Aircraft Measurements of Atmospheric Electricity Including Ionospheric Potential

Fair-Weather Electrical Properties of the Atmosphere

Global Electrical Circuit

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Abstract

A modified dedicated atmospheric electrical research aircraft has been used to study fair-weather conditions over the ocean. Measurements include interactive parameters including: electric field, both polar conductivities, aerosols, temperature, relative humidity, turbulence, sea surface temperature and ionizing radiation.

The oceanic regime is advantageous compared to over land for studying fair-weather electricity and the global circuit because of clean air and no thermal activity from ground heating. Also there is no radon or ionizing radiation from uranium by-products in the ground which affect conductivity and electric field at ground locations.

However, oceanic conditions have a problem. There always is an electrode effect causing a positive space charge layer in the lower roughly 100 meters, mostly concentrated near the surface. This space charge causes increases of electric field near the ocean typically in the range of 20 to 80% of the unamplified fair-weather field intensity. This space charge blanket would have strongly affected the Carnegie electric field measurements which have generally been accepted as the gold standard for the absolute value of Earth's fair-weather electric field intensity. This sailing ship's masts and moveable rigging also would have affected the measurements. The classic "diurnal variation" of fair-weather electric field intensity obtained from the Carnegie data is of great importance in global circuit research, but in the presence of space charge it could have been influenced by diurnal variations in wind and eddy diffusion that sometimes exist over the ocean.

It is found that cosmic radiation, the source of most atmospheric ionization and thus conductivity, is responsible for only about 10% of the radiation at ground level, the remaining 90% is from radon and radiation emitters in the ground. Over the ocean cosmic radiation provides all the ionization so the ionization rate is 10% of the rate over ground containing uranium, which includes most of Earth's land surface.

Vertical profiles show the inverse relationship of conductivity and electric field intensity with variations caused by aerosols. A basic feature of the exchange layer often found over the ocean is a rapid decrease in conductivity and increase in electric field in the upper part of the mixed layer due to the growth of hygroscopic aerosol. When the relative humidity reaches about 80%, deliquescence occurs and water vapor causes the particles to grow rapidly, thus reducing their mobility. Thus electric field profiles can show large values in the upper half of the planetary boundary layer up to the inversion.

Recent electric field soundings have provided the first estimates of ionospheric potential in recent years. Absolute values will not be available until the aircraft electric field system is recalibrated, but initial estimates suggest Vi is about the same as the last measurements in 2004. Additional Vi measurements will be made and reported.

Aircraft Measurements of Atmospheric Electricity Including Ionospheric Potential

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This talk will show how various environmental factors affect atmospheric electric structure from ground level up through the atmosphere and describe some interesting findings from hundreds of aircraft and balloon electric field and conductivity soundings. Our measurements in the electrode layer over the ocean are the only ones of this kind.

When I began studying the global circuit in the early 1970s, it became clear that its temporal variation could not be observed reliably from the ground because of environmental noise, and that measuring its magnitude would require ionospheric potential (Vi) electric field soundings. Therefore, as a pilot with an airplane, I decided to use the aircraft to make the measurements and developed instrumentation to make reliable fair-weather electric field measurements from the aircraft. To minimize noise the initial research was done over the ocean in the Bahamas where clean trade-wind air has traveled across the Atlantic. This research has continued with aircraft measurements obtained mostly over the ocean. Balloon soundings were also made over land and some Pacific islands. To date 323 Vi soundings have been obtained which provide a unique library characterizing the electrical structure of the atmosphere over land and sea. In several experiments Vi measurements were made periodically through 24-hour periods to observe the universal-time diurnal variation of global circuit intensity. Kasemir (PAGEOPH 100, p. 70) has reported that from a ship at sea, 7 or more days of data must be averaged for the UT diurnal pattern to appear. We find a single day's UT variation can be measured in real-time through a series of Vi soundings.

Fig. 1. There are two major environmental factors affecting atmospheric electrical measurements. Over land there are aerosols, radon and other ionizing radiation from the ground which modulate conductivity and electric field intensity. Over the ocean there is a layer of positive space charge due to the electrode effect.

Fig. 2. Use of an aircraft provides a way to make soundings and obtain data in favorable cloud-free oceanic locations distant from sources of pollution, radon and ionizing radiation from the ground. Since the same system is used for each

measurement, variations due to differences between sensors are eliminated.

Fig. 3. This map shows the locations and number of soundings where Vi data have been obtained. So far 238 aircraft and 85 balloon soundings have been made. Locations include both hemispheres from Darwin, Australia to Spitzbergen, north of Norway. Some of these were simultaneous Vi soundings made by two aircraft or balloons in widely separated locations to verify the assumption that the ionosphere, away from polar cap regions, is in effect an equipotential surface.

Fig. 4. The meteorological research aircraft used since 1980 is this Beechcraft Baron with 380 hp turbocharged engines giving it a ceiling of 33,000 feet. Two engines provide safety for ocean flying. Instrumentation includes electric field, both polar conductivities, aerosols, microturbulence, scintillometers for gamma radiation (which includes cosmic radiation, radon and emanations from the ground), a Geiger counter (for alpha, beta and gamma radiation}, temperature, relative humidity and sea surface temperature with an infrared thermometer. Three Gerdien tube conductivity sensors mounted under the wing are not seen here.

The electric field system uses radioactive probes 1 meter apart on a vertical mast at the wingtip. The differential electrometer is in the wingtip close to the antenna to reduce input capacitance and response time. The outer 2 meters of the wingtips are covered with electrically conductive paint to stabilize the distribution of charge on the wing surface so the geometry of the resulting electric field remains constant and can be common mode rejected.

Fig. 5. The electric field system must be calibrated in flight since on the ground the aircraft would be grounded which would change the electric field being measured. To calibrate a series of low passes are made past an electric field system on the ground. The top part of the vertical mast with a radioactive probe 1 meter above the ground was cut off in the photograph.

Fig. 6. It is necessary to consider ionizing radiation from Uranium bi-products in the ground which is the major source of atmospheric conductivity near the earth's surface. Gamma radiation is measured with two 3-inch diameter sodium iodide scintillometer tubes. They are arranged one over the other separated by a horizontal 2 cm thick lead plate in order to differentiate radiation from the ground from cosmic radiation mostly coming from above. The figure shows that when the aircraft is on the ground taxiing for takeoff, the bottom tube has a higher count rate than the top tube which is shielded from much of the ground radiation by the lead plate. The solid line shows altitude. After takeoff, by about 100 meters altitude, the signals drop to about 10% of what they were at ground level because most of the ground radiation is screened and cosmic radiation provides most of the signal. Thus we find that near the ground, ionization from sources in the earth is much stronger than cosmic radiation, which

controls most of the atmosphere's conductivity above about 100 meters. After takeoff there is a reversal and the top tube detecting cosmic radiation has a higher count rate than the bottom tube because most of the radiation from the ground is left behind. At 10,000 feet the cosmic radiation rate is about twice what it was near the ground. After landing the top and bottom rates again reverse with the bottom becoming larger and the rates increase by a factor of 10 to their pre-takeoff levels.

