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ADDITIONAL LINE-OF-SIGHT METHODOLOGY TO THAT PRESENTED BY JOHN W. STROHBEHN IN "THE USE OF LINE-OF-SIGHT MICROWAVE PROPAGATION IN REMOTE ATMOSPHERIC PROBING"

C. I. Beard

Boeing Scientific Research Laboratories

Seattle, Washington 98124

ABSTRACT

These remarks present some promising microwave and infrared techniques, not covered in Strohbehn's preceding paper, which are now being tested in line-of-sight tropospheric scattering. Newly measured parameters of the incoherent scattered microwave field are sensitive to wavefront sphericity, to wind speed, and to the eddy wavenumber spectrum. A recommendation for advancing the state of the art is given by a proposed experimental program.

1. INTRODUCTION

These remarks were made following the paper by Strohbehn (1968). Since the writer is in general agreement with Strohbehn's points, except for the topic in Section 6 below, the following remarks present information on some promising line-of-sight measurement procedures additional to those given by Strohbehn. These techniques have only relatively recently been applied to line-of-sight tropospheric paths; the information on them is mainly in Company reports and thus not widely distributed. Therefore, the intent of these comments is primarily to supplement and complement the presentation of Strohbehn by bringing this material to the attention of the Panel. The topics are listed in the following Sections; references given by Strohbehn are not repeated to save space.

2. MEASUREMENT OF INTEGRATED MICROWAVE INDEX OF REFRACTION

Since microwave methods respond only to the microwave index of refraction of the atmosphere, Professor Strohbehn touched on some measurement methods. In addition to the approaches at ITSA/ESSA and MITRE, however, the writer wants to acquaint this Panel with a different type of method, an infrared transmissometer, developed by Tank (1967) at Boeing Scientific Research Laboratories (BSRL). Briefly, an infrared line-of-sight beam is split into three parts, each filtered by a bandpass filter; one is in a window at 2.12 microns (μ), one is in an oxygen absorption band at 1.27 μ, and the third is in a water vapor band at 1.86 μ. Ratios of the O_2 and H_2O intensities to the window intensity are taken to cancel scintillation; these ratio signals then provide the instantaneous values of the line-integrated values of the dry and wet terms of the index of refraction equation, and they can be combined to give n. In connection with Strohbehn's comment that M. C. Thompson has suggested a method of measuring the integrated index of refraction using two optical wavelengths and one at microwaves, it should be added that the three wavelength IR system results are to be combined with K-band (20-26 GHz) results of Kreiss (1967) to improve the overall accuracy of the determination of n.

In future line-of-sight experiments some one of these methods for measuring integrated index of refraction along the path should be included. This is especially true for the longer paths, say 10 to 50 miles, on which microwave measurements have actually been made in the past as a function of meteorological data taken at each end of the path but without really knowing the intervening medium. In those days the methods mentioned above were not available, but now there is no excuse except the deepening money crisis. (See Section 4 for related remarks.)

3. SPHERICAL WAVES

In different places of Strohbehn's report (Parts II and V), he has mentioned the little attention given to spherical wavefronts and the need for more work. The writer wants to support this view and add an additional voice to the need for more work in this direction. This opinion is based on experimental results showing the importance of sphericity (Beard, 1962). Since the subject is important to the interpretation of experimental results, the following references to theoretical work by deWolf (1967), Twersky (1963), and Ishimaru (1968) are being added to those given by Strohbehn. Further remarks on sphericity will be made in Section 6.

4. AGENCY FOR METEOROLOGICAL EQUIPMENT

Strohbehn's suggestion for "an agency through which one could secure either funds for or temporary loans of meteorological equipment" is a suggestion which should be given the full backing of this Panel. The need for such equipment and thus for such an agency becomes obvious upon reading the published literature describing microwave propagation experiments, line-of-sight or otherwise. Equipment such as the path-integrated index of refraction methods mentioned in Section 2, microwave cavity refractometers, etc., whose primary functions are to obtain meteorological parameters, are too costly for the budgets of many experimenters. One of the Panel participants mentioned that NCAR has a program of this type; this is commendable. The writer strongly recommends that this Panel make, or recommend the making of, a study of the type and level of overall program desirable. An effective lending program could significantly raise the national level of the quality and meaning of propagation research.

