PRINCIPLE OF RADIO ELECTRIC DETECTION
(Radar)

compiled by Commander H. BENCKER, I.H.B.

History.

In 1925 Gregory Breit and Merle A. Truve, Carnegie Institution, Washington, conceived the idea of directing towards the higher atmosphere trains of short impulses of electro-magnetic waves of which they observed the echoes in order to measure the elevation of the *ionosphere,* i. e. of the hypothetic reflecting ionised layer of variable altitude surrounding the terrestrial atmosphere, the existence of which explains the system and certain anomalies of far distance transmission of electro-magnetic waves used in wireless telegraphic communications.

Before the year 1939 experiment had shown that short waves, above 10 meters wave length, had considerable range and were reflected against the upper layers of the earth's atmosphere (Heaviside and Appleton's layers). An hertzian very short signal reflected by the layer produced, in return, an echo and the interval of time between the departure of the signal and the return of the echo permits the determination of distance in terms of the velocity of propagation of electro-magnetic waves, i.e. 300.000 km. per sec. By this mean the reflecting layer was found to lay at about 100 kilometers, the measured interval being 1/3.000 of a second. This result was obtained by a similar technique to that used at sea for measuring depths by the echo sounding method.

Principle.

Radio electric detection by means of impulsions or radio ranging is based on the same principle as above which was already known long before the War. However in the present case, owing to the very high velocity of electro-magnetic propagation in air the interval of time to be measured is extremely short and we have to no longer deal with 10th or 100 th of second, but with much shorter quantities which are expressed in fractions of the *micro-second* (μ s) or 1 millionth of a second. For electro-magnetic ranging purposes the micro-second corresponds in fact to a distance of 150 meters (165 yards) in consequence of the formula :

$$D^{\text{meters}} \text{ (distance)} = \frac{1}{2}\, 0{,}3 \text{ km. (kilometers)} \times t\ \mu\text{s (micro-seconds)}$$

During war time the censor kept the necessary secret concerning the composition and functioning of electro-magnetic apparatuses (D.E.M. in France, Radio location in England) which are better known by their American appellation as RADAR (Radio Detection and Ranging) and which played such an eminent role in air and Naval defence and attack operations.

The Radar apparatus transmits invisible rays with frequences near to that of light, it receives the return radiations reflected by the neighbouring obstacles. Its range is much higher than the perception possibilities of the human eye even assisted by the most powerful optical apparatuses. The transmission can be made by night, in foggy weather and through haze. Moreover the Radar apparatus measures the distance to obstacles as with an optical range finder.

The above properties makes it of use in peace time to Air and Sea Navigation by helping under all conditions to eliminate the dangers of collisions at sea, etc., by detecting and ranging the various obstacles from great distances.

Description.

Radar consists of a transmitting and receiving projector of electromagnetic waves, the directional beam being reflected by the obstacle to be detected. Its accuracy is increased proportionately as the waves used are shorter, however in such case the range is smaller. There exist various kinds of Radar according to the purpose required, some with great range and great dimensions using rather long waves, such as for installations for protecting coasts and for great distance research ; other using shorter waves to perform a more accurate ranging within a short distance.

The transmitter E (*fig.* 1) sends at the instant t_0 a very short radioelectric signal which propagates with the velocity of light V and which is reflected on the obstacle O at the distance D, the receiver R (always situated very near the transmitter) records the echo return at time $t_1 = t_0 + t$ such as : $t = \frac{2\,D}{V}$.

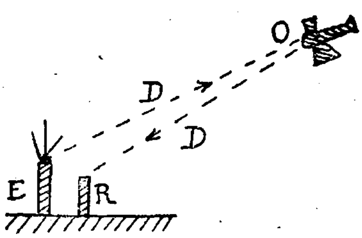

FIG. 1

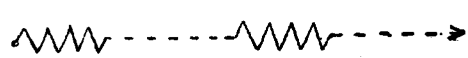

FIG. 2

The distance measured by Radar is calculated as a function of t. The reflected field produced by the radiated echo is very much weaker than the incident field, and it is therefore necessary to diminish the transmitted wave when its departure is registered and to amplify the reflected wave received and recorded. In order to make the distinction between the transmitted signal from the returned echo the signals transmitted by the Radar consist of short impulses of high-frequency short wave trains or « pulses » (*fig.* 2) the duration of each of which is from 1 to 10 micro-seconds, separated by relatively long blank intervals, from 1/25 to 1/4000 of second duration, during which each echo has sufficient time to reach the receiver and producing there a record clearly distinct from the departure signal.

