LINE-OF-SIGHT MICROWAVE PROPAGATION

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ABSTRACT

In the following paper a review of the uses of microwave line-of-sight propagation in remote atmospheric probing is given. The review concentrates on use of the following types of measurements: (1) the use of total electrical path length for measuring average density and water vapor content; (2) the use of amplitude and phase fluctuations over a single path for determining the form of the turbulence spectrum; (3) the use of angle-of-arrival data for measuring the decrease in refractivity; and (4) the use of multiple-element receiving antennas in determining wind speed, atmospheric parameters, and atmospheric models. The paper has not included a study of absorption effects, scattering by rain, fog, snow, or hail, or the effect of ducts.

A review is given of the connection between microwave measurements and meteorological parameters, and the basic electromagnetic theory on which the analyses are made. A few suggestions for future work in these areas is given.

1. INTRODUCTION

The major objective of the following paper is to assess the feasibility of microwave line-of-sight experiments in investigating significant meteorological problems. It is probable that such a paper will reveal more about the strengths, weaknesses, and prejudices of the author than about the feasibility of remote probing. A review of the literature reveals that the emphasis on the use of the radio experiments to study the atmosphere is somewhat unusual. The major effort in radio experiments has been to predict the significant propagation characteristics affecting microwave systems with the smallest number and most easily obtainable meteorological parameters. In many situations the meteorological parameter studied has only an indirect relation to the meteorological parameter that directly influences the propagation of radio waves. Though this approach is of tremendous utility to the radio, communication, or systems engineer, it usually makes this type of data of relatively little significance when attempting to answer the reverse question about the feasibility of studying meteorological parameters with radio waves.

In selecting and discarding topics to include in this report some fairly arbitrary decisions had to be made. Furthermore, some topics were given a rather light treatment because of this reporter's lack of deep knowledge on the subject. The topic of atmospheric absorption and its use in studying the constituents of the atmosphere has been excluded on the grounds that it is an area that has been studied in some detail in the past, and can also be included under the heading of radiometry. The topics of scattering of microwaves by rain, snow, fog, or hail has been excluded for two reasons: First, it has been fairly extensively studied previously, and second, techniques such as high powered radars are much more useful in giving a detailed picture. The study of strong inversions or radio ducts has been excluded mainly because of a lack of knowledge, but could well be very relevant. This area also overlaps with beyond-the-horizon propagation, and possibly can be studied more effectively there.

The topics which have been included are: (1) studying the average total refractivity along a path by measuring absolute electrical path length; (2) studying the fluctuations in the atmosphere using phase fluctuations at one or two receiving sites; (3) studying the decrease of the refractive index with altitude by studying angle-of-arrival information; and (4) studying fluctuations in the atmosphere using a multiple-element array as a receiving antenna.

The paper has been divided into the following sections. In Part 2, the relation between meteorological parameters and microwave measurements, it is shown that radio measurements can only measure variations of the refractive index, and conclusions about meteorological parameters are inferences drawn from these measurements. In Part 3, theoretical background, it is shown that the formulas used in the microwave region are actually derived for the optical wavelength range and that further work is needed both in extending the results for longer wavelengths and in approximating actual experimental configurations. In Part 4, possible experiments, the experiments mentioned previously and their relation to meteorological quantities are discussed. In Part 5, related programs and future developments, a few suggestions for improving future work are given. In Appendix 1, the important formulas, pertinent equations and their limitations are reviewed.

2. THE RELATION BETWEEN METEOROLOGICAL PARAMETERS AND MICROWAVE MEASUREMENTS

From the point of view of the radiophysicist attempting to explain microwave measurements, the atmospheric quantity of direct interest is the dielectric constant, ε, or equivalently the refractive index, $n(\varepsilon = n^2)$. In this paper the term dielectric constant refers to the relative dielectric constant referred to the free space value, ε_0. Since in the atmosphere n is very close to 1, it is common to define a more sensitive parameter, the refractivity N, as $N = (n-1) \times 10^6$.

The relationship between the refractive index and meteorological parameters is normally a function of the frequency of the electromagnetic wave and the constituents of the atmosphere, and may be expressed in the following form [Bean, 1966]

$$N = \frac{A'_{N1} P_{N1}}{T} + \frac{A'_{O} P_{O}}{T} + \frac{A'_{WV} P_{WV}}{T} + \frac{A''_{WV} P_{WV}}{T^2} \tag{2}$$

where P = pressure, T = absolute temperature, N1 = nitrogen, O = oxygen, and WV = water vapor.