5. ARRAY MEASUREMENTS

An antenna array with which the field is sampled at several points in space simultaneously (essentially) is obviously a desirable, worthwhile device as shown by the results of Lee and Waterman (1966). The mathematical extensions developed by Lee, as reported on quite favorably by Strohbehn, offer new possibilities, especially that of measuring the transverse wind at ten positions along the path.

Consideration should also be given to the "depth of focus" and the "diameter" of the focused volume in comparison to the eddy scale sizes, to the number of such eddies within the contributing focused volume, and to the amplitude and phase structure of the focused field over the eddies included in this volume. Such information, along with the type of statistical treatment to be used with this information, are also needed to estimate the resolution and accuracy of the method. It is to be hoped that resolution tests will be performed against measured wind velocities at the path altitude at various locations along the path length. The system capabilities obviously warrant tests of this type.

The second use of the array given by Strohbehn is to determine C_n^2 at different points along the path. The only comment here is to point out that this approach involves an even more restrictive assumption (that of a wavenumber spectrum for locally-homogeneous, isotropic turbulence) than those assumptions for the single receiver (Taylor's hypothesis and homogeneity). The third array approach, of trying to determine the wavenumber spectrum, is a task the "phase quadrature" experiment (described in Section 6 below) is also set up to investigate.

6. PHASE QUADRATURE MEASUREMENT, USING ONLY ONE RECEIVER

The author wants to acquaint the Panel with a new way of extracting useful information from the single path, only one receiver configuration. Professor Strohbehn has essentially "written off" this type of experiment for three reasons. His first, that Taylor's hypothesis must be assumed, does not seem too critical in view of some confirming tests reported in the literature. The second, the assumption of homogeneity over the path length, is a severer requirement to satisfy. The third reason results from his considering only relative phase variations of the total received field (and/or angle of arrival variations with two receivers); he rightly states that these are insensitive to atmospheric models. The writer wants to point out that by considering the full amount of information available in the system, one can obtain the statistics of the phase quadrature components of the incoherent scattered field itself, which is the entity produced by the fluctuating medium and thus most sensitive to it.

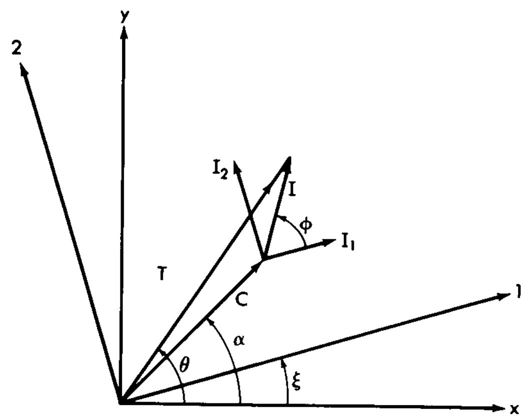

Figure 1. Phasor Diagram of the Received Field and its Components.

Figure 1 showing the phasor diagram is included merely for clarity. T is the instantaneous magnitude of the total received field at an instantaneous phase θ, I is the instantaneous magnitude of the random incoherent field with phase quadrature components I_1 and I_2, and C is the magnitude of the time-average coherent field at a fixed phase α, with all phases referred to, say, the transmitted field along the x-axis. The fields are resolved along two phase quadrature axes, 1 and 2, which can be rotated to any desired angle ξ. Because of the coherent field on a line-of-sight path, it is qualitatively clear from Figure 1 that the phase (θ) of the total field is not sensitive to the statistics of the incoherent field; Beard (1962) has shown this insensitivity quantitatively in a laboratory type of "line-of-sight" path at the same time that the phase quadrature components were measured to show the actual incoherent field statistics.

The phase quadrature method determines several parameters which may be useful in characterizing the medium:

1) The statistics of the phase quadrature components of the incoherent scattered field (such as probability distributions, variances, spectra, correlations, etc.).

