the value of the $E_Q E_X$ product, presented in Fig. 120, remained small compared to the values it attained during the 1654 to 1657 Z pass shown in Fig. 102.

Two subsequent east–west passes across the north end of Merritt Island, between 1714:30 and 1719:30 Z, show the positive charge persisting yet a little longer. Thereafter, the electric field at SPTVAR quickly became dominated by the electric field of the more active part of the merged cloud mass to the north, and the part of the cloud that had been studied by SPTVAR continued to dissipate. Indeed, by 1711:28 lightning signatures, presumably originating in the cloud to the north, began to appear in the electric field measured by SPTVAR. It is interesting that the KSC surface electric field mill array did not detect the positive charge observed by SPTVAR from 1707 to 1717 Z.

The pilot reported that there was a persistent rain shaft associated with the cloud SPTVAR studied beginning about 1625 Z and that by 1647:30 Z a lot of the cloud in the lower level was gone and there was a big anvil overhead. At 1649:20 Z he reported that he was crossing below the cloud at 11,700 ft, and at 1653 Z he reported that there was not much left of the cloud below 12,000 ft. He reported at 1658 Z that the cloud was moving rapidly to the northwest. Shortly thereafter, at 1659:30 Z, he reported that he had never seen any lightning flashes in the cloud. By 1701:40 Z the pilot noted that he was seeing down through where the cloud had been, including where the rain shaft had been, and that the cloud had rained itself out below 12,000 ft.

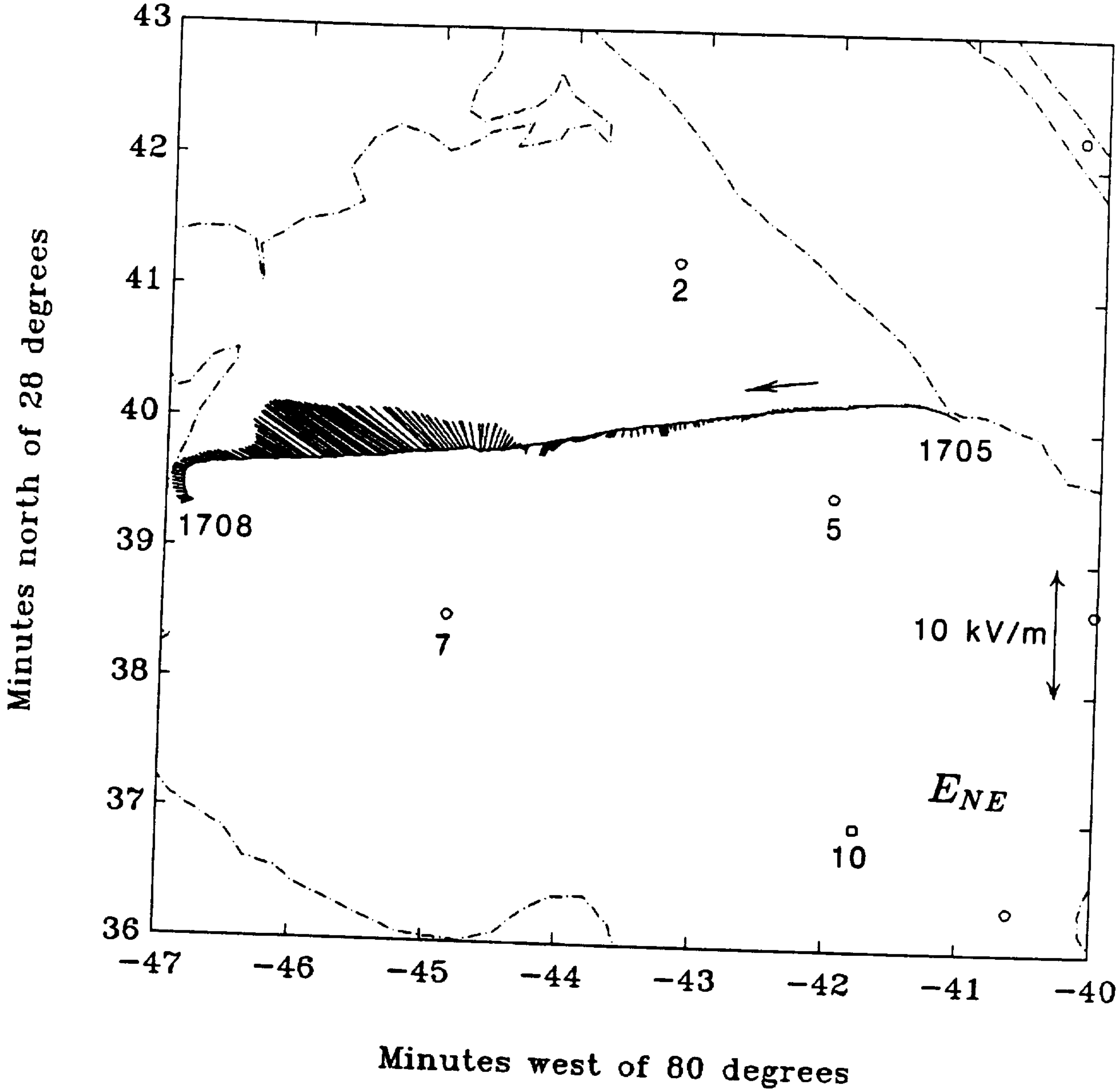


Figure 112: E_{NE} vectors plotted along the SPTVAR flight track from 1705 to 1708 Z on 19 August 1989.

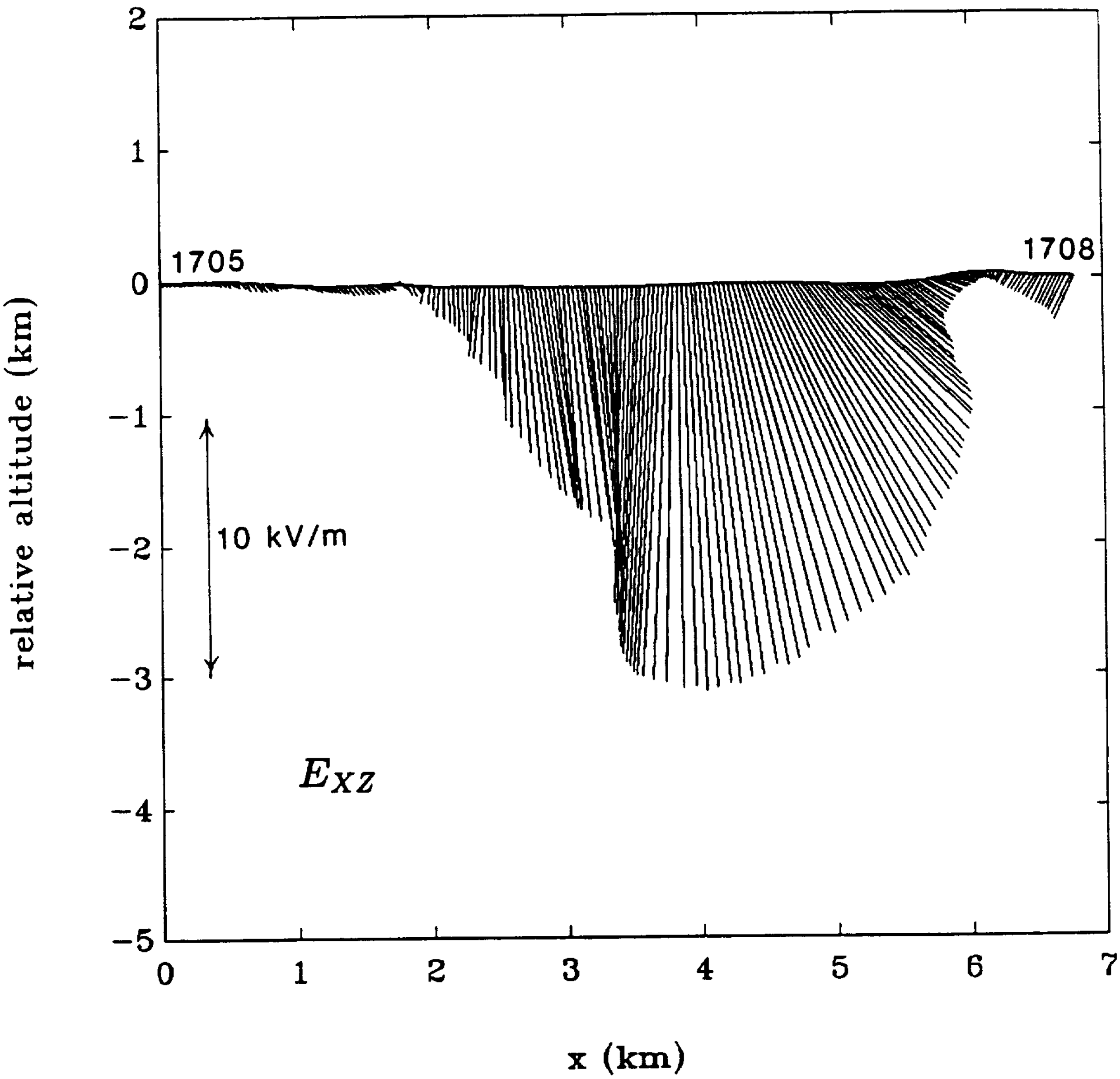


Figure 113: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1705 to 1708 Z on 19 August 1989.

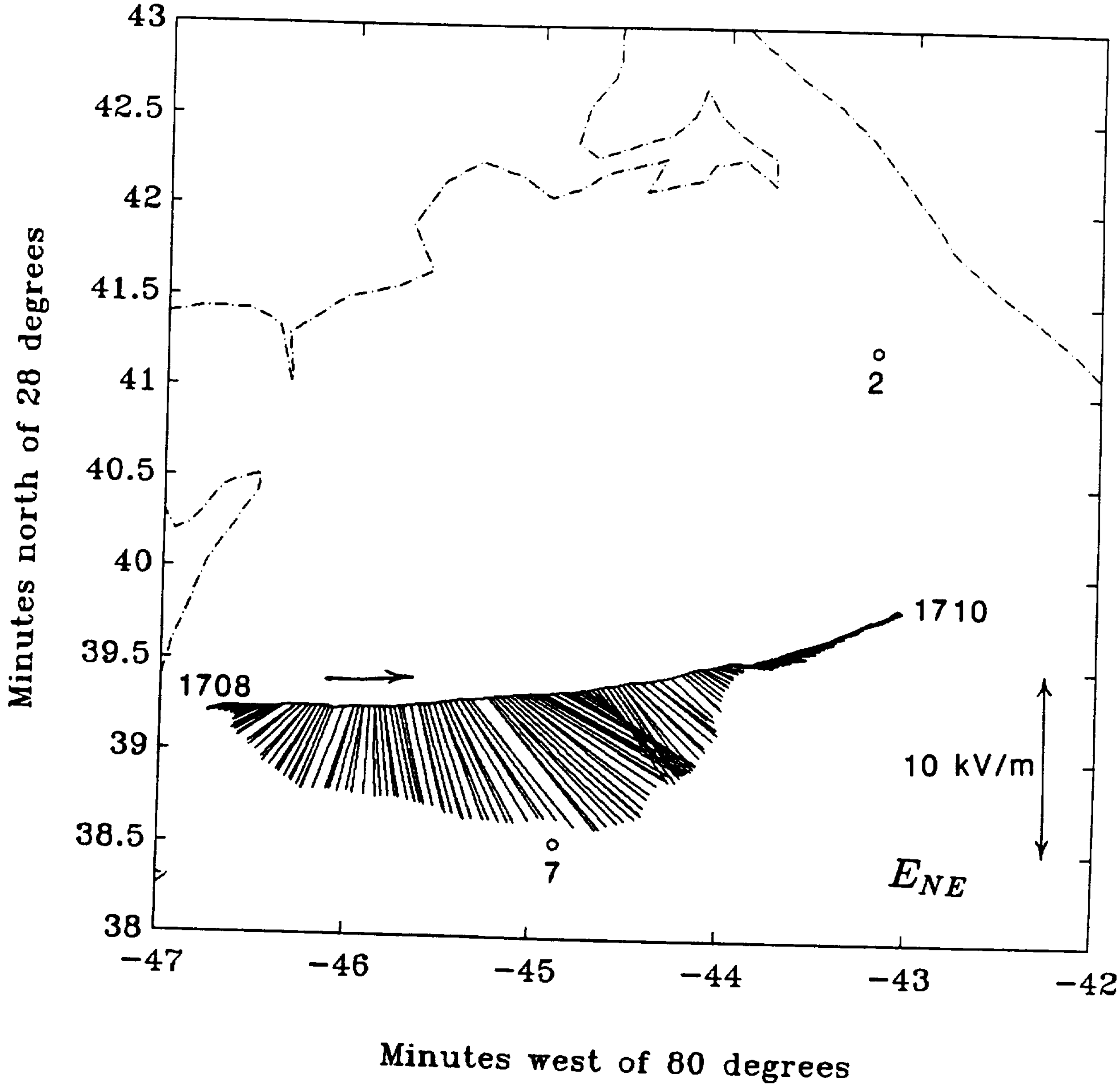


Figure 114: E_{NE} vectors plotted along the SPTVAR flight track from 1708 to 1710 Z on 19 August 1989.

