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A REVIEW OF TRANSHORIZON PROPAGATION AS A POSSIBLE TOOL FOR REMOTE PROBING OF THE ATMOSPHERE

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ABSTRACT

This report reviews transhorizon propagation experiments from the viewpoint of their possible use as remote atmospheric probes. It is concluded that the state or structure of the atmosphere cannot be inferred unambiguously from measurement techniques used in experiments reported to date. Extensions or combinations of available techniques, however, appear promising for use in the remote probing of the atmosphere.

1. INTRODUCTION

This report considers the topic of transhorizon propagation or tropospheric scatter in the light of its possible use as a technique for the remote probing of the earth's atmosphere. This technique, like all radio techniques, can yield information only about the index of refraction or dielectric constant of the atmosphere. Since the mechanism which is usually involved in the transmission of these UHF or microwave radio signals beyond the optical horizon is the refractive index variations or fluctuations in the atmosphere, these variations or fluctuations are the parameters which can most readily be studied by this measurement technique. This report does not deal with the topics of "ducting" or other average refractive effects or with the effects of rain or other precipitation. Some of the atmospheric parameters which are possible candidates for study using transhorizon propagation measurements are

1. drift (wind) and internal motions as they affect the doppler spectrum or fading of the radio signals;

2. statistical characteristics or properties of the random fluctuations or variations in the atmosphere as they are related to frequency and angular dependence of the mean scattered power;

3. nonuniformities in the statistical characteristics of the atmosphere such as inhomogeneity or anisotropy which exist to a scale resolvable by practical measuring devices (usually antennas);

4. stratification tendencies in the atmosphere.

Currently these parameters cannot be determined with much certainty as will be seen in the following review of reported transhorizon propagation experiments.

In this report the term "remote probing" is interpreted to mean the unambiguous determination of the state or structure of the atmosphere or the quantitative determination of some atmospheric parameter from radio measurements made at locations (usually on the ground) remote from the region being investigated. All information necessary for determining the parameter value or atmospheric state should be contained in the radio measurements themselves or in other simultaneously made measurements, that is, it should not be necessary to include in the interpretation of the state or the parameter value any assumptions which are not supportable by the direct measurements themselves. The measured atmospheric parameters may be localized in time (fractions of seconds) or space (a few feet) or may be averaged over some larger region in space (hundreds or thousands of feet) or time (a few hours). Parameters averaged over extremes of space (for example the atmosphere from the earth's surface to the end of the sensible atmosphere) or time (over many hours or even days) are not considered useful in defining the state of the atmosphere with remote probing. Because of these quite definitive requirements placed on the interpretation of the words "remote probing" this report tends to be somewhat pessimistic in its view of results from transhorizon propagation experiments which have been conducted in the past.

Much of the early work in transhorizon radio propagation was concerned with communications system applications and the parameters which were measured in experiments were usually long-term averages which were not very useful for determining atmospheric characteristics at any given time. A screening of the literature has been made and experiments which deal with parameters which are of use only to communications system designers are not included in this review. That is, this report concerns itself with the subject of transhorizon propagation only as it relates to remote probing of the atmosphere.

2. A BRIEF REVIEW OF THE THEORY OF TRANSHORIZON PROPAGATION

The theories which attempt to describe transhorizon propagation phenomena can usually be classified into two groups. The models which are used to describe the variations or fluctuations in the refractive index of the atmosphere are the major distinguishing features of the groups.

2.1 The Turbulence Theories

By far the greatest effort expended in trying to describe the transhorizon propagation phenomena has been based on a statistical description of turbulence in the atmosphere. A rather extensive review of this subject can be found in Staras and Wheelon (1959). The subject has been treated by many authors (for example, Booker and Gordon 1950; Staras 1952, 1955; Gordon 1955; Booker and de Bettencourt 1955; Villars and Weisskopf 1955; Balser 1957; Wheelon 1957, 1959; Bolgiano 1960). In the turbulence treatment, the refractive index (or dielectric permittivity) fluctuations are described as a small random change about mean level. Early work (for example, Booker and Gordon, 1950) dealt with the time fluctuations at a point in space; however, later work proceeds from the three-dimensional spatial variations (for example, Staras, 1955 or Wheelon, 1959). The formalism in either case proceeds along similar lines.

The dielectric permittivity can be expressed as $\varepsilon(\vec{r},t) = \bar{\varepsilon} + \Delta\varepsilon(\vec{r},t)$ where $\vec{r}$ is a 3-dimensional space vector and $\bar{\varepsilon}$ is the mean of the permittivity. In most cases $\Delta\varepsilon(\vec{r},t)$ is treated as a random process which is stationary in time and both homogeneous and isotropic in space. Associated with $C(\vec{R},t) = \langle \Delta\varepsilon(\vec{r},t) \cdot \Delta\varepsilon(\vec{r}+\vec{R},t) \rangle$, the correlation function, is a spectrum $\Phi(\vec{k})$ related to the correlation function by

$$C(\vec{R}) = \int_V \Phi(\vec{k})\, \varepsilon^{j\vec{k}\cdot(\vec{R})}\, d^3\vec{k}$$

with time variation suppressed. For the typical transhorizon propagation path geometry in Fig. 1, the wave equation is solved (Staras and Wheelon, 1959; Balser, 1957; Wheelon, 1959; Staras, 1952) using the Born (Single-scattering) approximation to yield an equation for the ratio of received power to transmitted power $\frac{P_R}{P_T}$. Omitting constants of proportionality,

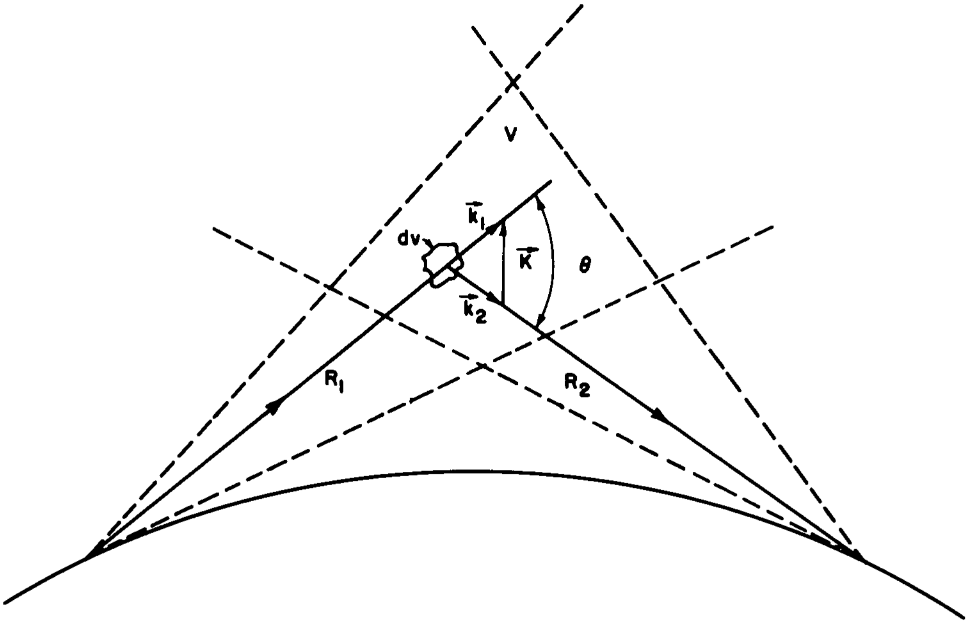


FIG. 1 PATH GEOMETRY FOR TURBULENCE THEORY

$$\frac{P_R}{P_T} \propto \frac{1}{\lambda^2} \int_V \frac{G_T \; G_R}{R_1^2 \; R_2^2} \; \Phi \; (\vec{K}) \; d^3 \; V$$

where the G's are gains of the transmitting and receiving antennas and K is the particular wavenumber $|\vec{K}| = \frac{4\pi}{\lambda} \sin \frac{\theta}{2}$. (Staras and Wheelon, 1959. This is often expressed as a function of scattering cross section $\sigma(\vec{K})$ as

$$\frac{P_R}{P_T} \propto \lambda^2 \int_V \frac{G_T G_R}{R_1^2 R_2^2} \; \sigma(\vec{K}) \; d^3 \; V$$

where $\sigma(\vec{K}) = \frac{\pi^2}{\lambda^4} \; \Phi(\vec{K})$ (Staras and Wheelon, 1959) .

For antennas with beams sufficiently narrow so that $\sigma(\vec{K})$ is approximately constant over the region in space, ΔV , within the half-power beamwidths of both antennas, the narrow-beam approximation can be applied and the integration can be reduced to a product

$$\frac{P_R}{P_T} \ \tilde{\propto}\ \lambda^2 \frac{G_T G_R}{R^4} \sigma(\vec{K}) \ \Delta V$$

Most of the experimental work reported in the literature is compared in some way with equations derived as described above.

For inhomogeneity in the statistics of the refractive index fluctuations, the spectrum $\Phi(\vec{K})$ is in some way a function of the spatial coordinates $(\vec{r})$. For anisotropy in the statistics, the spectrum $\Phi(\vec{K})$ is a function of the orientation of the $\vec{K}$ vector as well as of its magnitude. Some effects of anisotropy have been treated theoretically (for example, see Staras 1955). Nonstationarity is a situation wherein the spectrum $\Phi(\vec{K})$ is a function of time and is usually (but not always) slowly varying compared with the random fluctuations which make up the spectrum itself.