2) The incoherent power $\overline{I^2} = \sigma_1^2 + \sigma_2^2$.

3) $K^2 \equiv (\sigma_2^2/\sigma_1^2)_{max}$ = the maximum ratio of the variances of the phase quadrature components ($K^2 \equiv \geq 1$).

4) The phase rotation angle (ξ in Figure 1) of the axes to obtain the maximum value of K^2; this is the rotation angle of the equiprobability ellipse.

Examples of a few of these parameters are becoming available from a tropospheric experiment (Beard, 1968) which was set up just for the purpose of investigating the relationship of these parameters to the scattering medium. On a 3.57 km path the phase quadrature components show that the incoherent field lies almost entirely at a phase angle of $\pm$ 90° with respect to the coherent field, $K^2 >> 1$, and this component is closely normally distributed. This result agrees with the near field model of Wheelon and Muchmore (1955) and is consistent with the scale sizes encountered. In Figure 2 is shown a calculated power spectrum for this larger quadrature component (at $\pm$ 90° to C); the interesting feature is that it drops four orders of magnitude with a - 8/3

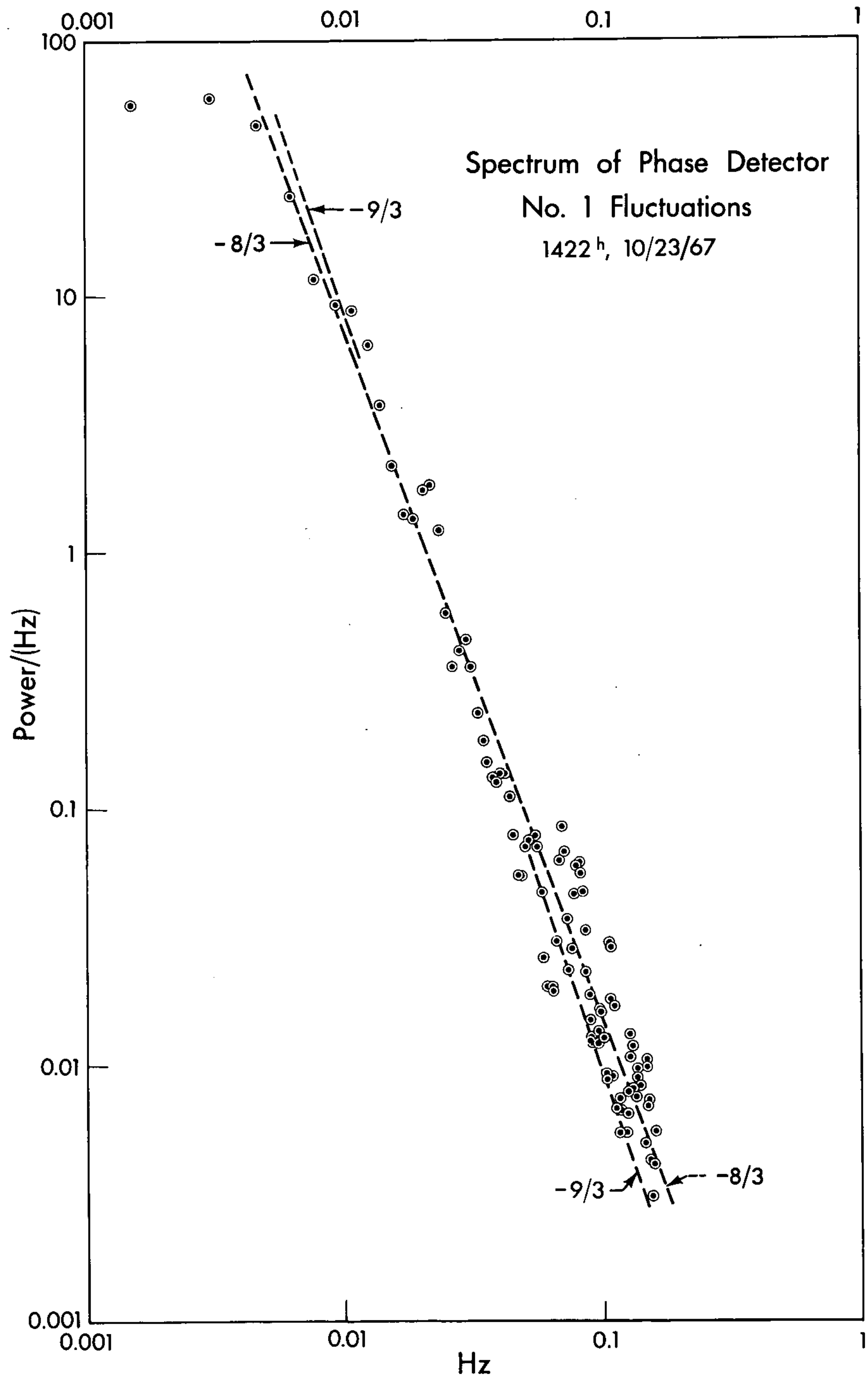

Figure 2. Power spectrum of the incoherent field component in phase quadrature to the coherent field.

(or possibly - 9/3) slope, but definitely not a - 7/3 or - 10/3 slope. (A one-dimensional $\kappa^{-5/3}$spectrum integrated along the path becomes a $\kappa^{-8/3}$spectrum.) This result relates to the question of Strohbehn (page 14 of his paper), "Can an experiment differentiate between a $\kappa^{-11/3}$turbulence spectrum versus a κ^{-4}or a κ^{-3}spectrum?" It might also be mentioned that even in this first spectrum, the scale size information extends over a range of approximately 1.5 decades. Whether information content down to scale sizes limited by aperture smoothing can be obtained depends on signal-to-noise ratios obtainable from magnetic tape reduction in the future.

There is an indication that there may be a relationship of the incoherent power to the wind speed, but with the few data available one should say only that the point looks worth pursuing.