At least 100 high-frequency oscillations in each « pulse » or « top » are necessary to obtain from the obstacle a back radiated field, consequently very high frequencies must be used ; for a 1 micro second « pulse » the frequency should be 10^9, corresponding to 3 meters wave length.

The signals or « pulses » are themselves renewed at a certain frequency called « recurrence frequency » comprised between 25 and 4000. Moreover, the obstacle which constitutes a kind of secondary reflector, has a proper vibration period the wave length of which is of the order of its geometrical dimensions : resonance with maximum echo production takes place if the transmission wave length is nearly equal to it.

For a given transmission power the field produced at a distance is relatively more intense as the wave length is shorter. Consequently very short « centimetric » waves have been used (of 3 centimeters approximately) i. e. 1,2 inches. These very short waves have properties approaching those of infra red and luminous rays ($\lambda = 80\ \mu$ and $0.8\ \mu$)* they propagate in a straight direction and their energy can be concentrated in a single narrow beam similar to those projected by lenticular light-houses and suitable to be directed.

In order to concentrate in the transmitted beam a sufficient power so that the reflected beam is sufficiently strong to actuate the receiver, the aerials of the transmitter and the receiver consists of small half-wave length doublets (several centimeters long) situated at the focus of two parabolic mirror (*fig.* 3) fed by means of a specially constructed cable (of the coaxial type) for very high frequence current transmission.

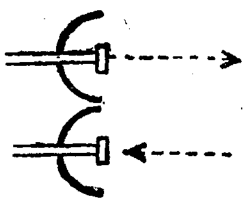

FIG. 3

The increased frequency of electro-magnetic oscillations determines a directional increase and reflecting possibilities : consequently the waves to be used should be either of ultra-short waves type (frequency : 30 to 300 MHz, $\lambda = 10$ to 1 meter) or micro-waves (frequency > 300 MHz and $\lambda < 1$ meter). Above 3 to 6 meters wave length it would be necessary to use directional

*The higher limit for infra red emission (mercury arc) is 314 μ = 0,314 millimeters. The shortest electro-magnetic wave obtained (Nichols and Tear) 200 μ = 0,200 millimeters.

aerials of very large dimensions, under 3 meters very high transmission power should be used to avoid the inconvenience of noticeable absorption increase.

Recording.

For the recording of Radar signals a *cathodic oscilloscope* is used, the working of which is described below (*fig.* 4).