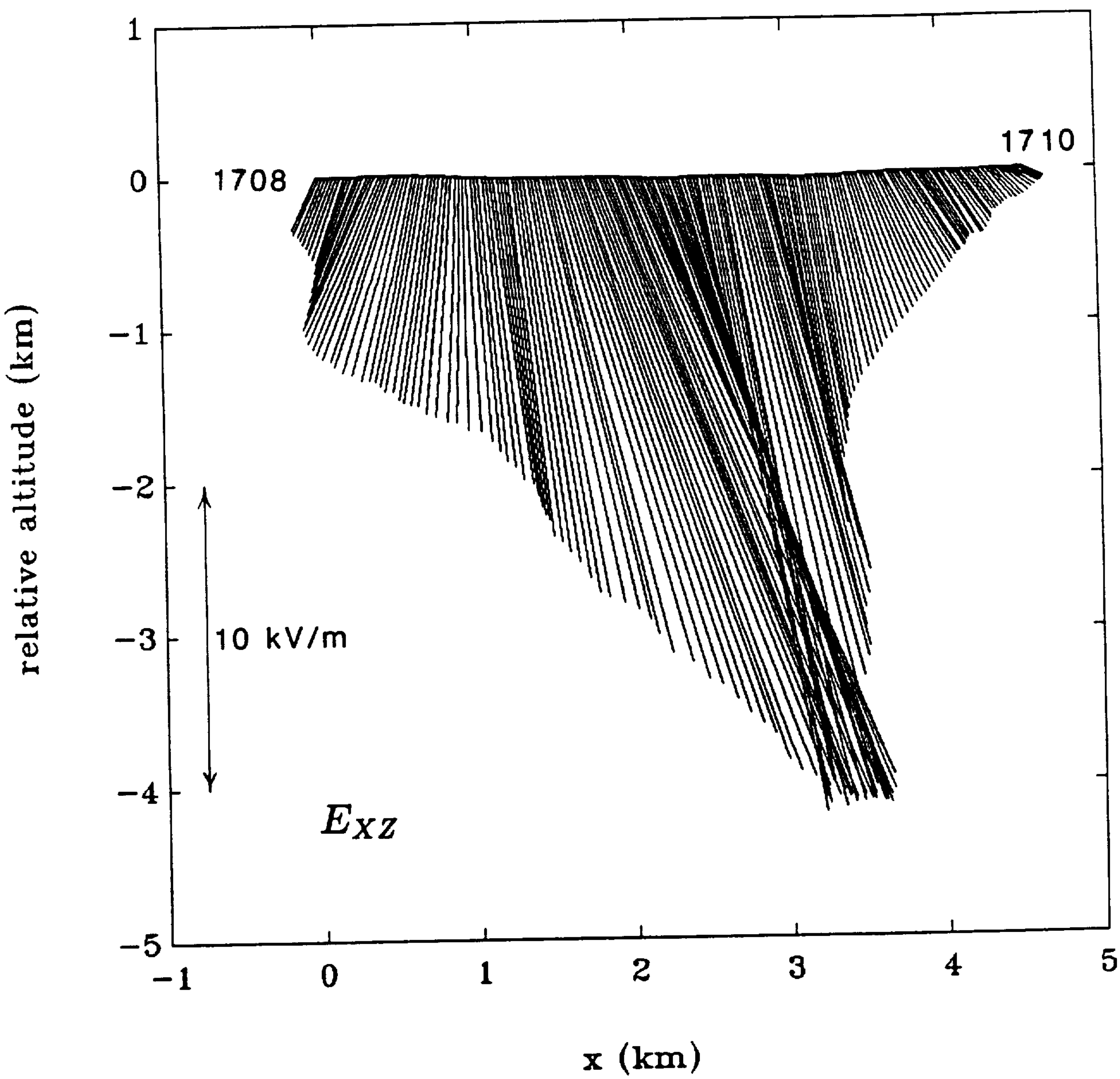


Figure 115: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1708 to 1710 Z on 19 August 1989.

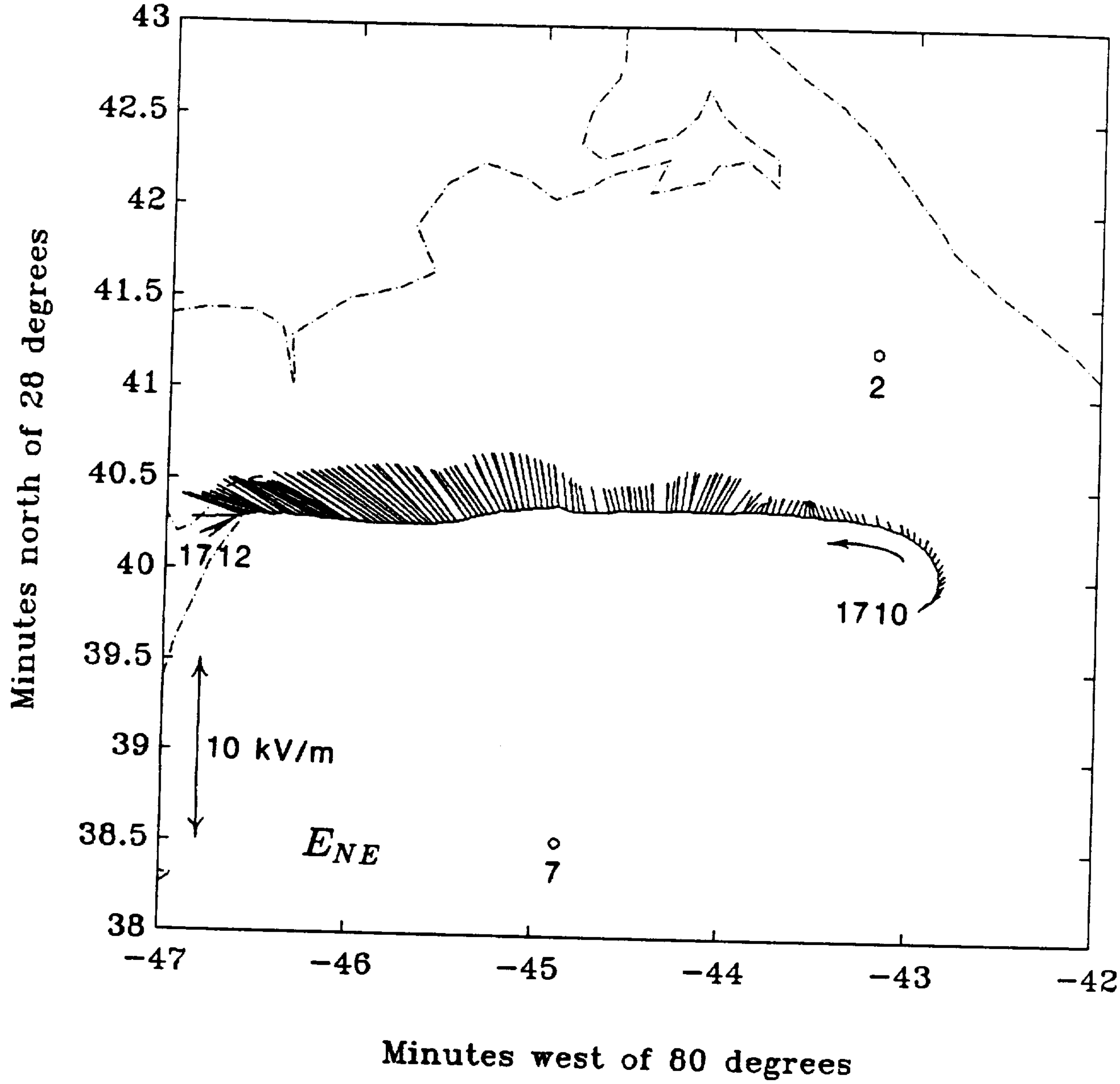


Figure 116: E_{NE} vectors plotted along the SPTVAR flight track from 1710 to 1712 Z on 19 August 1989.

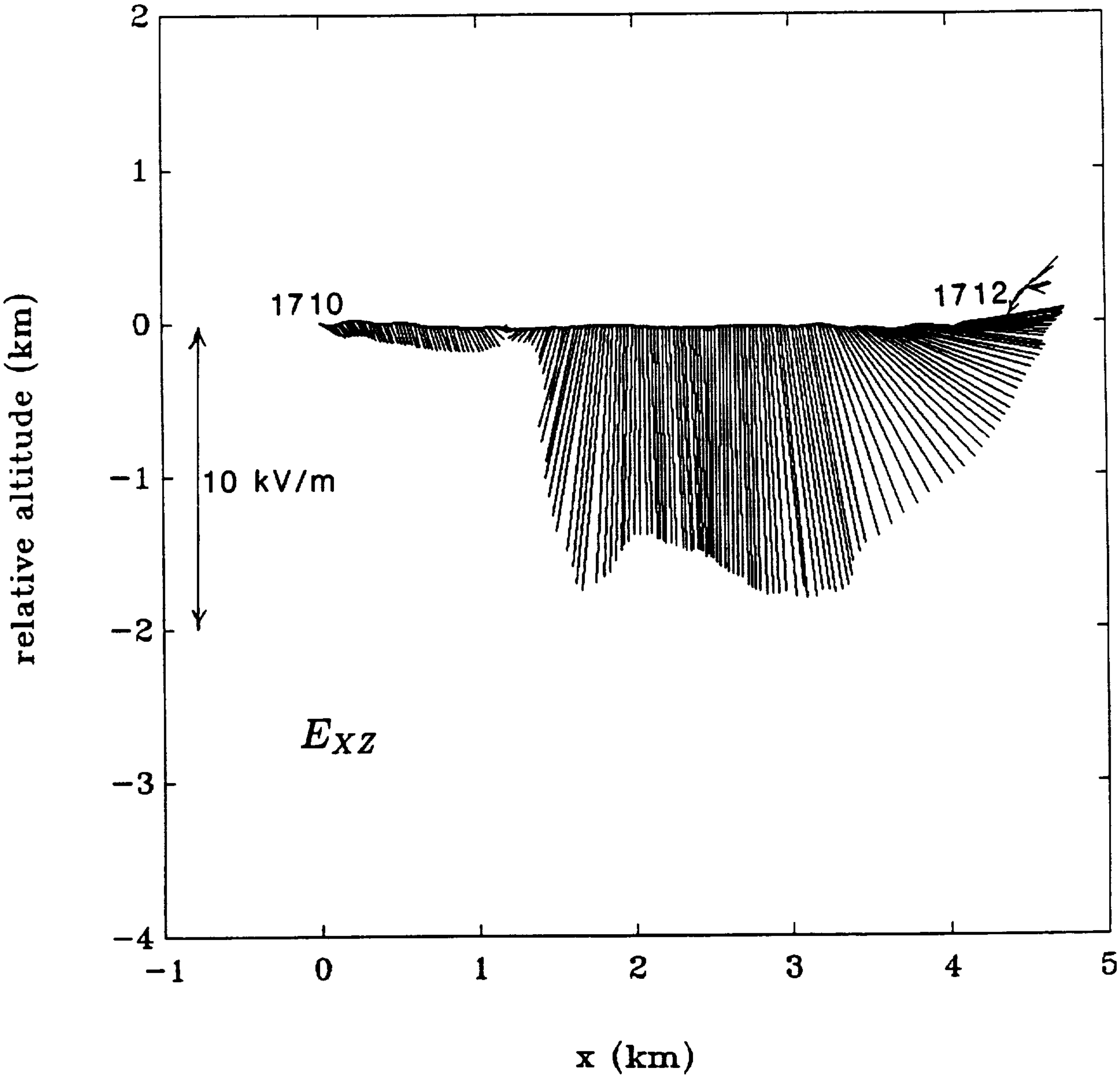


Figure 117: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1710 to 1712 Z on 19 August 1989.

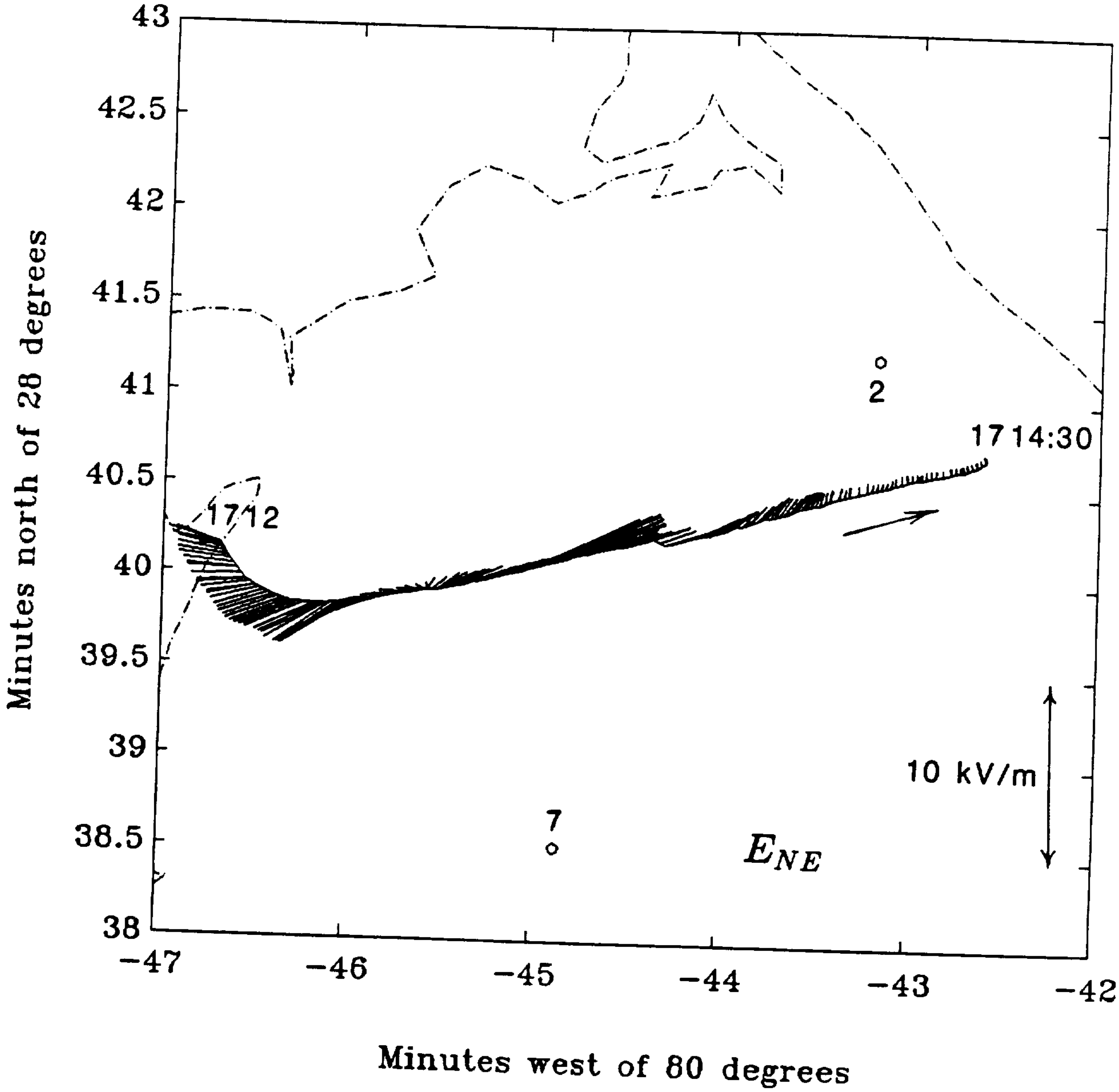


Figure 118: E_{NE} vectors plotted along the SPTVAR flight track from 1712 to 1714:30 Z on 19 August 1989.