The constant A' gives the polarization effect due to distortion of charge distributions, and A" is the effect associated with the orientation of polar molecules. Neither nitrogen nor oxygen have permanent electric dipole moments, so that only water vapor contributes a significant A" term. Since the composition of dry air normally maintains a constant ratio of nitrogen to oxygen, eq.(2) may be written as

$$N = 77.6 \frac{P_{DA}}{T} + 72 \frac{P_{WV}}{T} + 3.75 \times 10^6 \frac{P_{WV}}{T^2} \tag{3}$$

where DA = dry air. The commonly accepted values for the constants have been inserted. It may be shown that the influence of other gases, mainly carbon dioxide, cause less than a 0.02 per cent error. Assuming normal atmospheric parameters, eq.(3) is considered valid for frequencies up to 30 GHz. The water vapor resonance at 22 GHz and the oxygen resonance at 60 GHz causing little effect below 30 GHz [Bean, 1966].

If rainfall and absorption effects are ignored, all information about meteorological or atmospheric parameters that can be learned from microwave measurements must be inferred from their influence on eq. (3). Microwave measurements can be used to measure average spatial and time values of N or spatial and time fluctuations about the average value. Inferences about the temperature, pressure, water vapor content, wind velocity, turbulence or other atmospheric parameters must come from assumptions about the influence these parameters have on eq.(3). It is apparent that since N is a function of three parameters, P_{DA}, P_{WV}, and T, that it is impossible to unravel the influence of any one of these parameters without more measurements, or a priori knowledge about the influence of these parameters. Furthermore, since eq.(3) is reasonably independent of frequency in the microwave region below 30 GHz, multiple frequency experiments cannot easily overcome this limitation. It is worth noting that a combination of microwave and optical measurements can be very useful in separating water vapor and dry air effects.

Because of the fluctuations in temperature, pressure, and water vapor, the refractive index is a random function of both space and time: n(x,y,z,t). If a time average is taken over some reasonable period (the amount of time will be dictated in practice by the phenomena that are being studied), then short term fluctuations are removed and gross average features become apparent. For example, it is often assumed that $\langle n(x,y,z,t)\rangle$ is only a function of altitude, $\langle n(x,y,z,t)\rangle = f(z)$.

When studying average refraction effects, only the f(z) variation is taken into consideration. However, for some problems altitude effects may be negligible but local terrain effects lead to considering the differences in the average value of n at different locations, $\langle n(x,y,z,t)\rangle = g(x,y)$. For example, if a propagation path passes partly over land and partly over water it is reasonable to expect the average value of the refractive index to be different in the two locations.

In many applications the gross features are ignored and only the fluctuations are of interest. In these problems the expected value of n is often assumed to be constant, $\langle n(x,y,z,t)\rangle = n_0$, and the spatial or time fluctuations are studied. In most cases it is the spatial covariance function (or its associated Fourier transform) of n that is considered:

$$C_n(\underset{\sim}{r}_1,\underset{\sim}{r}_2) = \langle [n(\underset{\sim}{r}_1) - n_0][n(\underset{\sim}{r}_2) - n_0]\rangle$$

$$\Phi_n(\underset{\sim}{\kappa}) = \frac{1}{(2\pi)^3}\iiint_{-\infty}^{\infty} C_n(\underset{\sim}{r})\, e^{i\underset{\sim}{\kappa}\cdot\underset{\sim}{r}}\, d\underset{\sim}{r} \qquad (4)$$

In general, of course, it is possible to combine the two effects and study them together. It does not appear that we have advanced far enough to take that step at this time. One comment should be made about the proces of averaging. The amount of information to be gleaned from an experiment will be highly dependent on the investigator's skill at analyzing the data. It is customary to make many simplifying assumptions when proceeding with this analysis. Unfortunately it is not uncommon to make an assumption that will hide a great deal, if not all, of the physical meaning of the data. For example, if data is averaged over widely varying meteorological conditions it is virtually impossible to relate the data to any meaningful atmospheric model. As another example, if there is a trend in the data over the sampling time, it can rarely be uncovered if the data analysis assumes a stationary process. Unfortunately there has been very little work concerned with the basic problems of geophysical data analysis. Data analysis, at the present time, relies mostly on the intuitive skill of the investigator.

If the atmosphere is pictured as a medium composed of eddies or blobs having different dielectric constants, and it is assumed that as the wind blows these eddies move with the air, but remain essentially unchanged ("frozen hypothesis"), then determination of the motion of the dielectric blobs corresponds to a measurement of the wind velocity. (This assumption appears to be more justified the smaller the size of an eddy.) On the other hand, it is conceivable that other changes could also give apparent velocity motions which are not related to the actual motion of the air. As an example, any type of wave motion, such as gravity waves, could produce this type of effect. Again, there is no method of separating these effects using radio measurements. Either meteorological measurements need to be made, or knowledge about the physical limitations of one source of apparent motion versus another source must be used.

