REMOTE DETECTION OF THERMALS BY MEANS OF HORIZONTAL ELECTRIC FIELD MEASUREMENTS

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INTRODUCTION

In the past, sailplane pilots have had no sensor for determining the location of regions of lift other than their eyes. They might have headed for a cumulus cloud or a convenient ridge oriented perpendicular to the wind when searching for rising air. Atmospheric electric field measurements from a sailplane may offer another means of locating thermals and using them more effectively by indicating the regions of maximum lift. This technique has been suggested in the past by MacCready (1954, 1971).

The basic principle is dependent on the vertical gradient of space charge density in the atmosphere. In general an excess of positive ions (compared to negative ions) exists in the atmosphere, and the concentration decreases with altitude. A particularly dense region exists in the planetary boundary layer within a few tens of meters from the earth's surface. This charge can be fed into convective updrafts through horizontal convergence near the ground and be carried aloft by the thermal. Thus pockets or columns of positive charge can accumulate in thermals, particularly near the top, where they will set up electric fields. Measurements of the horizontal component will indicate the direction of the charge center (marking the thermal) from a sailplane. This paper will discuss use of such measurements to increase soaring efficiency.

Review of fair-weather atmospheric electrical conditions

In order to understand the mechanism it is necessary to understand some aspects of fair-weather electricity. The subject is gone into more completely in texts by Chalmers (1967) and Israel (1971). "Fair-weather" in atmospheric electricity essentially implies regions distant from thunderstorms, dust storms (or other electrical generators), precipitation or extensive cloud layers. Thunderstorms generally are considered the main electrical generator maintaining the earth's electric field. Potential gradient, the term used in making electric field measurements, is the negative of the electric field, i.e., it is a vector of equal magnitude but

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in the opposite direction. While the mechanism by which thunderstorms make electricity is still not agreed upon (and probably several exist), most investigators concur that the upper portion of a thundercloud contains excess positive charge and the bottom contains negative charge excess. Thus a dipole model can be assumed in explaining how thunderclouds maintain the earth's electric field.

The atmosphere contains ions of both signs mostly caused by cosmic radiation ionizing air molecules. Because of the variation of conductivity with height, a small excess in ions of one sign will occur. Since the earth is charged negatively and the upper atmosphere positively due to the polarity of thunderclouds, this excess charge in the atmosphere is positive. Typically, near the earth's surface 1000 ion pairs (an ion of each sign) per cm^3 will be present. However, the net positive charge is only a few ions per cm^3 generally. There appears to be great variation from one location to another, and this is a function of air mixing, pollution, radioactive gases and other factors. While 1 to 10 elementary charges per cm^3 may be typical over land with convection present, measurements on a mountain in New Mexico indicate 200 elementary charges per cm^3 were typical and at times space charge densities of over 1000 elementary charges per cm^3 were recorded (Vonnegut and Moore, (1958)).

A thunderstorm acts as a generator by causing the positive space charge above it to move upward into the highly conductive upper layers of the atmosphere. Similarly negative ions move downward. Because of high conductivity in the upper atmosphere the charge moves sideways redistributing itself homogeneously around the earth in much less than a second at a height of 60 km. For purposes of atmospheric electricity this height is called the "equalizing layer". It is at a potential that is fairly constant at any given time all over the world. This potential is about +300,000 volts relative to the earth. The "equalizing layer" can be considered the outer conductor of a spherical capacitor, the inner conductor of which is the earth. Between them the atmosphere acts as a leaky dielectric through which charge drifts. Under a thunderstorm large electric fields exist; these can be sufficient to cause point discharge from sharp objects on the earth's surface. When most pronounced this is recognized as Saint Elmo's fire. Because the bottom of a thunderstorm is charged negatively, positive charge enters the atmosphere in the point discharge leaving negative charge on the earth. This is the primary factor accounting for the earth's charge. Cloud to ground lightning provides an additional 10%. Because the earth is a good conductor the negative charge distributes itself uniformly over the surface, and a vertical electric field is established in the atmosphere all over the world. The fair-weather electric field intensity is about 120 volts per meter in all fair-weather regions near the earth's surface. It decreases exponentially with altitude due to the exponential increase in atmospheric conductivity.

In fair-weather regions positive ions in the atmosphere drift downward toward the negative charge on the earth, and negative ions drift upward. Two-thirds of the atmospheric charge would be lost in about 20 minutes in the lower atmosphere due to conductivity allowing the charge to leak away if the electrical generator maintaining the field, thunderstorms, were turned off. However, thunderstorms are always occurring at various places on earth, particularly near longitudes where it is afternoon. The fair-weather field intensity varies simultaneously all over the world as a function of the sum of worldwide thunderstorm activity. The minimum occurs at about 0400 GMT and the maximum (about 30% higher) about 1900 GMT.

The distribution of space charge density with altitude varies greatly as a function of atmospheric mixing. When there is strong mixing beneath the inversion the density gradient will be small, and the average space charge through the mixing layer may be only 1 elementary charge per cm^3 although there still may be a layer of space charge close to the earth depending on the details of low level mixing and terrain. With weak or widely-spaced convection a relatively dense layer of space charge can exist near the earth, and 10 to 100 elementary charges per cm^3 may occur in the lowest 100 meters of the atmosphere. The particular high values measured on a mountain in New Mexico were probably confined to a layer less than 50 meters thick.

Another region where high space charge densities will occur is at the interface of two horizontal layers of different conductivity such as at the inversion when thick haze exists below that level. Here through a depth of 50 meters a positive space charge density of 50 elementary charges per cm^3 may exist. Thermals acquire excess positive charge densities compared to their surroundings from these two regions of relatively high positive space charge densities. The technique to be described operates by sensing the direction from a sailplane to the regions of relatively high density positive space charge in thermals.

Mechanism for electrical thermal detection

Figure 1 illustrates how space charge should be redistributed in the atmosphere by a thermal and the resulting electric field equipotential lines. Whether a thermal is continuous (as a column extending up from the earth), a bubble, a plume or a vortex ring, essentially the same electric field configuration will exist. Near the earth's surface air carrying positive charge converges toward the thermal and is entrained in the rising air. Near the top of the column, where a cloud may form if the air is sufficiently moist, the air will decelerate; the space charge concentration will be greater in this volume than in the surrounding air. Similarly, a buoyant bubble formed near the earth will contain higher density space charge than its surroundings. The diagram shows these volumes as positive charge centers. Because the earth is a good conductor, an image of the electrical charges in the atmosphere but of opposite sign can be considered to exist in the earth in mapping the electric field.

