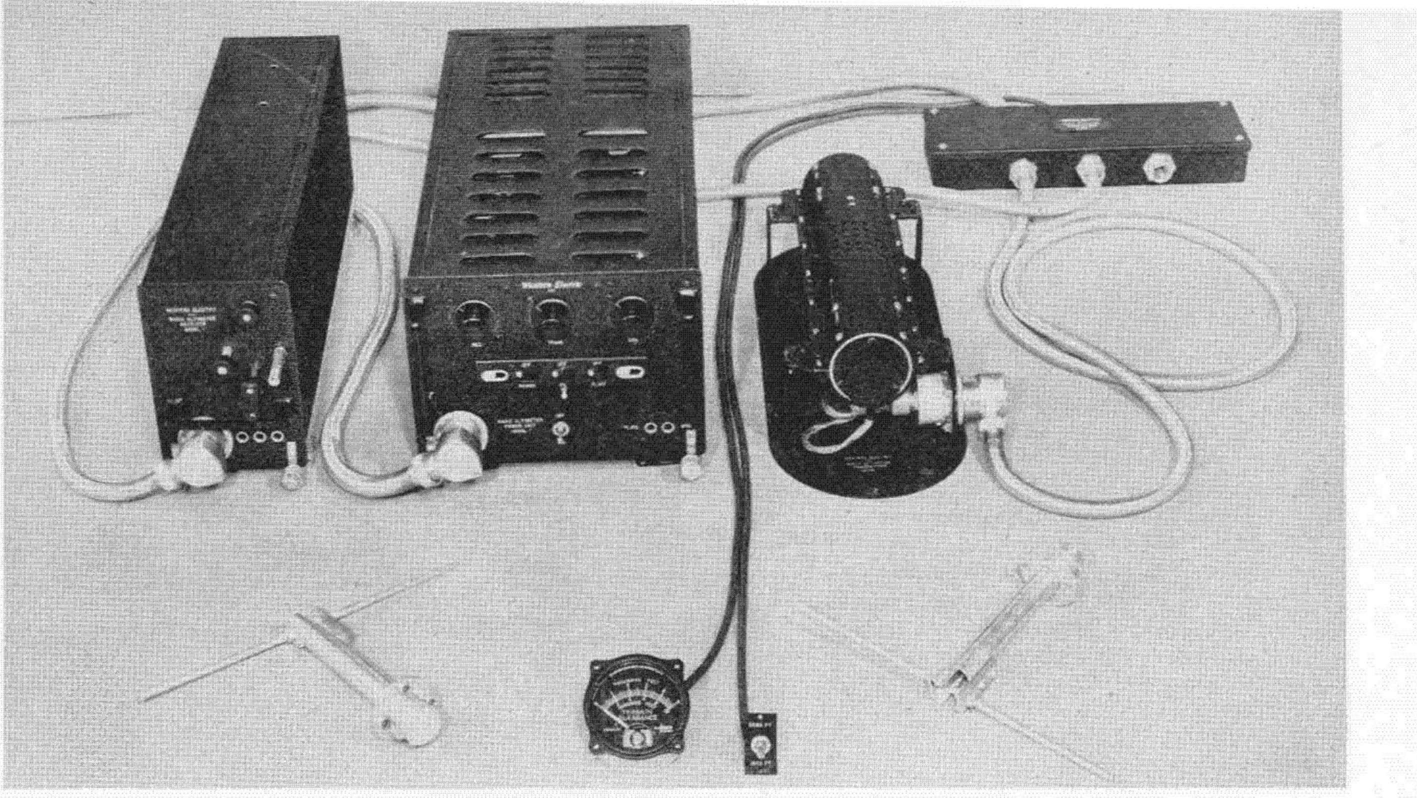

Fig. 1—Left to right: receiver, power unit, transmitter.