The atmospheric physicist often encodes his knowledge of small scale atmospheric motions in terms of a velocity spectrum, $\phi_v(\kappa)$. In particular, it is often assumed that the conditions in the atmosphere can be described using a homogeneous and isotropic turbulence model. Under these conditions, it has been shown [Tatarskii, 1961], that the spectrum of a conservative passive additive will have the same form as the velocity spectrum. Using these results, it can be argued that the spectrum of the refractive index variations is identical in form to the spectrum of the velocity fluctuations. Therefore, measurements on the refractive index spectrum using microwave measurements can be directly related to the shape of the velocity spectrum.

3. THEORETICAL BACKGROUND

In assessing the theoretical formulations available to understand line-of-sight microwave propagation, it appears that there exists no careful formulations of the problem. Most workers have used either ray or geometrical optics or adapted diffraction theory results derived for optical wavelengths. Furthermore, the diffraction theory results have only been worked out in great detail for the plane wave case, and just recently expressions have appeared assuming a spherical wave and a finite antenna beam at the transmitter. Literature concerning the question "Given a particular set of experiments, what and how accurately can various meteorological parameters be ascertained?" is virtually non-existent. (Even when radio experiments are used to infer meteorological parameters, it is unusual for the uncertainties or statistical significance of the results to be discussed).

The most complete treatment of the basic theoretical formulas is probably included in the monographs of Tatarski [1961, 1967]. In these works the different approaches to the electromagnetic problem are derived starting from Maxwell's equations, and it is possible to examine the approximations involved. Despite the orientation of these books towards optical propagation, it is explicitly stated where and why the derivations become invalid for longer wavelengths.

In the derivation of these equations, it is always assumed that only the scalar wave equation need be used. This assumption is equivalent to assuming that the scattered depolarized field is much smaller than the scattered field in the original direction of polarization. The condition under which this is assumed valid is for $\lambda << \ell_0$, where ℓ_0 is the inner scale of turbulence. For scale sizes smaller than ℓ_0, it is assumed that there is no significant energy in the turbulence. In order for polarization effects to be important there must be a significant gradient in the refractive index, i.e., a significant change in the refractive index must occur in a distance of the order of a wavelength or less. In the atmosphere $\ell_0 \approx 1$ to 10 millimeters, and at optical wavelengths the condition $\lambda << \ell_0$ is easily satisfied. However in the microwave range the condition $\lambda << \ell_0$ is no longer true, and it is necessary to make a much more careful analysis starting from the vector wave equation. To this person's knowledge such an analysis has not been done (a graduate student and the author are presently trying to solve this problem and have obtained some preliminary results.) It seems apparent that the restriction $\lambda << \ell_0$ is much too strong when concerned with depolarization effects and it should be possible to relax it considerably. It therefore seems reasonable that the scalar wave equation should still be valid even over much of the microwave range. Unfortunately, this still does not immediately permit the use of the optical equations, since the condition $\lambda << \ell_0$ is used in other places in the derivation. (See note at end of paper)

If a geometrical optics or ray tracing approach is used, the additional condition, $L << \ell_0^2/\lambda$, is required. This condition arises from analyzing the path lengths for which diffraction effects should become important when considering the scattered field. Even for $\ell_0 = 10$ mm, this condition would appear to make geometrical optics of questionable validity for all microwave experiments. This statement, however, needs to be qualified. First of all, the restriction arises from considering when diffraction effects become important, but without carefully analyzing the importance of this effect on different quantities, e.g., amplitude or phase. By the very nature of diffraction it is expected that it will affect the amplitude results much more strongly than the phase. Also it seems reasonable to expect that the diffraction effects are much more important when considering fluctuations about a mean value compared to considering the mean value itself. Secondly, the given conditions are sufficiency conditions. If the conditions are met the theoretician believes his results will agree with experimental observables. However, there is no way to guarantee that a much weaker set of conditions does not exist under which the derived results will still hold.

If a wave optics approach is used the present derivations relax the condition $L \ll \ell_0^2/\lambda$, but retain the condition $\lambda \ll \ell_0$. In the early optical work the Born approximation (single scatter theory) was used, but later workers have primarily concentrated on Rytov's method (multiple scatter theory). For microwave propagation there does not seem to be any inherent advantage of Rytov's method over the Born approximation, but the results from Rytov's method will be used as they are more carefully developed in the literature. Both approaches are essentially perturbation solutions of some form of the wave equation, and are only valid for fluctuations that are small compared to the mean value. This condition is well satisfied for almost all conceivable microwave paths in the earth's atmosphere. The importance of the assumption $\lambda \ll \ell_0$ in these equations appears to need further work. This assumption is not only used in neglecting the depolarization term, but also to argue that the scattered radiation is confined to a small angle about the original direction of propagation. It is this further assertion that is difficult to justify. As the wavelength approaches the size of a turbulent "blob" or eddy, it is reasonable to expect wide-angle scattering. While this wide-angle scattering may not be important for phase effects, it may well be influential with respect to amplitude fluctuations. If wide-angle effects are important the influence of finite antenna beams must also be considered. In Appendix I a summary of the basic formulas and their restrictions are given.