One of the promising exploratory features of this method is the use of the ratio $K^2 = (\sigma_2{}^2/\sigma_1{}^2)_{max}$. This ratio is sensitive to the sphericity of the illuminating and receiving wavefronts (Beard, 1962), and it is most sensitive in the "mid-field" region. Since K^2 is sensitive to the eddy scales, this writer advances the hypothesis that K^2 can be used to explore the eddy wavenumber spectrum by examining K^2 for various frequency "slices" of the power frequency spectra of the two phase quadrature components of the incoherent field. The low fluctuation frequencies should be associated with the larger scale sizes, and the high fluctuation frequencies with the small scales. K^2 should thus be large at the low frequency end of the spectrum since near-field conditions are approached, and K^2 should decrease toward the high-spectral frequencies as far-zone conditions are approached for smaller scale sizes. The one test that has been made with the spectra of the two components is encouraging and warrants a full test of the hypothesis.

The fourth parameter ξ, the phase rotation of the equiprobability ellipse, may be rotated with respect to the coherent field (Beard, 1962), and the writer has also found that the rotation angle may change with sphericity in rough surface scattering. Whether such behavior occurs in this particular tropospheric experiment is not known yet and awaits digital reduction of the magnetic tape data.

Since the "mid-field" region is related to a phase delay $k\ell^2/8L$, where $k = 2\pi/\lambda$, ℓ is the eddy scale size, and L is the path length, there are clearly three variations on the line-of-sight theme to change the sphericity:

a) A multi-wavelength experiment (with the same antenna beamwidths) seems best since the meteorology remains constant.

b) Two paths of different length L; the obvious difficulty is to traverse nearly the same atmospheric conditions.

c) The third method is to make measurements in various weather conditions, letting the weather change the scale sizes.

In summary, in this method of measuring the phase quadrature components of the received field at one receiver, four parameters of the incoherent scattered field are determined. Various of these parameters are sensitive to the eddy wavenumber spectrum, the wind speed, and to the sphericity of the transmitting and receiving wavefronts. A hypothesis is advanced to use one of these parameters, K^2, as a means of exploring the eddy size wavenumber spectrum.