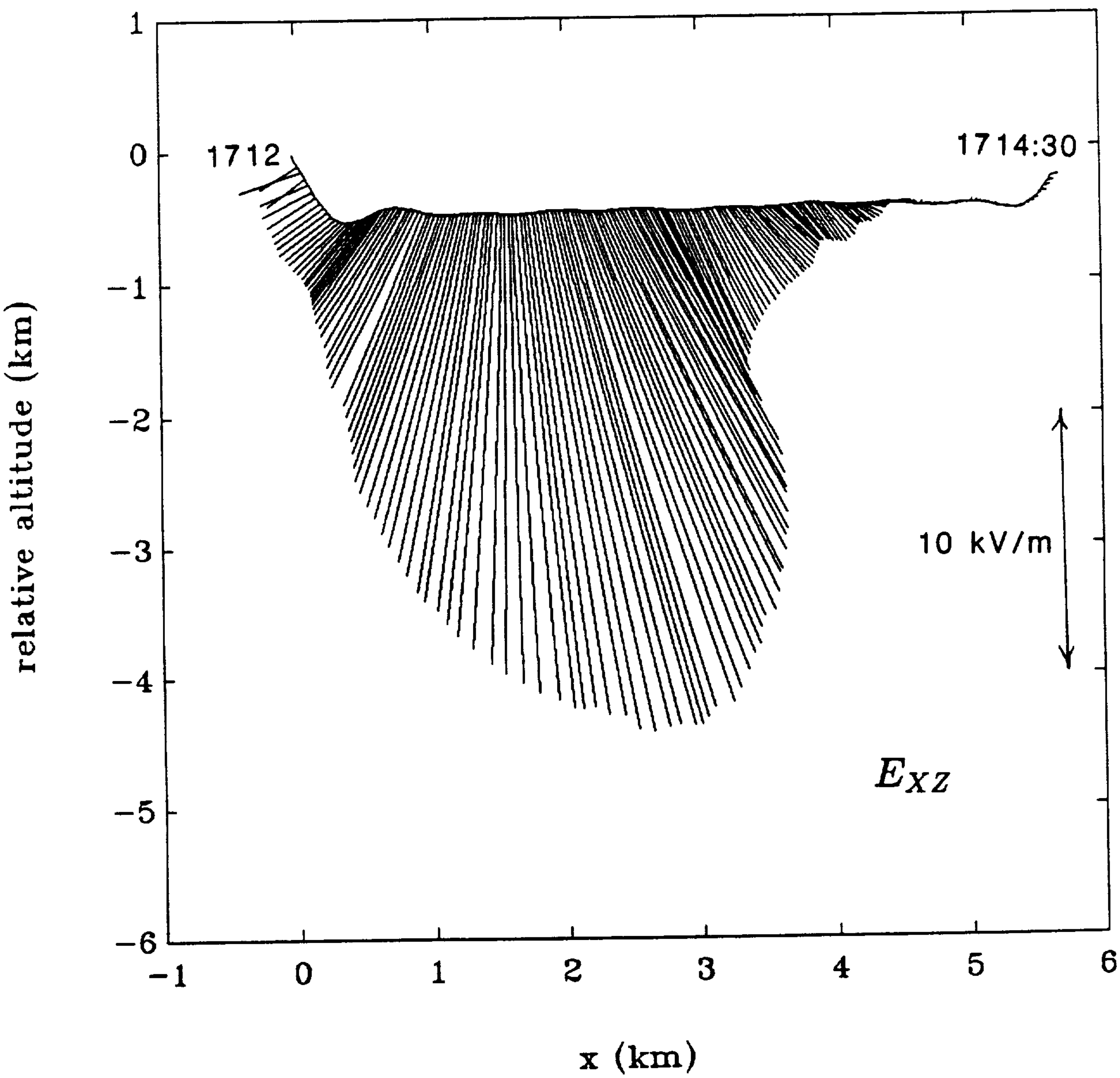


Figure 119: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1712 to 1714:30 Z on 19 August 1989.

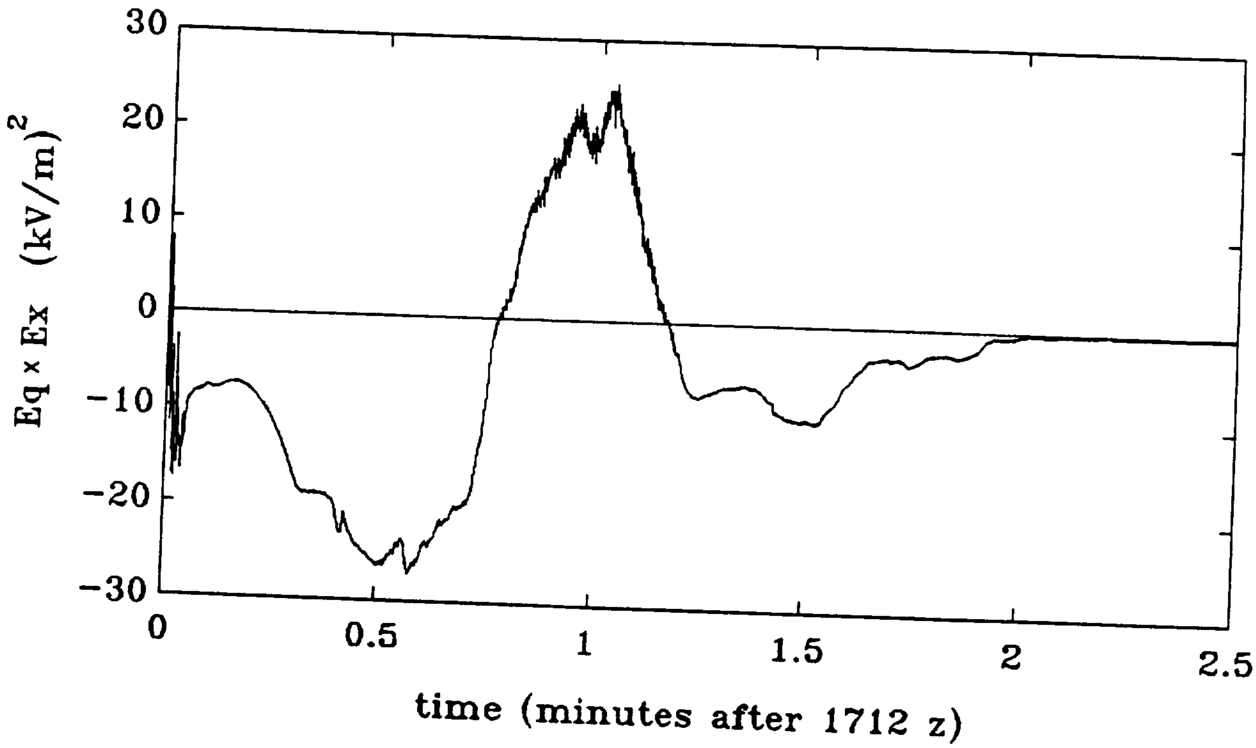


Figure 120: The product $E_Q E_X$ for 1712 to 1714:30 Z on 19 August 1989. Large positive values of this product, as in Fig. 102, would indicate the presence of plumes of charge behind SPTVAR and that the electric field components measured by SPTVAR during such times were incorrect.

Indeed, during the entire time that this cloud was studied, 1612 to 1720 Z, there do not appear to have been any lightning flashes associated with the cloud. Since there are measurements indicating that small convective clouds can generate lightning within 10 minutes of first starting to electrify, and since the largest charge magnitude determined from the SPTVAR data was about 5 C, this was a marginally electrified cloud.

Since the launch commit criteria rely heavily on cloud top heights as an indication of the likelihood of a cloud being electrified, it is instructive to look at the cloud-top height of this cloud during its development and electrification. The best information on cloud-top heights was obtained from the McGill radar. The large dots connected by dashed lines in Fig. 121 show the maximum height at which 5-dBZ reflections were recorded from this cloud over a time span of 65 minutes and indicates that the cloud's 5-dBZ top was over 23,000 ft (7 km) before electrification began but never exceeded 28,000 ft (8.5 km) This situation may be contrasted with that of the later growth north of the original cloud with which the study cloud merged by 1710 Z, as shown in Fig. 98. By 1720 Z, SPTVAR was detecting lightning signatures, apparently due to this northern cloud. The maximum heights of 5-dBZ echos for this northern cloud are shown by the plus symbols connected by small dots in Fig. 121. By the time lightning activity began, its 5-dBZ top was in excess of 32,800 ft (10 km) and growing rapidly.

Since the 5-dBZ top of the cloud that SPTVAR studied was above the −10 °C level (21,000 ft) for the entire time interval shown in Fig. 121, the launch criteria would have forbidden launching rockets through or within 5 nautical miles of the cloud. Furthermore, since the visible top was probably somewhat higher (and certainly from 1633 to 1712 Z when the 5-dBZ top was above the −20 °C level), the launch criteria would have forbidden launch of a rocket within 10 nautical miles of the cloud. Due to its marginal electrification, small charge magnitudes and failure to generate a lightning flash during its electrical life, we do not know if lightning could have been triggered had a rocket launched through this cloud.

Comparison of electric field measured by balloon-borne field mills and by airplane.

Near the end of this day's flight, a group led by Serge Chauzy of Universite Paul Sabatier in Toulouse, France, had a series of four electric field mills strung along the tether of a balloon aloft over the rocket-triggered-lightning site on Mosquito Lagoon. The highest mill was at 500 m and the balloon itself was at about 550 m. Besides the French mills there was an additional field mill (of a different design, provided by by Tom Marshall of The University of Missippi and Dave Rust of the National Severe Storms Laboratory) at 200 m on the balloon tether. There were several other mills at ground level, both on land and on Mosquito Lagoon. At 1747:20 Z an electric field strength of −6 kV/m was reported from the field mill at 500 m on the balloon tether. SPTVAR passed over the balloon going west at 1750:40 Z and after reversing course passed about 1/2 mile north of

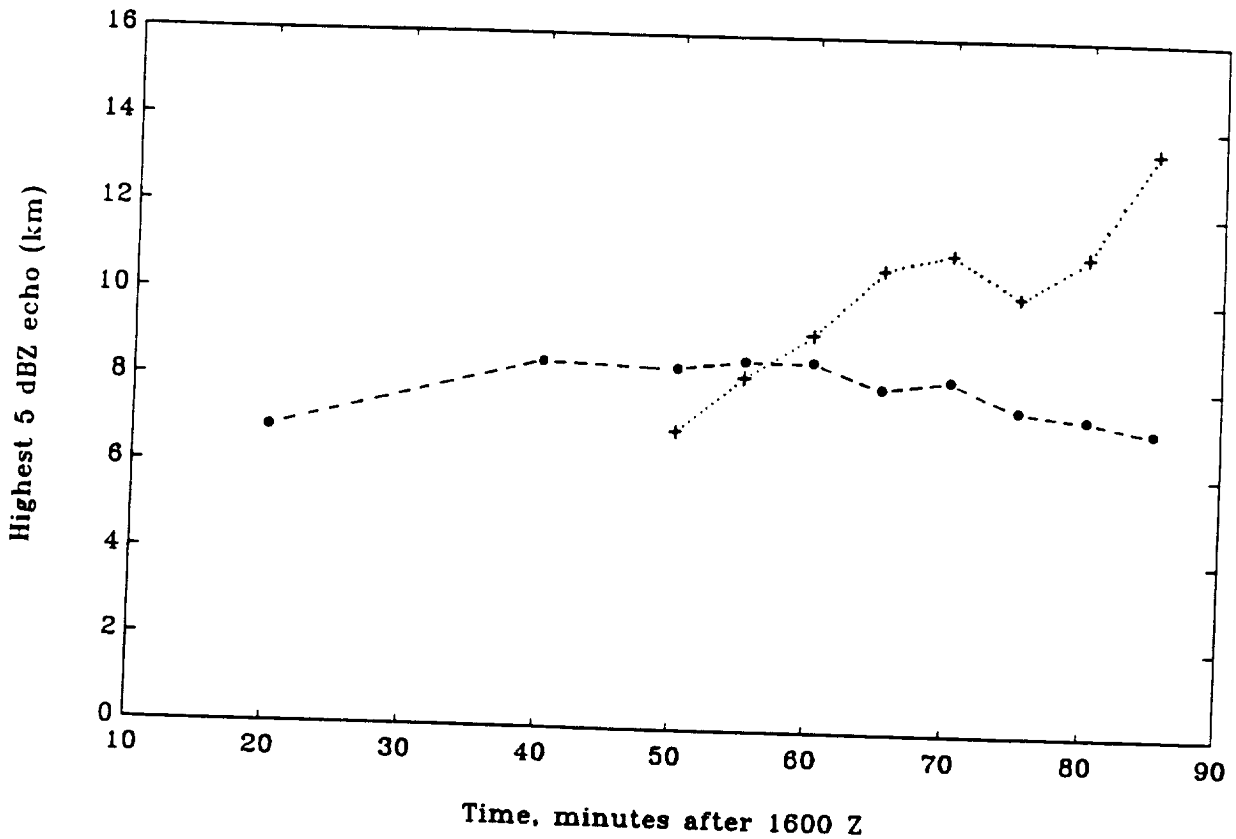


Figure 121: Maximum heights of 5-dBZ echo from the weakly electrified cloud studied on 19 August 1989 (o) and for the later developing cloud to the north (+).

