POSSIBILITIES OF RADIO DIRECTION-FINDING WITH DECAMETRIC WAVES AS A MEANS OF RADIO NAVIGATION

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1. *Elementary Comparison of Radio Navigational Systems.*

Prior to the last war, practically the only long-distance radio navigational aid consisted of radio direction-finding by means of hectometric waves. In spite of the high degree of refinement reached by this system, it has now been almost completely abandoned for the reasons explained by M. GRAS in his lecture on radio direction-finding by decametric waves.

The hectometric direction-finders were installed on airfields or in the immediate vicinity; by means of an aerial ranging capacity up to several hundred metres, the finder and receiver were operated directly by the air-security operator responsible for ensuring communication with aircraft heading for the airport, and this operator supplied the correct heading to the plane.

During the war, various other long-range navigational aids were studied and used for military purposes: LORAN in the United States and SONNE in Germany. When the principles of these new aids were made public, the tendency was to consider them as a definite solution of the problem of long-range radio navigation, and their accuracy and convenience were reported as being far above anything that had been obtained previously by radio direction-finding.

It had been forgotten, as it often still is, that all radio navigational methods are based on the propagational properties of electromagnetic waves, and that their accuracy and precision are limited by the same physical phenomena, regardless of the principle and type of equipment used, provided the latter is well enough built to exclude an instrumental error of excessive size.

The physical properties of electromagnetic waves depend essentially on frequency, and the limit of accuracy which may be obtained in a radio navigational system of a given geometric type is determined as soon as this frequency is known. To take a more precise example, let us consider the simplest geometric shape which enables a coordinate to be obtained: that of a triangle ABC. If it is desired to determine a coordinate of point C with respect to points A and B, the path-length difference AC — BC is measured. The properties of the system are determined throughout as soon as the dimensions of the figure and the speeds of propagation of the electromagnetic waves along AC and BC are known.

If the base AB is shorter than one wavelength, and the transmitter is placed at C, the instrument used to measure the phase differences at A and B is a radio direction-finder; for a given phase difference, the locus of C closely approximates a straight line Oz: the radio direction-finder supplies only one bearing.

If we base ourselves on the same geometry, but place the transmitters at A and B and the receiver at C, a similar arrangement is obtained, which in its simplest form is a « Sonne » or « Consol » system (in which the only azimuths obtained are those whose phase differences are odd multiples of a half-wavelength), but which in a more developed form becomes a system such as the Navaglobe device.

Once the frequency and geometrical shape have been obtained, all three systems are therefore capable of the same range of accuracy. Provided we control the quality of construction, the errors mainly derive from two causes:

(a) The propagation paths AC and BC are not in an absolutely straight line, and at a given moment a systematic error will occur with respect to the position of point C;

(b) As the energy is propagated along multiple paths, the shape of the signal is no longer entirely retained upon arrival, and the velocity of propagation is not well-defined over both paths. The phase difference proper is variable and ill-defined: the bearing obtained is subject to oscillation, or there is a certain fuzziness in the measurement, depending on the system used. The error with respect to the point C position is generally of an ambiguous nature.

This latter defect almost exclusively applies to ionospheric propagation, and essentially occurs when decametric waves are used. The former deficiency, on the other hand, more or less affects all frequencies; but it is important to note that it practically disappears if very low frequencies are used exclusively in the case of paths over the sea.

Sensitivity of azimuth measurement increases with the length of baseline AB: a given path-length difference AC — BC corresponds to a difference in azimuth proportional to the length AB. The tendency is to increase the distance between A and B in order to obtain a higher sensitivity; in one case a long-base direction-finder is thus obtained, and experience shows that the error arising from (b) is reduced.

If the distance AB is increased to a point where it is no longer negligible with respect to the distances AC and BC, the locus of C may no longer be assimilated to a straight line Oz: it is one or more hyperbolae whose foci are located at A and B. The so-called « hyperbolic » systems which follow this arrangement (GEE, LORAN, DECCA, RANA, etc.) usually make use of two transmitters A and B which are locked in phase, either by a power line AB, or by radio.