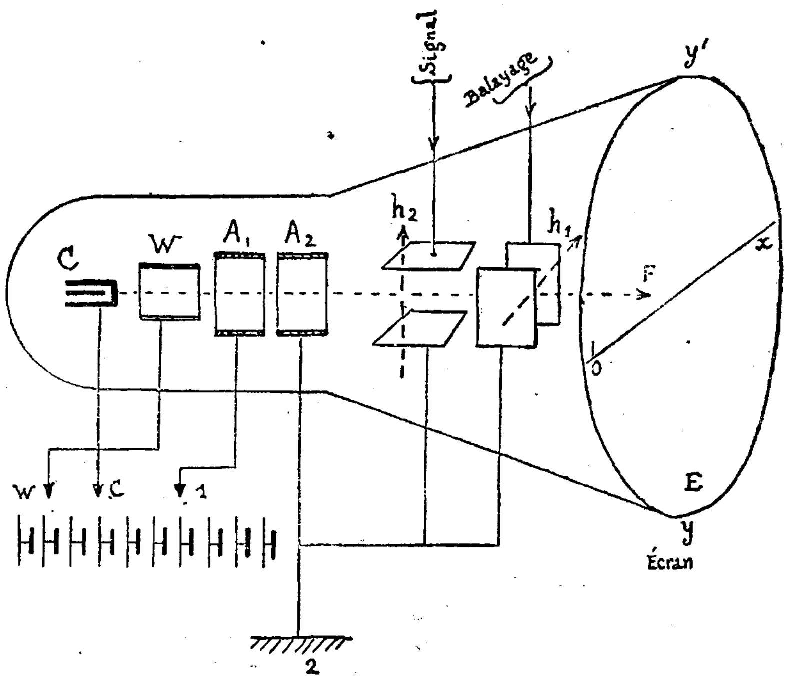

FIG. 4

The cathodic valve consists of a vacuum bulb, sometimes containing a gas under very low pressure, containing a cathode C heated indirectly which emits an electronic beam CF. This beam crosses cylinder W (called Wehnelt cylinder) which plays the role of a diaphragm to concentrate the electrons, thanks to its negative polarisation as compared with the cathode the latter might be regulated by means of the slide w permitting the concentration of the electronic beam intensity which produces, when striking the fluorescent screen E, situated at the bottom of the valve, a luminous « spot ».

The 2 cylinders A_1 and A_2 of different potential, positive as compared with the cathode constitute accelerating anodes fulfilling the role of electronic lenses, the slide 1 which determines the tension of the 1st anode, governs the concentration of the electronic beam at the point of impact on the screen.

Between the anodes and the screen is placed a system of 4 deflecting plates grouped in parallel by pair. The two last ones are vertical and when applying between them a so called sawtooth shaped tension they produce an electric field h_1 which deviates the electro beam so that the luminous spot describes with a uniform motion on the screen a straight line ox and determines its returns after each run very rapidly to its departure position O on the left hand side of the screen. The motion thus realised constitutes the "horizontal sweeping" (balayage horizontal). The two other plates are horizontal and if the radar signal is applied to this pair, the produced field h_2 gives the electronic beam a vertical deflection parallel to the screen diameter yy'.

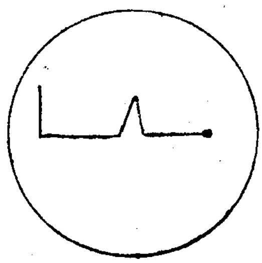

FIG. 5

Taken as a whole the screen of the oscilloscope shows the aspect of Fig. 5, i. e. that of an horizontal luminous line broken by vertical indentations, representing the echos. The pulse departure signal coincides with the beginning of the horizontal sweeping (balayage) because when the spot is at the point of departure of the sweeping the transmitter sends the pulse.

The electronic beam simultaneously impelled by the combined action of the two pairs of plates produces a displacement of the luminous spot which records on the screen, in rectangular coordinates, the phenomenon to be studied.

For exemple : if it is proposed to make graphically the study of a periodical potential difference applied to plates AB (*fig.* 6) and if another potential difference is applied to plates CD, synchronous to the former but producing lateral displacement of luminous spot proportional to time, an electronic beam

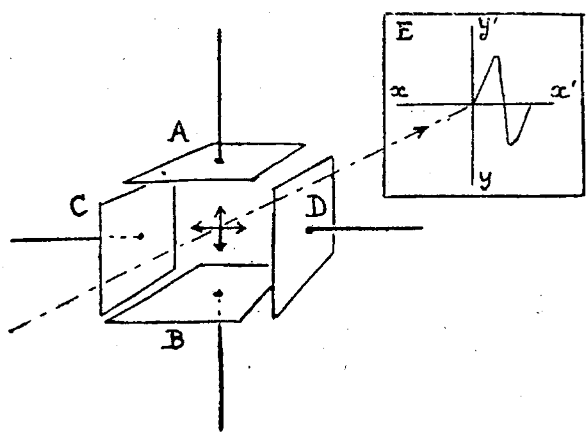

FIG. 6

is obtained simultaneously impelled by the combined actions of the 2 pairs of plates and the displacement of the luminous spot will represent graphically, in rectangular coordinates, the phenomenon referred to.

Various appliances (multivibrator, intermittent auto-oscillating valves, etc.) the description of which would be outside this elementary statement, permits one to realise the necessary synchronisation between the two varying potentials and consequently the variation proportionate to time as indicated above.