the balloon at 1754:13 Z, all the while at an altitude of 12,000 ft. At 1804:36 Z, SPTVAR once again flew nearly over the balloon. At 1750:40 Z, SPTVAR measured $E_Z = 250$ V/m, while at 1754:13 and 1804:36 Z, SPTVAR measured $E_Z = -200$ V/m and $E_Z = -50$ V/m respectively. SPTVAR began descending at 1759 Z and by 1817 Z was leveling at 1,700 ft while lining up to fly past the electric field mill just below the balloon. SPTVAR passed this upper mill at 1818 Z with the mill about 150 ft off the left wing tip. Unfortunately, the instrumentation at the triggered-lightning site was not ready at that time. SPTVAR made four more passes past the upper mill on the balloon tether and then returned to PAFB. On the fourth and fifth passes the French group and associated personnel were able to record the electric field readings from the various mills on the balloon tether and on the ground. The electric fields measured by SPTVAR, the French mills at 250 and 500 m on the balloon tether, the Marshall-Rust mill at 200 m, and one of the mills on the ground are summarized in Table 4. The three SPTVAR passes at 12,000 ft are included in the table.

During the low altitude passes, SPTVAR measured fair weather field at 500 m altitude. The electric field at the ground and at 200 m agreed with that measured by SPTVAR, but values from the two upper mills disagreed strongly with the SPTVAR measurement. One possible explanation of the disagreement is that the upper mills on the balloon tether were measuring a field due to charge on the tether or on the balloon.

Table 4: Comparison of the vertical component of $\vec{E}$ measured by SPTVAR and four mills on the tether of a balloon at 1,800 ft over the rocket-triggered-lightning site on 19 August 1989.

	Field Mills on Balloon Tether (identified by altitude)				SPTVAR Altitude	
Time (Z)	0 m	200 m	250 m	500 m	3.7 km	500 m
1750:40	−1.0 kV/m	−0.5 kV/m	−2.0 kV/m	−5.0 kV/m	+250 V/m ± 100 V/m	-
1754:26	−1.0 kV/m	+1.0 kV/m	−1.5 kV/m	−3.5 kV/m	−250 V/m ± 100 V/m	-
1804:36	−0.5 kV/m	+0.5 kV/m	−0.8 kV/m	−1.4 kV/m	−50 V/m ± 100 V/m	-
1818:03	-	-	-	-	-	−50 V/m ± 100 V/m
1819:15	-	-	-	-	-	−55 V/m ± 100 V/m
1821:07	-	-	-	-	-	−60 V/m ± 100 V/m
1825:57	0.0 kV/m	0.0 kV/m	−1.0 kV/m	−1.0 kV/m	-	−70 V/m ± 100 V/m
1827:06	0.0 kV/m	0.0 kV/m	−1.0 kV/m	−1.0 kV/m	-	−63 V/m ± 100 V/m

A.3.7 Summary: 26 August 1989 (89238)

Highlights:

- SPTVAR studied a cloud that had become electrified southwest of KSC mills 23 and 25 and moved away toward the south-southwest and thus would not have endangered operations along the Atlantic coastline.
- SPTVAR also investigated the electric field near mill 18 due to a cloud which remained west of the Space Center.

Weak high pressure continued to dominate the southeast United States. A convergence line extended from central Georgia into the Atlantic about 275 km northeast of the Cape. The sounding was very moist. The winds were westerly below 6,000 ft and easterly above. The steering level flow was north-northeasterly at 5 to 10 knots. Activity was expected to form between 1700 and 1800 Z and move inland.

At 1400 Z on this day a large area of precipitation was moving toward KSC and a few lightning flashes were recorded by the LLP lightning location system. The 1200 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 122.

A reproduction of the PC plot of the SPTVAR track for this flight with E_{XY} vectors plotted at intervals along the track is shown in Fig. 123. SPTVAR took off at 1811 Z to study a large cloud over the southwest corner of R2934. This cloud was making lightning by the time SPTVAR approached it, having become electrified somewhere southwest of mill 25. The cloud moved toward the south-southwest and SPTVAR followed it until it was well out of the restricted area. There were many lightning flashes recorded in the electric field mill data from SPTVAR. The cloud was well electrified by 1824 Z and was still electrified at 1915 Z when SPTVAR abandoned the cloud shortly after having measured $E_Z = +50$ kV/m at 1909 Z while at 12,000 ft altitude.

Although this strongly electrified cloud was never directly over the Space Center, 22 of the mills in the KSC surface field mill array recorded numerous lightning-caused electric field offsets. Mills 25 and 23 were the nearest mills to the storm and the electric fields recorded by them suggest that the storm's initial electrification occurred to the southwest, possibly over the Indian River. Since the cloud became electrified southwest of the field mill array and moved to the south-southwest, away from the launch complexes along the Atlantic shoreline, this cloud was not a direct threat to launch operations.

After 1915 Z, SPTVAR sampled the electric field over mill 7 and then made penetrations of a cloud over the western shore of Merritt Island between the NASA and Bennett (highway 528) Causeways. The cloud, with LWC up to 5 g/m^3, was not electrified. Although no significant electric field was recorded during this time, 1915 to 2030 Z, there were a few indications in the data of distant lightning.

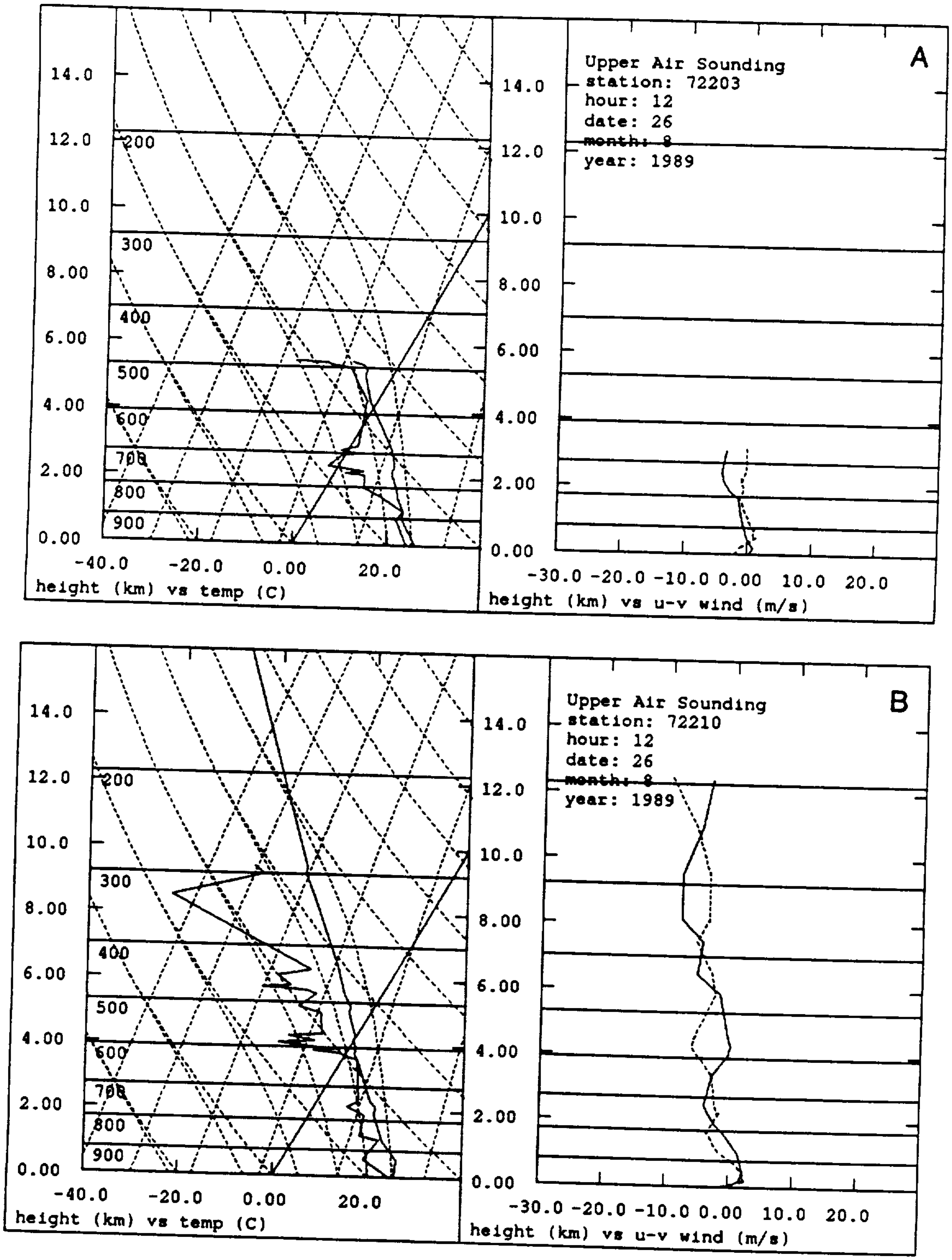


Figure 122: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa (B), Florida, soundings on 26 August 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

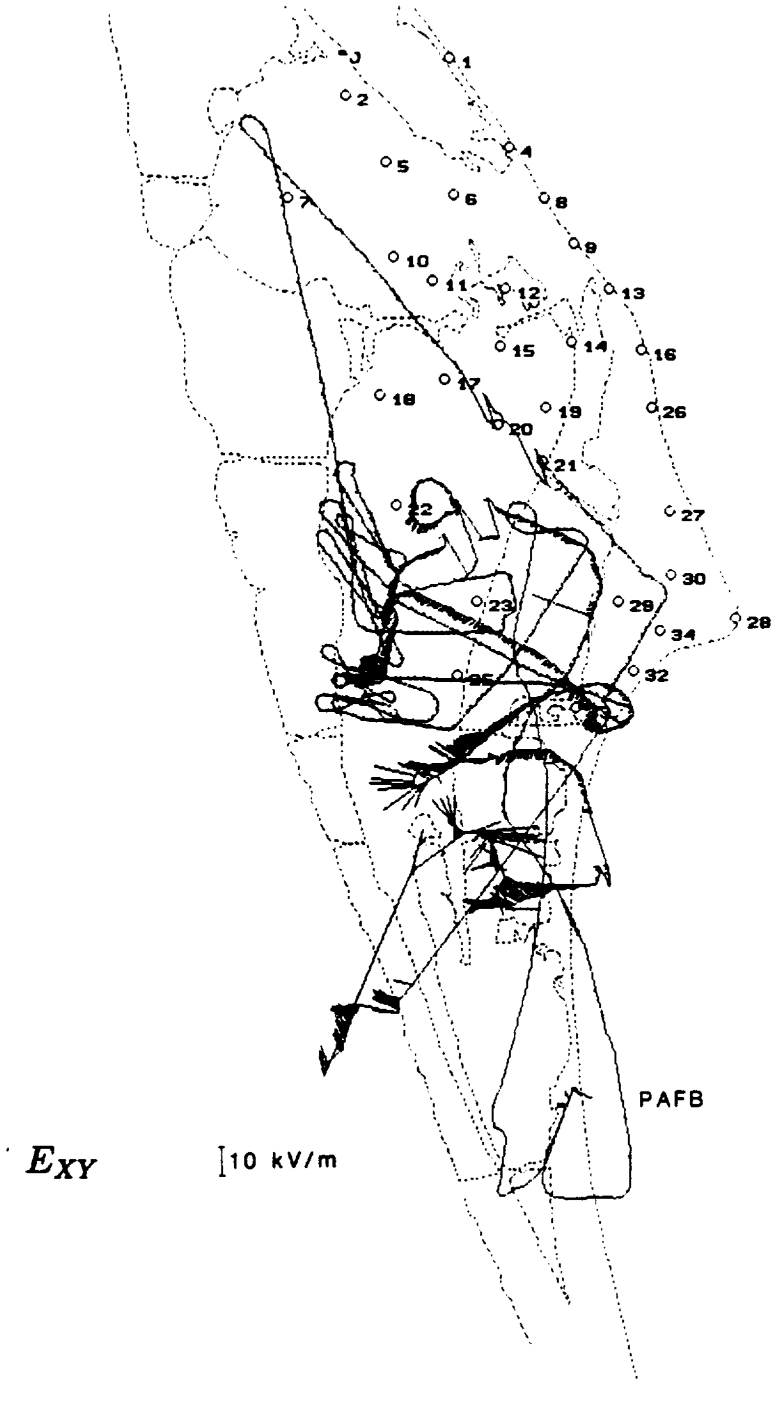


Figure 123: PC plot of E_{XY} vectors along the SPTVAR flight track of 26 August 1989. Some glitches from the Loran positioning system are evident.

