AN INVESTIGATION OF NON-RECIPROCITY IN OBLIQUE-INCIDENCE IONOSPHERIC RADIO PROPAGATION

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AN INVESTIGATION OF NON-RECIPROCITY IN OBLIQUE-INCIDENCE IONOSPHERIC RADIO PROPAGATION

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SUMMARY

An investigation was made of certain aspects of non-reciprocity of oblique-incidence radio wave propagation. A series of specially designed and carefully controlled experiments were devised to transmit identical, synchronized signal pulses in opposite directions over the same ionospheric propagation path between Fairburn, Georgia, and Ipswich, Massachusetts, a base path distance of approximately 1565 kilometers. Each station contained identical facilities, consisting of transmitters and receivers, rhombic antennas, and synchronization equipment to insure that the transmitted pulses were identical and time synchronized. The pulses were transmitted at 1/3 second intervals. Transmissions took place for a variety of propagation conditions.

The receiver signal output was proportional to the logarithm of the signal input. Hence a wide range of signal strengths could be covered by the oscilloscope recording the signals. The output signal pulses were displayed on linear time base oscilloscopes and the oscilloscope traces were recorded with movie cameras. The different pulses received, for a single transmitted pulse, corresponded to the signals received via the various ionospheric layers. The pulses received most often were from single-hop reflections from the E, F1, and F2 ionospheric layers. These signals were designated as 1E, 1F1, and 1F2, respectively. The moving-film strips from each station were superimposed with correct time alignment and photographed to provide a composite film. The pulse amplitudes, representing the logarithm of the receiver input signal amplitudes, on

each film frame were measured on a convenient linear scale and tabulated.

The amplitudes of pulses received from opposite directions via the same propagation mode were plotted on the same graph, giving a record of relative signal strength variation versus time. Analysis of these graphs revealed periods during which the signal pulses varied in a non-reciprocal manner. One observed non-reciprocal type was that in which one signal increased in amplitude while the other signal simultaneously decreased. Another type of non-reciprocal behavior was characterized by a similar but out-of-phase variation. The usual duration of each non-reciprocal variation was in the range of six to 15 seconds, with the typical value for the out-of-phase variation being of the order of ten seconds. Every experiment contained periods of non-reciprocity.

The sample correlation coefficient for the signals propagated in opposite directions via the same path was computed. Extreme values for the correlation coefficient were 0.97, indicating nearly perfect correlation, and -0.07, indicating an almost independent relationship.

In order to investigate what effect, if any, different ionospheric conditions or frequencies of propagation had on non-reciprocal behavior, results of experiments for certain common conditions were grouped together. The ionospheric groupings were: (1) Winter day (2) Summer day (3) Summer night and (4) Summer sunrise-sunset. The groups of propagation frequency were: (1) 8.35 - 8.45 Mc (2) 10.55 - 11.85 Mc (3) 16.55 - 16.95 Mc (4) > 20 Mc. For each group, the sample correlation coefficients and the total durations of non-reciprocity for the oppositely-traveling signals were averaged.

The calculated average non-reciprocity for the 1E mode of propagation was lower than that of the other modes in all groups considered, except the sunrise-sunset (transition) condition group. The average 1F1 non-reciprocity was less than the 1F2 mode non-reciprocity except for the winter-day conditions, when the F2 ionization intensity is higher than that of the F1. The average summer-night 1E non-reciprocity is higher than the winter-day value which is in turn higher than the corresponding summer-day figure. The summer-day non-reciprocity average for the F1 mode is less than the winter-day average while the opposite is true for the F2 mode. Hence there is an observed relation between non-reciprocity and both ionization level and ionospheric activity, with more average non-reciprocity occurring during periods of lower degree of ionization and higher ionospheric activity.

There was no observed relationship between non-reciprocity and the propagation frequency groups. The highest average non-reciprocity for different modes occurred with different frequency groups and no trend was established. The 1E non-reciprocity was, however, lower than the 1F1 and 1F2 values for all frequency groups examined.

The winter day average correlation coefficients were 0.77, 0.28, and 0.43 for the 1E, 1F1, and 1F2 propagation modes, respectively. The corresponding values for summer day conditions were 0.82, 0.46, and 0.40. The summer night 1E coefficient was 0.70, lower than both the winter day and summer day values, but higher than the average value, 0.58, for the combined night-time 1F1 and 1F2 layers. The lowest 1E coefficient, 0.19, was for the sunrise-sunset transition period.

There was close general agreement between the average total duration of non-reciprocity and the average correlation coefficient, with lower correlations associated with longer periods of non-reciprocity.

CHAPTER I

HISTORY OF THE PROBLEM

The importance of long range radio communication need not be discussed; it is used with good reliability in countless ways in an ever increasing number of fields. After the discovery that it was possible to establish radio communications over much greater distances than those theoretically possible by means of ground wave propagation, much research was devoted to investigating the cause and effects of this phenomena. Increased theoretical knowledge and improved experimental equipment and techniques eventually enabled the prediction of propagation conditions for a given season of the year, hour of the day, geographic location, and distance of transmission and all this for three months in advance.[*] As in many fields of science and technology, additional knowledge in the field of long range radio communications was not sufficient, but required even more information regarding its nature. More detail regarding the behavior of the radio waves[**] during long distance communication is required. The purpose of this study was to add information to one phase of this behavior.

Early History.--The first suggestion that ionized or conducting layers existed in the upper atmosphere was made by Balfour Stewart (1)[***] in 1878

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[*] See, for example, the U. S. Department of Commerce serial publication, Basic Radio Propagation Conditions, CRPL Series D.

[**] Throughout this paper, the term "radio waves" will refer to the short wave, or High Frequency (3 to 30 megacycles/second) portion of the electromagnetic spectrum, by which most long range radio communication is maintained.

[***] Numbers in parentheses refer to the bibliography.

to explain the diurnal variation of the earth's magnetic field. At that time, experimental equipment that could test his theory had not been perfected. In 1901 Marconi succeeded in sending a wireless signal from Cornwall, England to Newfoundland, a path which comprises a significant portion of the earth's curved surface across the Atlantic Ocean. This feat seemed to contradict the theory of wave propagation along the earth's contour, according to which long distance communication by this means was prevented by the attenuation effects of the earth's surface. Calculations made in an attempt to explain the observed results in terms of diffraction phenomena failed to justify the bending of the radio waves around this much of the earth's curved surface (2). In 1902 Heaviside in England and Kennelly in America independently suggested that the earth was not surrounded by free space, but by conducting regions which could reflect the radio waves downward, thus preventing the waves from escaping into space. Heaviside further predicted that this conductivity was due to ions produced in the upper atmosphere by energy of solar radiation. This suggestion closely followed the earlier theory of Stewart. The explanation of the effect of ionized particles on the propagation of radio waves was presented by Eccles (3) in 1912, with further details being added by Larmor (4) in 1924. The Eccles-Larmor theory is recognized as the basic theory dealing with radio wave propagation in the ionosphere.

Although theoretical analysis of upper atmospheric conducting regions* had been going on for some time, no experiments had directly proved their existence. The existence of the regions were first directly

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*For a brief discussion of the formation of the ionosphere and the basic theory of radio wave propagation through it, the Appendix may be consulted.

proved in 1925 when Appleton and Barnett compared the intensities of fading signals received simultaneously on a loop and on a vertical antenna. The measured angle of arrival demonstrated a downcoming wave, proving that this wave could have come only from reflection off the Kennelly-Heaviside layer. Additional experiments not only verified this result, but contributed information regarding the height and reflecting ability of the layer. Breit and Tuve (5) in 1926 devised an experiment in which a short pulse, rather than a continuous signal, was transmitted. A receiver located a few kilometers away received not one, but two or more pulses. The first pulse, strongest in amplitude, was attributed to the ground wave, while later arriving pulses were attributed to the reflections from the ionized region. Later work proved the existence of multiple, well-defined regions of ionization, each having its own layer* structure. These different ionized regions were collectively called the "ionosphere," as suggested by Watson-Watt, and this term has been universally accepted.

