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NACA RADIO GROUND-SPEED SYSTEM FOR AIRCRAFT

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SUMMARY

A method that utilizes the Doppler effect on radio signals for determining the speed of an airplane and the distance traveled by the airplane has been developed and found to operate satisfactorily. In this method, called the NACA radio ground-speed system, standard readily available radio equipment is used almost exclusively and extreme frequency stability of the transmitters is not necessary. No complicated equipment need be carried in the airplane, as the standard radio transmitter is usually adequate.

Actual flight tests were made in which the method was used and the results were consistent with calibrated airspeed indications and stop-watch measurements. Inasmuch as the fundamental accuracy of the radio method is far better than either of the checking systems used, no check was made on the limitations of the accuracy.

INTRODUCTION

A number of different systems can be used to measure the speed of an airplane and the distance the airplane travels by the use of Doppler effect on radio signals; but the greater number of the systems are either inaccurate or difficult to use, except at exceedingly high speeds. The most obvious method of measuring speed, for example, is to use a frequency meter to measure the change in frequency due to Doppler effect as the distance is varied between the transmitter and the frequency meter. This system requires a frequency meter of extreme sensitivity and a transmitter with unusual stability. Such transmitters and frequency meters have not been developed.

An improvement, which is still not satisfactory for accurate measurements at normal speeds - that is, speeds less than 750 miles per hour - is to measure the beat frequency between the moving transmitter and a similar transmitter at either station when the distance is varied between the two transmitters. The required frequency stability would still be unreasonable for accurate work.

Another system is to measure the apparent beat frequency in the airplane, which is moving between two synchronized transmitters. This system has several disadvantages that would make it difficult to use. Complicated equipment to synchronize the transmitters is required, and the telephone line used to synchronize the stations has to be extremely free from noise. A small amount of distortion results in a phase shift or even a swing of several cycles per second in the frequency of one transmitter. This effect is due to the fact that the synchronizing frequency transmitted over the telephone line is multiplied many times to obtain the radio frequency. The measuring equipment has to be in the moving object, which is an advantage for some uses, but for aircraft research work it is usually more convenient to have the measuring equipment on the ground.

A fourth system consists in transmitting a signal from one station and receiving this signal in a second station, dividing this frequency by a suitable multivibrator, and retransmitting the resulting signal to the original source. The returned signal is then multiplied and compared with the original signal. The beat between the two signals is proportional to the velocity of one station with respect to the other. This system can be operated either by sending the signal from an airplane to the ground and having a harmonically related signal sent back to the airplane for speed determination in the airplane or by sending the signal to the airplane from the ground and having a harmonically related signal sent back to the ground. This system is complicated and involves sending and receiving harmonically related signals without feedback or blocking of the receiver.

Another system is to measure speeds by picking up signals reflected from the airplane itself, which in this case needs no transmitter, and comparing these signals with the originally transmitted signals. This measurement probably can be made with radar type of equipment if it is available.

The system that appears most satisfactory for the present purposes and that is believed to be original is described in the following section. In this method, called the NACA radio ground-speed system, standard readily available radio equipment is used almost exclusively and extreme frequency stability of the transmitters is not necessary. No complicated equipment need be carried in the airplane, as the standard radio transmitter is usually adequate. This system has been adapted to the accurate measurement of the speed of airplanes and operation has been quite satisfactory.

DESCRIPTION OF METHOD

A transmitter in the airplane of which the speed is to be measured transmits a continuous-wave radio-frequency signal, which is heterodyned by a ground station. Receivers at each end of the flight path receive this heterodyne note differently because the frequency of the moving transmitter is apparently increased with respect to the end of the course it is approaching and decreased with respect to the end of the course from which it is receding.

By adding the audio-frequency signals – that is, the heterodyne notes – received by the two receivers, a beat frequency that is proportional to the speed of the airplane is obtained. The heterodyne note received at one end of the course must be sent either by wire or by radio to the opposite end of the course in order that the two signals may be mixed. The radio transmission allows greater flexibility in choosing the course and permits the use of completely mobile equipment; however, a telephone wire is more reliable, requires less equipment, and does not require a second assigned frequency. Figure 1 shows diagrams of these systems.

As an example, the airplane transmitter on a frequency f_1 is heterodyned by a ground station operating on a frequency f_2. The beat note $|f_1 - f_2|$ must be between 30 and 6000 cycles per second in order that standard radio apparatus can be used. If f_D is a frequency equal to the velocity of the airplane in wave lengths per second of its transmitter, one receiver receives a note $|f_1 - f_2 - f_D|$ and the other receives a note $|f_1 - f_2 + f_D|$.

The value of $2f_D$ is obtained from the beat between the signals received at the two ends, that is,

$$|f_1-f_2+f_D| - |f_1-f_2-f_D| = 2f_D = \frac{2 \times \text{velocity of airplane}}{\text{wave length of airplane transmitter}}$$

It should be noted that the first-order effect of frequency drift in either transmitter is canceled out. The value of f_D depends on the frequency of the transmitter in the airplane; however, variations in this frequency will be less than 0.1 percent even with ordinary equipment, thus eliminating the necessity for stability of an impossibly high order. The stationary transmitter can be at any convenient location on the ground as long as the signal received at both ends of the course does not differ too greatly in intensity from the signal from the airplane.

As f_D is equal to the velocity of the airplane in wave lengths per second, each cycle represents a distance along the course equal to one-half wave length of the moving transmitter. By recording these cycles along with timing lines, an accurate time-distance record is obtained from which the speed of the airplane can be calculated.

If the airplane moves in such a way that the change in the distance to both receivers remains constant, no beat frequency will be recorded. This type of flight would be along a hyperbolic path with the receivers at the foci. A family of such hyperbolas, which represent what could be considered standing waves as far as the film record is concerned, is shown in figure 2. An airplane flying along one of the hyperbolas in figure 2 will produce no beats between the received signals. When the change in the distance from the airplane to one receiver is different from the change in the distance to the second receiver by a distance equal to one wave length of the transmitted signal from the airplane, one complete cycle will be recorded. This method allows several variations in the use of the system.

PRELIMINARY TESTS

The first check of the practicability of the method was made on November 4, 1940 at Langley Field, Va. The receivers were located approximately 2 miles apart. The airplane flew the course once in each direction at an altitude of 250 feet and with an airspeed of approximately 160 miles per hour. The wind was practically with the course at 5 miles per hour at the ground. The airplane transmitted on a frequency of 3312.5 kilocycles and the ground transmitter was operated on a frequency approximately 2000 cycles lower. The signals received at one end of the course were retransmitted on 4600 kilocycles to an additional receiver located at the other end of the course. The audiofrequency signals received on 3312.5 kilocycles and 4600 kilocycles were mixed and the beat frequency was recorded on a standard NACA recording galvanometer along with 1/2-second timer marks. Sections of these records are shown in figure 3. Figure 3(a) shows a section of a record with the airplane flying against the wind, and figure 3(b) is a section of a record with the airplane flying with the wind. The speeds were calculated to be 154.5 miles per hour and 158 miles per hour, respectively.

A second test was made November 7, 1940 between Langley Field and Big Bethel, Va., a distance of approximately 4.6 miles. The same procedure was followed as in the first test except that the signals received at one end of the course were sent to the other end by a telephone wire.

The wind was at an angle of approximately 30° with the course and had a velocity of about 15 to 19 miles per hour at the Langley Field meteorological station. In order to insure the accuracy of the airspeed indication, the pilot was provided with a calibrated airspeed indicator connected to a suspended pitot-static head. (See reference 1.)

The pilot also checked his time to fly the course. Some variation in the speeds as determined by stop-watch readings and the radio method is to be expected. The pilot could not hold the airspeed closer to 160 miles per hour than approximately 5 miles per hour because of rough air. The speed by the radio method was determined over the center part of the course; whereas the stop-watch determination was for the total distance.

Figure 4(a) shows a section of a record taken with the airplane flying against the wind and figure 4(b) is a section taken with the airplane flying with the wind when the telephone return was used.

Table 1 shows the ground speeds calculated from the radio ground-speed records and from stop-watch readings. The ground-speed as determined by the radio method and the stop-watch readings was consistent with the indicated airspeed and the wind conditions prevailing. As a result of the preliminary tests, it was believed that satisfactory performance could be expected from the radio ground-speed system.

EQUIPMENT

A permanent installation of the following equipment has been made: Hammarlund model 110Lx Super-Pro receivers are used and are mounted in suitable relay racks with the auxiliary equipment. One small relay rack contains a receiver, suitable filters, impedance matching transformer, and a power supply for 12-volt direct-current operation or 117-volt alternating-current operation. A loud speaker is also installed in the small rack to assist the operator in monitoring the received signal. A photograph of this equipment is shown in figure 5. Figure 6 is a circuit diagram of this installation.

The recording apparatus, as shown in figure 7, is mounted in the large relay rack with the signal mixing channel, the timer, the receiver, the monitoring equipment, and the power supplies. Also is shown a small relay rack containing a third receiver, which is used if the signal is transmitted from the far end of the course by radio instead of by a telephone line. A block diagram of the apparatus in the large relay rack is shown in figure 8. The antenna receives the heterodyne note (approx. 1000 cps) between the stationary ground transmitter and the transmitter in the airplane. After detection in the receiver, the signal is filtered and impressed on the signal mixer in which it is mixed with the similar signal that comes from the far end of the course. The signal from the far end of the course is amplified before it is sent to the mixer. The signal amplitudes are controlled by a gain control in the amplifier and the audio-gain control in the receiver. A cathode-ray oscilloscope is used to monitor the two signals entering the signal mixer. Figure 9 shows a circuit diagram of the signal mixer and the filter channel. The output of the signal mixer is a difference frequency between the two input signals and is recorded on film by a standard NACA recording galvanometer. A photograph of the recording galvanometer with the cover removed is shown in figure 10. The film drums contain 20 feet of film and are easily replaceable through the front grilled door panel. A film speed of 1/2 inch per second is normally used.

An NACA chronometric timer is used to put 1/2-second timing marks on the film record. The recorder also has a second timing line operated at line frequency, 60 cycles per second, which does not appear on the original records. Figure 11 shows later records, one at a higher film speed.