The essential differences in these systems result from the choice of frequency, even more, perhaps, than from different geometric dimensions, the latter being more often restricted by natural convenience than left to the entire discretion of the installation service.

These long-base systems are subject to the errors caused by (a), like the short-base systems. They are affected by (b) to a lesser degree, but the increased separation of A and B gives rise to errors and difficulties in phase synchronization.

The use of pulses (as in LORAN) does not enable the phenomena of multiple paths to be overcome except in cases where definitely separate propagation paths occur: the ground-wave and E-wave; or the E-wave and F-wave, for example. This process does not solve the difficulty, which is constant in the case of ionospheric propagation, of close-lying multiple paths, by which a continuous distortion of the time of rise of each pulse is formed. The gain obtained through the use of pulses has been computed statistically, in the case of radio direction-finding, following British research (paper communicated to the C.C.I.R. in 1953); it was considered to be negligible, in view of the increased complexity of the system and the required increase in the bandwidth.

The direct measurement of the phase differences of sine waves appears to be much more satisfactory, since this enables an economizing of the bandwidth and results in a saving of power.

An equivalent hyperbolic system could just as easily be built by placing the transmitter at C and measuring the phase differences between A and B upon reception. A very-long-base radio direction-finder would thus be obtained which would be no more difficult to construct than the known hyperbolic systems. (The ambiguity as between the various hyperbolae could easily be resolved by means of short-base slave direction-finders). The airborne equipment would be simplified, at the expense of an increase in shore equipment and shore-based personnel.

But paradoxically enough, civil aviation, which has always been reluctant to increase the bulk and cost of airborne equipment, has decided that the only ultimate solutions to radio navigational problems are precisely those which present such inconveniences, so that no consideration has been given to this type of system. The reason for such a choice derives from the practical possibilities of operation: the specialized operator still considered essential in air navigation is available for measuring purposes at the time selected by the officer-in-charge, whereas if the airborne equipment were of the passive type the risk of saturation would require the presence on the ground of a large staff, which as a rule would have little to do, but which would be able to carry out simultaneously all the measurements requested in an emergency, such as in the case of bad weather occurring during a period of maximum traffic.

2. *Use of a Radio Direction-finding Network for Radio Navigational Purposes.*

The only known system which approximates the above-mentioned scheme is the radio direction-finding net, which in its simplest form consists of two complete radio direction-finders placed at A and B. In order to increase the accuracy obtained, the use of a single direction-finder supplying a single bearing is thus resolutely discarded. As in any case the results supplied by two instruments at A and B must be centred at some single point, the number of direction-finders can be increased with no untoward delay in the centralization process, but with an increase in accuracy and coverage of extensive areas if the sites for the direction-finders are chosen with care.

Position-fixing by means of a complete direction-finding network therefore appears to be the only possible method of using radio direction-finding for radio navigational purposes, whenever the selected frequencies correspond to a preponderantly ionospheric form of propagation, in which the error affecting individual measurements of azimuth is too large to warrant the use of an isolated measurement.

Owing to the numerical importance of errors under such propagation conditions, the setting-up of a radio direction-finder network must essentially be determined according to their variation as regards the various parameters and in such a way as to reduce to the utmost their effect on the final result.

The first parameter to be considered is the frequency. Although azimuth errors appreciably decrease as the frequency is increased from 3 to 30 Mc/s, the effect is too slight to require consideration in a siting problem. In general, moreover, no control can be exercised as regards the frequency, and its order of magnitude is imposed by the propagation conditions over the path considered at the time of use.