In the past much discussion has centered about the shape of the spectrum $\Phi(\vec{K})$ but currently the Kolmogorov spectrum which exhibits an input range at small values of $\vec{K}$, an inertial subrange in which $\Phi(\vec{K}) \propto \frac{1}{K^{11/3}}$, and a dissipation range for large values of $\vec{K}$ (for an example of this spectrum see Staras and Wheelon 1959) seems to be quite generally accepted. Since experiments do not appear to bear out the universal validity of this spectrum, however, (see the review of experiments in this report) another possibility which includes a buoyancy sub-range has been proposed by Bolgiano (1962). Various developments based on turbulence theory, such as synchronous beam swinging estimates (Booker and de Bettencourt 1955), have been made. In beam swinging, for example, θ is varied in the experiment thus varying $\Phi(\vec{K})$ since $|\vec{K}| = \frac{4\pi}{\lambda} \sin \frac{\theta}{2}$. The measured P_r is then proportional to $\Phi(\vec{K})$. In the general case where beams cannot be considered narrow the volume integration is quite difficult.

The subject of signal fading due to drift and internal motions has been treated only lightly in the literature as have other subjects such as transmission bandwidths and instantaneous signal estimates.

2.2 Layer Theories

These theories are based on partial reflection from stratified atmospheric layers which exhibit a relatively large change in refractive index (dielectric permittivity) over a short distance (usually height). Theoretical development based on this description of the variation in index of refraction has not been as extensive as that based on turbulence. Major contributions are contained in Bauer (1956), Friis, et al. (1957) and du Castel (1966).

The starting point for the layer theories is the amplitude (voltage) reflection coefficient for an abrupt, infinite dielectric discontinuity with index of refraction change across the discontinuity of $\Delta n = |n_2 - n_1|$. This reflection coefficient (ρ) is derived in almost all texts in electromagnetic theory and for the small angles involved in the transhorizon propagation geometry it simplifies to $\rho \approx \frac{2\Delta n}{\theta^2}$ where θ is the scattering angle. (See Fig. 2).

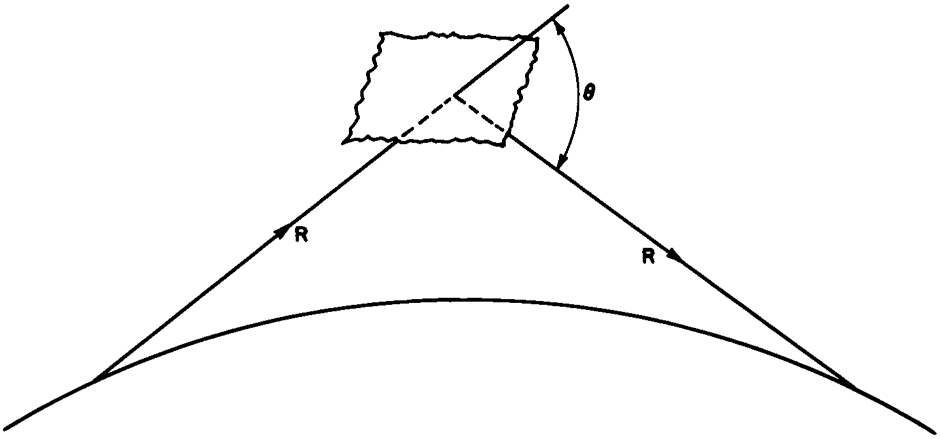


FIG. 2 PATH GEOMETRY FOR LAYER THEORY

If the discontinuity is gradual (as it probably is for the atmosphere) then the reflection coefficient takes on a frequency dependence, an angular dependence and layer thickness dependence (Wait 1964). The ratio of received power to transmitted power for an infinite layer is given by

$$\frac{P_R}{P_T} = \frac{G_T G_R}{64\pi^2} \frac{\lambda^2}{R^2} \rho^2$$

where again the G's are the antenna gains and R is the distance between receiver and transmitter. For finite layers Fresnel zone effects enter into this ratio and for layers small compared to a Fresnel zone a scattering cross-section situation exists again and

$$\frac{P_R}{P_T} = \frac{G_T G_R}{16\pi^2} \frac{\rho^2}{R^4} \left(A \frac{\theta}{2}\right)^2 \qquad \text{(Friis, et al.,1957)}$$

where the symbols are as before and A is the area of the layer.

Statistics may enter this theory, for example, in the spatial distribution of layers, in size and intensity distributions and in distributions of curvature for non-flat layers (du Castel 1966).

Layer theory results have been compared with experimental results by Crawford, *et al.*, (1959). The agreement does not seem to be any better or any worse than the agreement between other experiments and theories based on turbulence models.

Signal level distributions, doppler spectrum, focusing effects, and instantaneous signal characteristics for sinusoidally shaped layers have been treated by Waterman and Strohbehn (1963) and Gjessing (1964). The possibility that large angular velocities may be produced by fleeting reflection points on irregular surfaces is demonstrated by these investigators. The treatment of signal characteristics in general from the viewpoint of layer theories is still in an elementary state.

The layer theories have been generally used to describe transhorizon signal characteristics in a deterministic manner while the turbulence theories inherently describe only the statistics of those signals.

This is by no means a comprehensive review of all the theory of transhorizon propagation but it includes most of the main areas of development and should provide a basis for viewing the experimental work in the next section. The theory of transhorizon propagation mechanisms is far from complete. The development of topics such as envelope fading and doppler spectrum of the radio signal has been barely started. It would appear that because of the variability in the results from different time periods the subject of transhorizon propagation theory might benefit at this time by being approached more strongly from the viewpoint of explaining each individual experimental observation for each limited time period, rather than by trying to find universal constants to fit averages over long time periods and over many experiments.

3. EXPERIMENTAL PROGRESS

Many of the early experiments in transhorizon radio propagation were conducted to determine the long-term statistical characteristics of the transhorizon signals because these parameters are of interest to designers of communications systems. In experiments of this type, parameters such as mean signal level, signal level distributions (for determining communications reliability), usable frequency bandwidths, and effective antenna size (aperture-to-medium coupling loss) were measured, usually as long term averages. These measurements were made at different frequencies and over transmission paths of different lengths over different terrains and with different minimum scattering angles. While these experiments were invaluable in the development of the transhorizon propagation mechanism as a communications medium, the long-term averages and simple parameters measured could be used almost equally well to support either theories based on atmospheric turbulence or theories based on reflection from atmospheric layers. It seems that for the purpose of probing the atmosphere, measurements which could be used to determine the state of the atmosphere over time periods of a few minutes to a few hours are desirable. Also because of the complex nature of the atmosphere it appears that the simultaneous measurement of several separate parameters is required to produce a good description of its state. For these reasons, experimental works in the field of transhorizon propagation have been screened and those which do not appear to contribute substantially to the question of remote probing (i.e., do not have sufficient "resolution") (for example: Ames, et al.,1955; Bullington, et al.,1955; Janes and Wells 1955; Rogers 1955; Yeh 1966; Mellen, et al.,1955) have not been included in this report. A number of works, however, whose major effort is along the communications system line but which also contain a few measurements of the types considered later in this section are included.

Experiments which involve the measurement of total path phase, doppler spectrum and group delay and which make use of phase-coherent measurements between precision frequency sources are omitted from this report because they are being reported on by Professor W. P. Birkemeier. This section will consider the types of measurements which have been made in transhorizon propagation experiments, conclusions which have been reached and possible limitations.

3.1 Beam Swinging Experiments

In its simplest form this type of experiment involves the "swinging," in azimuth or elevation, of a large, narrow-beam parabolic antenna which is being used either for transmitting or receiving. The receiver output is recorded during the swing to produce an angular response pattern for the antenna. Variations of this technique involve "swinging" both the transmitting and receiving antennas, or swinging the antenna feed, or using a large phased array with some means of appropriately varying phase shifts in feed lines, or using antennas with multiple stationary feeds.

During a beam swing in either azimuth or elevation the significant scattering region changes position in the atmosphere. Also the effective scattering angle (i.e., the magnitude of the scattering wave vector $\vec{K}$) changes. For a swing in azimuth the direction of the scattering wave vector $\vec{K}$ also varies, but the wave vector direction remains constant or essentially constant during an elevation swing.

If the atmosphere were in a homogeneous, isotropic, stationary turbulent state during many elevation swings of a narrow beam, then the average of the angular response patterns from the swings would trace out the spectrum of the turbulence. Predictions of the form of averaged azimuth response patterns for such a turbulent state have been made. (Booker and de Bettencourt 1955; Strohbehn 1963; Koono, et al.,1962). The average patterns for both azimuth and elevation are generally broader than the patterns for the same narrow beam antennas used on a line-of-sight path. The exact modifications to theoretical response patterns to account for non-narrow beams or anisotropic or inhomogeneous turbulence do not seem to be directly available in the literature but some intuitive estimates of this effect can be made. Nonstationarity in signal statistics which is due either to nonstationary atmospheric conditions or to inhomogeneous atmosphere drifting through the scattering region presents a more formidable problem which has received little treatment.