Most of the ionospheric studies were made by the pulse-sounding method developed by Breit and Tuve. The time delay between the transmitted pulse and the pulse received by reflection off the ionosphere was measured on an oscilloscope using the pulse-repetition frequency to synchronize the time base. If it is assumed that the pulse travels with the velocity of light in free space, the time delay over the path length can be used to calculate the reflecting layer's height. Actually this assumption is not correct since the pulse is retarded as it encounters ionized

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*A region is a division in the ionosphere which is clearly separate from the others. A layer is a well-defined maximum of ionization within a region.

particles. This method, however, does give an "equivalent" height, useful in examining the ionospheric layers. The pulse method also indicates the reflectivity of the layers.

The composition and variation of the ionosphere is quite complex. In addition to the generally regular variations resulting from changing solar radiation conditions, there are many random fluctuations. Some fluctuations result from meteor or sunspot activity. Some variations are as yet unexplained. Jordan (6) mentions that these variations are similar to the weather in that the general behavior may be predicted in advance while short irregularities often occur. For a certain hour of the day and season of the year, the average amount of available solar radiation determines the ionospheric regions with some uniformity. As the name region implies, there are no recognized exact boundaries of each region's location; instead there are centers of maximum ionization about which the ionization gradually decreases, then increases to a maximum in another region. Jordan (7) defines the E region to be the region between 89 and 137 kilometers above the surface of the earth, Mitra (8) uses 90 to 110 kilometers for the same region, and the Annals of the International Geophysical Year Instruction Manual (9) specifies 100 to 120 kilometers. These variations merely indicate a question of degree of a region. The average location of the E region may be considered to be between 95 and 120 kilometers. Below the E region is the D region, at an average height of 60 to 90 kilometers. It is present only during daytime and is an absorbing region for radio frequencies and causes little, if any, reflection. Its presence is indicated not by the ordinary pulse reflection method but by recognizing strong absorption of signals below the E region during daylight hours. Heights of 150 to 400 kilometers describe the F region which sometimes separates into two components, the F2 above and the F1 below. The ionization intensity and general behavior of the two are somewhat different. However, at night the F1 and F2 regions blend into a single region. The letter designation of the regions is rather arbitrary, but started with "D" so that any still lower regions found could be lettered in the same sequence. Possible existence of a G region above the F2 region has been suggested by Mitra (10) but no strong evidence has been found to support this theory. Within each region are well-defined layers of maximum ionization. Sometimes a very strong layer appears suddenly at the E region height and lasts for short periods of time. This "sporadic E" layer, designated E_s, usually travels in a manner similar to a cloud, and can reflect much higher frequencies than can the normal layers. Its cause is not well understood, but is partially due to meteor activity in the normal E region. More comprehensive information on the formation and nature of the ionospheric regions can be found in the literature (11), (12).

Vertical-Incidence Propagation Studies.--Most of the early investigations of the ionosphere were carried out by the pulse method at vertical incidence propagation, that is, pulses of radio frequencies were transmitted upward and the pulses reflected downward were received at, or in close proximity to, the transmitter. Multiple "echoes" were usually received, due either to reflections from different layers or to the signal being reflected from the ground and then again from the ionosphere. Pulses in the latter category are much smaller in amplitude than "single-hop" echoes because of the additional energy loss in the ground and the increased path length in ionized areas. It was observed that when the radio frequency was increased the pulses traveled farther into the ionosphere before being reflected. As the frequency was further increased, a certain frequency was reached for which no reflected pulse was received. At this so-called "critical" frequency the signal completely penetrated the ionosphere and was not reflected. These phenomena are in accord with the theory discussed in the Appendix. The vertical incidence transmissions, or "soundings" as they were called, gave valuable information regarding the equivalent height of each of the layers and the critical frequency at the time of transmission. After many of these experiments were performed at ionospheric sounding stations located at different parts of the world, the accumulated data made apparent the general nature of ionospheric variability. It was seen that the E layer critical frequency was almost zero just before dawn, rose to a maximum shortly after noon, then gradually decreased to a low value at night. The F1 layer follows a diurnal variation similar to that of the E layer. The F1 layer, however, persists at night since the layer's low density prevents rapid recombination of electrons and positive ions. During the day the F2 layer displays some characteristics similar to the E and F1 layers but is more irregular in its behavior. The winter pattern for the E and F1 layers is similar to the summer pattern, except for reduced maximum ionization density due to the lower solar zenith angle. The F2 ion density is greatest in winter and least in summer. There is also less distinction in separation of the F1 and F2 layers in winter (13). Other variations found are linked to sunspot cycles. During periods of sunspot maxima the ion densities of the E, F1, and F2 layers increase, causing higher critical frequencies than found during sunspot minima. Absorption of the D region is highest during sunspot maxima. Many short term fluctuations have been observed which can not be classified into any regular behavior.

Oblique-Incidence Propagation Studies.--While the vertical-incidence experiments revealed considerable information regarding the nature of the ionosphere, the research workers still had in mind the ultimate use of the acquired knowledge. The purpose of most of the study was to increase the ability to communicate by radio waves over long distances with reasonable reliability. Attention was therefore turned toward applying ionospheric data to this goal. Three useful theorems relating oblique-incidence reflection frequencies to the observed frequencies reflected from vertical-incidence are the secant law, Breit and Tuve's theorem, and Martyn's theorem (14). These theorems, while assuming flat earth, flat ionosphere, and no earth magnetic field, are very useful in explaining oblique-incidence propagation. Consider Figure 1 (15). Let a wave be transmitted at T and strike the ionosphere at A at an angle ϕ_o. If sufficient ionization is present, the wave will be bent away from the vertical throughout the layer, leave the layer at C, and return to the earth at R. The secant law relates the frequency at oblique-incidence, f_{ob}, that is reflected from the same true height to the frequency at vertical incidence, f_v at the mid-point of the path. This relation is:

$$f_{ob} = f_v \sec \phi_o \tag{1}$$

Breit and Tuve's theorem states that the time required by the wave traversing the true path TABCR at the actual velocity* is the same as that

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*The reader is reminded that the wave is propagated more slowly as it enters the ionospheric medium.