Briefly speaking, the system consists, in its general form, of the following appliances :

a) An ultra-short wave transmitter ;

b) A receiving apparatus, the output terminals of which are connected to plates AB of the oscillograph (*fig.* 6) ;

c) A cathodic ray oscillograph ;

d) An arrangement for producing the synchronisation and the necessary proportionality to time of the potential difference to be applied to plates CD of the oscillograph (*fig.* 6) ;

e) An arrangement governing the transmission of signals from the transmitter in synchronisation with the above arrangement (d), so that at the exact "zero" instant of the transmission of the signal should correspond to the "zero" instant of the lateral motion of the luminous spot actuated by the potential difference applied to plates CD of the oscillograph.

The transmitting apparatus emits a signal, the latter during its direct travel is recorded by the receiving apparatus. After reflection on the object the distance of which is to be determined, the signal is again recorded by the receiving apparatus. The direct and reflected signals are of the type indicated by figure 7.

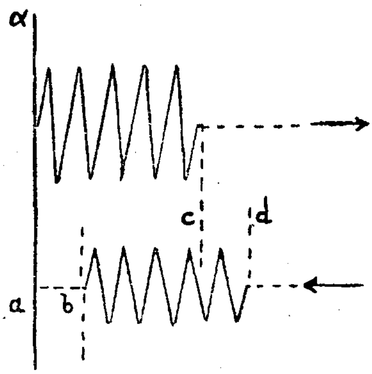

FIG. 7

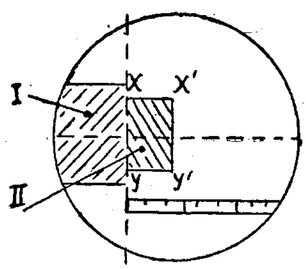

FIG. 8

Segment ab, which represent the interval of time during which the signal has travelled the distance from the transmitter to the object and back equals cd.

Through the oscillograph (owing to the persistence of the images on retina) a luminous mark is observed which is produced by the high frequency ondulating movement of the luminous spot. Two zones are to be distinguished (*fig.* 8) : one of major amplitude (I) corresponding to the end of the direct transmission and the second one (II) of smaller amplitude corresponding to the end of the reflected emission.

The distance to be measured is a function of the length XX' (*fig.* 8) corresponding to $\overline{cd}$ on figure 7. By a suitable adjustment of the apparatus in order to have the line XY in coincidence with the zero of the distance scale, the line X'Y' will indicate on the scale the distance to be measured (*fig.* 8).

In order that the receiving apparatus placed quite close to the transmitter be not saturated at the departure, it is made unsensitive during a very short period. When the pulse returns after being reflected on the obstacle it is first amplified and then recorded under the form of a peak. Another more distant obstacle may also send back another echo from the same original impulse and determine a second peak. In such case the screen would show two echos (*fig.* 9).

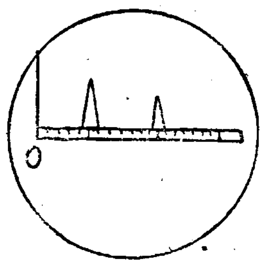

FIG. 9

The recurrent frequency of transmission being much larger then 16 per second the aspect of the peak on the fluorescent screen appears fixed owing to the persistence of luminous influences on the retina.

The scale of abscisses is divided in round distances provided by the oscillations of a standardised quartz and the position of the peak shows directly the distance to the detected object by means of an easy interpolation. In order to eliminate the latter a wave showing a square peak of variable duration and perfectly calibrated might be super-imposed on the screen to the above phenomenon : Its terminal mark is made to coincide with the spot from the echo and the distance is read on a dial the displacement of which is connected with the control. The movements of the detected obstacle produce a corresponding displacement of the echo peak on the oscillograph screen.

The Radar provides the exact distance within 150 meters for the less accurate apparatus and within several meters only for the more improved appliances.

2nd METHOD (*Distance determination by receiving in phase opposition*). Let us consider (*fig.* 10) the transmitter E and receiver R separated from each other by D and distant from O (the object the distance of which is to be determined) by D' and D'' respectively. A signal transmitted from E will be received in R directly and also after reflection in O. It is possible (by varying slowly the transmission wave-length) to obtain the critical wave-length for which both direct and reflected signals reaches R in phase opposition, this is apparent when a minimum reception is obtained.

