A Terrain Clearance Indicator *

By LLOYD ESPENSCHIED and R. C. NEWHOUSE

There is described a radio altimeter that gives continuously on the plane a measurement of the separation between the plane and the earth's surface or projections therefrom. There is projected from the plane and reflected from the earth back to it a very short radio wave, the frequency of which is continuously swung back and forth. The returned wave is thereby made to differ from the outgoing wave in frequency by an amount that is proportional to the echo path; and the difference or "beat" frequency is indicated on a frequency meter calibrated in feet of separation. The paper outlines some of the early efforts in this field, some of the technical problems involved, the theory of the system and the practical experimental results that have been obtained.

Introduction

THE problem of an altimeter for aviation has engaged the attention of many inventors and experimenters for twenty years or more. As a result, about every conceivable fundamental method of attacking the problem, by the utilization of acoustic or electric phenomena, is disclosed in the art, including the many U. S. patents on the subject.

The familiar aneroid altimeter has reached a high degree of perfection and enables the pilot to maintain level flight at any desired altitude but it gives no clue as to the variation of the elevation of the terrain beneath. The pilot has to know his position at all times and perform a mental calculation, in order to know his height above the ground at any given moment. A number of airplanes have drifted off their normal courses and have crashed on higher ground.

An altimeter based upon the use of a sound echo is subject to two fundamental limitations. The first of these limitations is the extremely high noise level produced by the airplane's motors and propellers, which tends to submerge the relatively weak echo at heights of more than a few hundred feet. The second is that the speed of sound is not enough greater than the speed of airplanes. At a height of one thousand feet approximately two seconds are required for a sound to travel to the ground and return. In this time interval a modern airplane would travel six hundred feet and the clearance may have changed materially.

* Read before the Institute of Aeronautical Sciences at the Chicago meeting, November 19, 1938, and to be printed in the Journal of the Institute.

There is in radio the corresponding phenomenon of an echo, an electric-wave reflection. The velocity of a radio signal is so great that an echo from the earth's surface is almost instantaneous; in fact, the time interval is so small as to give rise to a problem in measuring it. For instance, for heights less than a thousand feet the time to be measured is less than two millionths of one second.

The method used in the present instrument is extremely simple in theory. A radio transmitter is provided on the airplane which sends toward the earth a signal, the *frequency* of which changes at a definite rate with respect to time. The signal is reflected by the earth and returns as an echo after a time delay equal to twice the height, divided by the velocity of propagation. During this interval the frequency of the transmitter has changed and now differs from that of the echo by an amount equal to the product of the rate of change of frequency and the time of transit. The reflected wave is combined in the plane receiver with some of the outgoing wave energy and the difference or "beat" frequency is measured by a frequency meter. Since the reading of the meter is that of the "beat" frequency, it is proportional to the time delay of the echo and, hence, to height and thus can be calibrated directly in feet.

Early Efforts

The evolution of this method is interesting because it illustrates how one art is built upon another, and also the familiar story of separate inventors arriving at the same answer almost simultaneously, actually somewhat in advance of the existence of instrumentalities having the characteristics required to make the invention practically serviceable.

Many systems employing electromagnetic waves for the purpose of indicating altitudes of an aircraft have been proposed.[1] Among early workers in this field who independently of each other were concerned with methods involving frequency modulated waves were J. O. Bentley [2] of the General Electric Company; Professor W. L. Everitt [3] of Ohio State University and certain students in his department of Electrical Engineering including the junior author [4] and M. W. Hively; and the senior author.

Under the direction of Professor Everitt, some experimental work on the frequency modulation method, using wire lines, was undertaken in the school year 1928–29. On the basis of this work a grant was made by the Guggenheim Fund for the promotion of aeronautics and an investigation was continued with experimental tests, during the following school year under the auspices of the Ohio State Engineering Experiment Station. The experiments were reported upon in the bulletins of the Station, and in a graduate thesis [5] of the junior author and J. D. Corley.

As early as 1920, the senior author proposed the use of electric wave reflection in railway safety systems [6] and entertained the idea of frequency-modulated transmission with beat-tone detection for measuring distance along a track. Radio wave reflection for aircraft altitude determination was considered at times from 1926 to 1930 when a patent application was filed [7] for an arrangement similar to that which has been worked out, including the use of a frequency meter to give continuously a visual indication of the altitude.