Figure 12 is a photograph of a 100-watt transmitter, which is used as the stationary ground transmitter. This transmitter is used unmodulated for these tests; it is sometimes used modulated for communication and coordination of the tests.

Normally the transmitter already installed in the airplane is used and is tuned to the assigned frequency, 3850 kilocycles. A small 15-watt transmitter is installed in the airplane if necessary or more convenient. This transmitter is a crystal-controlled unit without modulation equipment, which is not necessary for the present purposes. A circuit diagram of this transmitter is shown in figure 13.

VELOCITY CALCULATIONS

If the airplane flies directly between the antennas of the two receivers, the beat frequency recorded is directly proportional to the velocity of the airplane and the frequency of its transmitter. Each recorded cycle will represent a distance traveled equal to one-half the wave length of the transmitted signal. In figure 14 the recorded beat frequency and the distance traveled per record cycle are plotted against the frequency of the transmitter in the airplane with the speeds of the airplane as parameters for the previously given conditions of flight.

When the airplane is directly between the receivers but flying at an angle with the course, the film record indicates the component of the velocity of the airplane along the course. For small angles, the cosine is practically 1.00, which causes negligible error because of the inability of the airplane to fly a true course.

If the airplane flies parallel to the line between the receivers but not on the direct line between the receivers, the distance traveled by the airplane is greater per record cycle. This case is practical because, with an airplane flying at a high altitude, the airplane could not usually fly directly between the receiver antennas. Figure 15 shows this correction in percent for three different positions along the course plotted against the ratio of the altitude of the airplane to the distance between the receivers. Plots of this correction are made for the case when the airplane is in the center of the course, when the airplane is one-third the distance between the receivers from either receiver and when the airplane is one-fifth the distance between the receivers from either receiver.

The radio ground-speed system is at present operated with a distance between the two receivers of approximately 75,000 feet. A plot of altitude correction applied to the usual constant of 2 recorded cycles per wave length traveled by the airplane is shown in figure 16. Five parameters of altitude are plotted. If the airplane is off the straight-line course horizontally as well as vertically, the correction will be applied in the same manner, except that the perpendicular distance to the line between the receivers (the slant height) will be used in calculating the correction.

The velocity of the airplane and the distance traveled may be calculated from the recorded cycles and the timing cycles, if the direction of flight and the position of the airplane are known, by the following equations:

$$V = \frac{n\lambda}{t\ \cos\psi}\left(\frac{1}{\dfrac{a}{\sqrt{c^2+a^2}} + \dfrac{b}{\sqrt{c^2+b^2}}}\right)$$

$$s = \frac{n\lambda}{\cos\psi}\left(\frac{1}{\dfrac{a}{\sqrt{c^2+a^2}} + \dfrac{b}{\sqrt{c^2+b^2}}}\right)$$

where

V speed of airplane

s distance traveled by airplane

λ wave length of transmitter in airplane

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n number of record cycles

t time

ψ azimuth angle between flight path and line between receivers

c perpendicular distance from airplane to line between receivers

a and b distance to receivers from point of intersection of perpendicular from airplane to line between receivers

It is assumed that the airplane maintains constant altitude, which is not difficult in flight. Any error due to the flight-path angle is very small and the error approaches zero very rapidly as the angle becomes small.

When the airplane is flying in the center of the course and directly between the receivers, the equations for speed and distance simplify to

$$V = \frac{n\lambda}{2t}$$

$$s = \frac{n\lambda}{2}$$

These simple equations can be used as long as the altitude is a small percentage of the distance to either receiver.

If the ground-speed course is used to measure airspeeds, the velocity of the wind is, of course, important. Correction for the component of the wind velocity along the course can be made by averaging the velocity of the airplane as measured flying in each direction or by determining the wind velocity at that altitude by other means and correcting for it.

For accurate measurements of airspeed, the tests should be made only on days when the wind velocity is low relative to the velocity of the airplane. At high velocities of the airplane the wind becomes of less importance on a percentage basis. The use of this system for investigating winds at high altitudes has been considered.

In the center of the course, when the airplane starts the run on the upwind side of the course and finishes on the downwind side and flies with a heading corresponding to the compass course between the stations, the cross wind has no effect on the speed measurements except for geometric error when the airplane gets too far off the course laterally. Correction may be made for cross winds by flying the airplane along a true course and the airspeed can be obtained by dividing the measured ground speed by the cosine of the angle of drift.

POSSIBLE VARIATIONS OF SYSTEM

Measurement of Velocity of an Airplane in a Dive or of a Falling Body

The velocity of an airplane in a dive may be measured by diving the airplane directly at one receiver so that the distance between the airplane and a second receiver is a constant, as would be the case if the second receiver was a considerable distance away and at right angles to the flight path. The proper flight path would actually be on the surface of a sphere with a radius equal to the distance between the receivers. If the distance between the receivers is large compared with the distance between the airplane and the receiver, however, the surface of this sphere becomes a plane surface for all practical purposes. Each record cycle then represents a distance traveled toward the receiver equal to one wave length of the radio-frequency signal sent from the airplane.

Care must be taken that the distance to the second receiver remains constant or changes a negligible amount, or that the flight path is known accurately so that proper corrections can be made. The error, for the first approximation, is proportional to the sine of the angle between the flight path and the line between the receivers. This error does not approach zero as rapidly as when the error is a function of the cosine of the angle, which is the case when horizontal velocities are measured. Errors in the angle of flight path in the other plane, when the flight path is not directly toward one receiver but the distance to the second receiver remains constant, are not so critical because they are proportional to the differences in a cosine function. In order to keep the error below 1 percent, even when the altitude is small in comparison with the distance between the receivers, the angle between the flight path and the line between the receivers must not vary more than approximately 1/2° from 90°.

Inasmuch as it is doubtful that the flight path can be established to this order of accuracy, other data may be necessary to make the corrections that depend on the angle of the dive. One method of obtaining the additional data is to use three receivers in a line and dive at the center receiver. The horizontal distance traveled along the line connecting the receivers can be determined from the beat between the signals received in the two outer receivers. The vertical distance traveled can be determined from the beat note between the center and either outside receiver. In this system as in the other, a stationary transmitter is of course necessary to heterodyne the signal transmitted by the airplane.

Another alternative is to use a second airplane (or an airship) as one end of the course and dive an airplane between the airplane (or airship) and a ground station. This method simplifies the corrections and is similar to the ground-speed system. The signal received in the airplane (or airship) must be sent to the ground by an additional radio link; this link can, however, be an ultra-high-frequency transmission inasmuch as the ground station would always be in sight. This variation may lend itself to the study of falling bombs.

It is suggested that, if this method of measuring velocities in a dive is considered, a thorough and detailed study be made to ascertain if the necessary conditions can be met.

Multiple Systems

By use of two complete radio ground-speed systems placed at right angles, the exact position of the airplane and more than one component of its velocity can be calculated at any time from the recorded cycles, if it is assumed that the position of the airplane at one instant is known. If it is possible to place two additional receivers on a vertical line, furthermore, the position of the airplane in space can be calculated from the three film records. These multiple systems may be simplified by placing the course lines at angles other than right angles and by using only three receivers in the two-coordinate system and four receivers in the three-coordinate system. This simplification is made by using one receiver on two or more courses, but the calculation is more difficult.

GENERAL CONSIDERATIONS

The number of recorded cycles per second in any use of the radio ground-speed system depends directly on the frequency of the radio signal transmitted from the airplane. The higher the operating frequency the shorter the distance the airplane must travel to obtain the same number of recorded cycles. This fact is important because a definite number of cycles is required to determine the frequency within a given limit of accuracy. Experience has shown that, with the apparatus under normal conditions, the number of cycles can be determined to approximately 1/10 cycle, which requires at least 20 cycles to obtain an accuracy of 0.5 percent or the airplane has to travel a distance of about 1/2 mile when operating on 3850 kilocycles. When the system is operated on approximately 100 megacycles, 100 feet of travel would be required to give a sufficient number of record cycles. The number of cycles could be determined to a considerably higher degree of accuracy than 1/10 cycle without normal static and interference that are always present in some degree.

Other considerations, such as obtaining an assigned frequency that does not interfere with other services, the adaptability of standard radio apparatus available, and the natural frequency of the recording galvanometer available, are often the deciding factors in the selection of the operating frequency.

Theoretically, it would seem that the greater the distance between the receivers the higher the accuracy of the measurements and the higher the airplane could fly without using the more complex method of calculating the velocity of the airplane from the recorded frequency. This assumption is not necessarily true, as the distance between the receivers must be so limited that the signals received at both receivers are the result of direct radiation from the airplane and ground transmitters and are not signals reflected from the Kennelly-Heaviside layer. The paths of such reflected signals are not constant, would not be reliable, and might of course have unknown angularity corrections with the change in position of the airplane. A second reason that the length of course is limited is that, as the length of course increases, the transmitter power required for acceptable reception also increases at a higher rate. It is also not generally convenient or economical from a practical standpoint to operate two receiving stations at a great distance.

The problem of getting one received signal back to the recorder is more difficult as the distance between the receivers is increased. The problem of the longer telephone line is not so serious as that of the radio return because this link is approximately twice the distance traveled by the other radio signals, which may result in fading or a large amount of interference.

CONCLUDING REMARKS

The NACA radio ground-speed system for determining the velocity and the distance traveled by an airplane has been developed and operation has been quite satisfactory. The ground speed of an airplane could be obtained to 0.1 percent by a method requiring only a radio transmitter operating on a suitable frequency in the airplane; however, it is doubtful if the geometry of the course will be known to this order of accuracy.

If the system is to be used to check true airspeed, the airplane need fly only the center mile of the course in both directions to allow accurate speed determinations to be made. It is recommended that the tests be made only on days when the wind velocity is low relative to the velocity of the airplane to prevent serious errors due to changes in wind velocity.

The velocity of an airplane in a dive may be determined by using this system. Greater accuracy in flying a known flight path is, however, required than for horizontal flight; as a result, the possibility of appreciable errors in measured velocity is increased.

Multiple courses may be arranged which give more than one component of the velocity. Greater accuracy could be expected with these multiple courses as a rigid flight path would not be necessary.

The NACA radio ground-speed system would lend itself to the accurate measurement of distance; or, if the distance were known, the speed of radio waves could be accurately checked. This system for accurately measuring distance might be useful for such purposes as charting bottoms of rivers or for laying buoys and mines in known positions.