In order to fulfill this requirement, it is of course necessary that the difference of the number of half-wave length contained in the travel EOR and that contained in the direct travel ER, be an odd number. Let λ_1, be the wave length fulfilling this requirement then we have the following relation :

$$\frac{D' + D''}{1/2\ \lambda_2} - \frac{D}{1/2\lambda_1} = n\,\frac{\lambda_1}{2}.$$

where *n* is an odd number.

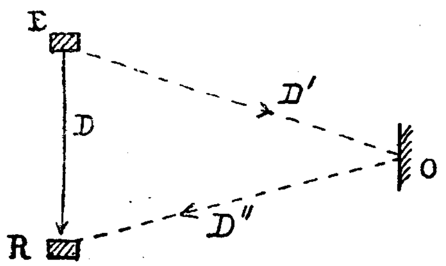

Fig. 10

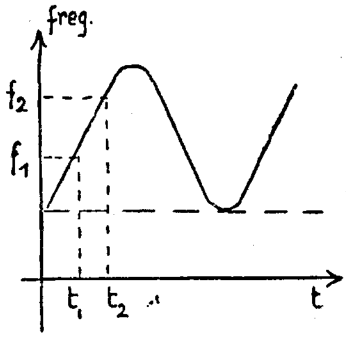

Fig. 11

By progressively decreasing the wave length a maximum reception corresponding to phase concordance of the two signals recorded in R will be noted at a certain instant, then a new minimum is obtained corresponding to. a new phase opposition, let λ_2 be the new value of the wave length for which the above condition is fulfilled :

Then :

$$\frac{D' + D''}{1/2\ \lambda_2} - \frac{D}{1/2\lambda_2} = (n + 2)\,\frac{\lambda_2}{2}.$$

These group of equation resolved in terms of $\frac{D' + D''}{2}$ (the mean distance to be determined) enables one to determine these distances in terms of λ_1, λ_2 and of the known distance D, separating the transmitting and receiving stations.

3rd Method (*Beat method*). — This method is based on the following principle : Let us assume that a transmitter emits continually on short wave a signal of constant amplitude the frequency of which is varied in proportion to time according to a definite rule as shown on figure 11.

Let us consider also a non-selective receiver syntonized according to the same rule for the range of frequencies used in the transmission.

At the instant t_1 the transmission has the frequency f_1 ; after reflection from the object the distance of which is to be determined, the signal reaches the conjugated transmitter-receiver at instant t_2. At that moment the receiver records two signals, a reflected one of frequency f_1, and the direct one of frequency $f_2—f_1$. The result will produce in the receiver a beat the frequency of which equals $f_2—f_1$; it is possible to determine such frequency which is a function of the distance to the reflecting obstacle and which varies in proportion with the latter distance.

Theoretically the frequency of the beat being known, the curve on fig. 11 enables us to determine the interval of time corresponding to the total travel of the reflected signals, this interval together with the knowledge of propagation speed of echo magnetic waves (3×10^8 metres/sec.) provides the distance of the object in consideration.

In practice, a transmitting system in close agreement with the law expressed by the theoretical curve shown must be used, also an arrangement for the determination of frequency $f_2—f_1$, calibrated so that the control shows for instance in meters the distance to be determined corresponding to the above difference $f_2—f_1$.

Direction Detection.

For the detection of direction (bearing or azimuth and angle of elevation) a system of movable directional aerials (*fig.* 12) is used. For azimuth determination, the receiver consists of two groups of movable parallel horizontal aerials A and B connected by a wire L bringing between them a half-wave length phase-lag. When the object to be detected is equally distant from the two groups each of them records equal and opposite tensions and consequently the receiver records nothing.

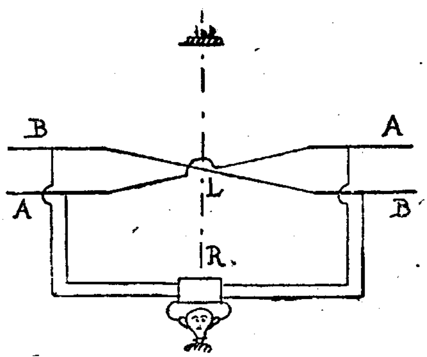

FIG. 12

If the obstacle is on the either side of the bissector of the system, the inequality in the return passage of the waves produces an echo. The azimuth is determined by orienting the gear so that the echo be suppressed.

