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HALF-HELMHOLTZ COILS, WITH HIGH ACCESS TO THE UNIFORM FIELD; AND, A SECTORIAL COIL SCHEME FOR SPEEDING UP THE EXPERIMENTAL APPROACH TO SOME MAGNETIC LENS DESIGNS

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April, 1963

IP-615

ACKNOWLEDGEMENTS

The writer much appreciates the co-operation of the Magnet Wire Research Laboratory, Anaconda Wire & Cable Company, Muskegon, Michigan, in making up and furnishing, without charge, the Epoxy-filmed copper strip used in building the coils shown in Figure 1. One is also indebted to Mr. J. D. Tebo, Technical Relations Department, Bell Telephone Laboratories, for sounding out his colleagues as to the novelty of these ideas; and to many others who have likewise been approached.

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SUMMARY

When Helmholtz coils produce a uniform field, access to the uniform region may be hindered for vision or apparatus, by one of the two coils, in some cases. "Half-Helmholtz" coils have been devised, giving high access. By using opposed compensating coils, nearly all of the coil bulk is moved to one side of the operating plane. Also described is a new sectorial coil idea that should greatly facilitate the experimental approach to magnetic lens design, when such compensating coils are used.

HALF-HELMHOLTZ COILS

Helmholtz Coils

The famed Helmholtz coil arrangement has one purpose: that of producing, within a given volume, a near-uniform magnetic field, without resort to the use of iron cores.

The design calls for two round coaxial coils, each of mean radius R, spaced apart (between midplanes) by the distance R, and with coil section dimensions kept to a suitably small fraction of R. With coils in series additive, a near-uniform field is then produced in the central region of the structure.

The uses of these coils are so numerous but so scattered, that no one could catalog them; but the frequency with which photographs are published, showing applications, indicates wide use in research, measurement, and so on. Helmholtz coils, axially aligned with the earth's field, can nullify it, thus giving a field-free region; or, they can produce a field of the desired strength. These are apparently the two most usual types of applications.

Objective

Cases can arise in which, if Helmholtz coils only as large as need be were used, suitable access to the uniform field region cannot be had: the view may be blocked by one of the two coils; or room for apparatus using the field cannot be secured. The only remedy is to make the coils enough larger to permit access. This could sometimes call for very large coils to achieve a small effect in a small space.

Precisely this difficulty arose in the writer's work with electrospherics and magnetospherics.[1,2] Here, it was desired to have a near-uniform vertical field through a circular area of a horizontal plane. Helmholtz coils would do the job, but the upper coil was a nuisance and a handicap. How to get rid of it? It was this need that led to the "Half-Helmholtz coils" ideas described below.

The idealized objective was to achieve a coil assembly with all coils entirely below the operating plane, yet have a nearly uniform field up through an area of considerable radius as compared with coil bulk. The design achieved does not quite realize this objective, but it does give very high access to the operating plane; and it will be pointed out that the complete realization may be possible.

This objective cannot be realized by any combination of coils below the operating plane, if all coils are connected additive. The key idea is to be willing to operate a coil in reverse.

<u>Main Coil</u>

All four coils in Figure 1 are in series. Each has 130 turns of copper strip, 0.375 inches by 10 mils, Epoxy-filmed. The film is good for 300 volts, and there is no extra insulation between turns.

The two lower coils have a mean R of four inches. If these two coils only were spaced to have this same distance between their mid-planes, they would then be Helmholtz coils. Thus, one way to think of the present design is that, as a first step, the top Helmholtz coil has been moved down to merge with the bottom one. This single main coil (composed of the two shown) would put a curving field (dotted lines)