To a first approximation the two charge centers can be considered as a dipole that would have an electric field configuration resembling that of Figure 1. It is seen that an aircraft measuring the horizontal field component would have the largest signal to work with near the altitude of the top of a thermal column or near the height of a bubble. However, excess positive charge also exists within the column, and the horizontal components at altitudes between the top of the thermal and the earth will be greater than suggested by the diagram. Another factor not depicted is that horizontal components near the earth will be larger than further up because the charged air entering the

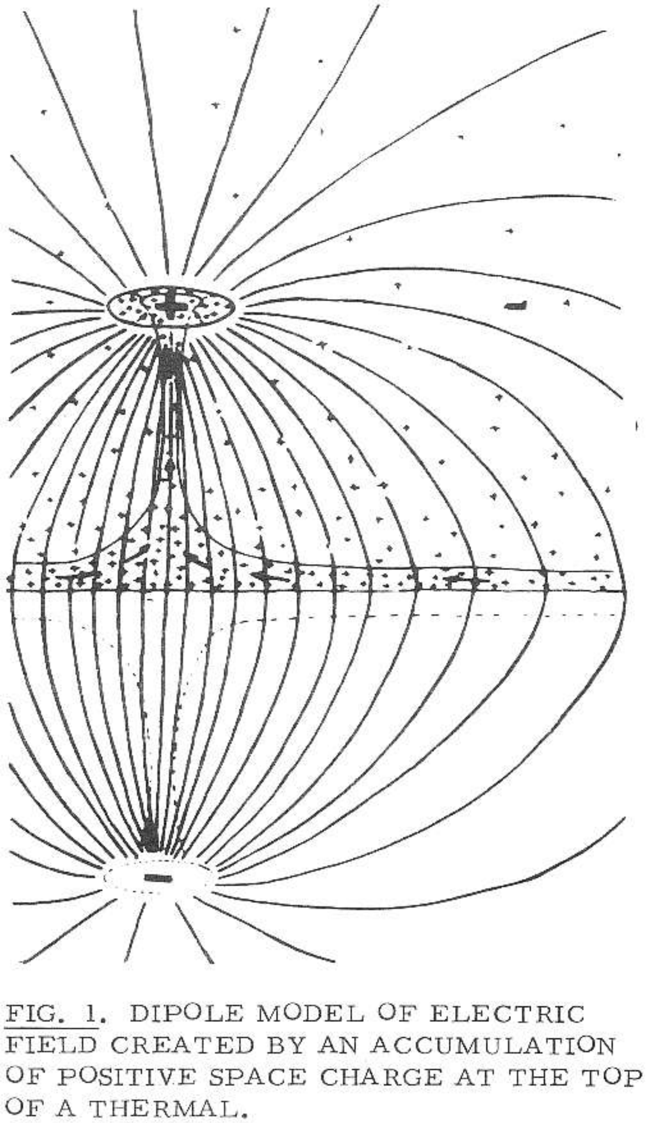

FIG. 1. DIPOLE MODEL OF ELECTRIC FIELD CREATED BY AN ACCUMULATION OF POSITIVE SPACE CHARGE AT THE TOP OF A THERMAL.

base of the column will mix with entrained surrounding air through the sides of the thermal during its ascent and be diluted. The decrease in charge concentration with altitude in the thermal will be enhanced because of the increase in conductivity with altitude which will increase the rate of change dissipation. On the other hand, the entrainment of surrounding air into the thermal as it passes through an inversion could supply a fresh supply of positive charge to the upper portion of the thermal.

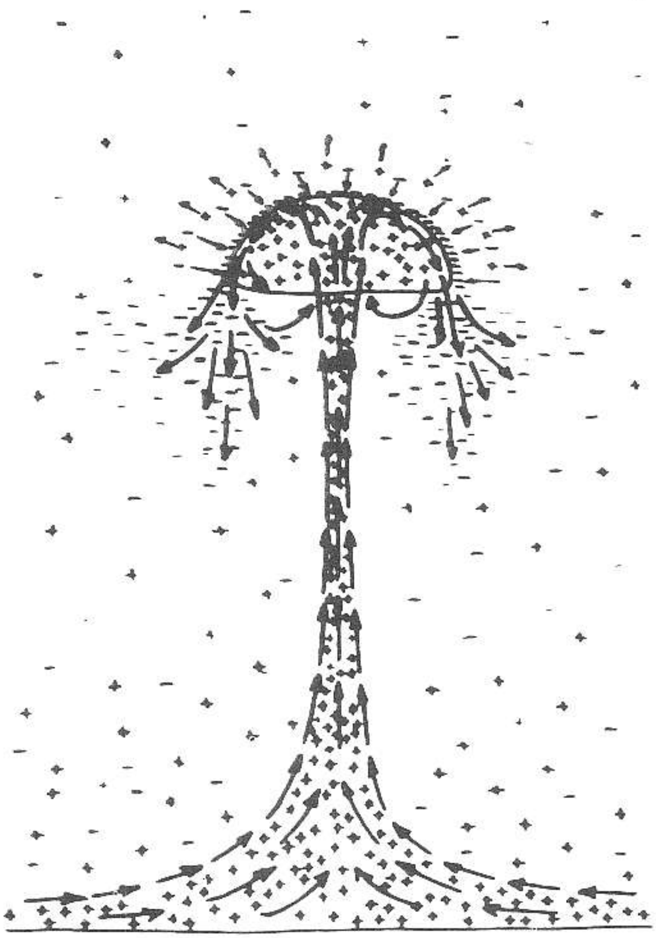

FIG. 2. AIR MOTIONS AND DISTRIBUTION OF SPACE CHARGE IN AND AROUND A THERMAL.

In Figure 2 a columnar thermal is envisioned in more detail. The semi-circular dome near the top depicts a cloud which may or may not be present depending on the mositure of the air. Air trajectories are depicted by arrows. At the top of the thermal a vortex-ring type of circulation is shown. The air rises above the neutral buoyancy level -- which might be in the lower portion of the cloud -- and falls back to the sides as in a fountain. Some of the air recirculates back into the central portion where there is rising air, some may continue downward with appreciable velocity, and some may spread out sideways. Positive charge from near the earth is shown being carried aloft in the thermal. A diffuse pocket accumulates at the top of the thermal. This charge would generate an electrical force on the ions of the atmosphere such that positive ones would move away and negative ones would move toward the cloud of positive charge at the top of a thermal. If a liquid water cloud exists, the negative ions become attached to cloud droplets near the cloud surface, forming a layer of negative charge that is probably less than 10 meters thick. This has been called a "screening layer" because it can prevent the diffuse positive charge within the cloud from being seen electrically. Even without a cloud of water drops, a similar effect may take place if sufficient haze or pollution particles are present for the negative ions to become attached. The negative ion sheath covering the top and sides of the cloud of water droplets or haze particles would move along with the air unfolding at the top of the thermal and descending down the sides as depicted in Figure 2. Pockets of negative charge could accumulate to the sides of thermals near the neutral buoyancy level and in the downdraft regions. Unless these factors were understood, electric field detection of thermals might be quite confusing and the patterns seem chaotic. If a sailplane came near a local pocket of negative charge while flying toward a thermal marked by positive charge there might be a reversal of the potential gradient. The author apparently encountered such conditions as will be described subsequently. The suggested model is supported by measurements of Vonnegut, et al., (1962) in which the vertical potential gradient was recorded from an airplane passing under cumulus clouds charged from the ground by space charge generating apparatus. The charge was carried aloft into the clouds by the mechanism suggested in Figures 1 and 2. Their data showed positive charge overhead when the airplane was passing under the central portion of the cloud and positive charge was being released on the ground. Negative charge was encountered near the lower edges of the cloud as suggested in Figure 2.