RADAR'S PEACEFUL COUSIN

BY WARREN AMSTER

BEHIND the word "Radar" is the story of a revolution in the waging of aerial war. The planning, the tactics, and the participating aircraft of a modern air offensive are designed to cope with radar-directed defenses. Heavy bombers have been driven up to 30,000 feet by the accuracy of radar-aimed anti-aircraft fire. They may be forced even higher. The elaborately planned and precisely executed diversionary raids that accompany a major bombing mission are for the purpose of confusing otherwise virtually impenetrable defenses. And the revolution has taken place suddenly. Changes and experimentation in both German and Allied air tactics reveal the lack of experience on both sides in the new type of warfare. Many lessons have been learned, and there are many more to come. Peace will permit the discharge from military service of devices that will have a tremendous effect on commercial aviation. For some day radar will resume its original role of speeding aerial cargoes and saving passenger lives.

Radar started out peacefully enough. Between 1928 and 1938 several laboratories investigated the phenomenon of radio-wave reflection. Most of these experiments were attempts to develop commercial equipment for airline use. And most of the attempts failed. The technical problems involved in developing the equipment proved too complex for most investigations with the limited resources usually allotted for such projects. Successful radar-type equipment is almost entirely a product of war-inspired research. A notable exception is the Western Electric terrain clearance indicator, developed by the Bell Telephone Laboratories around 1938.

As its name implies, the Western Electric instrument shows a pilot his distance from the ground. It fills a long-felt need in the aviation industry, which has never had an instrument for just this purpose. The airlines which had encouraged the development were contemplating general installation in their transports when the war interrupted their plans. Publication of information about the equipment ceased abruptly, and improvements since 1939 are military secrets. The 1939 product had only one serious fault. Its maximum reading was 5,000 feet, not enough for routine airline operations. Otherwise its performance was altogether satisfactory. Recent information indicates that models currently in use with the armed forces are greatly improved. Early postwar products will be even better, and they may well operate up to the range of a conventional altimeter.

BAROMETRIC ALTIMETER

The instrument that the terrain clearance indicator augments and may eventually replace is the barometric altimeter. Any such general replacement probably will be slow because the barometric-type instrument is simple, relatively cheap and, most important, light in weight. It can indicate any height to which it can be carried. At moderate altitudes a good altimeter with a careful setting gives a very accurate reading. But even with the best instrument, the barometric altimeter has several inherent faults.

Varying weather conditions cause fluctuation in the pressure of the atmosphere. Flying complicates this condition by moving the altimeter through different types of weather. Radio contact with the ground is necessary to make required corrections on the altimeter. Any mistake in setting shows up as a constant error in true height except at very high altitudes. This does not matter much if the altimeter shows that the plane is 25 feet higher than a true altitude of 10,000 feet. But in bad weather when a plane is flying close to the ground, and the altimeter shows that the plane is 25 feet higher than it really is, the error can be the difference between landing and crashing. Adding to this danger is the appreciable lag in reading of the conventional altimeter. After a normal