7. A PROPOSED EXPERIMENT

Out of this comparison emerges the outline of a line-of-sight experiment *supreme*. It incorporates the most encouraging features of the newer programs and must be performed over a fully meteorologically instrumented path. It should include the following:

a) A phase and amplitude array experiment (Section 5 above) in both the horizontal and vertical planes, operating simultaneously.

b) A "phase quadrature" experiment (Section 6 above) on the field received by the center antenna of the array and operated simultaneously with the array. (A phase reference link from the transmitter to the receiver is required.)

c) A path-integrated microwave index of refraction measurement (Section 2 above) made simultaneously with (a) and (b) above, possibly by the infrared-K-band system now in operation.

d) Comprehensive meteorological measurement of the path, for example, wind velocity at the path altitude at various points along the path, wide spectral response recordings of many parameters such as temperature and humidity, microwave refractometer index of refraction, wind shear, shadowgraph photographs for transverse scale sizes, etc.

The very magnitude of this program in terms of complexity and variety of equipment, expense, manpower, data processing, etc., indicates that a cooperative program and/or facility of some kind might not be inappropriate.

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COMMENTS ON PAPERS BY DRS. STROHBEHN AND BEARD

by
Akira Ishimaru

Department of Electrical Engineering
University of Washington
Seattle, Washington

I have a number of points to make concerning the presentations of both Drs. Strohbehn and Beard. They are as follows:

1. On the assumption $\lambda \ll l_0$.

There are two possible ways to relax this assumption.

(a) The assumption is basically equivalent to taking the saddle point approximation of the integral; therefore the assumption may be relaxed (Bremmer, 1964).

(b) Tatarski's argument of using $\lambda \ll l_0$ is based on the plane wave case. Other waves, such as spherical and beam waves may not require this condition. In particular, the beam wave theory does not seem to require such an assumption.

2. Importance of the filter function for beam waves.

The spectrum of the field at an observation point is a product of a filter function and a power spectrum of the index of refraction. The filter function for the plane wave is well known (Tatarski). But the filter function for the beam wave has an additional factor involving the size of the beam. Thus, depending on whether the beam size is large or small compared with the inner and outer scale of turbulence and the Fresnel radius for the distance, we would expect different spectral behaviors; this may be useful in probing atmospheric characteristics.

It may also be noted that the beam spreading and the fluctuation characteristics of the focused beam, which is now under study, may yield additional information.

3. Measurement of the structure function.

Since atmospheric turbulence is basically nonhomogeneous, and is better approximated by Kolmogorov local homogeneity, its characteristics may be better measured by structure functions rather than by covariance functions. The amplitude fluctuations are basically homogeneous due to the effect of the filter function, but the phase fluctuation is affected much more by the outer scale of turbulence. Thus, the measurement of the phase structure function may be more useful.

4. Difference between the average and effective refractive indices.

Recently, Tatarski and Keller made an extensive study on the propagation of the average field and corresponding effective refractive index, n_{eff}. For example, for scalar waves

$$(\nabla^2 + k^2 n^2) = O \text{ , and}$$

$n = \bar{n} + n_1$, where $\bar{n}$ = average index of refraction and n_1 is the fluctuation. Then

$$(\nabla^2 + k^2 n^2_{eff}) \bar{u} = O$$

where $\bar{u}$ is the average field, and n_{eff} does not equal $\bar{n}$ but depends on the correlation function of n_1. This difference may have to be taken into account when considering the absolute path. especially when the fluctuation is significant.

5. Regarding Dr. Beard's experiment.

Dr. Beard's phase quadrature experiments seem to be quite consistent with the theoretical results outlined by Dr. Strohbehn. As is well known, at short distance, the mean square fluctuation increases as L (distance) while the mean square amplitude fluctuation increases much more slowly as L^3. On the other hand, at large distances, the mean square phase and amplitude fluctuations are about the same. Beard's results appear to correspond with these predictions. On the other hand, the Russian workers observed that the log-amplitude seems to obey Gaussian statistics in their optical experiments. This should be compared with the statistics which Dr. Beard is investigating.

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