Estimates of averaged angular response patterns for beam swinging experiments have been made for a layer theory (Friis, et al., 1957) but again uniformity in the distribution of layers and assumptions as to the distributions of layer sizes, orientations and intensities were required. Some estimates of the characteristics of angular response patterns for beam swings made in time periods short compared to changes in the atmosphere have been made (Strohbehn and Waterman 1964; Stein, et al.,1959) for both the turbulence theories and layer theories but the characteristics to be expected under many different atmospheric states are not clear from the existing theoretical work.

Table I is a listing of beam swinging experiments found in the literature. Figure 3 contains a few examples of beam swinging data. The early experiment reported by Waterman (1953, 1957) utilized a relatively broad receiving beam and a narrow-beam transmitting antenna (radar) which was rotated at a uniform azimuth rate so that the beam swing took less than 1/5 second. The near-instantaneous angular response patterns contain examples with multiple maxima and examples of broadened maxima which are indicative of signal arriving from azimuth angles slightly (of the order of $1/2^{\circ}$) off the great circle path.

TABLE I

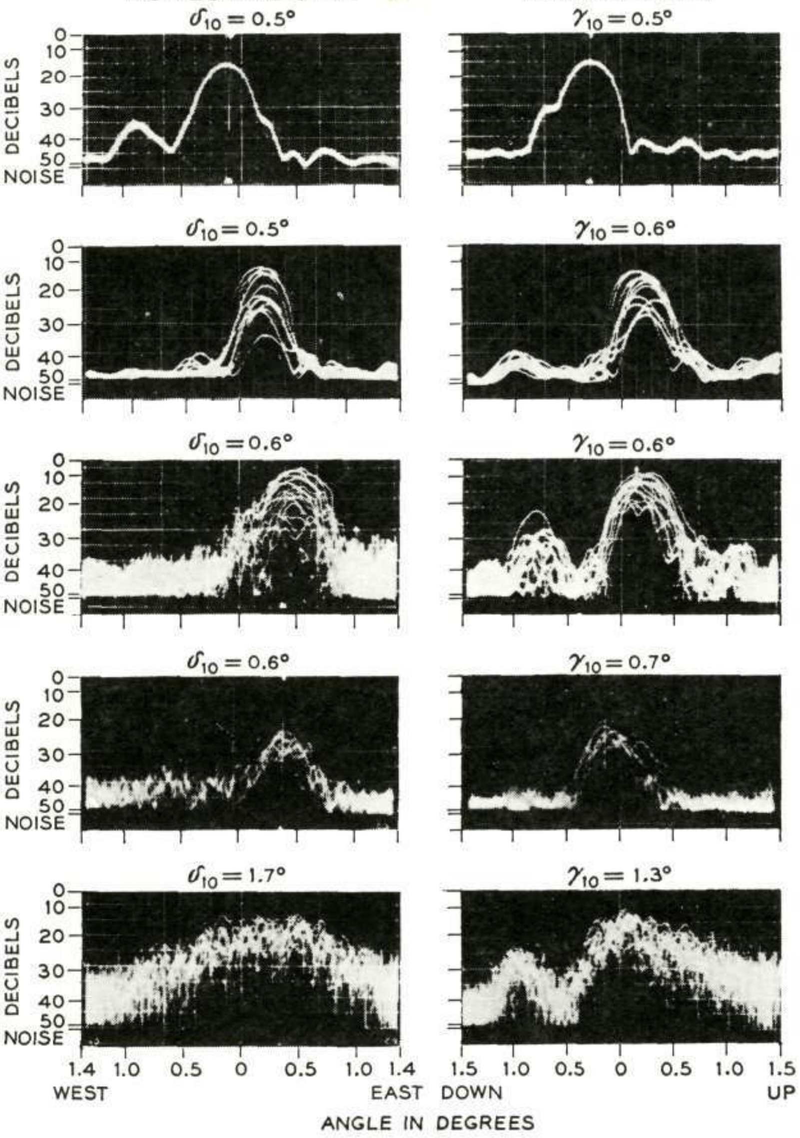
BEAM SWINGING EXPERIMENTS

Author	Date Pub.	Path Location	Swing Az or El	Scan Period (sec.)		Swing Method	Swing Ant. Beamwidth (Deg.)	Freq. (Gc)	Path Length (miles)	Min. Scat. < (Deg.)	Met. Data
Waterman, et al.	1953 1957	Calif.	Az	1/5	ALL EXPERIMENTS CONTAIN EXAMPLES OF AVERAGED RESPONSE PATTERNS	Rotate T Ant.	0.9	3	92 to 177	~ 1.7	None
Trolese	1955	Ariz.	Az& El	Slow		Rotate R Ant.	1.75	9.4	46	--	Wind profile 100 mi off path
Chisholm, et al.	1955	Mass. N.J.	Az& El	Slow		Rotate R and T&R Ant.	0.7 T&R	3.7	188	--	None
Waterman Strohbehn	1958 1963 1966	Calif. Calif.	Az	1/10		8 ele. phased array-rapid phase shifting	0.5 Az 5 El	3.1	101	0.91	Wind & N profiles 25 mi off path
Crawford, et al.	1959	N.Y. N.J.	Az& El	15		Rotate R Ant.	0.3	4.1	171	--	Wx. map only
Harai, et al.	1960	Japan	Az	Avg. pt.by pt.		Rotate T Ant.	1.0	2.1	147 214	1.55 2.7	--

TABLE I (Continued)

Author	Date Pub.	Path Location	Swing Az or El	Scan Period (sec.)		Swing Method	Swing Ant. Beamwidth (Deg.)	Freq. (Gc)	Path Length (miles)	Min. Scat. < (Deg.)	Met. Data
Ortwein, et al.	1961	Calif.	Az&El	Avg. pt. by pt.	ALL EXPERIMENTS CONTAIN EXAMPLES OF AVERAGED RESPONSE PATTERNS	Rotate T & R Ant.	3/4 est.	9.4	190 144 78	--	N profiles extensive Wx.
Chisholm, et al.	1962	East Coast U.S.	Az El	34^{o}per sec. slow		Rotate T Ant.	2.8	0.4	618	6.7	--
Koono, et al.	1962	Japan	Az El	1/60		Rotate R Feed	0.5	2.1	184	2.18	--
Cox	1967	Calif.	El	1/100		Meas. Δ phase & amplitude compute beam	0.25 El 5 Az	3.2	102	0.84	--
Kieburtz, Fantera	1966	N.Y.	Az& El	8 sample beams in space		Sample from 8 discrete beams	.32 Az&El	7.8	184	--	None

See also: Bolgiano, 1963
Gjessing 1960, 1963, 1964, 1966



(a)
DIFFERENCE
IN MEDIANS
60' TO 8' DISHES
=16 1/2 DB
MEDIAN OF 8'
DISH = — DBM
SEPT. 14, 1956
2:40 PM

(b)
— DB
− 65 DBM
SEPT. 18, 1955
10:30 AM

(c)
15 DB
−80 DBM
SEPT. 1, 1956
3:40 AM

(d)
14 DB
−116 1/2 DBM
JAN. 16, 1956
4:00 PM

(e)
8 1/2 DB
−96 DBM
JULY 9, 1956
9:50 AM

Fig. 3(a) ANGULAR RESPONSE PATTERNS

(From Crawford, A.B., et al., "Studies in Tropospheric Propagation Beyond the Horizon," BSTJ, Sept. 1959)
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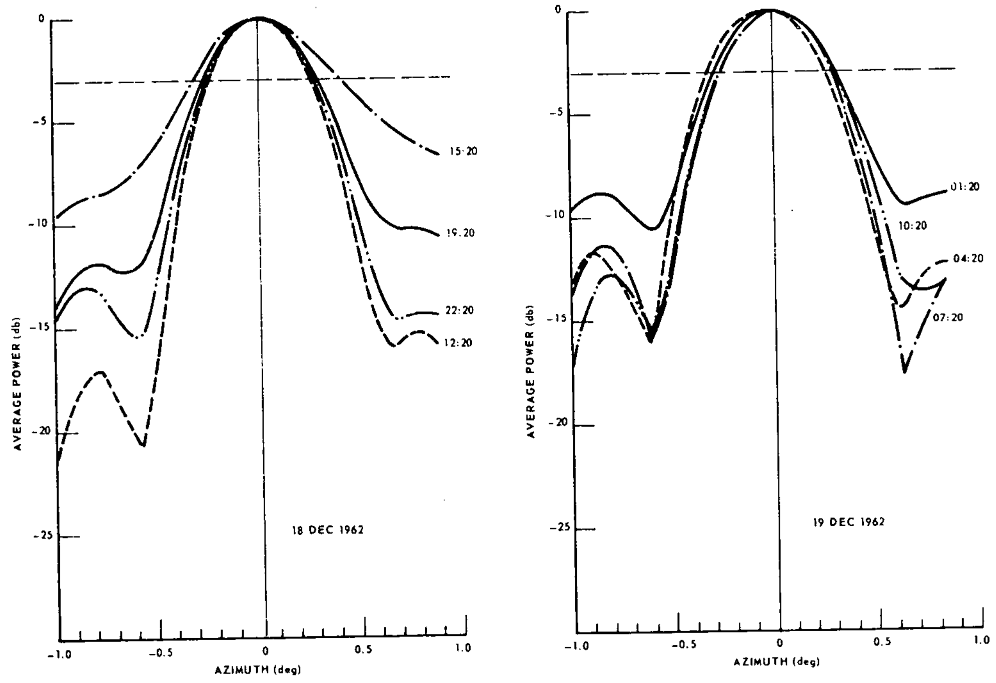

FIG. 38. AVERAGE ANTENNA-RESPONSE PATTERNS FOR 18-19 DEC 1962.