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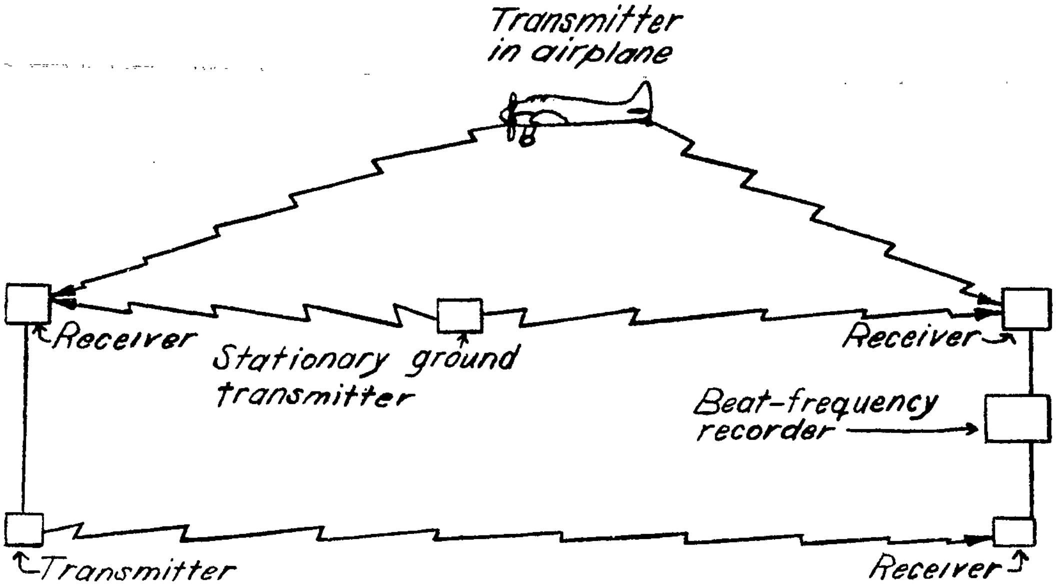
REFERENCE

1. Thompson, F. L.: The Measurement of Air Speed of Airplanes. T.N. No. 616, NACA, 1937.

TABLE I. - CALCULATED GROUND SPEEDS

[Corrected airspeed, 160 mph; wind velocity, 15 to 19 mph, and wind direction, 30° to line of flight, at the Langley Field meteorological station]

Run	Direction of flight	Velocity calculated from radio method (mph)	Velocity calculated from stop-watch readings (mph)
1	N 75° W	141.5	141.5
2	S 75° E	173.5	175.5
3	N 75° W	140.8	142.5
4	S 75° E	176.3	176.2
5	N 75° W	144.9	144.5
6	S 75° E	177.0	181.5
Average of runs N 75° W		142.4	142.8
Average of runs S 75° E		175.6	177.7
Average of six runs		159.0	160.2



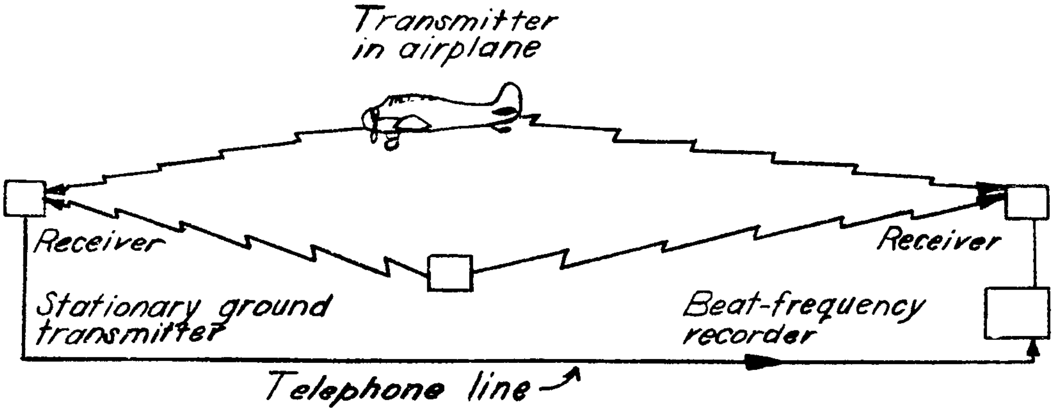


Figure 1.—Diagrams of radio-ground-speed systems.

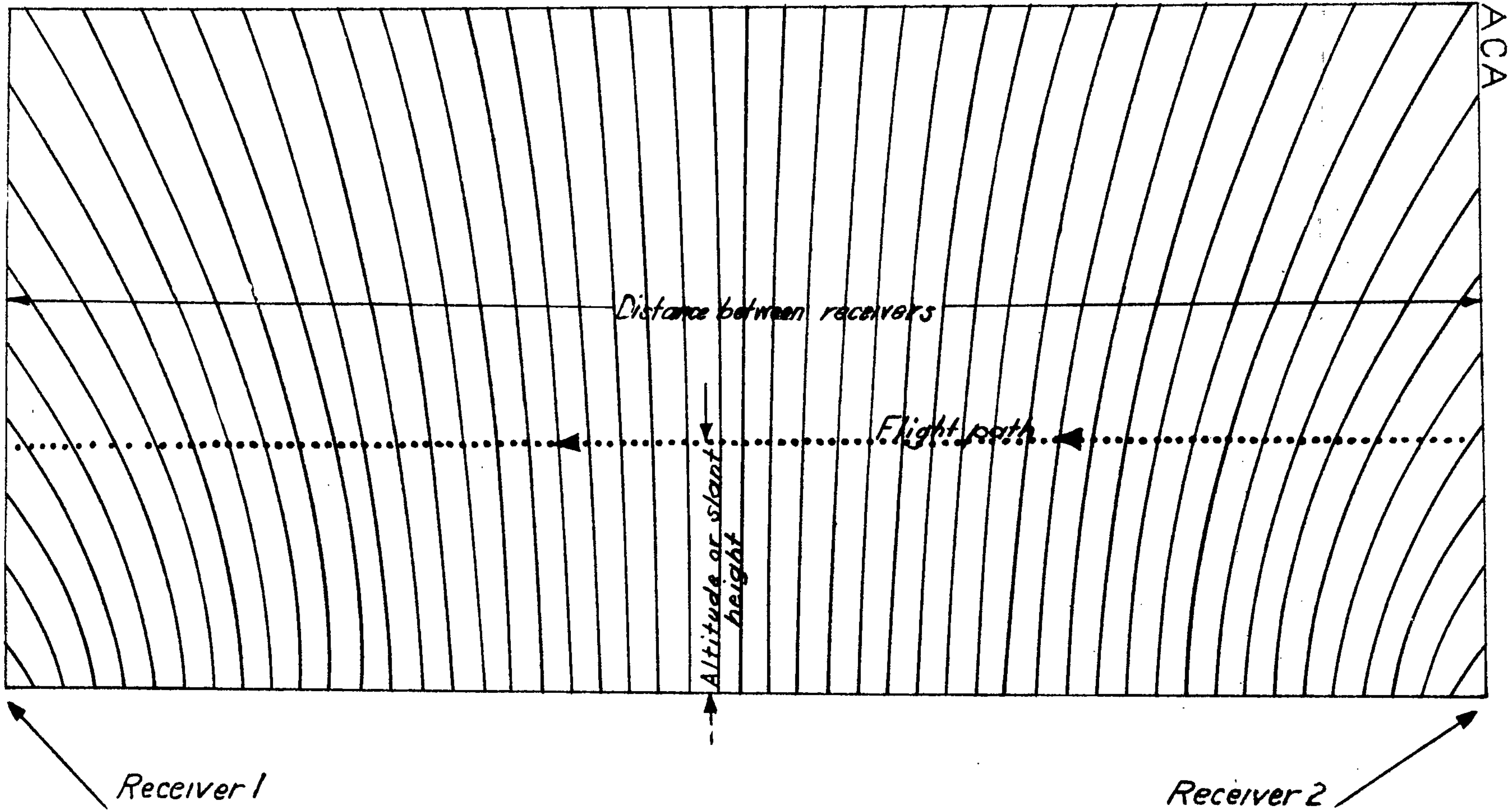
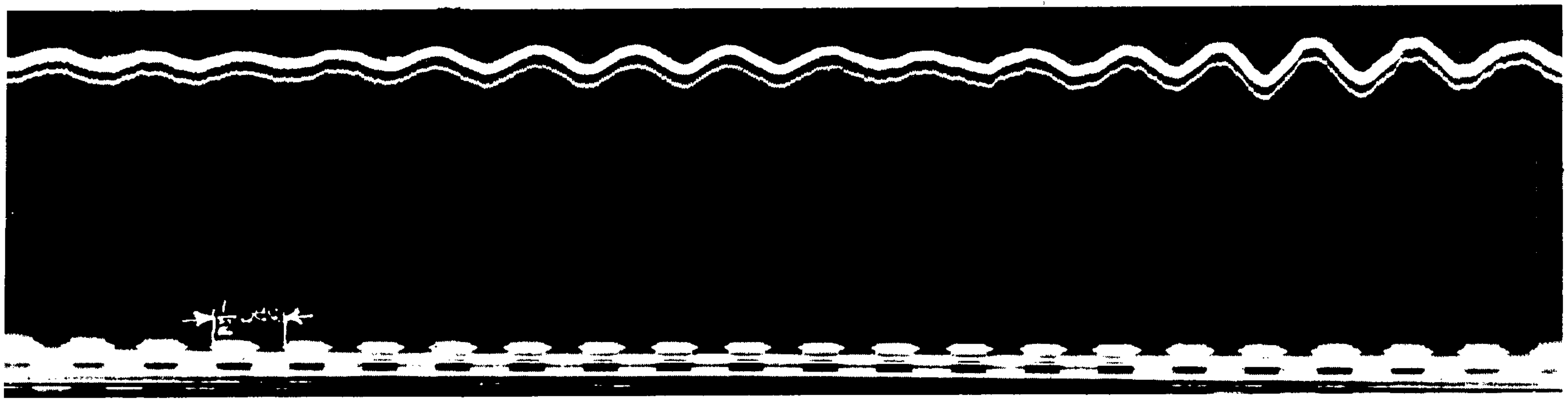
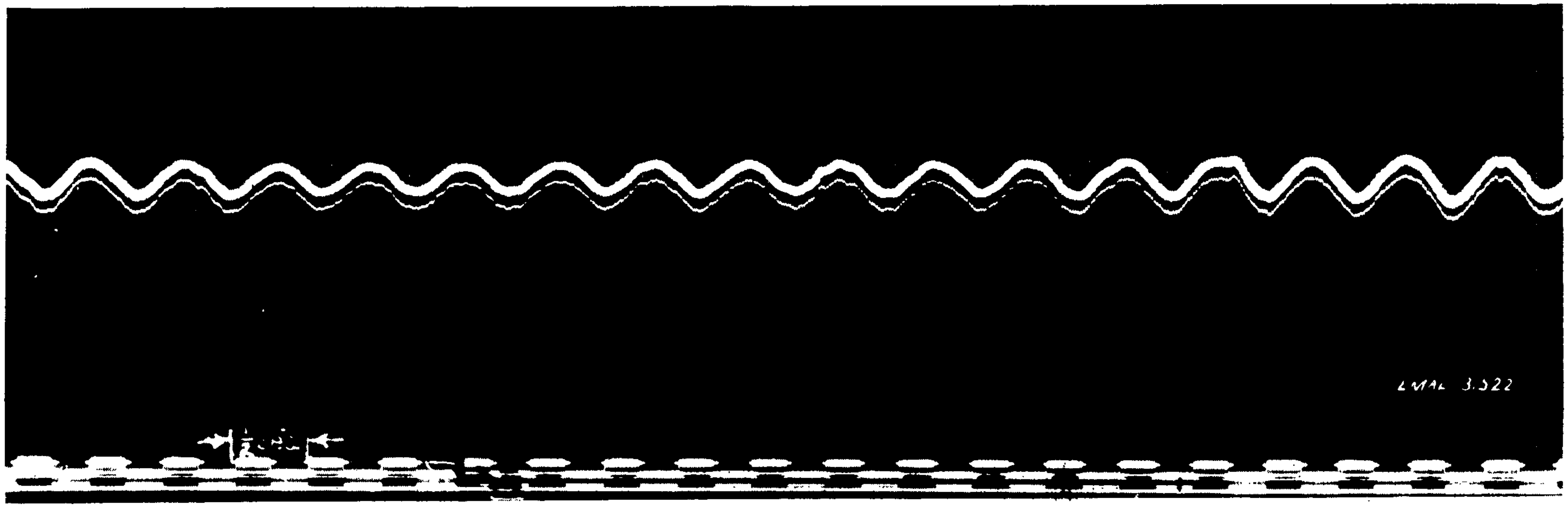