Fig. 7. Electric field measurements by the Carnegie research vessel have provided much of the fundamental information used to develop the global circuit model. The "Carnegie curve" universal-time diurnal variation, derived from averaging electric field data from 82 selected fair-weather days during its last cruise in 1929, turns out to be a reliable estimate. This is remarkable since the measurements were made from a ship sailing in a sea of always present electrode effect space charge that, with the turbulence generator over the ocean (as with the convective generator over land), would enhance field intensity and make it quite variable. This picture shows the ship and its rigging that would greatly influence the measurements which were made from the stern of the ship. The ship's structure and sails would cause a large and variable reduction factor that would affect the electric field. As explained in Chalmers' textbook, electric field measurements obtained with a reduction factor, in the presence of space charge, cannot be accurate since some of the lines of force will terminate on the variable space charge rather than on a flat ground plane, and the reduction factor will not be constant.

The issue of the Carnegie measurements being influenced by the electrode effect space charge and turbulence generator as well as the variable reduction factor affecting their accuracy is discussed because these measurements are often considered as the "gold standard" for fair-weather electric field measurements.

Fig. 8. This is the "Carnegie curve" diurnal variation of electric field obtained from the selected days' electric field measurements. The mean is in the 130-140 V/m range which is consistent with our and other's measurements

Fig. 9. This figure detailing the electrode layer over the ocean comes from 77 soundings in the Bahamas; it shows the accumulation of positive space charge below about 100 meters. The space charge density decreases rapidly from about 100 elementary charges per cm^2 at 10 meters to about 10 at 100 meters and 2 at 500 meters. Note that on days with no whitecaps, i.e., low wind velocity, the space charge density near the surface is almost twice as high as on windy days with whitecaps, due to turbulent dispersion.

Fig. 10. The large and variable effects of space charge on the electric field over the ocean are seen in these low altitude measurements. Aircraft altitude is shown by the heavy line at the bottom of the graph. After the descending Vi sounding, the aircraft

flew at about 20 feet above the ocean where the electric field varied from about 150 to 240 V/m. The electric field increases are due to plumes of positive space charge carried aloft by turbulent air motions. As the aircraft made 20-mile runs at increasing heights, the intensity decreased at each step. Above the inversion at 3500 feet the trace smooths out as there are no more updrafts. (Conductivity not shown here.)

Fig. 11. This figure shows details of electric field variations on two 20-mile runs at 20 feet on a different day. The electric field varies from about 120 V/m minimum to over 200 V/m maximum. One can estimate the average electric field intensity without the turbulence generator over the ocean, in other words due to the global generator, by looking at the minima among the quasi-periodic variations as these are at locations where there is no enhanced field from accumulations of positive charge overhead; the low point average is about 120 V/m. After the aircraft climbed to 2000 feet on the right side of the record there were no more electric field fluctuations. The two polar conductivities are also depicted and show no fluctuations; so the electric field variations had to be caused by space charge.

Fig. 12. This dual sounding of electric field and conductivity over the ocean illustrates the convective generator. Above the inversion at 1 km they track each other inversely as expected. (They appear to be in phase here because the conductivity sensor output voltage is negative.) From the inversion down to the sea surface the conductivity remains constant but there is an increase of electric field by more than a factor of two due to the electrode effect space charge carried upward by air motions. Our data shows that this generator contributes on average about half as much as electrified clouds to electric field intensity near the ocean surface. Both generators together produce the electric field in this region.

Fig. 13. A major effect on electric field profiles over the ocean is caused by the growth of sea salt particles from absorption of water vapor, which is called "deliquescence". Relative humidity increases with altitude. At about 75% relative humidity a rapid growth of the sea salt particles begins leading to a sharp decrease in ion mobility and conductivity with a corresponding increase in electric field creating a characteristic "ledge" in the electric field profile. This figure illustrates an extreme example of a ledge in the upper part of the marine boundary layer due to deliquescence. In the dry air above the inversion there is a rapid decrease in electric field due to the increase in conductivity. Electric field soundings always show this characteristic rapid decrease at the inversion. The sounding also shows the ever present electrode layer close to the ocean. Earlier on this flight the aircraft took off from Albany, New York where, over land, there were no sea salt particles and no ledge.

Fig. 14. Finally the time history of ionospheric potential is brought up to date. The last previous measurements were in 2004 as reported in Markson, Bull. AMS, Feb.

2007. Recently there have been opportunities to make 10 additional Vi measurements in 2011 and 2013. The new data show no change from the range of earlier measurements back to 1966. This was just after the 1962 – 1966 period when there was an anomalous increase in Vi due to intense atmospheric nuclear testing for a few years prior to the anticipated onset of the test ban treaty in October 1963.

It is hoped that there will be opportunities to obtain additional Vi measurements in coming years.

Aircraft Measurements of Earth's Electric Field and Controlling Factors over Land and Ocean

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- Modulating factors over land: man-made and natural aerosols, radon, ionizing radiation from the ground, thermal convection
- Modulating factors over the ocean: the electrode layer of space charge, turbulent plumes of space charge, deliquescence of sea salt particles

Fig. 1

Why Aircraft Electric Field Soundings are the Best Way to Measure Vi

- Aircraft can conduct soundings over the ocean which has cleaner air and no thermal convection from heating of the ground.
- Aircraft can fly to a favorable region with no or few clouds.
- The same instrument is used for all measurements avoiding calibration differences between different sensors, e.g., as with radiosondes.
- Aircraft can spiral upward in the same columnar resistance cylindrical volume thus avoiding errors from making the sounding in cylinders with different electric field profiles.