Previous electrical measurements of convection

Before the electric field measurements from a sailplane were begun, several years experience in making such measurements had been acquired during a program in which a powered aircraft was used. This aircraft, a Starfire one-of-a-kind home-built, is equipped to measure the vertical component of the atmospheric electric field using polonium (radioactive) probes seen at the left wing tip in Figure 3. During the course of this work, measurements made when flying at constant altitude have suggested that convective patterns were being recorded. A brief look at some of these data will illustrate the potential for airborne electric field detection of convection and how space charge may be accumulated by convection in the atmosphere.

Figure 4 was made during constant level runs at heights of 5, 50 and 160 meters over the ocean in the Bahamas. Atmospheric conditions favored organized convection. Just above an ocean surface is a region particularly rich in positive space charge produced by the breaking of bubbles and the "electrode effect" (see Chalmers (1967)). Measurements indicated a space charge density of 72 elementary charges per cm^3 in the 5 to 50 meter height layer. Sharp increases in the vertical potential gradient when flying at 5 meters suggest the presence of positive charge above the plane at the time these anomalies were recorded. They were probably caused by organized convection -- perhaps in the form of horizontal roll vortices (Kuettner (1971)) -- with a spacing of about 2 km between rolls. The updrafts were weak and periodicity in the potential gradient record was no longer present at a height of 160 meters probably because the space charge had dissipated through conduction and air mixing.

FIG. 3. STARFIRE AIRCRAFT USED IN ATMOSPHERIC ELECTRICAL RESEARCH.

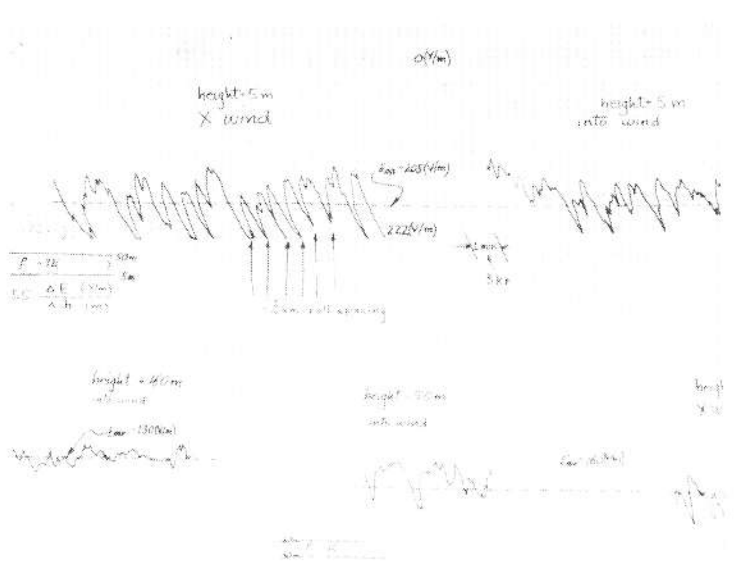

FIG. 4. GRAPHIC RECORDINGS OF VERTICAL POTENTIAL GRADIENT ILLUSTRATING ORGANIZED CONVECTION OVER THE OCEAN.

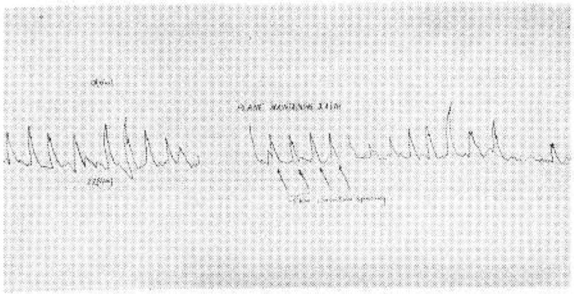

FIG. 5. GRAPHIC RECORDING OF VERTICAL POTENTIAL GRADIENT MADE ABOVE THE INVERSION ILLUSTRATING ORGANIZED CONVECTION WITHIN THE MIXING LAYER.

Figure 5, showing data taken at another time and location, illustrates sharp decreases in the vertical potential gradient flying at 3.4 km crossing the Gulf Stream east of Miami. Here the spacing of the anomalous changes in potential gradient is about 5 km. These were presumed to be caused by pockets (or lines) of positive space charge accumulating at the inversion beneath the aircraft due to organized convection in the mixing layer. The air mass over the Gulf Stream when this flight was made in December would favor instability with cool air over warmer water.

Figure 6, depicting air flow patterns and the relative space charge distribution during organized convection over the ocean, is a schematic attempt to explain Figures 4 and 5. In the case of the airplane flying near the sea, positive charge density is increased in the air column above the airplane when it is passing through a rising plume; thus the potential gradient increases at these locations. When the airplane is flying above the inversion it passes over pockets (or lines) of positive charge which are at the inversion over the thermal plumes. The potential gradient decreases when the airplane is over these regions. Details concerning these measurements will be published separately.

These data suggested that the horizontal electric field measurement might be useful in locating updrafts and the airplane was instru-

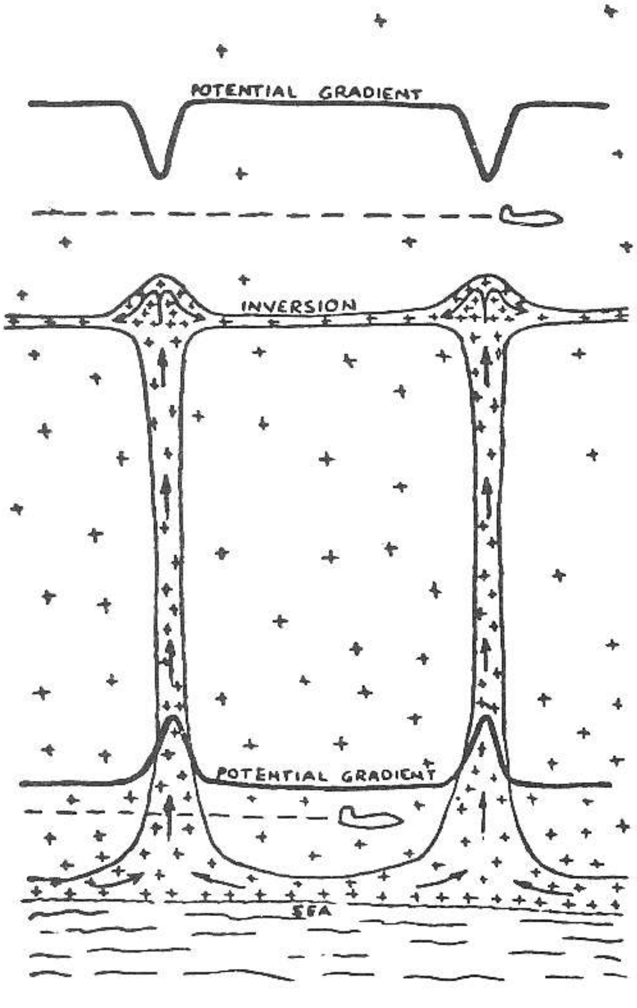

FIG. 6. SCHEMATIC EXPLANATION OF FIGURES 4 and 5.

mented to measure the potential gradient between wingtip probes. Normally, clear of clouds and over flat land, there should be little or no horizontal component of the atmospheric electric field. However, initial measurements indicated that frequently during convective conditions in both clear and cloudy skies appreciable horizontal fields were present. Typical values were 1 to 2 V/m (volts per meter). Sometimes as much as 5 V/m was observed. These values were at a height of 3 km where typical vertical field intensities are 15 to 20 V/m.