The effect of azimuth is scientifically established; largely important errors are produced by the terrestrial magnetic field whenever the path of propagation is no longer parallel or perpendicular to its horizontal component. But in the mean latitudes this effect occurs only in the case of steep slopes of the propagation path — over very short distances, therefore — and in the case of frequencies approximating the critical frequency. Apart from these frequencies and short distances, the variation in terms of azimuth may be neglected.

The scattering of azimuth measurements around their mean value, on the other hand, varies strongly with distance. Two processes are the underlying causes of this variation: first the lateral ionospheric deviation, caused by the general inclination of the ionized layers, increases as the distance decreases; secondly the polarization error due to the instrument's sensitivity to the field's horizontal component likewise increases with the value of the component, i.e. over short distances.

The following table supplies data regarding the variation as against distance of the typical angular error deviation about the mean azimuth measured in the case of two interesting types of instrument: one is a radio direction-finder with four fixed Adcock aerials, and the other is an instrument of much larger dimensions.

Distances in km.	Typical Error Deviation			
	4-aerial instrument		Long-base instrument	
	Angular error in degrees	Transversal error in degrees	Angular error in degrees	Transversal error in degrees
200	5	17		
300	4	21	2	10
500	2.8	24	1.9	17
600	2.5	26	1.6	17
800	2.2	31	1.45	20
1500	2	52	1.35	35

The same table shows the typical linear transversal error deviation : Transversal error = distance x angular error (in radians), the only parameter of definite interest to the user. The advantage of arranging the pattern in such a way that the maximum distance to be measured is well under 1500 km. readily appears; on the lower end of the scale it must be remembered that under 300 km. the number of impossible measurements (fuzzy bearings) rapidly increases; these cases have been eliminated from the statistics as mathematically they would supply an infinite error and would prevent estimation of the errors in the other cases. Under 200 km., the number of impossible measurements is very large, and the errors are of considerable size in the other cases. The minimum range of measurement should finally be regarded as being of the order of 300 km.

But this method of evaluation eliminates certain causes of error, and we are interested in the overall evaluation of errors such as they are actually met with. The following table is a condensation of the results of more than 20,000 measurements carried out over the space of a year with an Adcock direction-finder with fixed aerials of a later type than the preceding one.

Distances in km.	Typical Non-Centred Deviations	
	Angular error σ_o degrees	Transversal error σ_d km.
320 to 500	2.2	15
500 to 800	2.5	28
800 to 1 250	2.1	35
1 250 to 2 000	2.2	60
2 000 to 3 200	2.0	90
3 200 to 5 000	2.4	170

Each « measurement » is the mean of 10 instantaneous measurements occurring over a period of 3 minutes; no correction of instrumental or systematic error has been applied to the measurements, so that the statistics of the preceding table represent typical non-centred deviations in the errors. The azimuths are random and the frequencies range between 3.5 and 14 Mc/s.

The advantage readily appears of maintaining the maximum direction-finding range in the neighbourhood of 1000 km., although the minimum in the vicinity of 1000 to 2000 km. has almost disappeared, masked by other more constant errors.

The indicated statistical information may be obtained without applying any correction for systematic error to the bearings. If it were possible to determine statistically the systematic error as against the various parameters from measurements on knows transmitters, the results shown could be appreciably improved; but as this is not a definite possibility in every case, particularly in desert areas, no account has been taken of this fact here.

It must also be considered that these results were obtained from measurements carried out by fairly powerful known transmitters; bearings taken on small fixed transmitters or on shore-based or shipborne mobile transmitters are seldom as good. Airborne transmitters, however, are an exception to this rule, and experience has shown that it is often possible to obtain bearings thereon that are comparable in value to those of powerful fixed transmitters.

Knowledge of the transversal error appearing in the preceding tables is not sufficient to give a correct view of the position-fixing error obtained with several radio direction-finders. This error may be determined beforehand, in terms of the typical transversal error deviation, provided a few assumptions are made for purposes of simplification. The corresponding theories would be far beyond the scope of the present description, but a fairly simple final formula may be given which is generally applicable to the case of radio navigation in the air.

