STORM-STATIC RADIO INTERFERENCE
PHENOMENA ORIGINATING ON
AIRCRAFT

by

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STORM-STATIC RADIO INTERFERENCE PHENOMENA ORIGINATING ON AIRCRAFT

by

E. C. Starr

A dependable system of moderate-range communication is essential to the success of modern, scheduled aerial transportation. The radio telephone, utilizing controlled electromagnetic radiations for the transmission of intelligence, is highly successful under most flight conditions. All airplanes used in regular passenger transportation in the United States are equipped with two-way radio telephone apparatus. This equipment is employed not only for voice communication between the airplanes and ground stations, but also as an aid to navigation when visibility is poor and "contact" flight is not feasible. The navigational aids are of extreme importance when flights are to be made in heavy weather and the compasses, altimeters, air speed indicators and chronometers are not alone adequate for the positive determination of the course of flight.

The radio aids fall in three general classes.
Successful voice communication with ground observers enables the pilot to allow for approximate wind errors and to know the limits of visibility from the ground.

The radio compass, utilizing the well-known directional properties of the loop antenna, can be used as a "homing" device or to check location by triangulation. The radio range, or beam, can be employed as a continuous course marker making possible the flight of an exact course between two terminals.

These aids are successful in their operation during normal weather conditions but at times when they are most needed, during heavy weather with low visibility, they may become useless. Flight research has shown that certain precipitation conditions accompanying atmospheric storms cause large, high-speed, all-metal airplanes to become charged electrically and, subsequently, to discharge to the surrounding atmosphere producing local radio disturbances of severe intensity. It has been found that these charges are accumulated by a number of different mechanisms, and that the discharge is a process of maintaining the potential of the airplane at a value not greatly different from that of its surroundings.

Tests in flight and on the ground have indicated that these discharges are the same as those which can be created by high, direct voltages impressed upon point
electrodes. An extensive study was made of the nature of these discharges and of means available for controlling them.

The nature of the radio interference accompanying point discharges was investigated both experimentally and mathematically, and good correlation was obtained between the experimental and predicted results.

The shielded-loop radio receiving antenna was found to exhibit, under most storm-static conditions, a notable property of rejecting interference and accepting desired signals. This characteristic was investigated experimentally and mathematically and again the experimental and theoretical performances checked closely.

It is suggested that a systematic electrical discharging arrangement can be installed on airplanes to control effectively the accumulated charges and reduce the radio interference resulting from their dissipation to the atmosphere. In a limited form such discharging equipment has been tested in flight and has been found to give promise of a high degree of success.
THE RADIO COMPASS

In common with the magnetic and gyroscopic compasses, the radio compass alone is not adequate for successful instrument or "blind" flying. When it is used as a "homing" device the nose of the plane will be maintained in such a position as constantly to point toward the radio transmitter. However, in the presence of a cross wind, a rather devious route may be flown resulting in the airplane arriving at its destination in a direction different from normal. If the magnitude of the cross wind is known, the resultant drift can be compensated and the plane will remain on its normal course. An off-course condition of serious character may arise due to unreported, heavy cross winds.

A method has been developed for the combined use of the magnetic or gyro and radio compasses. This method is illustrated on page 5. The course is to be flown in such a manner as to maintain a constant angular relationship between the radio compass and the magnetic or gyro compass. This angle is set when the airplane is in some known position on the course and held constant throughout the flight. It will be observed that if the actual course of flight deviates to right or left of the true course,
BLIND FLYING WITH COMBINED RADIO AND GYRO
OR MAGNETIC COMPASSES

Course to be flown in such a manner as to maintain a constant angle between Radio and Gyro or Magnetic Bearings
the difference angle between the radio and gyro or magnetic compass will change, indicating an off-course condition. This method can be used to best advantage only when the radio compass is being used as a "homing" device, that is, when the airplane is flying directly toward the radio transmitter.

If two or more radio transmitters, located at some distance apart, can be received on the radio compass, it is possible by triangulation to locate the position of the receiver with a fair degree of accuracy. However, since the airplane is changing its position rapidly, such observations must be taken in rapid succession if they are to give satisfactory results.

Due to reflections from the wings and fuselage of metal airplanes, the radio compass requires a calibration chart showing the errors introduced when receiving from different directions with respect to the axis of the airplane. Such a calibration curve is shown on page 7. It will be noted that maximum corrections of the order of six degrees are necessary in certain positions and also that the farthest experimental point from the mean curve is approximately two degrees. This would tend to indicate that the radio compass may be depended upon to give indications having maximum error, when corrected for direction with respect to the axis of the airplane,
RADIO COMPASS CALIBRATION
ON
PORTLAND RANGE AT WASHOUGAL, WASH.

BOEING 247-D, NO. 365, BELLY LOOP, SHIELDED
REFERENCE STANDARD GYRO COMPASS

---

RADIO COMPASS READING - DEGREES

CORRECTION - DEGREES
of approximately two degrees.

Several modifications of the radio compass are now available and a few of them are quite highly developed. The simplest compass makes use of the well-known directional properties of the loop antennae. When a bearing is being taken, the loop is so oriented as to give a null reading, this position being considerably more accurate than that for a reading of maximum signal intensity.
THE RADIO RANGE

In the previous section it was indicated that it is possible to employ the combined magnetic or gyro and radio compass to fly a true course regardless of cross winds. The technique involved, however, is not simple, and the desired radio transmitters, upon which "homing" directions can be taken, are not frequently available.

A radio range or beacon system has been developed which, to a large extent, eliminates these objections. The type of range which at present is installed, or is superseding others, on the major airways of the United States employs vertical-tower radiators so combined into an antennae system as to produce definite directional patterns.

With reference to the diagram of page 10, if two vertical radiators, a, and b, are spaced apart a distance d and driven in phase opposition, a useful radiation pattern is obtained. In the illustration referred to the towers are spaced one-quarter wave length and the maximum resultant radiation is, therefore, 41 per cent greater than that resulting from either radiator independently. It will be noted also that at a point midway between the two towers there is zero radiation, and since vertical
Combined radiation in plane of towers

Cone of Silence

"a" radiation

"b" radiation

ANTENNA ELEVATION IN PLANE OF TOWERS

Towers driven in phase opposition
towers propagate a vertically polarized wave, the area immediately above the pair of towers is devoid of radiation. This point, therefore, may serve as a marker and is known as the "cone of silence."

It will be observed that the waves combine as they do because of two factors. They are first, the separation between the radiators and second, the phase difference between the driving voltages of the two radiators. For the condition shown on page 10, it is obvious that if both waves were traveling in a direction normal to the plane of the towers, they would have equal distances to travel in arriving at any given point, and hence, would cancel each other completely. The result would be a line of zero radiation intensity.

The field pattern obtained by such a pair of radiators is illustrated on page 12. In this case the point p is any point on the horizon, the locus of which is a circle with center at the radiators. The radius vector of each of the curves is proportional to the field strength radiated by the antenna in the direction of that vector. It will be noted that for tower separations closer than approximately one-quarter wave length, the field patterns are essentially circular. In every case the radiation in the 90-degree and 270-degree directions is of zero intensity.
RELATIVE FIELD STRENGTH
Two-Tower, Phase-Opposition Radiators

Tower Separation: ① - 1; ② - 1/2; ③ - 1/4; ④ - 1/16
If the two radiators are not driven in exact phase opposition, a field pattern such as that illustrated on page 14, may be obtained. In this case the tower separation is one-quarter wave length and the driving phase difference is 150 degrees. Equal currents are supplied to both radiators. It will be observed that the radiation in the zero-degree direction is now much stronger than that in the 180-degree direction and the axes of zero field strength have been shifted from their former 90-degree and 270-degree positions. As a means of comparison, the dashed circle indicates the relative field strength of one radiator alone drawing the same current as is supplied to each radiator in the combined pattern. These directional patterns are readily analyzed and their equations are developed in appendix I. It should be noted that these equations apply exactly only when the radiators are operating on a flat, perfectly-conducting plane. The presence of buildings, towers, and mountains tends to alter considerably the patterns obtained.

In the United States Department of Commerce Type TL radio range, the above patterns are combined in pairs to obtain the desired courses. Four radiators are erected on the corners of a rectangle in such a position that
RELATIVE FIELD STRENGTH
Two-Tower, Equal-Current Radiator. Tower Separation; \( \lambda/4 \)
Driving Phase Difference; 150°

\( \alpha = 0° \)
\( \alpha = 30° \)
\( \alpha = 60° \)
\( \alpha = 90° \)
\( \alpha = 120° \)
\( \alpha = 150° \)
\( \alpha = 180° \)
\( \alpha = 210° \)
\( \alpha = 240° \)
\( \alpha = 270° \)
\( \alpha = 300° \)
\( \alpha = 330° \)
\( \alpha = 360° \)

Point on horizon P.
their normal patterns lie at 90 degrees with respect to each other. The resultant field pattern is that illustrated on page 16. In this case diagonally opposite towers are driven in phase opposition and the driving energy is alternately switched from one pair of radiators to the other. The radio carrier wave is modulated at a frequency of the order of 1000 cycles per second, and is so keyed ordinarily that one pair of towers radiates an "A" signal and the other radiates an interlocking "N". An airplane, then, in position 1 would receive a strong signal from the radiators transmitting the "N", and no signal at all from the other pair of radiators. If this airplane were moved around to position 2, it would receive substantially the same signal from the "N" radiators as in the first position and also weak signals from the "A" radiators. When in position 3, the plane would be receiving signals of equal intensity from both sets of radiators. Since the dot and dash of the "A" are interlocked with the dash and dot of the "N", the signal received in this position would be essentially a continuous note of modulation frequency. This is the on-course signal and is easily differentiated from the off-course predominant "N" on one side changing to the "A" on the other side.

It is obvious that if simple equal-current, phase-opposition radiators were employed for such a radio range
FIELD PATTERN OF "A" LOOP

FIELD PATTERN OF "N" LOOP

EQUISIGNAL COURSE

PLANE IN POSITION:

1. Strong "N"
2. "N"
3. Equisignal "A"
4. Equisignal "A"
5. Strong "A"

SIMPLE AURAL RADIO RANGE
transmitter, the courses would lie at 90 degrees with respect to each other and would, in general, be useful only in one direction. However, by driving the opposite towers in some phase difference other than 180 degrees, as indicated on page 14, and also by changing the signal strength in certain radiators by insertion of resistances, it is possible to shift or bend these equisignal courses to any desired position. In order to make possible the accurate final adjustment of the course position, the energy is usually fed from the transmitter to the radiators through a movable-primary transformer known as a goniometer. This device enables the proper distribution of energy between the two sets of radiators to obtain the exact course position desired.

The above type of radio range is extremely successful over flat terrain and gives a beam width of from 100 to 200 yards per mile of distance from the radiators. Under normal conditions, the range signals with the present amount of power are intelligible over distances of at least 100 miles. The equisignal courses, however, tend at times to bend in mountainous terrain due to reflections and they may even break up into multiple courses. This feature is, of course, highly undesirable, and the major course must be flown enough times in good visibility to
enable the differentiation between the main and false courses. Certain weather conditions have also been known to produce perceptible shifts in the range courses.

It is evident that a satisfactorily operating radio range would enable the accurate flight of a given course under conditions of zero visibility. The "cone of silence" markers together with the low-power localizers enable the flight personnel to determine their exact position as well as course of flight. The only other equipment then necessary to make complete instrument flying successful is an adequate landing system. These devices are now being developed and will be in general use within the next few years.
In heavy weather, particularly in violent squalls and in air mass fronts, it is especially important that the radio ranges be operative. Under these conditions local cross winds of severe intensity may tend to drive the airplane far from its course unless the range signals can be received satisfactorily. Unfortunately, such weather conditions are usually accompanied by some form of precipitation. There may be snow, rain or frost crystals in the air. Experience has shown that an airplane flying at speeds materially above 100 miles per hour into such precipitation, in general, has its radio reception very seriously impaired. The interference may appear in any one of, or in a combination of several different forms.

It has been known since the early days of radio communication that electrical discharges from conductors, either of low or high voltage, will produce interference in receiving equipment. The making or breaking of a low-voltage circuit will produce a shock disturbance in the receiver. Low-voltage vibrating type interruptors and machine commutators may produce such a rapid succession of these shock disturbances as to create a musical note.
in the receiver. High-voltage corona discharges on conductors and insulators are known to create serious radio interference. On the airplane the high-voltage ignition system of the engine must be very carefully shielded to avoid the introduction of heavy shock interference into the receiving equipment.

In many of the above types of interference, the actual disturbance occupies a relatively small part of the total time. Even though the disturbing impulses may occur in rapid succession, their individual duration is so small as to leave relatively long intervals during which no disturbance occurs. In the case of vibrating interruptors, commutators, and alternating-current corona discharges, the undisturbed interval may be of considerable magnitude relative to the disturbed interval. In such cases it is possible to build into the receiving equipment a very rapid automatic volume control which will tend to bias the receiver to zero gain during the interval for which the disturbance level is higher than that of the carrier wave of the desired signal. (B 4)* The disturbance is thereby caused essentially "to commit suicide" within the receiving set, in that the set is effectively turned off at the moment a noise impulse arrives and is turned back on again during intervals between successive noise impulses. The desired signal, therefore, comes

* Bibliographical reference number.
through in an intelligible form.

Some of the radio interference created by an airplane flying at high speed into an area of precipitation is of such a type as to be susceptible to improvement by noise-suppressor circuits. When the airplane is in a light snow of relatively large individual flakes, the interference created is generally of a typical low-frequency vibrator type. Such interference could be removed by noise-suppressor circuits. However, when the flight is through most forms of precipitation of normal density, the interference created is of such a continuous character that no noise-suppressor circuit at present available has any beneficial effect. The interference ranges in character from a harsh, rasping sound in the head phones to a varying high-pitched musical note. The intensity frequently becomes so high as to make necessary the reduction of receiver gain to a point where the normal radio range station, in the absence of interference, could be read only a very short distance from the transmitter. Such storm-static conditions may exist for only brief periods during the passage through a precipitation area or, in the event of flight along an air mass front, they may exist for a matter of 30 minutes or more. Under such conditions the radio range cannot be read, and no reception
of voice communication from the ground or other airplanes is possible. The flight personnel must, therefore, resort to dead reckoning to maintain the course at a time when the radio navigable aids are most essential.
As airplanes became larger and speeds became higher, the storm-static interference problem became more acute. A number of accidents were directly attributable to airplanes being off-course due to their having lost the radio range under storm conditions, and then having encountered unreported squalls which drove them unknowingly into dangerous terrain. The hazard was recognized by pilots as well as by administrative personnel and efforts were started to attempt to solve the problem. At first it was thought that the interference was due to charged particles of precipitation impinging upon the exposed radio antennae. In an effort to eliminate this difficulty the antennae conductors were covered with rubber insulation but no improvement was obtained. It was reported by a number of pilots that under certain cold, dry-snow and frost-crystal conditions, the airplane wind shields had been seen to glow with a brush discharge. At times these brushes were reported to become so severe as to give the appearance of the wind shield sparking over completely. Under these same conditions, the rubber deicers on the leading edges of the airplane wings were observed to glow with brush discharges, and at times to appear practically to spark completely across. The tips of the
propellers were observed to glow at times with a typical St. Elmo's Fire.

These reports definitely established the fact that an electrical charging mechanism was taking place which was causing insulated areas on the airplane to attain very high potentials with respect to the ship itself. If that were the case, it was reasonable to assume that by the same mechanism the entire airplane was being charged to potentials considerably above that of the surrounding atmosphere. It was further evident, since the insulated surfaces such as wind shields and rubber deicers were being charged to potentials considerably above those of the airplane proper, that the potential of the ship was being held down by some form of discharge mechanism. In other words, it appeared that the wind shields and deicers were discharging to the ship, adding to the charge it was receiving by similar action, and the whole was discharging to the atmosphere. If such were the case, at least one source of the observed radio interference was the direct-current brush or corona discharge from sharp extremities of the airplane to the atmosphere.

Recognizing this possibility, the United Air Lines Transport Corporation undertook a systematic study of the problem. A regular ten-passenger, two-motor Boeing
Type 247-D transport airplane was withdrawn from passenger service and made available as a research ship. A number of the seats were removed and a test bench for scientific instruments was installed in their place. A partial view of the arrangement is shown on page 26.

The exterior of the plane was equipped with a number of charge- and discharge-measuring electrodes. The electrodes which gave the most interesting results were as follows:

(1) A short rod projecting from the side of the fuselage directly behind the left propeller tips.

(2) A sphere supported below the fuselage and behind the pitot stub.

(3) A 30-inch pointed rod projecting from the nose of the plane ahead into undisturbed air.

(4) An insulated plate in the form of a hollow disk, conforming to the streamlined shape of the nose of the plane.

(5) Three pointed rods, each approximately 12 inches long, projecting from each wing tip.

(6) A 30-inch pointed retractable rod extending rearward from the tail of the ship.
INTERIOR VIEW OF STORM-STATIC RESEARCH AIRPLANE SHOWING SYNCHRONIZED GRAPHIC-RECORDING MILLIAMMETERS AND CURRENT AMPLIFIERS
The nose electrode and nose plate, wing tip electrodes and tail electrode are illustrated on pages 28, 29 and 30. Each of the various electrodes was well insulated from the airplane and was connected through conductors to a terminal board beneath the test bench inside the cabin.

The instruments used in determining the currents of charge and discharge, and the polarity and character of these quantities were as follows:

1. Two highly-sensitive vacuum-tube electrometers.


3. Three synchronized Esterline-Angus graphic recording milliammeters, driven by a three-element vacuum-tube ammeter.


5. A special Bell Telephone Laboratories receiver equipped with noise-suppressing circuit.

6. Various microameters and auxiliary equipment.

The graphic recording instruments from which the most orderly data were obtained, together with their driving vacuum-tube ammeter are shown on page 26.
NOSE ELECTRODE AND NOSE PLATE
INSTALLED ON BOEING TYPE 247-D AIRPLANE
FOR STORM-STATIC RESEARCH
LEFT WING-TIP ELECTRODES
INSTALLED ON BOEING TYPE 247-D AIRPLANE
FOR STORM-STATIC RESEARCH
RETRACTABLE, POINTED TAIL ELECTRODE
INSTALLED ON BOEING TYPE 247-D AIRPLANE
FOR STORM-STATIC RESEARCH
The airplane was also equipped with an intercommunication telephone system which could be connected to the output of a radio receiving set being driven by any one of the following antennae:

(1) The standard "Belly V" beacon receiver antenna.

(2) The short-wave transmitting antenna.

(3) A shielded loop projecting beneath the fuselage of the plane and located approximately on a line between the two engines.

(4) A shielded loop in a streamlined housing above the nose of the airplane.

(5) A diagonal antenna extending from the end of horizontal fin to a position approximately mid-way of the fuselage of the ship.

(6) An interchangeable shielded loop or crossed dipole projecting forward from the nose of the ship.

Neither of the last-named antennae could be employed at the time the nose electrode and nose plate were in use. Most of these antennae are illustrated on pages 28 and 55. For a time a straight wire antenna inclosed in a non-conducting tube coated with a high-resistance
conducting compound was installed beneath and parallel to the fuselage of the airplane.

In the early work an attempt was made to observe the charge and discharge currents on indicating instruments and to correlate these currents with the radio interference observed on the different antennae. It was soon learned, however, that the conditions change so very rapidly that it was not possible to make notes fast enough to obtain an accurate record.

Before many tests had been made it was observed that all of the wire antennae gave approximately similar results. The one exception was the antennae extending toward the rear of the ship and this one was found to have a consistently higher noise pick-up property than the others. It was also observed that the shielded loop antennae, in agreement with previous tests, gave a noticeably higher signal-to-noise pick-up ratio than any of the wire antennae.

Since the standard "Belly V" beacon receiver antenna gave results essentially as good as any of the wire antennae, it was used as the comparison standard throughout most of the tests. It was found that the interference picked up by this antenna, as soon as any of the pointed electrodes began to pass an appreciable current, became severe.
When the electrode currents passed the order of 5 to 15 microamperes, the interference in the "Belly V" became so intense as to make impossible the reception of radio range signals even when relatively near the range transmitter.

The discharge interference picked up by the shielded loop antennas was noticeably much less than that picked up by the "Belly V", but when the electrode currents approached orders of magnitude of 50 microamperes or more, the loop interference became excessive.
ELECTRICAL CHARGE AND DISCHARGE RECORDS

In order to determine something of the mechanism of the airplane charge and discharge phenomena, the graphic recording milliammeters were so connected as to obtain simultaneous records of three phenomena. For some of the tests, the nose plate, nose and tail electrodes were used, and for other tests the wing tip and tail electrodes were employed.