The angle of elevation is determined in the same way by using a movable vertical aerials system. Consequently the complete set includes a distance oscillograph, an azimuth oscillograph and a elevation oscillograph with 3 observers respectively.

For transmitting wave length of several meters the horizontal or vertical aerials are also several meters long so that the dimensions of the first electromagnetic D.E.M. apparatuses were very combersome.

The production of decimetric and centimetric waves for pulses by means of split anodes and cavity magnetrons has permitted the construction of Radars functioning on 10 centimeters wave length with orientable parabolic mirrors aerials systems in which the transmission is located into a very narrow beam directed along the reflectors axes of symmetry ; so that by directing this towards the obstacle to be detected the distance, the bearing and the elevation searched for are directly obtained.

For this search one has been lead to associate Radar using medium waves (3 to 1 meter) with those using very short waves (40 to 5 centimeters) the first ones for far distance exploration make rough measurements and are used as finders associated with the second ones, these latter performing the accurate measurements. The first are always installed ashore or on board large vessels, the other of less dimensions may be carried on aircrafts or tanks.

Aerials and reflectors for the transmitter and for the receiver may be driven by means of an electric motor their axes being kept parallel in such a way that the areas to be explored may be automatically and spirally swept.

In the " Position Plane Indicator " (P.P.I.) a real map of the explored landscape is projected onto the screen of the cathodic oscillograph. A panoramic screen is used onto which the echos according to their nature produce diversely illuminated spots.

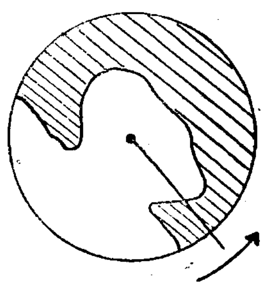

FIG. 13

The luminous spot traverse the screen in a very short time (less then $1/16^{th}$ second in order to maintain to persistence of luminous impressions on retina) by means of an arrangement similar to that used in television : the plates of the oscillograph are rotated around the geometric axe of the apparatus in synchronisation with the aerials and reflectors rotation, the departure of the traverse being from the center of the field of the cathodic screen (*fig.* 13). In this way the luminous spot traverses only a radius of the screen instead of a diameter and the images of obstacles met with are defined in polar coordinates.

The driving of plates through the glass tube is made by means of a fixed inductor producing a rotating field which drives a rotor connected with the plates inside.

Another arrangement consists of keeping motionless the two pairs of plates of the oscillograph and to apply such tensions to each pair that their composition in function of time gives the necessary sweeping, hence the echo is applied in order to modulate the Wehnelt electrode of the oscillograph and this varies the illumination of the screen according to the nature of recorded echos : their position on the screen depends on their distance and location on the ground and this entire system of more or less marked spots builds up the landscape as swept by the transmitted field realising in this way a kind of electronic optic without luminous waves (*fig.* 13).

To detect vessels or objects situated on the surface of the sea, such as buoys, periscopes, etc., theory shows that the impulse waves should be centimetric because the hertzian field is nul at sea surface and increases with elevation as rapidly as the wave length is short.

Centimetric transmissions are obtained by means of special electronic valves : the magnetron and the klystron.

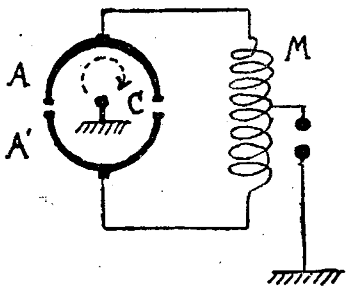

FIG. 14

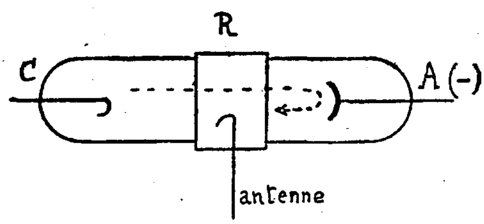

FIG. 15

In the *magnetron* the anode is split and consists of two half cylinders AA' centered on the cathode consisting of a heated filament C (*fig.* 14). The anodes are raised to a very high potential of the order of 10.000 volts, establishing an intense field along the cylinder axe. In such conditions the electrons emitted by the cathode are travelling curved paths and the aperiodic circuit M is the focus of very high frequency oscillations corresponding to centimetric wave length.