Until recently all the theoretical developments were based either on ray tracing or plane waves. The more general problem of spherical waves and finite antenna beams has received very little attention. Recently there have been several papers [Schmeltzer, 1967; Carlson and Ishimaru, 1967], again concerned with optical propagation, that have studied this problem. As yet, the importance of these considerations in given experimental configurations is not well understood, and needs to be studied further. However, it is reasonable to expect that the restriction $\lambda \ll \ell_0$ is much less important for spherical or beam waves than for plane waves.

The final type of study, which seems extremely scarce in the literature, is a theoretical analysis of the utility of microwave experiments in remote sensing. In other words, given some meteorological parameter that it is desired to investigate via microwave measurements, how accurately can the parameters be measured.

The following type of questions need to be answered: (1) Does the measurement determine a spatial average over the entire path or can localized properties be determined? If so, how localized? (2) How accurately may meteorological quantities, such as wind velocity, temperature, and humidity, be measured? (3) How sensitive is the measurement to different realistic models for the atmosphere? For example, can an experiment differentiate between a $\kappa^{-11/3}$ turbulence spectrum versus a κ^{-4} or a κ^{-3} spectrum?

Unfortunately very little of this type of analysis appears in the literature, the most notable exceptions are papers by Muchmore and Wheelon [1955] and Strohbehn [1966], which are directly concerned with the sensitivity of line-of-sight experiments in determining the turbulence spectrum. Presently Robert Lee at Stanford is carrying out this type of analysis and some of his results are available elsewhere in this report.

It appears that there are two areas of theoretical work that need to be pursued before definitive statements about the possibilities and limitations of microwave line-of-sight propagation can be fully assessed with respect to remote probing of the atmosphere. First, there is the need for further basic theoretical work concerned with line-of-sight propagation in the microwave frequency range. This work will either verify the extension of geometrical optics or wave optics results into the microwave region, or will produce new expressions which should be used. This work will undoubtedly be done first assuming a plane wave source and must be extended to include the more practical case of spherical waves and finite antenna beams. Second, there is a need for careful theoretical analysis of what can and cannot be learned from specific experimental measurements. In other words, the type of analysis that will answer the kind of questions raised above.

4. POSSIBLE EXPERIMENTS

In analyzing the feasibility of using radio measurements as a tool for studying the atmosphere, a quick survey of the literature reveals that you are fighting the crowd. While there is a great deal of literature on different types of propagation experiments, the emphasis is on predicting the propagation effects with the simplest meteorological parameters possible. In a large number of papers there is no mention of meteorology at all; in others the objective is to predict the radio effects using the simplest meteorological measurement. While this objective is certainly entirely proper and desirable for communication and system studies, such as predicting range rate error or pointing error, it makes a great deal of the work of very minor importance for remote probing studies.

Therefore, in estimating the value of certain types of studies, it was necessary to make estimates based on very little direct information and a large amount of guess work or intuition. As a result, the opinions given should be taken quite tentatively.

4.1 Absolute Path Length Measurements

In geodesy it is necessary to determine the actual path length between two points as accurately as possible. When using radio means, the relation between the radio electrical length and the actual path length is given by

$$L_f = L(1 + \overline{N}_f \times 10^{-6}) \tag{5}$$

where L_f = radio electrical length measured at frequency f, L = actual path length, and $\overline{N}_f$ = the refractivity at frequency f averaged over the entire path. If L were known accurately enough then the above relation could be used to find the spatial average of $\overline{N}_f$, the quantity of interest in remote probing. However, the geodesist has found that it is easier and more accurate to find L by radio means, and one of his problems is to remove the error introduced by $\overline{N}_f$. Therefore it is unreasonable to expect that L will be known accurately, and that $\overline{N}_f$ can be determined directly from eq.(5). Part of the problem must be to include a method of determining L as part of the radio measurement. One method is to use the dispersive characteristics of $\overline{N}_f$, i.e., the variation of $\overline{N}$ with frequency is known and may be used to determine L. This approach has been attempted using centimeter and millimeter wavelengths but has been discontinued [Sullivan, 1965]. However, dispersive effects are much stronger for optical frequencies and hence this experiment can be performed more accurately there. Thompson [1968] has shown that a three-wavelength experiment, two in the optical and one in the microwave, can be used to determine total density and water vapor density to about 0.5 per cent, or better than 1N unit for $\overline{N}$. He projects that these accuracies could be improved by one or two orders of magnitude for the total density. It is possible that the same technique could be performed in the millimeter and submillimeter band using the dispersion effects that occur because of the water vapor and oxygen lines. However, with the present state of technology, the dual optical-microwave system seems more suitable. This technique will not be discussed in more detail here as it appears that it will be more thoroughly covered in another paper.