At that time, however, a really practical terrain clearance indicator could not be built due in large part to the lack of suitable radio instrumentalities. Vacuum tubes capable of operating on frequencies approximately fifty times higher than those generally available were indicated as necessary before a satisfactory system could be built.

A long-range program, however, of vacuum tube development for high frequencies was under way in Bell Telephone Laboratories. This resulted in the production of suitable tubes, and they were described by A. L. Samuel [8] to the Institute of Radio Engineers in October, 1937. One of these was capable of providing a stable output of between five and ten watts at a frequency of approximately 500 megacycles, so it became feasible to undertake the development of a practical terrain clearance meter.

The Japanese have been experimenting recently with apparatus operating upon the same basic theory and a paper [9] was published in Japanese in 1936. A later paper [10] was published in English in 1938 by the same author, which describes the apparatus and the results of tests made on the ground over short distances with the equipment at rest.

Technical Problems

At the time this development was undertaken a number of questions presented themselves as to what the earth's surface would do to the incident wave in reflecting it. It seemed possible that the signal might be so scattered and broken in reflection by small irregularities that the echo would be more like static than a useful signal.

Even if the reflected signal proved satisfactory over the smoother surfaces, it was hard to predict what would happen when flying over timber land or over very irregular mountainous terrain. There was also the question of what would happen when the surface happened to be that of a city where an airplane flying at 250 to 300 feet per second passes over several buildings and streets with abrupt altitude changes of possibly hundreds of feet several times in the course of one second.

Even with the most directive systems that can be devised, the beam radiated from the airplane is so spread that echoes can be expected to arrive simultaneously from several surfaces, for instance from both the leaves on the trees and the ground between the trees, or from the top of a building and from the adjacent street.

Several problems were anticipated in the apparatus itself. The theory is based upon a frequency-modulated signal free from any amplitude modulation, and it was questioned whether a transmitter could be built to operate on ultra-high frequencies which would be sufficiently free from amplitude modulation, when subjected to the vibration of the airplane, to be satisfactory. Since the receiver utilizes both the direct and reflected signals in making the altitude measurement, it is necessary that some signal be picked up directly from the transmitting antenna but not enough to overload the receiver and thus prevent reception of the echo. It was expected that difficulty would be encountered in sufficiently reducing the direct signal.

After considering all these problems, it was decided that the cheapest and easiest way of determining the answers was to build the apparatus and try it out to see if correct operation could be obtained, first, under the more or less ideal conditions of flying over smooth water and, then, over less favorable surfaces.

Most of the measuring equipment available for radio frequency test work is useless at ultra-high frequencies. Hence, it was necessary to get the system functioning as a whole before any means were available for determining the best adjustment of the radio-frequency parts of the system. Because of the difficulty of providing, while on the ground, an adequate reflector at distances of from a few feet to thousands of feet from the apparatus, it was necessary to install the equipment in an airplane very early in the development and make most of the tests during flights. Nearly a hundred airplane flights were made in one of the Bell Telephone Laboratories' airplanes during the development period of seven months which preceded the public demonstrations made in the United Air Lines Flight Research Airplane.

Operation and Theory

The fundamental parts of the altimeter in relation to their application are shown in Fig. 1. An ultra-high frequency oscillator is provided, whose frequency is varied up and down by a modulator which consists of a small rotating variable condenser driven by a motor. The oscillator is connected through a coaxial transmission line to a transmitting antenna which is located on one of the lower surfaces of the airplane. The signal is radiated downward by this antenna. A radio receiver is connected through a similar coaxial line to a second antenna similarly located but arranged in such a way that a minimum of direct signal is received from the transmitting antenna and as much echo as possible from the ground. The direct and reflected signals are