The Americans have produced very powerful magnetrons of several hundreds of kilowatts operating on 10 centimeters wave length for a very short period, the waves generated in the tube are transmitted out by means of a small hook connected to the aerial circuit.

In the *klystron* (or Mac Nelly valve) a resonnant cavity R is placed between the two electrodes (*fig.* 15). The anode is raised to a negative potential and the electrons emitted by the cathode are repelled towards the resonant cavity and produce ultra-high frequency oscillations : the waves are generated in the same way as above.

Other apparatuses employ as velocity modulators thermo-ionic tubes producing a wave which mixes with the returning wave obtaining beats of medium frequency. Sometimes also for the reception of ultra-short waves, instead of thermo-ionic tubes, detecting valves are used consisting of silice crystal, in contact with a tungstene thread called " catwisker " hermetically sealed in a small silvered-copper tube the functioning of which is similar to the galene detector used in former wireless receivers (*fig.* 16).

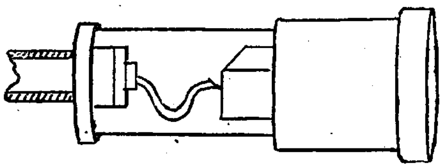

FIG. 16

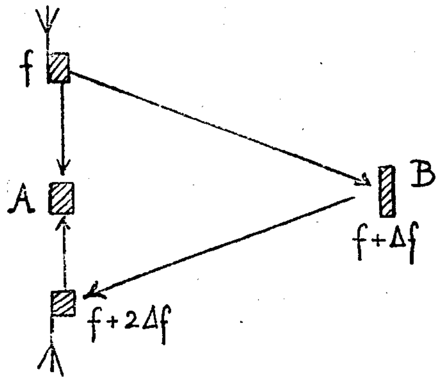

FIG. 17

Centimetric waves are propagated only along straight line as in the case of light. For sea surface exploration the range is consequently limited owing to the earth's curvature.

Exploration and reconnaissance Radars are capable of measuring distance to about 150 meters ; the ranging apparatuses heavier and more cumbersome installed in large vessels give an accuracy from 50 to 10 meters, much higher than that provided by the most improved range-finders, moreover the appliances may be used equally well during night time or in foggy weather.

A special device permits the instantaneous determination of the speed of a moving object by using the Döppler-Fizeau impression and measuring the difference of frequency of the direct wave and the reflected wave.

The determination of the object's (target) speed component in the transmitter object plan may obviously also be made by coordinating distance variation as measured by one of the above methods with time.

The determination may also be made by using the electro-magnetic echo of the displacement. Owing to the Döppler impression the echo frequency is different from the radiated frequency of a number of Hz proportional to the considered component of the displacement velocity.

If (*fig.* 17) *f* is the frequency of the signal sent by the fixed transmitter located in A, the frequency of the signal received in B will be $f + \Delta f$ in which Δf is the frequency variation due to the Döppler impression resulting from the target velocity.

The echo radiated from B, the frequency of which is f + Δ f will be received in A, for the same reason with the frequency f + 2 Δ f.

This reflected signal frequency combining with that of the direct transmission will produce beats the frequency of which enables to deduce the instantaneous velocity of B in A-B direction, or better, the component of the velocity of B in the plan A-B.

Practical Use.

The study of radio detection by means of directed very short waves, initiated in France in 1931 by the work of M. David and practically realised by the S.F.R. (Société Française Radioélectrique) in 1934, using 16 centimeters waves, was put into practice for the first time by British Engineers who have designed the first apparatuses functioning on metric waves.

The first Radar station was installed in 1935 at Orfordness on the English coast for ships detection (range 65 km.). In 1938 the range was increased to 260 km., the normal range is in the vicinity of 160 km.