4.2 Relative phase measurements, using one or two receivers

There has been a large amount of work on this problem from the point-of-view of determining phase variations and resulting errors in angle-of-arrival. Unfortunately, from the point of view of remote probing, very little of this data has been analyzed with the objective of critically studying the atmosphere. The major use of such data would be in the determination of the form of the spectrum of the refractive index fluctuations. When employing one receiver almost nothing can be inferred without an independent measurement of the wind velocity. Given the wind velocity and assuming the "frozen hypothesis" is valid, it is

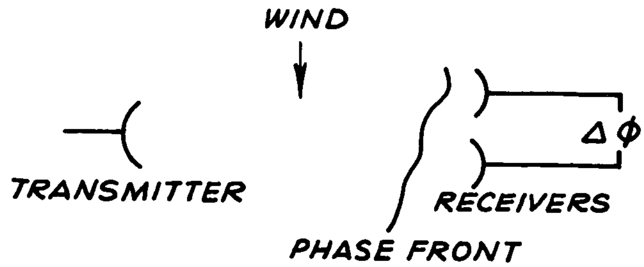

Fig. 1 Phase Measurements

possible to interpret the phase fluctuations in terms of refractive index variations. However, in this interpretation it is necessary to take into account the effect of the antenna aperture in averaging the phase fluctuations [Norton, 1965]. The major problems in interpreting this type of experiment are the following: (1) It is impossible to test the validity of the frozen hypothesis; (2) The interpretation assumes the atmospheric conditions are homogeneous over the entire path. For almost any reasonable microwave propagation path this assumption will be highly suspect, and there is no way to isolate non-homogeneous conditions from other effects using radio results. (3) There is some evidence that phase measurements are the least sensitive in discriminating between different atmospheric models [Muchmore and Wheelon, 1955; Strohbehn, 1966]. However, the covariance function measured in this way is a measure, in some sense, of the outer scale of turbulence. The interpretation of such data must be done carefully since for these scale sizes the turbulence is rarely isotropic.

When using two receiving systems, the phase differences at the two receiving sites may be used to estimate the average wind velocity over the path or may be combined to give angle-of-arrival information. This combination has essentially the same drawbacks as the phase measurements, except there is evidence that angle-of-arrival measurements are more sensitive than phase in discriminating between atmospheric models.

Even though these types of measurements are extremely valuable in interpreting the effect of the atmosphere on different proposed radio systems, it seems that they are much less valuable in the area of remote probing. For remote probing many of the ambiguities of the single or double path measurement can be resolved by a multiple-element array, as will be discussed in another section.

4.3 Refraction Measurements

In estimating the angle-of-arrival errors introduced by the atmosphere when tracking airplanes or space vehicles it is important to take into account the amount of bending of the rays because of the decrease in the average refractive index as a function of altitude above the earth's surface. Again the objective of most of the work has been to estimate the propagation

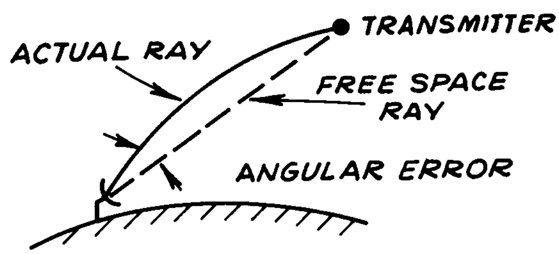

Fig. 2. Refraction Measurements

effect using as simple an atmospheric parameter as possible. In this problem it has been found that a reasonable prediction can be made by using a linear equation to relate τ, the amount of bending of the ray, and N_S, the refractivity at the surface [Bean, 1966]. There also have been efforts at using more complicated models and radiosonde data in making predictions.

It is an intriguing possibility to turn the problem around and to investigate the possibility of tracking an object whose exact position is known and use the results to predict the decrease of the average refractive index with altitude. Whether such measurements would be sensitive enough to distinguish between a linear or exponential decrease of refractivity is not clear. However, it seems somewhat doubtful because of the ability to predict the bending from as simple a measurement as the surface refractivity. Furthermore, the major contribution to the bending is near the earth's surface, where a linear approximation can be made to the exponential decrease. There is also a noise problem in the sense that small scale inhomogeneities will cause fluctuations in the angle-of-arrival. The method should also be applicable to studying elevated ducts. In the above discussion it has been assumed that the measurements are made from a vehicle that is transmitting. It is obvious that the same type of measurements can be made using a radar. It should also be noted that in the millimeter region atmospheric absorption prohibits transmission at low angles of elevation (high refraction effects) [Straiton, 1965].

4.4 Array Measurements

The use of microwave arrays in measuring atmospheric parameters is just beginning to be fully realized. With present equipment it is now feasible to measure and record amplitude and phase information at eight or ten different receiving antennas.