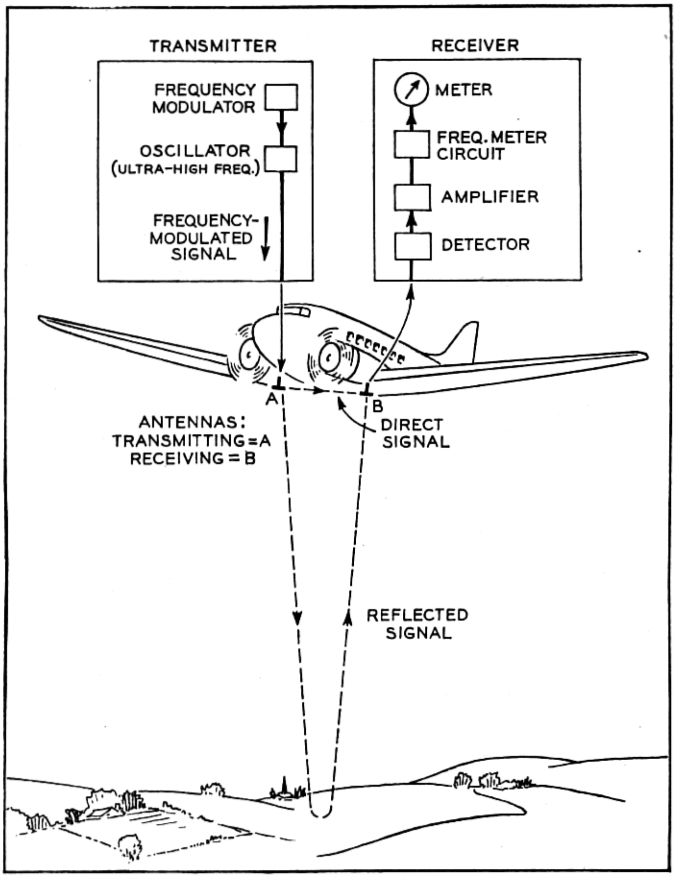

Fig. 1—Overall system.

applied to a detector circuit in the receiver. The output of this detector is a signal of a frequency equal to the instantaneous difference existing between the direct and the reflected signals and is proportional to the height of the plane above the terrain. This signal is amplified by the receiver and applied to a frequency meter or counter circuit which is so designed that a current proportional to the frequency and, hence, to the height flows through a meter calibrated in feet and located on the airplane's instrument panel. A number of types of indicating frequency meter circuits [11] of the condenser charge and discharge variety have been described in the technical literature.

The operation of the system can be understood more easily by reference to Fig. 2. The variation of the transmitter frequency with

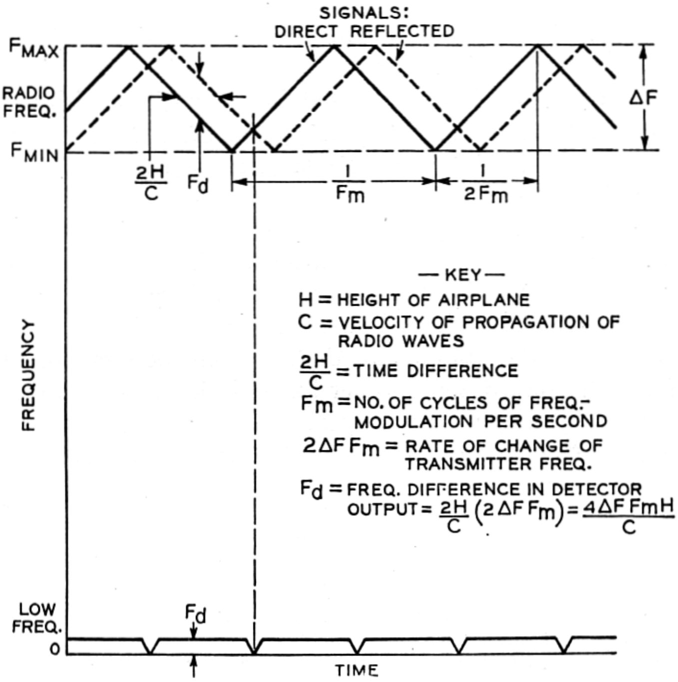

Fig. 2—Operating theory.

time is indicated by the solid sawtooth line.* The value of the ordinate of this curve at any point is the transmitter frequency for the corresponding time. The frequency is varied from $F_{MIN.}$ up to $F_{MAX.}$ and back F_m times per second, so the rate of change of frequency is $2\Delta F\ F_m$ when ΔF is substituted for $F_{MAX.} - F_{MIN.}$ The linear frequency variation shown, while ideal, is not essential for the successful functioning of the apparatus. The dashed sawtooth line represents the variation with time of the frequency of the echo signal from the earth's surface. This curve is displaced to the right by a time equal to twice the height divided by the velocity of propagation, or, in other words, the time it took the radio signal to go down to the earth and