The airplane proved to be a poor platform for electric field measurements relative to thermals because of its relatively fast speed and large turning radius. Even more important was the problem of the vertical field component introduced into the wingtip-to-wingtip measurement in a bank. It quickly became apparent that it would be necessary to measure the potential gradient longitudinally. Large vertical separation occurs between wingtips when a plane is banked compared to the longitudinal axis which remains essentially horizontal in a turn. Even if the vertical component were compensated for by flying at a constant bank angle and introducing a bias voltage, it is inherently more difficult to maintain a constant bank angle than a constant pitch angle. Also, when flying a sailplane, it is necessary to frequently vary the bank angle while searching for lift and thermaling.

A single engine airplane does not provide good sites for locating antennas at the nose and tail which would have been required to measure the longitudinal horizontal component. Thus a sailplane was acquired and instrumented to continue the investigation. Besides flying slowly it offers suitable mounting locations at the nose and tail for the necessary antennas.

Estimates of horizontal electric field associated with thermals

Two simple charge geometries have been assumed -- a sphere and a cylinder -- in order to estimate field strength as a function of distance from a charged thermal. For simplicity, mirror image charge which will decrease the horizontal field somewhat, particularly near the earth's surface, has been neglected. On the other hand, charge in the rising thermal column which will increase the horizontal field to the sides of the thermal column has been omitted. Figure 7 is a set of tables listing potential gradient at distances from 0.1 to 30 km from a charge center for space charge densities of from 0.1 to 1000 elementary charges per cm^3. For simplicity, all the charge is considered to be at the center of the spheres or along the axis of the cylinder. The three top tables are for spherical clouds of charge while the bottom one is for an infinitely long cylindrical column of charge. The latter would approximate conditions half way up and to the side of a column of charge, without the charge concentration at the top of the thermal that would add to the horizontal component of the column itself.

For example, it is seen that in the case of a 100 meter diameter sphere of charge with a density of 10 elementary charges per cm^3 the electric field would be 0.2 V/m at a distance of 0.3 km from the center. This is about the detection threshold of the measuring system indicated by the diagonal dashed lines (to be discussed). It is estimated that field intensities to the left of the line can be detected. These tables suggest that thermals of typical sizes might be detected from a sailplane several km away, particularly if the sailplane were at an altitude about the same as the top of the thermal. This would be near cloud base, an altitude where sailplanes frequently fly. A particularly suitable region for electrostatic thermal detection should be above the inversion since the vertical electric field, the major source of noise, is typically reduced by a factor of two to ten passing up through the inversion because of the corresponding increase in conductivity.

For 100 m Sphere (V/M)

	D=0.1 (km)	0.3	1	3	10	30
ρ=0.1 (e/cm^3)	.02 (V/M	.002	–	–	–	–
1	0.2	.02	.002	–	–	–
10	2.0	0.2	.02	.002		
100	20	2.0	0.2	.02	.002	
1000	200	20	2.0	0.2	.02	.002

For 300 m Sphere

0.1	.5	.05	.005	–	–	–
1.0	5	.5	.05	.005	–	–
10		5	.5	.05	.005	–
100	500	50	5	.5	.05	.005
1000	5000	500	50	5	.5	.05

For 1 km Sphere

0.1	20	2	.2	.02	.002	–
1.0	200	20	2	.2	.02	.002
10	2000	200	20	2	.2	.02
100	2×10^4	2000	200	20	2	.2
1000	2×10^5	2×10^4	2000	200	20	2

For 100 m Diameter Cylinder

0.1	.03	.01	.003	.001	–	–
1.0	.3	.03	.01	.003	.001	–
10	3	.3	.03	.01	.003	.001
100	30	3	.3	.03	.01	.003
1000	300	30	3	.3	.03	.01

FIG. 7. POTENTIAL GRADIENT AS A FUNCTION OF DISTANCE AND SPACE CHARGE DENSITY FOR CHARGED SPHERES OF DIFFERENT DIAMETER AND A LONG CHARGED CYLINDER.

Instrumentation

Potential gradient has been measured from aircraft by electric field mills (Clark (1956)) and electrometers with radioactive probe antennas (Vonnegut and Moore (1961)). Field mills suffer from inherent noise problems due to contact potentials and rotating components. They are relatively heavy, and require large amounts of power to drive the rotating parts. Mounting them on an aircraft requires structural modification of the airframe. For these reasons they are not attractive for use in a sailplane.

Modern miniature solid state electrometers offer light weight, low noise, low power requirement devices capable of measuring the picoamp currents required. Their high input resistance, 10^{14} ohms when field-effect transistors are used, makes them suitable for electric field measurements using radioactive probes as antennas. Radioactive probes are well suited for aircraft measurements because of adequate ventilation which removes space charge from the vicinity of the probes which otherwise could distort the measurement. The electrometer/radioactive probe technique seems clearly preferable to field mills for potential gradient measurements from a sailplane.

The main problem in making airborne potential gradient measurements is eliminating fields created by charge on the aircraft from the measurement. This is difficult with a powered aircraft because the engine charges the airframe and considerable precaution and experience is required. With a sailplane the problem is considerably easier but still the system must be able to handle charging that can occur when the craft strikes particles in the air or by movements in the cockpit; rubbing a plexiglas canopy can give it a high charge.