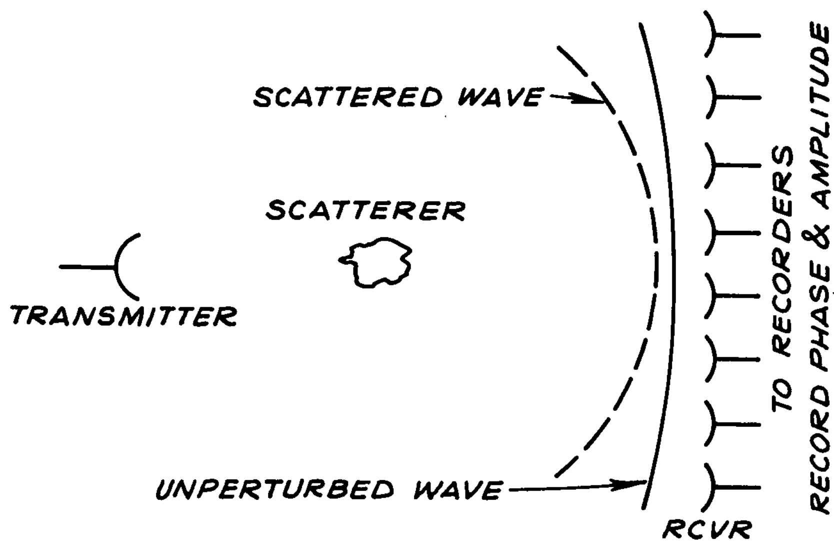

Fig. 3. Multiple Element Array

Because of the multiplicity of measurements made there is the possibility of resolving the ambiguities present in a single antenna measurement and the possibility of investigating properties which must be assumed as true under simpler measurement configurations. These advantages are obtained at the expense of more complicated and expensive equipment and the necessity for highly sophisticated data reduction techniques. However, for investigating processes as complex as those in the atmosphere, these complications seem extremely worthwhile. In analyzing the possibilities of array measurements in determining meteorological parameters it seems worthwhile to divide the discussion into three categories: (1) the measurement of apparent wind speed; (2) the determination of meteorological parameters at different points along the path, given that some atmospheric model is assumed, and (3) the determination of an atmospheric model.

When considering the measurement of apparent wind speed, the remarks made in Section 2 should be repeated. A radio measurement can only determine the apparent motion of the refractive index fluctuations in space. The interpretation of these motions as a blob of air moving with the average wind or as a wave motion in the refractive index caused by another type of mechanism cannot be distinguished by radio measurements alone. Therefore, when discussing the measurement of wind speed below, the more general interpretation given above is implied. It appears to this author that the influence of wave motions in causing apparent wind speed changes is not well understood and could bear further investigation.

According to some as yet unpublished work by Robert Lee of Stanford, it is believed possible to obtain the projected component of the windspeed across the path at 10 different positions along the propagation path with an accuracy on the order of 10 per cent. (As yet this technique has not been proven.) This wind speed is more or less instantaneous in time but spatially averaged over some segment of the propagation path. The multiple element array is ideally suited to this type of measurement.

The second approach is to assume some form of an atmospheric model, for example, assume $\Phi_n(\kappa)$ is of the form [Tatarskii, 1967]

$$\Phi_n(\kappa) = 0.033\, C_n^2 \kappa^{-11/3} e^{-\kappa^2/\kappa_m^2}$$

$$\kappa_m = 5.92/\ell_0$$

where C_n^2 is a measure of the intensity of the turbulence. Note that making such an assumption implicitly rules out a number of mechanisms as contributing to the propagation problem. The form assumed implies that the atmosphere can be described by locally - homogeneous isotropic turbulence. This assumption rules out stratification effects and anisotropy as playing a major role. Given that the assumption is made, however, it is possible to determine a parameter, such as C_n^2 at different points along the path. The above approach, which is extremely useful when the form of the atmospheric model is reasonably universal, must be used with some caution in the real world. While the form of the spectrum given above is probably the best model available, it is in no sense universal and is only expected to exist under certain reasonably restrictive conditions. Therefore this type of approach should only be used when other considerations make the model reasonable.

The third approach is to attempt to use the measurements to actually determine the form of $\Phi_n(\kappa)$ under different meteorological conditions. This is a much more difficult problem than the preceding, since there are a number of parameters to be determined.

Furthermore, $\Phi_n(\kappa)$ is defined for all wavenumbers from o to ∞, but the best a given experiment can accomplish is to measure $\Phi_n(\kappa)$ over some range of κ.

The following comments are taken from a private communication from Robert Lee at Stanford. From amplitude covariances the microwave array type of experiment is sensitive to blob sizes about one-half the Fresnel zone radius (on the order of 6 meters for an 8 mm wavelength and 25 kilometer path). The range of wavenumbers is typically one octave. Phase covariances are mainly controlled by the largest scale sizes and information can be learned about the region around L_0, the outer scale of turbulence, again approximately one octave, is important. It is expected that the effects of anisotropy can be determined and also the decay time of eddies.