A.3.8 Summary: 1 September 1989 (89244)

Highlights:

- SPTVAR investigated clouds over KSC which remained below 20,000 ft (6.1 km) and did not become electrified.
- SPTVAR measured the electric field outside an electrified cloud just west of Titusville. The electric field measurements indicated mostly negative charge in the cloud and above the SPTVAR flight altitude of 12,000 ft (3.7 km).
- Late in the SPTVAR flight both SPTVAR and KSC field mill 7 measured electric field from a cloud that apparently experienced a brief period of electrification as it topped out at about 30,000 ft (9.1 km). However, there was a discrepancy in the times during which the airplane and the surface field mill measured the electric field of negative charge in the cloud. Nevertheless, various launch commit criteria weather rules would not have permitted a launch through or near this cloud.

A high pressure axis extended over the Midwest and down into the Gulf of Mexico through Louisiana and Mississippi. An upper-air trough was forcing the ridge to weaken at the upper latitudes. There was convection over the KSC/CCAFS area at 1200 Z that appeared to be associated with a weak easterly wave. The sounding was relatively moist. The winds veered from southeasterly at 1,000 ft to easterly at 13,000 ft, and northerly throughout the rest of the troposphere. The steering flow was south-southeasterly at 5 knots. Scattered thunderstorms associated with the tropical wave were expected.

The 1200 Z West Palm Beach sounding is shown in Fig. 124.

The SPTVAR flight track is shown in Fig. 125. When SPTVAR took off at 1700 Z there were small clouds over KSC. SPTVAR ascended to 12,000 ft (3.7 km) and studied a cloud over Merritt Island just west of the KSC industrial area and between mills 18 and 22. The cloud failed to develop significantly and began breaking up at its base. SPTVAR moved to a newer cloud just east of mill 18. This cloud also broke up. Only fair-weather electric field was measured by SPTVAR from take-off to 1827 Z while monitoring these clouds over KSC.

Since the clouds over KSC were dissipating, SPTVAR at 1830 Z began to study a cloud west of the Indian River and Titusville. As SPTVAR flew along the southeast side of this cloud the electric field data indicated negative charge in the cloud to the northwest of the SPTVAR path. Figure 126 shows E_{NE} vectors for 1840 to 1853 Z during which time

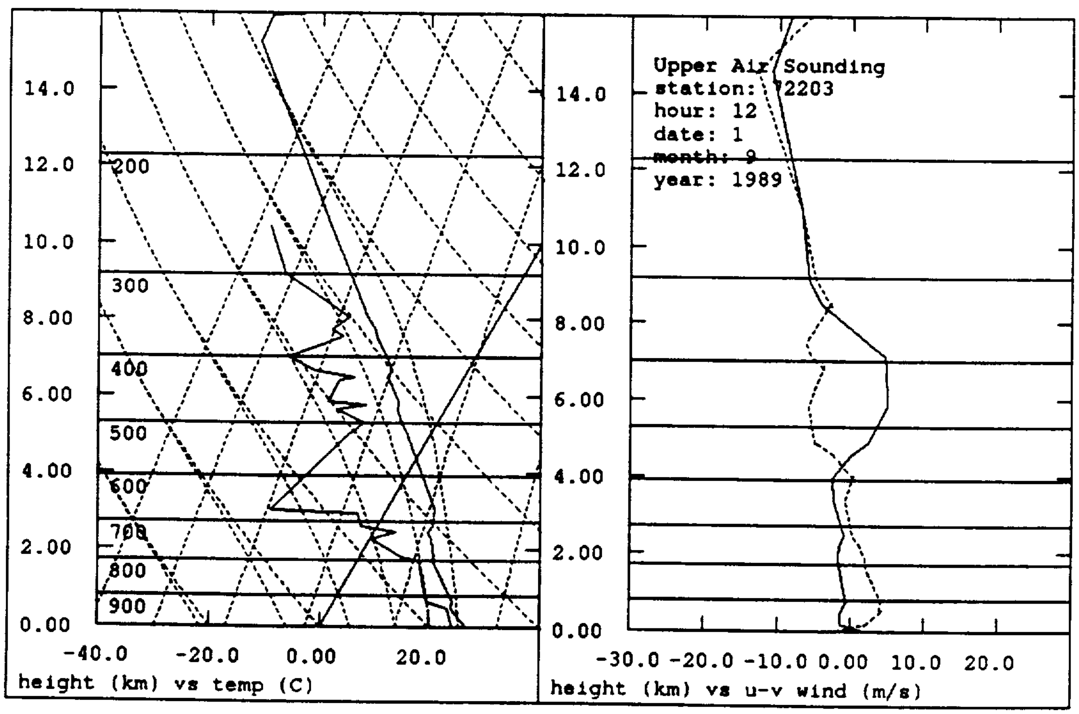


Figure 124: Skew T diagrams for the 12 Z West Palm Beach, Florida, sounding on 1 September 1989. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

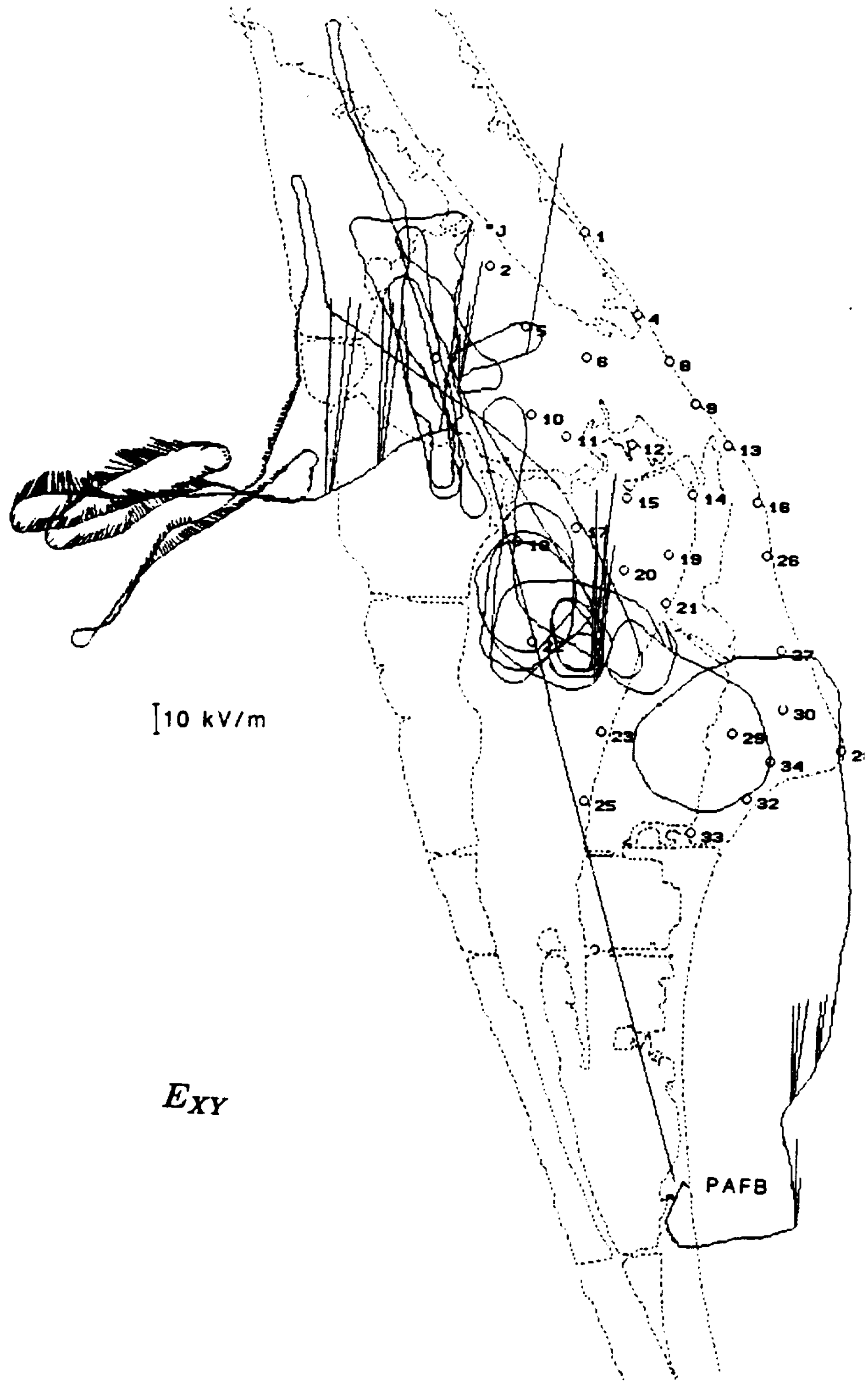


Figure 125: PC plot of E_{XY} vectors along the SPTVAR flight track of 1 September 1989. The anomalous E_{XY} vectors plotted along the flight track are the result of telemetry interference.

SPTVAR made three runs along the side of the cloud. The composite plot of E_{XZ} vectors along the SPTVAR altitude profile in Fig. 127 for these three flight segments confirms the negative polarity of the cloud charge and also shows that the charge was several km above the SPTVAR altitude.

The next two flight segments are shown in Fig. 128. The pattern of E_{NE} vectors during the first segment was somewhat more complicated than on the three previous segments (Fig. 126) with a large lightning-induced field change at the middle. The second (west-to-east) pass had a simpler vector pattern, showing a negative charge north of SPTVAR's flight track. Figure 129 shows the altitude profile and E_{XZ} vectors for these two segments. The vector pattern for the east-to-west pass is not very clear, but that for the west-to-east pass shows once again that the cloud charge was several km above the SPTVAR flight altitude.

At 1915 Z, KSC mill 7, which along with all the other KSC mills had previously been measuring nominal fair weather electric fields, measured $\nabla V = -27$ V/m. The ∇V contour plot for this time, Fig. 130, shows a closed $\nabla V = 0$ contour around mill 7 suggesting the presence of charge aloft. As the electric field measured by mill 7 increased, SPTVAR was directed to investigate the source. For the remainder of the flight, 1920 to 1951 Z, SPTVAR flew parallel to the Indian River and more or less over mill 7. Contour plots of ∇V measured by the surface field mill array covering this period are shown in Fig. 131.

While headed toward the south-southeast at 1918 Z, SPTVAR's pilot described the cloud over the mill 7 area as having reached 30,000 ft and become soft on top. The SPTVAR flight path from 1920 to 1931 Z is shown in Fig. 132. At first SPTVAR flew toward the south and while passing through the cloud, **A** to **B** in the figure, measured E_{NE} vectors the convergence of which indicated negative charge to the southwest of mill 7. After exiting the cloud at **B**, SPTVAR turned back north, reentering the cloud at **C**. The E_{NE} vectors before and after the turn have a persistent direction which once again illustrates the satisfactory calibration of the SPTVAR electric field measurement. Shortly after SPTVAR reentered the cloud while headed north the electric field at SPTVAR returned to fair-weather values. SPTVAR passed mill 7 and exited the cloud at **D**.

Figure 133 shows that at 1931 Z SPTVAR turned toward the west, passed through a cloud while turning toward the south, **A** to **B**, and flew just west of mill 7 at about 1935:40 Z. The divergence of the E_{NE} vectors at 1935 Z as SPTVAR approached mill 7 indicates that there was then a positive charge (**C**) to the northwest of mill 7. Farther south the vectors appear to have converged, indicating a weak negative charge south of mill 7. A plot of E_{XZ} vectors along the SPTVAR altitude profile for the portion of the flight shown in Fig. 132 during which SPTVAR was headed south-southeast, Fig. 134, shows that the positive charge was one or two km above the 12,000 ft (3.7 km) flight altitude. The figure also shows that the apparent small negative charge south of mill 7 was below the SPTVAR flight level. During this passage SPTVAR's pilot commented that the cloud was apparently