* A simple harmonic wave that changes in frequency from instant to instant is no longer a single frequency but a series of discrete frequency components. In the present instance, the number of cycles of frequency modulation per second is small compared to the transmitter frequency swing, so the spectrum occupied by the signal is substantially that of the swing itself.

return. This results in a frequency difference between the direct and reflected signals which is equal to the product of the time delay $2H/C$ and the rate of change of frequency, and is given by the equation,

$$F_d = 4\Delta F\ F_m H/C \text{ cycles per second.}$$

The difference is plotted again at the bottom of the diagram and appears as a series of trapezoids of height F_d. The time delay, $2H/C$, has been greatly exaggerated in comparison with $1/F_m$, the time interval corresponding to one cycle of frequency modulation, in order to make the difference, F_d, large enough to show on the diagram. F_d is actually only a few cycles in hundreds of millions. It will be noted that F_d drops momentarily to zero twice for each complete sawtooth variation of the transmitter frequency. This is due to the necessity of varying the transmitter frequency first up and then down, instead of forever in one direction. Hence the theory must be considered from the standpoint that one altitude measurement is made for each upward and another for each downward sweep, ΔF, of transmitter frequency so that a total of $2F_m$ measurements are made per second. The number of cycles of frequency F_d, occurring during one frequency sweep, is

$$F_s = F_d \times \frac{1}{2F_m} = 2\Delta F\ H/C,$$

since $\frac{1}{2F_m}$ is the time of one sweep, ΔF. F_s is directly proportional to both the height and to the amount of transmitter frequency change, ΔF.

The fact that $2F_m$ separate measurements are made per second is important only when considering small altitudes. The height which gives a value of unity for F_s corresponding to a frequency meter signal of $2F_m$ cycles per second is the minimum height which can be indicated since lower altitudes give the same reading. Lower altitudes cause only a fraction of a cycle of frequency, F_d, to be generated per sweep, but since this fraction is repeated $2F_m$ times per second, it constitutes a signal of the same frequency $2F_m$ and is so counted by the frequency meter. In order to make this minimum altitude small, it is necessary that ΔF be large, since they are inversely proportional to each other. A frequency sweep of approximately 25 megacycles is required to provide measurements down to the present minimum of about twenty feet. If a high antenna efficiency is to be obtained over a band 25 megacycles wide, it is necessary that the percentage variation from the average frequency during the modulation cycle be small. This

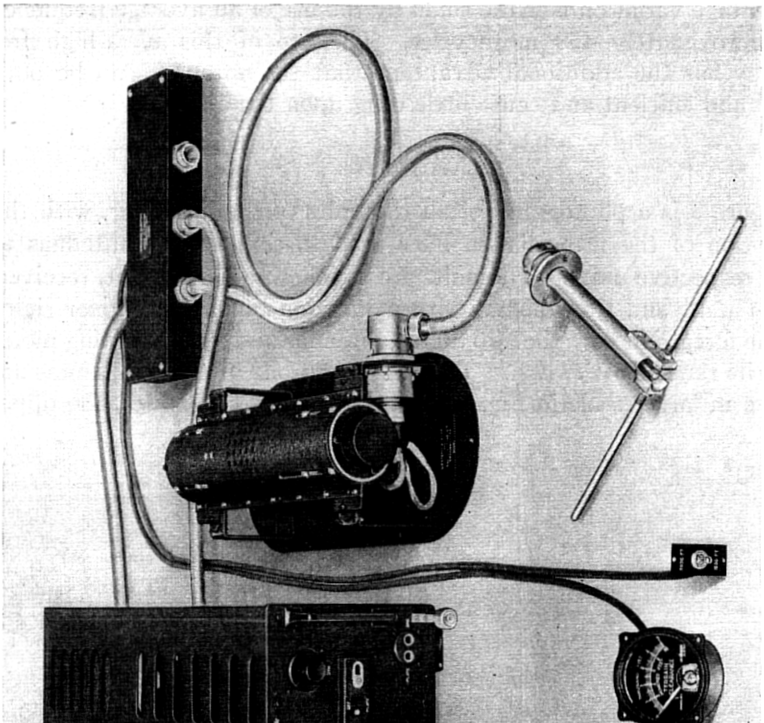

Fig. 3—Terrain clearance indicator units.

percentage variation is made small by the use of an average frequency of approximately 450 megacycles. The use of this ultra-high frequency has the additional advantage that the antennas can be both small and efficient and cause little drag upon the airplane.