A great number of records were obtained by flights in different types of precipitation in various cloud formations, and examples of these records are given on pages 35 to 40 inclusive. The record on page 35 is typical of those obtained under dry snow conditions. It will be noted that the nose plate charged negatively, whereas the nose and tail pointed electrodes discharged positively. That is, in the case of the nose plate record the airplane was positive with respect to the plate, while in the case of the nose and tail electrodes, the ship was negative with respect to the points. Since no appreciable ionization could be taking place from the nose plate, it was obvious that this surface was charged negatively by the precipitation in which the airplane was flying. The points, however, since they would readily
PLANE DISCHARGE CURRENTS, NOSE PLATE, NOSE AND TAIL ELECTRODES
UPPER, NOSE PLATE, CENTER, NOSE ELECTRODE; LOWER, TAIL
PRECIPITATION: DRY SNOW
SCALES: UPPER 0.1, OTHERS 10 MICROAMPERES PER MAJOR DIVISION, 0 UNITS PER MIN.
PLANE NEGATIVE FOR NEGATIVE DEFLections
BOEING 247-D
PLANE DISCHARGE CURRENTS, NOSE AND TAIL ELECTRODES
ABOVE, NOSE; BELOW, TAIL
PRECIPITATION: MODERATE SNOW
SCALES: 4 MICROAMPERES PER MAJOR DIVISION, 8 UNITS PER MINUTE
PLANE NEGATIVE FOR NEGATIVE DEFLECTION
BOEING 247-D
PLANE DISCHARGE CURRENTS, NOSE AND TAIL ELECTRODES
ABOVE, NOSE; BELOW, TAIL
PRECIPITATION: HEAVY SNOW, CENTER OF CLOUD
SCALES: 4 MICROAMPERES PER MAJOR DIVISION, 8 UNITS PER MINUTE
PLANE NEGATIVE FOR NEGATIVE DEJECTION
BOEING 247-D
PLANE DISCHARGE CURRENTS, WING-TIP AND TAIL ELECTRODES

UPPER, RIGHT WING: CENTER, LEFT WING: LOWER, TAIL

PRECIPITATION: WET SNOW

SCALES: 10 MICROAMPERES PER MAJOR DIVISION, 5 UNITS PER MINUTE

PLANE NEGATIVE FOR NEGATIVE DEFLections

BOEING 247-D
PLANE DISCHARGE CURRENTS, WING-TIP AND TAIL ELECTRODES

UPPER, RIGHT WING: CENTER, LEFT WING: LOWER, TAIL

PRECIPITATION: LIGHT, DRY SNOW

SCALES: 10 MICROAMPERES PER MAJOR DIVISION, 8 UNITS PER MINUTE

PLANE NEGATIVE FOR NEGATIVE DEFLECTIONS
BOEING 247-0
PLANE DISCHARGE CURRENTS, NOSE PLATE, NOSE AND TAIL ELECTRODES

UPPER, NOSE PLATE; CENTER, NOSE ELECTRODE; LOWER, TAIL

PRECIPITATION: HEAVY SNOW, CENTER OF CLOUD

SCALES: UPPER 0.1, OTHERS 4 MICROMETERS PER MAJOR DIVISION; 10 UNITS PER MIN.

PLANE NEGATIVE FOR NEGATIVE DEFLECTIONS

BOEING 247-D
admit of ionization, were discharging this negative electricity into the atmosphere. This was a typical condition experienced in dry-snow and frost-crystal areas.

A somewhat similar record on page 36, giving only the nose and tail electrode currents, shows the airplane discharging negative electricity to the atmosphere. In this case the airplane was in a condition of moderate snow which was not particularly dry.

An interesting condition is indicated by the record on page 37. The plane was flying in moderate snow and then suddenly entered a region of heavy snow toward the center of a cumulus cloud. The tail electrode began discharging negative electricity rather heavily and the nose electrode inverted its polarity, indicating that negative electricity was flowing from the region ahead of the ship, through the longitudinal conductors, and out the tail of the airplane. This condition would indicate the presence of a high electrical voltage gradient within the cloud. It will be observed that the airplane very suddenly emerged from that region into one of reversed gradient, that is, the nose electrode was in a positive region and the tail electrode in a negative region. Another slight reversal followed this condition and then the airplane settled down to an electrical discharge
of negative electricity from both nose and tail electrodes. These rapidly changing gradient conditions were experienced frequently in all of our work, particularly in cumulus or heat clouds. The radio interference accompanying high cloud-gradient conditions was always of such a character as to give the effect in the headphones of running through the entire musical scale. In the background there would also usually be a harsh, rasping type of interference.

An interesting case of the airplane discharging heavily from all electrodes on which measurements were being taken is recorded in page 38. The very consistent character of the negative electricity discharge from both wing tips and from the tail electrode is shown. It will be noted that the change of intensity of the discharge from any one electrode is accompanied by a similar change in the discharges from the other two electrodes. It is obvious that the ship was being charged negatively very strongly by some action of the precipitation in which it was flying. In this case the precipitation was heavy snow. The uniform vertical deflections present at periodic intervals in each graph were created by a special timing device and represent one-minute intervals. The radio interference accompanying the discharge in this case was very severe and of harsh character.
An interesting condition of high traverse gradients is illustrated in the record of page 39. In this case it will be observed that the right wing was in an area which was very strongly negative with respect to that surrounding the end of the left wing. Transverse currents of considerable magnitude were flowing from wing tip to wing tip as a result of this short circuiting action. It will be noted that near the end of the record a slight reversal of the gradient occurred. It is interesting also that in this case the tail electrode has been relatively inactive. Its tendency was to alternate somewhat between negative and positive discharges of relatively weak magnitude.

A condition different from any other so far discussed is brought out in the record of page 40. In this case the nose plate was receiving positive electricity at a time when both the nose and tail electrodes were discharging negatively. A period of longitudinal gradient reversals is also brought out in this record. The most interesting feature, however, is that the ionization electrodes were indicating heavy negative discharges at a time when exposed surfaces represented by the nose plate, were receiving positive electricity. This indicated charging mechanisms that were apparently considerably different from those in the other records.
The precipitation into which the plane was flying was evidently positively charged or the impact of the air foils with this precipitation resulted in a positive charge. The ship, however, was being charged negatively as indicated by the negative discharges. This leads to the belief that the propeller action in breaking up the heavy snow flakes was such as to result in a heavier negative charge on the plane than positive charge accumulation by contact of the air foils with the charged snow flakes.

A careful study of the discharge records leads to several rather definite and other somewhat obscure conclusions. It is well-known that cloud masses can become heavily charged by some type of thermal activity similar to that described by Simpson. (B 5). When an airplane flies into one of these charged areas it must gradually attain the potential of that area, first by electrostatic induction and later by actual contact with the charged precipitation. A potential gained in such a manner would place the ship at the same potential as the region in which it is flying, and hence would result in no localized voltage gradients, that would produce corona discharges.

It has been shown that the airplane can become charged
either positively or negatively with respect to its surrounding medium, the negative, however, being predominant. This phenomenon indicates that the contact with and breaking up of particles of precipitation by the airfoils and propellers result in charging the plane to a potential different from that of the particles themselves. The extreme wind-shield and deicer potentials observed at times indicate that contact with and breaking up of dry snow and frost crystals particles results in extremely high charge accumulations. The record of page 40 indicates that the action of the airfoils of the propellers may be such as to produce negative charges on the airplane from positively charged precipitation.

In large storm areas, where the precipitation is rather general and where the vertical air currents are not pronounced, a reasonably uniform charging condition may exist. At such times the airplane will attain a high negative potential with respect to the surrounding atmosphere and will discharge continuously. However, in squally conditions, notably in heat clouds, the charged areas are not at all uniform. The airplane may, therefore, fly from an area of low charge to one of much higher potential in a very brief period of time and, in so doing, the ship must be brought to the potential of the new
region. This change will result in heavy corona discharges of short duration between the plane and the higher-potential region into which it is flying. Subsequently, as the ship leaves this high-potential region and enters one of lower potential, the reverse operation will take place, that is, the ship will discharge its higher voltage to the lower potential region. Most of the high longitudinal gradients illustrated in the records were due to conditions of this character. The so-called "crying" or musical-note static in the radio receivers was observed to accompany these particular conditions, and it will be shown under "Point Discharge Studies", that positive corona discharges under many conditions characteristically produce this type of interference.

In order to check the ability of the propellers to produce electrical charges by breaking up water particles, the test plane was subjected to a spray test on the ground. The left motor was allowed to operate at approximately normal speed and a stream of water from the Portland, Oregon, City supply was directed into the propeller. It was observed that the electrode mounted behind the propeller indicated the accumulation of a positive charge. When the same test was made at Cheyenne, Wyoming, the electrode indicated a charge but this time
of reversed polarity. This characteristic indicates that the breaking up of water particles by propeller action may produce charges in a manner similar to that observed when drops of water are allowed to fall into a vertically rising air current.

A number of years ago some experiments were performed in the Electrical Engineering Laboratories of Oregon State College which indicated that if the salt content of the water which was allowed to drop into the rising air current were less than approximately eight parts per million, the spray which was blown from the water drops during their fall through the air current would be negatively charged. The droplets themselves attained a positive charge. When the salt content was increased a point was reached at which no charging action took place. If the salt content were further increased the polarities were reversed, that is, the spray would attain a positive charge and the water droplets a negative charge. This experience lends strength to the belief that the propellers, in breaking up certain types of precipitation, are largely responsible for the charges accumulated on the airplanes. Further substantiation of this belief is brought out by the fact that a large, all-metal airplane in a "power stall" is reported to give heavy radio interference when in bad static regions, whereas a "dead stall" in the same region results
in a marked reduction of the radio interference.

It was found that the discharge currents under practically all flight conditions fluctuate very rapidly. Some of the observations indicated transverse currents as great as one milliampere, and discharges from the tail electrode approaching the same order of magnitude were recorded on a few rather extreme occasions.

The characteristic St. Elmo's Fire discharge, so frequently reported as being observed during the hours of darkness at the propeller tips, is undoubtedly due to two elements. The first is that these propeller tips are very sharp, and since they extend out a considerable distance from the shielding influence of the fuselage and wings, they constitute excellent discharge points. The second is that due to the very high peripheral speeds of these propellers, as well as their pitch, a low pressure region exists near the tips. Since ionization occurs much more readily at low absolute pressures than in the normal atmosphere the discharges would take place in these regions at reduced potentials.

Two of the general types of cloud formations in which flight tests were made are shown on pages 49 and 50. The cumulo-nimbus or heat cloud on page 49 was of the violently agitated type, resulting in rapid changes from one type of charging action to another. Practically every type of
MODERATELY CHARGED CUMULO-NIMBUS CLOUD
LOWER WILLAMETTE VALLEY, OREGON
BETWEEN TWO MODERATELY HEAVY OVERCASTS
SISKIYOU MOUNTAINS, CALIFORNIA
ALTITUDE 12,000 FEET
charge is represented in such a cloud when tests are flown at various levels. The heavy rain and snow near the lower edge of the cloud is predominately positive, while the light drier snow in the upper part of the cloud usually releases negative charges upon contact with the frontal surfaces of the airplane.

The photograph on page 50 illustrates a condition frequently encountered in cross country flight. The airplane is in a clear region between two moderately heavy overcasts. In this position the range signals can be received clearly because there is no precipitation, and hence no static other than the occasional crash variety due to localized atmospheric discharges more or less distant from the plane. In both the lower and upper overcasts, however, there was a moderate amount of snow and frost and the accompanying radio interference was considerable.

The influence of size and speed of aircraft upon the charging action observed in precipitation areas and hence the influence of these same features upon the radio interference created, is pronounced. The larger and faster ships, since their frontal areas are larger and since their speeds are greater, make contact with more particles of precipitation per unit time than the smaller
ships. The result is a definitely higher charge and discharge rate together with a greater volume of interference. The broad wing spans and great axial lengths of the larger ships cause them to span greater areas and hence to create greater disturbances in the regions of high voltage gradients.

Since various areas on the airplanes experience such pronounced charging actions under certain storm conditions, it is evident that very thorough bonding should be practiced between all parts of the airplane. Occasions have arisen in which the cowling about the engines has become disconnected electrically from the nacelle. Under this condition radio interference of severe character is produced when the ship is flown through precipitation areas. The cowling repeatedly charges up and discharges through sparks to nearby bonded metal parts.

Any exposed insulating surfaces such as the wind shields, the deicers, insulating housings over radio loops and the exposed landing wheel tires, will, under certain conditions as outlined previously, accumulate electrical charges which will dissipate themselves in the form of sparks to nearby metal supports. This condition can be alleviated only by causing the surfaces of the offending elements to provide a leakage path to nearby
bonded metal parts. It is interesting to note that the ice caps which under certain precipitation conditions will form on the leading edges of the air foils, can have charges developed on their exposed surfaces. Since the ice accumulated at high altitude forms a very excellent insulator, the ice cap creates in effect, a localized insulated area similar to the deicer boots and wind shields.
The rapidly fluctuating character of the voltages encountered in the flight tests indicated the desirability of making tests on the airplane with more accurately controlled voltages. It was felt that flight conditions might be simulated by mounting the plane on insulators and charging it to a sufficiently high direct potential to cause exposed points to enter into corona. Information had been obtained on the magnitudes of discharge currents to be expected under storm conditions and the type of radio interference created had been observed carefully. It was felt that if these same conditions could be developed on the ground under accurately controlled conditions, much more consistent results could be obtained.

In line with these thoughts, the research plane was taken to Oakland, California, and mounted on high-voltage insulating supports in one of the large hangars at the Oakland Airport. The photograph on page 55 illustrates the ship set up on insulators for the high-voltage direct-current tests. Adequate insulation was provided to prevent the appearance of any brush discharges from the landing gear and wheels toward the concrete floor.

An improvised high-voltage rectifier, utilizing
BOEING TYPE 247-D RESEARCH AIRPLANE ON INSULATING SUPPORTS FOR HIGH-VOLTAGE DIRECT-CURRENT CORONA DISCHARGE TESTS
X-ray equipment, was assembled and adjusted to give a maximum potential of the order of 100,000 volts to ground. The circuit employed for this rectifier is given on page 58. It will be observed that with this arrangement it is possible to obtain from a transformer developing 50 kv peak, an output voltage, either positive or negative with respect to ground, of 100 kv dc. The principle advantage of this circuit is that the maximum inverse potential applied to either high-vacuum tube is the same as the output potential, and furthermore, it is necessary to use a transformer having a rating of only 50,000 volts line to ground.

With a potential of the order of 50,000 volts applied to the airplane, conducting surfaces connected to ground were brought up into close proximity to the various discharge points mounted on the airplane. Observers inside the cabin of the plane noted that currents of the same order of magnitude could be drawn from these points by this arrangement as were obtained in flight. They furthermore observed that the radio interference created by such discharges was of exactly the same character as that which had been noted during the flight tests.

Following these preliminary tests, arrangements were made to suspend conducting points from the tail electrode
HIGH-VOLTAGE RECTIFIER FOR ENERGIZING AIRPLANE
IN CORONA-DISCHARGE TESTS
Capacity: 100,000 Volts, Line to Ground
RECTIFIER CIRCUIT USED IN AIRPLANE GROUND TESTS
of the ship toward the concrete floor for a series of
discharge tests. It was felt that if the concrete floor
were used as the ground plane, the currents would distri-
bute so widely and return to the generator through such
a broad conducting medium as to prevent the creation of
disturbances in the radio antennae due to these currents.

For the first series of tests, a 0.25-inch steel
rod was sharpened with a rather long taper and was suspended
11 inches from the concrete floor. High-voltage ignition
conductor was used for the support in order to eliminate
the possibility of corona discharges from the conductor
itself. The tail electrode was well-covered with rubber
insulating tape to prevent it from going into corona.
Observations made during the hours of darkness indicated
that no visible discharges were taking place from any
part of the plane other than the point where the discharge
was desired. For the first tests, no resistance was
placed in the discharge lead and the radio beacon receiver
was connected to the "Belly V" antenna.

A local signal generator was employed to create
a background carrier wave, for which the beacon receiver
was tuned, which was modulated at a frequency of approxima-
tely 1000 cycles per second. It was so located, together
with the gain setting of the radio receiver, as to produce
a rectified output in the head-phone circuit of 0.5 microamperes. For all tests the receiver gain setting was kept at approximately the same point and a signal of 0.5 microamperes was obtained by so locating the local signal generator as to produce the desired output.

Since most of the flight work had indicated that the ship was discharging negative electricity, the first ground tests were made with the point negative with respect to the concrete floor. The results of the tests with this arrangement are given in appendix V, table II, and are illustrated by the curves on pages 61 and 62. These curves indicate that the maximum discharge current obtained was 110 microamperes and that the accompanying radio noise was severe only in the lower regions. This characteristic was checked many times and it was found that even though considerable current was being discharged, no appreciable interference was produced except at the highest values of current and again for currents of the order of less than 20 microamperes. At approximately 13 microamperes the radio interference was extremely severe. The character of the noise produced in the headphones was very similar to that which had been observed in flight tests.

The radio receiver was then connected to the lower shielded loop antennae and another set of data was taken.
AIRPLANE DISCHARGE CHARACTERISTICS

DISCHARGE ELECTRODE: Vertical rod 0.25 in. dia. pointed, 11 in. from concrete floor.
Polarity of ship: Negative
Background noise: Local signal generator, 0.5
Antenna: Lower "V"
Series resistance: \( R = 0 \)

Temp. 60° F.
Bar. 29.8 in.
Humid. 66 %
AIRPLANE DISCHARGE CHARACTERISTICS

DISCHARGE ELECTRODE: Vertical rod 0.25 in. dia.
pointed, 11 in. from concrete floor.
POLARITY OF SHIP: Negative
BACKGROUND NOISE: Local signal generator, 0.5.
ANTENNA: (a) Lower "V". (b) Lower loop (shielded).
SERIES RESISTANCE: $R = 0$.

Temp. 60° F.
Bar. 29.8 in.
Humid. 66 %
These data are given in table II and it will be observed that no interference was created except at the low-current point referred to above. The interference at this point was not of a severe magnitude although it was definitely noticeable. This result again checked the flight-test data very accurately. It had been noted in storm flying that the shielded loop had much better signal-to-noise ratio pick-up characteristics than the open antennae, and here again exactly the same characteristics were exhibited. It was now thought that the ground tests were probably a very good check on the flight tests because the same orders of magnitude of currents, the same type of interference, and the same selectivity of the shielded loop over the open antennae were observed.

It was felt that the rather large backing of the rod point was producing a shielding action which was influencing the characteristics at the higher voltages. Accordingly, a 7.5-inch length of tungsten wire with a diameter of 0.007 inch was suspended from the same support with the spacing reduced to three inches. The polarity of the ship remained negative and the same local signal generator output was maintained as previously. The results of the tests on this electrode are given in tables III and IV. It will be observed that the maximum currents were of the order of 580 microamperes and the radio interference as
obtained from the lower or "Belly V" antenna was severe throughout the entire voltage range. The shielded loop in this case also gave considerable interference for the higher current values, tapering down to relatively low interference at the lower voltages. The curves of pages 65 and 66, illustrate these data graphically. Again it will be noted that the shielded loop provides a very favorable signal-to-noise ratio over the open antennas.

By charging the airplane to a relatively high potential, and then cutting off the rectifier, it was possible to allow the charge to leak down slowly and thereby to obtain a number of points for currents lower than those obtained for the lowest voltage setting of the rectifier. These points are presented graphically on page 70 and it will be noted that below 50 microamperes the interference on the open antenna decays to zero with no characteristic high peaks as were observed in the case of the pointed rod.

A resistance of 28 megohms was now connected in series with the discharge point and further tests were made. The data obtained with this arrangement are presented in tables III and IV, appendix V, and in the curves of page 66. It will be observed that the insertion of resistance reduced the interference for a given discharge current to a marked degree. The interference
AIRPLANE DISCHARGE CHARACTERISTICS

DISCHARGE ELECTRODE: Vertical wire 7.5 in. long
0.007 in. dia., 3 in. from concrete floor.
POLARITY OF SHIP: Negative
BACKGROUND NOISE: Local signal generator, 0.5
ANTENNA: (a) Lower "V" (b) Lower loop (shielded)
SERIES RESISTANCE: $R = 0$

Temp. 60°
Bar. 29.8 in.
Humid. 66%
AIRPLANE DISCHARGE CHARACTERISTICS

DISCHARGE ELECTRODE: Vertical wire 7.5 in long, 0.007 in. dia. 3 in. from concrete floor.
POLARITY OF SHIP: Negative
BACKGROUND NOISE: Local signal generator, 0.5.
ANTENNA: (a) Lower "V" (b) Lower loop (shielded).
SERIES RESISTANCE: (1) R = 0 (2) R = 28 meg.