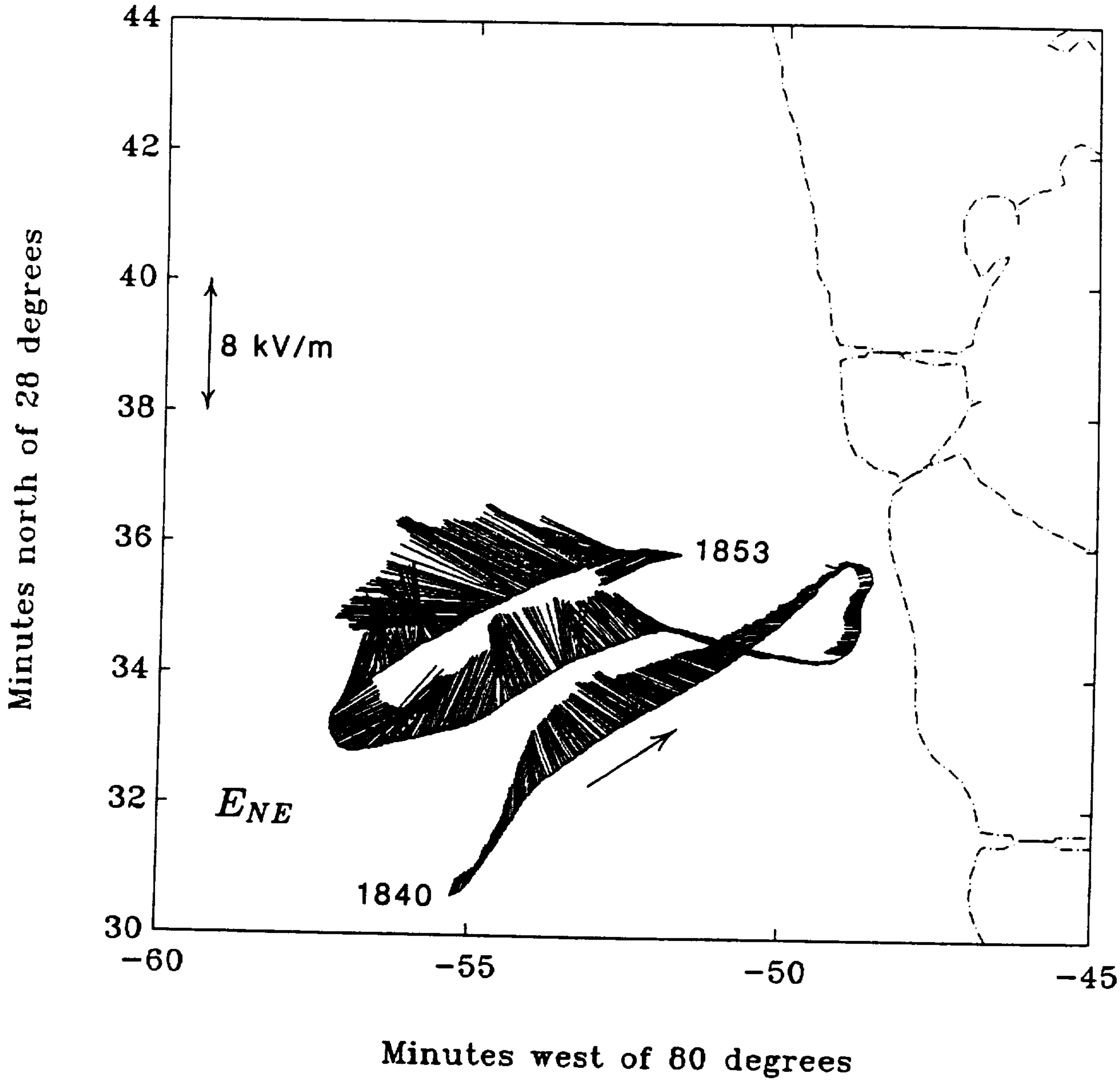


Figure 126: E_{NE} vectors plotted along the SPTVAR flight track from 1840 to 1853 Z on 1 September 1989.

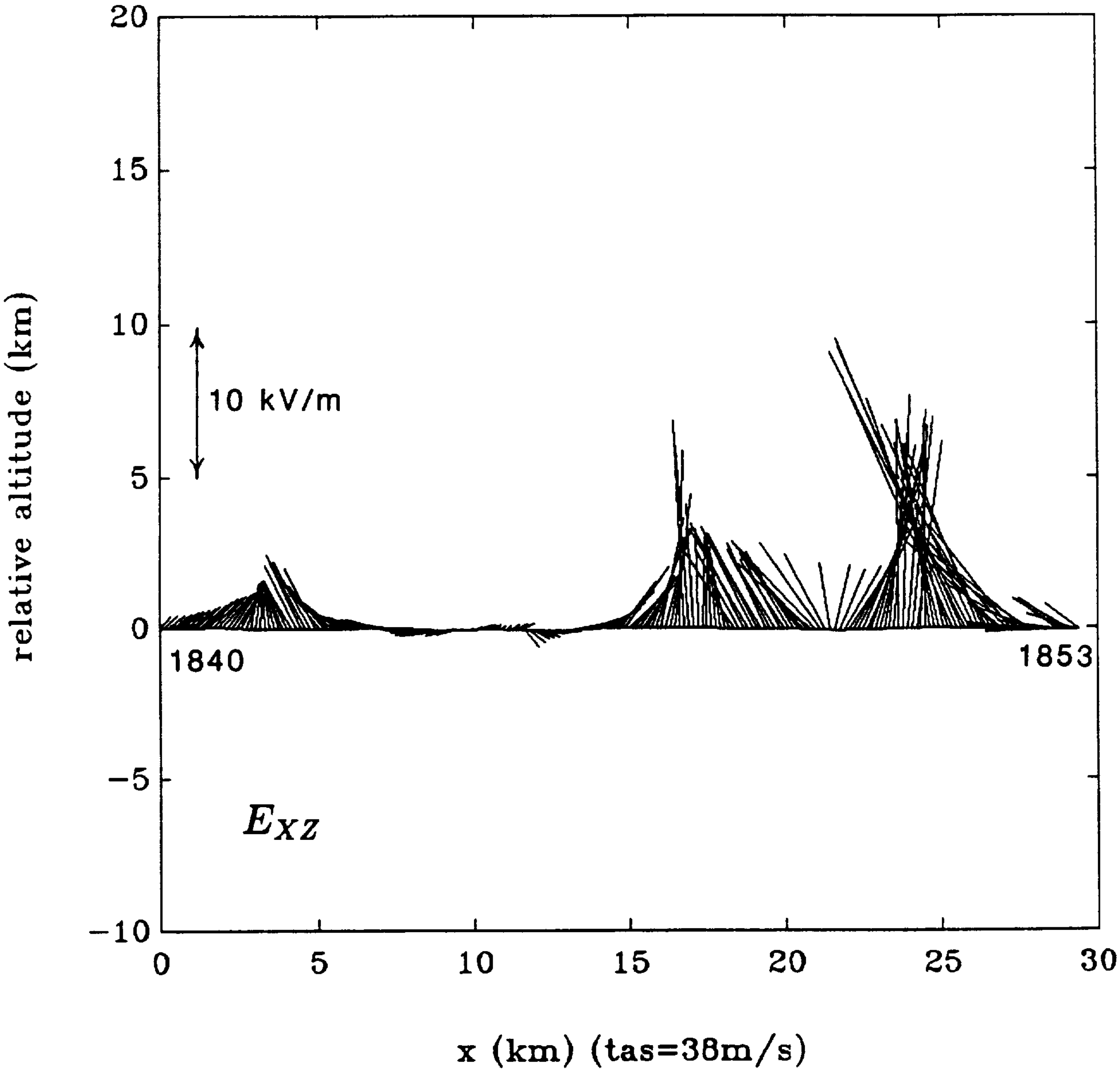


Figure 127: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1840 to 1853 Z on 1 September 1989.

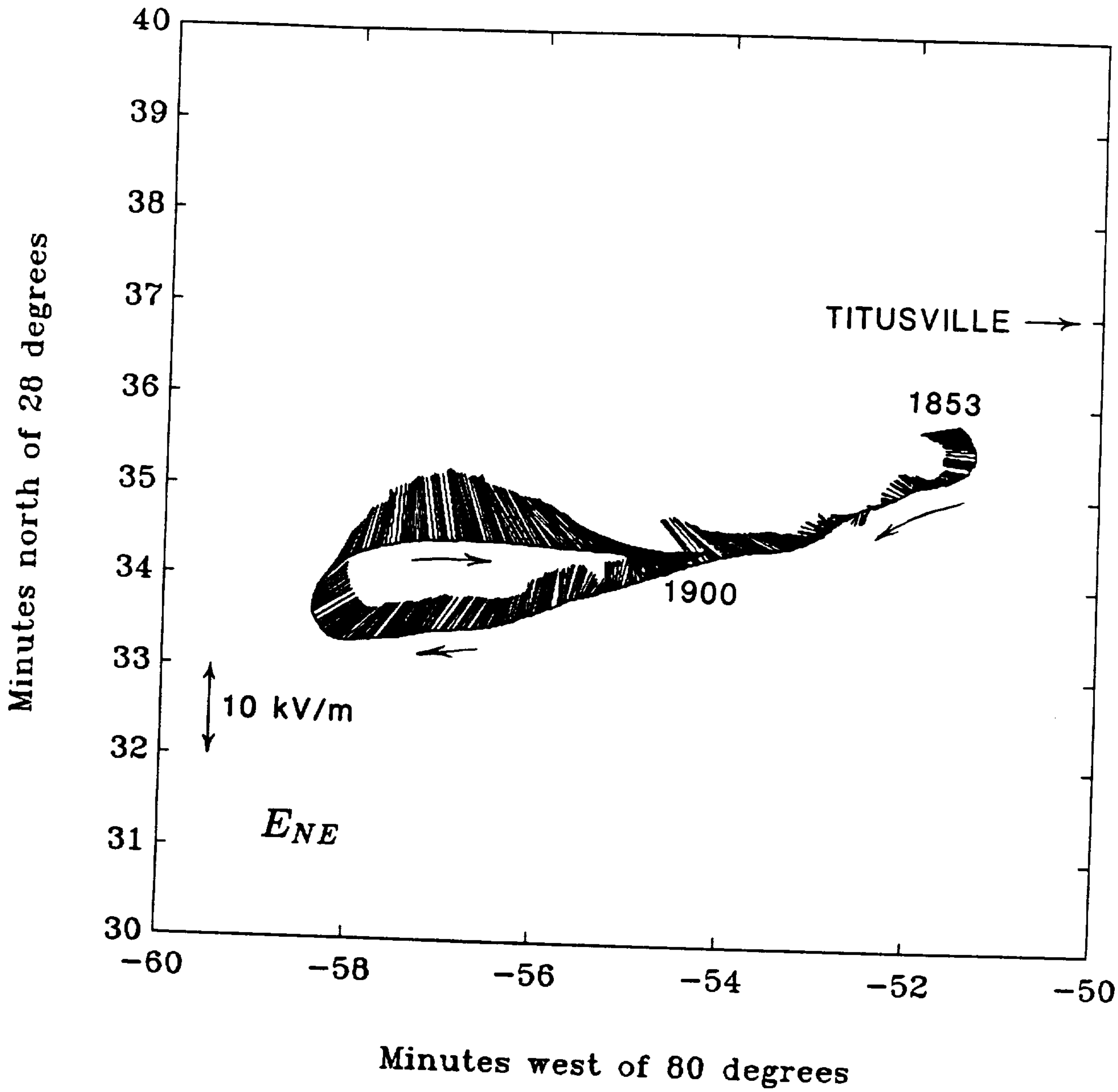


Figure 128: E_{NE} vectors plotted along the SPTVAR flight track from 1853 to 1900 Z on 1 September 1989.

C3

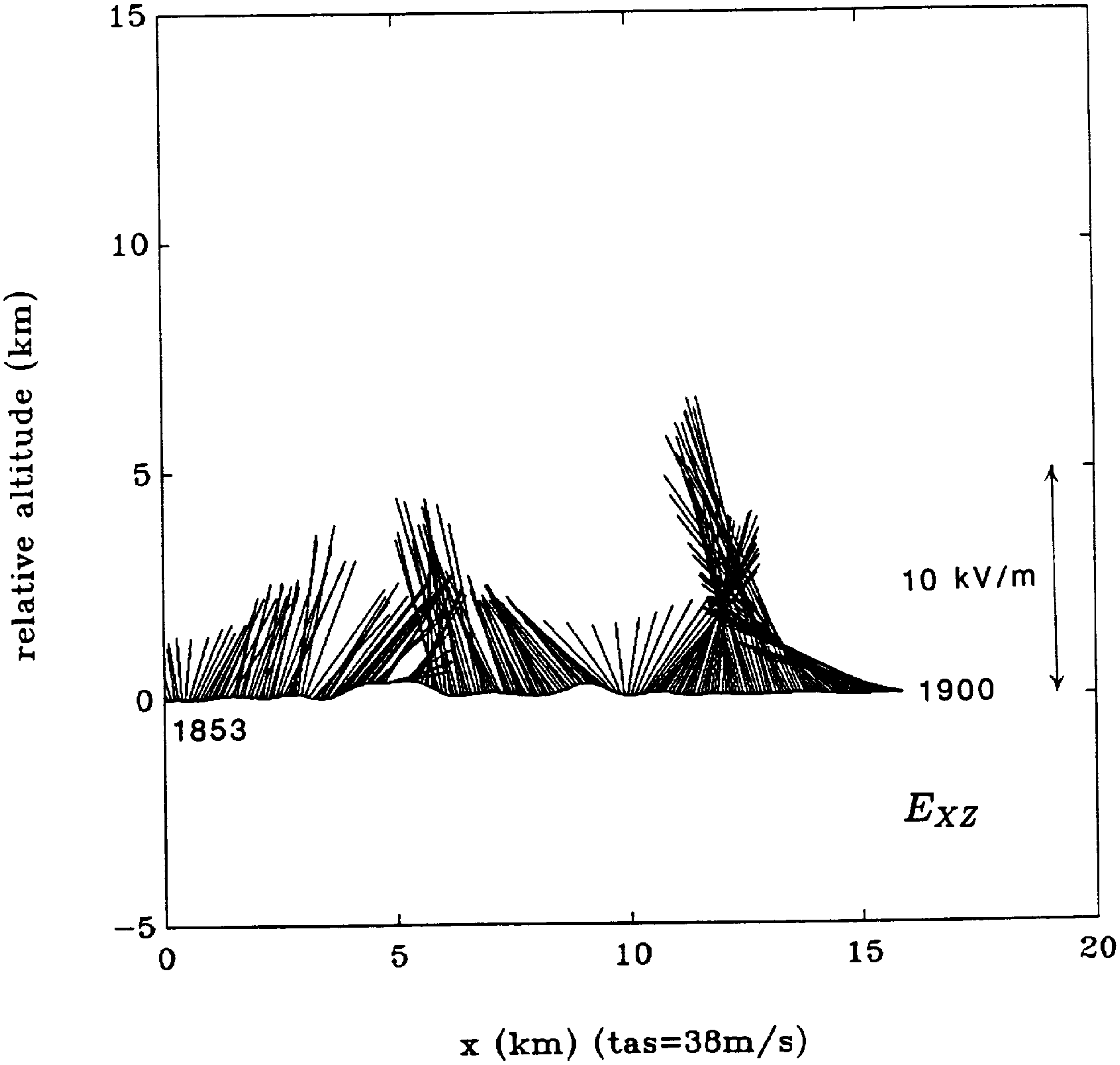


Figure 129: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1853 to 1900 Z on 1 September 1989.