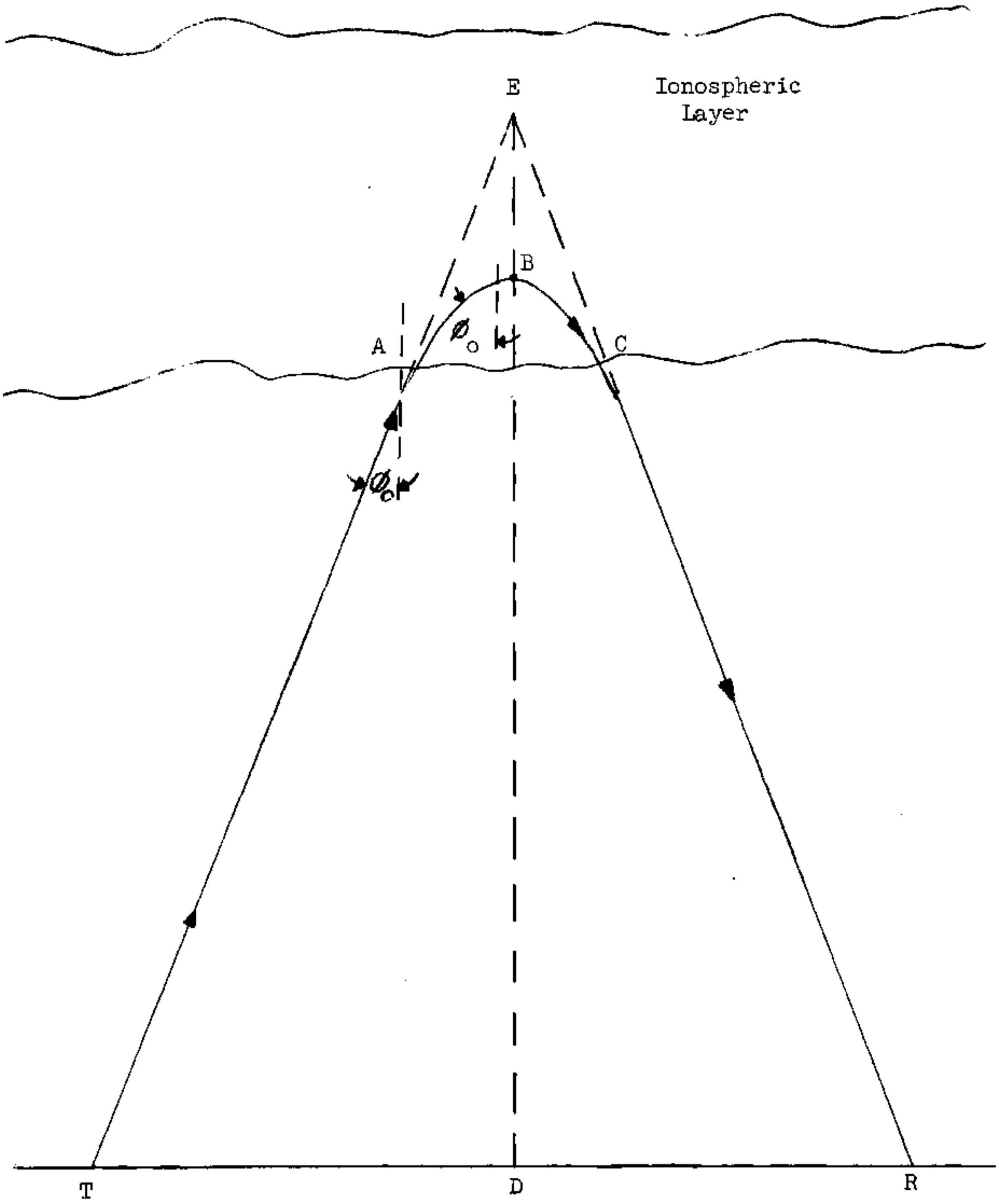

Figure 1. Oblique Incidence Propagation Path.

required traversing the triangular path TER at the free-space velocity. Martyn's (16) theorem states that the "virtual" height of the f_v equals the equivalent triangular path height of f_{ob}, if f_v and f_{ob} are vertical- and oblique-incidence frequencies, respectively, reflected from the same true height. Various methods have been devised to obtain the maximum usable frequency (MUF) that could be used at any time for a given distance of transmission. Smith (17) gives a graphical method for obtaining MUF's and skip distances in terms of vertical propagation conditions. His method is used by the National Bureau of Standards in Washington for making these radio predictions. Appleton and Benyon (18) also present a theoretical determination of the MUF's,taking a curved earth into account. The Radio Research Board in England uses the latter method to publish curves indicating the relation between the MUF and vertical-incidence critical frequency and distance factors. Appleton and Benyon did recognize the occurrence of conditions in which transmission is possible at frequencies higher than the "normally predicted" values. Millington (19) gives a theoretical derivation relating oblique-incidence transmission and vertical-incidence data, with some refinements on Smith's assumptions.

In addition to these methods there are other similar means of predicting actual transmission conditions from observed vertical-incidence data. Considerable experimental work has been performed to test these predictions. Beynon (20) conducted experiments over a 715 kilometer base path to compare observed and calculated MUF's. He found the two to be in general agreement although the observed MUF was sometimes higher than the calculated value by about one per cent, corresponding to a difference in frequency of approximately 0.7 Mc Propagation for these experiments was mainly via the F2 layer. Cox and Davies (21) conducted two-way, pulsed sweep-frequency experiments over a 2360 kilometer base path and found the vertical-incidence theories to be "qualitatively correct." Each end of the path had a transmitter and receiver to examine data for both directions of propagation. They found the observed and calculated values to be in close agreement, particularly during periods of "quiet" ionospheric activity. An important point mentioned by them was the question of reciprocity. They state:

> It is inherent in the theory that a certain type of reciprocity should prevail. One does not expect to obtain equal amplitudes or polarizations at the two ends and, in fact, it was often noticed that a particular echo was only seen at one end. Without detailed measurements of aerial polar diagrams and of noise, no deductions can be made from this. It would be expected that the path-times in each direction would be identical. This cannot be measured, since there is no common reference of timing.

They assumed that the transmission times for the two directions of propagation were equal and compared the time interval between the different echo pulses received at each station. Any difference in time interval at the two stations was considered by the authors to be evidence of non-reciprocity. Although the transmission was stronger in one direction than in the other, no measurable departure from this type of reciprocity was ever observed. In another sweep-frequency, oblique-incidence propagation experiment, over a 2355 kilometer path, Chapman et al. (22) also considered reciprocity effects. They too assumed that the transmission times in both directions were the same although they realized that it was not possible to make a direct test of this because of the lack of a common time reference. They point out:

> It has not yet been adequately demonstrated that propagation of radio signals in the ionosphere is completely reciprocal. Indeed, the influence of the earth's magnetic field may be such that the principle of reciprocity* may not always hold. Hence this point is worthy of investigation.

They were, however, referring to reciprocity in generaly and not to any particular type such as delay time, MUF, relative amplitude variations, or the like.

The fact that in some cases radio waves propagated over the same path, but in opposite directions, both closely follow the general theory, yet differ somewhat from each other is very interesting. Investigation into any one of the particular non-reciprocity tests, such as delay time or relative amplitude variation, would uncover further information on how the ionosphere affects radio waves. One of these investigations of non-reciprocity serves as the basis for this thesis.

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*A discussion on the principle of reciprocity is included in the following chapter.

CHAPTER II

SPECIFICATION OF THE PROBLEM

Statement of the Problem.--The problem was to study a particular characteristic of radio waves propagated through the ionosphere. This was done by setting up a specially designed and carefully controlled experiment to investigate reciprocity of radio-wave signal amplitude variations. The signals were transmitted by identical equipment at stations located 1565 kilometers apart. The transmission of radio waves took place for a good representation of conditions causing variations in the ionosphere such as frequency of propagation, time of day and season of year. The data from these experiments were studied with the intent of verifying the existence or non-existence of the non-reciprocal ionospheric effect on the radio-wave amplitudes. The nature and degree of this non-reciprocal effect, as well as its observed dependence on ionospheric conditions, were investigated. A statistical analysis was made for representative experimental trials in order to obtain a quantitative measure of the degree of association between the waves propagated in opposite directions. No attempt was made to give a mathematical explanation of the observed phenomena. The experimental data, coupled with the known general behavior of the ionosphere, was used to analyze the existence and extent of non-reciprocal signal amplitude variation.

Purpose of the Research.--As was previously mentioned, it is no longer sufficient to know that one can most likely communicate with another at a given distance, using a certain maximum frequency at a particular time.

Radio waves are now used for much more complex purposes than voice communication, so that relative signal strength of the waves becomes a more critical factor.

It is not the purpose here to elaborate on any specific applications of the information derived from this study, but only to remind the reader of the aspects of some recent, complex radio communication techniques and the problems encountered. It is hoped that information from this study will assist in dealing with some radio communication problems.

The purpose of the experiments was to compare simultaneous radio signal transmission in opposite directions over the same ionospheric propagation path. In particular, comparison was made to determine existence of any non-reciprocal relations between the two signals. The experiments were performed for a variety of ionospheric conditions to see which had significant effect on non-reciprocity. In order to limit changes in the radio signals to ionospheric effects, it was necessary to establish equal operating conditions at the two stations and the synchronization of their transmitted signals.