Temp. 60° F.
Bar. 29.8 in.
Humid. 66 %
pick-up of the shielded loop was actually reduced to zero throughout the entire range of currents observed. Although some interference was still obtained from the open antenna, a marked improvement in its performance was produced.

These results immediately suggested the possibility of using in flight some type of trailing discharge conductor. The flight tests had indicated that the interference problem could be solved only by preventing the charging of the plane to potentials greatly different from those of the surrounding atmosphere, or by dissipating these charges without disturbing the radio receiver. It was obvious that if the potential of the plane, by means of some discharging device, could be maintained at a value near that of the surrounding atmosphere, then no corona discharges could take place except in the event of passing through high-gradient regions where the plane is effectively short-circuiting high differences of potential. Since these latter conditions are only transient in their character, they are not particularly objectionable. This trailing-wire discharger, with high-resistance noise suppressors, has been tried in flight and found to be very beneficial under certain conditions.

After a satisfactory amount of negative-polarity data had been obtained, the rectifier was reversed.
and provisions were made for obtaining positive-discharge data. Because of the very much greater sparking distance of point-to-plane electrodes with point positive than with point negative, it was necessary to increase the space between the end of the fine tungsten wire and the concrete floor from three inches to 7.5 inches. Otherwise, the set-up employed was exactly the same as for the negative tests. The data obtained from these tests are given in table V and VI, appendix V. Some very peculiar characteristics were noted. Reference to the curves of page 69 will show that as the potential of the ship was raised slowly from 30 kv to 75 kv, the interference received by the open antennae, regardless of the fact that the current had risen to over 120 microamperes, was practically zero. Then very suddenly the interference jumped to a high value, and as the voltage was further increased, continued on to still higher values. Observations of the discharge point indicated that prior to the sudden burst of interference the discharge was in the form of a very fine point of localized ionization. At the instant the interference started, a long ionized streamer was observed to burst out from the end of the discharge electrode.

Again the shielded loop gave results similar to its previous performance in that its noise pick-up was vastly
AIRPLANE DISCHARGE CHARACTERISTICS

DISCHARGE ELECTRODE: Vertical wire 7.5 in. long, 0.007 in. dia., 7.5 in. from concrete floor.
Polarity of Ship: Positive
Background Noise: Local signal generator, 0.5.
Antenna: (a) Lower "V" (b) Lower loop (shielded).
Series Resistance: $R = 0$

Temp. 60° F
Bar. 29.8 in.
Humid. 61 %
less than that of the open antennae. No positive-polarity data were taken on the pointed-rod electrode.

A different analysis of the positive-discharge data is given by the curves of page 71. It will be noted that in this case the interference picked up by the open-wire antenna jumped from practically nothing at all to a very high value at approximately 110 microamperes. As the current was further increased to 190 microamperes, the interference followed a rather devious but increasing path. When the current was allowed to die out, by reducing the voltage on the ship, the interference remained at a fairly high value on down to low values of discharge current. These characteristics brought out the fact that the presence of ionization streamers was responsible to a considerable extent for the radio interference produced by the positive corona discharges.

Again the insertion of a discharge resistance of 28 megohms resulted in a marked improvement in the radio noise characteristics. Curve A-2 of page 71 illustrates the improvement obtained by the use of resistance. This curve is for decaying currents and represents ionized-streamer discharges from the highest to the lowest values. It will again be observed from curve B-2 of page 71, that the resistance completely eliminated the noise pick-up of the shielded loop.
AIRPLANE DISCHARGE CHARACTERISTICS

DISCHARGE ELECTRODE: Vertical wire 7.5 in. long, 0.007 in. dia., 7.5 in. from concrete floor.

POLARITY OF SHIP: Positive

BACKGROUND NOISE: Local signal generator, 0.5.

ANTENNA: (a) Lower "V" (b) Lower loop (shielded).

SERIES RESISTANCE: (1) R = 0 (2) R = 28 meg.

Temp. 60° F.
Bar. 29.8 in.
Humid. 61 %
The data obtained from the ground tests on the research airplane emphasized the necessity of additional basic studies in three different fields. The first subject requiring investigation was that of the character of high-voltage direct-current point discharges. The data so far obtained had indicated an erratic behavior of the interference produced by point discharges. It was felt that a comprehensive study of the subject should be made in order to understand better the nature of the controlling factors in this type of discharge.

The second subject requiring intensive study was the mechanism of the radio interference produced by corona discharges from point electrodes and the nature of the noise-suppressing influence of resistances in discharge circuits. The third subject was an extensive study of the characteristics of the shielded loop antenna with a view to determining the reason for its noise rejecting properties and further improving upon this property if possible. These subjects were taken up in the above order and they will be discussed in subsequent sections of this report.
The point discharge study was made in considerable detail. It was soon learned that the type of discharge obtained was dependent very largely upon the geometry of the point employed, and that the radio interference accompanying the ionization was very definitely a function of the discharge characteristics. The maximum potentials required were of the order of 50 kv dc and it was essential that the voltage ripple be reduced to a minimum. The currents involved were of the order of microamperes and, since it was desired to record by means of the Duddell oscillograph both the discharge current and the accompanying radio interference, it was necessary that a current amplifier be employed. In recording the radio interference on this oscillograph, it was necessary only to provide an impedance-matching transformer between the low-frequency output of the radio set and the vibrator circuit.

The general test circuit used is given on page 74. A full-wave high-vacuum rectifier was employed for the high-voltage generator, and a loading capacitance of one microfarad was used to reduce the voltage ripple. The output voltage of the rectifier was determined by sphere gaps used within their proper polarity range and correlated with the voltmeter-coil instrument, designated as V on
RESISTANCE-COUPLED LINEAR AMPLIFIER
FOR OSCILLOGRAPHIC STUDY OF
HIGH-VOLTAGE DC POINT DISCHARGES

\[ A_1 = 150 \mu\text{A} \quad E_b = 315\text{V} \quad R_1 = 5000\text{--}25000\text{\Omega} \]
\[ A_2 = 5\text{mA} \quad E'_b = 125\text{V} \quad R_2 = 0.5\text{meg.} \]
\[ A_3 = 250\text{mA} \quad E_c = 6\text{V} \quad R_3 = 200\text{\Omega} \]
\[ C_1 = 1.0\mu\text{f} \quad E'_c = 90\text{V} \quad C_2 = 0.25\mu\text{f} \]
\[ E s = 113\text{V} \]
the diagram.

A two-stage linear vacuum-tube amplifier employing a Type 57 and a GE Type FP 110 tube was constructed. This is a resistance-coupled amplifier, and by means of a proper setting of the bias voltage $E_c$, it is possible to utilize the amplifier over its entire range for either positive or negative polarities on the point $P$. It was convenient, by connecting the deflector-plates of a cathode-ray oscilloscope across $R_1$ or across $R_3$, to obtain wave-form checks against the indications of the Duddell oscillograph. These checks, as given in table XV, indicate that the Duddell oscillograph was responding with a satisfactory degree of accuracy. In the case of steep-front impulses of current or radio output, this oscillograph gave somewhat erroneous peak indications, and the vibrators displayed a minor tendency to fall into damped oscillations at their natural period. These characteristics, however, were not at all disturbing.

The capacitance $C_2$ was necessary to prevent feed back and consequent oscillations in the amplifier circuit.

To examine the radio interference created by discharges from the point $P$ to a plane, the conductor connecting the plane to the short-circuiting switch around $A_1$ and $R_1$ was carried once around the loop antenna of a Western Electric radio field-strength measuring set. (B 7)
The position of this coupling loop was so adjusted that no difference in radio output was observed when $R_2$ was introduced or short-circuited. The coupling was sufficiently loose to prevent the oscillations set-up in the antenna circuit of the field strength set from feeding back into the current amplifier and giving erroneous indications in the amplifier output.

Types of Discharge

Early in the point discharge studies it was observed that when the point is positive with respect to the ground plane, there are three distinct types of discharges to be obtained. These discharge types are dependent upon the geometry of the point employed and are illustrated on page 81. Type I is characteristic of the discharge obtained throughout the range of voltages available, from a sharp, slender point. In total darkness a small bead of ionization is visible at the end of the point and a tapering sheath of ionization extends for a short distance back up from the point. An extremely interesting characteristic of this type of discharge is that no radio interference accompanies it.

The discharge indicated as Type II is characteristic of that obtained from points which have a rather acute angle
TYPE I
Point: Sharp, slender.
Current: 42.5 MUA

TYPE 2
Point: No.0 steel needle.
Current: 48.0 MUA

TYPE 3
Point: Sixty-degree conical.
Current: 41.5 MUA

DIRECT-CURRENT CORONA DISCHARGES
ELECTRODES: POINT TO PLANE. POLARITY: POSITIVE.
SPACING: 10.2 cm. VOLTAGE: 44.0 KV
of backing. That is, in general, if the angle made by the surface of the point with its center line is approximately 30 degrees or less, and the point is carefully polished, this type of discharge will almost always occur. It may be described as a long, sharp ionized needle extending a considerable part of the distance between the point and the plane, and the current accompanying it for a given voltage is characteristically high. The radio interference produced by this type of discharge is severe and is characteristically harsh.

The type of discharge practically always obtained from a rough point or one which has a rather blunt backing, such as a conical point with sides making an angle of 60 degrees with the center line, is that illustrated as Type III on page 77. In this case there is a typical bead of ionization adjacent to the point proper, and then a rather slender stem extending below the bead for a short distance before the discharge blossoms into a broad plume. The current drawn by this type of discharge is in general the lowest of the three and the radio interference produced has a characteristic musical note. The pitch of this note may run from the order of several thousand cycles per second down to less than 100 cycles per second, and is exactly similar to that described as being observed under certain conditions in airplane flight tests.
It would appear then, that at least Type II and Type III discharges occur from airplanes in flight under certain storm conditions.

Oscillograms

Oscillographic records of point-discharge currents and the accompanying radio disturbances are interesting. The oscillogram presented on page 80 shows the discharge current and radio noise characteristics of a 60-degree positive point, spaced 10.2 centimeters from the ground plane and operating at a potential of 15.2 kv. The average current, as indicated by a D'Arsonval microammeter, was 2.0 microamperes. The scales were such that the current zero line blends in with the actual current wave between the impulse peaks. The timing wave employed was 1000 cycles per second and it will be observed that the average frequency of the current impulses was approximately 500 cycles per second.

It is important to note that the radio noise surges occur exactly in synchronism with the current impulses, there being no radio output during the intervals of steady current flow. These current impulses, when viewed on the screen of a cathode-ray oscillograph employing a high-speed
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: 60° POINT TO PLANE; SPACING, 10.2 CM.
POINT POSITIVE, PLANE GROUNDED; E = 15.2 KV., I = 2.0 MICROAMPS.
UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE
TIMING WAVE: 1000 CYCLES
sweep, are very similar to those of an impulse generator. Curve I of page 115 is typical of the individual impulses superimposed upon the steady direct current. It is obvious then that these impulses create the interference response in the radio receiving equipment. This subject will be treated further in the next section, "Nature of Radio Interference Arising from Corona Discharges." The discharge accompanying this oscillogram was a very small Type III.

When the voltage on the same point was increased to 38 kv, the current increased to 28.3 microamperes, and the radio noise and current appeared as is shown on the oscillogram of page 82. The individual impulse character is still present in the current wave but the impulses are spaced much more closely, the frequency now being of the order of 2200 cycles per second. The radio interference, although somewhat irregular in character has the same general frequency as the impulses in the discharge current. The slightly wavy zero line was due to a parasitic voltage picked up by the highly sensitive amplifier employed in the work.

When the electrode was changed from a 60-degree to a 45-degree point, the discharges obtained were somewhat unstable in that they would occasionally shift back and
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: 60° POINT TO PLANE; SPACING, 10.2 CM.
POINT POSITIVE, PLANE GROUNDED; E = 38.0 KV., I = 28.3 MICROAMPS.

UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE
TIMING WAVE: 1000 CYCLES
forth from Type II to Type III. The 45-degree point is on the border line between the geometry which consistently gives the Type III discharge and that which gives Type II. The oscillogram of page 84 was taken with this point operating at 43.5 kv to the ground plane. At the moment the exposure was made an observer reported that the discharge changed from Type III to Type II and the record of this change is given on the oscillogram. The typical high-frequency succession of current impulses produced by the Type III discharge is indicated in the first part of the oscillogram. On three occasions however, there were breaks indicating that a change in discharge type was about to occur. Near the end of the oscillogram this change did occur, and the irregular current wave and associated radio interference typical of the Type II discharge is shown in the last one-third of the record. It will be noted that there is a distinct change in the character of the radio interference in that the definite periodicity of the output impulses is largely gone. It is also of interest that the current has risen from 42 microamperes during the Type III discharge to 47 microamperes during the Type II discharge.

At this point in the work, some question arose as to whether or not the high-frequency pulsation character
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: 45° POINT TO PLANE; SPACING, 10.2 CMS.
POINT POSITIVE, PLANE GROUNDED;  E = 43.5 KV., I = 42-47 MICROAMPS.
UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE
TIMING WAVE: 1000 CYCLES
of the currents indicated by the oscillograms, for particular types of discharges, actually had occurred in the discharges themselves or were a characteristic of the circuit used in the measurements. In order to answer this question, a double, 60-degree point was made up in the form indicated by the photograph on page 86. The two points were similar, although not exactly the same, and were sufficiently close together to create a certain amount of mutual interference between their individual discharges. It was felt that if the circuit were responsible for the definite periodicity of the current impulses, then this type of double discharge would give the same result as a single individual discharge. However, the oscillogram of page 87, which shows a very definite beat or heterodyne action in the current ripple, indicates that each point had its own individual impulse frequency and that the two were sufficiently different to produce a pronounced beat in the resultant current ripple. The circuit was thus shown to be responding with a good degree of accuracy.

It has been mentioned that the Type 'I' discharge which is obtained from sharp, slender positive points is free from radio interference. This characteristic is illustrated by the oscillogram of page 88. The radio output is seen to contain no interference whatever, while the current wave
DIRECT-CURRENT CORONA DISCHARGES
ELECTRODES: DOUBLE, SIXTY-DEGREE POINT TO PLANE.
SPACING: 10.2 cm.   POLARITY: POSITIVE
CURRENT: 48.3 MUA VOLTAGE: 44.0 KV
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: DOUBLE 60° POINT TO PLANE; SPACING 10.2 CM.
POINT POSITIVE, PLANE GROUNDED; E = 33.0 KV., I = 26.0 MICROAMP.
UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE
TIMING WAVE: 1000 CYCLES
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: SLENDER, SHARP POINT TO PLANE; SPACING, 10.2 CM.
POINT POSITIVE, PLANE GROUNDED; E = 43.2 KV., I = 40 MICROAMPERES
UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE
TIMING WAVE: 1000 CYCLES
shows a number of very small impulses. These disturbances are evidently not sufficiently great to create any interference in the radio receiving set.

After the earliest types of points had been subjected to a rather complete study under positive polarity conditions, the high voltage generator was reversed and the studies were repeated for negative polarities. It was soon learned that all types of points, when of negative polarity, give discharges having essentially the same appearance. They seem similar to the type obtained for a positive sharp, slender point. A comparison between the Type I discharge obtained on negative polarity and the Type III obtained when positive, for the same identical point, is given on page 90. It will be noted that the glow at the point of the electrode is very intense in the negative case, and that the current is approximately 20 per cent higher than for the same voltage when positive.

The radio interference produced by the negative discharges was very erratic in its character for all types of points except the sharp, slender one illustrated on page 77. In this case, again, no appreciable interference was produced within the range of voltages available for the test.

The oscilligram on page 91 compares with that of page 89, with the difference that the former is negative.
TYPE I
Polarity: Negative.
Current: 49.6 MUA

TYPE 3
Polarity: Positive.
Current: 41.5 MUA

DIRECT-CURRENT CORONA DISCHARGES
ELECTRODES: SIXTY-DEGREE POINT TO PLANE.
SPACING: 10.2 cm.
VOLTAGE: 44.0 KV
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: 60° POINT TO PLANE; SPACING, 10.2 CM.
POINT NEGATIVE, PLANE GROUNDED; E=16.6 KV, I=3.0 MICROAMP
UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE
TIMING WAVE: 1000 CYCLES
and the latter is positive. The currents and voltages were of the same order of magnitude and identical points were used for both. It will be observed that the negative discharge current, in common with the positive as illustrated on page 80, is made up of a continuous value with a superimposed high-frequency series of small impulses. The frequency of these impulses is of the order of 2000 cycles per second as compared with approximately 500 cycles per second in the positive case. The amplitude of the negative impulses is considerably less than that of the positive. Again the radio interference is well synchronized with the current impulses although somewhat less regularly so than in the positive case.

For the very low discharge currents it was occasionally observed that in the negative case also, a tendency toward the musical note was produced by the interference in the radio receiver. When the voltage is increased to higher values, the negative impulses lose their individual distinction. In the case of most types of points, the radio interference becomes very erratic sometimes rising to high values and then dropping off to practically nothing only to rise again, perhaps to intermediate values as the voltage is slowly changed.

The oscillogram of page 93 compares with that of page 87 in that the points and discharge currents were identical
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: 60° POINT TO PLANE; SPACING, 10.2 CM.
POINT NEGATIVE, PLANE GROUNDED; E=36.2 KV., I=28.3 MICROAMPS
UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE
TIMING WAVE: 1000 CYCLES
with polarities reversed. It will be noted that in the positive case the radio interference peaks were much higher than in the negative case although the latter condition seemed to give the more irregular interference. Close observation will bring out the fact that the current wave in the negative case is made up of a continuous value plus a heterogeneous succession of current impulses. A great many of these impulses will be observed to start in the positive direction. In other words, the average current is negative but many of the impulses are in such a direction as momentarily to reduce the current rather than increase it as is practically always the case with positive polarity. This reversal phenomenon was particularly evident when the oscillograph screens were observed visually.

In the experimental work with negative discharges, the 60-degree point was practically the only one that could be depended upon to give finite radio-interference characteristics of any regularity whatever. Furthermore, points that were made of steel or copper were rapidly altered in their characteristics by oxidation and positive ion bombardment. Points constructed of tungsten gave much better results for operation over long periods of time.

An oscillogram of the sharp, slender point operating at 39 microamperes negative is shown on page 95. This oscillogram compares with that shown on page 88, the
DIRECT-CURRENT CORONA DISCHARGE CHARACTERISTICS

ELECTRODES: SLENDER, SHARP POINT TO PLANE; SPACING, 10.2 CM.

POINT NEGATIVE, PLANE GROUNDED; E = 38.5 KV., I = 39.0 MICROAMP.

UPPER, RADIO NOISE; LOWER, CURRENT WITH ZERO LINE 

TIMING WAVE: 1000 CYCLES
difference being only in polarity. It will be observed that there is practically no radio interference and that the current contains no apparent ripple. It should be explained that the slight appearance of radio interference was due to an extraneous disturbing factor, foreign to the test set-up.

**Characteristic Curves**

A series of discharge-current and radio-interference data was taken on each of several different types of electrodes. These data are presented in tables VII, VIII, IX, X, XI, XII, XIII, and XIV, appendix V. The discharge characteristics of a 30-degree conical point to plane are shown graphically on page 97. It will be observed that the negative currents are considerably higher throughout the entire range than the positive, and that the negative radio interference is very erratic. The character of discharge occurring during this test was Type I for the negative and Type II' for the positive. Type II' it should be explained, is somewhat of a combination of Types II and III, the long ionization needle of the Type II discharge being somewhat shortened and surrounded by a halo approaching the Type III characteristic. This type of discharge occurs frequently in the transitional period between
DIRECT-CURRENT POINT DISCHARGE CHARACTERISTICS

ELECTRODES: THIRTY-DEGREE CONICAL POINT TO PLANE.
SPACING: 10.2 cm.

POLARITY:
- POSITIVE - ●
- NEGATIVE - ○

BAROMETER: 740.4 mm. Hg.
TEMPERATURE:
- DRY BULB = 22.3 Deg. C.
- WET BULB = 18.0 Deg. C.

CURRENT

RADIO NOISE
the shorter Type III and Type II discharge. The radio interference produced by the Type II discharge is of consistent character and, in general, is much more severe than that obtained from the same point operating at the same voltage but of negative polarity.

The performance of the 45-degree point is shown graphically on page 99. It is similar in most every respect to the 30-degree point. The positive discharge is again Type II throughout most of the range, although at the lower voltages a Type III appeared. This type of discharge is somewhat of a combination of the Type I and the Type III discharges in that the plume forms very close to the point, there being only a very short, concentrated streamer connecting the point with the diminutive plume.

The discharge characteristics of the 60-degree point are shown on page 100. The currents and positive noise are somewhat similar to those given by the sharper points, but the negative radio noise is now reasonably consistent, although considerably less severe than the positive. The types of discharge for this point were a pure Type III for the positive and a Type I for the negative.