Figure 2. - Section of a family of hyperbolas representing the standing waves between the receivers with respect to the recorded cycles. For a distance traveled by the airplane, represented by the distance between hyperbolas, a definite number of cycles, depending on the radio frequency, is recorded.

Fig. 2

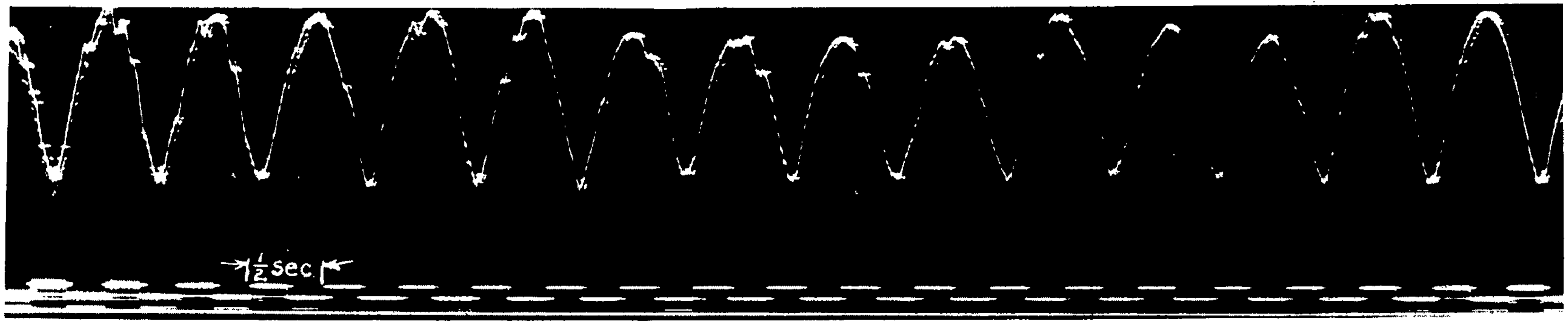


(a) Airplane flying against the wind.



(b) Airplane flying with the wind.

Figure 3.- Radio ground-speed records with radio return.



(a) Airplane flying against the wind.

(b) Airplane flying with the wind.

Figure 4.- Radio ground-speed records with telephone return.

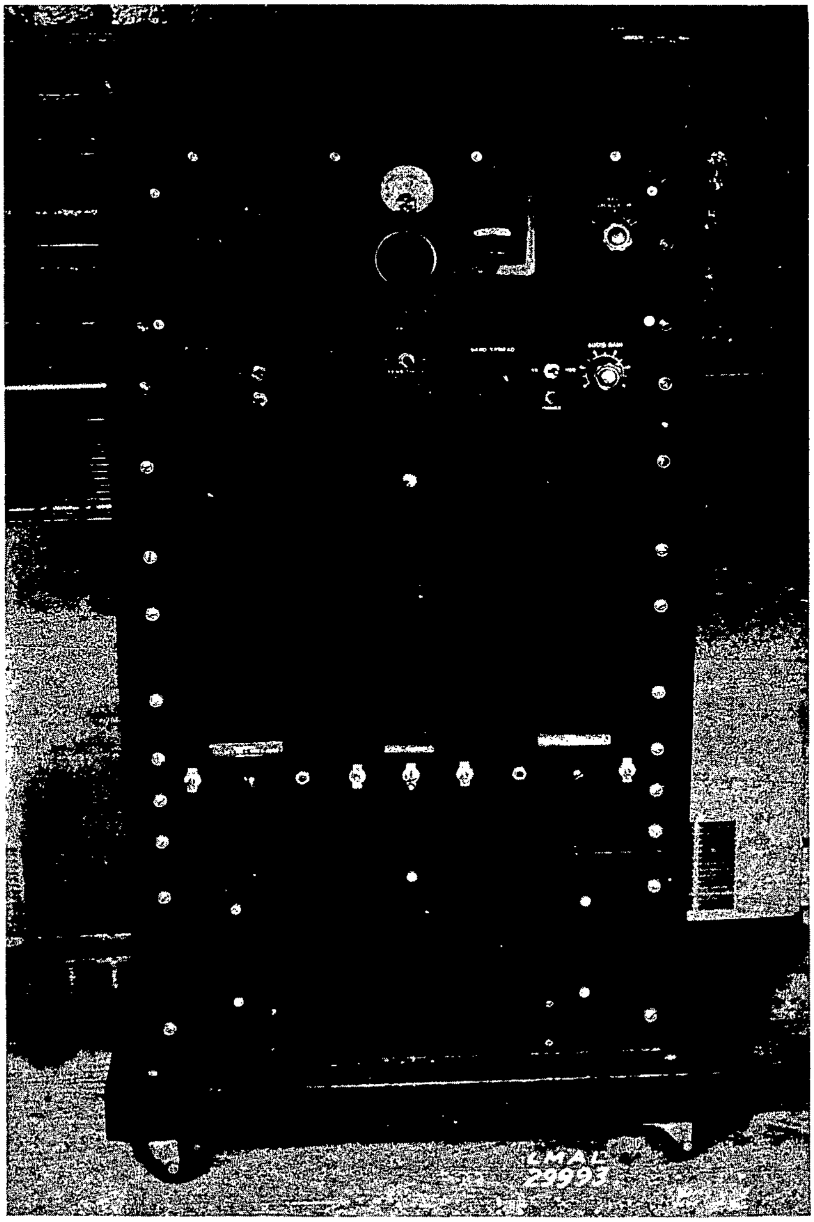


Figure 5.- Receiver mounted with filter and power supply.

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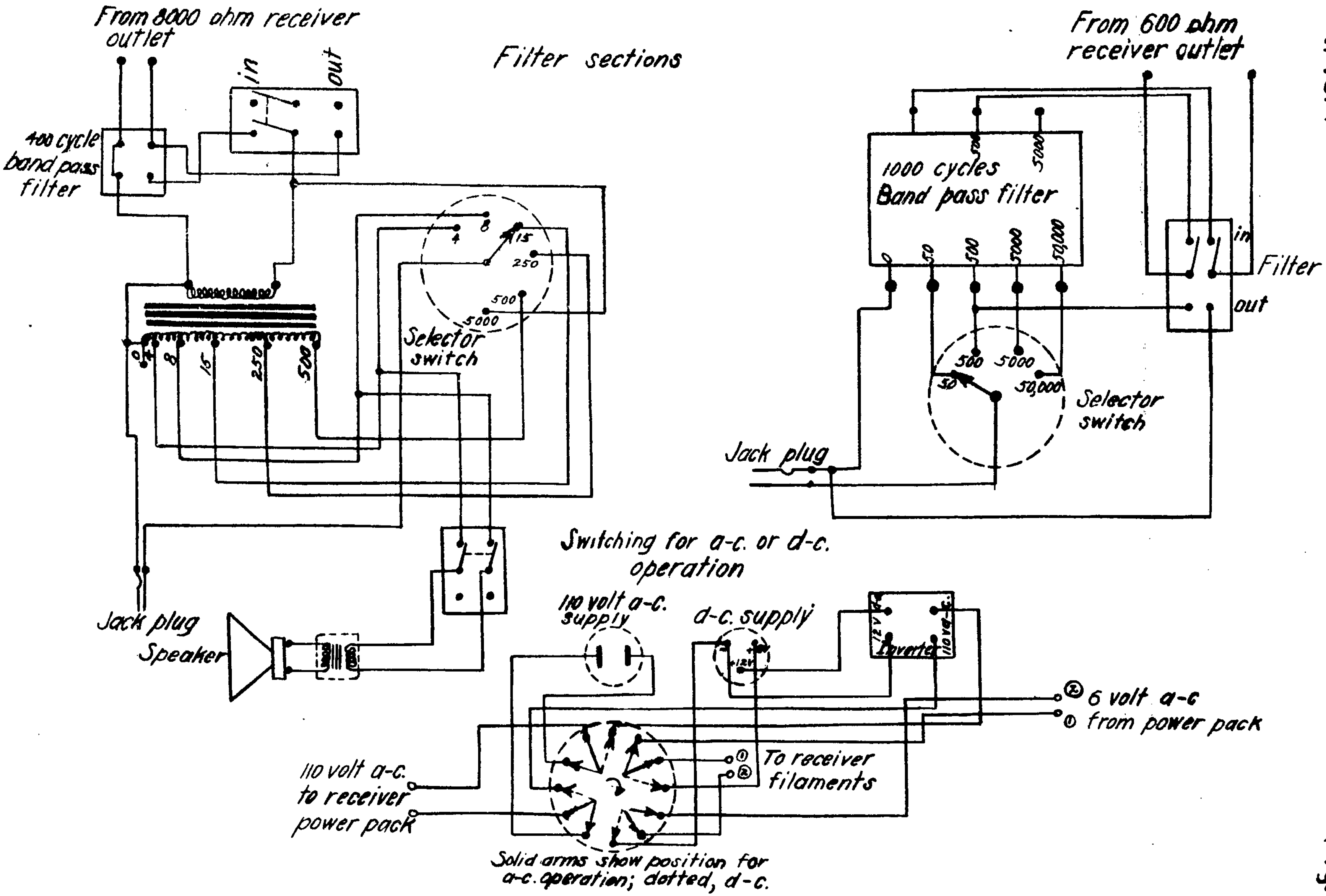