Apparatus

Figure 3 is a photograph of all the units of the altimeter, with the exception of the transmission lines used to connect the antennas to their respective units. The units are as follows: left to right, receiver, power unit, and transmitter, with a junction box in the upper right. In the foreground are the two dipole antennas and the indicating meter with its range-shift switch. The meter and one of these antennas are shown in larger scale in Fig. 4. The meter has two scales, the upper

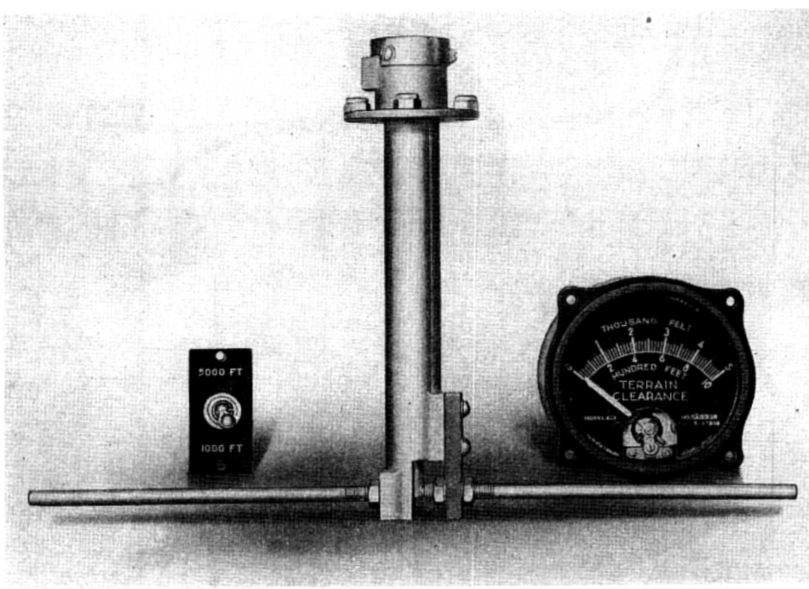

Fig. 4—Antenna, meter, and range switch.

extending from 0 to 5000 feet and the lower 0 to 1000 feet. The position of the range switch determines the scale to be used in reading the meter.

Figure 5 shows an assembly of the various units located approximately as they would be installed in an air transport. The transmitter, power unit, receiver and a junction box are installed in the baggage compartment just aft of the cockpit with cable connections