From the above remarks it is apparent that measurements using multiple-element arrays should be extremely useful in measuring atmospheric parameters. It should be noted that the above analysis was based on the assumption that wave optics formulas of the type given in the Appendix are valid in the microwave region. There must be some reservations about this formulation until a more careful analysis of the problem for microwaves has been completed. Furthermore, the conclusions given still must be regarded as tentative in nature, as there is a need for much more work in this area of analysis and interpretation of experimental results.

It should be remarked that similar measurements at optical wavelengths will make available much the same information as for the millimeter. Phase measurements should reveal substantially the same information and for the same scale sizes. Amplitude measurements, however, will emphasize much higher wavenumbers, close to the ℓ_0 range of the spectrum. In this sense optical and millimeter measurements should be complementary.

5. RELATED PROGRAMS AND FUTURE DEVELOPMENTS

The major work in the area of microwave line-of-sight research is being performed at the Institute for Telecommunications Sciences and Aeronomy, the University of Texas, and Stanford University (see Bibliography). The work at ITSA seems to be primarily mission oriented in the sense that the work is more oriented towards predicting the effect of propagation on systems and less oriented toward remote probing. The work at the two universities is more oriented towards the remote probing aspects. It should be noted that at times it is difficult to separate the two orientations. There are of course numerous single-path experimental facilities. The most sophisticated multiple-element array is that of Lee and Waterman at Stanford [1966].

I envision the experimental progress in this area in the next decade or so to be very similar to the progress of the last ten years--slow. At present there are only a few facilities capable of performing sophisticated experiments and analyzing the data. Even during times of relative scientific wealth it was difficult to secure money for experiments that were oriented towards fundamental research in atmospheric physics. The support, even for many of the best programs, has been justified on the basis of applications. It appears that in the immediate future this situation will get worse, perhaps relaxing toward the end of the next five years. For example, to my knowledge, there are no plans for more multiple-element arrays. Furthermore, there is no indication that the rather unfortunate situation of the past where few good radio experiments were combined with good meteorological experiments will drastically change in the future.

There are a few general recommendations that I would like to make. First, that efforts be made to see that radio measurements of a given type are made in a number of different meteorological situations. For example, when designing a radio experiment serious consideration should be given to making such experiments semi-portable when possible. In particular, it would be desirable to have several multiple-element arrays in reasonably different climates and different terrains. Secondly, there is a tremendous need for better meteorological measurements in conjunction with radio measurements. As a particular suggestion, an agency through which one could secure either funds for or temporary loans of meteorological equipment would be extremely valuable. It is not uncommon for certain agencies to fund radio experiments for systems studies, but not allow funding for meteorological equipment. If a scientist had a readily available and sympathetic second source for this type of equipment, it is quite possible better measurements would be made.

With regard to theoretical investigations there are several interesting problems that require further development. First, there is a need for a closer look at the basic theoretical expressions for amplitude and phase fluctuations and their validity in the microwave range. Second, there has been very little work in the area of the effect of finite antenna beamwidths, etc., on the basic expressions. Third, there is a great need for careful analysis of exactly what can be learned about the atmosphere from microwave experiments. In general, it would be surprising if there were suddenly any great interest in attacking these problems. However, there is an indication that there are at present a few workers who are investigating some of these problems, and it is reasonable to expect that some progress will be made in the next few years.

6. APPENDIX: THE IMPORTANT FORMULAS

A. Geometrical Optics

Restrictions: $\lambda \ll \ell_0$, $\sqrt{\lambda L} \ll \ell_0$, where λ = wavelength, L = path length and ℓ_0 = inner scale of turbulence.

Phase formulas:

$$S(\underset{\sim}{r}) = k \int_0^r ds\, n(\underset{\sim}{s}) \qquad \text{(A1)}$$

$$S_1(\underset{\sim}{r}) = k \int_0^r ds\, \delta n(\underset{\sim}{s}) \qquad \text{(A2)}$$

$$C_s(\rho) = \langle S_1(L,0) S_1(L,\rho) \rangle \qquad \text{(A3)}$$

$$C_s(\rho) = 2k^2 L \int_0^\infty C_n[(x^2+\rho^2)^{1/2}]dx = 2\pi \int_0^\infty F_s(\kappa) J_0(\kappa\rho)\kappa\, d\kappa \qquad \text{(A3)}$$

$$F_s(\kappa) = 2\pi k^2 L\, \Phi_n(\kappa) \qquad \text{(A4)}$$

where
- S = total phase change
- S_1 = fluctuation of phase about its mean value
- k = $2\pi/\lambda$, λ = wavelength
- L = path length
- $C_s(\rho)$ = covariance function of the phase fluctuations
- ρ = $[y^2+z^2]^{1/2}$ = distance between two receivers
- $C_n(r)$ = covariance function of the refractive index
- $F_s(\kappa)$ = two-dimensional spectrum of the phase fluctuations (two-dimensional Fourier transform of $C_s(r)$)
- $\Phi_n(\kappa)$ = Three-dimensional spectrum of the refractive index fluctuations (three-dimensional Fourier transform of $C_n(r)$)
- κ = spatial wavenumber