Some Related Investigations.--The purpose of this section is to review theoretical and experimental investigations of reciprocity of radio wave propagation through the ionosphere. The restrictions and limitations of each investigation will be mentioned.

In a paper by Carson (23), "Reciprocal Theorems in Radio Communication," he discusses the "reciprocal theorem" of Rayleigh (24), taken from the latter's book, Theory of Sound:

> Let there be two circuits of insulated wire A and B and in their neighborhood any combination of wire circuits or solid conductors in communication with condensers. A periodic electromotive force in the circuit A will give rise to the same

> current in B as would be excited in A of the electromotive force operated in B.

Carson points out that this theorem, extremely useful in circuit theory and communication engineering, is valid only for systems in which the currents flow in linear, invariable circuits and does not apply exactly to the case of radio transmission. He also discusses the Sommerfield-Pfrang reciprocity theorem:

> If A_1 and A_2 are two antennas located at O_1 and O_2 respectively, and have arbitrary orientations, and signals are first sent from A_1 and received by A_2 and then sent with the same average power from A_2 and received by A_1, then the intensity and phase of the electric field at the receiver A_1 will be equal to that previously produced at A_2, regardless of the electrical properties and geometry of the intervening media and the form of the antennas.

Carson states that the latter theorem contains restrictions which "seriously limit its applicability to radio transmission.problems." Limitations mentioned are: (1) the relations $D = \epsilon E$, $B = \mu H$, and $I = \sigma E$ must be linear, (2) the transmitting and receiving antennas must both behave like simple electric or magnetic dipoles, and (3) the transmitting and receiving antennas must both be very far removed and isolated from other conducting bodies, including the earth. These limitations, Carson states, greatly limit the theorem because of practical engineering considerations and usual operating conditions. Carson (25) discusses a "generalized Rayleigh reciprocal theorem," developed by him in his paper, "A Generalization of the Reciprocal Theorem." In this paper he points out that the Rayleigh Reciprocal Theorem is for quasi-stationary systems and that it expressly excludes radiation. Carson proves this generalized Reciprocal Theorem:

> Let a distribution of impressed periodic electric intensity $\overline{F'} = F'(x, y, z)$ produce a corresponding distribution of current intensity $\overline{u'} = u'(x, y, z)$, and let a second distribution of equi-periodic impressed electric intensity $\overline{F''} = F''(x, y, z)$ produce a second distribution of current intensity $\overline{u''} = u''(x, y, z)$, then
>
> $$\int(\overline{F'} \cdot \overline{u''})\, dv = \int(\overline{F''} \cdot \overline{u'})\, dv, \qquad (2)$$
>
> the volume integration being extended over all conducting and dielectric media. $\overline{F}$ and $\overline{u}$ are vectors and the expression $(\overline{F} \cdot \overline{u})$ denotes their scalar product.

This was later stated in a more concrete form:*

> If an electromotive force is inserted in the transmitting branch of antenna A_1 and the current is measured in the receiving branch of A_2, then an equal current (both as regards amplitude and phase) will be received in the transmitting branch of A_1 if the same electromotive force is inserted in the receiving branch of A_2.

Carson further states:

> The only serious restriction on the generality of this theorem is that magnetic matter is excluded: in other words it is assumed that all conducting and dielectric media in the field have unit permeability. This restriction is theoretically to be regretted, but is not of serious consequence in important practical applications.

In the first mentioned paper by Carson (23), he is more specific on the theorems' limitations: "Both theorems fail when the waves are propagated in an ionized medium in which the earth's magnetic field has an appreciable effect on the conduction currents. This fact makes the application of the Reciprocal theorems to short wave transmission somewhat doubtful...."

Another theoretical discussion of reciprocity of radio waves propagated through the ionosphere is given by Budden (26). He recognizes that previous reciprocity theorems assume that the "dielectric constants, conductivities, and permeabilities through which the radiation passes must

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*Commonly called the Rayleigh-Carson theorem.

be symmetric tensors," a requirement not satisfied by ionospheric magneto-ionic medium. Budden's theorem proves that for a horizontally stratified ionosphere and presence of earth's magnetic field, then when the path between transmitter and receiver is in the "magnetic meridian" (North-to-South or South-to-North propagation) the reciprocity theorem applies when: (1) the transmitting and receiving antennas both radiate or receive waves whose electric vector is in the plane of incidence, (2) both antennas radiate or receive waves whose electric vector is horizontal, and (3) if the electric vector radiated or received by one antenna is horizontal and in the plane of incidence for the other antenna, then there is reciprocity in signal amplitude but a 180° phase change for the two directions of transmission. Budden's theorem holds for any electron density, collision frequency with height radio-wave frequency, number of reflections or "hops" from the ionosphere, and for the allowance of curved earth. With any departure from reciprocity, Budden claims, "it will in general be found that communication in one direction is easier than in the other."

Budden's restriction of transmission in the magnetic meridian still excludes the general case of long range propagation. In the experiment described by this paper, propagation was along a 45° Northeasterly and Southwesterly bearing, <u>not</u> along a magnetic meridian, so that non-reciprocal effects could be expected according to the theory.

There have also been experimental investigations of non-reciprocity of radio waves. A general observation made by amateur radio operators ("hams") is that on occasions operator A may receive operator B's signal "strong and clear" while operator B cannot receive operator A's signal of the same frequency. There are usually too many differences in operating conditions in this case, however, and the observations are too general for specific conclusions. Eckersley et al. (27) showed that in some cases, transmission of long radio waves over great distances was not as "good" in one direction as that in the reverse direction. It is admitted that much more data was required for a complete check. In another study, Eckersley et al. (28) made tests on two-way radio transmission over a 393 kilometer base path using the pulse method. The transmission frequency was varied together in small steps on each station and the received pulse pattern displayed on oscilloscopes. As the frequency was increased, each station noted the frequency at which its received pulse disappeared i.e., the MUF. This was repeated for a large number of trials and then the records were compared. It was found that the frequency at which the high-angle and low-angle rays* converged (the MUF) and then faded out was very nearly the same for both directions of transmission, being within 0.03 Mc/sec. They deduced that this particular condition was consistent with reciprocity and suggested that other features of radio waves propagated through the ionosphere were reciprocal. They did not investigate the signal amplitude for reciprocity, nor give any discussion regarding this particular feature other than the general statement above.

A more recent experiment testing reciprocal radio transmission conditions was conducted by Meadows (29) in 1954. The general method used and precautions taken in his experiment were very similar to those used in this experiment. Some of these points are: (1) A-scope** display of the

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*The high-angle and low-angle rays are discussed in the Appendix.

**The "A-scope" display pattern is one in which the height of the received pulses indicates the signal strengths and the spacing of the pulses represents their delay times.

received pulse group, (2) a common antenna for transmitting and receiving, and (3) careful control to insure that frequencies of transmission for both directions were close enough to render negligible "frequency-diversity" effects. The base path used by Meadows was 740 kilometers, 8° West of the magnetic meridian,* with a transmission frequency of 5.1 Mc. The equipment design and procedure used were quite thorough in order to obtain precise and consistent results. The A-scope presentation display was adjusted to scan only 1E and 1F** (both ordinary ray) echoes at three presentations per second. The observation time totaled 886 minutes during daylight hours on 13 days in May, 1954. Any non-reciprocal signal amplitude fading longer than 1/3 second could be noticed. Out of the total observation time of 886 minutes, definite non-reciprocal effects occurred for only 8.4 minutes, or one per cent of the time. On three days there was perfect reciprocity and on one day the non-reciprocity occurred seven per cent of the time. During non-reciprocal fadings, one transmitter's frequency was changed slightly to determine if they were due to frequency diversity resulting from misalignment of transmitter frequencies; at no time was this found to be the case. Inspection was made to see if the E-pulse echo was larger than the F-pulse echo for one direction of transmission and smaller for the other direction of transmission, a conclusive test of non-reciprocity regardless of equipment linearity; no such variation was found. Meadows acknowledges the fact that the evidence for

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*Meadows acknowledges Budden's theory with the special reference to transmission being required along the magnetic meridian for reciprocity.