The very interesting and useful discharge characteristics of the sharp, slender point are given on page 104. It will be observed that the currents for this electrode were the highest of all the different points tested, but
DIRECT-CURRENT POINT DISCHARGE CHARACTERISTICS

ELECTRODES: FORTY-FIVE-DEGREE CONICAL POINT TO PLANE.
SPACING: 10.2 cm.

BAROMETER: 747.6 mm.Hg.
TEMPERATURE:
DRY BULB = 22.6 Deg.C.
WET BULB = 18.0 Deg.C.
POLARITY:
POSITIVE - ●
NEGATIVE - ○

CURRENT

RADIO NOISE

VOLTAGE TO GROUND PLANE, KV-DC
DIRECT-CURRENT POINT DISCHARGE CHARACTERISTICS

ELECTRODES: SIXTY-DEGREE CONICAL POINT TO PLANE.

SPACING: 10.2 cm.

BAROMETER: 757.1 mm.Hg.
TEMPERATURE:
DRY BULB = 23.0 Deg.C.
WET BULB = 18.4 Deg.C.
Polarity:
POSITIVE - ●
NEGATIVE - ○

VOLTAGE TO GROUND PLANE, KV-DC

DISCHARGE CURRENT, MICROAMPERES

RELATIVE RADIO NOISE

RADIO NOISE

CURRENT

RADIO NOISE
DIRECT-CURRENT POINT DISCHARGE CHARACTERISTICS

ELECTRODES: SHARP, SLENDER POINT TO PLANE.
SPACING: 10.2 cm.

BAROMETER: 745.1 mm. Hg.
TEMPERATURE:
DRY BULB = 23.8 Deg. C.
WET BULB = 18.2 Deg. C.
POLARITY:
POSITIVE - ●
NEGATIVE - ○

CURRENT

RADIO NOISE

VOLTAGE TO GROUND PLANE, KV-DC

DISCHARGE CURRENT, MICROAMPERES
RELATIVE RADIO NOISE
the radio interference, with the exception of one very weak disturbance at a relatively low voltage, was zero throughout the entire range. During practically all of the tests with this particular point, no interference was obtained on either polarity over the entire voltage range. The points indicating a small amount of interference were included on this particular curve because on one occasion a slight amount of interference did occur in that region.

Mechanism of Discharge

The foregoing curves and oscillograms point clearly to the nature and mechanism of high-voltage direct-current discharges from points. Again, as in the case of alternating-current corona discharges from conductors, space-charge phenomena are controlling factors in the point discharge mechanism (B 8)(B 9).

When the discharge electrode is positive, and of a blunt-backed type such as the 60-degree conical point, a general ion migration seems to account for a continuous flow of current between the point and the ground plane. Positive streamers periodically project into space from
the point, creating positive space charges which momentarily block further ionization until they have become reduced in intensity to the point where a succeeding streamer can develop. Since the entire point is symmetrical, having a region of high electrical field concentration surrounded by a relatively large background shield, the phenomena repeat with definite regularity. The frequency of repetition depends largely upon the voltage and, therefore, upon the current being discharged from the point. These individual positive streamers are responsible for the current impulses superimposed upon the otherwise relatively steady flow of current.

In the case of the sharper points with a less effective backing, the space charges do not build up with such definite regularity and the positive streamers are of a more random character. The orderly repetition of current impulses does not, therefore, occur.

Surrounding the end of the extremely sharp point with a long slender shank, the positive space charge seems to build up to a stable equilibrium and remain there over a wide range of discharge currents. This space charge blocks off the development of any positive streamers and hence no current impulses occur.

In the case of the negative polarity, the positive ion space charges are established in the region of high potential gradients and tend to move in toward the point
of discharge. As they approach it closely the voltage gradients build up to the point where further discharges occur. This mechanism results in the extraction of large numbers of electrons from the electrode and its vicinity. For low values of negative discharge currents, these electrons move outward with relatively low velocities and create, momentarily, a negative space surrounding the point. These phenomena result in the negative current impulses appearing in the circuit between the plane and ground. However, at the higher voltage, the clouds of electrons are projected with much higher velocities and result in the rapid creation of high positive space charges which actually block off, momentarily, the passage of more electrons out into the inter-electrode space. Hence the current appearing in the ground circuit tends to drop off abruptly as each of these high positive space charges is created, thus resulting in apparent positive impulses on the negative current flow. As these positive space charges move in toward the ionization point, breakdown occurs with great abruptness and hence the fronts of the current impulses are exceedingly steep although the impulses themselves are not large in magnitude.

Two of the most interesting phenomena brought out by the above tests are as follows:
1. A sharp, slender point can be caused to discharge positive or negative electricity, in amounts up to at least 40 or 50 microamperes per point, without creating any appreciable radio interference.

2. Rough points, which microscopically are sharp points with rather blunt backing, produce the most severe negative radio interference and also produce the musical-note type of positive interference.

It is proposed to carry on more extended studies of the high-voltage point discharge phenomena.
NATURE OF RADIO INTERFERENCE
ARISING FROM CORONA DISCHARGES

The nature of high-voltage direct-current point discharges as brought out by the oscillographic study outlined in the previous section, gave a very definite clue to the mechanism of the radio interference produced by such discharges. It was evident that the disturbances were created by the steep-wave-front current impulses. Particularly in the low-current positive discharge studies, was it obvious that each current impulse was accompanied by a heavy shock in the radio.

The essentials of the circuit employed in these tests, so far as the coupling to the radio field strength set is concerned, are given in the diagrams on page 107. The electrical equivalent of this circuit as it might be set up for a deliberate low-frequency study is shown on the same page. In the actual circuit the input to the radio receiver is through an inductive coupling between the circuit carrying point discharge current and the parallel-resonant antenna circuit of the radio receiver. The waves at the left of the discharge point indicate what might be expected of the voltage appearing on the point and also on the space charge surrounding the point, indicated in the diagram by the arc of a circle, as the recurrent impulses develop.
ACTUAL CIRCUIT

TEST CIRCUIT WITH LOOP PICK-UP
The impulsive currents, in flowing to ground through the circuit which is inductively coupled to the radio set, induce transient voltages in the antenna circuit of the radio receiver. These transient voltages set the tuned antenna circuit into oscillation at its natural period, and since the resultant oscillation has a definite decrement due to circuit losses, the high-frequency oscillation driven into the radio-frequency amplifiers is effectively modulated and appears in the output circuit as a surge of energy. The intensity of this surge depends upon the amplitude of the oscillation induced in the antenna circuit by the steep-wave-front current impulse in the ground circuit of the discharge electrodes. Since the induced voltage is equal to \( M \frac{di}{dt} \), the steepness of wave front of the current impulse as well as its magnitude, influences this voltage. A current impulse of high amplitude and steep wave front would, therefore, be expected to induce a severe oscillation in the tuned antenna circuit of the radio receiver and a resultant heavy surge in the output.

In many cases of radio disturbances produced by point discharges, the coupling from the discharge point and the space charge to the radio antennae is capacitive. This type of circuit is illustrated on page 113. It will be observed that here again the individual current impulses
H.V. Ld

ACTUAL CIRCUIT

Rd

Cs

Ce

EQUIVALENT CIRCUIT

Ld Rd Cse

Cs Cse

Csg

ANTENNA TO DISCHARGE POINT PICK-UP
occurring in the discharge circuit produce similar, although much smaller, current impulses in the primary of the antenna-circuit coupling coil. The same mechanism, therefore, applies in this case as in the former with respect to the transient excitation of the tuned radio-frequency circuits. The equivalent circuit for low-frequency studies of this type of interference pick-up is given on the same page.

In the case where the discharge occurs from a grounded point toward a high-voltage space or plane, the circuit of page 111 applies. This is the condition most frequently encountered in aircraft storm-static radio interference. Again the current impulses occurring in the discharge circuit have their counterparts, due to capacitive coupling, in the primary of the antenna coupling coil.

Impulse Excitation of Oscillatory Circuits

It is evident that in every practical case, the coupling of the radio receiver to the discharge circuit is such as to cause steep-wave-front currents to pass through the primary of the antenna coupling transformer when similar currents appear in the corona discharge circuit. The subject resolves, therefore, into a study of the impulse excitation of oscillatory circuits.
ANTENNA TO GROUNDED POINT PICK-UP
An equivalent circuit for such a study is given on page 113. In this case the quantities $R$, $L$, and $C$ are the constants of the circuit of an impulse generator. The mutual inductance $M$, coupling the impulse generator to the oscillatory circuit, is assumed to be very small relative to $L$, and hence a negligible amount of the disturbance created in the oscillatory circuit is fed back into the exciting circuit. The quantities $R'$, $L'$ and $C'$ are the constants of the oscillatory circuit.

If the key in the exciting circuit is raised to the upper position, the capacitor $C$ is charged by means of the battery to a certain voltage. If this key is then depressed, the capacitor will discharge through the circuit composed of $R$, $L$, and $M$, and if $R$ is greater than the critical value, this discharge will be impulsive in character. Such an impulse will cause the same type of voltage to be induced in the oscillatory circuit as the discharge impulses in the high-voltage point-discharge circuits cause to be induced in the tuned antenna circuit of the radio receiver. The oscillatory circuit should, therefore, respond to the impulse excitation in a manner exactly similar to that in which the high-frequency circuits of the radio receiver respond to the impulses in the antenna circuit.

The complete circuit of page 113 has been treated
EXCITING CIRCUIT

OSCILLATORY CIRCUIT

IMPULSE EXCITATION OF OSCILLATORY CIRCUIT
mathematically in appendix II and curves derived from equation (1) are given on page 115. These curves indicate the wave shape of the currents created in the exciting circuit of page 113 for different values of the quantities $R$ and $L$. The capacitance $C$ and battery voltage remain constant. Solid curve number 1 is the result of relatively low inductance and low resistance. Solid curve number 2 is the result of the same inductance as was used for number 1 but with $R$ increased by a factor of four. Solid curve number 3 is the result of the same resistance as was employed for number 2, but with the inductance multiplied by eight.

The dotted curves show the voltages which the respective current waves would inject into the oscillatory circuit through the mutual inductance $M$. It will be observed that waves number 1 and number 2 induce the same maximum voltages but have much different times of duration, number 2 being the shorter. Wave number 3 induces a very much lower voltage with a relatively long time of duration. The general equation of these voltages is (2), appendix II.

When such voltages are induced into the oscillatory circuit, the potentials resulting at $e$ are given by equation (7). So long as the resistance $R'$ is kept below
IMPULSE CURRENT WAVES

INFLUENCE OF RESISTANCE AND INDUCTANCE IN DISCHARGE CIRCUIT

1. L = 10 mH: R = 50,000 ohms
2. L = 10 mH: R = 200,000 ohms
3. L = 80 mH: R = 200,000 ohms
   C = 100 mmf.

SOLID CURVES: CURRENT, DOTTED CURVES: \( \frac{di}{dt} \)
the critical value, these potentials will be oscillatory in character. The amplitude of the oscillation will be determined very largely by the character of the voltage induced in the oscillatory circuit by the mutual inductance, M.

The waves of page 117 were calculated by means of equation (7), appendix II, and illustrate the type of oscillatory voltage appearing at e when the three different impulsive currents of page 115 are caused to flow in the exciting circuit. The amplitude of the voltage produced by impulse wave number 1 is relatively large. Wave number 2 results in a somewhat smaller voltage at e while exciting wave number 3 produces an oscillation of the lowest amplitude of all. Of particular interest is the fact that the introduction of higher resistances in the exciting circuit, resulting in impulse current waves of lower amplitude, produces correspondingly lower amplitudes of oscillation at e.

Of further interest is the effect of increased inductance in the exciting circuit. The introduction of this higher inductance at L, together with the same resistance at R as was employed for impulse wave number 2, results in a current wave of essentially the same maximum amplitude but of greatly reduced steepness of front. The relative
IMPULSE EXCITATION
OF OSCILLATORY CIRCUIT

CIRCUIT CONSTANTS

\( R = 20 \text{ ohms}, \quad L = 10^{-5} \text{ henrys}, \quad C = 10^{-9} \text{ farads} \)

![Graph of impulse excitation of oscillatory circuit with three exciting waves labeled 1, 2, and 3. The graph shows capacitor voltage in volts versus time in microseconds.](image)
amplitudes of oscillatory waves number 2 and number 3, page 117, illustrate the effectiveness of this reduced steepness of front of the exciting impulses in producing lower amplitudes of oscillation at e (page 113).

The above analysis indicates that not only resistance but also inductance in the high-voltage point-discharge circuits should be effective in reducing the impulse excitation of the tuned antenna circuit of the radio receiver. This analysis also indicates very definitely that the type of radio interference produced by these high-voltage discharges is of impulse excitation character, the only high-frequency oscillations appearing in general being those set-up in the antenna circuit of the radio receiver, at the frequency for which it is tuned, by the impinging impulse.* It is evident, therefore, that any operation upon the interfering circuit which will lessen the amplitude and reduce the steepness of wave front of the individual current impulses will result in improved radio interference characteristics.

* In certain cases parts of the circuit carrying the discharge currents are driven into complex, damped high-frequency oscillations and interfering energy is radiated directly. This mechanism, however, is believed to be the exception rather than the rule, particularly in direct-current corona phenomena.
The foregoing analysis was checked experimentally and the results are given in table XVI. The same data are presented graphically on page 120. A 60-degree conical point was employed, and the series resistance changed from zero to two megohms and the series inductance from zero to 37.2 millihenrys. A reduction of over 50 per cent in the radio interference was produced by the two-megohm resistor. A further 50 per cent decrease followed the introduction of the inductance. The inductance employed was not of a particularly good radio-frequency type, but it did verify the analysis and result in a definite improvement in the radio interference characteristics.

It is evident that the introduction of large amounts of resistance and inductance, with a minimum of distributed or shunt capacitance, in the high-voltage discharge circuits will result in minimized radio interference characteristics. Certain precautions, however, must be employed in using these resistors and inductors. Reference to the circuits of pages 107, 109, and 111 will show that the voltages of the discharge points may be expected to change abruptly with each impulsive discharge when resistors and inductors are incorporated in the discharge circuit. To prevent these sudden changes of voltage from inducing current impulses in the radio antenna, some form of shielding about the point might be necessary.
DIRECT-CURRENT POINT DISCHARGE CHARACTERISTICS

ELECTRODES: SIXTY-DEGREE CONICAL POINT TO PLANE.

SPACING: 10.2 cm.

BAROMETER: 745.0 mm Hg.
TEMPERATURE:
DRY BULB = 22.4 Deg. C.
WET BULB = 18.1 Deg. C.
POLARITY:
POSITIVE — •

RELATIVE RADIO NOISE

DISCHARGE CURRENT, MICROAMPERES
RADIO RECEIVING ANTENNAE

Energy abstracting devices for radio receiving equipment fall in three general classes:

1. The extended-conductor or open-wire antenna.

2. The simple loop antenna.

3. The shielded loop antenna

The extended-wire type responds to the traveling electromagnetic wave and is also sensitive to any electrostatic field in its vicinity. The true wave of electromagnetic radiation is composed of equal electric and magnetic components and the voltage induced in the open antennae is essentially the same as that created in space by the passage of the wave. Induction fields, however, preponderantly electrostatic or magnetic, can be caused to exist but their space coverage is relatively very limited. An extended-wire antennae in the presence of these induction fields will respond to both types. (Appendix III)

The unshielded loop antenna may be either of a balanced
or unbalanced type. In the latter case, the loop will respond to both magnetic and electric fields. The magnetic response is essentially by transformer action. The electric response is due principally to charging currents flowing through the loop circuit to ground.

The balanced loop responds well to magnetic excitation, again by transformer action, but is very insensitive to electric excitation. In this case, the charging currents due to electric fields flow to ground equally in both directions through the loop, thus effectively cancelling any pick up which might result. If the mid-point of this balanced loop is grounded, a similar cancelling of electric-field pick up will occur.

The shielded radio loop, when shielding is composed of a broken, metallic tube surrounding the turns of the loop and is balanced to ground, is responsive only to the magnetic field. In this case, any changing electric field terminating on the loop produces currents which are conducted to ground in practically equal magnitudes and in opposite directions around the two parts of the shield. Consequently, no potential is induced in the loop proper due to these charging currents flowing to ground. Any improvement in the shielding design which will tend to maintain a balance between the charging currents flowing
to ground through the two sides of the shield, will be beneficial in its results. The cross section of the shield itself seems to present a short circuited area to the impinging electromagnetic signal waves and has some undesirable attenuating effects upon the received signal. This condition undoubtedly could be improved considerably by properly laminating the shield in a direction parallel to its minor axis.
THE SHIELDED LOOP ANTENNA

It was brought out very definitely in the sections on Flight Research and Ground Tests that the shielded loop possessed marked advantages over the extended-wire antenna in its ability to discriminate between the desirable signal and undesirable "static" interference. This feature has been known for several years, particularly as regards effectiveness with certain types of static, and it has been employed advantageously in a number of fields. Its effectiveness in the attenuation of storm static on aircraft is due to the fact that this static interference originates fundamentally as a high-voltage low-current discharge phenomenon. The electric fields associated with these discharges are necessarily intense while the magnetic fields, due to the relatively feeble character of the currents, are very weak.

It has been shown that the discharge currents are composed of steady values with superimposed double-exponential impulses. Such currents may be represented by a complex series of multiple-frequency waves. These waves will produce true electromagnetic radiations. However, since the alternating components are very small, the radiation fields, which are functions of the currents, will necessarily be weak. The electric induction fields, on the
other hand, are intense because the voltages involved are of the order of several thousand. An open antenna should therefore respond strongly to the electrostatic fields in the vicinity of the corona discharges, and weakly to the magnetic fields accompanying these discharges. (Appendix III).

The properly shielded loop on the other hand, as has been shown in the previous section, rejects the electrostatic induction interference and accepts only the magnetic field. This magnetic field has essentially two components. (Appendix IV). The first is that of induction which varies directly with the current and inversely as the square of the distance from the source. The second is that of radiation which not only varies directly with the current but also with frequency, and inversely as the first power of the distance. The well-known radiation and induction equations indicate that these two components of the field are of equal intensity at a distance from the radiator equal to the radiated wave length divided by 2π. (Appendix IV).

In the case of the beacon receivers, the wave length is of the order of 1000 meters and the distance of equality between the magnetic components of the induction and radiation fields is approximately 159 meters. At distances of
the order of 10 to 50 feet from the source of interference, the radiation component of the magnetic field would then be expected to have a value of the order of 2 to 10 per cent of that of the induction component. The shielded loop will respond to this resultant magnetic field even though it is weak, and at short distances the response will be almost totally to the induction component. The strength of interference pick-up in the shielded loop should then vary almost exactly as the inverse square of these short distances from the interference source. (Appendix IV).

This law has been found to apply in some tests conducted in their Chicago Laboratories by the Communications Staff of the United Air Lines. (B 10).

The interference pick-up of the open antenna due to its exposure to the intense electric fields, should be expected to be great. It is shown in appendix III-A that the electrostatic pick-up of such an open antenna from an essentially localized source should be a function of the voltage of the source, and for the intermediate distances chosen, should be a function of the approximate inverse cube of the distance from this source. This prediction is also borne out by the results of the United Air Lines tests referred to above. (B 10).
**Improvement of Shielded Loop**

The problem of reducing the interference pick-up of the shielded loop is primarily one of removing the source of disturbance as far as possible from the loop, taking advantage of the inverse square law, and of reducing as much as possible the amplitude and wave front of the individual current impulses in the discharges.

The relative sensitivities of the shielded loop and open antenna to corona-discharge static suggest a possible means of further improvement in the loop characteristics. The charging current flowing in the antenna or loop shield due to electrostatic induction is proportional to and, at that point, is in phase with the magnetic field emanating from the conductor inducting the electric field. Hence, the voltage-inducing capacity:

\[
\frac{di}{dt} = K \frac{d\phi}{dt}.
\]

If an arrangement were established whereby a small amount of this charging current were caused, by mutual induction, to inject a voltage into the shielded-loop circuit equal to and in phase opposition with the loop output due to the corresponding magnetic field, a complete cancelling action would result.
A small, open antenna, such as an isolated area in the extremity of the loop shield, could be connected through a shielded lead-in and a variable, reversible mutual inductor to the loop output circuit. Such an antenna could be made to have a very weak signal response while retaining its sensitivity to the interfering electrostatic field. By proper adjustment of the mutual inductor, the small magnetic voltages of the loop could be cancelled in the output circuit by the voltages obtained from the charging current.

Since the loop has a definite directional sense to interference as well as to signals, the above arrangement would be most effective if the source of the principal interference could be localized in a definite plane.