Figure 8 is a block diagram of the major components in the sailplane electric field measuring system. An antenna with a radioactive probe is in front of the nose; another is behind the rudder. An input buffer amplifier is near each antenna. Their signals go to a differential amplifier in the cockpit. Readout is on a Rustrak recorder on the cabin floor. This diagram illustrates how charge on the aircraft is eliminated from the measurement. A more detailed description of the instrumentation and its development will be published separately. The potential difference is measured between two radioactive probes on highly insulated antennas. Since the effective

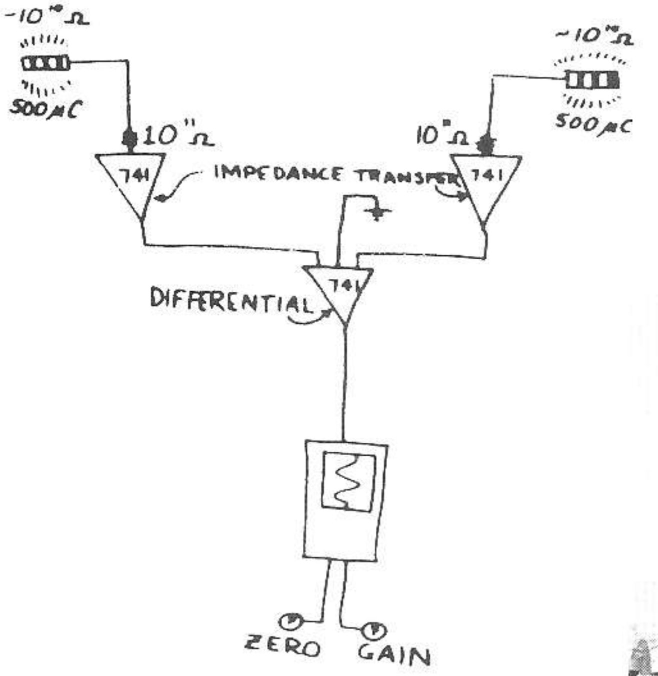

FIG. 8. BLOCK DIAGRAM IN ELECTRIC FIELD MEASURING SYSTEM.

resistance of the ion cloud created by the radioactive material which couples the antenna to the atmosphere is about 10^{10} ohms, higher input resistance is required for the measuring system. In the sailplane 10^{11} ohms is used to minimize the time constant. For thermal detection only qualitative data is needed. Quantitative measurements require at least 10^{12} ohms input resistance. Field effect transistors at the inputs to the 741 operational amplifiers unload the signal source. Charge on the aircraft is eliminated from the measurement through differential function of another operational amplifier with its common connection grounded. In a differential measurement the potential of the common point can vary since this potential does not effect the potential difference between both inputs; i.e., if one input voltage is A, the other input voltage is C and the common voltage is B, then AB - CB = AB + BC = AC. The output of the differential amplifier goes to a recorder that serves as a meter as well as a device for letting the pilot remember the field intensity as a function of headings flown. Gain and zero controls are provided.

Figure 9 is a side view of the Tern sailplane used in this research. The front to back potential difference is measured between antennas at the nose and tail.

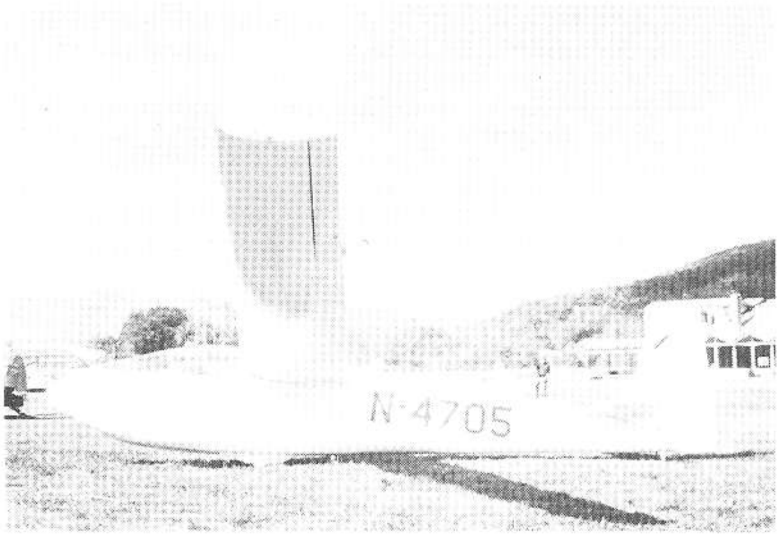

FIG. 9. SIDE VIEW OF TERN SAILPLANE SHOWING LOCATION OF FRONT AND REAR ANTENNAS

A close up of the front antenna is seen in Figure 10. The radioactive element is mounted on an antenna which is a metal tube extension of the pitot tube. This arrangement does not effect the function of the airspeed indicator and allows the antenna to be positioned at a point of electrical symetry in front of the nose to reduce problems associated with aircraft charge. The antenna is insulated from the pitot by a teflon sleeve and is connected to the input amplifier by a wire routed through the air duct.

In Figure 11 the rear antenna is shown. It is a flexible rod mounted

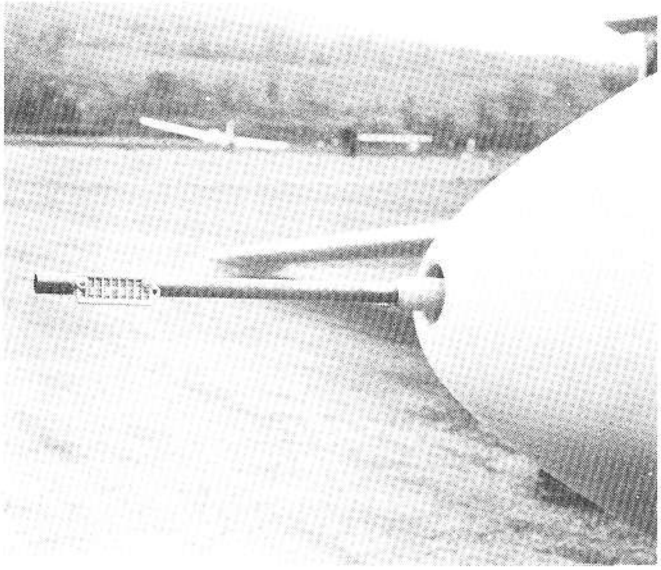

FIG. 10. CLOSE UP OF FRONT ANTENNA SHOWING RADIOACTIVE ELEMENT.

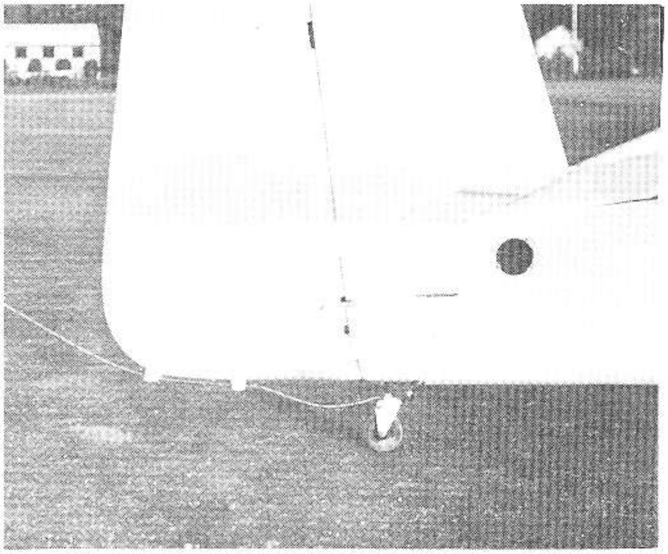

FIG. 11. CLOSE UP OF REAR ANTENNA

on the bottom of the rudder by teflon insulators and bent upward so as to be level with the front antenna when the sailplane is in its normal flight attitude. This is to minimize the effect of the vertical electric field in the measurement. The rear antenna is connected to its input amplifier by a wire running through a rudder cable hole in the fuselage.