It is assumed that n radio direction-finders are evenly distributed in azimuth about the mobile to be located, and that they are an appreciably constant distance apart, such that the typical transversal error deviation in terms of distance is appreciably equivalent to σ_d in the case of all the direction-finders. Under these conditions, a minimum-area surface may easily be determined, which is such that a probability P_R exists of finding the mobile inside this surface, over a large number of tests caried out under identical conditions. If the parallax or the angle at the mobile subtended by the overall radio direction-finding network is larger than 180°, this surface is a circle whose radius is supplied by the formula:

$$R^2 = -\frac{2\sigma_d^2}{n} \log_e (1 - P_R)$$

If a probability of 0.95 is selected, the formula becomes:

$$R^2 = \frac{6\sigma_d^2}{n}$$

By taking 12 bearings, we get:

$$R = 0.7\,\sigma_d$$

Thus, under the conditions mentioned, 12 direction-finders may be expected to give the position of an airplane at 1000 km. in 95 % of cases to within 25 km. (with $\sigma_d = 35$ taken from the preceding table).

For parallaxes under 180°, the formulae become more complicated; but for a parallax of 90°, which is an advisable minimum for radio-navigational purposes, the errors corresponding to the stronger probabilities (0.90 to 0.98) are approximately 30 % higher than those given by the preceding formulae.

When the probable transversal errors are not the same for all bearings, which in particular occurs when the distances from the direction-finders to the point requiring to be fixed are not the same, a good approximation may still be obtained by replacing the square of the typical deviation by the harmonic mean, covering all the finders, of the corresponding individual quantities:

$$\frac{n}{\sigma_d^2} = \frac{1}{\sigma_{d1}^2} + \frac{1}{\sigma_{d2}^2} \;\ldots\; + \frac{1}{\sigma_{dn}^2}$$

3. *Organization of a Radio Direction-finding Network for Radio Navigational Purposes.*

The previous considerations may be summarized in the following conclusions:

(a) The magnitude of the angular errors arising in radio direction-finding with decametric waves requires the use of a radio direction finding network in order to obtain a complete fix, instead of a single finder supplying an azimuth or heading;

(b) The optimum ranges for radio direction-finding purposes are located between 300 km. and a maximum of 1500 km.;

(c) the network's parallax for the points to be determined should be at least 90° and, if possible, 180°;

(d) The radio direction-finders should consequently be evenly distributed around the area involved, the maximum distance between stations being 3000 km.;

(e) The number of radio direction-finders should be sufficient to ensure the required accuracy, on the assumption that each contributes but one bearing per fix, the latter representing the average of ten instantaneous measurements spread over a maximum 3-minute period;

(f) The frequencies of the radio direction-finding transmissions should be selected according to the range, in such a way that a suitable field is provided for the instruments (of the order of at least 10 μ V/m).

The required organization is directly dependent on these conclusions.

1. The radio direction-finding network should be subordinate to a single operations office, which receives the beatings taken and combines them to supply a position-fixing zone, known according to a given level of probability. In the case of radio navigation, the corresponding operations should be simplified to the utmost and made highly automatic for the sake of a maximum increase in speed.

Under present research conditions, optical processes, whether by transparency or by projection methods (PICQUENARD Patent No. 1,005,897, dated 14th October 1947, and GUERIN Patent No. 1,007,646 dated 17th March 1948) appear most likely to supply the desired results within an acceptable amount of time by combining approximately ten bearings.

2. The radio direction-finding stations should be in permanent and instantaneous contact with the operations office, preferably by means of special telephone circuits. If such telephone circuits are impracticable, they may be replaced by an exclusive radiocommunication system, operating on exclusive frequencies.

3. Requests for fixes coming in from aircraft to the qualified air navigation station can be relayed immediately to the radio direction-finders without passing through the operations office, by hooking up the station with the interconnecting radio direction-finder circuit.