Fig. 2

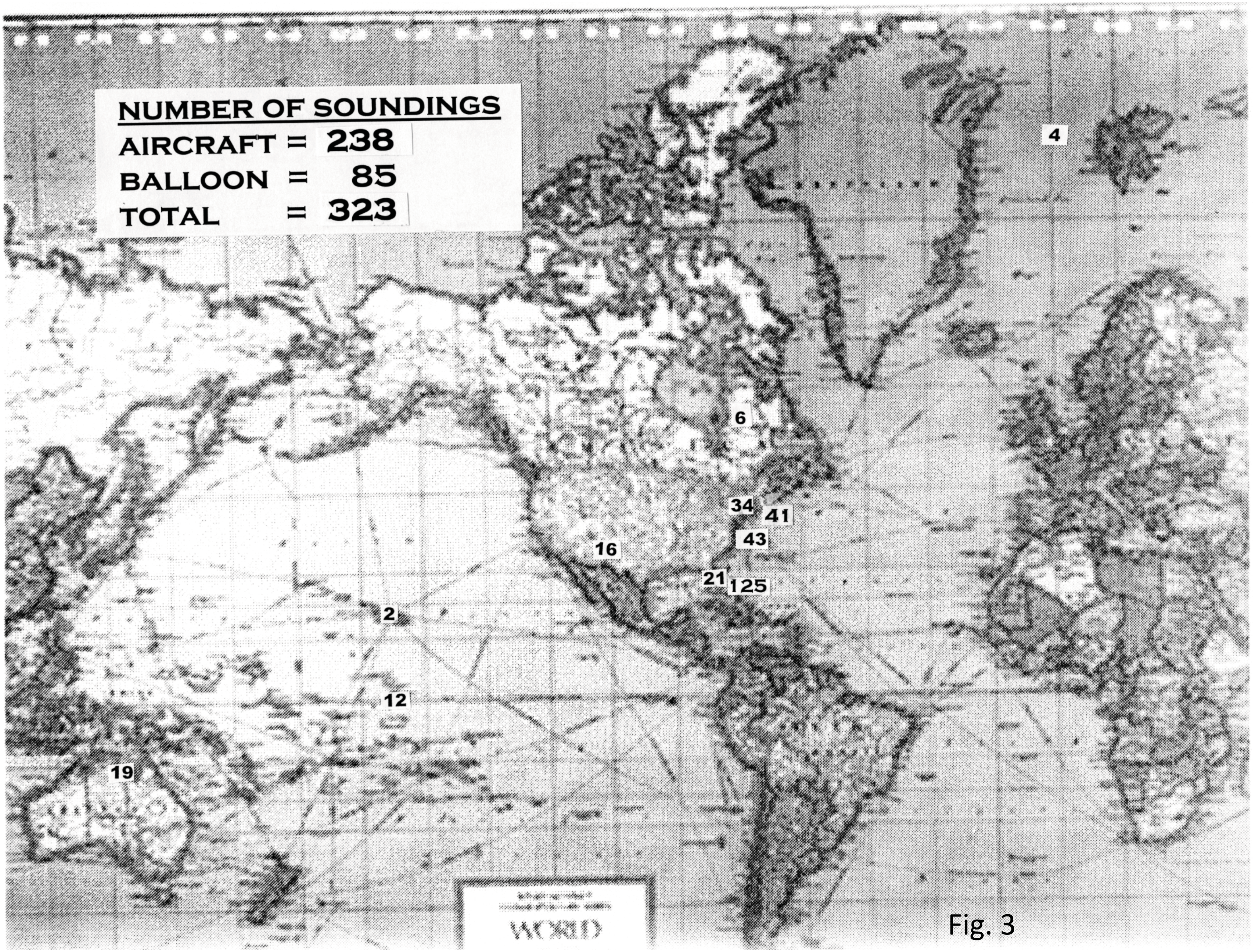
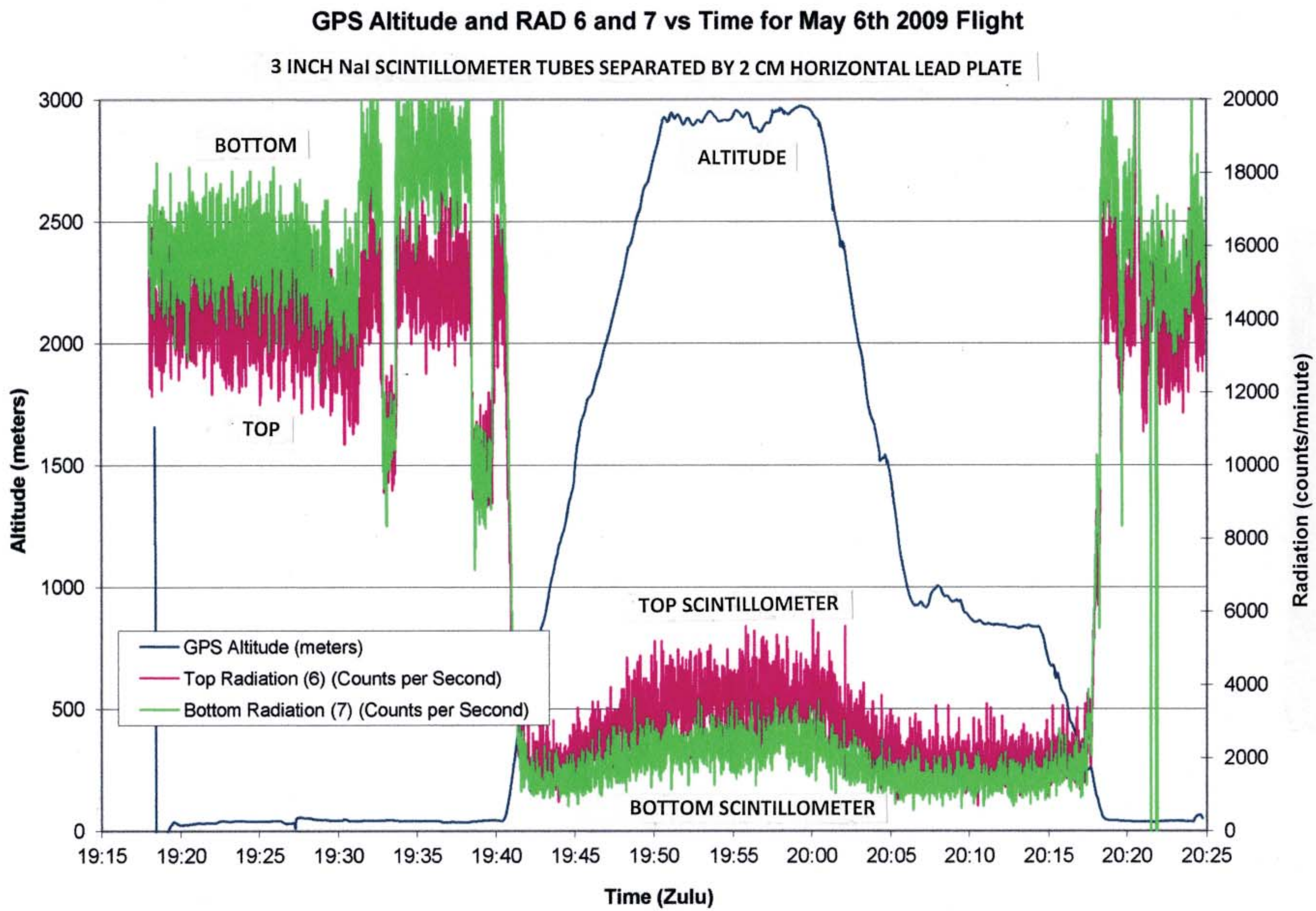

NUMBER OF SOUNDINGS
AIRCRAFT = 238
BALLOON = 85
TOTAL = 323
4
6
34
41
43
16
21
125
2
12
19
WORLD
Fig. 3

Fig. 12. Beechcraft TurboBaron aircraft used for measurements of ionospheric potential. The vertical fair-weather electric field is measured between the radioactive probes above and below the wingtip. The picture was taken at Andros Island, Bahamas, a region where many of the past ionospheric potential soundings have been obtained over nearby ocean areas.