Figure 12 is a picture of the differential amplifier (large box) and front antenna input amplifier (small box) mounted in front of the instrument panel. Each input amplifier is located as close to its antenna as possible to minimize the time constant. The differential amplifier box can be considerably smaller than the one pictured which had been used in the airplane and contains a power supply.

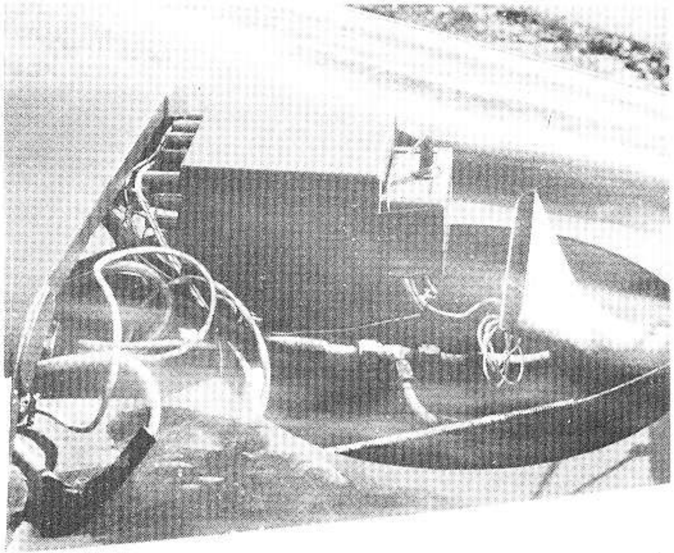

FIG. 12. FRONT INPUT AMPLIFIER AND DIFFERENTIAL AMPLIFIER. UNITS LOCATED IN FRONT OF INSTRUMENTS IN CABIN.

The output of the differential amplifier is displayed on a strip chart recorder mounted on the cabin floor where it can be read along with the rest of the flight instruments (see Figure 13).

Rapid response time is desirable in the system so that field strength can be associated with variations in heading when the sailplane is circling. Flying a tight circle in which it takes 20 seconds to complete 360 degrees, the heading variation is 18 degrees per second. The time constant of the system described is approximately one-third of a second.

It was decided to measure the horizontal potential gradient from front to rear since the longitudinal

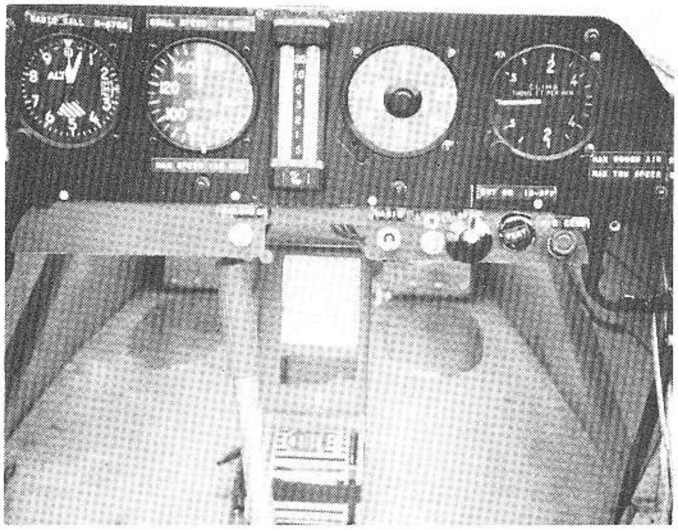

FIG. 13. PILOT'S EYE VIEW OF INSTRUMENTS. RECORDER MOUNTED ON THE FLOOR DISPLAYS ELECTRIC FIELD DATA. ELECTRIC FIELD SENSITIVITY AND ZEROING CONTROLS SHOWN.

axis remains relatively horizontal during turns; if the measurements were made between wingtips, a large signal would be introduced in a bank. Wingtip probes on a 15 meter wingspan sailplane in a 30 degree bank would sense a potential difference of 150 volts in a vertical field of 20 V/m. This is ten times the horizontal potential difference available if the horizontal potential gradient is 1 V/m, i.e., the noise would be ten times the signal. The limiting factor in determining the sensitivity of the system is the vertical component of the electric field. With front to back probes, it is important to minimize variations in the pitch axis. If the distance between front and rear probes is 7 meters, a pitch variation of 1 degree causes a 12.5 cm vertical separation between the probes. In a vertical field of 20 V/m, this is 2.5 volts. A horizontal field of 1 V/m would produce a signal of 7 volts between the probes. In practice, small variations in pitch will be occuring, but they can be somewhat averaged out -- especially with the graphic recorder -- so that a mean value can be estimated. This will be a function of angle of attack, i.e., air speed. The mean needle position can be shifted to the center of the recorder scale with the zero control. When the sailplane can be flown smoothly with little variation in pitch angle, it is estimated that a field as small as 0.2 V/m can be detected. The diagonal dashed lines in Figure 7 were thus placed at this sensitivity limit. The ultimate sensitivity of the system is a few mV/m obtainable only in a static situation. Piloting skill in maintaining constant pitch angles will be an important factor in maximizing the sensitivity of the instrument. In rough air near thermals larger pitch variations will occur, but stronger field strengths will produce a compensating effect.

Operational procedure

How is this instrumentation used? Before takeoff the zero is adjusted so the needle is in the center of the meter and sensitivity is low. The system is set up so that a deflection of the needle to the right indicates positive charge is ahead of the glider and deflection to the left means positive charge is to the rear. On tow the needle should move to the right as the glider's nose is up and the vertical field is sensed. If the needle does not move the sensitivity should be increased; if it goes off scale, sensitivity should be reduced or the needle can be brought back on scale with the zero control. Rocking the nose up and down should cause corresponding needle movements to the right and left. This is a test that the system is operating properly. The sensitivity is adjusted so typical pitch variations of a few degrees correspond to about ± 15% of full scale deflection. The device may not work on tow because of charge on a non-conducting tow rope. This can be recognized by the needle deflecting to full scale on either side and the zero control being unable to bring it back on scale. After release from the tow plane, the apparatus should work normally. The needle will come back on scale and be adjustable with the controls. Readjustment of the zero center position is necessary whenever airspeed is changed because of the pitch angle variation. It is important to maintain as constant an airspeed as possible to allow the most sensitive setting when searching for thermals. Pitch variation is the critical noise source, limiting the gain at which the instrument may be set. When regions of space charge are approached, the gain will have to be greatly reduced.