The use of this device in connection with crossed loops seems to offer good possibilities.

It would probably be necessary to control the coupling inductor from the receiver control panel in order to obtain the proper balance for different conditions.

Experimental work has shown that the corona-discharge-static response of an unshielded, unbalanced loop, with one end of the loop grounded, may be less, for certain loop positions, than that of a completely shielded loop (B 10).
This characteristic is probably a demonstration of the cancelling action described above. The charging current flowing to ground through the loop conductors induces a voltage in phase opposition to that of normal loop pick-up when this loop has a certain orientation with respect to the interfering source. If the loop is rotated 180 degrees, the two voltages are placed in phase conjunction and increased interference intensity results.

If the electric and magnetic components of the fields impinging upon the loop and antenna arrangement described above produce voltages of equal magnitudes, as in the case of electromagnetic waves, the cancelling action would remove not only the interference but also the signal. It will be shown, however, in the next section, "Electric and Magnetic Induction" that at short distances from high voltage interfering sources, the electrostatic component may be much greater than the magnetic and hence only a relatively weak open-antenna response will be required.
ELECTRIC AND MAGNETIC INDUCTION

The subject of voltage and energy abstraction by electric and magnetic induction, in the case of conducting elements of simple geometries, is one which lends itself rather readily to a mathematical analysis. In appendix III such an analysis has been made. The simple geometries of a straight, over-head conductor inducing voltage and power in loops and conductors parallel to the first element were chosen. These conditions simulate, to a limited extent, the case of a loop antenna receiving voltage and energy by magnetic induction from a radiating conductor, as well as the case of an extended antenna receiving voltage and energy by electrostatic induction from the same conductor. In the final analysis, examples were chosen in which the only current flowing in the inducing conductor was that due to its voltage, frequency and capacitance to ground. The open-circuit voltage and maximum energy obtainable from the inductively-coupled circuits were then computed.

In the case of a radio receiver, the antenna circuit is one of parallel resonance, and since the grid circuit of the first stage of the radio-frequency amplifier is of extremely high impedance, the over-all impedance of the input circuit is high. Although it takes energy to drive
this circuit, the response is more a matter of the voltage induced in the input circuit than of the maximum energy available at that point.

For a pick-up loop of the same length as the inducing conductor, equation (45) appendix III, page 169, gives the open-circuit voltage of magnetic induction. It will be observed that this voltage is a function of the square of the frequency. For loops of shorter length than the inducing conductor, but located near the driving end, equation (51) appendix III, applies. Again, the voltage is a function of the square of the frequency.

The open-circuit voltage induced electrostatically on an extended, parallel conductor by the potential on an inducing conductor, is given in equation (24) appendix III. This equation indicates that the induced voltage is independent of frequency and is dependent only upon the voltage of the inducing conductor and upon the inter-conductor and ground capacitances.

The maximum power which can be obtained by magnetic induction from the full-length loop illustrated on page 154, is given by equation (47), appendix III. This equation is complex but contains factors indicating that the power varies with the cube of the frequency and the square of the voltage. For loops of fractional length located near the driven end of the conductor, this equation
becomes (53), the power being still a function of the cube of the frequency and the square of the voltage.

In the case of electrostatic induction employing the circuit of page 164, the maximum power available is given by equation (40), appendix III. This equation indicates that again the power is proportional to the square of the voltage, but this time to only the first power of the frequency. From the above equations, it is evident that at relatively low frequencies the voltage and power induced electrostatically may be much higher than that induced magnetically, whereas at high frequencies the exact reverse of these conditions may obtain.

Appendix III examples were worked out for the purpose of determining the voltages and powers to be obtained from certain conductor arrangements and frequencies. The conditions of the examples are given on page 172. For the full-length loop, magnetic pick-up at 100 cycles per second, the open-circuit voltage is only $4.33 \times 10^{-5}$ volts, whereas the electrostatic open-circuit voltage is $2.18 \times 10^3$ volts. With the frequency raised to one megacycle, the magnetic voltage becomes $4.33 \times 10^3$ volts, and there is no change in the electrostatic potential. It is shown that the induced open-circuit voltages are identical at a frequency of $7.08 \times 10^5$ cycles per second.

If the pick-up loop only is reduced in length to
1 per cent of its former value, the magnetic voltage at 100 cycles per second is \(3.59 \times 10^{-7}\) volts. At 1 megacycle this voltage becomes 85.9 volts. Under this condition, to obtain the same voltages from both electrostatic and magnetic inductions the frequency must be raised to 5.03 megacycles.

The maximum power obtainable from the full-length loop by magnetic induction at 100 cycles per second is shown to be \(9.4 \times 10^{-9}\) watts, whereas this power becomes \(9.4 \times 10^3\) watts when the frequency is raised to 1 megacycle. The maximum power obtainable by electrostatic induction from the full-length conductors at 100 cycles per second is \(2.69 \times 10^{-2}\) watts, and if the frequency is raised to 1 megacycle this power becomes 269 watts. The frequency for equal maximum powers by both types of induction becomes \(1.69 \times 10^5\) cycles per second. For the short pick-up conductor and loop, but with full-length inducing conductor, the maximum powers become equal at \(1.09 \times 10^5\) cycles per second.

If the short pick-up loop is retained, but the inducing conductor is reduced to four per cent of its original length, namely to four meters, the frequency for equal power by both types of induction becomes \(3.11 \times 10^6\) cycles per second. The induction voltages become equal at \(26.8 \times 10^6\) cycles per second. Appendix III, equation(1).
It is thus necessary, for this condition, to raise the frequency to relatively very high values to bring about voltage and power equalities by the two types of induction.

The foregoing analyses indicate that electrical disturbances which are fundamentally of a high-voltage character may be expected to create a much greater response in a radio receiver driven by an open antenna than in one which is driven by a shielded or balanced loop. As has been noted previously, these conclusions are in exact accord with those obtained experimentally.
CONTROL OF ELECTRICAL DISCHARGES
FROM AIRCRAFT

Since it is apparently impossible to prevent the accumulation of electrical charges during flight through certain storm conditions, corona discharges from extremities of the aircraft must of necessity occur when the potential difference between these extremities and the surrounding atmosphere become sufficiently high. It has been shown that these discharges will produce interference in the radio receiving equipment on board the aircraft unless they are so controlled as to prevent the appearance of random, steep-wave-front current impulses.

It is probable that some discharging action is obtained through the medium of the ionized exhaust gas from the engines. It has been suggested that further discharging could be produced by projecting an ionized solution into the atmosphere from the charged airplane. Such methods, however, at present seem inadequate and it is apparently necessary to resort to some ionization device to maintain the proper potential equilibrium.

A conductor trailing from the tail of the airplane and terminating in one or more sharp, slender points would be expected to discharge considerable energy to the region immediately surrounding the points. It has been shown that such sharp, slender points produce discharges,
regardless of polarity, which for low and intermediate values of current are free from the disturbing current impulses. To guard against interference from other types of discharges which might form in the vicinity of these points, it would be well to supply the trailing conductors with resistive and inductive wave suppressors.

There are many conditions of flight through severe storm areas where a single trailing conductor would not provide adequate discharging capacity. In those cases it would doubtless be desirable to have point dischargers of the sharp, slender variety, with resistive and inductive wave suppressors, on the wing tips and probably also on the nose of the plane. The wing tip electrodes, and also possibly other discharge points at the extremities of the vertical and horizontal fins, might be of either a trailing or projecting type. Other sharp projecting edges and points on exposed parts of the airplane should then carefully be removed.

It is probable that under some conditions of heavy charging, the radio transmitting antenna may go into corona. To avoid such possibilities, in a final clean up this antenna might be equipped with a moderately heavy rubber insulation. Such insulation would have the effect of reducing the potential gradient at the surface of the
conductor and would thereby increase the voltage required for ionization.

The end to be worked toward would be that of allowing sufficient energy to be discharged from the controlled points to keep the potential of the plane low enough, with respect to the surrounding atmosphere, to prevent discharges from occurring elsewhere.

The propellers may be found to be serious offenders. In that event it might be necessary to ground the engines to the fuselage of the ship only through high-resistance and inductance suppressors.

Exposed, normally insulating surfaces such as wind shields and deicer boots can be made electrically conducting and thus prevent the accumulation of sufficient charge on such surfaces to cause sparking over to metal supports.

It has been suggested that it might be beneficial to excite all of the controlled discharge points on the airplane by means of a high-voltage oscillator thus causing the discharge to occur periodically, permitting radio reception to be effective during the dead periods. The actual development of this scheme seems physically difficult, but it might be expected to give positive results.
CONCLUSION

The incorporation on a test airplane of all the numerous results and suggestions outlined in this report would entail a great amount of time and expense. The problem must eventually be solved if the progress of aerial navigation is to continue. It is to be hoped that through active cooperation of all interested agencies this solution will be reached in the not-too-distant future.


APPENDICES I TO V

APPENDIX I, pp. 142-144:

APPENDIX II, pp. 145-149:
Impulse Excitation of Oscillatory Circuits.

APPENDIX III, pp. 150-180
Voltage and Energy Abstraction by Induction

APPENDIX III-A, pp. 181-183
The Approximate Variation with Distance of the Potential Induced Electrostatically in Space by an Elevated, Charged Disc.

APPENDIX IV, pp. 184-188
Electromagnetic Radiation and Induction

APPENDIX V, pp. 190-205
Tables I to XVI
The following discussion applies to an antenna composed of two equal-height vertical radiators driven at the same frequency.

With reference to the diagram of page 10, the relative instantaneous radiation field strength at point P on the horizon under conditions of perfect transmission is:

\[ f_p = b \sin \theta + a \sin (\theta + \beta - \frac{\lambda}{\lambda} 360) \]

\[ = b \sin \theta + a \sin (\theta + \beta - 360 \frac{d}{\lambda} \cos \alpha) \] \hspace{1cm} (1)

Where:

\( f_p \) = relative instantaneous field strength.

\( b \) = relative field strength at P from vertical radiator "b."

\( a \) = relative field strength at P from vertical radiator "a."

\( \theta \) = angle of progression of last positive wave front past P ("b" radiation), degrees.

\( \beta \) = phase angle between driving voltages of "a" and "b", degrees.

\( d \) = distance between radiators, meters.

\( \lambda \) = wave length of radiation, meters.
\[ \alpha = \text{angle which radius vector joining \( P \) and center point of line between radiators makes with plane of towers; counter-clockwise rotation.} \]

Equation (1) applies accurately only when the distance from radiators to point \( P \) is great relative to \( d \), the tower separation.

The value of \( \Theta \) for maximum instantaneous resultant radiation at \( P \) can be obtained by differentiating (1) with respect to \( \Theta \) and equating to zero.

\[
\frac{df_p}{d\Theta} = b \cos \Theta + a \cos (\Theta + \beta - \frac{\ell}{\lambda} 360) \\
= b \cos \Theta + a \left[ \cos \Theta \cos (\beta - \frac{\ell}{\lambda} 360) \\
- \sin \Theta \sin (\beta - \frac{\ell}{\lambda} 360) \right] = 0 \quad (2)
\]

Equation (2) divided by \( \cos \Theta \) gives:

\[
b + a \cos (\beta - \frac{\ell}{\lambda} 360) \\
- a \tan \Theta \sin (\beta - \frac{\ell}{\lambda} 360) = 0 \quad (3)
\]

Then:

\[
\tan \Theta_m = \frac{b + a \cos(\beta - \frac{\ell}{\lambda} 360)}{a \sin (\beta - \frac{\ell}{\lambda} 360)} = \frac{b + a \cos(\beta - 360 \frac{d}{\lambda} \cos \alpha)}{a \sin (\beta - 360 \frac{d}{\lambda} \cos \alpha)} \quad (4)
\]
Where:

\[ \theta_m = \theta \text{ for maximum resultant radiation.} \]

For equal values of \( a \) and \( b \):

\[ \theta_m = \frac{1}{2} \left( 180 - \beta + 360 \frac{d}{\lambda} \cos \alpha \right) \tag{5} \]

and:

\[ f_{pm} = 2 b \sin \theta_m \]

= relative maximum instantaneous radiation (total) at "P."
APPENDIX II

IMPULSE EXCITATION OF OSCILLATORY CIRCUITS

With reference to the diagram on page 113, the current flowing in the exciting circuit is a double exponential of the form:

\[ i_1 = \frac{E}{2BL} \left[ e^{(b-a)t} - e^{-(b+a)t} \right] \text{ amperes} \quad (1) \]

The voltage \( e_g \) introduced by induction into the oscillatory circuit is of the form:

\[ e_g = M \frac{di_1}{dt} = \frac{ME}{2BL} \left[ (b-a)e^{(b-a)t} + (b+a)e^{-(b+a)t} \right] \quad (2) \]

Where:

- \( E \) = impulse-generator excitation voltage
- \( e = 2.718 \)
- \( a = \frac{R}{2L} \)
- \( b = \left( \frac{R^2}{4L^2} - \frac{1}{LC} \right)^{1/2} \)
- \( \left( -\frac{R^2}{4L^2} > \frac{1}{LC} \right) \)
- \( L \gg M \)

The quantities \( R, L, \) and \( C \) are the constants of the
exciting circuit in ohms, henries, and farads respectively.

Since the sum of the voltages around the oscillatory circuit must equal the applied voltage:

\[ e_{R'} + e_{L'} + e_{C'} = e_g \]

or

\[ R'i + L' \frac{di}{dt} + \frac{1}{C'} \int idt = e_g \]  \hspace{1cm} (3)

in which \( R', L', \) and \( C' \) are the constants of the oscillatory circuit in ohms, henries, and farads respectively.

Equation (2) substituted in (3) and differentiated gives:

\[
L' \frac{d^2i}{dt^2} + R' \frac{di}{dt} + \frac{i}{C'} = \frac{ME}{2bL} \left[ (b-a)^2 e^{(b-a)t} - (b+a)^2 e^{-(b+a)t} \right] \]

(4)

This equation can be solved by methods given in any standard textbook on differential equations (B 6).

The solution of the above differential equation is

\[
i = \frac{ME}{2bLL'} \left[ \frac{(b-a)^2 e^{(b-a)t}}{(b-a+a')^2 + b'^2} - \frac{(b+a)^2 e^{-(b+a)t}}{(b+a-a')^2 + b'^2} \right] \\
+ \left( K_2^2 + K_3^2 \right) \frac{1}{b'} e^{-a't} \sin \left[ b't + \tan^{-1} \left( \frac{K_2}{K_1} \right) \right]
\]  \hspace{1cm} (5)
in which

\[
a' = \frac{R'}{2L'}
\]

\[
b' = (\frac{1}{L'C'} - \frac{R'^2}{4L^2})^{\frac{1}{2}} \quad \left(\frac{1}{L'C'} > \frac{R'^2}{4L^2}\right)
\]

\[L' \gg M\]

\[K_1 \text{ and } K_2 = \text{constants of integration}\]

The voltage appearing across the capacitance of the oscillatory circuit (which is usually the voltage applied to the grid of the first detector or radio-frequency amplifier in a radio receiving set) may be found from an integration of equation (5) thus:

\[
e_{C'} = \frac{1}{C'} \int_0^t e \, dt
\]

The result of this integration between the limits indicated, since at \(t = \infty\), \(e_{C'} = 0\), is:

\[
e_{C'} = \frac{b'vL'C'}{2bL'C'} \left[ \frac{(b-a)s}{(b-a+a')^2 + b'^2} \right.
\]

\[
+ \frac{(b+a)e^{-(b+a)t}}{(b+a-a')^2 + b'^2} \left.ight]
\]

\[
+ \frac{1}{a'^2 + b'^2} \left[ \frac{K_1 + K_2}{a'^2 + b'^2} e^{-a't} \right.
\]

\[
\sin \left[ b' t - \tan^{-1} \left( \frac{b'K_1 + a'K_2}{b'K_2 - a'K_1} \right) \right]
\]
From the condition that at \( t = 0, \ i = 0 \), from equation (5) the following expression for the integration constant \( K_2 \) can be obtained:

\[
K_2 = \frac{2ME \left[ a'(b^2-a^2)+a(b_{L}^2+a_{L}^2) \right]}{LL' \left[ (b-a+a')^2+b_{L}^2 \right] \left[ (b+a-a')^2+b_{L}^2 \right]} \tag{8}
\]

Further, from the condition that at \( t = \infty, \ e_r = 0 \), the relation is obtained:

\[
\frac{b'K_1+a'K_2}{a'+b'b'} = \frac{ME}{LL'} \cdot \frac{(b^2-a^2)+(a'_{L}^2+b_{L}^2)}{[b-a+a']^2+b_{L}^2 \left[ (b+a-a')^2+b_{L}^2 \right]} \tag{9}
\]

From these last two relations, \( K_1 \) and \( K_2 \) can be computed.

It can be shown by manipulation of (8) and (9) that

\[
\tan^{-1} \frac{b'K_1+a'K_2}{b'K_2-a'K_1} = \tan^{-1} \frac{b'[b^2-a^2+(a'_{L}^2+b_{L}^2)]}{a'[b^2-a^2+(a'_{L}^2+b_{L}^2)](2a-a')} = \alpha \tag{10}
\]
and that

$$\left( \frac{K_1^2 + K_2^2}{a_1^2 + b_1^2} \right)^{1/2} = \frac{b'K_1 + a'K_2}{a_1' + b_1'} \csc \alpha$$

Hence the constant in the expression for the capacitor voltage $e_0$ in equation (7) may be computed by using equations (10) and (11).
In the analytical study of certain interference-refecting properties of the shielded-loop radio receiving antenna, it is helpful to analyze the general phenomena of magnetic and electric induction. The same analysis is also helpful in the study of inductive coordination between power and telephone circuits.

To a very large extend in the case of radio receiving equipment and to a lesser degree in telephone circuits, the output response is a function of the voltage induced in the input circuit. A certain amount of input power is also necessary. However, in the case of radio receivers, the input circuit is one of parallel resonance which approaches infinite impedance and zero power. The output of this resonant circuit is to the high impedance grid of a vacuum tube, leaving the overall input impedance very high in its order of magnitude.

In the following analysis the inducing conductor is assumed to be parallel to the pick-up conductors. Equations (3), (10), (23), (24), (44), (45), and (51) give induction voltages. It will be noted that in the case of magnetic induction the voltage is a function of frequency, current in the inducing conductor, spacing and length.
The magnetically induced voltage \((51)\) due to charging current in the inducing conductor is a function of the frequency squared, the voltage and length of the inducing conductor, the length of the pick-up loop and the spacings. This latter condition simulates, in a way, the case of a radio receiving loop in the field of a high-frequency conductor.

In the case of electrostatic induction, the voltage is independent of frequency and length (where the length is not too small) and is a function of effective interconductor. These capacitances can be expressed in terms of spacings and conductor sizes as in equations \((32)\) and \((34)\).

The maximum power that can be obtained by induction is given in equations \((20), (21), (22), (39), (40), (46), (47), (52),\) and \((53)\). It will be noted that the maximum power of magnetic induction is a function of the frequency, the square of the length of the pick-up loop, the square of the current in the inducing conductor, the square of a spacing factor and is a reciprocal function of the self inductance of the pick-up loop.

In the case of electrostatic induction the maximum power is a function of the frequency, the voltage of the inducing conductor squared, the effective capacitance between the two conductors squared and is a reciprocal
function of twice the sum of the effective inter-conductor capacitance plus the effective ground capacitance of the pick-up conductor.

The maximum power of magnetic induction due to charging current in the inducing conductor is given by equation (53). In this case, which again simulates in a way the case of a radio receiving loop in the field of a high-frequency conductor, the power is a function of the cube of the frequency, the square of the length of the loop, the square of the voltage and length of the inducing conductor, the square of a spacing factor and is a reciprocal function of the self inductance of the loop.

It will be noted that the power of electrostatic induction varies directly with frequency whereas that of magnetic induction due to charging current varies as the cube of the frequency.
Consider the circuit of page 154. The flux in the loop D-D' due to the uniform current $i$ in the long, straight conductor A is (neglecting ground reflections):

$$\phi_d = S \int_{X_1}^{X_1'} \frac{0.2i}{X} dX = 0.2i S \ln \frac{X_1'}{X_1}$$

$$= 0.2i S \ln \frac{X_1'}{X_1} \quad (1)$$

Where length of loop is $S$ and induction intensity at point $X$ is:

$$H = \frac{0.2i}{X}$$

In air:

$$B = \frac{0.2i}{X} \text{ cgs lines/cm}^2$$

Then the voltage induced in the loop is:

$$e_d = \frac{d\phi_d}{dt} \cdot 10^{-8} \text{ volts}$$

$$= (0.2 I_m \cos \theta \ln \frac{X_1'}{X_1})2\pi f \cdot 10^{-8} \quad (2)$$

($i = I_m \sin \theta$)
MAGNETIC INDUCTION
\[ E_d = \frac{0.4 \sin f}{\sqrt{2}} \cdot 10^{-8} I_m \ln \frac{X_1}{X_1} \text{ volts effective (3)} \]

(open circuit)

Where \( I_m \) is the crest value of the sinusoidal current in conductor \( A \), \( f \) is the frequency, and \( S \) is the length of the loop in centimeters.