Fig. 4

Fig. 5



GPS Altitude and RAD 6 and 7 vs Time for May 6th 2009 Flight
3 INCH NaI SCINTILLOMETER TUBES SEPARATED BY 2 CM HORIZONTAL LEAD PLATE
BOTTOM
TOP
ALTITUDE
TOP SCINTILLOMETER
BOTTOM SCINTILLOMETER
GPS Altitude (meters)
Top Radiation (6) (Counts per Second)
Bottom Radiation (7) (Counts per Second)
Altitude (meters)
Radiation (counts/minute)
Time (Zulu)
0
500
1000
1500
2000
2500
3000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
19:15
19:20
19:25
19:30
19:35
19:40
19:45
19:50
19:55
20:00
20:05
20:10
20:15
20:20
20:25

Fig. 6

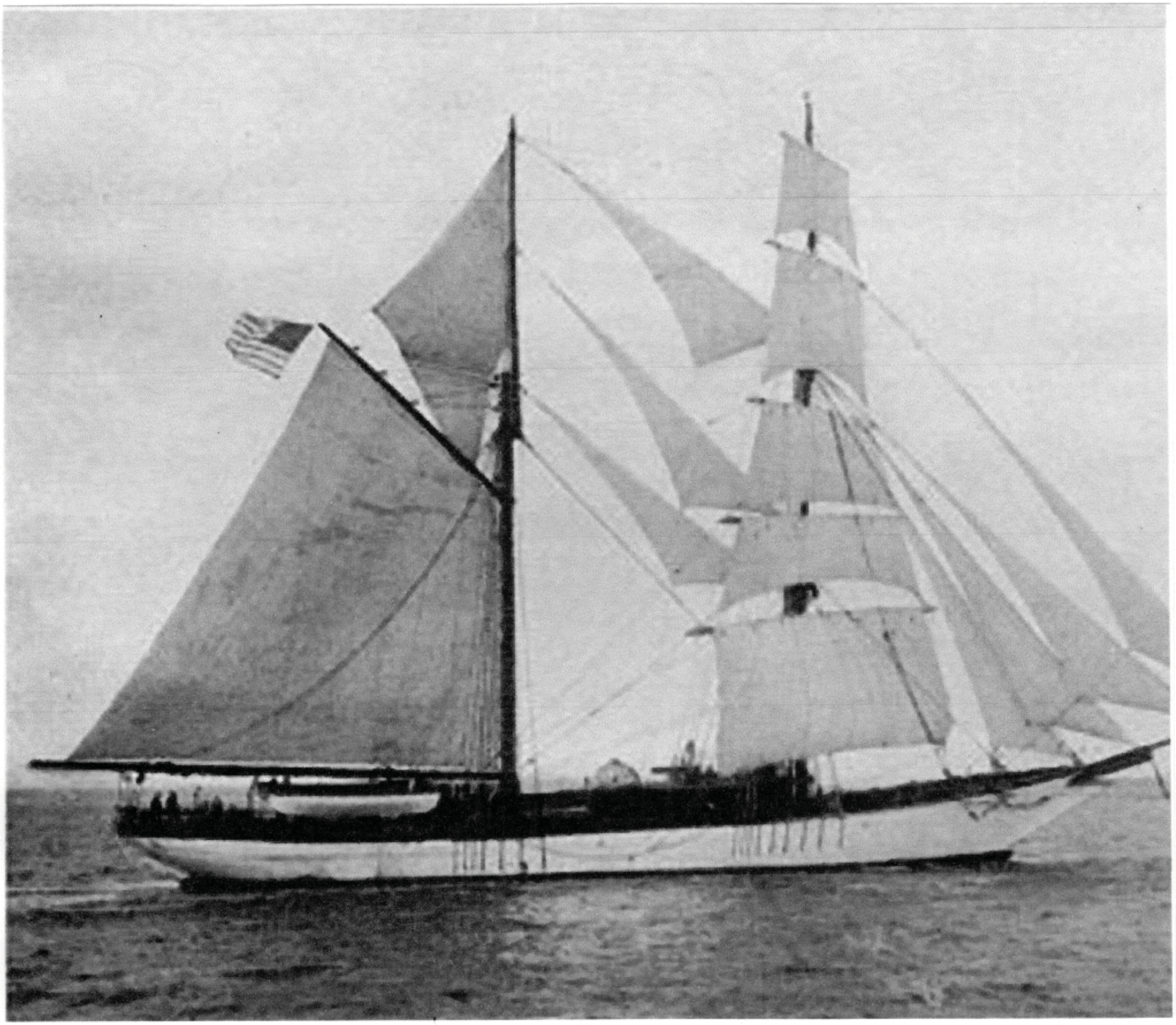


Fig. 7

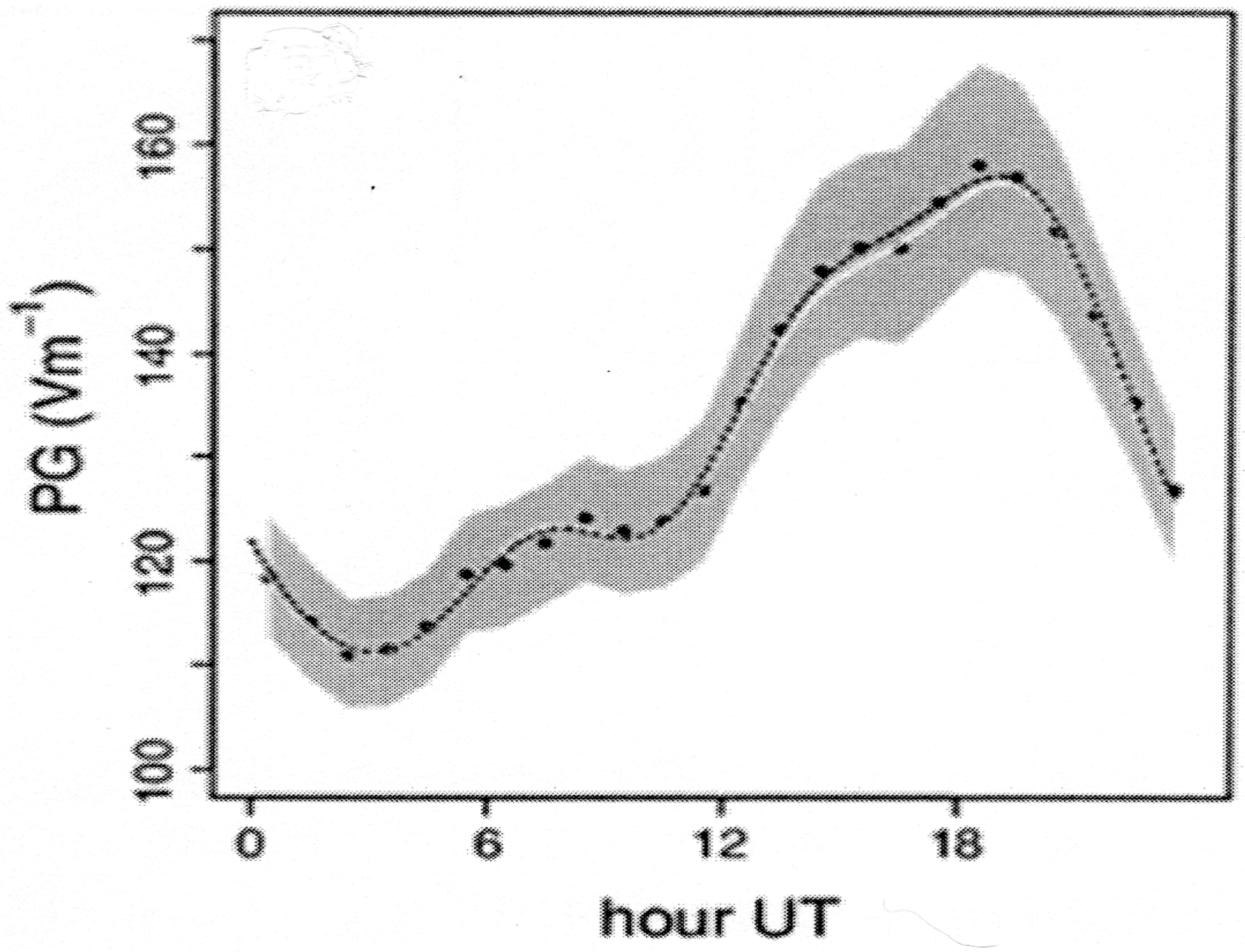
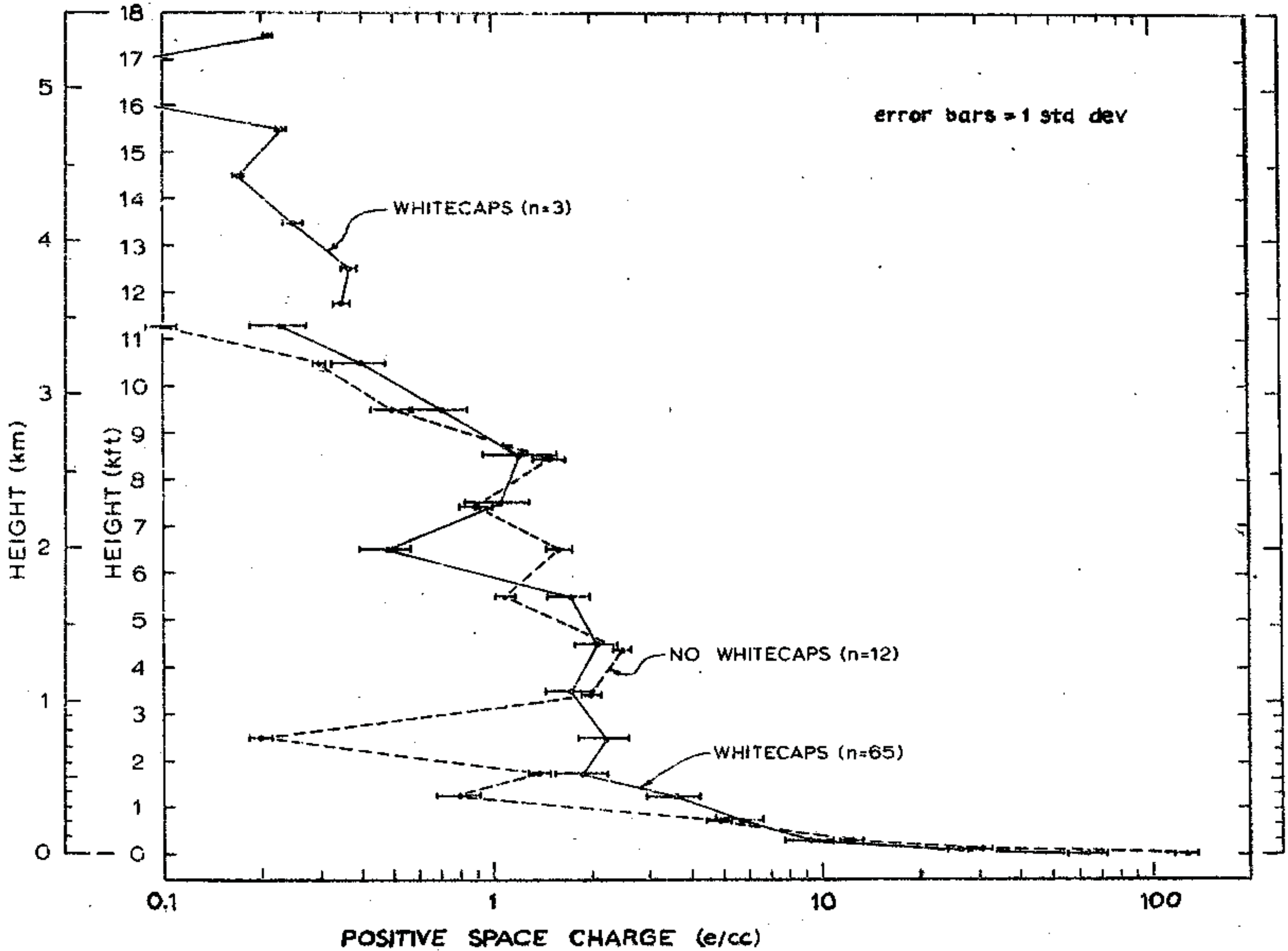


Fig. 8



error bars = 1 std dev
WHITECAPS (n=3)
NO WHITECAPS (n=12)
WHITECAPS (n=65)
HEIGHT (km)
HEIGHT (kft)
POSITIVE SPACE CHARGE (e/cc)