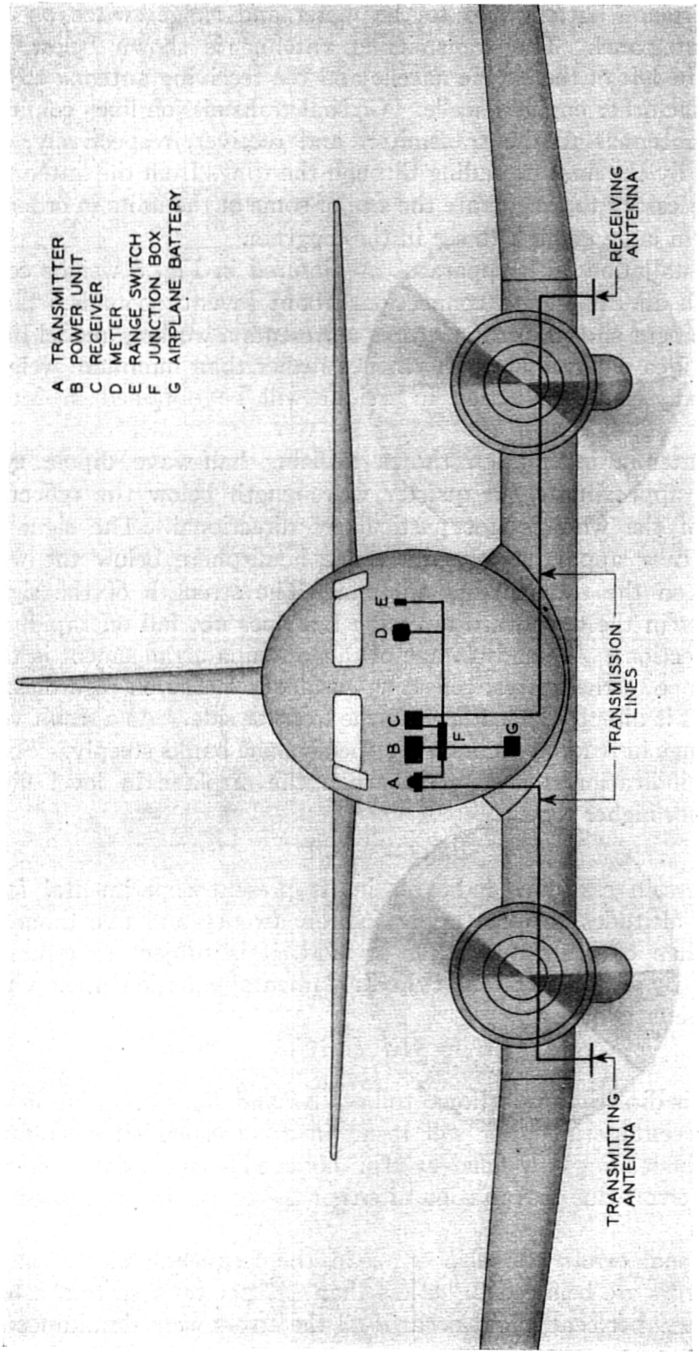

Fig. 5—Airplane installation.

to the airplane battery and to the meter and range switch on the instrument panel. The transmitting antenna is shown below the wing to the left of the engine nacelle and the receiving antenna to the right of the other engine nacelle. Coaxial transmission lines connecting the antennas to the transmitter and receiver, respectively, are indicated by the lines extending through the wings from the antennas. It was necessary to exaggerate the size of some of the units in order to make them large enough to see in the diagram.

The installation with apparatus as pictured in Fig. 3 weighs complete with all cables and connections about seventy pounds. Since the equipment shown in the pictures represents a working model built with the idea of attaining performance rather than minimum weight, undoubtedly some reduction in weight will be obtained in future models.

The antenna installation shown utilizing half-wave dipole type antennas approximately a quarter wave-length below the reflecting surface of the wing is not particularly directional. The signal is radiated over approximately the whole hemisphere below the wing centered on the transmitting antenna. The strength of the signal is greatest in the downward direction but does not fall off rapidly in other directions. The advantage of this antenna arrangement is that the distance to the nearest reflecting surface is measured regardless of whether it is directly beneath, or to the front or side. As a result very little change in reading occurs when the airplane banks steeply. Some advance indication also is given when the airplane in level flight approaches higher terrain.

Performance

The terrain clearance indicator in its present experimental form indicates altitudes between approximately twenty and five thousand feet. When over smooth water or land, it is subject to errors as indicated by a consideration of the fundamental equation upon which the altimeter is based,

$$F_d = 4\Delta F\, F_m\, H/C.$$

Since F_d is directly proportional to both ΔF and F_m, any variation of a given percentage in either will result in a corresponding percentage error in the reading of the meter. It is believed from the data available that the errors due to variation of either ΔF or F_m do not exceed ± 1 per cent.

Additional errors can also occur in the frequency meter circuit. These errors are believed to be less than ± 7 per cent, so that a total error of ± 9 per cent might occur if all the errors were simultaneously in the same direction. Fortunately, all these are of a percentage nature, so that the error in feet becomes smaller as the ground is approached. An absolute error in the indication is still possible because of the limitations of the milliammeter used on the instrument panel. The Weston aircraft meter used is guaranteed to be correct to within one per cent of its full scale reading at any point on its scale, which permits maximum errors of ten feet on the 1000-foot scale and fifty feet on the 5000-foot scale.