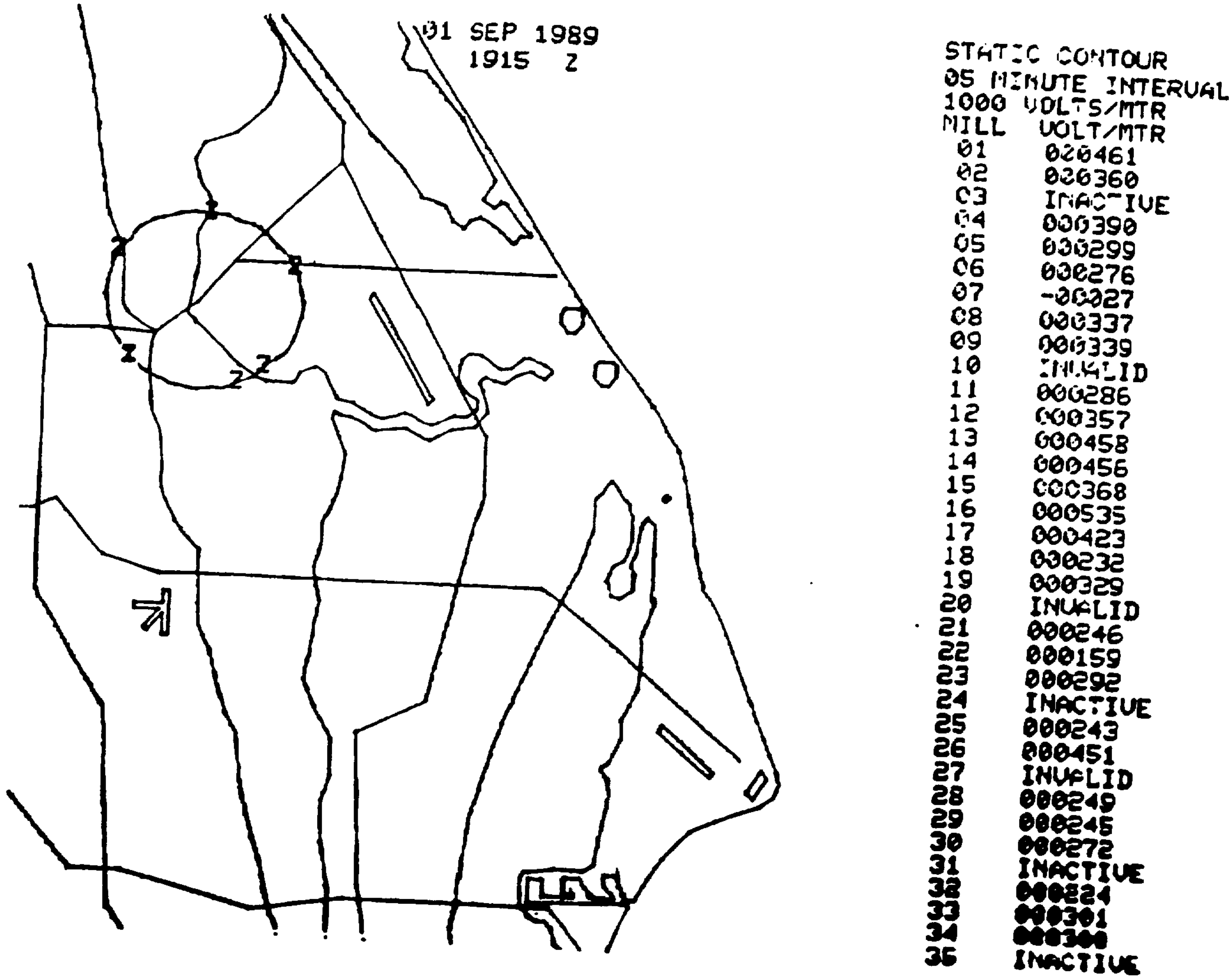


Figure 130: KSC surface ∇V contour plot for 1915 Z on 1 September 1989. Note the closed contour around mill 7.

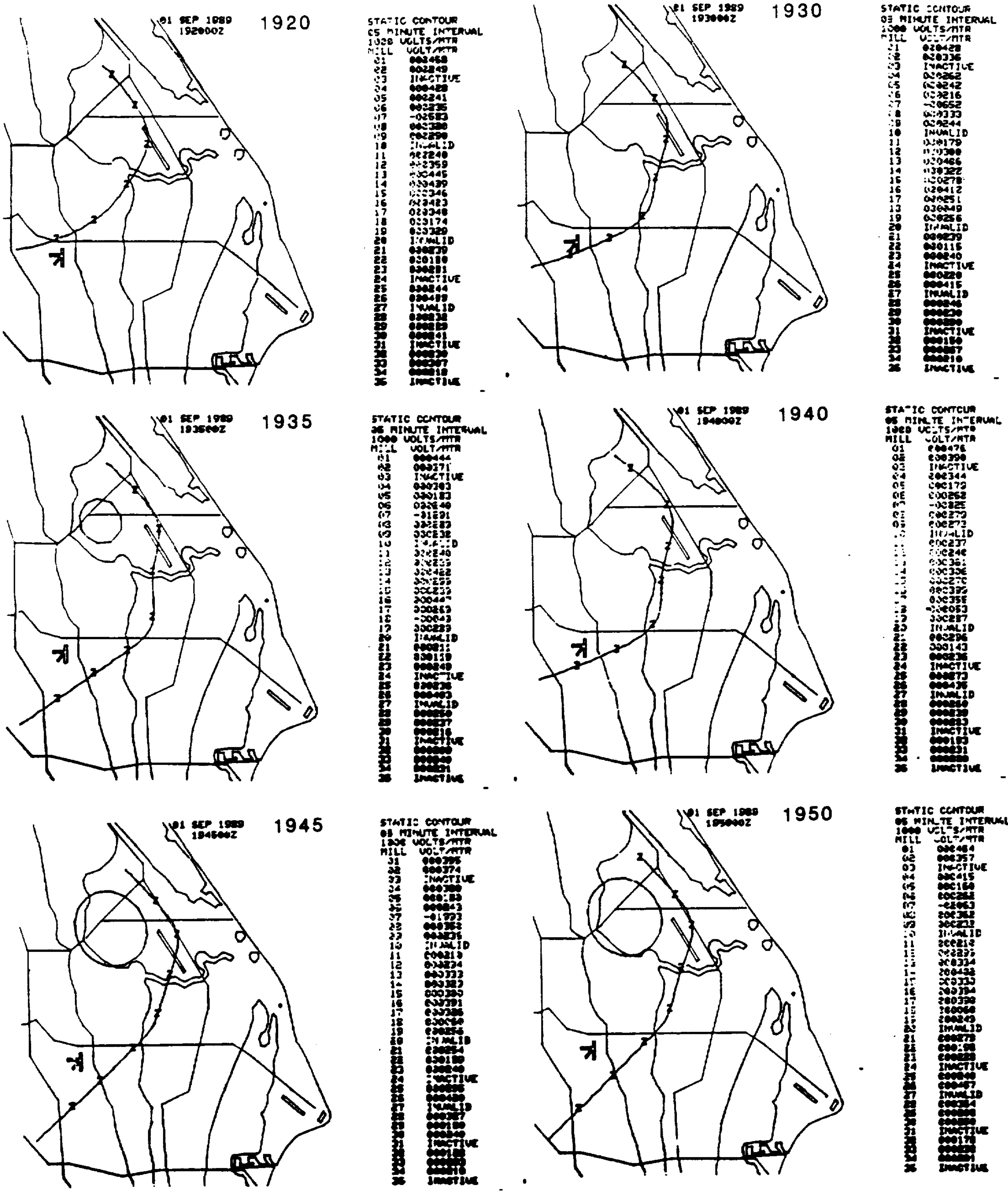


Figure 131: KSC surface ∇V contour plots for 1920 to 1950 Z on 1 September 1989. The plot for 1925 Z has been skipped since it is much like the one for 1930 Z. Note the closed contours around mill 7 at 1935, 1945 and 1950 Z.

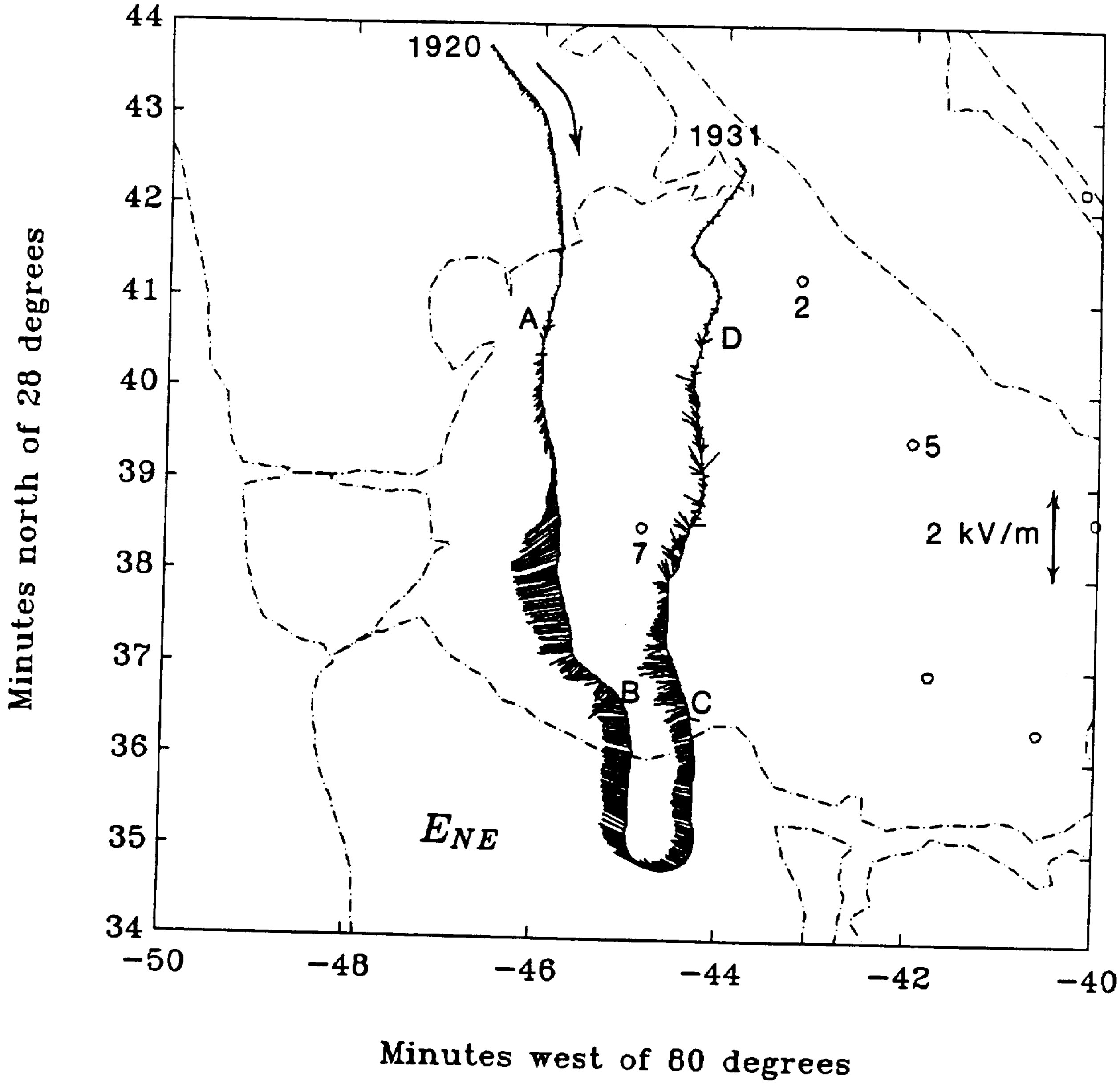


Figure 132: E_{NE} vectors plotted along the SPTVAR flight track from 1920 to 1931 Z on 1 September 1989.

disintegrating and that he "...must be chopping along [the] bottom of what is left of [the] cu[mulus]." (The brackets enclose editorial material that has been added.)

After turning back toward the north at 1939 Z, SPTVAR flew just to the east of mill 7 as shown in Fig. 135. At 1942 Z when just north of mill 7, the SPTVAR data again indicates a small positive charge. This charge is not, however, apparent in the data after SPTVAR turned back toward the south and passed just west of mill 7 at about 1947 Z.

During the time that SPTVAR was flying back and forth near mill 7, the electric field measured by mill 7 was consistently positive and reached a peak value of about +3 kV/m at 1951 Z. The KSC strip-chart recording of the electric field measured by mill 7 from 1910 to 2010 Z is shown in Fig. 136.

The SPTVAR pilot's observations and the electric field measurements made by SPTVAR at 12,000 ft (3.7 km) suggest the following scenario. The cloud grew to about 30,000 ft (9 km) and experienced a brief period of electrification just before its dynamic growth stage came to an end and the top "went soft." At 1923:30 and 1937 Z, SPTVAR measured the electric field of the cloud's negative charge as it fell toward the ground on precipitation. At 1935 and 1942 Z, SPTVAR measured the electric field of the cloud's positive charge, always above the negative charge, as it also fell toward the ground. The negative charge fell to the ground well south of mill 7, while the positive charge did so just north of mill 7.