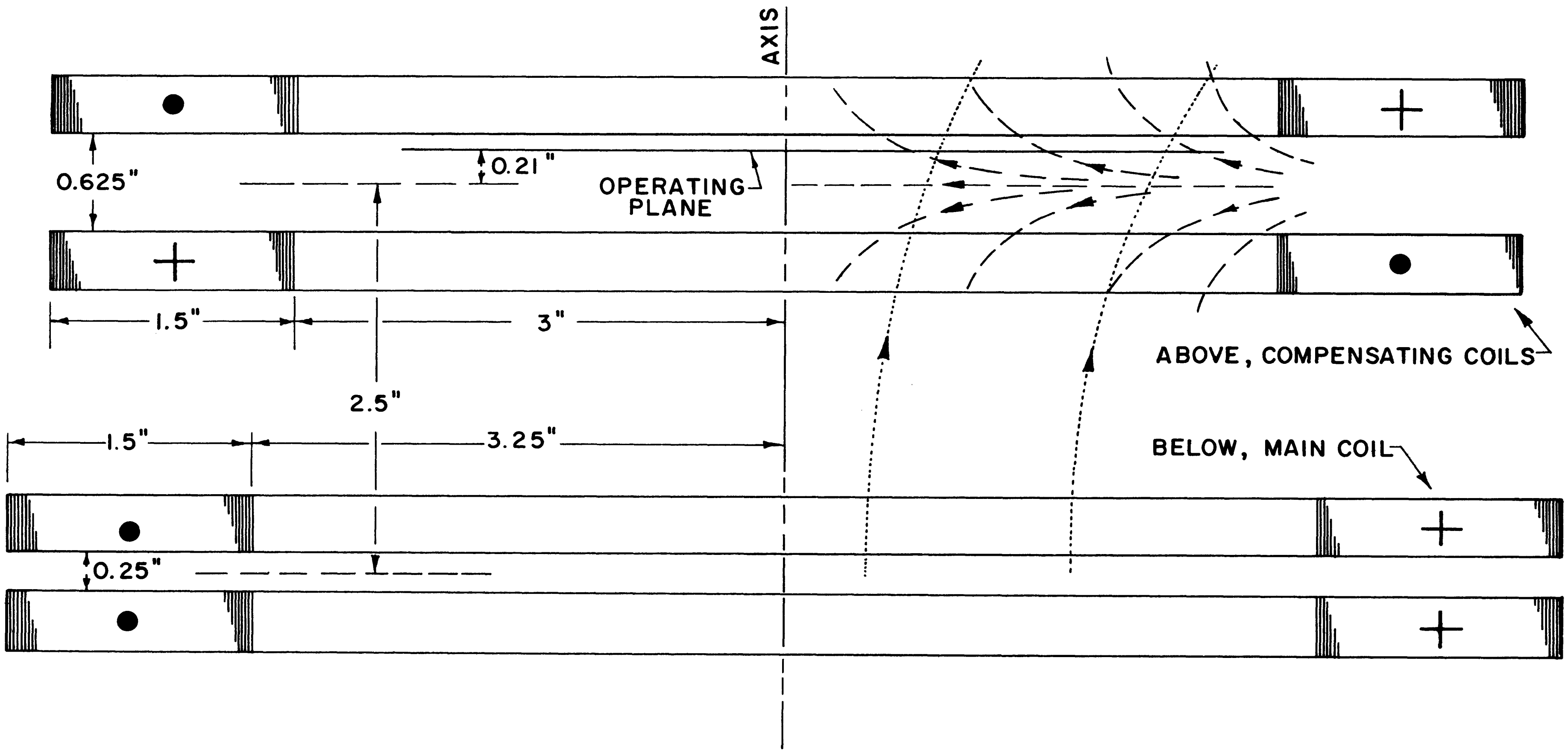

Figure 1. Half-Helmholtz Coils, Giving High Access to a Near-Uniform Field Through a Considerable Area of the Operating Plane.

through the operating plane which, as to uniformity, is defective in two ways: the vertical component density decreases with the radius, and the unwanted radial component increases.

Compensating Coils

The compensation coils are now added, to cure both defects of the main field. These mutually opposed coils set up a field (dashed lines) such that, with the operating plane somewhat above the common mid-plane of the coils, the vertical density component increases with the radius, and the radial component does likewise. With a suitable geometry, the two fields should produce a near-uniform vertical resultant through a considerable area of the operating plane.

Field Uniformity Achieved

Vertical flux density vs. radius is plotted for several levels in Figure 2, density in the center of the operating plane being taken as 100%. Curve A, taken at the compensating coil midplane, shows the uncorrected main field, since vertical compensating flux is zero in this plane.

Moving up by 0.21 inches to the operating plane, compensation becomes effective, Curve C, and an almost uniform field obtains out to 1.5 inches. Or, Curve B, 0.11 inches down from the operating plane, we can go out 2.25 inches and still have vertical uniformity to within slightly more than $\pm$ 1%.

As to volume considerations, the dash-line rectangle indicates a volume 0.42 inches high, with radius of 1.75 inches, having vertical uniformity to within $\pm$ 3%.