Fig. 3(b) AVERAGE ANTENNA-RESPONSE PATTERNS
FOR 18-19 DEC 1962

(From Strohbehn, J.W., "Transhorizon-Propagation Measurements and Simulated Angular-Response Patterns," Final Report on Proj. 2270, Stanford Electronics Labs, Oct. 1963)

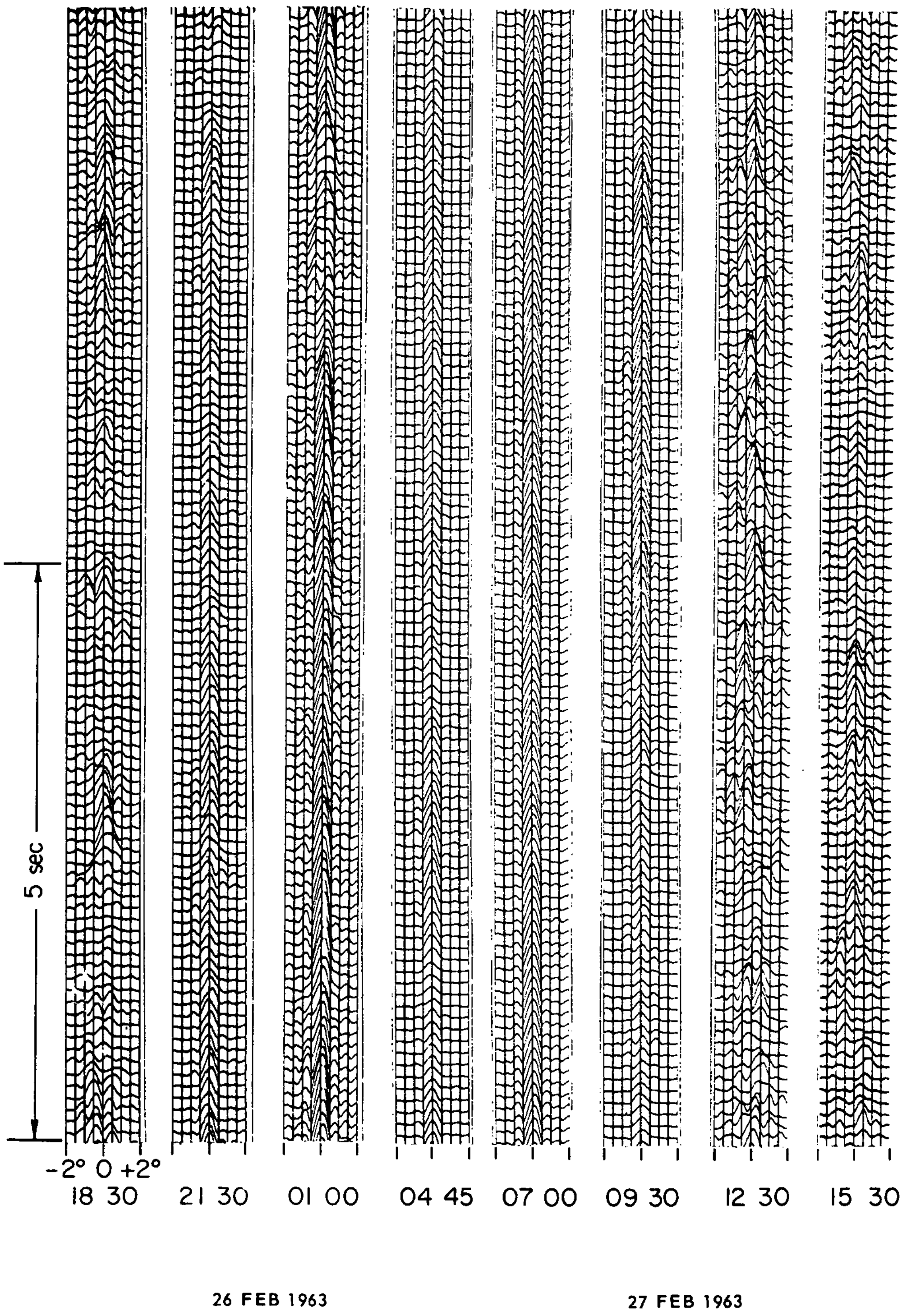

Fig. 3(c) AZIMUTH ANGULAR-RESPONSE PATTERNS

(From Strohbehn, J.W., "Transhorizon-Propagation Measurements and Simulated Angular-Response Patterns," Final Report on Proj. 2270, Stanford Electronics Labs, Oct. 1963)

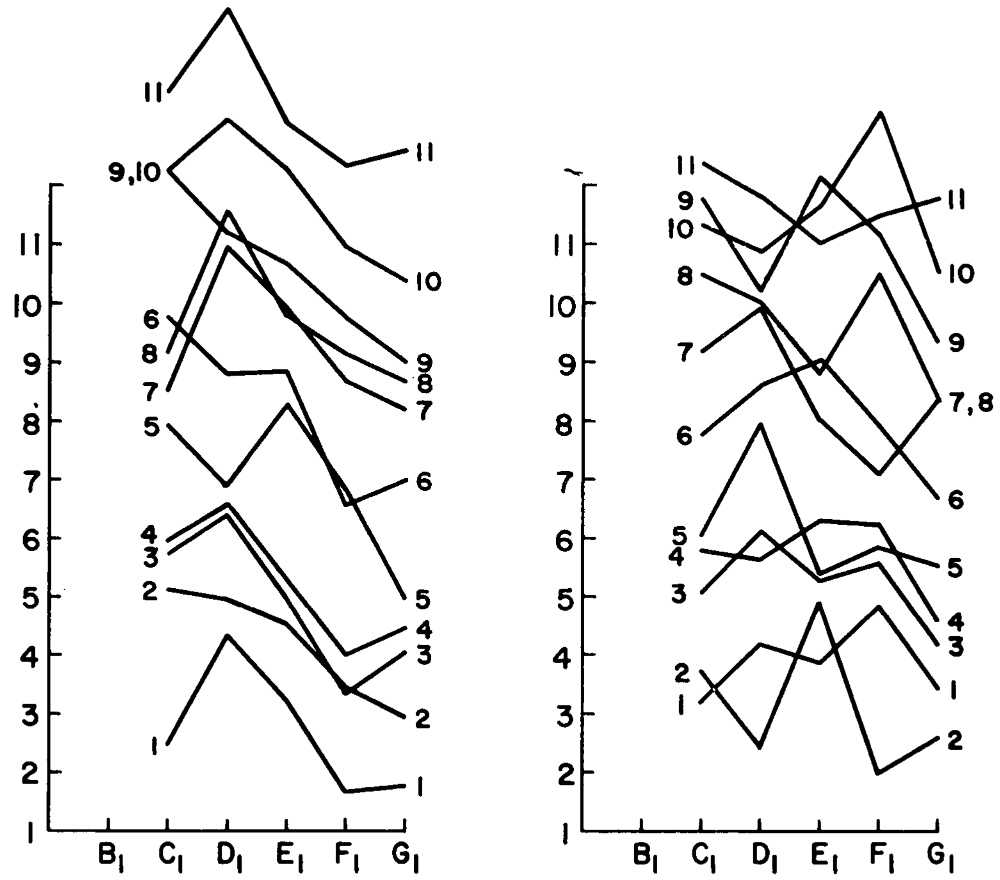

Fig. 3(d) INSTANTANEOUS INTENSITIES RECORDED FROM 5 NARROW BEAM ANTENNAS SEPARATED APPROXIMATELY 1/3 DEGREE IN AZIMUTH

(From Kieburtz, R.B. & Fantera, I.A., "Angle-of-Arrival Measurements Performed Over a 296-KM Troposcatter Path," Radio Science, November 1966, by permission of author)