Fig. 9

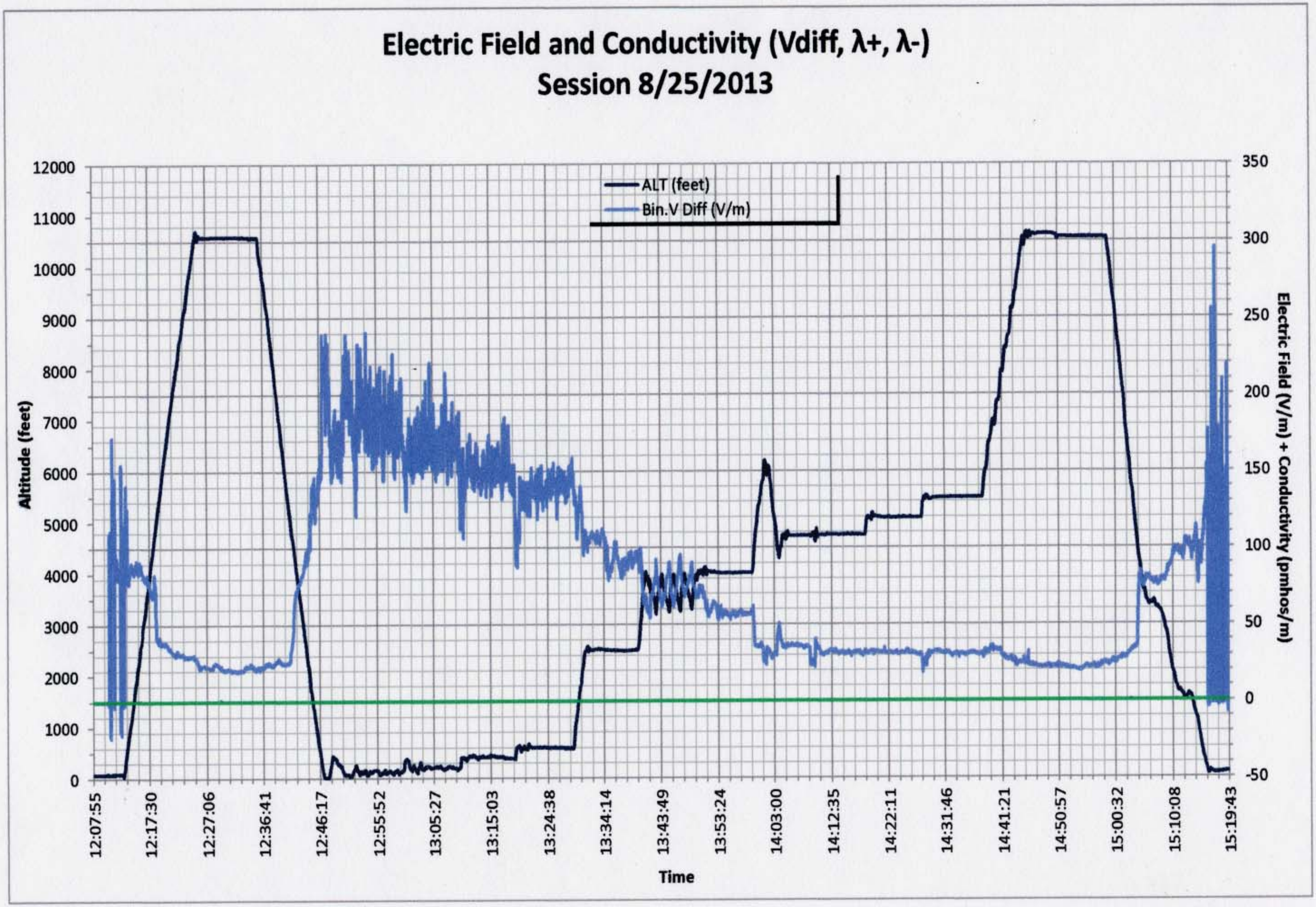

Electric Field and Conductivity (Vdiff, λ+, λ-)
Session 8/25/2013
ALT (feet)
Bin.V Diff (V/m)
Altitude (feet)
Electric Field (V/m) + Conductivity (pmhos/m)
Time
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
350
300
250
200
150
100
50
0
-50
12:07:55
12:17:30
12:27:06
12:36:41
12:46:17
12:55:52
13:05:27
13:15:03
13:24:38
13:34:14
13:43:49
13:53:24
14:03:00
14:12:35
14:22:11
14:31:46
14:41:21
14:50:57
15:00:32
15:10:08
15:19:43