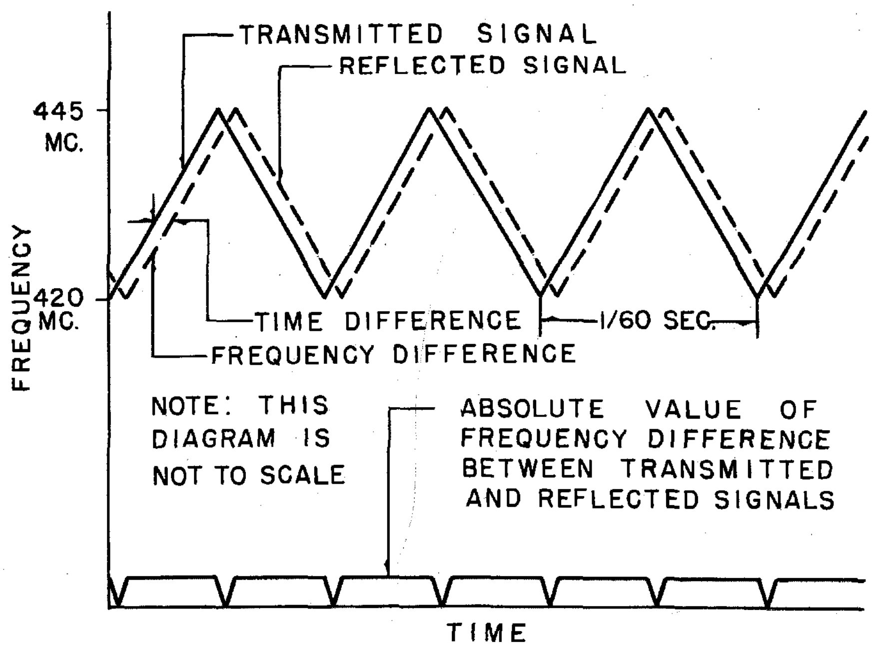

Fig. 2—Diagram showing frequency modulation wave form.

landing a barometric instrument will still indicate altitude and then gradually settle to a zero reading. Most of these undesirable operating characteristics can be improved by changes in instruments, improved ground-to-plane communication, and better route-marking systems. However, there is one difficulty with the barometric altimeter that cannot be overcome. Because it is dependent on the pressure of the atmosphere for its reading, the barometric altimeter indicates height above sea level, not height above ground. Should a pilot get lost in mountainous country, he can easily fly into a peak still thinking that he is 5,000 feet from the nearest ground. A barometric altimeter shows only whether a plane is high enough to clear the tallest obstruction in the vicinity. Maintaining such an altitude is sometimes difficult and uncomfortable except in special aircraft. In bad weather the problems of blind landing are also of great importance. All the bad characteristics of the barometric altimeter combine to make it almost useless for this purpose. In an effort to obtain an improved type altimeter, a great deal of work has been done to develop altimeters not based on the barometric principle.

REFLECTION PRINCIPLES

For many years ships have used the echo of sound to determine the depth of water below them. Sound travels slowly enough so that simple stop-watch timing gives the desired accuracy. The same principle might conceivably be used for aircraft. However, the high noise level of an airplane in flight is enough to discourage most investigators from trying to use sound reflection for altitude determination. Also, the speed of modern aircraft is near enough to that of sound in air to result in a serious lag in true reading. Experiments with sound as a reflection medium have been unsuccessful for just these reasons. A logical next step was the use of radio waves as a reflection medium. A great many complications immediately become apparent. Ordinary broadcast-band and short-wave radio signals cannot be used for the type of instrument required in aircraft. The waves are too long. A signal transmitted from a low-flying airplane would reflect from the ground before a full wave had been broadcast. Ultrashort wave signals are needed. Besides the advantage of the length of the wave, ultrashort wave signals have another property that makes them very desirable. The high frequency provides room for an ample spread in the frequency-modulated signal required in this type of instrument.

Frequency modulation makes possible the continuous-reading feature of the terrain clearance indicator. The type of modulation is slightly different from most applications of frequency modulation, but the basic principle remains the same. As with all frequency modulation, the strength of the broadcast signal remains constant and the frequency is varied. In this application the fact that the modulation is not affected by changes in signal strength assumes tremendous importance. The strength of the reflected signal depends not only on the height of the airplane but on the nature of the ground below. Because of the frequency modulation, no errors in reading result from the changes in signal strength. The receiver responds to changes in frequency only. However, the signal strength must be above a certain minimum value in order for the receiver to detect it. It is this minimum reflected-signal strength that limits the effective range of the terrain clearance indicator.