**Numerals in front of the designated ionospheric region refer to the number of reflections from that region during propagation.

apparent non-reciprocal paths was obtained so infrequently that measurements of amplitude averaged over short periods (about one minute) would have shown little differences in the two directions, and that any differences could possibly be due to sampling or instrumental errors. A shortcoming of the experiment, this writer believes, is the lack of different propagation conditions over which the test was made, such as different times of day (especially at night), seasons of the year, and frequencies of transmission. Since it is not conclusively known what effect, if any, different conditions of the transmitting media have on reciprocity, it seems worthy to conduct tests for these varying conditions. Likewise, different frequencies penetrating to different heights of refraction within the layers may indicate a frequency dependent effect or show whether equipment variations enter into the problem. Meadows hinted that non-reciprocal amplitude effects may be expected to be more pronounced on longer-distance transmission paths, but "if these are in fact due to non-reciprocal swinging of the plane of polarization as has been suggested, they might still be expected to be of reasonably short duration, and to show little preference for a particular direction of transmission." He also indicated that a statistical analysis of signal amplitudes, though requiring "instrumental complication," would be "academically desirable."

Another experiment, utilizing a somewhat different technique, was performed by Laver and Stanesby (30). This test was made over two transmission paths, one between the United States and the United Kingdom, the other between the United Kingdom and Australia, each path being several thousand kilometers in length. A common antenna was used for sending and receiving an unmodulated carrier wave. One important difference in technique was utilized however: the transmission took place in one direction for two minutes while the other station received and recorded the signals, then a 30 second change-over was required, after which transmission commenced from the other station for two minutes. The authors acknowledged that differences in time between opposite transmissions may have accounted for some of the observed non-reciprocity. In view of the ionospheric variations encountered by this writer during experimental work, 30 seconds is indeed a sufficient time for the ionospheric medium to change radically. Laver and Stanesby mention that changes noticed between successive transmissions in one direction could be interpolated to give a rough approximation of the change that took place in the meantime. This may or may not be correct. A signal amplitude which is about the same as an amplitude transmitted three minutes (a two-minute transmission plus two 30-second change-overs) previously does not mean that there was little or no change during the interval. This writer has observed large signal amplitude variations in a shorter interval of time on many occasions (see the figures of Relative Signal Strength versus Time in the chapter entitled, "Experimental Results"). The authors did recognize that their experiment gave an indication of long term reciprocity only. They stated that "truly simultaneous and continuous transmissions on the same frequency would be virtually impossible in practice...." The Laver and Stanesby experiment collected usable data for the U. S. - U. K. path during a three day period in June and for the U. K. - Australia path during a five week period in June, July, and September, both links obtaining night-time data. For the U. S. - U. K. experiment, 13.332 Mc was used and three frequencies, 11.992, 13.332, and 14.30 Mc were used for the U. K. -

Australia trials. Each plotted point used for comparison of the signal attenuations represented the average value taken over a two minute transmission. Similar antennas, rhombics, were used for the U. K. - Australia trials but a Yagi array was used at the United States station. The authors observed periods of definite non-reciprocity lasting for as long as two hours. There was no significant difference in the amount of non-reciprocity between the U. K. - U. S. and U. K. - Australia transmissions.

This writer believes that it is more informative to obtain results over a longer period of time so that any sudden, violent ionospheric activity would not give misleading conclusions of usual signal strength variation. It is also believed that much better transmission synchronization is possible and essential for accurate reciprocity studies. The experiment described in this paper was performed by using identical equipment and operating techniques at each end of the transmission link. Synchronization was maintained between pulse transmissions for all data gathering trials. The experiments were performed for a variety of ionospheric conditions and transmission frequencies in order to determine which of these factors affected any observed non-reciprocity.

CHAPTER III

INSTRUMENTATION AND EQUIPMENT

This chapter describes the equipment used in performing the experiments and the reasons for which it was chosen.

In order to study accurately the effects of the ionosphere on oblique incidence radio waves, certain requirements must be met. First, the transmitted signal must be adequate for the demands of the problem. It must be of sufficient strength to travel the several hundred kilometer path and still be considerably stronger than any local noise present. There must be a reasonably wide range of frequencies available for use in order to cope with changing ionospheric and local conditions, with any frequency used being accurate within close tolerances. Furthermore, the signal should be in a form that can be conveniently and accurately displayed, recorded and measured. Secondly, the signals transmitted in opposite directions along the transmission path must be synchronized, since information received at different intervals of time would naturally be different due to the acknowledged transient behavior of the ionosphere. Third, the receiving, recording, and calibration equipment must be compatible with the transmitted signals' specifications. Slight differences at the receiving end would cause two identical, synchronized signals to appear different, an observation which could be incorrectly attributed to the ionosphere. Proper recording devices are needed to transfer the information to a form convenient for analytical purposes. Finally, something should be known about the condition of the ionosphere, which has already been shown to be generally periodic in nature, at the time of the experiment. The latter is not so critical as far as analytical purposes are concerned, but is helpful in the technical aspect of the experiment. This includes matters such as establishing satisfactory voice communications, suggesting possible frequencies used in and assisting in the interpretation of data from an experiment. These were the chief factors taken into consideration in setting up the experimental equipment.

Transmitting, Receiving, and Synchronization Equipment.--To generate the signal for transmission, a Rogers* sweep frequency ionospheric sounder transmitter was used. This transmitter was designed to feed a rhombic antenna with pulsed radio frequency (henceforth abbreviated "r-f") power over a frequency range from 1.050 to 24.950 Mc. When used with the Time-Stepped Frequency Unit (abbreviated T.S.F.U.) subsequently explained, the signals were transmitted over the frequency range in steps of 0.10 Mc at one-second duration of transmission per frequency. Thus the entire frequency sweep required four minutes. The signal pulses were approximately 100 microseconds in duration, gaussian shaped, and were transmitted at the rate of 30 pulses per second. Peak power output was 20 kilowatts with the average power output being approximately 50 watts. The transmitter's main groups were the preamplifier unit, pulse unit, power supply, and front panel with operational controls.

The function of the preamplifier was to modulate the variable frequency oscillator (VFO) with a 30 Mc signal and to amplify the lower sideband to provide drive for the power amplifier tubes. One of the

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*Rogers Magestic Electronics Limited, Transmitter Model RM 328 and Power Supply Model RM 625 - Part No. 854-515A.

preamplifier unit sections contained a 30 Mc crystal oscillator and associated components which provided the 30 Mc signal, called the fixed frequency oscillator (FFO), to the mixer tubes. The amplitude of the 30 Mc signal was controlled by the amplitude of the gaussian pulse at the suppressor grid of the oscillator tube. The r-f signal (VFO), supplied externally by the T.S.F.U., was fed to the mixer tubes where, mixed with the 30 Mc signal, it produced the desired frequency by means of the tuned plate circuit. Both the r-f amplifier and the mixer tubes were cut off until a square pulse applied to their respective grids brought the tubes to normal class A operation. The driver tube and the tuned plate circuit were located in another compartment. Screen potential was supplied by square pulses as was the case in the r-f amplifier.

The pulse unit, containing pulse transformers, pulse amplifiers, and stepping control circuits, was used to amplify externally supplied square and gaussian pulses and to provide stepping signals for the two ledex units which stepped the transmitter's output frequency. Amplitude of the pulses fed to the 30 Mc oscillator was controlled by a potentiometer placed at the gaussian pulse unit.