Figure 6.—Circuit diagram of power supply and filters for receiver mounted in small rack.

Fig. 6

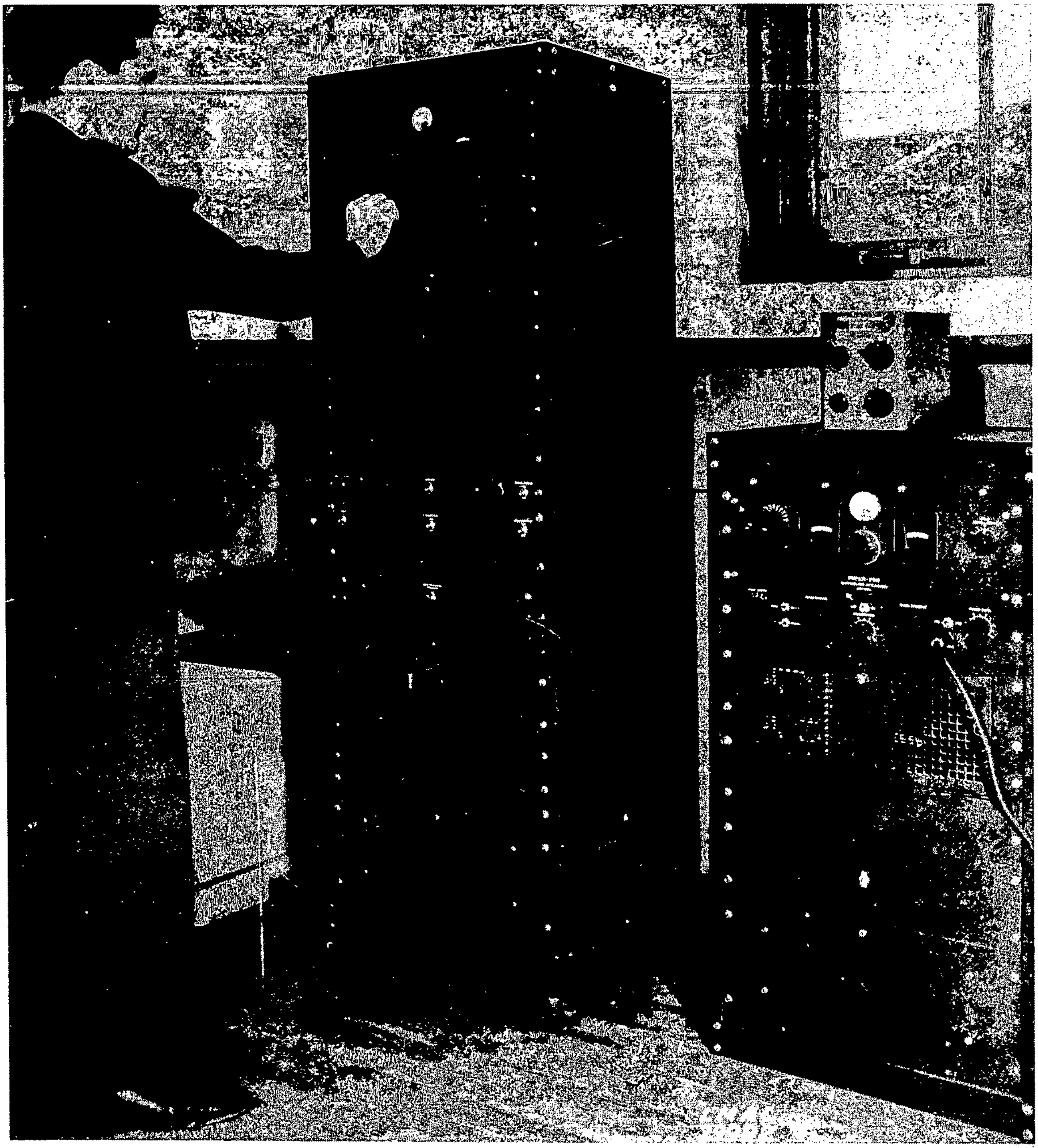

Figure 7.- Radio ground-speed recorder and auxiliary receiver.

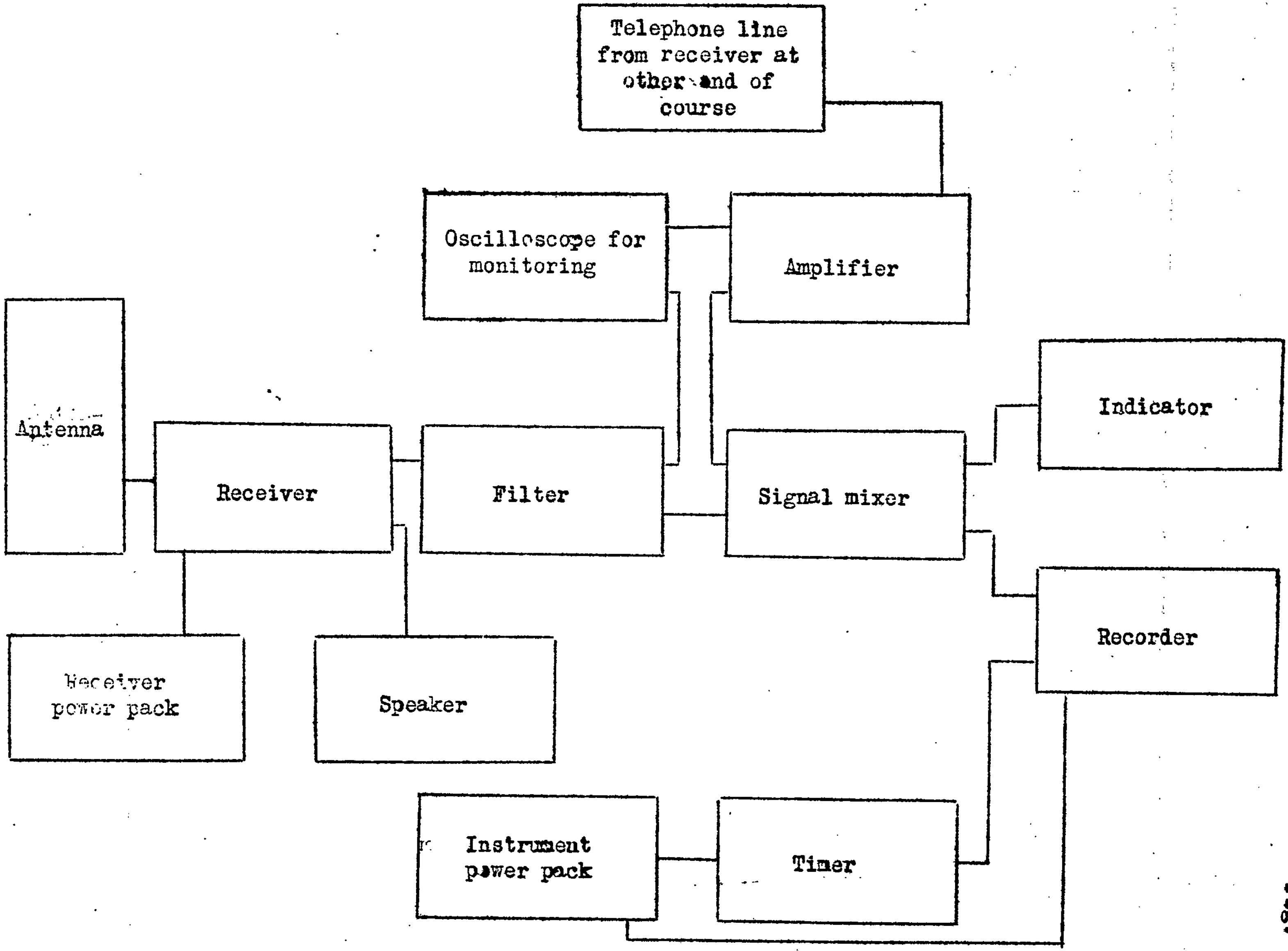

Figure 8.- Block diagram of radio-ground-speed recorder.