Fig. 10

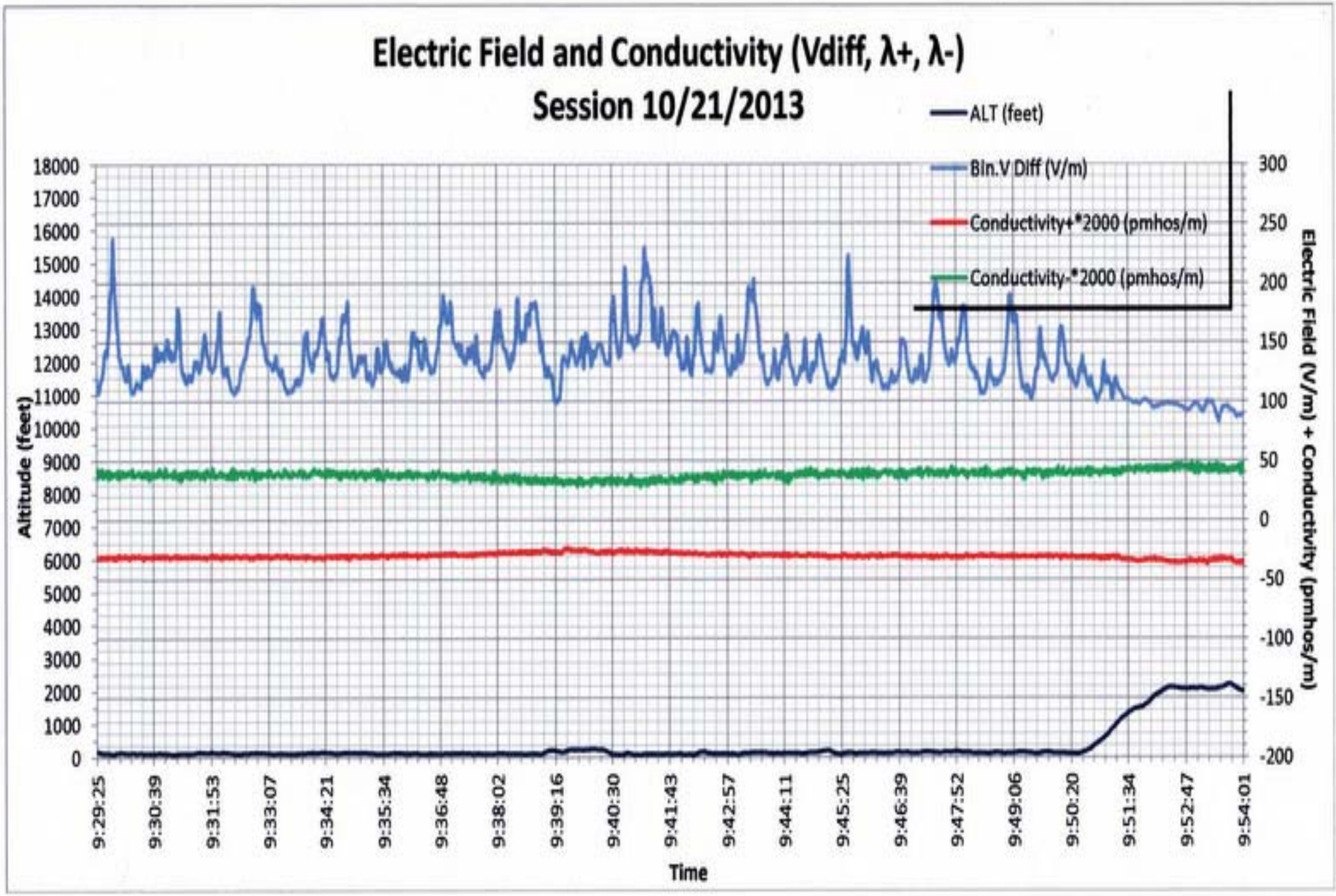
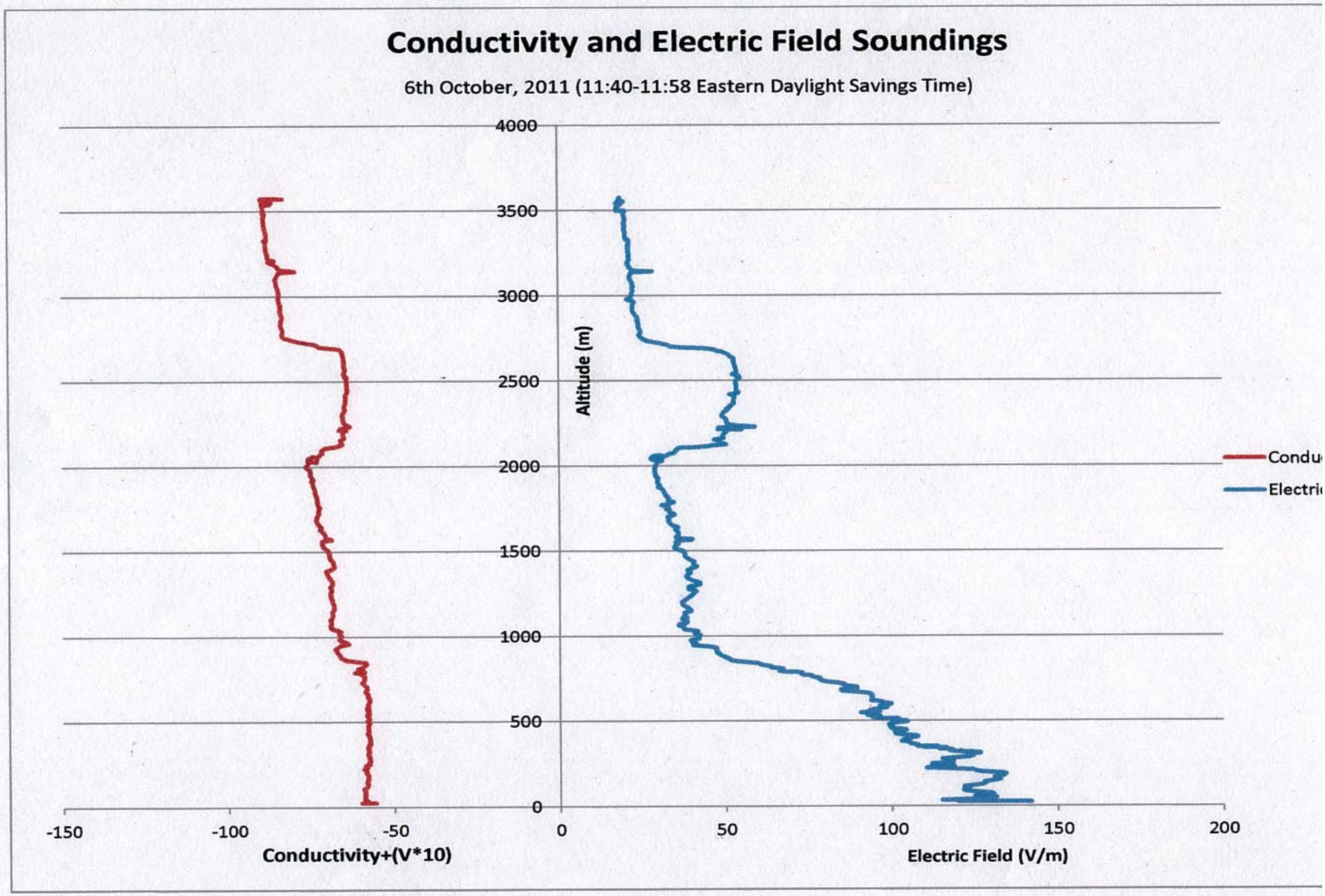
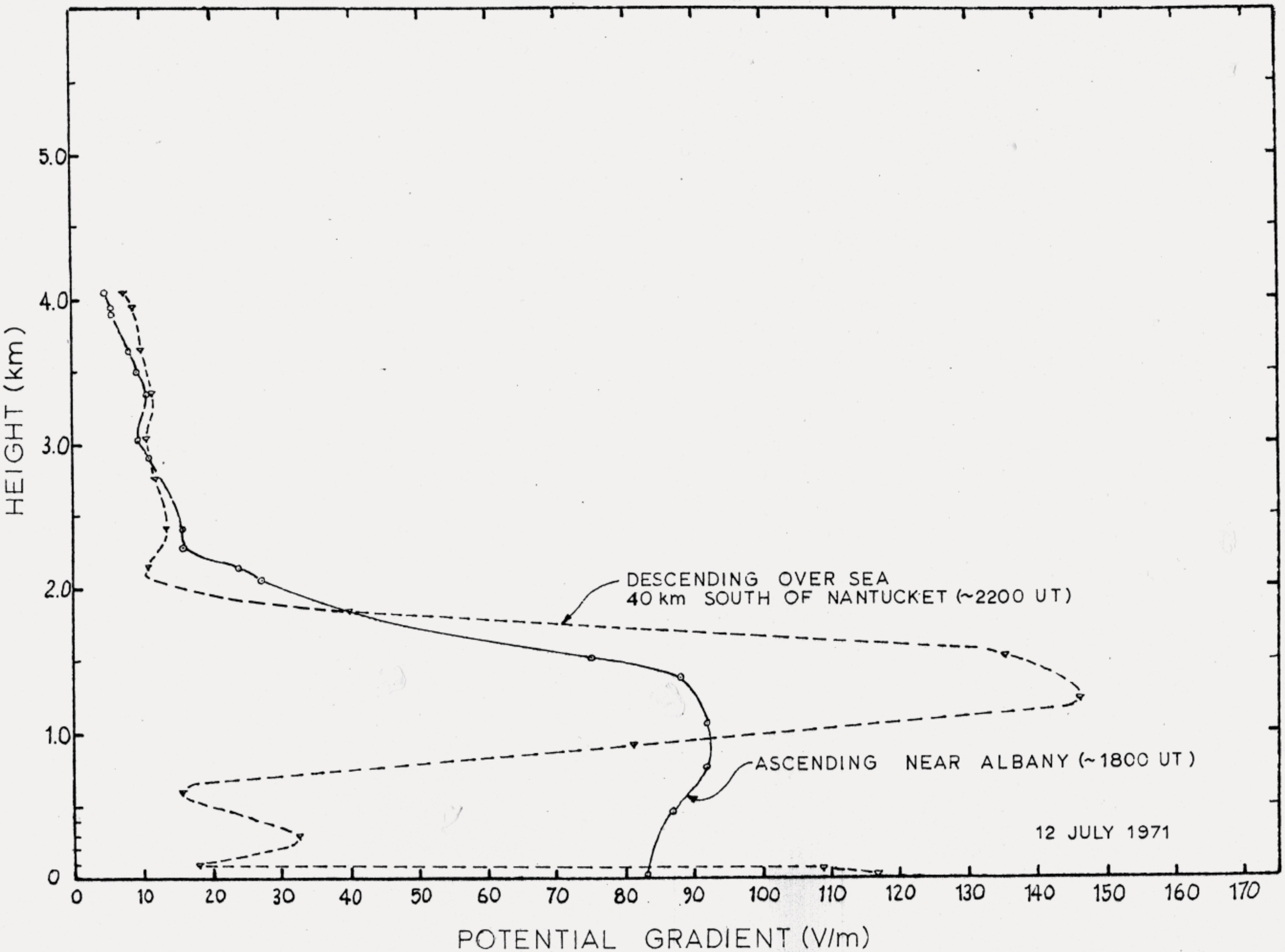