OPERATION

The Western Electric instrument is made in three basic units as shown in Fig. No. 1. Receiver, transmitter, and power unit can be located at any convenient place in the airplane, and the indicator is placed on the instrument panel. The transmitter and receiving antennae are alike. They are located about 12 feet apart on the underside of the wing and one-quarter wave length below the metallic wing skin. This location produces a desirable reflection of the transmitted signal in a downward direction. The transmitter operates on a frequency that varies from 420 to 445 megacycles. This variation is produced by rotating the tuning condenser with a small synchronous motor driven by a separate, 60-cycle oscillator. The frequency time variation has a saw-tooth pattern. With this type of modulation the frequency change is directly proportional to time. The time it takes for the signal to travel to the ground and be reflected back to the airplane is proportional to the height of the airplane. It is the frequency difference between the transmitted and reflected signals that is measured and changed into height readings. Fig. No. 2 shows graphically the wave pattern of transmitted and reflected signals. The receiving antenna receives a weak signal directly from the transmitter as well as the reflection from the ground. The direct signal is intentionally reduced in strength to near the magnitude of the reflected waves. The frequency difference between these two signals produces a beat frequency capable of very precise measurement. In this way, the very short time required for the signal to travel to the ground and return is evaluated indirectly by a measurement of an audio frequency.

The amplifier incorporated in the receiver has the special characteristic of increasing the amount of amplification with increased frequency. Since the beat-frequency increases with altitudes, and the signal strength decreases, a fairly uniform output from the amplifier is obtained over a wide altitude range. In this way, the beat-frequency signal receives the greatest possible amplification without overloading the equipment at low altitudes. To prevent fictitiously high readings due to harmonics of the fundamental beat frequency, controlled negative feedback is introduced around the amplifier. At this stage the signal is strong enough to be fed into the indicator.

The dial that appears on the instrument panel of the airplane is an electronic frequency counter, calibrated directly in feet of altitude. Its function is to indicate the frequency of the interference between the signals picked up by the receiving antenna, and to translate this beat-frequency into feet of altitude. A semi-logarithmic scale provides increased accuracy in reading at low altitudes. In order to obtain even greater accuracy, two ranges are used. A switch provides selection of a zero to 1000-foot or a zero to 5000-foot range.

When ready for installation, the complete equipment weighs about 65 pounds. In operation it draws 26 amperes at 12 volts from the aircraft electrical system. Standard radio-wiring connections are used between units with the exception of the antenna connections. Here, concentric transmission lines are used and it is desirable to keep them as short as possible. An installation suggested by the manufacturer places the transmitter, receiver, and power supply in the baggage compartment behind the pilot, and the indicator and range switch on the instrument panel.

PERFORMANCE

Testing of the equipment was carried out in a standard, airline transport over a wide variety of ground surfaces. The transmission pattern of the effective signal was found to be a hemisphere below the airplane. This transmission pattern results in a true, ground-clearance reading even when the airplane is in a steep bank or flying level over irregular ground. Fig. No. 3 shows this characteristic graphically. The other performance characteristics of the instrument also are desirable. Any errors in reading are in per cent of true reading, if the equipment is properly installed and adjusted. With all separate errors in the same direction, a maximum of nine per cent is possible. There is no lag in reading at any time. The operation of the equipment causes no interference with ground-to-plane radio, and under ordinary circumstances terrain clearance indicators of adjacent aircraft will not interfere with each other. The maximum possible reading is determined by the type of terrain under the airplane.

Over most smooth ground the accuracy is excellent up to 5000 feet. Water is the best reflecting medium, and sandy ground without vegetation is next. Rough ground, buildings, forests, and "radio dead" ground cause the maximum effective reading to decrease. The result is either fluctuating readings, or short periods when there is no reading at all. However, up to 2500 feet the accuracy is excellent over any type of terrain. Fortunately, any error due to bad ground characteristics results in a fluctuating or fictitiously low reading. No combination of circumstances can cause a steady reading that is above the true ground clearance. The radio equipment is designed to handle reflected signals up to 16,000 feet. Above 5000 feet the needle goes off the scale at the high end, and it remains off the scale until the altitude is near 15,000 feet. Here, though it may drop back on scale momentarily, it cannot give a steady, fictitious reading.