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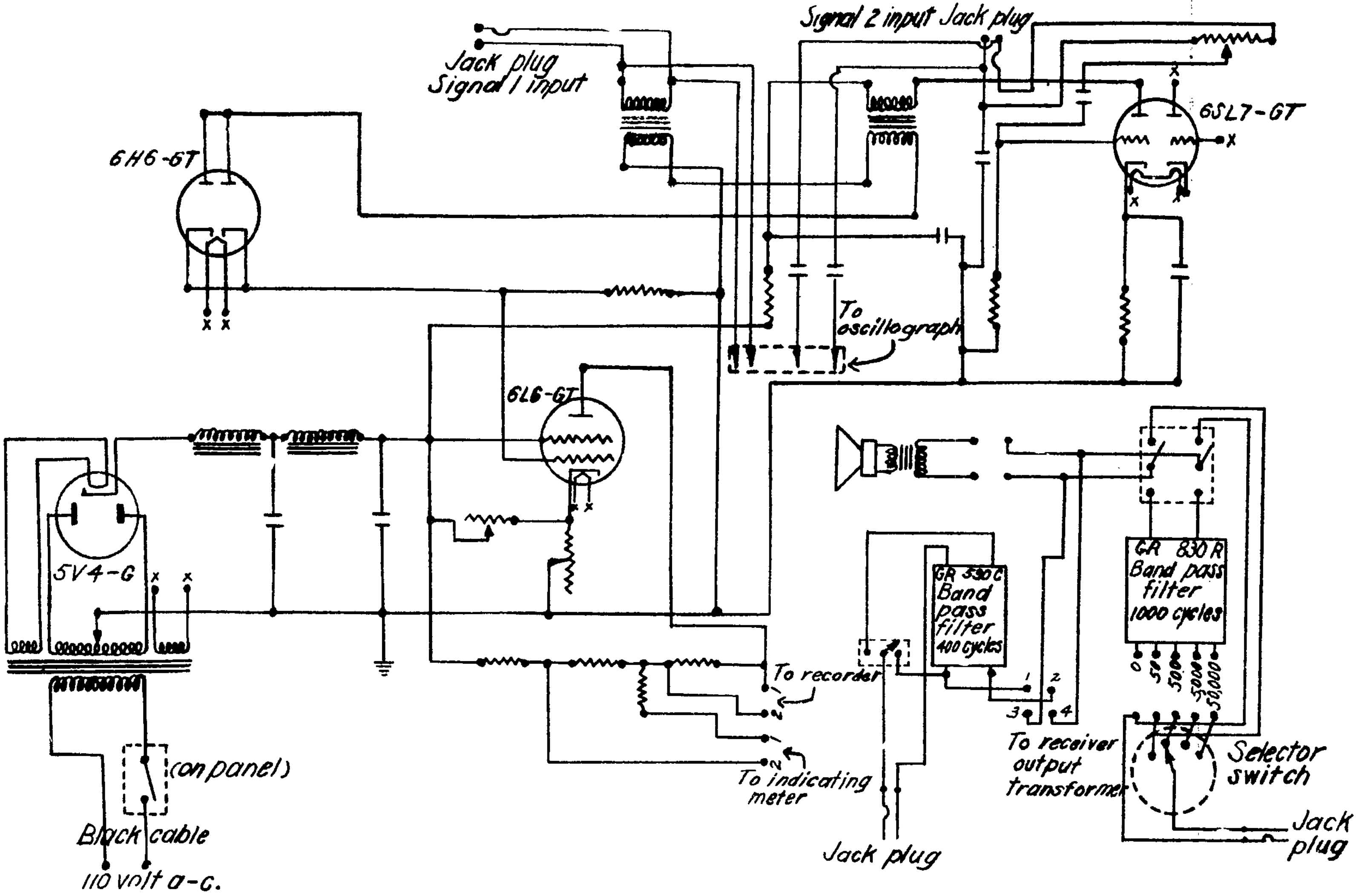

Figure 9.– Circuit diagram of mixer and filter channels in large rack.

Fig. 9

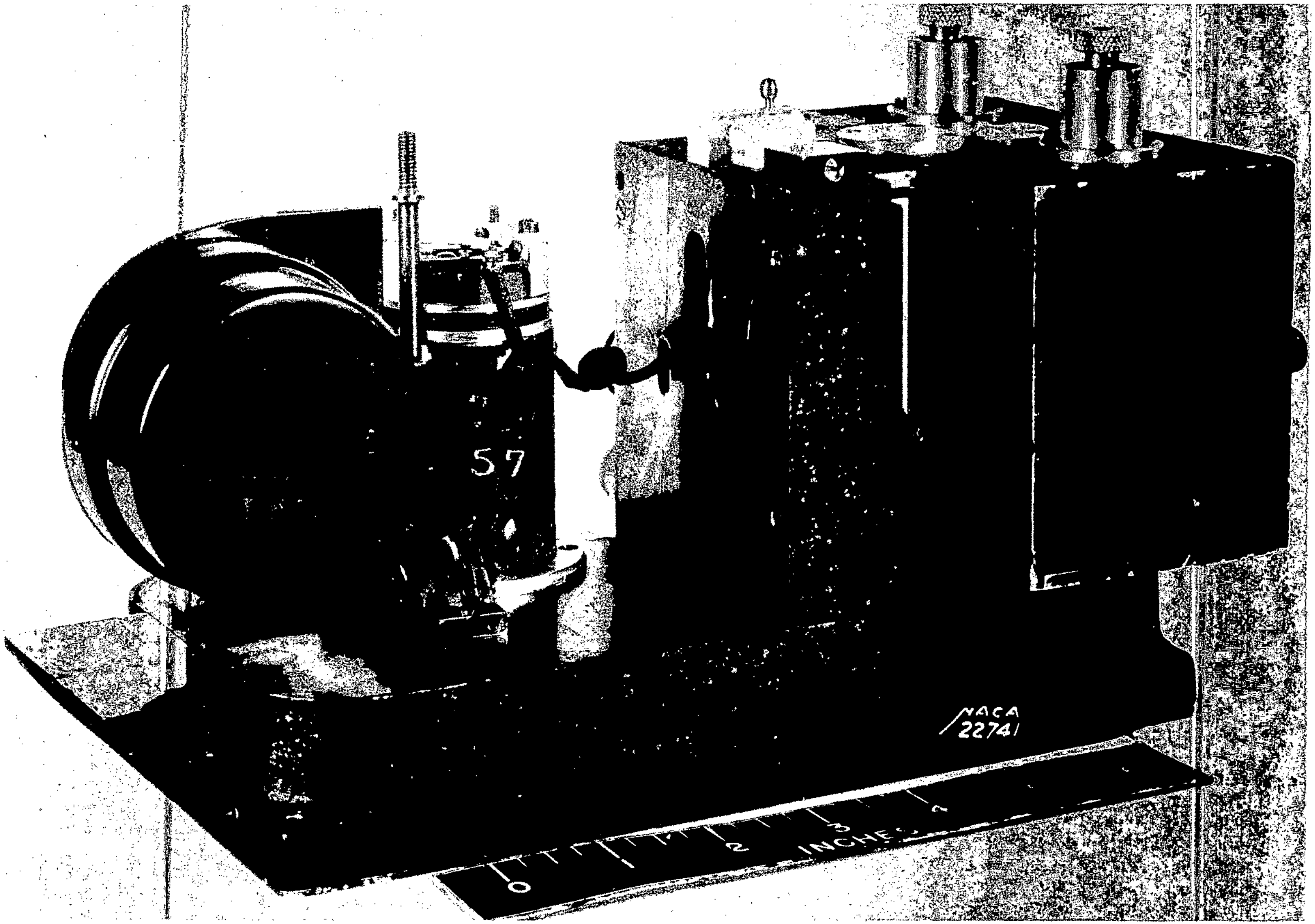

Figure 10.- NACA photographic recording galvanometer, cover removed.

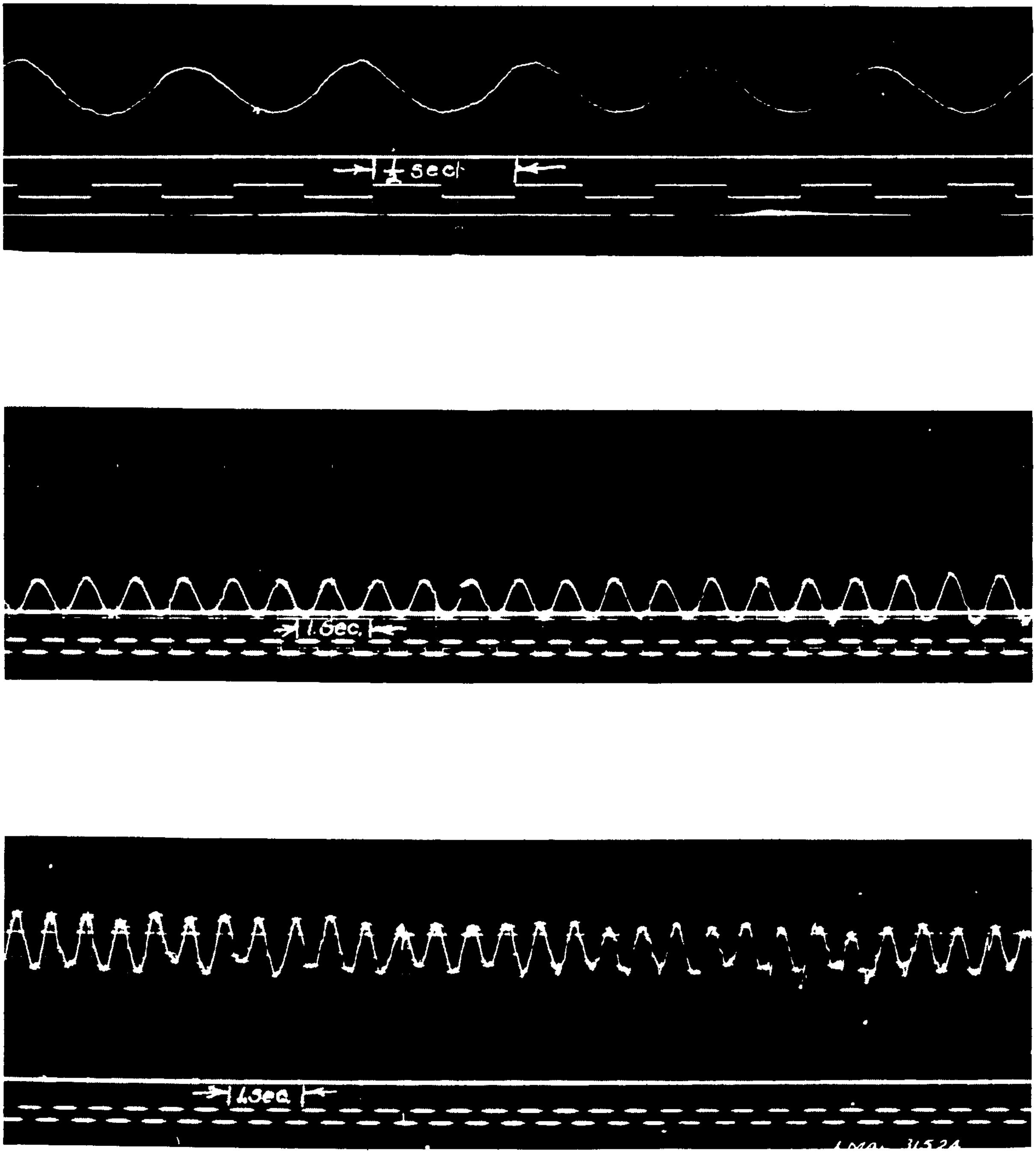

Figure 11.- Typical radio ground-speed records.