The power amplifier unit transformer matched the output tubes to the 600 ohm band pass filter which attenuated any harmonics present. The filter could be adjusted to compensate for variations in the antenna reactance. Antenna terminal connections were made to the low-pass filter output of this unit. To keep the transmitter power output as nearly constant as possible over the frequency range, part of the signal at the grid of the power amplifier tubes was rectified and fed back to control the gain of the 30 Mc oscillator. The power amplifier tubes and the 30 Mc oscillator tubes were modulated by the gaussian pulse so that a gaussian-shaped r-f pulse was supplied to the antenna. Since the mixer, r-f amplifier, and power amplifier tubes were operated in push-pull and in class A condition, harmonic distortion was minimized. To obtain proper attenuation of harmonics, all of the stages employed tuned circuits.

Two ledex units were attached to the rear of the preamplifier and power amplifier units. Wafer switches attached to these ledex units provided a homing circuit that maintained synchronization of the preamplifier and the power amplifier units during frequency stepping. The homing circuit was independent of external stepping signals and operated only when the two units were not in step.

The front panel contained a dial that indicated in one Mc steps, the actual frequency being transmitted. Manual switching of the preamplifier was possible, as separate push button controls enabled operation of the two ledex units separately while the homing circuit was held open. Otherwise the preamplifier and power amplifier units stayed in step automatically. The front panel contained various indicator lights and meters used for monitoring performance.

The power supply unit* was rack mounted with the transmitter and contained all equipment necessary to provide voltages required by the transmitter. It operated from 117 volt ± 10 per cent alternating-current line voltage. Total power consumption of transmitter and power supply was 300 watts.

This transmitter met the first requirement of the study. It provided a signal pulse of sufficient strength, accurate frequency, wide

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*Rogers Majestic Power Supply Model RM 625.

frequency range with power output nearly constant over the range, and gaussian-shaped in order to conserve frequency spectrum space. (This pulse shape was also convenient for display and calibration.)

To maintain synchronization of the two station's transmitters, precise timing of each transmitter's pulses and a method for comparing each timer to a common time reference was necessary. A loran standard oscillator model 0-76-U, controlled the clock and timing mechanism. This standard had an accuracy of one part in 10^7 and long term stability of one part in 10^8. Correct time was indicated by a clock and also by flashing decade counters. Separate counters were used to indicate the minutes (two counters), seconds, and tenths of seconds. The clock's hour reading was not essential for operations. While the clock and decade counters indicated the same time, the time given by the counters was in the more precise and convenient form for switching operations and stepping frequencies. A variable oscillator was used in connection with the timing circuit of the decade counters which enabled the changing of the relative time between the loran standard and the counters. The reason for doing this will be explained in the next chapter.

The programmer controlled the timing pulses, derived from the decade counters, that were applied to the T.S.F.U.* The T.S.F.U. in turn controlled the frequency stepping of the transmitter and receiver. The programmer determined: (1) when the timing pulses were to be applied to initiate the frequency sweep, (2) whether the transmitter power was to be used during the cycle, (3) if time indicator signals were to be applied

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*Rogers Majestic Electronics Ltd., Time-Stepped Frequency Unit, Model RM 166.

during the cycle, (4) if the cycle was to be repeated automatically upon its completion, and (5) if manual interruption of the cycle at any step (or frequency) in the cycle is to take place. The programmer thus provided for flexibility of operation with the transmitter frequencies, either individually or during a sweep cycle.

The T.S.F.U. changed the transmitter output frequency in accordance with the timing signals received from the time interval generator. The T.S.F.U. frequency range of output signals was from 31.05 to 54.95 Mc covered in 240 steps of 100 Kc, at odd multiples of 50 Kc. When mixed with the 30 Mc oscillator of the transmitter, these frequencies provided the beat frequency range of 1.05 to 24.95 Mc, also in 100 Kc steps, used for the transmitter output. The externally supplied timing pulses, occurring at intervals of not less than one second and having a duration of not less than 35 milliseconds, initiated and controlled the stepping cycle. At the end of the cycle, the equipment automatically switched to the "wait" position and remained in that position until another starting cycle was initiated by a signal from the programmer. The stepping would not hold at any other position in the cycle unless manually interrupted by the operator. The T.S.F.U. output frequency was designed to remain within plus or minus one kilocycle of the nominal value indicated, with the accuracy and freedom from drift being determined solely by the units' crystal oscillators. The output was supplied to two separate connectors which fed the ledex rotary solenoids giving motive power for switching the frequency stepping circuits. One solenoid switched the megacycle steps (one through 24) while the other solenoid switched the 100 kilocycle steps within each megacycle range. After the 950 Kc step the signal stepped the megacycle reading one position and the kilocycle output stepped to 150 Kc and swept through that megacycle range. After 54.950 Mc of the T.S.F.U. (actual transmitter output and dial readings were 24.950 Mc) the next signal returned the equipment to the "wait" position to await the next sweep cycle initiating signal. The T.S.F.U. operated from a 115 volt, ± 10 per cent, a-c source and consumed 100 watts.

Once the equipment at both stations was synchronized, the time interval generator and T.S.F.U. maintained synchronization within approximately 0.0002 seconds over a considerable interval of time (unless, of course, there was a power line surge or equipment failure). The method of originally establishing synchronization will be discussed in the next chapter.

To receive the pulses transmitted from the other station a dual conversion, superhetrodyne, amplitude-modulated receiver was used.* The receiver was used with the T.S.F.U. which stepped the receiver circuits in the same manner and at the same rate as it stepped the transmitted frequencies. Hence the receiver was tuned to the transmitted pulses throughout the sweep frequency range of 1.05 to 24.95 Mc. For a fixed-frequency transmission the receivers were manually tuned to the transmitted frequency and held there by the manually operated, sweep cycle interruption switch. The receiver was designed so as to have constant gain over the entire frequency range for a particular gain setting.

Since the receiver used the same antenna as the transmitter it was necessary to have a voltage limiting device at the tuned circuit to prevent excessive transmitter voltages from breaking down the receiver tubes

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*Roger Majestic Electronics Limited, Model RM 425.

or components. A "T-R switch"* was used because of its high speed of operation and low capacity. To compensate for this protection, large reactances (arranged in lattice form to make receiver sensitivity more uniform with frequency) were inserted between the T-R switch and the antenna to limit the current and to prevent excessive detuning and power loss in the antenna circuit of the transmitter. The receiver output provided positive pulses to a separately supplied oscilloscope for A-scope display purposes. Since the dynamic range of the display device was limited, it was necessary to compress the wide amplitude range of input pulses to cover only a few decibels, yet in a manner fast enough so that any pulse would not affect the amplitude of a closely following pulse. An automatic gain controlled logarithmic amplifier was used to give an output proportional to the logarithm of the input. This enabled a wide signal range, about 70 decibels, to be accommodated. Other receiver design features included a good noise figure and good rejection of spurious signals.

Antenna.--To receive and transmit the signal pulses and voice communications, a three-wire, terminated, full rhombic antenna was used at each station. The full rhombic antenna is highly directive and, when terminated, gives a strong signal in the desired direction of transmission and minimizes all other lobes in the radiation pattern. The rhombic antenna gives a relatively low angle of radiation, from zero to 20 degrees, over a broad operating frequency range. The antenna system included the transmission line, antenna curtain, and dissipation line. The transmission line consisted of two conductors spaced 12 inches apart, with a characteristic impedance of 600 ohms. The antenna curtain was composed of

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*A neon gas gap.

three conductors grouped at the front and rear poles of the antenna. The three-wire arrangement enhanced the broadband frequency characteristics of the antenna. Of secondary importance was the lowering of the characteristic impedance to match the 600 ohm transmission line. The dissipation line acted as a resistance dissipating the power arriving at the end of the antenna, giving the unidirectional radiation pattern. It consisted of a down lead connected at the rear pole and a modified exponential line placed on the ground along the antenna's major axis. Antennas at both stations were constructed from rhombic antenna "kits," described in the War Department Technical Manual "Antenna Kit for Rhombic Transmitting Antenna."* Since the kits contained identical equipment and the construction details used were the same, characteristics of the antennas were assumed to be identical. After construction of the antenna in Fairburn, Georgia, field tests made to compare its calculated and measured field strength pattern showed close correlation. Figures in the Appendix show the horizontal and vertical radiation patterns of the antenna. Theoretical discussion of rhombic antennas may be found in the literature (31).