At low altitudes the terrain clearance indicator has some interesting characteristics. In an airplane flying over a city at a moderate altitude, the needle wavers somewhat, indicating the height difference between street level and the roofs of buildings. Over flat country the needle jumps whenever the airplane passes over a building or tree. A ship causes the same effect when the airplane is flying over water. This phenomenon results from the slightly directional nature of the transmitted signal. In landing, the contour-following characteristics become very pronounced, and the needle indicates the ground contour quite precisely. Any airplane which is dangerously close below another is clearly indicated on the dial of the upper airplane. Cloud formations do not cause a false reading.

This simplified description of the Western Electric terrain clearance indicator and its operation does not attempt to suggest the number and the difficulty of the problems encountered in its development. However, the difficulty of the over-all problem is shown by the fact that the Western Electric equipment is the first commercial product of its type to be announced. Some of the individual research problems encountered were particularly

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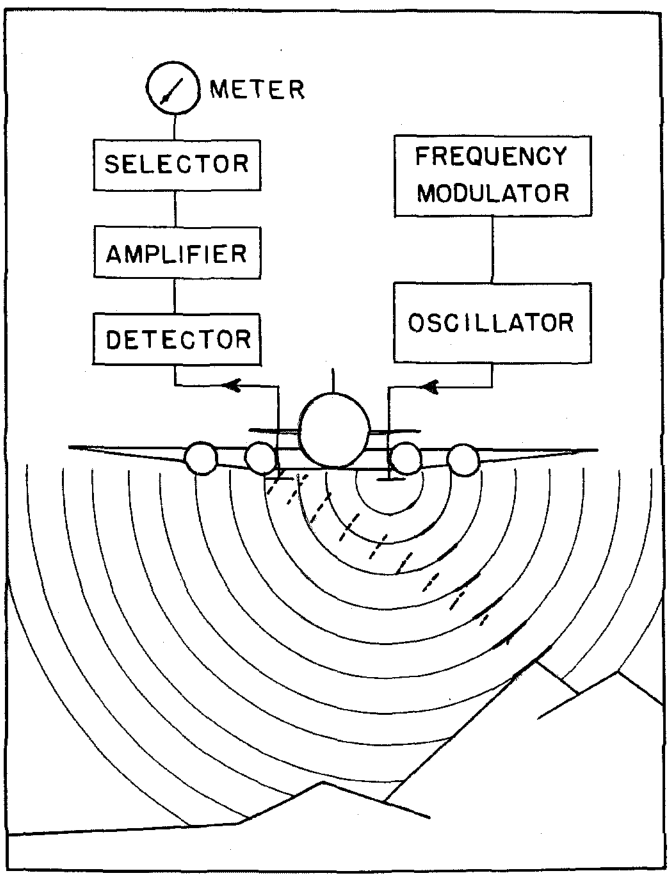

Fig. 3—Diagram showing circuit and transmission pattern.

fuel oil spray which is burned in the inlet manifold. Both types work satisfactorily, but each also has its disadvantages. In the electrical heater an immense amount of energy must be used to obtain good performance. This electrical input will range up to five or six thousand watts for a medium-sized automotive engine and difficulty is often experienced in keeping the coils from burning out. This is a tremendous drain on any standard sized battery. Also, the coils offer a certain amount of restriction to the inlet air, which is undesirable while the engine is in operation.

The best starting is probably experienced with the use of the "flame-thrower" type of heater. This unit mixes air with fuel and sprays the atomized mixture past a sparking electrode into the inlet manifold. (A blow torch works equally well.) The only difficulty experienced lies in getting enough flame into the manifold to heat the air sufficiently and yet not so much that all the intake oxygen will be burned before reaching the cylinders. Proper adjustment of the unit usually will rectify this problem. This type of unit has been proved quite successful in field use. A typical curve of starting time versus temperature is shown in Fig. No. 4. These curves readily indicate the necessity of the heater.