The current in the loop \( D-D' \) is:

\[ I_d = \frac{E_d}{Z_d} = \frac{E_d}{\sqrt{R_L^2 + \frac{2\pi f L_s^2}{L}}} \text{ amperes effective} \]

Where \( L_s \) is the self inductance of the loop.

When:

\[ I_d R_L = I_d (2\pi f L_s) = 0.707 E_d \]

the power delivered to the resistance, \( R_L \), is maximum.

The self inductance of the loop \( D-D' \) is (neglecting ground reflections):

\[ L_s = \frac{\phi_s}{I_d} \cdot 10^{-8} \text{ henry/cm.} \]

Where:

\[ \phi_s = 0.2 I_d \left[ \int_{r_d}^{b} \frac{1}{X'} \, dX' + \int_{0}^{b-r_d} \frac{1}{b-X} \, dX' \right] \]

\[ = 0.2 I_d \left[ \ln X' \left|_{r_d}^{b} - \ln(b-X) \left|_{0}^{b-r_d} \right. \right] \]

\[ = 0.2 I_d \left[ \ln \frac{b}{r_d} - \ln \frac{b-r_d}{0} \right] \]
= 0.2I_d \left[ \ln \frac{b}{r_d} - \ln \frac{r_d}{b} \right] \\
= 0.4I_d \ln \frac{b}{r_d} \\

lines per centimeter length of loop \quad (5)

Where \( r_d \) is the radius of conductors \( D \) and \( D' \).

Hence, when \( \frac{S}{b} \) is large (and considering only flux external to the conductors):

\[
L_s = 0.4 \ln \frac{b}{r_d} \cdot 10^{-8} \text{ henry/loop cm} \\

(6)

Where the length of the loop is not great relative to its breadth, an extra term must be added to (6) to care for the inductance of the end connections. Then, approximately, for low frequencies:

\[
L_{s1} = 0.40 \left[ s(2.303 \log \frac{b}{r_d} - \frac{b}{S} + 0.25) \\
+ b(2.303 \log \frac{s}{r_d} - \frac{s}{b} + 0.25) \right] 10^{-8} \\
\text{henry} \\

(7)

The exact equation for the inductance of a rectangle in free space is: (B 1)*

\[
L_{s2} = 0.921 \left[ (s + b) \log \frac{2s}{r_d} - s \log (s + g) \\
- b \log (b + g) \right] 10^{-8} + 0.40 \left[ \mu \delta(s + b) \\
+ 2(s + r_d) - 2(s + b) \right] 10^{-8} \text{henry} \\

(8)

*Numbered references in Bibliography.
\[ g = \left( s^2 + b^2 \right)^{\frac{1}{2}} \]

\[ \mu \delta = 0.25 \text{ for low frequencies in air.} \]

**Influence of Ground Reflections**

Equations (1), (3), (5), (6), (7), and (8), apply strictly only when the conductors are suspended above a ground plane of relatively poor longitudinal conductivity, that is, when the ground currents resulting from magnetic flux penetration are negligible. This condition is generally true in practice. However, if the earth, or reference plane, is perfectly conducting, no flux penetration can exist, and reflection occurs from the earth surface. This reflection, in its influence upon the flux at point \( X \) produced by the current in \( A \), can be simulated by the image conductor \( A \) carrying the current \( I \) in the opposite direction, the whole system being immersed in free space.

Then:

\[ \phi_d' = \int_{x_1}^{x_1'} \frac{0.21}{X} \, dx + \int_{x_2}^{x_2'} \frac{0.21}{X} \, dx \]

\[ = 0.21 \, \text{S} \ln \frac{x_1' x_2'}{x_1 x_2} \]

(9)
Equation (9) indicates that if \( h_2 \) and \( h_3 \) are small compared to \( h_1 \), \( \phi'_d \) approaches two times \( \phi_d \). Also, if the perfectly-conducting round is far removed, \( X_2 \) approaches \( X'_2 \) and equation (1) obtains.

The loop voltage given by equation (3) now becomes:

\[
E'_d = (0.4\pi fsl \ln \left( \frac{X'_1 X'_2}{X_1 X_2} \right)) 10^{-8} \text{ volts effective} \quad (10)
\]

This is the open-circuit voltage of the loop when conductor \( A \) is carrying effective current \( I \).

The self inductance of the loop is also influenced by its proximity to the conducting ground plane. This influence can be simulated by an image loop \( D-D' \) carrying the current \( I_d \) in the opposite direction. The effect is again one of magnetic flux reflections.

The self inductance of a loop, the plane of which is normal to the ground plane, is then:

\[
L'_s = \frac{\phi'_s}{I_d} \cdot 10^{-8} \text{ henry/cm} \quad (11)
\]

Where:

\[
\phi'_s = 0.2I_d \left[ \int_{R_d}^{b} \frac{1}{X'} \, dX' + \int_{0}^{b-r_d} \frac{1}{b-X'} \, dX' - \int_{2h_3+b}^{2h_3+2b} \frac{1}{X''} \, dX'' + \int_{2h_3+b}^{2h_3+2b} \frac{1}{X'''} \, dX''' \right]
\]
\[
\phi_s = 0.2I_d \left[ \ln \frac{b}{r_d} - \ln \frac{r_d}{b} - \ln \frac{2h_a + b}{2h_a} + \ln \frac{2h_a + 2b}{2h_a + b} \right]
\]

\[
= 0.461 I_d \log \left[ \frac{(b/r_d)^2}{(2h_a + b)^2} \right] \left( \frac{4h_a(h_a + b)}{(2h_a + b)^2} \right)
\]

lines per cm length of loop

Then, from (11) and (12): (considering only flux external to conductors before reflection):

\[
L'_s = 0.461 \log \left[ \frac{(b/r_d)^2}{(2h_a + b)^2} \right] 10^{-8}
\] henrys per loop cm

If the plane of the loop is not normal to the ground plane, equation (13) becomes:

\[
L'_s = 0.461 \log \left[ \frac{(b/r_d)^2}{d_2^2 + (h_a + h_a)^2} \right] 10^{-8}
\]

where \(d_2\) is the distance between the vertical projections on the ground plane of the two sides of the loop D-D'.

Unless otherwise noted, the above equations for induced voltage and self inductance apply with good accuracy only when \(h_1, h_2,\) and \(b\) are small relative to \(S\) and \(S'\).

Equations (7) and (8) only, include the influence of the internal flux of the conductors.
Loop End Effects

When the loop is short relative to its breadth \( b \) an end fringing-effect term must be subtracted from equations (13) and (14). This term is, approximately:

\[
L_e = 0.4b \left( \log \left( \frac{b}{r_d} \right)^2 \frac{4h_3(h_3 + b)}{(2h_3 + b)^2} \right) \cdot 10^{-8} \text{ henrys (15)}
\]

Under the same conditions an additional term must be added to these same equations to care for the inductance of the end connections. When the quantities \( b/r_d \) and \( s'/r_d \) are large, this term is approximately:

\[
L_o = \left[ b(0.921 \log \frac{s'}{r_d} + 0.1) - 0.48 \right] 10^{-8} \text{ henrys (16)}
\]

The sum of equations (13) or (14) and (16), minus (15), gives a total inductance which is a slight amount too small. A closer approach to the exact value might be obtained by using the average of the above sum and the value given by equation (8).

Maximum Power

The resistance for maximum power abstraction is, from (4):
\[ R_{Lm} = 2\pi f L_{st} \]

\[(I_d E_R = \text{max.}) \]

Where: \( L_{st} = SL_s \), the total self inductance of the loop.

Also, since the negative self inductance drop is one component of the total voltage induced in the loop:

\[ I_d R_{Lm} = 0.707 E_d \]

\[ I_d = \frac{0.707 E_d}{R_{Lm}} \quad (18) \]

The power \( P_{Lm} \) dissipated in the resistor is:

\[ I_d^2 R_{Lm} = \frac{0.5 E_d^2}{R_{Lm}} \text{ watts} \]

\[ = \frac{1}{4R_{Lm}} \left[ 0.4S\pi f l_m \ln \frac{X_2}{X_1} \right]^2 \times 10^{-16} \]

\[ = \frac{1}{2R_{Lm}} \left[ 0.4S\pi f l m \ln \frac{X_1'}{X_1} \right]^2 \times 10^{-16} \quad (19) \]

Then, from (6) and (17):

\[ P_{Lm} = \frac{0.723 S f (I \log \frac{X_2}{X_1})^2}{\log \frac{b}{r_d}} \quad (20) \]

for the maximum dissipation condition.

When the conductors are near a perfectly conducting plane, from (10), (14) and (17), equation (20) becomes:
\[ P'_{Lm} = \frac{1.45 \times S \times I^2 (\log \frac{X_1 X_2}{X_1 X_2})^2}{\log \left[ \left( \frac{b}{r_d} \right)^2 \left( \frac{4h_2 h_3}{d_2 + (h_2 + h_3)^2} \right) \right]} \cdot 10^{-8} \text{ watts} \] (21)

For any total self inductance \( L_{st} \) of the pick-up loop D-D' having length \( S' \) parallel to A, equation (21) becomes:

\[ P'_{Lm} = \frac{0.667 \times S' \times I^2 (\log \frac{X_1 X_2}{X_1 X_2})^2}{L_{st}} \cdot 10^{-16} \text{ watts} \] (22)
Consider the circuit of page 164. With switch \(S_w\) open the voltage induced electrostatically on conductor B by the potential E on conductor A is:

\[
E_b = E \frac{C_{ab}}{C_b + C_{ab}}
\]

This potential is independent of frequency. In the following analysis, the effective values of \(C_{ab}\) and \(C_b\), for switch \(S_w\) open and closed, will be determined.

From the theory of the potential (B 3) it can be shown that:

\[
E_b = E \frac{\log \frac{X_2}{X_1}}{\log \frac{2h_1}{r}}
\]

From (23):

\[
C_{ab} = \frac{E_b C_b}{E - E_b}
\]

The only dielectric flux emanating from B is that which enters B from A. If \(X_1\) is large relative to \(h_e\), and \(h_e\) large relative to \(r_B\), the total flux leaving B is:

\[
\Psi_B = 2\pi r_B D \text{ coulombs}
\]

where \(r_B\) is the radius of conductor B and D is the flux density at B. This statement is true only when the potential of B is equal to its space potential due to A.
ELECTROSTATIC INDUCTION
The field of A is then relatively undisturbed by the presence of B. The same flux both enters and leaves B.

The effective capacitance of B to ground is then:

$$C_b = \frac{\psi_b}{E_b} \text{farads}$$  \hspace{1cm} (27)

From the theory of the potential:

$$D = \frac{2 \ h_1 \ \psi}{2\pi \ X_1 \ X_2} \text{coulombs/cm}^2$$  \hspace{1cm} (28)

Where:

$$\psi = c_a \ E = \frac{2 \cdot 41E \cdot 10^{-13} \text{coulombs}}{\log \frac{2h_1}{r}}$$  \hspace{1cm} (29)

= total flux per cm from A to ground. (neglecting end effect).

Then:

$$D = \frac{4.82 \ h_1 \ E}{2\pi \ X_1 \ X_2 \ \log \frac{2h_1}{r}} \cdot 10^{-13}$$  \hspace{1cm} (30)

Equations (26) and (30) substituted in (27) give:

$$C_b = \frac{1.53 \ r_b \ h_1 E}{E_b \ X_1 \ X_2 \ \log \frac{2h_1}{r}} \cdot 10^{-13} \text{farads/cm}$$  \hspace{1cm} (31)

From (24):

$$C_b = \frac{1.53 \ r_b \ h_1}{X_1 \ X_2 \ \log \frac{X_2}{X_1}} \cdot 10^{-13} \text{farads/cm}$$  \hspace{1cm} (32)
Equation (31) substituted in (25) gives:

\[ C_{ab} = \frac{1.53 r_b h_1 E}{(E - E_b) X_1 X_2 \log \frac{2h_1}{r}} \cdot 10^{-13} \text{farads/cm (33)} \]

From (24):

\[ C_{ab} = \frac{1.53 r_b h_1}{X_1 X_2 \log \frac{2h_1 X_1}{r X_2}} \cdot 10^{-13} \text{farads/cm (34)} \]

Where:

\[ X_1 = \left[ (h_1 - h_2)^2 + d^2 \right]^{1/2} \]
\[ X_2 = \left[ (h_1 + h_2)^2 + d^2 \right]^{1/2} \]

The effective capacitances \( C_b \) and \( C_{ab} \) remain essentially constant, when \( X_1 \) is large compared to \( h_2 \) and \( E \) is large compared to \( E_b \), for small changes of the potential of \( B \) from its space potential due to \( A \). It can be shown that for this condition, the maximum energy abstraction from \( A \), by the resistance \( R \) connected to \( B \), occurs when:

\[ R_c = \frac{1}{2\pi f (C_{ab} + C_b)} \text{ohms (37)} \]

For \( C_b \gg C_{ab} \), \( R_c \approx X_{cb} \text{ and the current in } R_c \text{ is equal to that in } C_b \). The voltage drop across \( R_c \) is then 70.7% of the space potential of \( B \).
The current in the resistor is:

\[ I_{Rc} = \frac{E}{\left[ R_c^2 \left(1 + \frac{C_b}{C_{ab}}\right)^2 + \left(\frac{1}{2\pi f C_{ab}}\right)^2\right]^{1/2}} \text{ amp.} \quad (38) \]

The maximum power is:

\[ P_{cm} = I_{Rc}^2 R_c \]

\[ = \frac{E^2}{2\pi f \left(C_{ab} + C_b\right) \left[ R_c^2 \left(1 + \frac{C_b}{C_{ab}}\right)^2 + \left(\frac{1}{2\pi f C_{ab}}\right)^2\right]} \text{ watts} \quad (39) \]

Then, from (37) and (39):

\[ P_{cm} = \frac{2\pi f C_{ab}^2 E^2}{2 \left( C_{ab} + C_b \right)} \text{ watts} \quad (40) \]

Equation (40) indicates that the maximum power available is proportional to the square of the voltage on A and to the square of the length \( S' \) of the pick-up conductor B.
Relative Induction Magnitudes

If the only current flowing in conductor A is that due to its capacitance to ground, assuming this current to be led away transversely through the ground plane and assuming a "nominal π," that is, one half the "charging" current fed in at each end of A, the approximate current active in magnetic induction (3), (10), (20), and (21) is:

\[ I = \frac{E}{2X_{ca}} = \frac{2\pi fC_a E}{2} \text{ amperes} \]  \hspace{1cm} (41)

where \( C_a \) is capacitance to ground of conductor A, is:

\[ C_a = \frac{2.41 \cdot 10^{-13}}{\log \frac{2h_1}{r}} \text{ farads/cm} \]  \hspace{1cm} (42)

where \( X_1 \) and \( X'_1 \) are large relative to \( h_2 \) and \( h_3 \).

Then, when \( \frac{S}{h_1} \) is large:

\[ I = \frac{7.57 fE}{\log \frac{2h_1}{r}} \cdot 10^{-13} \text{ amperes/cm} \]  \hspace{1cm} (43)

The voltage of magnetic induction from charging current is then, from equations (43) and (3):

\[ E_d = \frac{2.19 S^2 r^2 E \log \frac{X'_1}{X_1}}{\log \frac{2h_1}{r}} \cdot 10^{-20} \text{ volts} \]  \hspace{1cm} (44)
In the presence of a perfectly conducting ground plane, (43) substituted in (10):

\[ E_d' = \frac{2.19 \times 10^{-20} E \log \frac{x_1' x_2}{x_1} \times 10^{-20}}{\log \frac{2h_1}{r}} \text{ volts} \quad (45) \]

The maximum power from magnetic induction due to charging current from equations (43) and (20) is:

\[ P_{Lm} = \frac{4.14 \times 10^{-33} E^2 (\log \frac{x_1'}{x_1})^2}{\log \frac{r}{r_d} (\log \frac{2h_1}{r})^2} \text{ watts} \quad (46) \]

In the presence of a perfectly conducting plane, from equations (43) and (21):

\[ P_{Lm}' = \frac{8.28 \times 10^{-33} E^2 (\log \frac{x_1' x_2}{x_1 x_2})^2}{(\log \frac{2h_1}{r})^2 \log \left[ \left( \frac{b}{r_d} \right)^2 \left( \frac{4h_2 h_3}{d_2 + (h_2 + h_3)^2} \right) \right]} \]

\[ \times 10^{-33} \text{ watts} \quad (47) \]

Equations (44), (45), (46), and (47) apply to full-length loops where \( S/h_1 \) is so large as to make end effects negligible.

For loops of fractional length \( S' \) the current in \( A \) which is effective in inducing voltage in the loop \( D-D' \) is very nearly:
\[ I' = 2\pi f C'_a E \]  
\[(48)\]

where \( C'_a \) is the capacitance to ground of \( A \) over a length of \((S - S')\) cm. Hence:

\[
C'_a = \frac{2.41 \left(S - S'\right)}{\log \frac{2h_1}{r}} \cdot 10^{-13} \text{ farads} \tag{49}
\]

Then:

\[
I' = \frac{1.51 f E (S - S')}{{\log} \frac{2h_1}{r}} \cdot 10^{-12} \text{ amp.} \tag{50}
\]

The voltage of magnetic induction due to charging current \((45)\) then becomes:

\[
E'_d = \frac{4.37 f^2 E S' (S - S')}{\log \frac{2h_1}{r}} \frac{X_1 X_2}{X_1 X_2} \cdot 10^{-20} \text{ volts} \tag{51}
\]

The maximum power of magnetic induction due to charging current \((47)\) for a loop of fractional length \( S' \) is, from equations \((50)\) and \((21)\):

\[
P'_{Lm} = \frac{3.31 f^3 E^2 S' (S - S')^2}{(\log \frac{2h_1}{r})^2 \log \left[ \left(\frac{b}{r_d}\right)^2 \left(\frac{4h_2 h_3}{d^2 + (h_2 + h_3)^2}\right) \right]} \cdot 10^{-32} \text{ watts} \tag{52}
\]
Equation (52) indicates that the maximum resistance 171
power is a function of the cube of the frequency, the
square of the voltage on A, the length of the pick-up
loop S' and the square of the quantity (S - 0.5 S').

Equation (52) applies to pick-up loops in which the
ratio of length S' to breadth b is so great as to make
end effects negligible. For any total self inductance
L_{st} of the loop D-D' having length S' parallel to A,
equation (52) becomes:

\[
P_{Lm} = \frac{1.52 \pi S' B^2 (S - \frac{S'}{2})^2 (\log \frac{X_i X_e}{X_i X_e})^2}{L_{st} (\log \frac{2h_1}{r})^2} \cdot 10^{-40}
\]

watts \hspace{1cm} (53)
Example I (Voltage)

Full-Length Loop, Magnetic

Assume full-length pick-up loop (page 158) receiving voltage and power inductively due to the charging current to ground flowing in the inducing conductor.

Let:

- \( h_1 = 1100 \text{ cm} \)
- \( E = 100,000 \text{ V} \)
- \( h_2 = 100 \text{ cm} \)
- \( S = 10,000 \text{ cm} \)
- \( h_3 = 10 \text{ cm} \)
- \( r = 0.5 \text{ cm} \)
- \( X_1 = 1000 \text{ cm} \)
- \( r_b = r_d = 10 \text{ cm} \)
- \( X_1' = 1090 \text{ cm} \)
- \( b = 90 \text{ cm} \)
- \( X_2 = 1200 \text{ cm} \)
- \( d = 0 \)
- \( X_2' = 1110 \text{ cm} \)
- \( f = 100 \text{ cps} \)

Assume further: Ground-plane conductivity: infinite.

Then, from equation (45):

\[
E_d' = \frac{2.19 \times 10^8 \times 10^4 \times 10^5 \log \frac{131 \times 10^4}{111 \times 10^4}}{\log \frac{2200}{0.5}} \times 10^{-20}
\]

\[= 4.33 \times 10^{-5} \text{ volts} \] (54)

If the frequency is raised to \( 10^6 \text{ cps} \), (54) becomes:

\[
E_d' = 4.33 \times 10^3 \text{ volts} \] (55)
Full-length Conductor Electrostatic

If the loop is replaced by a single conductor of height \( h_1 \), the voltage of electrostatic induction equation (24), is:

\[
E_b = 10^5 \frac{\log \frac{1200}{1000}}{\log \frac{2200}{0.5}}
\]

\[
= 2.175 \times 10^5 \text{ volts (56)}
\]

Hence, if in (55) the frequency is reduced to:

\[
\left[ \frac{2.175}{4.33} \right]^{\frac{1}{2}} 10^6 = 7.08 \times 10^5 \text{ cps}
\]

the induced voltages are identical.