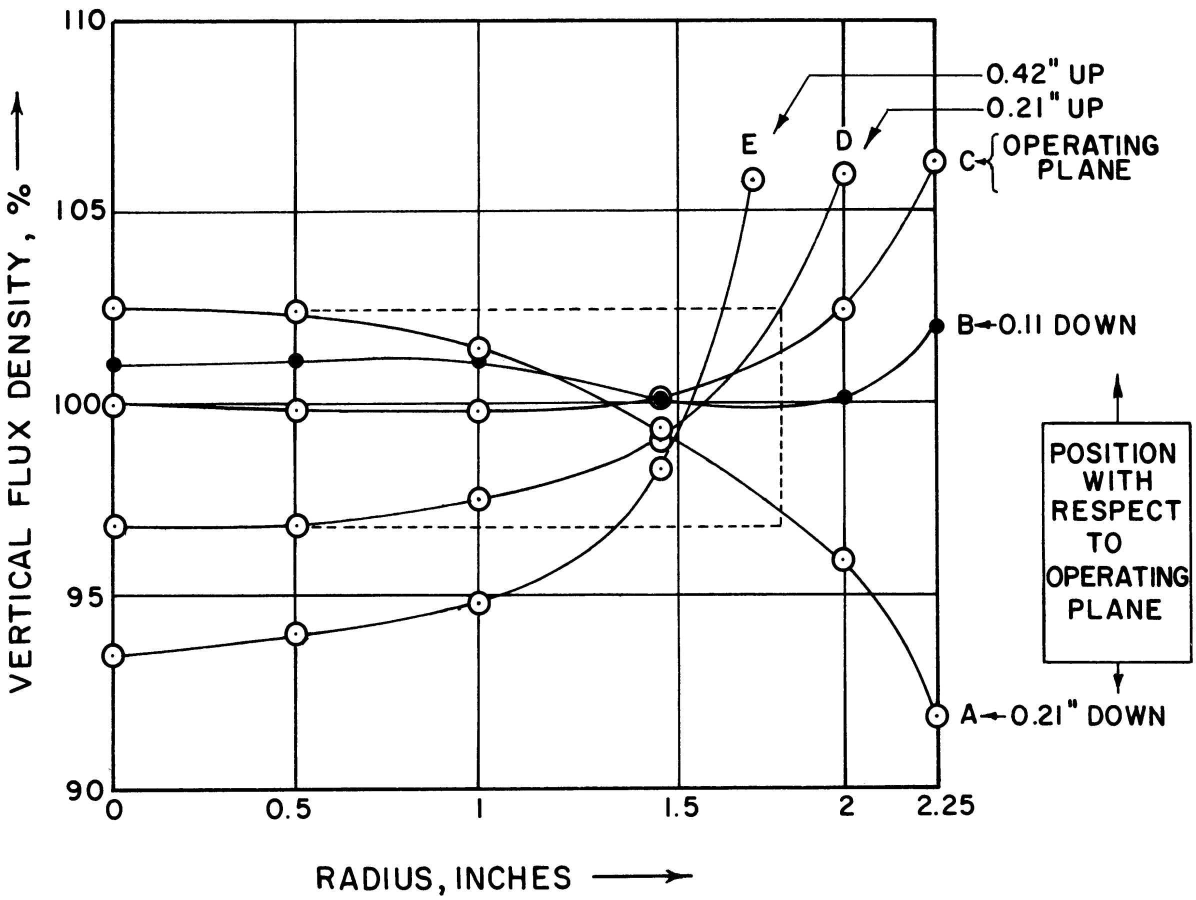

Figure 2. Test Results: Uniformity of Vertical Flux Density from Half-Helmholtz Coils, in the Operating Plane and at Other Levels.

Flux was measured with a 20-turn fine wire search coil one inch in diameter, connected to a vacuum tube voltmeter, with 60 cycle current in the coils.

The Half-Helmholtz Design

This present design was arrived at the hard way. The writer first adopted a tentative geometry and tried it out, on paper, using every feasible shortcut for field calculations. Anyone who has done this knows how tedious it is, and how many hours can go into filling up tables with figures. The first guess was, of course, inadequate; but the insight gained from it, plus many hours of subsequent calculations, yielded the final design. Construction and testing amply verified the paperwork predictions as to uniformity. The calculations are too lengthy to be included here.

It was the tediousness of the above work that served to give birth to the new experimental approach described later on.

The coils described above yield a central area density in the operating plane of 63 lines per square inch per ampere, or 9.8 gauss per ampere.

It should be noted that the high-access advantage of the Half-Helmholtz has a price tag attached. The price paid is in terms of coil bulk: for the same field strength per ampere, total copper weight is a little more than doubled. This could no doubt be reduced if an optimized design were worked out.

A fairly broad inquiry has turned up no one who has heard or read of the Half-Helmholtz idea, and it therefore may be new.