When flying over rough water, wooded terrain or cities, reflected signal is received from surfaces at different distances simultaneously, resulting in addition and subtraction interference effects, thus sometimes momentarily reducing the echo signal below the minimum required for accurate indication. In such a case, the meter hand may swing down momentarily as much as 10 per cent. For the present limited transmitter power and receiver sensitivity, at altitudes above 2500 feet, these momentary signal reduction effects become progressively more serious when flying over irregular surfaces so that for a substantial part of the total time the echo signal may be below the minimum required for correct meter reading. This is indicated by a reading fluctuating between 3000 and 5000 feet when flying at 5000 feet over a surface dotted by buildings, timber, etc. The meter swings up to the correct reading every time the airplane passes over a smooth field or body of water of any size. Up to 2500 feet the echo signal has proved to be sufficient for steady operation over all kinds of terrain.

Tests have been made over New York, Raritan, Newark and San Francisco Bays, Great Salt Lake, Lakes Erie and Michigan, the timbered mountains of Washington and Oregon, the deserts and mountains of the southwest and the cultivated areas of the midwest during the period of the recent demonstration flights made with the equipment installed in the United Air Lines Flight Research Airplane.

An indication of the character of the surface over which the airplane is flying is given by the variations in the meter reading. A city usually causes rapid fluctuations of the order of fifty feet, depending, of course, upon the height and the spacing of the buildings. Cultivated farmland causes fluctuations of lower frequency and amplitude. An isolated high object such as a skyscraper or a chimney is indicated only by a slight meter kick as the airplane passes over it, which may not be noticed by the observer. If the airplane passes over only a few feet above the object and the top is large enough to contribute momentarily most of the echo signal received by the airplane, the indication is unmistakable and the correct distance to the object is indicated by the meter. For instance, the gas storage tank near the Chicago airport is an excellent object upon which to demonstrate the altimeter performance. The instrument is useful as a position indicator when approaching an airport on a course which crosses an obstruction of appreciable height and size since the moment of passage over the obstruction is clearly indicated. In fact, use as a position indicator may be one of the altimeter's most valuable applications.

A study of the circumstances in connection with a number of crashes in the west during recent years has revealed that in most of the cases the airplanes crashed after having been within a few feet of the ground without the pilot knowing it for several minutes before they struck. In such a situation the terrain clearance indicator should be capable of warning the pilot in ample time to avert a crash.

The writers wish to express their appreciation of the contributions of a number of other members of the technical staff of the Bell Telephone Laboratories to the success of this project.

References

1. H. Loewy, *U. S. Patent* 1,492,300.
   H. Loewy, *U. S. Patent* 1,585,591.
   C. F. Jenkins, *U. S. Patent* 1,756,462.
   E. F. W. Alexanderson, *U. S. Patent* 1,969,537.
   F. H. Drake, *U. S. Patent* 1,987,587.
2. *U. S. Patent* 2,011,392 issued August, 1935 to J. O. Bentley.
3. Page 29 of "Solving the Problem of Fog Flying," a publication of the *Daniel Guggenheim Fund for the Promotion of Aeronautics*, 1929.
4. "Altitude Measurements by Reflected Electro-Magnetic Waves" by Murray Hively and R. C. Newhouse, Ohio State University Library, 1929.
5. "An Electro-Magnetic Altimeter" by R. C. Newhouse and J. D. Corley, Ohio State University Library, 1930.
6. *U. S. Patent* 1,517,549 issued December, 1924 to Lloyd Espenschied.
7. *U. S. Patents* 2,045,071 and 2,045,072 issued June, 1936 to Lloyd Espenschied.
8. "A Negative Grid Triode Oscillator and Amplifier for Ultra-High Frequencies," A. L. Samuel, *Proceedings of Institute of Radio Engineers*, *25*, Oct. 1937 (1243).
9. "A Research of Direct Reading Altimeter for Aeronautical Use by Radio Reflection Method," Sadahiro Matsuo, *Journal I. E. E.* Japan, No. 571, February, 1936.
10. "A Direct-Reading Radio-Wave-Reflection Type Absolute Altimeter for Aeronautics," Sadahiro Matsuo, *Proceedings of Institute of Radio Engineers*, Vol. 26, 1938 (848).
11. *Trans. A. I. E. E.* 49, 1930 (1331).
    Proc. I. R. E. 19, 1931 (659).
    Review of Scientific Instruments 6, 2, January, 1935.
    Journal of Scientific Instruments 14, 1937 (136).