Electric Field and Conductivity (Vdiff, λ+, λ-)
Session 10/21/2013
ALT (feet)
Bin.V Diff (V/m)
Conductivity+*2000 (pmhos/m)
Conductivity-*2000 (pmhos/m)
Altitude (feet)
Electric Field (V/m) + Conductivity (pmhos/m)
Time
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
300
250
200
150
100
50
0
-50
-100
-150
-200
9:29:25
9:30:39
9:31:53
9:33:07
9:34:21
9:35:34
9:36:48
9:38:02
9:39:16
9:40:30
9:41:43
9:42:57
9:44:11
9:45:25
9:46:39
9:47:52
9:49:06
9:50:20
9:51:34
9:52:47
9:54:01

Fig. 11



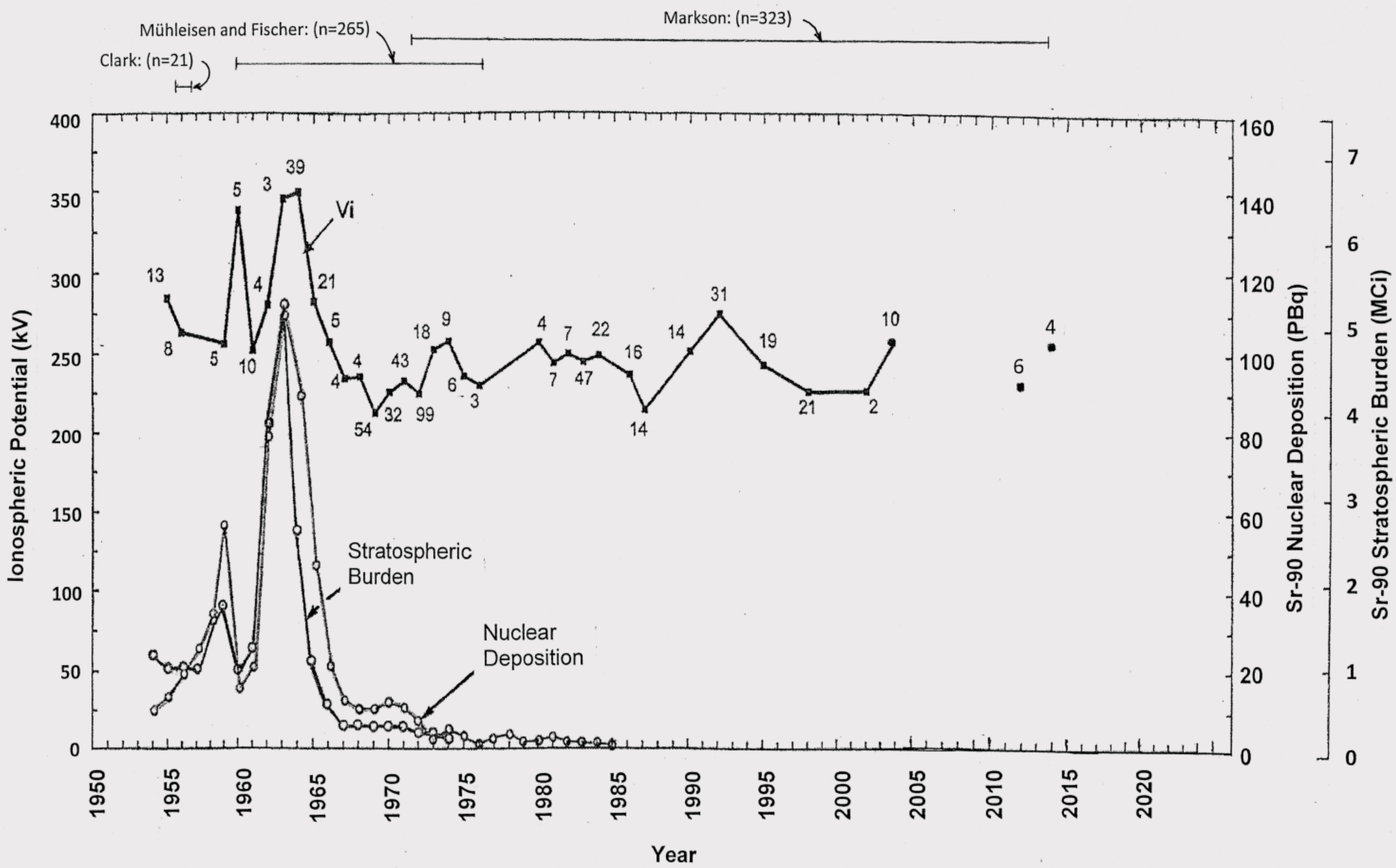
Conductivity and Electric Field Soundings
6th October, 2011 (11:40-11:58 Eastern Daylight Savings Time)
Altitude (m)
4000
3500
3000
2500
2000
1500
1000
500
0
-150
-100
-50
0
50
100
150
200
Conductivity+(V*10)
Electric Field (V/m)

Fig. 12



HEIGHT (km)
5.0
4.0
3.0
2.0
1.0
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
POTENTIAL GRADIENT (V/m)
DESCENDING OVER SEA
40 km SOUTH OF NANTUCKET (~2200 UT)
ASCENDING NEAR ALBANY (~1800 UT)
12 JULY 1971

Fig. 13



Mühleisen and Fischer: (n=265)
Markson: (n=323)
Clark: (n=21)
Vi
Stratospheric Burden
Nuclear Deposition
Ionospheric Potential (kV)
Sr-90 Nuclear Deposition (PBq)
Sr-90 Stratospheric Burden (MCi)
Year

Fig. 14