Mention might be made regarding the selection of the site chosen for conducting these ionospheric experiments. The best location for a rhombic antenna is over level ground, since variation in antenna height changes both the horizontal and vertical radiation patterns. There should be no large obstructions in the immediate vicinity and the terrain in front of the terminated end should be level for at least one mile. There should be no man-made electrical noise sources such as high voltage lines, and electrical machinery across the signal path. The antenna should not be placed over heavily wooded areas because of high absorption losses (32).

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*War Department manual TM 11-2617.

Of course the site had to be reasonably accessible for operating personnel and feasible to rent on a contract basis. Since the terrain in the Atlanta, Georgia area is hilly, aerial photographs had to be studied to select sites topographically suitable. From these sites, the other factors led to selection of the chosen Georgia site as the one best meeting all requirements.

Calibration and Recording Equipment.--To display the signal pulses the receiver output was applied to an oscilloscope.* This instrument was flexible in use and could be used with many sweep rates and methods of signal presentation. A 16-millimeter movie camera** with hood attachment for fitting over the oscilloscope face was used for taking photographic records of the A-scan presented signals at each station. Separately supplied motor and controls drove the camera film and controlled shutter operation in synchronism with the transmitted pulse output rate. This will be further discussed in the next chapter.

To get a photographic record of the ionospheric virtual height versus frequency, helpful in visualizing the ionospheric condition at the time the record was made, another oscilloscope*** also obtained signals from the receiver output. A specially constructed motor-drive mechanism provided the time base sweep whose rate coincided with the transmitted frequency sweep rate (four minutes). Received signals were presented as

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*Tektronix, Model 545.

**Keystone, Model A-9.

***Dumont Type 304-A.

B-scan display[*] along the other axis while a time exposure photograph was taken with a Polaroid Land Camera with attached hood mount.[**]

Voice Communication Equipment.--Voice communication between the two stations was essential for performing an experiment. A Crosley type T-368C/URT radio transmitter was used. This transmitter covered frequencies from 1.50 to 20 Mc with an output power of 500 watts. The voice receiver used was a Collins U. S. Army Signal Corps Model R-396A/URR, with a frequency range of zero to 34 Mc. Five separate Air Force channel frequencies were allocated for use during the experiments to establish reliable communications despite varying ionospheric and local noise conditions. The same rhombic antenna used for pulse transmission and reception was also used for voice communications. A manually operated switch disconnected the pulse transmitter high voltages from the communication equipment and inserted proper Balun[***] matching circuits for the voice transmitter. Leakage through the antenna switch permitted vocal information, though weak in signal level, to be received at either station while that station was transmitting pulses, provided the other station interrupted its pulse transmission and switched to the voice transmitting condition. Sometimes, due to extremely bad ionospheric conditions, high noise levels, or power line failure, voice radio communications could not be maintained. In this case regular telephone service was available to provide the information necessary for operation or establishment of radio communication.

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[*] B-scan display is that which represents the signals as intensity modulated, or blacked-out, portions of the time base line, the positions of these portions corresponding to the time of arrival of the signals.

[**] Type 2620, mounted with a Dumont Type 353 Oscillograph Mount.

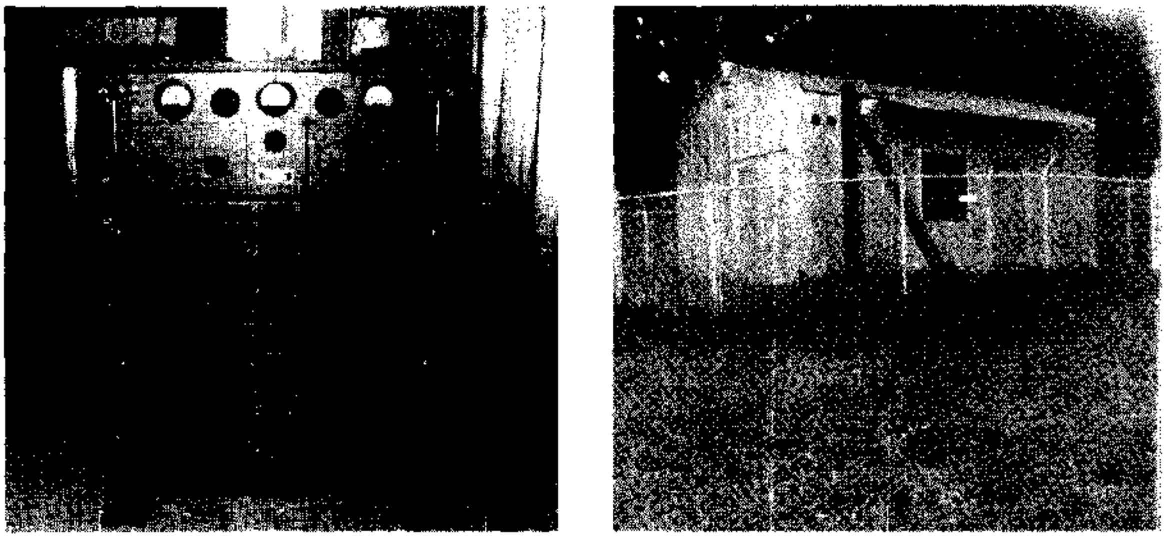
[***] Method denoting the insertion of an unbalanced load circuit to match a balanced feed line of different characteristic impedance.

Figure 2 shows an aerial view of the rhombic antenna and station at Georgia, taken during antenna calibration tests. Figure 3 shows the station and the major pieces of equipment used.

Figure 2. Aerial View of Station at Georgia.

A. PULSE TRANSMITTER, RECEIVER, AND TIMING EQUIPMENT

B. VOICE RECEIVER AND RECORDING EQUIPMENT



C. VOICE TRANSMITTER

D. EQUIPMENT HOUSING

Figure 3. Station Housing and Equipment.

CHAPTER IV

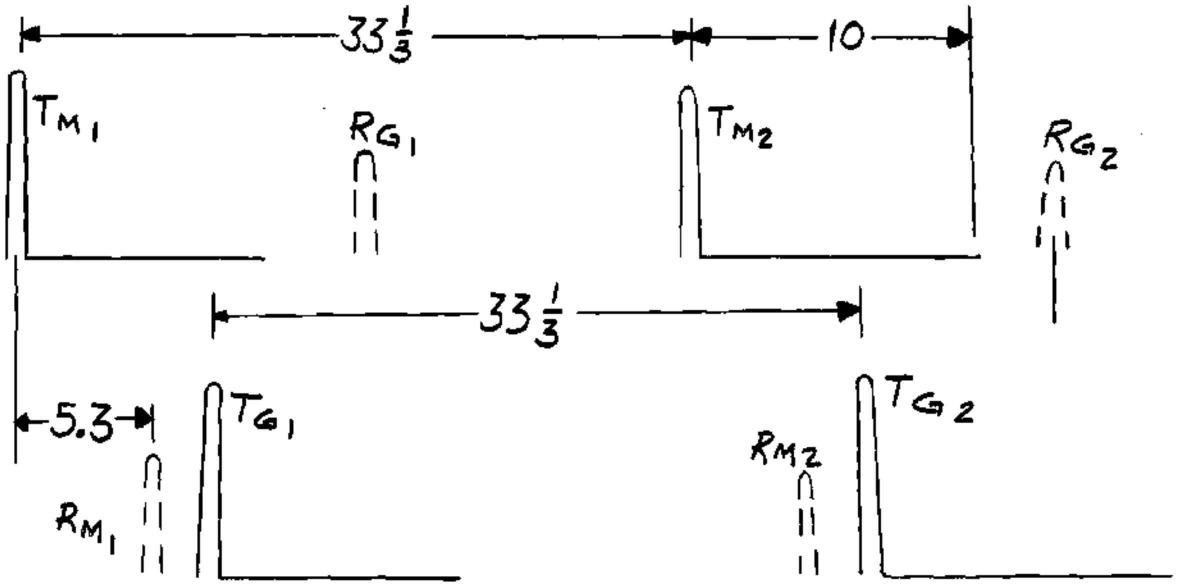
EXPERIMENTAL PROCEDURE

This chapter explains in detail the steps involved in obtaining, comparing, and processing the data used in studying the problem.