To locate lift, the sailplane is flown in a circle, and generally there will be enough horizontal field present so that the needle will have a maximum right deflection on one side of the circle and a maximum left deflection on the other side. Flying in continuous circles with the chart paper moving in the recorder, a sine wave will be produced on the chart. The heading at maximum right needle deflection will be toward positive charge; for maximum left deflection the reciprocal heading can be flown toward the positive charge. Zero and sensitivity controls are adjusted so the maximum and minimum of the sine wave occur near the edges of the chart. The zero position can be set by centering the sine wave on the chart. Another zeroing procedure that can be used when not flying in a circle is to rock the longitudinal axis of the plane through the horizon. The needle should be near center scale when the plane is horizontal and move back and forth through this position as the sailplane's nose passes up and down through the horizon.

Gain can be increased if the glider gains height since the vertical field decreases with altitude and this noise source will be less. In practice it is frequently necessary to readjust gain depending on field strenghts over a range of as much as 100 to 1. The needle centering zero control may also have to be readjusted if gain is increased because some of the vertical electric field is probably being sensed and nulled out by the zeroing voltage. Centering a thermal requires the same technique as locating one from a distance. It is interesting that, when spiraling in what appeared to be the center of a thermal or under the middle of a cloud base, sine waves generally appeared on the recorder indicating the precise center of charge was still to one side.

The recorder display helps show the direction to fly for lift. In addition it provides a reminder of the relative field strength. Flying toward charged regions field strength should increase. However, the situation may be confused by coming near pockets of space charge of the opposite sign. As previously described, the meter movements frequently do not present a coherent picture.

While the operational procedure may sound confusing at first, in practice one rapidly learns to use the equipment. The challenge lies in integrating the continual variations of field strength and direction with other factors such as the locations and configurations of clouds and mountains, wind flow, type of terrain, haze, turbulence and variometer readings. It is believed most soaring pilots will find the challenge enjoyable and rewarding.

Initial results

During the summer of 1972 flights were conducted from the North Adams, Massachusetts, airport to test the electric field detecting system. In general, it was necessary to fly in ridge lift or in thermals close to the mountains which surround the airport. It was apparent that, while the system operated satisfactorily, it was mostly measuring horizontal components of the fair-weather electric field created by the mountains. Figure 14 illustrates how the vertical fair-weather electric field lines of force would bend toward mountains and create horizontal components. These in effect are noise and made it difficult to separate horizontal fields due to thermals from those caused by the terrain. Although there were suggestions of thermals sensed against the background noise, it was necessary to get higher or farther away from the mountains in order to properly evaluate the system. Since mountains and ridges are particularly favorable soaring locations, the above illustrated a limitation that electric field thermal detection will have to live with. In addition, standing waves may carry space charge

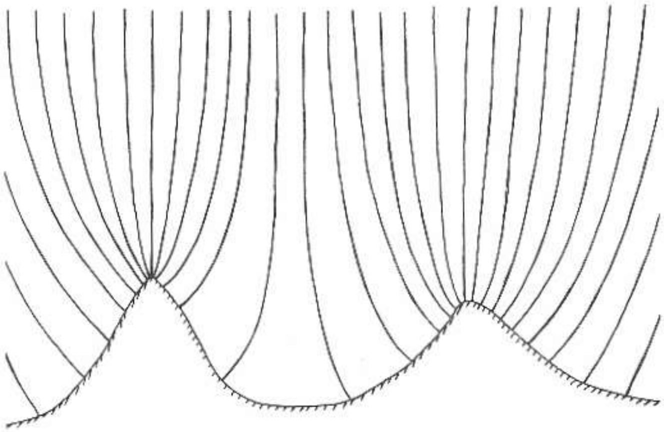

FIG. 14. DISTORTION OF THE VERTICAL ELECTRIC FIELD LINES DUE TO UNEVEN TERRAIN.

aloft and confuse the picture in mountainous terrain while possibly offering a new way to locate waves.

On October 15, 1972, a strong NW flow brought excellent soaring conditions with cloudstreets to the North Adams area. On this day, when it was possible to get high and away from the mountains, the electric field thermal detection system appeared capable of locating regions of lift. It seemed particularly effective when flying near cloud-base at about 2 km and appeared capable of locating thermals from distances of 1 to 2 km. The clouds appeared to be about 200 to 400 meters in diameter and 100 to 200 meters high.

Of particular interest were reversals in the sign of the potential gradient and strong downdrafts encountered when flying toward a region of positive charge. These are interpreted as possibly due to negative charge pockets associated with downdrafts at the periphery of thermals as suggested in Figure 2. By continuing on course, regions of good lift were generally encountered. In one case, away from clouds while flying toward positive charge, very strong descending air was flown into with no warning on the electric field meter. Pushing through the strong downdraft while holding course, a thermal was eventually reached. This downdraft with no negative charge may have been in agreement with Figure 2 but, since there was no cloud or haze, a screening layer did not form. Large fluctuations of the needle were frequently observed when lift was nearby.

On this day, like others, anytime a circle was flown, a sine wave was generated on the chart. Thus information suggesting preferential headings to locate lift regions was always available. Although flying toward positive charge when clear of mountains usually resulted in good lift, on this strongly convective day it is possible that thermals might have been encountered eventually on any random course if flown long enough. However, it was not necessary to fly the electrically suggested courses for very long before finding lift, and it is the author's impression that thermals were being located through the electric field measurements. When flying at cloud base along a cloud street, positive charge areas could be associated with the location of clouds. Once lift was encountered and the sailplane started spiraling, a maximum positive needle deflection was usually observed at one side of the circle during each turn. It appeared that correcting the circle in the direction indicated resulted in better lift.

It is emphasized that so far very little experience has been acquired with this technique. However, in good soaring weather, there have been encouraging indications that thermals can be located and centered using the system. Sufficient electrical signals certainly are available. The problem is to make sense out of them because they can be quite variable. The picture is not as clear as the idealized model suggested in the figures of this article. Undoubtedly the structure of thermals and space charge distributions can be complex. Potential gradient measuring instruments will sense a field that is the resultant of components contributed by all sources of charge. With several charged regions close to the point of measurement, the electrical picture is ambiguous. This is why it is still impossible to locate precisely the numerous charge centers in a thundercloud. When two or more charge centers are close to each other, and each has about the same charge, it will be necessary for the sailplane to be closer to one of them in order to define its direction. This is because electric field intensity is inversely proportional to the square of the distance from the measuring location to the center of charge. If charged regions contain unequal charge, field intensity is directly proportional to the quantity of charge so the measurement will be influenced more by the larger charged region of equidistant sources. These considerations tend to illustrate that electric field measurements from one location can only give information suggesting the direction of charge centers but not their distance since the amount of charge is unknown.

Future plans and possibilities

The research described above will be continued to explore the practical possibilities of electric field thermal detection. It would be important to try the system in various parts of the country where different space charge concentrations and convective patterns exist. The system might be particularly useful over flat country and where thermals are large and widely separated such as in desert regions. Also, high space charge concentrations, such as apparently exist over some mountains in the southwest United States, should produce relatively large horizontal electric fields when convection is present and may make possible thermal detection at greater distances than elsewhere.