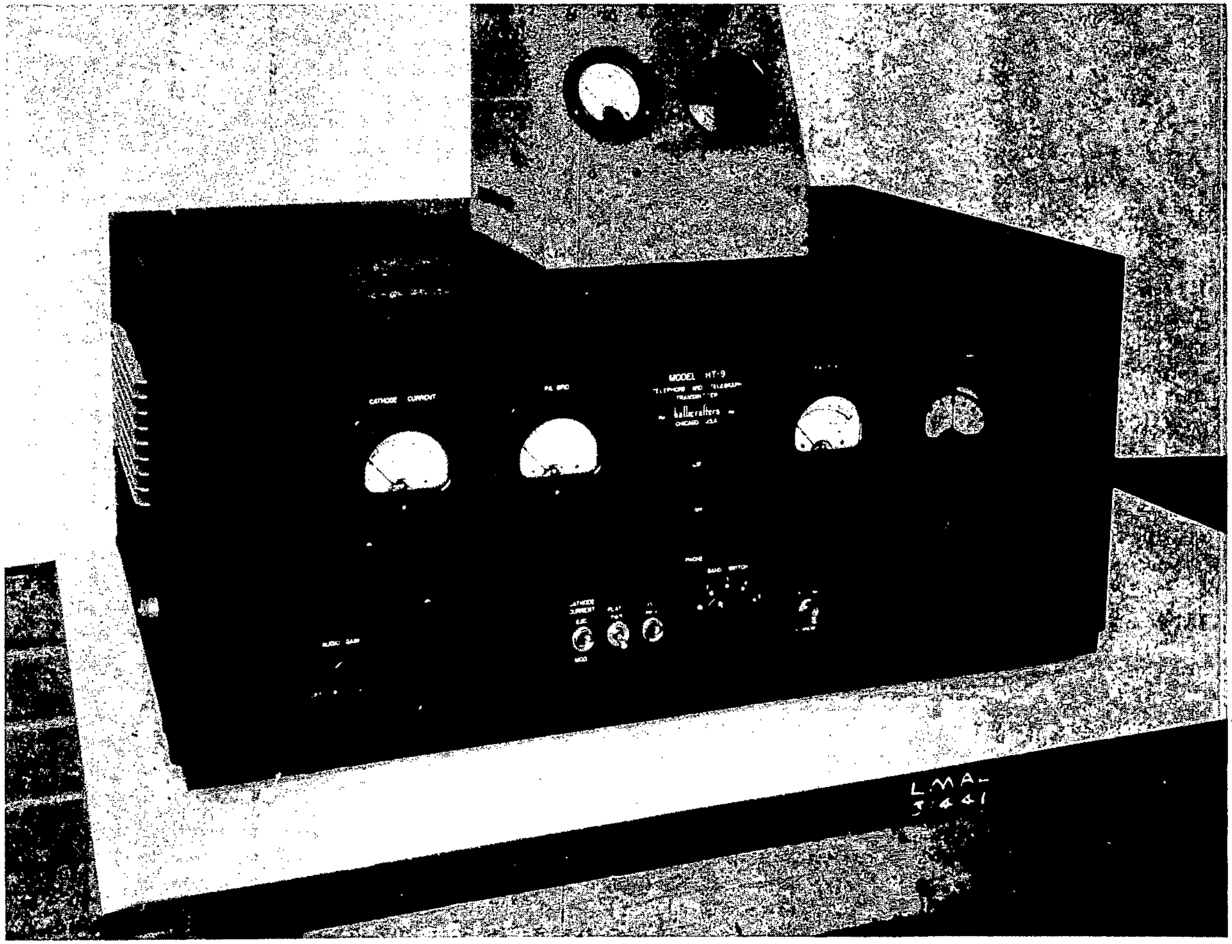

Figure 12.- Stationary ground transmitter.

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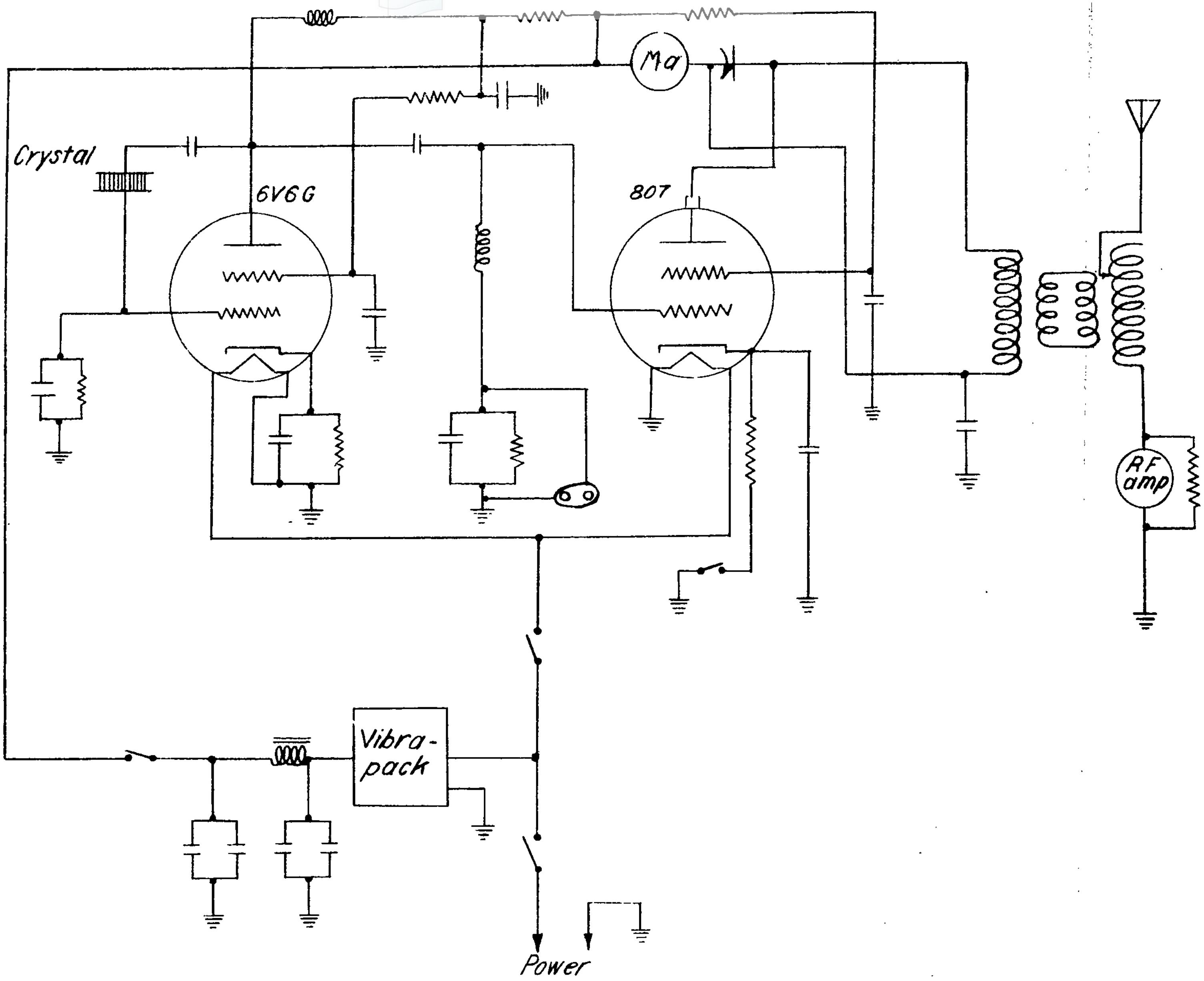

Figure 13.— Circuit diagram of airplane transmitter.