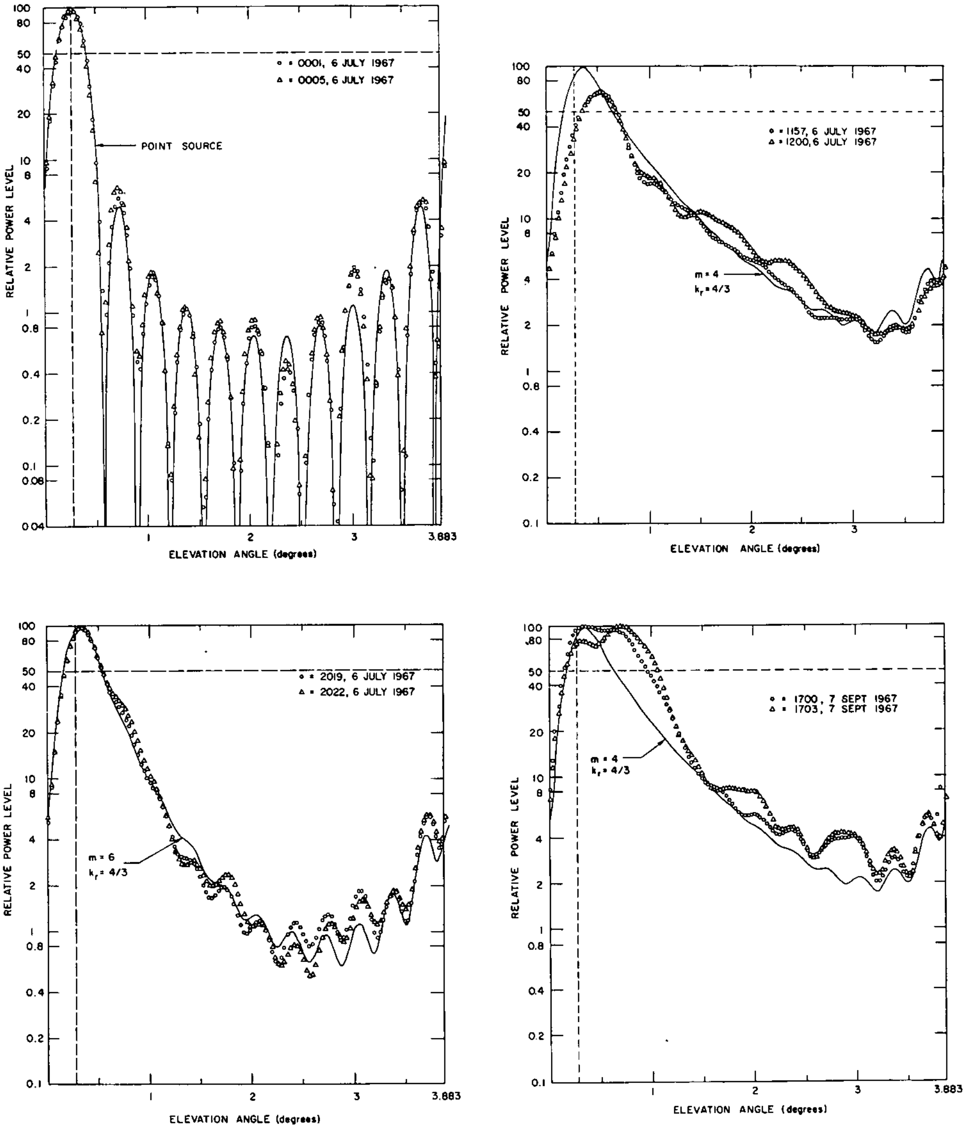

Fig. 3(e) AVERAGED ANGULAR RESPONSE PATTERNS IN ELEVATION

(From Cox, D.C., "Phase and Amplitude Measurements of Microwaves Propagated Beyond the Horizon," T.R. 2275-1, Stanford Electronics Labs, Dec. 1967)

The experiments reported by Chisholm, et al.,(1955, 1962) and Trolese (1955) contain a few examples of beam swings which illustrate angular response patterns broader than the patterns for the same antennas used on line-of-sight paths (i.e., broadened beams). The experiment reported by Crawford, et al (1959) contains many examples of angular response patterns from beam swings both in azimuth and in elevation. Exact interpretation of the individual swings is complicated by the fact that the 15-second duration of each swing was not short compared to signal fading rates. Photographic integration was used to produce averaged response patterns from several swings. There is considerable variability between the different response patterns taken at different time periods. As an example, the function describing the decrease in received power with increasing elevation angle is different at different times. The experiments reported by Harai, et al.,(1960) and Ortwein and Hopkins (1961) include averaged angular response patterns produced by swinging an antenna beam incrementally in angle and averaging the signal for periods of the order of minutes at each angular increment. The observed variability in the angular response patterns from one time period to another is again characteristic of such experiments although for some time periods nonstationarity in signal means hinders their interpretation.

Experiments reported by Waterman and Strohbehn (1958, 1963, 1966) include angular response patterns from azimuth beam swings with short (1/10 sec) periods and also averaged azimuth patterns made up of patterns from many rapid swings. The response patterns from the rapid swings show source regions in azimuth which are usually smaller than the 1/2° resolution of the beam, which occur individually or in simultaneous groups, which fade independently, and which move about sometimes at azimuth rates too fast (up to 600 mph at the minimum beam intersection point of the path) to represent transport of regions in the atmosphere. The characteristics of both the rapid swing patterns and the averaged patterns vary widely for different time periods but the averaged patterns are consistently narrower than would be predicted from a homogeneous turbulence theory. An experiment reported by Koono, et al.,(1962) presents angular response patterns from rapid (1/60 sec) beam swings in azimuth and averaged response patterns in both azimuth and elevation. A peculiar phenomenon reported is the existence of propagation paths both along the great circle and off-axis in azimuth when the transmitting beam is oriented off-axis in azimuth. It would seem that transmitting antenna sidelobes might cause such an effect but no mention is made of checking sidelobe levels. Otherwise the response patterns contain the large variability from time period to time period and the broadened average responses observed by others.

The experiment reported by Kieburtz and Fantera (1966) used 8 different beams oriented at different azimuth angles or different elevation angles to simultaneously sample the power received from the different angles. The sampled angles are thus points along an angular response pattern. These fluctuate rapidly and average to an angular response pattern which is broad compared to the line-of-sight pattern of the antennas used. The averaged elevation patterns are complex. The average pattern characteristics are different for different time periods.

The experiment reported by Cox (1967) includes angular response patterns from elevation beam swings with periods of 0.01 sec and averaged elevation patterns made up of patterns from many rapid swings. The response patterns from the rapid swings show source regions in elevation which are usually smaller than the 0.30 resolution of the beam, which occur individually or in simultaneous groups and which fade independently. The characteristics of both the rapid swing patterns and the averaged patterns vary widely for different time periods. The variation in the elevation patterns runs from some which indicate average source regions much less than 0.3° wide in elevation to average source regions which appear to be inhomogeneous in elevation angle (vertical). These averaged angular response patterns precisely illustrate the different characteristics seen in practically all the other beam swinging experiments in elevation.

Additional experiments reported by Bolgiano (1963) and by Gjessing (1960, 1963, 1964, 1966) involve beam swinging but are discussed separately later.

The ideal beam swinging experiment would appear to be one in which narrow beams both in azimuth and elevation and at both transmitter and receiver are swung simultaneously and rapidly with respect to atmospheric motions to sweep out the entire scattering volume. Motion of scattering or reflecting regions could be accurately followed this way. Averaged two-dimensional response patterns could be produced which would yield the scattering cross section of the common volume as a function of spatial coordinates. A measurement of the degree of homogeneity and a measure of angular dependence of the turbulence spectrum plus a measurement useful in determining anisotropy of turbulence would result. Even such an extensive experiment, however, is not sufficiently powerful alone to uniquely determine the atmospheric structure.

All of the experiments reported exhibit some limitations when compared to an ideal experiment. In some (Harai, <u>et al</u>.,1960; Ortwein and Hopkins 1961) averages are taken at different angles at different times. Nonstationary signal means contaminate data taken this way. Some experiments swing a beam narrow in either azimuth or elevation but not both (Waterman 1958; Strohbehn 1963; Strohbehn and Waterman 1966; Cox 1967). None of the experiments rapidly swings both transmitting and receiving antennas in both azimuth and elevation over the same time period. In spite of these limitations, the experiments when reviewed as a group show that

1. the experimental data contain much variability from one time period to another which is most probably indicative of different atmospheric states at different times.

2. the atmosphere exists in states which are sometimes quite homogeneous but at other times quite inhomogeneous in elevation angle (vertical direction).

3. extensive variations from time period to time period also exist in the azimuth angular response patterns (horizontal patterns) indicating either changes in homogeneity, isotropy, turbulence spectrum angular sensitivity, or even the scattering mechanism itself.

4. the experiments are not sufficiently definitive to differentiate between partial reflections from many layers and scattering from turbulent media since similar experiments can be shown to agree with predictions from both theories.

5. instantaneous scattering or reflecting regions small in extent move too rapidly at times to be caused by transport of atmosphere alone.

3.2 Pulse Transmission Experiments

The transmission of pulses over a transhorizon propagation path with precise timing at both ends should permit the determination of path length and thus an estimate of height of the scattering region or regions. Alternatively, if too many paths exist the resulting pulse distortion should give a measure of the extent of the scattering region.

Experiments involving the transmission of pulses were reported by Chisholm, et al, (1955, 1962) and are summarized in Table II. In these tests at times there was little or no broadening of pulse width even though during fades some pulse distortion occurred, at times more than one unbroadened discrete pulse was observed indicating more than one distinct scattering path and at times the pulses were broadened or smeared by multiple propagation paths. Differential delays of 2 to 8 μsec were observed between discrete received pulses resulting from the same transmitted pulse. Pulses were observed which corresponded to paths - 20,000 ft to + 90,000 ft above the minimum beam intersection point of a path which was 640 miles long. Both pulse broadening and distortion were reduced by using narrow-beam antennas.