The first equation (A1) may be used to calculate the average phase change $\langle S(r)\rangle = k\int^r ds \langle n(s)\rangle$ and is particularly useful in studying the beam bending due to refraction. In this case it is usually assumed that n(s) is only a function of height above the earth's surface. Eq. (A2) gives the phase fluctuation about its mean value. Eqs.(A3) are derived from (A2) and give the covariance of the phase fluctuations at two receivers, both a distance L away from the transmitter, and separated by a distance ρ. If the covariance function, $C_s(\rho)$, is known for all values of ρ, a two-dimensional Fourier transform leads to the two-dimensional spectrum of the phase fluctuations, $F_s(\kappa)$. It is obvious that complete knowledge of $F_s(\kappa)$ would lead to complete knowledge of $\Phi_n(\kappa)$. However, experimentally it is only possible to measure $F_s(\kappa)$ over some range of wavenumbers.

Amplitude formulas:

$$\chi(\underset{\sim}{r}) \equiv \ell n[A(\underset{\sim}{r})/A_0(\underset{\sim}{r})] = \frac{1}{2k} \int_0^x dx' \nabla_T^2 S_1(x',y,z) \qquad \text{(A5)}$$

$$C_\chi(\rho) = \langle \chi(L,0)\chi(L,\rho) \rangle$$

$$C\chi(\rho) = \frac{L^3}{6} \int_0^\infty \nabla_{T_1}^2 \nabla_{T_2}^2 C_n[(x^2+\rho^2)^{1/2}]\, dx \quad (A6)$$

$$F\chi(\kappa) = \frac{\pi L^3}{6} \kappa^4 \Phi_n(\kappa) \quad (A7)$$

where A $(\underset{\sim}{r})$ = amplitude at point $\underset{\sim}{r}$; ∇_T^2 = transverse Laplacian.

In eq.(A5), A(r) is the total amplitude. If it is assumed that $A(\underset{\sim}{r}) = A_0(r)+A_1(r)$, and $A_1(r) \ll A_0(r)$, then $\ln[A(r)/A_0(\underset{\sim}{r})] \approx [A_1(\underset{\sim}{r})/A_0(\underset{\sim}{r})]$. However, it is also very common to define $\chi(r)=\ln[A(\underset{\sim}{r})/A_0(\underset{\sim}{r})]$, where $\chi(\underset{\sim}{r})$ will be called the log-amplitude. It should again be noted that perfect knowledge of C_χ or F_χ would lead to exact knowledge of the form of $\Phi_n(\kappa)$, but again experimentally this is not possible. It is worth noting that the amplitude spectrum emphasizes a different range of wavenumbers than the phase spectrum.

B. Rytov's Method (Wave Optics)

Restrictions: $\lambda \ll \ell_0$, $L \ll \ell_0^4/\lambda^3$

Phase formulas:

$$F_s(\kappa) = \pi k^2 L\left(1+\frac{k}{\kappa^2 L} \sin \frac{\kappa^2 L}{k}\right)\Phi_n(\kappa) \quad (A8)$$

$$C_s(\rho) = 2\pi \int_0^\infty F_s(\kappa) J_0(\kappa\rho)\kappa\, d\kappa \quad (A9)$$

Amplitude formulas:

$$F_\chi(\kappa) = \pi k^2 L\left(1-\frac{k}{\kappa^2 L} \sin \frac{\kappa^2 L}{k}\right)\Phi_n(\kappa) \quad (A10)$$

$$C_\chi(\rho) = 2\pi \int_0^\infty F_\chi(\kappa) J_0(\kappa\rho)\kappa\, d\kappa \quad (A11)$$

The above formulas, which may be found in Tatarski [1961], are derived using Rytov's method of smooth perturbations. It is noted that both of the restrictions given above would limit the validity to wavelengths in the millimeter range or shorter, and to very short path lengths. However, the above restrictions are, in a sense, sufficiency conditions, and it is possible that they may be relaxed considerably. However, at present there is no theoretical basis for relaxing these restrictions. It is possible to make intuitive or physical arguments that the phase fluctuations should follow equations (A8) and (A9) reasonably well. For amplitude fluctuations it seems reasonable to expect more significant changes in the forms of the equations for longer wavelengths. The use of the above formulas in this paper is mainly based on the fact that they are the only ones available.

N O T E: Recent unpublished results by Clifford and Strohbehn have shown that the restriction $\lambda \ll \ell_0$ may be relaxed with no significant change in the appropriate formulas for microwaves, i.e. equations derived for the optical case (when $\lambda \ll \ell_0$) are still valid in the microwave case (when $\lambda \gtrsim \ell_0$).

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