Short Pick-Up Loop, Magnetic and Electrostatic

If the inducing conductor is of length \( S \) but the length of the loop is reduced to 100 cm = \( S' \), the voltage of electrostatic induction remains unchanged but that of magnetic induction becomes, from equation (51):

\[
E'_d = \frac{4.37 \times 10^4 \times 10^5 \times 10^2 \times 9.95 \times 10^3 \log \frac{131 \times 10^4}{111 \times 10^4}}{\log \frac{2200}{0.5}} \times 10^{-20}
\]

\[
= 8.59 \times 10^{-7} \text{ volts (57)}
\]
At $10^6$ cps, equation (57) becomes:

$$E' = \frac{85.9 \text{ volts}}{d}$$  \hspace{1cm} (58)

To obtain the same voltage from (57) as from electrostatic induction (56), the frequency must be raised to:

$$f' = \left[ \frac{2.175 \times 10^3}{85.9} \right]^{\frac{1}{2}} \times 10^6$$

$$= 5.03 \times 10^6 \text{ cps}$$  \hspace{1cm} (59)
Full-Length Loop, Magnetic

Assume same conditions and circuit dimension as those given under Example I.

Then, from equation (47), the maximum power which can be obtained from the pick-up loop is:

\[
P'_{Lm} = \frac{8.28 \times 10^{12} \times 10^{6} \times 10^{10} \times \left[\log \frac{131 \times 10^{4}}{111 \times 10^{4}}\right]^{2}}{\left[\log \frac{2200}{0.5}\right]^{2} \log \left[\frac{50}{1} \cdot \frac{4 \times 10^{2} \times 10}{(10^{2} + 10)^{2}}\right]} \cdot 10^{-33}
\]

\[
= \frac{4.28}{13.26 \times 3.428} \cdot 10^{-7}
\]

\[
= 9.4 \times 10^{-9} \text{ watts \hspace{1cm} (60)}
\]

If the frequency is raised to 10^6 cps, (60) becomes:

\[
P'_{Lm} = 9.4 \times 10^{3} \text{ watts \hspace{1cm} (61)}
\]

Full-Length Conductor Electrostatic

If the loop is replaced by a single conductor of height \(h_1\) and length \(S\) the maximum power of electrostatic induction, equation (40), is:

\[
P_{cm} = \frac{6.28 \times 10^{2} \times \epsilon_0 \times 10^{10}}{2 \left(\epsilon_{ab} + \epsilon_b\right)} \text{ watts \hspace{1cm} (62)}
\]
From (34):

\[ C_{ab} = \frac{1.53 \times 1.0 \times 1.1 \times 10^3 \times 10^4}{1.2 \times 10^6 \log \frac{2.2 \times 10^6}{6 \times 10^2}} \cdot 10^{-13} \]

\[ = 3.93 \times 10^{-13} \text{ farads} \quad (63) \]

From (32):

\[ C_b = \frac{1.53 \times 1.0 \times 1.1 \times 10^3 \times 10^4}{1.2 \times 10^6 \log \frac{1200}{1000}} \cdot 10^{-13} \]

\[ = 17.7 \times 10^{-12} \text{ farads} \quad (64) \]

Then, from (62), (63) and (64):

\[ P_{cm} = \frac{6.28 \times 15.5}{36.2} \cdot 10^{-2} \]

\[ = 2.69 \times 10^{-2} \text{ watts} \quad (65) \]

If the frequency is raised to \(10^6\) cps, (65) becomes:

\[ P'_{cm} = \frac{10^6}{10^2} \cdot 2.69 \times 10^{-2} \]

\[ = 269 \text{ watts} \quad (66) \]

The frequency \(f'\) for equal maximum power by both types of induction can be obtained as follows:

\[ \frac{f'}{100} \times 2.69 \times 10^{-2} = \left(\frac{f'}{100}\right)^3 \times 9.4 \times 10^{-9} \]
Short Pick-Up Loop, Magnetic

If the inducing conductor remains of length \( S \) but the loop is shortened to 100 cm = \( S' \) (page 154) the maximum power that can be obtained by induction due to charging current in the inducing conductor is, from equation (53):

\[
P'_\text{Lm} = \frac{1.52 \times 10^6 \times 10^4 \times 10^7 \times 9.9 \times 10^7 \times 5.17 \times 10^{-3}}{L_{st} \times 13.26} \times 10^{-40}
\]

watts

From (13), (15) and (16):

\[
L_{st} = \left[ 46.1 \log (8100 \times 0.33) - 32 \right] 10^{-8}
\]

\[
+ \left[ 90 (0.921 \log 100 + 0.1) - 40 \right] 10^{-8} \text{h}
\]

\[
= 2.61 \times 10^{-6} \text{h}
\]

Then, from (68) and (69):

\[
P'_\text{Lm} = 2.25 \times 10^{-10} \text{ watts}
\]
For a frequency of $10^6$ cps, (70) becomes:

$$P'_{Lm} = \frac{(10^6)^3}{10^3} \times 2.25 \times 10^{-10}$$

$$= 225 \text{ watts} \quad (71)$$

**Short Pick-Up Conductor Electrostatic**

If the short loop is replaced by a conductor of length $S'$ and height $h_1$ the maximum power that can be transferred is, from equation (40):

$$P_{cm} = \frac{6.28 \times 10^2 x_0^2 x_{ab} x_0}{2 (C_{ab} + C_b)} \text{ watts} \quad (72)$$

From (63): \hspace{1cm} ($S' = S \times 10^{-2}$)

$$C_{ab} = 3.93 \times 10^{-13} \times 10^{-2}$$

$$= 3.93 \times 10^{-15} \text{ farads} \quad (73)$$

And from (64):

$$C_b = 17.7 \times 10^{-14} \text{ farads} \quad (74)$$

Then from (72), (73) and (74),

$$P_{cm} = \frac{6.28 \times 10^2 \times 15.5 \times 10^{-30} \times 10^{10}}{2 \times 18.1 \times 10^{-14}} \text{ watts}$$

$$= 2.69 \times 10^{-4} \text{ watts} \quad (75)$$

If the frequency is raised to $10^6$ cps, (75) becomes:
\[ P'_{\text{cm}} = \frac{10^6}{10^2} \times 2.69 \times 10^{-4} \text{ watts} \]

\[ = 2.69 \text{ watts} \quad (76) \]

The frequency \( f' \) for equal maximum power by both types of induction is again obtained as in (67) and is:

\[ f' = 1.09 \times 10^5 \text{ cps} \quad (77) \]

**Short Inducing Conductor and Short Loop**

As long as the inducing conductor remains substantially longer than the pick-up conductor, the voltage and maximum power of electrostatic induction remain unchanged. However, the voltage and power of magnetic induction depend greatly upon the current in the inducing conductor and hence upon its length, the factor that determines its capacitance to ground.

If the length \( S \) is reduced to 400 cm with \( S' \) unchanged at 100 cm, neglecting end effects, the maximum power is from (53) and (70):

\[ P_{\text{LM}} = \frac{(400 - \frac{100}{2})^2}{(10,000 - \frac{100}{2})^2} \times 2.25 \times 10^{-10} \text{ watts} \]

\[ = 2.8 \times 10^{-13} \text{ watts} \quad (78) \]

The frequency \( f' \) for equal power by both types of induction is now, as in (67):

\[ f' = 3.11 \times 10^6 \text{ cps} \quad (79) \]
Thus a very high frequency is now necessary to obtain equal induction powers. A similar condition exists in the voltages.

From (51) and (57):

\[
E_d' = \frac{400 - \frac{100}{2}}{10,000 - \frac{100}{2}} \times 8.59 \times 10^{-7} \text{ volts}
\]

\[
= 3.02 \times 10^{-8} \text{ volts}
\]

The frequency \( f' \) for equal voltages by both types of induction is, as in (59):

\[
f' = \left(\frac{2.175 \times 10^3}{3.02}\right)^{\frac{1}{2}} \times 10^6
\]

\[
= 26.8 \times 10^6 \text{ cps}
\]
THE APPROXIMATE VARIATION
WITH DISTANCE OF THE POTENTIAL
INDUCED ELECTROSTATICALLY IN SPACE
BY AN ELEVATED, CHARGED DISC

From (10), Appendix III, for long, straight conductors:

\[ \text{log} \frac{X_2}{X_1} \]

\[ E_b = E \frac{2h_1}{\text{log} \frac{r}{2h_1}} \text{ volts} \]  \hspace{1cm} (1)

If the conductor is curved into a circle to form the edge of a disc of major radius \( R \), the dielectric flux remains essentially unchanged in the transverse plane, but diverges in the horizontal plane according to:

\[ \psi_h = \frac{R}{d} \psi \]  \hspace{1cm} (2)

Where \( \psi \) is the flux at the induction point from a straight conductor and \( d \) is the horizontal distance from the center of the disc to this point.

Then, approximately:

\[ E_b = E \frac{2h_1}{\text{log} \frac{r}{2h_1}} \cdot \frac{R}{d} \]  \hspace{1cm} (3)
Let:

\[ X_1 = d = 450 \text{ cm} \]
\[ h_1 = 120 \text{ cm} \]
\[ X_2 = (4h_1 + X_1^2)^{1/2} = 510 \text{ cm} \]
\[ R = 20 \text{ cm} \]
\[ r = 0.5 \text{ cm} \]

Then, from (3):

\[ E_b = E \frac{\log 510}{450} \cdot \frac{20}{450} = 8.8 \times 10^{-4}E \]  \hspace{1cm} (4)

For \( d' = 900 \text{ cm} \):

\[ X_2' = 932 \text{ cm} \]

\[ E_b' = E \frac{\log 932}{900} \cdot \frac{20}{900} = 1.24 \times 10^{-4}E \]  \hspace{1cm} (5)

For \( d'' = 1800 \text{ cm} \):

\[ X_2'' = 1819 \text{ cm} \]

\[ E_b'' = 1.78 \times 10^{-5}E \]  \hspace{1cm} (6)

For \( d''' = 225 \text{ cm} \):

\[ X_2''' = 329 \text{ cm} \]

\[ E_b''' = 5.52 \times 10^{-3}E \]  \hspace{1cm} (7)

It will be observed that in each case, reducing the distance fifty per cent increased the induction voltage approximately seven times. Hence, within the range chosen,
the electrostatic induction pick-up from a concentrated source would be expected to vary inversely as approximately the 2.8 power of the distance. Experimental tests gave an exponent of approximately 3.2.
The magnetic potential at a point $P$ in space is:

$$F = \frac{M}{d} = \frac{1}{d} \frac{d(F)}{ad} \sin \Theta \text{ gilberts} \quad (1)$$

Where $M$ is the magnetic pole strength, $d$ is the distance from the pole to point $P$, $i$ is the current flowing in the elemental conductor, $\Delta L$ and $\Theta$ is the angle between the axis of the conductor and the line joining $P$ and the center of $\Delta L$.

The magnetic field intensity at $P$ is the rate of change of $F$ with respect to $d$ and is:

$$\Delta H = \frac{d(F)}{dd} = -\frac{1}{d^2} \Delta L \sin \Theta \text{ oersted} \quad (2)$$

When the alternating frequency of $i$ is great and distance $d$ is appreciable, there is a definite lag between the current $i$ and the magnetic potential at $P$. Then:

$$F = \frac{I \sin 2\pi f(t - \frac{d}{v})}{d} \Delta L \sin \Theta \text{ gilberts} \quad (3)$$

and

$$\Delta H = \frac{d(F)}{dd}$$
\[
\Delta H = -\frac{I\Delta L \sin \theta}{d^2} \left[ \frac{2\pi fd}{v} \cos 2\pi f(t - \frac{d}{v}) \right]
\]

\[
-\frac{I\Delta L \sin \theta}{d^2} \left[ \sin 2\pi f(t - \frac{d}{v}) \right]
\]

= lines per square cm in air \hspace{1cm} (4)

The first term of (4) is the radiation term and is dependent upon the current and the frequency, and inversely upon the distance and the velocity \( v \) of wave propagation. It reduces to:

\[
\Delta H_r = \frac{2\pi fI\Delta L \sin \theta}{vd} \cos 2\pi f(t - \frac{d}{v}) \hspace{1cm} (5)
\]

The second term is the induction term and is independent of frequency. The velocity term enters only in the phase-position factor and distance enters as the inverse square. It is:

\[
\Delta H_i = -\frac{I\Delta L \sin \theta}{d^2} \sin 2\pi f(t - \frac{d}{v}) \hspace{1cm} (6)
\]

Integration of \( I\Delta L \) over the entire conductor (area under curve of maximum current distribution along radiator, ampere-centimeters), since \( H = B \) in space, (assuming all current elements in phase), gives:

\[
B_r = -\frac{2\pi f}{vd} \int_{0}^{L} I dL \hspace{1cm} (7)
\]

\[
\sin \theta \cos 2\pi f(t - \frac{d}{v})
\]
and

\[ B_i = - \frac{\int_0^L \vec{I} \cdot d\vec{L}}{d^2} \sin \theta \sin 2\pi f (t - \frac{d}{v}) \]  \hspace{1cm} (8)

The voltage induced by the radiation field in a conductor parallel to the radiator and in such a position that a line joining centers of radiator and conductor is normal to both, in free space is:

\[ E_{r} = 10^{-8} \sqrt{\frac{B_r}{10}} \]

\[ = \frac{6.28 f \int_0^L I_e dL}{d} \cdot 10^{-7} \text{ volts, effective, per meter} \] \hspace{1cm} (9)

Where:

\[ f = \text{cps} \]
\[ I_e = \text{effective antennae current in element } dL \]
\[ d = \text{distance in centimeters.} \]

The induction voltage in the above parallel conductor is:

\[ E_i = \frac{d(B_i)}{dt} \cdot 10^{-8} \]

\[ = - 2\pi f \frac{\int_0^L \vec{I} \cdot d\vec{L}}{d^2} \cos 2\pi f (t - \frac{d}{v}) 10^{-8} \] \hspace{1cm} (10)

\[ = 6.28 f \frac{\int_0^L I_e dL}{d^2} \cdot 10^{-7} \text{ volts, effective, per meter} \] \hspace{1cm} (11)
It will be noted that at a distance of 1 cm, (assuming a radiating conductor of infinitesimal diameter) the radiation and induction voltages are equal. These voltages are also mutually in phase.

The voltage induced in a loop of n turns, A sq cm area, in a line normal to the center of the radiator and lying in the plane of the radiator is (sides of loop in close proximity compared to λ):

\[ E_r = NA \frac{d (B_r)}{dt} \cdot 10^{-8} \]  \hspace{1cm} (12)

\[ = NA 4\pi f^2 \int_0^L \frac{I dL}{\nu d} \sin 2\pi f(t - \frac{d}{v}) \cdot 10^{-8} \]

\[ = 1.31 NA f^2 \int_0^L \frac{I_e dL}{d} \cdot 10^{-18} \]  \hspace{1cm} (13)

volts effective from radiation

Also:

\[ E_i = 6.28 NA f \int_0^L \frac{I_e dL}{d^2} \cdot 10^{-9} \]  \hspace{1cm} (14)

volts effective from induction

For a half-wave dipole in free space, with sinusoidal current distribution, the radiation term (9) reduces to

\[ E_r = \frac{60 I_e}{d} \text{ volts per cm} \]  \hspace{1cm} (15)
Where:

\[ I_e = \text{effective current at antinode} \]
\[ d = \text{distance in centimeters} \]
APPENDIX V

Tables I to XVI inclusive
TABLE I

RADIO COMPASS CALIBRATION ON
PORTLAND RANGE AT WASHOUGAL, WASHINGTON

Boeing 247-D No. 365, Belly Loop, Shielded
Reference Standard, Gyro Compass

<table>
<thead>
<tr>
<th>Gyro Compass (90°)</th>
<th>Radio Compass Deg.</th>
<th>Correction Deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>153</td>
<td>-3</td>
</tr>
<tr>
<td>70</td>
<td>162</td>
<td>-2</td>
</tr>
<tr>
<td>80</td>
<td>174</td>
<td>-4</td>
</tr>
<tr>
<td>90</td>
<td>182</td>
<td>-2</td>
</tr>
<tr>
<td>100</td>
<td>194</td>
<td>-4</td>
</tr>
<tr>
<td>110</td>
<td>198</td>
<td>+2</td>
</tr>
<tr>
<td>120</td>
<td>207</td>
<td>+3</td>
</tr>
<tr>
<td>130</td>
<td>218</td>
<td>+2</td>
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<tr>
<td>140</td>
<td>229</td>
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<td>238</td>
<td>+2</td>
</tr>
<tr>
<td>160</td>
<td>251</td>
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<tr>
<td>170</td>
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</tr>
<tr>
<td>180</td>
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<td>-4</td>
</tr>
<tr>
<td>250</td>
<td>342</td>
<td>-7</td>
</tr>
<tr>
<td>260</td>
<td>349</td>
<td>-2</td>
</tr>
<tr>
<td>270</td>
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<td>+1</td>
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<tr>
<td>280</td>
<td>9</td>
<td>+4</td>
</tr>
<tr>
<td>290</td>
<td>18</td>
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<td>+2</td>
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<td>310</td>
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<td>+3</td>
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<tr>
<td>320</td>
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<td>+8</td>
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<tr>
<td>330</td>
<td>60</td>
<td>+5</td>
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<tr>
<td>340</td>
<td>70</td>
<td>0</td>
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<tr>
<td>350</td>
<td>82</td>
<td>0</td>
</tr>
<tr>
<td>360</td>
<td>96</td>
<td>-3</td>
</tr>
</tbody>
</table>
TABLE II

AIRPLANE DISCHARGE CHARACTERISTICS
GROUND TESTS

Discharge Electrode: Vertical rod 0.25 in. diameter pointed, 11 in. from concrete floor.

Polarity of Ship: Negative

Background Noise: Local signal generator, 0.5

Series Discharge Resistance: $R = 0$

Barometer, 29.8 in.; Temp. 60°F; Humid. 66%

<table>
<thead>
<tr>
<th>Kilovolts Ship to Ground (Nominal)</th>
<th>Point Discharge Current (μA)</th>
<th>Relative Radio Noise</th>
<th>Point Discharge Current (μA)</th>
<th>Relative Radio Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower &quot;V&quot;</td>
<td>Lower Loop, Shielded</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.40</td>
<td>9</td>
<td>2.30</td>
<td>.51</td>
</tr>
<tr>
<td>10</td>
<td>1.80</td>
<td>10</td>
<td>2.30</td>
<td>.50</td>
</tr>
<tr>
<td>11</td>
<td>1.60</td>
<td>11</td>
<td>2.20</td>
<td>.51</td>
</tr>
<tr>
<td>12</td>
<td>3.70</td>
<td>12</td>
<td>3.70</td>
<td>.55</td>
</tr>
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<td>13</td>
<td>4.50</td>
<td>13</td>
<td>4.50</td>
<td>.50</td>
</tr>
<tr>
<td>14</td>
<td>2.30</td>
<td>14</td>
<td>2.30</td>
<td>.70</td>
</tr>
<tr>
<td>15</td>
<td>1.40</td>
<td>15</td>
<td>1.40</td>
<td>.53</td>
</tr>
<tr>
<td>16</td>
<td>1.10</td>
<td>16</td>
<td>1.10</td>
<td>.56</td>
</tr>
<tr>
<td>17</td>
<td>0.90</td>
<td>17</td>
<td>0.90</td>
<td>.51</td>
</tr>
<tr>
<td>18</td>
<td>0.71</td>
<td>18</td>
<td>0.71</td>
<td>.50</td>
</tr>
<tr>
<td>19</td>
<td>0.52</td>
<td>19</td>
<td>0.52</td>
<td>.50</td>
</tr>
<tr>
<td>20</td>
<td>0.53</td>
<td>20</td>
<td>0.53</td>
<td>.50</td>
</tr>
<tr>
<td>21</td>
<td>0.55</td>
<td>21</td>
<td>0.55</td>
<td>.50</td>
</tr>
<tr>
<td>22</td>
<td>0.65</td>
<td>22</td>
<td>0.65</td>
<td>.50</td>
</tr>
<tr>
<td>23</td>
<td>0.90</td>
<td>23</td>
<td>0.90</td>
<td>.50</td>
</tr>
</tbody>
</table>
**TABLE III**

AIRPLANE DISCHARGE CHARACTERISTICS
GROUND TESTS

Discharge Electrode: Vertical wire 7.5 in. long, 0.007 in. diameter, 3 in. from concrete floor.