Although this technique appears quite good for exploring the extent of the active scattering region, very little

TABLE II

PULSE TRANSMISSION EXPERIMENTS

Author	Date Pub.	Path Location	Pulse Length	Timing Accuracy		Freq. (Gc)	Path Length (miles)	Min. Scat. < (Deg.)	Met. Data
Chisholm, et al.	1955	Mass. N.J.	1.5 μ sec.	0.1 μ sec.	[Used different Ant. sizes]	3.7	188	---	None
Chisholm, et al.	1962	East Coast U.S.	1 μ sec.		[10 μsec. & 20 μsec. PRF]	0.4	640	≈ 6.9	None

work has been done using it. Again it would appear that pulse transmission would need to be used in conjunction with other techniques (such as beam swinging) to produce a reasonable picture of the scattering mechanism at any given time.

3.3 Frequency Sweep Experiments

Rapid sweeping of the transmission frequency during transhorizon propagation experiments has been used to determine what frequency bandwidth can be used for information transfer. The width of the frequency band over which fading is correlated is related to the separation between actual scattering locations in the scattering volume since the rapid fading is caused by phase cancellation between the signals from the different scattering locations. Estimates of the separation between scattering regions were made by Crawford, et al.,(1959) but there appears to be no extensive work relating these types of measurements to atmospheric characteristics. Frequency sweep experiments were run by Crawford, et al.,(1959), by Tremblay (1962) and Strohbehn (1963). They all report that the signal fades at different wide-spaced frequencies (several Mc apart) at different times. The frequency separation for a given correlation of the fading at two different frequencies varies from time period to time period. The estimate of frequency separation for decorrelation made by Crawford, et al.,on the basis of information from beam swinging measurements shows some agreement with measured frequency correlation widths. Chisholm, et al., (1962) transmitted 3 discrete modulation sidebands and measured the correlation of the fading between sidebands. His results also show a decrease in correlation between fading as the frequency separation increases. Table III summarizes these experiments.

3.4 Cross-Correlation Techniques

This type of experiment involves measuring the signal amplitude (or possibly phase) at two or more different antennas with different spacing and correlating the fluctuations between pairs of antennas. Ideally, measurements are made simultaneously at all antenna spacings of interest. The simultaneous measurements permit correlations to be compared with each other without contamination due to nonstationarity in the signal statistics. Predictions of correlation as a function of antenna spacing were made by Staras (1955). These were based on a uniform turbulence model which included some anisotropic effects and effects of height dependence of atmospheric fluctuation intensity. Table IV is a summary of experiments which measured spatial cross correlation.

Data from the experiment by Barsis, et al.,(1954) is compared with theoretical curves in Staras (1955). In general these are long-term averages. Chisholm (1962) formed cross correlations as a function of horizontal antenna spacing for two spacings only. Again these were long-term averages.

TABLE III

FREQUENCY SWEEP EXPERIMENTS

Author	Date Pub.	Path Location	Sweep Width	Sweep Rate		Freq. (Gc)	Path Length (miles)	Met. Data
Crawford, et al.	1959	N.Y., N.J.	20 Mc	30 cps	[28 ft Xmit. Ant. 60, 28 & 8 ft Rec. Ants.]	4.1	171	none
Tremblay	1962	France	200 Mc	1/20 sec/ sweep		3.4	187	--
Chisholm, et al.	1962	East Coast U.S.	[Discrete Frequencies 40, 60 & 100 Kc separation]			0.4	618	--
Strohbehn	1963	Calif.	20 Mc	312 cps	[wide Xmit. Ant. wide El but 0.5° Az Rec. Ant.]	3.1	101	--

TABLE IV

CROSS CORRELATION TECHNIQUES

Author	Date Pub.	Path Location	Vert Horiz	Total Ele- ments	Ave. Time	Element Spacings	Element Size	Freq. (Gc)	Path Length (miles)	Min. Scat. < (Deg.)	Met. Data
Barsis, et al.	1954	Colo. Kansas	V&H					0.1 1.0			
Chisholm, et al.	1962	East Coast U.S.	H	2	-	100 ft 700 ft	Small	0.41	618	6.7	--
Fehlhaber	1966	Germany	V H V&H	3 3 3			30 ft (Small)	1.75	260	2.6	wind
Cox	1966	Calif.	V	12	6 min	4.5 ft up to 50 ft	4 ft	3.2	102	0.84	--

This technique has been exploited somewhat more extensively by Fehlhaber (1967) who used simultaneous measurements from 3 antennas in 3 different configurations ($\begin{matrix}\circ & \\ \circ & \circ\end{matrix}$; $\circ\ \circ\ \circ$; and $\begin{matrix}\circ \\ \circ \\ \circ\end{matrix}$). The correlations show a large amount of variability from one time period to another. The comparisons of the correlation coefficient at a given vertical spacing with the correlation coefficient for horizontal antennas with the same spacing sometimes show evidence of anisotropy. For these comparisons the correlations were formed from data taken over the same time period. No evidence of vertical drift is seen in the vertical correlation functions. Shifts of the maxima of the horizontal correlation functions with time lag are a measure of horizontal drift velocity. This velocity correlates with some wind measurements.

Correlations of amplitude data taken simultaneously with 12 antennas spaced vertically were reported by Cox (1967). There is considerable variability in the shapes and widths of the correlation functions for different time periods. Characteristics in these functions are identifiable with characteristics observed in angular response patterns from beam swings produced by using the 12 antennas as a phased array. There is no evidence of vertical drift in the correlation functions with time lag. The correlation functions for some time periods agree quite well with the theoretical predictions of Staras (1955) but for other time periods the agreement is very poor.

This experimental technique, although quite powerful, is not sufficient to resolve the state of the atmosphere by itself. It has not been very widely used.

3.5 Examination of Fading Rates

Fading rates and Doppler spectra are closely tied to internal motions in the atmosphere and to drift of the atmosphere (wind). The subject of phase-coherent and frequency-coherent techniques is being reviewed by Professor Birkemeier and will be omitted here. A brief mention will be made, however, of the use of envelope fading to determine atmospheric motion. Three measures of envelope fading rate have been used. They are the number of positive-slope zero crossings per second, the width of the autocorrelation function, and power spectral density of the envelope. Table V summarizes these experiments.

In the experiment reported by Norton (1955) fading rates were found to be approximately proportional to transmitter frequency on the basis of 3 different frequencies. Fading rates correlated well with wind measurements.

Ortwein, *et al*, (1961) reported poor correlation between fading rates and wind measurement.

TABLE V

FADING RATE EXPERIMENTS

Author	Date Pub.	Path Location	Rate Parameter	Ave. Time	Element Size	Freq. (Gc)	Path Length (miles)	Min. Scat. < (Deg.)	Met. Data
Norton, et al.	1955	Colo. Kansas	No. of + slope 0 crossings			0.2 0.1 1.0	70 to 225	--	wind
Ortwein, et al.	1961	Calif.	Envel. Auto. corr. & spectrum		0.78^{o} 1.26^{o} 2.0^{o}	1.2 3.4 9.4	78 144 190	--	N profiles extensive Wx
Chisholm, et al.	1962	East Coast U.S.	Envel. Auto. corr.	≈ 10 min	28 ft	0.41	188 350 618	--	--
Strohbehn Strohbehn & Waterman	1963 1966	Calif.	Envel. Auto. corr.	2-1/2 min	8 element array 0.5^{o} Az 5^{o} El	3.1	101	0.91	Wind & N profile 25 mi off path
Cox	1966	Calif.	Envel. Auto. corr.	6 min	4 ft (5^{o})	3.2	102	0.84	--
Gjessing	1960 1964	Norway	Envel.		15 ft ($.75^{o}$)	6	100 210		N profiles surface data

Chisholm (1962) reports that the fading rate increases when antennas are aimed off path.

Strohbehn and Waterman (1963, 1966) and Cox (1967) show many samples of envelope autocorrelation functions. These vary considerably from time period to time period. Strohbehn shows that the width of the autocorrelation function usually follows the trend of measured winds. Cox reports shorter correlation times during the day than at night.

Laaspere (1958) reviews the topic of fading rates.

In general there are experiments in this area for which the fading rates correlate well with measured wind and some for which the correlation is poor. There does not appear to have been sufficient effort (theoretical or experimental) in this area to form useful conclusions. Fading rate measurement should be a fruitful technique to use in conjunction with other techniques (such as beam swinging) to produce some measurement of atmospheric drift and/or internal motion. Interpretation of these rates is somewhat clouded by the rapidly moving reflection points or scattering regions observed by Waterman (1958) in a rapid beam swinging experiment in azimuth. It appears that reflection points may move at rates not related to actual transport of atmospheric material. If this effect occurs frequently, it most certainly will contaminate the quantitative measurement of actual atmospheric motions, both internal and drift (wind).

3.6 Multiple Frequency Experiments

Experiments of this type are designed to measure the wavelength dependence of the atmospheric turbulence spectrum $\Phi(\vec{K})$. In order to yield information about the same atmospheric region both the transmitting and receiving antennas must illuminate the same atmospheric region (i.e., be wavelength scaled). Table VI summarizes experiments using more than one frequency.