The last method of applying heat to the aircharge (and probably the least used as far as starting is concerned) is to raise the temperature of compression. This may be done in several ways, which will be briefly noted here as a matter of interest. First, increasing the compression ratio obviously will raise the temperature. However, this is undesirable because of the high peak pressures imposed on the cylinders when the engine is in operation. Another method which effectively increases the compression ratio and which works very well on some engines, is to close the intake valve at "bottom dead center." Most engines have this valve close from 30 to 40 degrees F. "after bottom center" and as a result lose a certain amount of compression. For example, if an engine whose ratio was theoretically 15 to 1 had its intake valve close 45 degrees F. "after bottom center," its actual ratio might be about 12.5 to 1. This would make a considerable difference in the compression temperature.

CONCLUSION

With all these aids in mind, the final conclusion reached is that the application of heat is necessary for reliable starting. To keep the engine warm is possibly the best solution, so that the cranking requirements will not be great. The weight and size of the starting equipment can thus be reduced, and it is probable that the engine life will be increased by eliminating the possibility of scuffing pistons and cylinders because of improper oil films during the cranking period.

Radar's Peaceful Cousin

(*Continued from Page* 11)

interesting, and their solution showed great engineering skill and ingenuity.

DEVELOPMENT

No one organization is responsible for the entire development of the principle or for the product itself. Pioneer work was done by Dr. W. L. Everitt of Ohio State University in 1928 and 1929. However, the electronic units required to generate the high frequencies necessary were not available at that time, and no commercial model resulted directly from his work. The final development work was done largely by Lloyd Espenscheid and R. C. Newhouse of the Bell Telephone laboratories. The first public demonstration of the commercial product was in 1938. With the threat of war, the equipment was turned over to the armed forces, and the know-how that had come from its development was applied to research on radar.

The improved instruments that have been developed for the armed forces are based on the same principle as the commercial model. No specific information about them is available. However, it is known that the basic operating principle of this type of radio-reflection instrument is different in detail from the true radar. The difference is significant because the Western Electric type of device operates accurately at much shorter distances than a device based on the true radar principle. Postwar terrain clearance indicators will probably be a great improvement over those in service today, but the principle will be basically the same.

Several improvements were tried on the commercial model, but they were not reliable enough to use in regular operation. Further development will undoubtedly lead to improvements that will greatly increase the usefulness of the instrument. A minimum-altitude warning device is desirable for routine airline flying. Such a device must give a warning when the plane is closer to the ground than a predetermined distance. This feature would also serve as a collision warning. Another desirable improvement would be an increase in the effective maximum reading. At high altitudes there is little need for an instrument to indicate obstructions in a hemisphere below the airplane. By beaming the transmission downward, a marked increase in effective reading can be achieved. The use of true radar at extreme altitudes might provide a practical solution, if the installation does not become too cumbersome. Improvements in equipment should reduce both the weight and the power required. At present the instrument draws more power than light aircraft readily can provide. Weight reductions are possible on all units, and mass-production manufacturing methods should reduce the price enough to make every private flyer a potential owner.

THE FUTURE

Postwar aviation will not be the infant industry that it was in 1939. It will be a giant, powerful by all the criteria of industrial greatness. And this giant will not be content to grope blindly in the fog or to suspend operations at the sign of bad weather. The technology of radio direction and range finding has advanced to the point where all-weather flying is possible with large aircraft. Light, private aircraft need fear only violent weather. Devices such as frequency modulation ground-to-plane phone, radar, range beams, and instrument-landing radio-glide paths will be at the disposal of commercial aviation in the future. These radio navigation aids all require ground installations and ground cooperation with aircraft in flight. Unlike ground aids, the terrain clearance indicator is a part of the airplane, and it operates without outside assistance. For the private flyer as well as the commercial pilot, the added safety and simplicity that this instrument brings to flying will be of tremendous importance. In the future, the dial of a Terrain Clearance Indicator may well become as familiar as today's speedometer in the family sedan.

ACKNOWLEDGMENT

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