EXPERIMENTAL MAGNETIC LENS DESIGN
USING SECTORIAL COILS

Magnetic Lens

The term, magnetic lens, seems to have broad acceptance, even though not strictly defined. It is used here simply because it seems more appropriate than any other. It is taken herein to mean some arrangement of coils in air, that will give a desired volumetric field conformation having an axis of symmetry. Thus, the Half-Helmholtz coils amounted to a magnetic lens giving a quite uniform field in the operating plane, and a near-uniform field within a limited volume. Our discussion will use the Half-Helmholtz for purposes of illustration.

The Half Helmholtz design was arrived at by tedious calculation. The objective now is to arrive at such a design experimentally.

The Sectorial Coil

Suppose, after rough (but short) calculations, a first-trial experimental design has been fixed upon. The main coil is wound. Next, Figure 3, the compensating coils could be wound. Those shown are pancakes, each of 12 turns in one plane. If wound, they could be adjusted with respect to the main coil, an operating plane could be chosen, and a flux density exploration could be made. Three variables are now open for use, to improve the field conformation: the compensating coils could be moved up or down; or changed as to separation; and, the ratio of compensating current to main current could be changed.

But this can be done in simpler fashion. Let us, for design trial-and-error purposes, replace the two complete compensating coils by

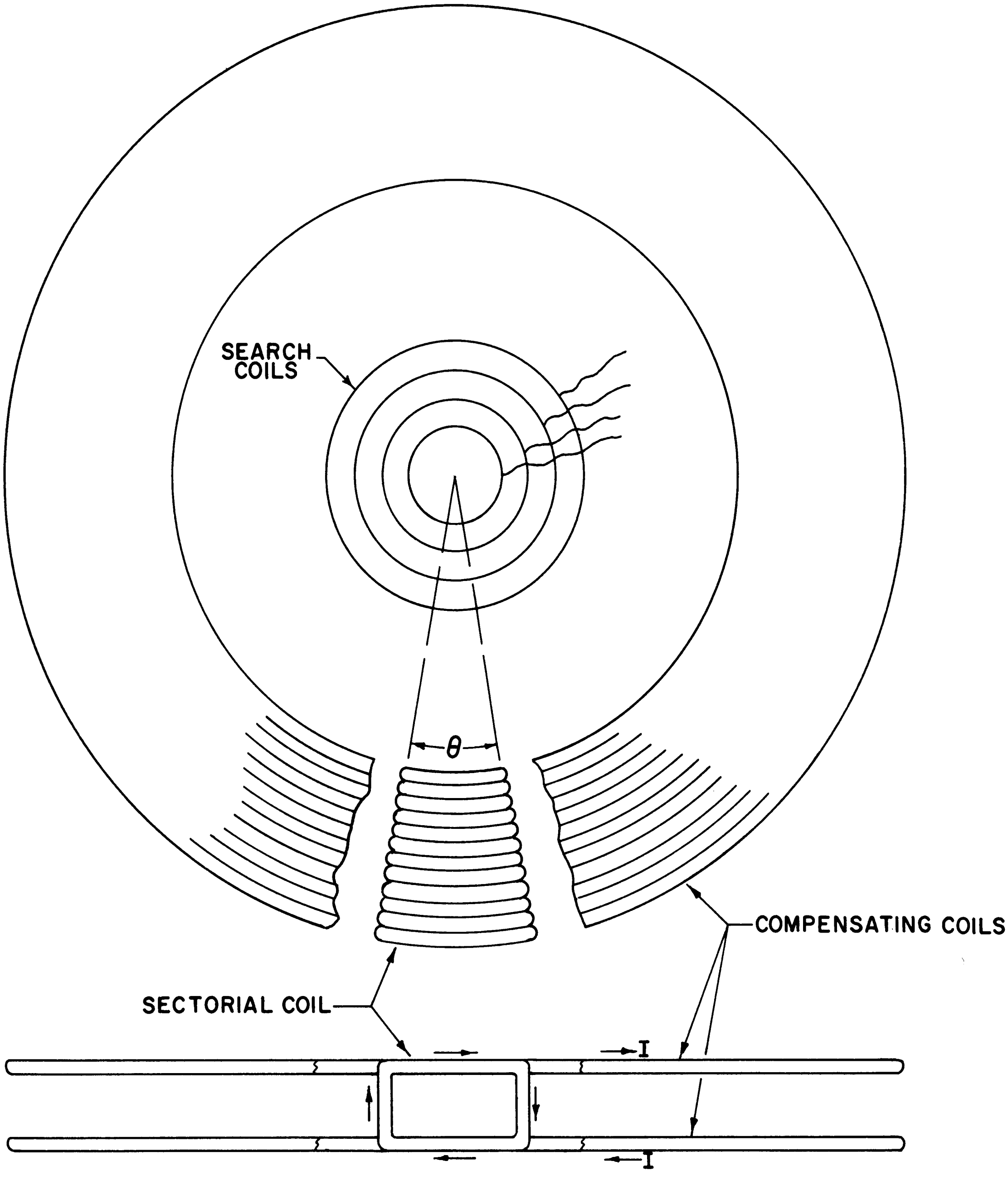

Figure 3. The Sectorial Coil, for Rapid Experimental Approach to Magnetic Lens Design. Experimentally, the Sectorial Coil Replaces the Complete Compensating Coils.