There are several experiments in the literature [for example, Bullington (1955); Chisholm, et al., (1955) and Crawford, et al., (1959)] which utilized more than one frequency but their results are not of a form which yields a direct interpretation of wavelength dependence over time periods of a few minutes (i.e., long enough to be statistically significant but short enough to avoid long-term drifts).

A multi-frequency experiment using antennas with similar beam patterns (antennas wavelength scaled) was conducted at Cornell University in 1956. According to Bolgiano (1959) at Cornell the results were not conclusive.

Bolgiano (1959) reported on an experiment by Chisholm, et al., (1957) which used scaled antennas (similar beam patterns)

TABLE VI

MULTIPLE FREQUENCY

Author	Date Pub.	Path Location	Element Scaling	Element Size	Freq. (Gc)	Path Length (miles)	Min Scat. < (Deg.)	Met. Data
Bullington Chisholm	1955 1955	(Two experiments utilizing 2 widely spaced frequencies)						
(Cornell Univ.)	1956	N.Y.		Scaled antennas		60		
Crawford, et al.	1959	(An experiment utilizing different frequencies)						
Bolgiano report of Chisholm et al. exp.	1959 1957	East Coast U.S.	Freq. scaled antennas	28 ft 5 ft	0.41 2.3	188	--	--
Ortwein	1961	Calif.	Freq. scaled antennas	2^o beams	1.25 3.41 9.36	190		N profiles extensive weather
Bolgiano	1964	N.Y.	Freq. scaled antennas	28 ft 10 ft 4 ft	0.84 2.8 9.1	67	--	Soundings 150 mi from path

at two frequencies. The results indicate that the wavelength dependence is not constant but varies from one time period to another. The experiment reported by Bolgiano (1964) involved 3 frequencies and wavelength-scaled antennas. There was unquestionable variation in the wavelength dependence of the scattering mechanism observed in this experiment. This could be due to changes in the turbulence spectrum itself or possibly to nonuniformities in the atmosphere.

The technique of using more than one frequency in a transhorizon atmospheric probe is a powerful tool but it alone is not sufficient to resolve the question of atmospheric structure at any given time.

3.7 Measurement of Anisotropy and Inhomogenity

An experiment reported by Bolgiano (1963) combined some aspects of the beam swinging and the multi-frequency experiments. Antennas with similar beam patterns (wavelength-scaled) were used at 3 widely separated frequencies (0.84 Gc, 2.8 Gc and 9.1 Gc). Averaged received power measurements were made with the 0.84 Gc antennas aimed 3^o off the great circle path, the 9.1 Gc antennas aimed along the great circle, and the 2.8 Gc antennas swung in alternate half hours from along the great circle to 3^o off the great-circle path. Average amplitude samples thus were taken of the scattering from the same two size (related to the wavenumber $|\vec{K}|$) components of 3 meters and 1 meter with the $\vec{K}$ vector vertical for the great circle path and at an angle of $\approx 70^o$ from the vertical for the path 3^o off the great circle. The results, which at times indicate different wavenumber (size) dependence for the different $\vec{K}$ vector orientations are interpreted to mean that the atmosphere was anisotropic (i.e., that $\Phi(\vec{K})$ was a function of direction of $\vec{K}$) for those time periods. At other time periods interpretation of the results indicates isotropic conditions. Again the variability from time period to time period is present. Since the data for a given comparison were not taken simultaneously, but at 1/2 hour intervals, one is forced to suspect that non-stationary conditions might have existed to contribute to the observed results, possibly in addition to conditions of anisotropy (or inhomogeneity). This experiment illustrates, however, that combinations of experimental techniques can be successfully applied to define better the state of the atmosphere over a given time period but it also points up the desirability or rather the necessity for measuring all required parameters simultaneously for a given interpretation.

An experiment reported by Gjessing (1960, 1963, 1964, 1966) involves carefully controlled synchronous swinging in azimuth and in elevation of both transmitter and receiver beams. The swinging is done in such a way that sometimes the scattering angle (i.e., $|\vec{K}|$) remains constant while the direction of $\vec{K}$

varies (combined azimuth and elevation swing), sometimes swings are made so that the direction of $\vec{K}$ remains constant while the scattering angle $(|\vec{K}|)$ varies (elevation swing only), and in other cases swings are made so that the scattering angle $(|\vec{K}|)$ remains constant and the direction of $\vec{K}$ remains constant to within $\approx 2^{\circ}$ (elevation swing only). In all cases the atmospheric scattering region varies during the swing. These measurements should indicate to some extent the degree of anisotropy and inhomogeneity and the angular dependence of the scattering cross section [and thus $\Phi(\vec{K})$]. Results of the experiments are interpreted to indicate that for some time periods the atmosphere is isotropic and homogeneous and for other time periods it is either anisotropic or inhomogeneous or both. A large amount of variability exists in the data from time period to time period. Interpretation of the data requires use of an inhomogeneity measurement to remove inhomogeneity from the isotropy data and the angular dependence data. Since the inhomogeneity may not be the same everywhere some error may result from this procedure. Also, again, all measurements are not made simultaneously--thus the specter of NONSTATIONARITY raised its head again. This experiment makes more complete use of the capabilities of synchronous beam swinging than does any other experiment reported to date and serves as a good example of the technique's versatility.

3.8 Meteorological Measurements for Comparison with Radio Measurements

For most of the transhorizon propagation experiments reported in the literature associated meteorological measurements either were not made at all or were gathered from existing, but usually not optimally located, weather stations. The experiments for which correlation between the radio observations and available meteorological observations was possible usually exhibit poor correlation. One exception to this experimental deficiency is noted in Ortwein, et al, (1961). During this experiment extensive surface weather data were collected, refractive index profiles were taken using airborne refractometers and supplementary balloon observations (pibals, Raobs and Rawindsondes) were made. Generally, the weather data were used to select time periods when turbulent conditions should exist. Radio data for these time periods were then compared with turbulence theory predictions. In general, effects of elevated inversions were noted on elevation angle beam swings but not on azimuth beam swings, large variations in atmospheric characteristics correlated with radio measurements and sometimes variations in wavelength dependence could be identified with variations in observed atmospheric structure.

Though the task is extremely difficult it appears that considerably more meteorological data need to be taken and more detailed meteorological analysis needs to be made than has been done in practically all propagation experiments conducted to date.

3.9 General Observations in the Experiments

The most striking feature observed in all the experiments is the wide range of variation in the measured parameters for different time periods regardless of what parameter or parameters were being measured in the experiment. This variation would indicate that all the experiments differentiate between different atmospheric states even though the states may be too complex to identify with the simple measurement or measurements made.

A second observation is that any given set of measurements can usually be interpreted in different ways. Examples are that beam swinging data with similar characteristics can be used to support both layer theories and turbulence theories, that data taken at different time periods can be combined and interpreted to indicate either inhomogeneity or nonstationarity due to changing atmospheric states or sometimes anisotropy, and that beam swinging data in elevation can be interpreted as an indication of different turbulence spectrum angular dependence or of a height dependence in the fluctuation intensity of turbulence (a kind of inhomogeneity). These problems result because there are not a sufficient number of measured parameters to permit the sorting out of all atmospheric states and assumptions of homogeneity or isotropy or stationarity are necessary to permit interpretation at all. Variations in one parameter like anisotropy which are "measured" in some experiments are assumed not to exist in the interpretation of other experiments.

A third observation, which must be made with care and caution because of the previous observation, is that during some time periods the atmosphere appears to be in a state of nearly isotropic, homogeneous, nonchanging (stationary) turbulence with a spectrum which is quite close to that predicted by Kolmogorov or Obukhov, while during other time periods the turbulence may be anisotropic and/or inhomogeneous and/or changing with time. During still other time periods the atmosphere may tend toward a stable state with the major irregularities being caused by stratified layers with different characteristics.

A fourth observation is that at times the significant scattering region is smaller than the resolution of angle- and distance-measuring instruments used in the experiments.

A fifth observation is that at times the measured parameters are quite stationary for time periods of the order of hours while at other times the measured parameters may change by a large amount in a few minutes.

A sixth observation is that the question of the mechanism of propagation (partial reflection or scattering from somewhat localized regions or scatterers) is not resolved. Evidence suggests that maybe there is not a unique mechanism but that scattering and partial reflection may both occur. This suggests that some problems in measuring atmospheric velocities may be encountered if the velocity measured by radio methods is partially due to fleeting reflection points.

The last observation made by this author is that during the conduct of most transhorizon propagation experiments the measurement and analysis of meteorological parameters is not sufficient for determining the state of the atmosphere at the time of the experiment.

3.10 Requirements for Definitive Experiments

The only obvious general conclusions which result from a careful survey of reports describing past transhorizon propagation experiments are that either

1. It is not possible to determine anything very definitive about the state of the atmosphere or atmospheric motion from such measurements, or
2. The "tools" used in experiments so far were not sufficiently powerful or sufficiently numerous to define the states or motions in the atmosphere.

Choice of 1. runs contrary to the history of scientific measurements; therefore 2. would seem to be the most likely conclusion. With this in mind possible ways to strengthen such experiments will be explored.

The atmosphere exists in a variety of different complex states which are functions of both space and time. A logical development of experimental requirements might progress as follows:

The problem of resolving the changes of atmospheric state with time requires that all measurements must be made simultaneously and suggests that measurements should be made at rates greater than rates of change in the atmosphere.