Polarity of Ship: Negative

Background Noise: Local signal generator, 0.5

Series Discharge Resistance: $R = 0$ and $R = 28$ megohms

Antenna of Radio Receiver: Lower "V"

Barometer 29.8 in.; Temp. 60°F; Humid. 66%

<table>
<thead>
<tr>
<th>Kilovolts Ship to Ground (Nominal)</th>
<th>$R = 0$</th>
<th>$R = 28$ megohms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Discharge Current Mu a</td>
<td>Relative Radio Noise</td>
</tr>
<tr>
<td>30</td>
<td>58.0</td>
<td>5.1</td>
</tr>
<tr>
<td>40</td>
<td>114.0</td>
<td>5.4</td>
</tr>
<tr>
<td>50</td>
<td>184.0</td>
<td>5.6</td>
</tr>
<tr>
<td>60</td>
<td>260.0</td>
<td>6.0</td>
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<td>6.3</td>
</tr>
<tr>
<td>80</td>
<td>460.0</td>
<td>6.5</td>
</tr>
<tr>
<td>90</td>
<td>580.0</td>
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</tr>
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<td>4.7</td>
</tr>
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<td>40.0*</td>
<td>4.5</td>
</tr>
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<td>30.0*</td>
<td>3.6</td>
</tr>
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</tr>
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<td>1.7</td>
</tr>
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<td>6.5*</td>
<td>6.5*</td>
<td>4.0</td>
</tr>
<tr>
<td>5.0*</td>
<td>5.0*</td>
<td>1.8</td>
</tr>
</tbody>
</table>

* Decaying
TABLE IV

AIRPLANE DISCHARGE CHARACTERISTICS
GROUND TESTS

Discharge Electrode: Vertical wire 7.5 in. long, 0.007 in. diameter, 3 in. from concrete floor.

Polarity of Ship: Negative

Background Noise: Local signal generator, 0.5

Series Discharge Resistance: \( R = 0 \) and \( R = 28 \) megohms

Antenna of Radio Receiver: Lower Loop, Shielded

Barometer 29.8 in.; Temp. 60°F.; Humid. 66%

<table>
<thead>
<tr>
<th>Kilovolts Ship to Ground (Nominal)</th>
<th>( R = 0 )</th>
<th>( R = 28 ) megohms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Discharge Current Mu a</td>
<td>Relative Radio Noise</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
<td>0.61</td>
</tr>
<tr>
<td>40</td>
<td>118</td>
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<td>50</td>
<td>188</td>
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<td>260</td>
<td>1.20</td>
</tr>
<tr>
<td>70</td>
<td>340</td>
<td>1.40</td>
</tr>
<tr>
<td>80</td>
<td>440*</td>
<td>1.65</td>
</tr>
<tr>
<td>90</td>
<td>560</td>
<td>1.80</td>
</tr>
</tbody>
</table>

*Decaying
TABLE V

AIRPLANE DISCHARGE CHARACTERISTICS
GROUND TESTS

Discharge Electrode: Vertical wire 7.5 in. long, 0.007 in. diameter, 7.5 in. from concrete floor.

Polarity of Ship: Positive

Background Noise: Local signal generator, 0.5

Series Discharge Resistance: R = 0 and R = 28 megohms

Antennae of Radio Receiver: Lower "V"

Barometer 29.3 in.; Temp. 60°F.; Humid. 61%

<table>
<thead>
<tr>
<th>Kilovolts Ship to Ground (Nominal)</th>
<th>R = 0</th>
<th>R = 28 megohms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Discharge Current Mu a</td>
<td>Relative Radio Noise</td>
</tr>
<tr>
<td>30</td>
<td>14</td>
<td>0.50</td>
</tr>
<tr>
<td>40</td>
<td>28</td>
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<td>143</td>
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</tr>
<tr>
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<td>164</td>
<td>8.50</td>
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<tr>
<td>90</td>
<td>186</td>
<td>9.00</td>
</tr>
<tr>
<td>75*</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>60*</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>35*</td>
<td>3.00</td>
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<td></td>
</tr>
<tr>
<td>14*</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

*Decaying
**TABLE VI**

**AIRPLANE DISCHARGE CHARACTERISTICS**

**GROUND TESTS**

Discharge Electrode: Vertical wire 7.5 in. long, 0.007 in. diameter, 7.5 in. from concrete floor.

Polarity of Ship: Positive

Background Noise: Local signal generator, 0.5

Series Discharge Resistance: $R = 0$ and $R = 28$ megohms

Antenna of Radio Receiver: Lower Loop, Shielded

Barometer 29.8 in.; Temp. 60°F.; Humid. 61%

<table>
<thead>
<tr>
<th>Kilovolts Ship to Ground (Nominal)</th>
<th>R = 0</th>
<th>R = 28 megohms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Discharge Current Mu &amp;</td>
<td>Relative Radio Noise</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>50</td>
<td>52</td>
<td>0.5</td>
</tr>
<tr>
<td>60</td>
<td>77</td>
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<tr>
<td>70</td>
<td>108</td>
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<tr>
<td>75</td>
<td>122</td>
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</tr>
<tr>
<td></td>
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</table>

*Decaying*
TABLE VII

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

Electrodes: 30-degree conical point to plane
Spacing: 10.2 centimeters
Polarity: Positive

Temperature: Dry Bulb: 22.3°C
Wet Bulb: 18.0°C
Barometer: 740.4 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage KV DC</th>
<th>Current Mu a</th>
<th>Relative Radio Noise *</th>
<th>Type Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
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<td>3.3</td>
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</tr>
<tr>
<td>11.0</td>
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<td>3.3</td>
<td>2'</td>
</tr>
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<td>14.2</td>
<td>2.5</td>
<td>3.3</td>
<td>2'</td>
</tr>
<tr>
<td>18.5</td>
<td>5.0</td>
<td>3.3</td>
<td>2'</td>
</tr>
<tr>
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<td>7.5</td>
<td>6.0</td>
<td>2'</td>
</tr>
<tr>
<td>24.6</td>
<td>10.0</td>
<td>13.0</td>
<td>2'</td>
</tr>
<tr>
<td>26.8</td>
<td>12.5</td>
<td>17.0</td>
<td>2'</td>
</tr>
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<td>29.0</td>
<td>2'</td>
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<td>17.5</td>
<td>39.0</td>
<td>2'</td>
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<td>20.0</td>
<td>52.0</td>
<td>2'</td>
</tr>
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<td>34.0</td>
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<td>2'</td>
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<td>143.0</td>
<td>2'</td>
</tr>
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<td>159.0</td>
<td>2'</td>
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<td>43.0</td>
<td>37.5</td>
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<td>2'</td>
</tr>
<tr>
<td>44.5</td>
<td>40.0</td>
<td>200.0</td>
<td>2'</td>
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* Radio gain 0.307
TABLE VIII

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

Electrodes: 30-degree conical point to plane
Spacing: 10.2 centimeters
Polarity: Negative
Temperature: Dry Bulb: 22.3°C
Wet Bulb: 18.0°C
Barometer: 740.4 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage (KV DC)</th>
<th>Current (μa)</th>
<th>Relative Radio Noise*</th>
<th>Type Discharge</th>
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<td>7.0</td>
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<td>1</td>
</tr>
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<td>0</td>
<td>1</td>
</tr>
<tr>
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<td>2.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>15.9</td>
<td>5.0</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>19.5</td>
<td>7.5</td>
<td>3.5</td>
<td>1</td>
</tr>
<tr>
<td>21.6</td>
<td>10.0</td>
<td>4.5</td>
<td>1</td>
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<td>24.0</td>
<td>12.5</td>
<td>4.0</td>
<td>1</td>
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<td>25.9</td>
<td>15.0</td>
<td>5.0</td>
<td>1</td>
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<td>17.5</td>
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<td>1</td>
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<td>28.8</td>
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<td>1</td>
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<tr>
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<td>22.5</td>
<td>2.0</td>
<td>1</td>
</tr>
<tr>
<td>31.4</td>
<td>24.5</td>
<td>10-40</td>
<td>1</td>
</tr>
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<td>27.5</td>
<td>1.0</td>
<td>1</td>
</tr>
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<td>30.0</td>
<td>1.0</td>
<td>1</td>
</tr>
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<td>36.5</td>
<td>32.5</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>37.8</td>
<td>35.0</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>39.0</td>
<td>37.5</td>
<td>30-150</td>
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<td>40.0</td>
<td>39.5</td>
<td>6.0</td>
<td>1</td>
</tr>
<tr>
<td>41.2</td>
<td>42.5</td>
<td>10-100</td>
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</tr>
<tr>
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<td>45.0</td>
<td>5.0</td>
<td>1</td>
</tr>
<tr>
<td>43.8</td>
<td>48.5</td>
<td>2.0</td>
<td>1</td>
</tr>
<tr>
<td>44.7</td>
<td>50.0</td>
<td>2.0</td>
<td>1</td>
</tr>
</tbody>
</table>

* Radio gain 0.603
TABLE IX

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

Electrodes: 45-degree conical point to plane
Spacing: 10.2 centimeters
Polarity: Positive

Temperature:  
- Dry Bulb: 22.6°C
- Wet Bulb: 18.0°C
Barometer: 747.6 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage KV DC</th>
<th>Current Mu a</th>
<th>Relative Radio Noise*</th>
<th>Type Discharge</th>
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</thead>
<tbody>
<tr>
<td>12.0</td>
<td>0.5</td>
<td>3.0</td>
<td>3'</td>
</tr>
<tr>
<td>12.5</td>
<td>1.0</td>
<td>6.5</td>
<td>3'</td>
</tr>
<tr>
<td>14.5</td>
<td>2.5</td>
<td>16.0</td>
<td>3'</td>
</tr>
<tr>
<td>18.0</td>
<td>5.0</td>
<td>23.0</td>
<td>3</td>
</tr>
<tr>
<td>21.6</td>
<td>7.5</td>
<td>24.5</td>
<td>3</td>
</tr>
<tr>
<td>24.5</td>
<td>10.0</td>
<td>36.0</td>
<td>2</td>
</tr>
<tr>
<td>26.5</td>
<td>12.5</td>
<td>52.0</td>
<td>2</td>
</tr>
<tr>
<td>28.5</td>
<td>15.0</td>
<td>65.0</td>
<td>2</td>
</tr>
<tr>
<td>30.0</td>
<td>17.5</td>
<td>85.0</td>
<td>2</td>
</tr>
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<td>32.0</td>
<td>20.0</td>
<td>101.0</td>
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<td>2</td>
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<td>153.0</td>
<td>2</td>
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<td>30.0</td>
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<td>2</td>
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<td>40.0</td>
<td>32.5</td>
<td>182.0</td>
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<td>41.5</td>
<td>35.0</td>
<td>195.0</td>
<td>2</td>
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<td>43.0</td>
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<td>43.7</td>
<td>40.0</td>
<td>218.0</td>
<td>2</td>
</tr>
</tbody>
</table>

*Radio gain 0.307
TABLE X

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

Electrodes: 45-degree conical point to plane
Spacing: 10.2 centimeters
Polarity: Negative

Temperature: Dry Bulb: 22.6°C
Wet Bulb: 18.0°C
Barometer: 747.6 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage (KV DC)</th>
<th>Current (Ma)</th>
<th>Relative Radio Noise*</th>
<th>Type</th>
<th>Discharge</th>
</tr>
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<tbody>
<tr>
<td>12.5</td>
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<td></td>
</tr>
<tr>
<td>15.6</td>
<td>2.5</td>
<td>8.3</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>18.5</td>
<td>5.0</td>
<td>12.4</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>21.2</td>
<td>7.5</td>
<td>15.7</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td>10.0</td>
<td>16.6</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>26.0</td>
<td>13.0</td>
<td>16.6</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>27.5</td>
<td>15.0</td>
<td>15.7</td>
<td>&quot;</td>
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<td>15.0</td>
<td>&quot;</td>
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<td>22.5</td>
<td>16.0</td>
<td>&quot;</td>
<td></td>
</tr>
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<td>33.0</td>
<td>25.0</td>
<td>16.0</td>
<td>&quot;</td>
<td></td>
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<td>27.5</td>
<td>8.2</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>36.0</td>
<td>30.0</td>
<td>50.0</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>37.5</td>
<td>32.5</td>
<td>8.5</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>38.0</td>
<td>34.2</td>
<td>167.0</td>
<td>&quot;</td>
<td></td>
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<td>1.5</td>
<td>&quot;</td>
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<td>4.0</td>
<td>&quot;</td>
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<tr>
<td>41.0</td>
<td>40.0</td>
<td>100.0</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>44.0</td>
<td>45.2</td>
<td>7.0</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>44.5</td>
<td>48.0</td>
<td>5.0</td>
<td>&quot;*Radio gain 0.603</td>
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</tr>
</tbody>
</table>

*Radio gain 0.603
TABLE XI

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

Electrodes: 60-degree conical point to plane
Spacing: 10.2 centimeters
Polarity: Positive

Temperature: Dry Bulb: 23.0°C
Wet Bulb: 18.4°C
Barometer: 757.1 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage (KV DC)</th>
<th>Current (Mu a)</th>
<th>Relative Radio Noise*</th>
<th>Type Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0.1</td>
<td>0</td>
<td>3</td>
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<td>13.5</td>
<td>1.4</td>
<td>15.5</td>
<td>3</td>
</tr>
<tr>
<td>15.5</td>
<td>2.3</td>
<td>34.0</td>
<td>3</td>
</tr>
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<td>22.3</td>
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<td>53.0</td>
<td>3</td>
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<td>28.1</td>
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<td>75.0</td>
<td>3</td>
</tr>
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<td>32.5</td>
<td>19.7</td>
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<td>3</td>
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<td>35.8</td>
<td>24.5</td>
<td>96.0</td>
<td>3</td>
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<td>38.3</td>
<td>30.6</td>
<td>97.0</td>
<td>3</td>
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<td>40.5</td>
<td>33.0</td>
<td>97.0</td>
<td>3</td>
</tr>
</tbody>
</table>

* Radio gain 0.307
TABLE XII

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

Electrodes: 60-degree conical point to plane
Spacing: 10.2 centimeters
Polarity: Negative

Temperature: Dry Bulb: 23.0°C
Wet Bulb: 18.4°C
Barometer: 757.1 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage (KV DC)</th>
<th>Current (Ma)</th>
<th>Relative Radio Noise*</th>
<th>Type Discharge</th>
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</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0.1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>15.5</td>
<td>2.0</td>
<td>5.5</td>
<td>1</td>
</tr>
<tr>
<td>22.3</td>
<td>7.8</td>
<td>16.5</td>
<td>1</td>
</tr>
<tr>
<td>28.1</td>
<td>17.5</td>
<td>25.0</td>
<td>1</td>
</tr>
<tr>
<td>32.5</td>
<td>23.8</td>
<td>30.0</td>
<td>1</td>
</tr>
<tr>
<td>35.8</td>
<td>28.8</td>
<td>30.0</td>
<td>1</td>
</tr>
<tr>
<td>38.3</td>
<td>35.0</td>
<td>40.0</td>
<td>1</td>
</tr>
<tr>
<td>40.5</td>
<td>37.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Radio gain 0.603
TABLE XIII

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

Electrodes: Sharp, slender point to plane
Spacing: 10.2 centimeters
Polarity: Positive
Temperature: Dry Bulb: 23.8°C
            Wet Bulb: 18.2°C
Barometer: 745.1 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage (KV)</th>
<th>Current (Ma)</th>
<th>Relative Radio Noise*</th>
<th>Type Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>0.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8.8</td>
<td>1.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>11.2</td>
<td>2.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>13.5</td>
<td>3.0</td>
<td>0</td>
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</tr>
<tr>
<td>16.5</td>
<td>5.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>19.7</td>
<td>7.5</td>
<td>0</td>
<td>1</td>
</tr>
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<td>0</td>
<td>1</td>
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<tr>
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<td>1</td>
</tr>
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<td>15.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
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<td>1</td>
</tr>
<tr>
<td>31.5</td>
<td>20.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>34.8</td>
<td>25.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>37.0</td>
<td>30.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>40.5</td>
<td>35.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>43.6</td>
<td>40.0</td>
<td>0</td>
<td>1</td>
</tr>
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</table>

*Radio gain 1.75
TABLE XIV

HIGH-VOLTAGE DIRECT-CURRENT POINT DISCHARGE CHARACTERISTICS

Electrodes: Sharp, slender point to plane

Spacing: 10.2 centimeters

Polarity: Negative

Temperature: Dry Bulb: 23.8°C
Wet Bulb: 18.2°C
Barometer: 745.1 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage KV DC</th>
<th>Current Mu a</th>
<th>Relative Radio Noise*</th>
<th>Type Discharge</th>
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</thead>
<tbody>
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<td>1.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>9.8</td>
<td>2.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>11.0</td>
<td>3.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>12.7</td>
<td>4.0</td>
<td>0+</td>
<td>1</td>
</tr>
<tr>
<td>14.2</td>
<td>5.0</td>
<td>0</td>
<td>1</td>
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<tr>
<td>16.5</td>
<td>7.0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>18.7</td>
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<td>1</td>
</tr>
<tr>
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<td>2</td>
<td>1</td>
</tr>
<tr>
<td>22.7</td>
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</tr>
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<td>15.0</td>
<td>0</td>
<td>1</td>
</tr>
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<td>26.5</td>
<td>17.5</td>
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<td>20.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>29.5</td>
<td>22.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>30.7</td>
<td>25.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>32.2</td>
<td>27.6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>33.8</td>
<td>30.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>35.4</td>
<td>33.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>36.5</td>
<td>35.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>39.0</td>
<td>40.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>40.7</td>
<td>44.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>41.3</td>
<td>45.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>43.0</td>
<td>50.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>45.1</td>
<td>55.0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

*Radio gain 1.75
### TABLE XV

**Duddell Oscillograph Amplitude Response Check**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Duddell Oscillograph</th>
<th>Cathode Ray Oscillograph</th>
<th>Ratio: Duddell to C. R. Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>4.50</td>
<td>2.45</td>
<td>1.09</td>
</tr>
<tr>
<td>H. F.*</td>
<td>2.00</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

| 60        | 1.75                  | 1.35                      | 1.07                            |
| H. F.*    | 1.60                  | 1.15                      |                                 |

| 60        | 1.75                  | 1.25                      | 0.97                            |
| H. F.*    | 3.65                  | 2.70                      |                                 |

* DC corona discharge from 60° conical point -- various voltages.*
TABLE XVI

HIGH-VOLTAGE DIRECT-CURRENT
POINT DISCHARGE CHARACTERISTICS

INFLUENCE OF SERIES RESISTANCE AND INDUCTANCE
UPON INDUCED RADIO INTERFERENCE

Electrodes: 60-degree conical point to plane
Spacing: 10.2 centimeters
Polarity: Positive
Temperature: Dry Bulb: 22.4°C
Wet Bulb: 18.1°C
Barometer: 745.0 mm. Mercury

<table>
<thead>
<tr>
<th>Voltage (KV DC)</th>
<th>Current (μa)</th>
<th>Relative Radio Noise</th>
<th>Discharge Resistance and Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.8</td>
<td>3.9</td>
<td>42.3</td>
<td>(R = 0, L = 0)</td>
</tr>
<tr>
<td>27.9</td>
<td>13.5</td>
<td>71.0</td>
<td>(R = 0, L = 0)</td>
</tr>
<tr>
<td>33.5</td>
<td>21.0</td>
<td>89.0</td>
<td>(R = 0, L = 0)</td>
</tr>
<tr>
<td>41.0</td>
<td>33.5</td>
<td>119.0</td>
<td>(R = 0, L = 0)</td>
</tr>
<tr>
<td>16.6</td>
<td>3.7</td>
<td>11.1</td>
<td>(R = 2 megohms)</td>
</tr>
<tr>
<td>27.9</td>
<td>13.5</td>
<td>22.2</td>
<td>(L = 0)</td>
</tr>
<tr>
<td>33.7</td>
<td>21.0</td>
<td>34.5</td>
<td>(L = 0)</td>
</tr>
<tr>
<td>41.2</td>
<td>33.5</td>
<td>55.5</td>
<td>(L = 0)</td>
</tr>
<tr>
<td>16.8</td>
<td>4.0</td>
<td>4.4</td>
<td>(R = 2 megohms)</td>
</tr>
<tr>
<td>28.0</td>
<td>13.5</td>
<td>9.4</td>
<td>(L = 37.2 mH)</td>
</tr>
<tr>
<td>33.7</td>
<td>21.0</td>
<td>14.4</td>
<td>(L = 37.2 mH)</td>
</tr>
<tr>
<td>41.2</td>
<td>33.5</td>
<td>26.6</td>
<td>(L = 37.2 mH)</td>
</tr>
</tbody>
</table>