the single sectorial coil shown, Figure 3. It is far cheaper and easier to wind; but can its use be validated? It can be, provided the field exploration is done by use of concentric search coils as shown.

Suppose the sector angle for the sectorial coil is 1/20 of 360 degrees. Then the total flux put through any search coil is precisely the same, for a given sectorial coil current, as it would be for the whole coils operated at 1/20 of that current. This is an outcome of axial symmetry. It is perhaps most easily seen by imagining that 20 sectorial coils could be placed around the circle, with the vertical sides coincident. The upward current of one side would cancel the downward current of the next, and the resultant currents would precisely be those of real compensating coils.

Except for separation change, the variations described above for the compensating coils (up or down, and change of current ratio) can now be carried out with the one sectorial coil.

Also, additional variations are possible. Within limits, the sectorial coil can also be moved in or out; and also, tilted. This adds two degrees of freedom, either or both of which might be all-important in arriving at the desired distribution. It is true that if either of these additional variations is resorted to, the sectorial coil is no longer a precise sector increment of the total coils it represents. However, such movements, within limits, could greatly reduce the trial-and-error work, thus soon leading to winding a new sectorial coil that would more closely be a true sectorial of the now-indicated compensators.

The Half-Helmholtz coil described herein has its operating plane about one-half inch below the top of the top compensator. It seems entirely possible that with the sectorial coil approach, a design could be worked out with the plane completely above any and all coils.

Volume Field Shaping

Insteady of getting a desired field through only one operating plane, it may be necessary to achieve a particular field conformation within a volume. This might call for more than one main field coil, and more than one compensating pair. The investigation now would include two or more plane-mounted concentric search coils distributed along the axis, with all sets alike. Using two search coils of the same diameter, but separated by a short axial distance, radial field components can be measured.

The sectorial coil opens up another possibility. Some desired field conformation within a volume might be achieved with one main coil and one pair of compensators, if we had complete freedom in shaping and locating each section of the two compensator coils. This opens up so many things to try, that at first, the idea seems distasteful. But experimentally, one could begin with winding a number of sectorials, all short, all alike as to angle, but of different axial dimensions. Three or four such, adjusted as to current, position in and out, position up and down, and as to tilt, might, with intelligent watching of results, soon indicate the answer. Their combined positions and strengths would indicate the design of the two compensators; and these might come out with very odd sections indeed.

So many workers have used so many coils for so many purposes, that a search of the literature to determine novelty for the sectorial coil concept would be almost hopeless. Also, it is certain that many designs have never been published. However, all who have been approached with these ideas have found them to be new in their experience.

CONCLUSIONS

1. A Half-Helmholtz coil combination has been designed, built, and tested, which, in effect, removes the upper Helmholtz coil, places it below with the lower coil, and, by using opposing compensator coils, achieves a quite uniform vertical flux density in a considerable area of the operating plane. The Half-Helmholtz coil idea appears to be new.
2. This combination gives very high access to the uniform field through the operating plane. It may thus become the design of choice, in cases where allied apparatus would require so much space that Helmholtz coils would become unduly large.
3. There seems to be the possibility that, with the sectorial coil approach, the Half-Helmholtz design could be optimized; also, one might get the operating plane completely above all coils.
4. For magnetic lens design, using the above combination (or even more than one main coil and more than one compensating pair) an apparently new idea - the sectorial coil - is described, by which the experimental trial-and-error approach to a design can be much facilitated. Instead of winding both compensators for a trial, a single small sectorial coil is wound, and tried with various positions and current strengths. The sectorial coil, in combination with concentric search coils, magnetically replaces the complete compensators, for experimental purposes. When the right combination is found, the sectorial coil directly dictates the design of the compensators.

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1. Moore, A. D. "Electrospherics and Magnetospherics." Electrical Engineering, Part I, February 1959, pages 148-155; Part II, March 1959, pages 229-235.

2. Moore, A. D. "Electrospherics and Magnetospheric Phenomena." AIEE Transactions, Communications and Electronics, Vol. 81, 1962. (Much the same as 1, but brought up to date in some respects.)