The problem of defining the atmospheric state in a small region probably is approached best by using high-resolution (narrow beam) antennas. The antenna beamwidths at all frequencies should be the same. It appears desirable to measure independently two parameters which should produce identical dependence at least for some atmospheric states. A good possibility is the use of a number of frequencies to establish the wavelength dependence of the scattering mechanism in the small region and simultaneously, from several receiving sites, (see Fig. 4) determine the angular dependence of the scattering mechanism in the same region. Antenna beams at different sites need to be scaled to illuminate the same volume from all sites. If the mechanism were turbulence which was homogeneous in the small region then angular dependence and wavelength dependence should be the same. Other states would

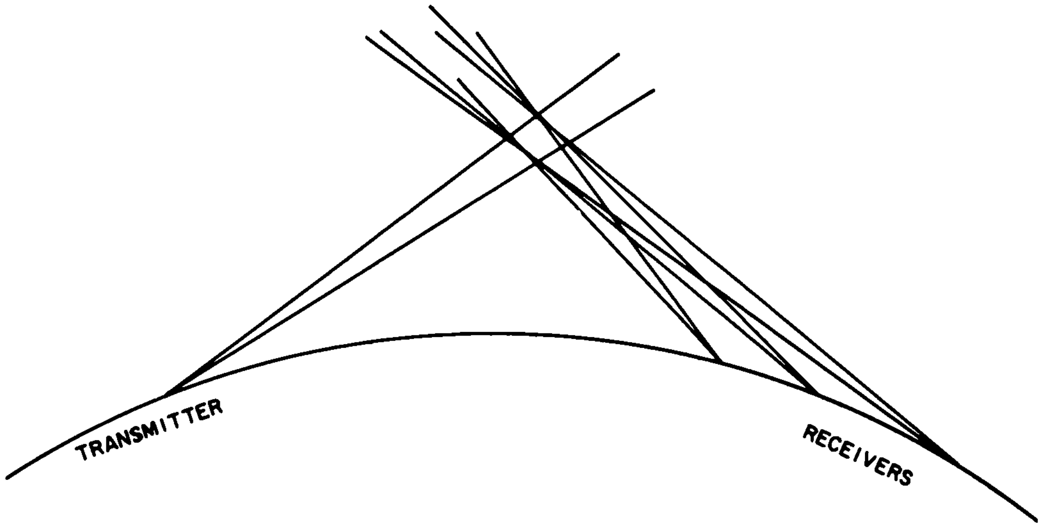

FIG. 4 GEOMETRY FOR DETERMINING ANGULAR DEPENDENCE

usually produce an angular dependence different from the wavelength dependence. The problem of describing the atmosphere throughout the entire volume accessible from the instrumentation sites might then be met by synchronously and rapidly sweeping the transmitting and receiving beams in such a way that the entire volume is swept out by the intersection region between the beams. This procedure should determine the extent of anisotropy and inhomogeneity in the entire volume. Height dependence of fluctuation intensities should also be resolvable. To produce a 3-dimensional picture of the atmosphere in the volume would require two sets of experimental apparatus operating perpendicularly to each other (crossed paths).

The measurement of doppler spectrum for velocity determination would require the precise generation of all frequencies. Since the procedure described above would permit the "tracking" of fleeting reflection points, the effects of these on the determination of actual atmospheric velocities from the doppler measurements could be defined.

So far these suggestions point to rather extensive experimental instrumentation and techniques which are extensions of techniques already applied individually. The data reduction requirements from such an effort also would be quite large since the instrumentation would produce something of a data explosion. It appears, however, that the collection of definitive data on atmospheric state from transhorizon propagation experiments would require at least two and probably all of the experimental capabilities mentioned above to circumvent the need for making insupportable assumptions about the atmosphere in order to interpret data from more limited measurements.

In addition to such an extensive electromagnetic measurement program, extensive meteorological measurements both on the surface and within the scattering region should be made and analyzed to provide an independent check on the results from the transhorizon propagation probe.

The basic requirements then appear to be

a. simultaneous rapid measurements

b. high angular resolution (from an antenna array or large multi-feed antenna) with the same beamwidths at all frequencies

c. multiple frequencies precisely determined

d. synchronous pointing of transmitting and receiving antennas

e. multiple receiving sites along the path line

It should be pointed out that even the pursuit of such an ambitious measurement program as that outlined above carries no guarantee of success at this time--it is only that such a program seems to be the most likely to succeed when viewed in the light of past experiments.

4. ADVANTAGES AND LIMITATIONS OF TRANSHORIZON PROPAGATION PATHS AS REMOTE ATMOSPHERIC PROBES

Assuming that the technique of transhorizon propagation measurements were developed into a useful probing tool, two of its advantages would be

a. Measurements could be made over a rather wide volume of space from one set of installations, and

b. Requirements for site locations would not be critical. (No mountains or tall towers would be required as might be for a line-of-sight probe).

Some of the limitations of the technique would be

1. It is best suited to measuring characteristics averaged over regions in space defined by the intersection of two antenna beams (on the order of several hundred to a few thousand feet square).

2. It is not suited to making measurements near the ground. The useful region starts several hundred feet to a few thousand feet above the ground depending on the paths.

3. It is more sensitive to atmospheric characteristics at altitudes near the minimum beam intersection altitude of a given path and the sensitivity falls off quite rapidly above this altitude because of the angular-dependent nature of any of the scattering or reflecting mechanisms.

4. Some means must be provided for rejecting data taken when aircraft fly through the scattering region.

5. FACILITIES AVAILABLE

There are no facilities available with the complex capability suggested in section 4 of this report; however, there are some facilities intact which have been or are being used in transhorizon propagation research. Below is a partial list of such facilities:

A. University of Wisconsin - Collins Radio

This facility is equipped with stable-frequency-generating equipment and is being used for path phase and doppler measurements. (See paper by Prof. Berkemeir in this Section.)

B. Stanford University, California

A large-aperture 12-element antenna array is available and is currently in use. The total aperture is adjustable but is currently set at 162.5 wavelengths (50 feet). The array is oriented vertically but can be positioned horizontally or even split for some horizontal and vertical resolution. The array and associated equipment must operate at 3.200 Gc because of the way both transmitter and receiver frequencies are generated. The frequencies are generated with sufficient precision to permit measuring the doppler spectrum. The basic data recorded are amplitude from each element and phase difference between adjacent elements. These measurements are made at rates up to 100 samples from all 12 elements per second. (See Cox 1967).

C. University of Washington

A 10-element horizontal antenna array with an element spacing of 17 feet (aperture 153 feet) is being constructed. This array will operate at about 900 Mc when completed.

D. Cornell University, New York

Equipment for conducting experiments at 3 frequencies (840 Mc, 2.4 Gc and 9.1 Gc) with wavelength-scaled antennas (28 feet, 10 feet, and 4 feet in diameter) for both transmitting and receiving has been used at Cornell. Availability of the equipment is not known to this author. (See Bolgiano, 1964).

E. Rome Air Development Center, New York

Multiple Feed 28 foot parabolic reflectors with 0.3° beams for use at 7.8 Gc have been used recently for angle of arrival measurements. (Kieburtz, et al., 1966). Availability is unknown.

6. SUMMARY

Many attempts have been made at determining characteristics of the atmosphere from characteristics observed in radio signals propagated beyond the horizon. From the viewpoint of scientific investigation much progress has been made in defining the problem area in general, the mechanisms involved, the parameter characteristics and ranges and to some extent the relationship between the parameters and the atmosphere. From the viewpoint of remote atmospheric probing, however, the interpretation of any one set of radio measurements is not sufficiently definitive to permit the unambiguous determination of atmospheric state or structure or the quantitative determination of some atmospheric parameter. That is, the interpretation of all measurements made to date requires the use of assumptions about the atmosphere which are not directly supportable by the measurements themselves. The outstanding feature of the characteristics of the transhorizon signals is their extreme variability from one time period to another. This variability indicates that the signal characteristics are a good discriminator of changes in the atmosphere itself.

It would appear that too much theoretical and experimental effort has been expended trying to determine universal, gross, overall characteristics for the atmosphere such as the turbulence spectrum $\Phi(\vec{K})$ when the experimental data seem to indicate that such universal characteristics do not exist for the wavenumbers $(\vec{K})$ involved in transhorizon propagation. More detailed and complex experiments seem to be required to provide a sufficient number of more or less independent parameters for use in sorting out the complex characteristics of the dielectric permittivity fluctuations in the atmosphere. These experiments should include sufficient meteorological measurements to provide a good check on the conclusions reached from radio signal measurements. Although results from past experiments suggest that the analysis of data from such complex experiments would yield a better description of the atmosphere than has been possible so far, there certainly is no guarantee that this success would be achieved.

Because of the present state of knowledge of transhorizon propagation phenomena, signals propagated beyond the horizon do not appear suitable for current use as remote atmospheric probes. Because of the variability in the characteristics of these signals, however, they do appear to hold considerable potential for such use. The development of this potential definitely should be continued. More definitive experiments which make use of combinations of measurement techniques and more complete theory to aid in the interpretation of the measurements are needed to develop this potential.

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