The first ship's radars were fitted in 1935 in the British Men-of-War "Rodney" and "Sheffield"; first intended for anti-aircraft protection it was recognized that the installation could also be used for navigational purposes.

In the year 1942 American experts after having improved the technique of centimetric and decimetric impulsions and were thus enabled to increase the accuracy of radio detecting apparatuses.

The screens (scopes) of the Radar act as many electric "eyes" far superior to the human eye to keep watch at sea and to guarantee the safety on board ship : by detecting obstacles, icebergs, reefs or shore features, by night or in foggy weather, and by distance ranging of buoys especially those fitted with a special top mark thus facilitating pilotage and access to estuaries and harbours by means of a kind of hertzien buoyage system.

Radar also locates on its screen the exact position of surrounding ships, the presence and distance of lighthouses and littoral landfall marks. It permits the guidance of ships from fixed shore stations along predetermined tracks whatever may be the meteorological conditions.

It is the source of a new series of navigation aids and methods serviceable also to air navigation. The determination of the bearing and speed of one or several ships approaching from the shore is made possible. It may be used as a radio-beacon. Also the approach of atmospheric disturbances and typhoons may be forecast by its use.

Radar Navigation Method.

Gee (*British*) *and Loran* (*American*) *System**. — Hertzian signals transmitted by 3 land stations in synchronisation to the nearest micro-second are

*Further details concerning LORAN will be given in *Hydrographic Review*, vol. XXIII, 1946.

recorded on board ship on the same screen. Owing to the different distances of ship (or aircraft) to the 3 stations these signals do not reach the ship at the same time and their records on the cathodic oscillograph are distinct along the time scale. Their relative spacement show the distance differences to transmitting stations taken in pair. These 3 values provide an exact fixed position on specially prepared charts on which have been drawn for each pair of stations hyperbols figuring the geometric loci of the points for which the track difference shows a given value.

Oboe (British) and Shoran (American) System. — A guiding system is now dealt with : The distance of the vessel to be guided (ship or aircraft) is permanently measured from a fixed radar station and an indication is given to the mobile by means of predetermined signals if it gets off to the right or left of the course intended to be followed.

For instance the signal (—) is transmitted as long as the vessel follows a circular track of which the station is the center, signal (. . . .) if the vessel gets off to the right, signal (· —) if he gets off to the left, the above information enabling the vessel to rejoin the prescribed course. Another conventional signal indicates the altering of the courses or tracks or the crossing into the subsequent controlling station area.

The guiding may also be obtained independently of shore stations the latter being used as ordinary Hertzian transmitters only. For this purpose a radar signal is transmitted by the ship, this signal brings on the response of 2 fixed stations A and A'. Each response is a measurement of the distance of each station and the ship is able to direct her course in order to follow a circular track the center of which is located at one of the stations the response of which is made to coincide with a fixed index.

The systematic guiding along arcs of circles or along straight lines may also be found applicable for sweeping or hydrographic purposes.

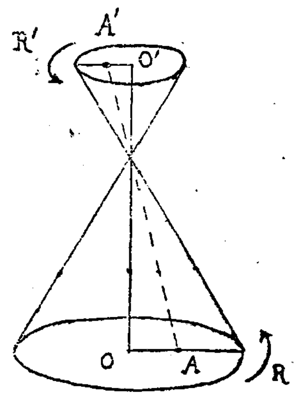

FIG. 18

Radar air photography.

Gen or H2S System. — A narrow hertzian wave beam travels around cone C (*fig.* 18) the base of which is to be explored. The extremity of the beam operates the sweeping of the radius OR, then that of the next radius and so on at a velocity of 60 revolutions per minute. The waves, reflected on the ground more or less intensively depending on the obstacle met with, are received back by the Radar and the electronic beam of the cathodic valve travels along the fluorescent screen so that the luminous spot travels along radius O'R' as the hertzian beam travels along the radius OR. Thus point A furnishes the image A' more or less strongly marked according to the reflected wave intensity. A complete figuration of the ground is thus obtained by the persistent fluorescence on the screen. The radiation travels through fog or may be carried out by night realising a kind of Hertzian light " television ".