Fig. 13

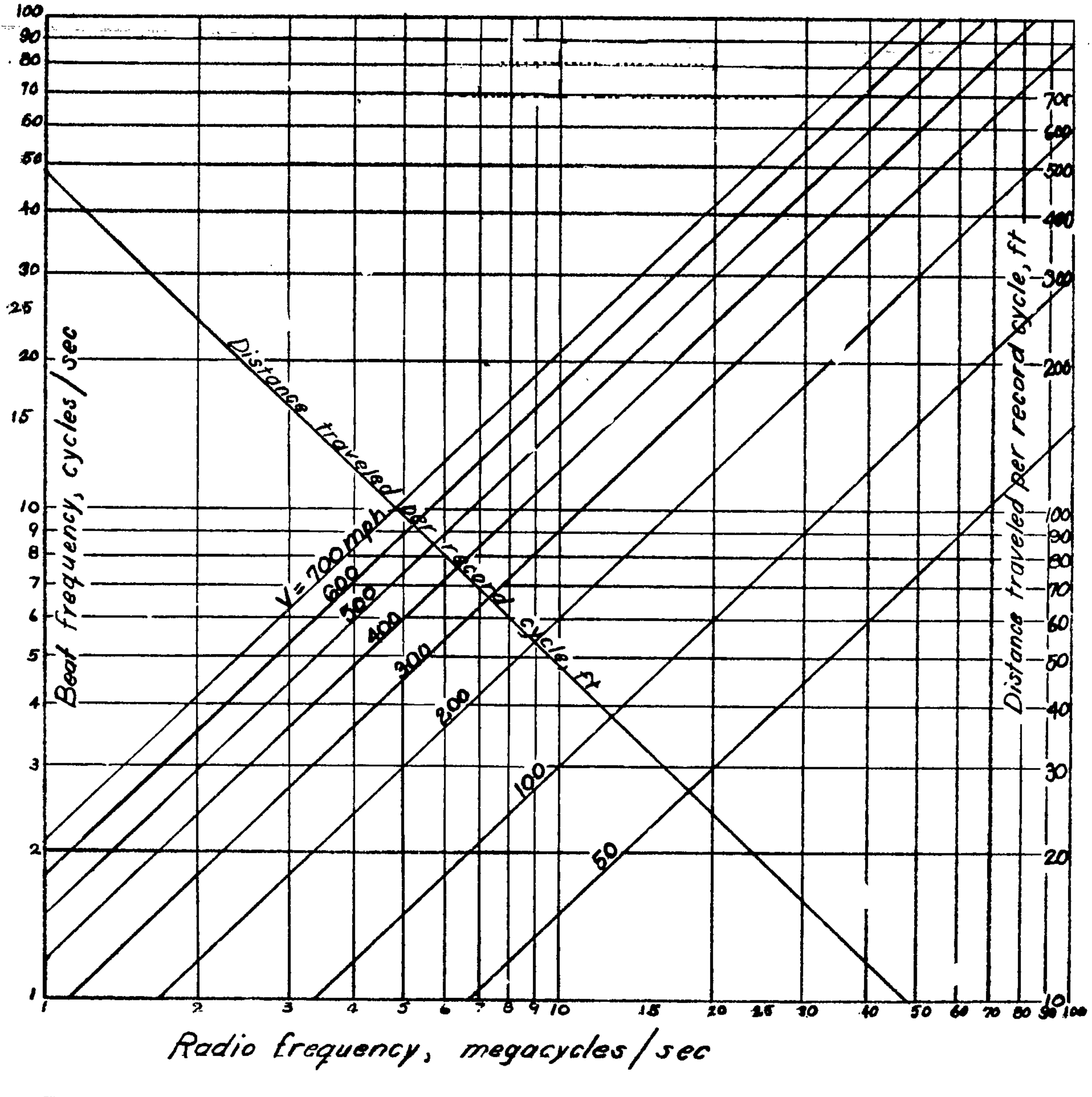

Figure 14.—Distance per cycle and beat frequency for different radio-frequency signals

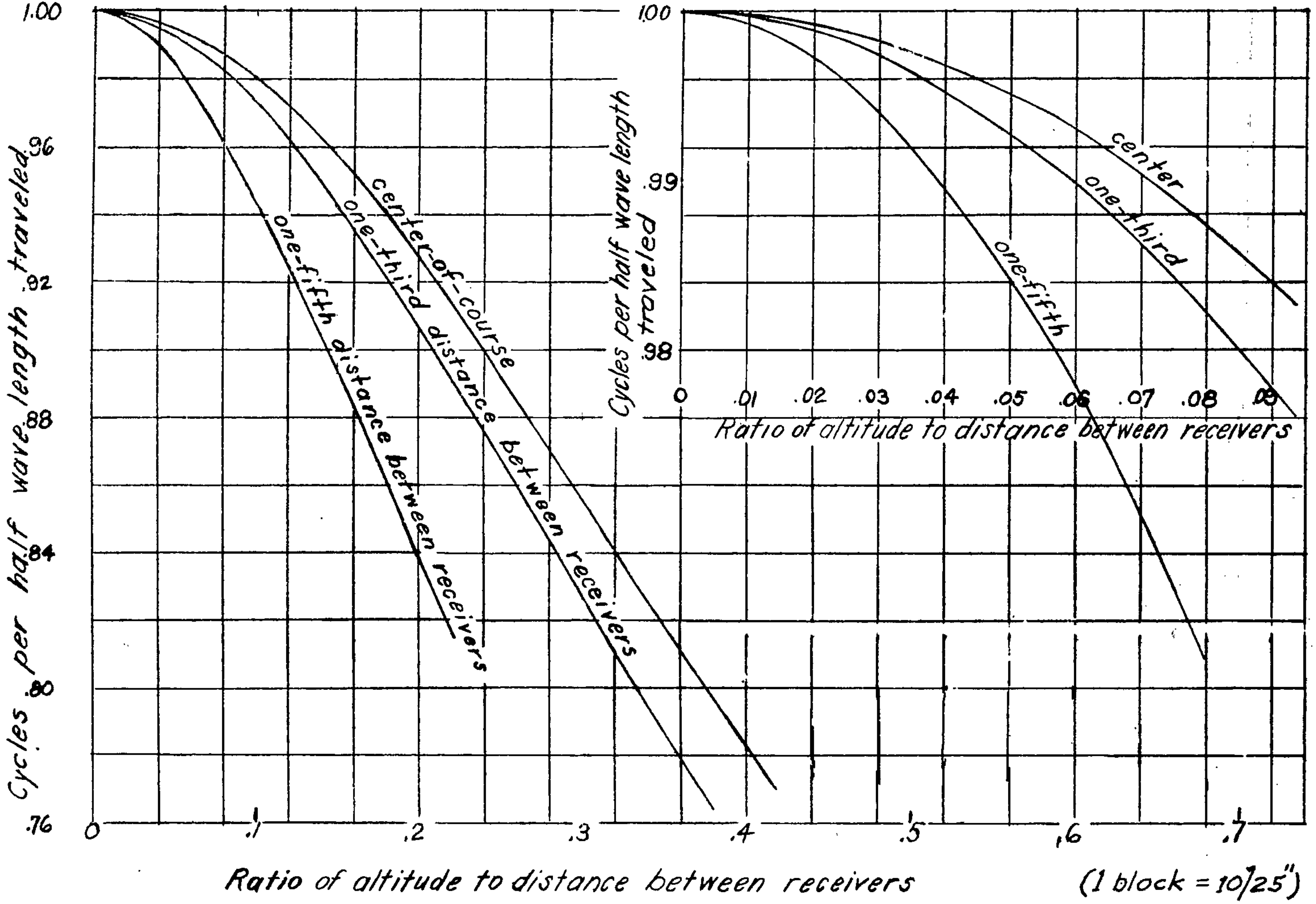

Figure 15.—Effect of altitude for three positions on course.

Fig. 16

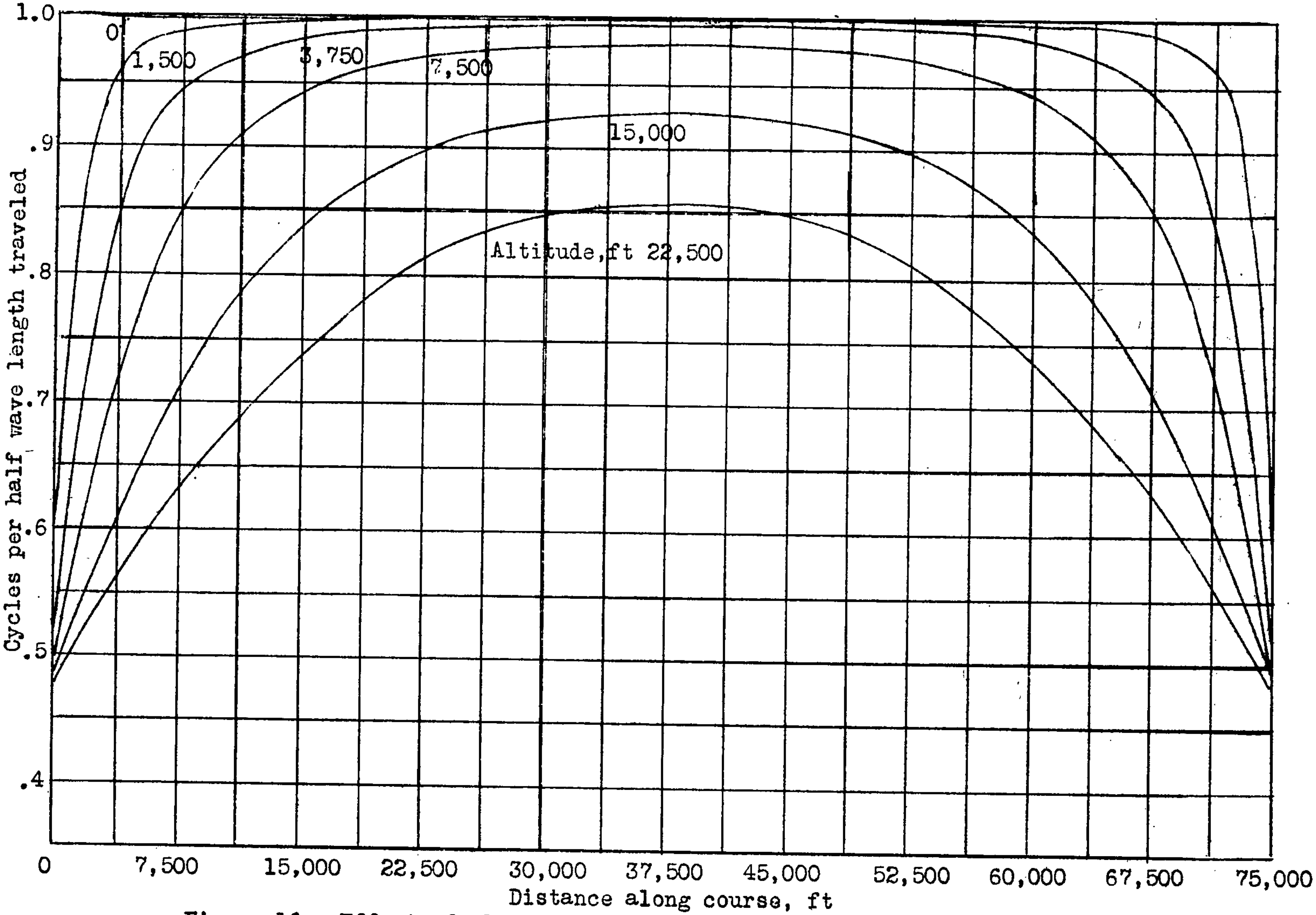

Figure 16.- Effect of altitude and position on recorded cycles.