On the other hand, the strip-chart recording shows the electric field measured by mill 7 to have been always positive from 1915 to 1957 Z and to have reached its peak value of about −3 kV/m at 1951 Z. Thus, mill 7 appears to have responded primarily to the negative charge with the positive charge perhaps responsible for the dip from 1934 to 1943 Z in the strip-chart recording of the electric field that it measured. The surface ∇V contour display did not directly reveal the positive charge. However, the $\nabla V = -1$ kV/m contour first present around mill 7 at 1935 Z and again at 1945 and 1950 Z (Fig. 131) was not present in the plot for 1940 Z because of the dip in the electric field at mill 7 apparently caused by the positive charge.

There is an unresolved disparity between the SPTVAR and mill 7 electric field measurements. The latest that SPTVAR measured electric field from negative charge was at 1937 Z, while mill 7 measured the strongest negative charge electric field at 1951 Z, some 14 minutes later!

The flight was terminated at 2008 Z.

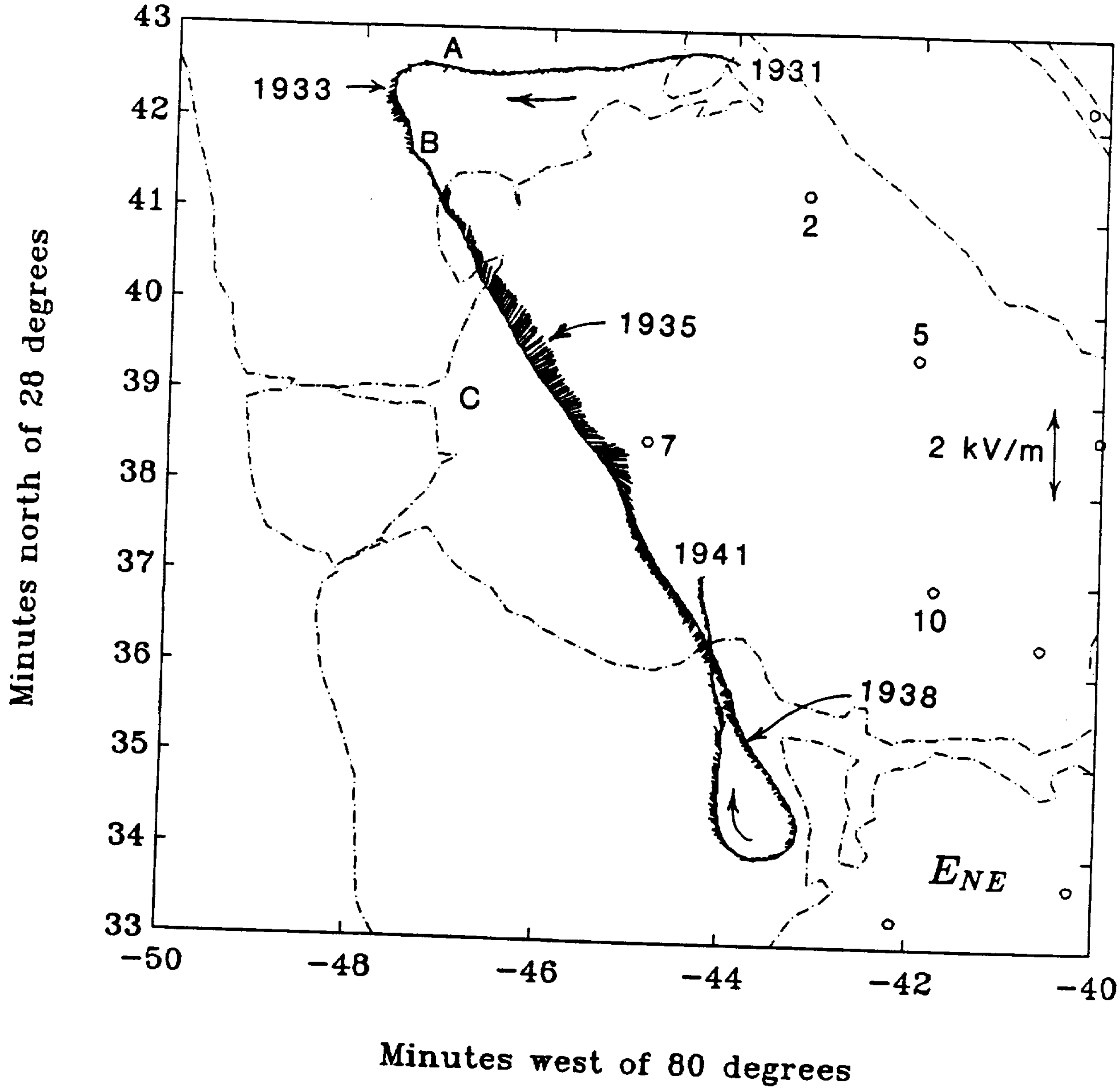


Figure 133: E_{NE} vectors plotted along the SPTVAR flight track from 1931 to 1941 Z on 1 September 1989.

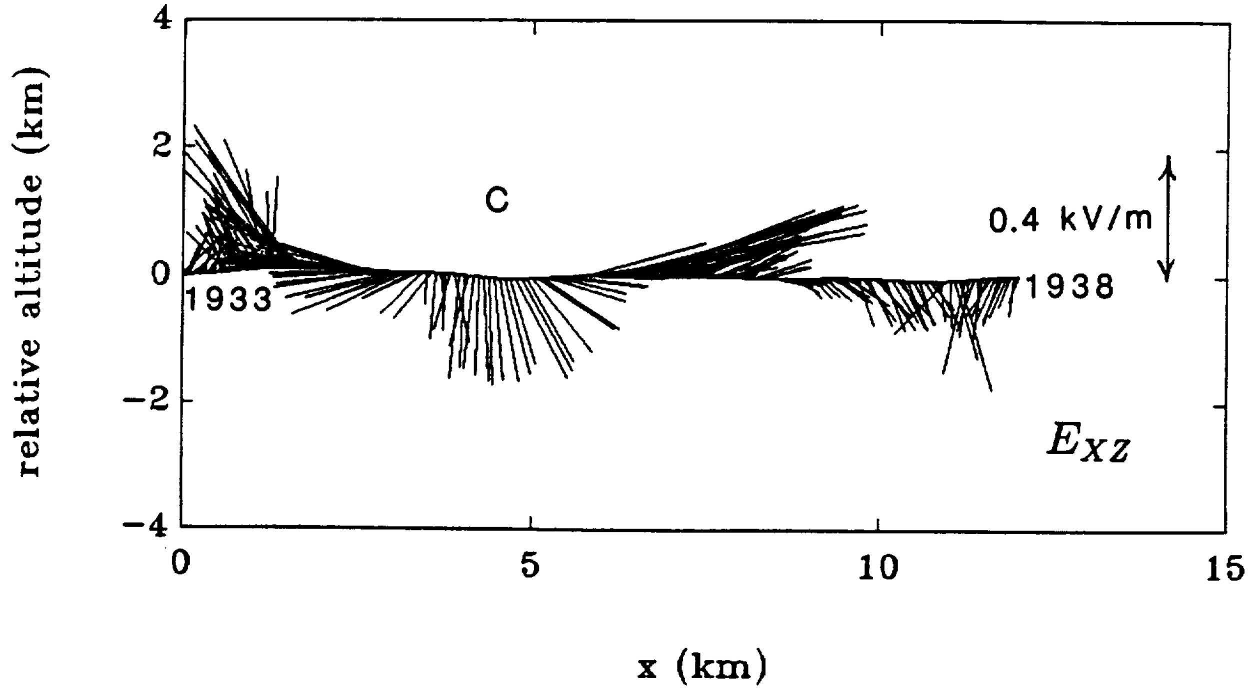


Figure 134: E_{XZ} vectors plotted along the SPTVAR altitude profile for 1933 to 1938 Z on 1 September 1989.

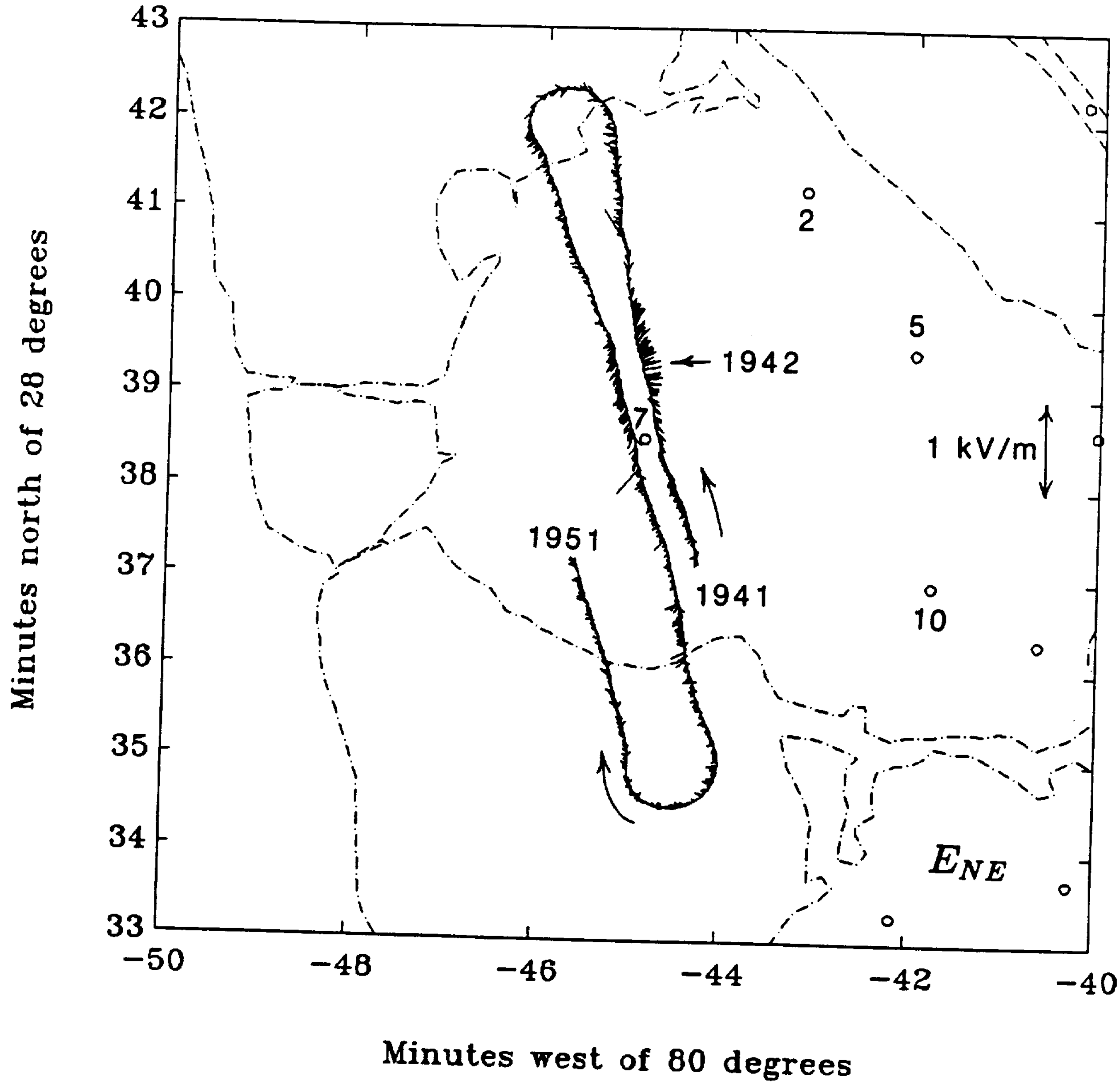


Figure 135: E_{NE} vectors plotted along the SPTVAR flight track from 1941 to 1951 Z on 1 September 1989.

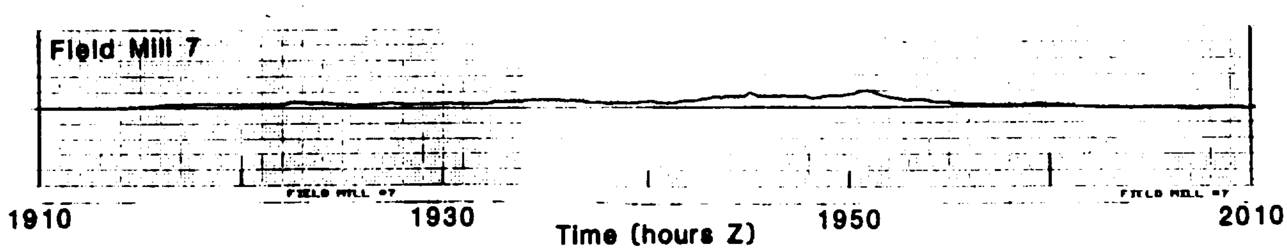


Figure 136: Strip chart recordings of electric field measured by KSC field mill 7 between 1910 and 2010 on 1 September 1989.

A.4 References

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B Acronyms Used in this Report

Acronym	Meaning
AFB	Air Force Base
ACS	Airplane Coordinate System
ARTCC	Air Route Traffic Control Center
CCAFS	Cape Canaveral Air Force Station
CIF	Communication and Instrumentation Facility
Cu	Cumulus (cloud)
EDT	Eastern Daylight Time
GCS	Geographic Coordinate System
KSC	Kennedy Space Center
LCS	Level-flight Coordinate System
LLP	Lightning Location and Protection (a corporation)
LWC	Liquid Water Content
NASA	National Aeronautics and Space Administration
NMIMT	New Mexico Institute of Mining and Technology
ONR	Office of Naval Research
PAFB	Patrick Air Force Base
PC	Personal Computer
RCC	Range Control Center
RH	Relative Humidity
SPT	PC computer program for plotting airplane ground track
SLF	Shuttle Landing Facility
SPTVAR	Special Purpose Test Vehicle for Atmospheric Research
Z	Universal coordinated time (Zulu)