It is planned to experiment with other techniques that may improve soaring efficiency. One will be to measure conductivity with a Gerdien capacitor. The conductivity of air near the ground is increased by radioactive gases and radioactive emanations from the earth. This air carried aloft in a thermal can be much more conductive (two to ten times) than the surrounding air. Glider flights by Rossmann (Israel, 1971) have been conducted in which such measurements were made.

Another approach will be to measure wet-bulb temperature gradients between the wingtips as well as possibly from nose to tail. Wet-bulb measurements indicate humidity, and thermals are significantly moister than their surroundings. Both components can be displayed simultaneously on a dual-channel graphic recorder or with cross-pointers on a single meter. The instrumentation is being designed initially so that a temperature difference of 0.1°C will give full-scale deflection on the meter at maximum sensitivity. MacCready (1971) suggested this technique to provide information that would indicate which direction to turn to position the sailplane in the region of maximum lift once a thermal is located. It will be interesting to compare the wet-bulb, conductivity and electric field measuring techniques. While the first two cannot be used for remote thermal detection, all three should be useful in obtaining information on the thermal structure. Centering thermals may also be enhanced through measurements of the vertical electric field as suggested by Figure 6.

In the future, variometer readings will be graphically recorded. With simultaneous records of the electric field, conductivity, moisture and lift, it may be possible to gain a better understanding of the structure and growth patterns of thermals. A tape recorder would be useful for verbally recording additional data such as air-speed, proximity to clouds, the location of smoke and haze, temperature and terrain. A limited amount of this information can be written on the charts.

An attempt may be made to measure the lateral (left-to-right) horizontal electric field component in addition to the front-to-back component. Eliminating the vertical component would be the big problem in this measurement. It might be done by electrically biasing the signal with a voltage proportional to the sine of the bank angle sensed by a gyro horizon. The vertical field magnitude would also have to be known and could be measured with vertical probes when the wings were level. Continuous recording of the vertical component should be valuable in centering lift as suggested in Figure 6.

A simpler approach to measuring the left-to-right horizontal component would be to position the radioactive elements at the ends of the horizontal member of a tee shaped antenna. The vertical member of the antenna would be the mast. It would be mounted on a longitudinal pin in the top of the canopy so it could be pivoted left or right. The bottom of the antenna mast would come down in the cockpit in front of the pilot. When circling, the pilot could move the mast by hand to keep it perpendicular to the horizon; thus the top of the tee with the radioactive elements could be kept parallel to the horizon at any bank angle and the vertical component eliminated. Having both horizontal field components, the resultant total horizontal electric field would be known at all times, and it would not be necessary to circle in order to find the direction of the positive charge. Figure 15 illustrates how both electric field components could be displayed on a meter with cross pointers -- an ILS indicator with glide slope could be used. In Figure 15, F/B indicates the front to back component and the L/R is for the left to right component. The system would be arranged so that the direction from the center of the meter to the point where the needles cross would be the direction toward the positive charge from the aircraft. While it would be nice to have both horizontal components, this is not necessary for thermal detection since the circling technique utilizing the front to back component alone seems sufficient. In fact, it is generally not necessary to fly complete circles; the nose can be swung back and forth horizontally through a heading corresponding to maximum right deflection of the needle in order to define the direction to fly for lift.

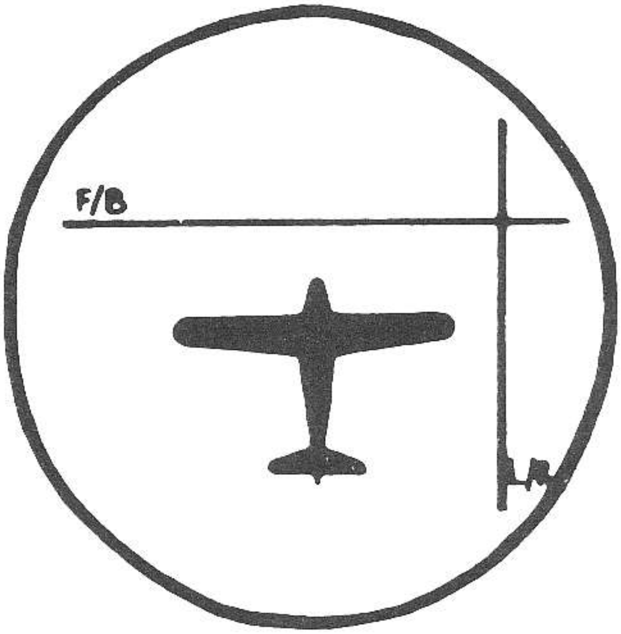

FIG. 15. CROSS POINTER DISPLAY OF TWO COMPONENTS OF THE HORIZONTAL ELEC TRIC FIELD.

Besides directly improving soaring efficiency, electric field measurements from sailplanes may benefit soaring indirectly by providing a new tool for learning more about convection. MacCready (1971) has suggested that instrumentation techniques should provide a considerably more efficient path toward improved soaring performance than further developments in sailplanes themselves. Preliminary results in the present program indicate that electric field thermal detection is possible. The potential of this technique seems considerable.

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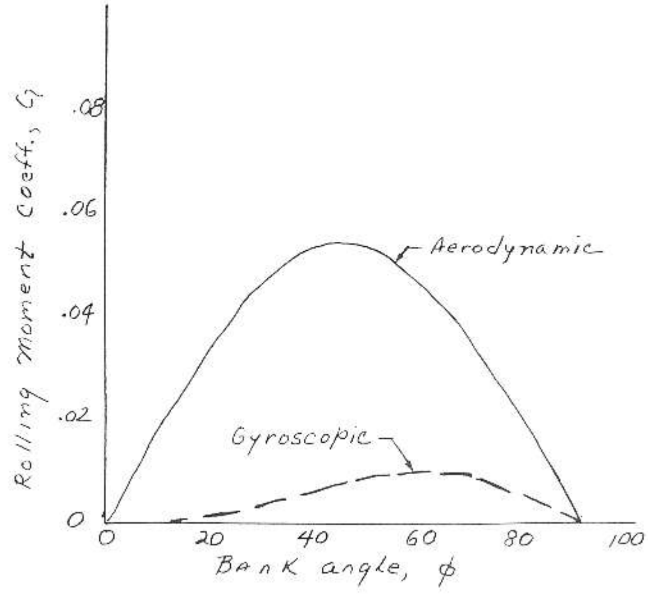

FIG. 4. VARIATIONS WITH BANK ANGLE OF AERODYNAMIC ROLLING-MOMENT COEFFICIENT DUE TO YAWING VELOCITY AND GYROSCOPIC ROLLING-MOMENT COEFFICIENT DUE TO TURNING; $C_L = 1.6$. (MOMENTS HAVE OPPOSITE SIGN)

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