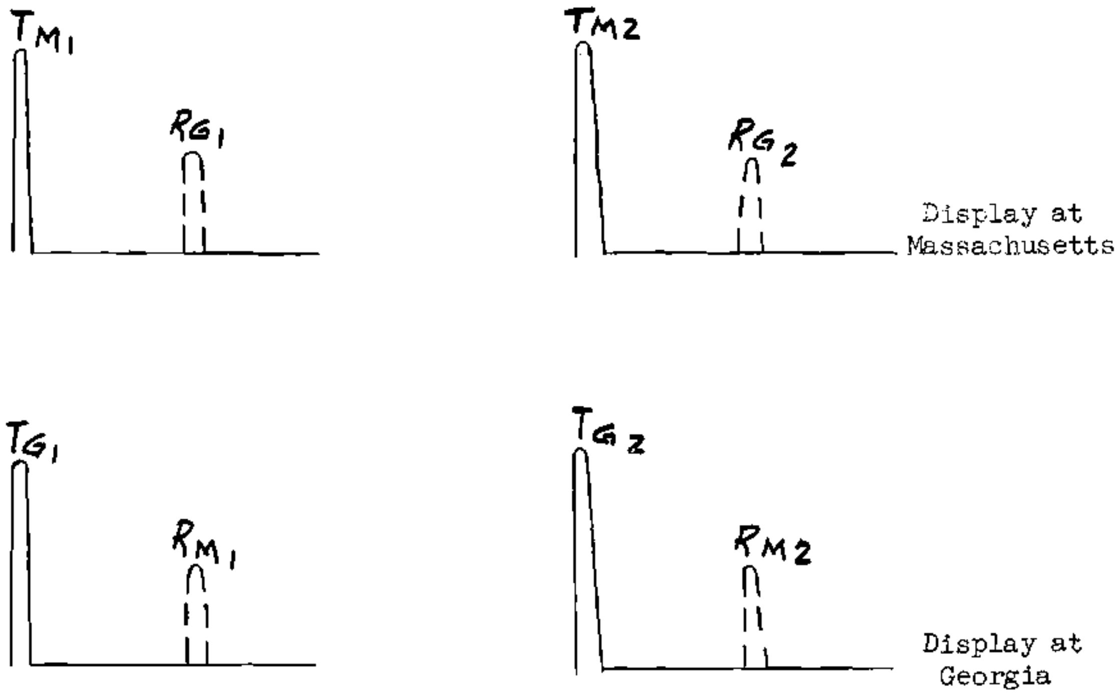
Establishing Communications and Synchronization.--A simple though necessary part of the study was the maintenance of good voice communications. Agreement was made by telephone or by radio as to the time of the next experiment and the frequency to be used for voice transmission. For most of the daytime experiments, 15.5875 Mc was the one of five allocated frequencies found most reliable. On rare occasions when local noise rendered that frequency unusable, a telephone call was made to arrange changing to one of the other allocated frequencies. During periods when the maximum usable frequency (MUF) was below 15.5875 Mc, such as late evening or early morning hours, one of the lower frequencies previously agreed on was set up for communications. If that frequency became unusable or if there was a communication power failure, telephone service was used to specify a new voice frequency or further operating instructions. Most of the time, however, good communications was maintained on the 15.5875 Mc channel.

In order to establish time synchronization between the two stations, some common time had to be referred to. The best reference available was the time signals received from radio station WWV. This source, near Washington, D. C., continuously broadcasts signal tones at one-second intervals and the correct time is voiced at five-minute intervals. The broadcasts are made on different frequencies to enhance good reception for varying ionospheric conditions and receiver distances. Each radio receiver was tuned to the clearest of WWV's frequencies and the programmer's time was compared with the broadcast time. If the difference in times, as indicated by comparing the programmer's decade counters with the broadcast signals, was not more than a few tenths of a second, a variable oscillator was introduced into the standard oscillator circuit that controlled the timing mechanism. This "fine" adjustment changed the oscillator frequency by a small increment which in turn sped up or slowed down the programmer's time. Close comparison of the programmer and broadcast times was possible by audially comparing the broadcast one-second signal pulse with the one-second "tick" actuated by the programmer and observing the flashing of the zero position on the one-tenth second decade counter. Audial comparison of these two signal pulses brought the programmer's time to within approximately 1/100 of a second of the broadcast time. When the operator judged the two times to be the same, he switched the oscillator from the "variable" to the "standard" condition. If the time difference had been of the order of seconds, the previous procedure to align the times would have taken too long. Instead, the decade counters were all switched to the zero positions to await the next time broadcast ending in "zero" (10:20, 5:50, etc.). On the broadcast "zero" pulse, the hold switch was released and the programmer's decade counters commenced to mark time. If the operator missed switching correctly, he made the necessary fine adjustment by means of the variable oscillator. After the operators at each station followed this procedure, the two station's times were in close proximity. They were not exactly synchronized because of the differences in the operators' manual time settings. This time difference, of the order of 20 to 30 milliseconds, was too large for the experiment.

To obtain more precise synchornization each transmitter (and receiver) was tuned to a specified frequency, well below the MUF and relatively free of local noise, for a continuous transmission. The A-scope display, ten milliseconds in sweep duration, was examined at each station for received pulses. The pulses from the other station usually could not then be seen on the oscilloscope display because the transmitted pulses (hence the oscilloscope time-base sweeps) were 33 milliseconds apart and out of synchronization. This relation is denoted by Figure 4, part A. The upper pulse train shows the display seen at Ipswich, Massachusetts, the lower train shows the display seen at Fairburn, Georgia. The large pulses at the left of the oscilloscope display (indicated by the heavy lines) represent the transmitted pulse that also triggers the oscilloscope sweep. T_{M_1} refers to a pulse transmitted at Massachusetts, T_{M_2} represents the next transmitted pulse; T_{G_1} is the pulse transmitted at Georgia, etc. R_{M_1} is the pulse echo received by Georgia from T_{M_1}; R_{G_1} the pulse echo received by Massachusetts from Georgia, etc. If the standard oscillator at one station was switched to the variable oscillator condition, the resulting small change in the time caused the transmitted pulses to change also. The oscilloscope sweeps at that station then shifted, as shown in Figure 4, to the right or left depending on how the oscillator frequency was changed. The pulse echoes received by the station not making the frequency change (the "passive" station) shifted in the opposite direction. This pulse shift was continued until the delay measured between the transmitted or "trigger" pulse and the echo pulse from the other station were the same for both stations. This condition was verified by voice communication. This method assumed that the equivalent paths in the two directions



A. Before Pulse Synchronization.



B. After Pulse Synchronization

(not to scale)

Time (Milliseconds) →

Figure 4. Pulse Train Relationship.

were the same, and was in accordance with synchronization techniques of previous oblique-incidence experiments (33). If there were more than one echo pulse present, a particular one was designated as the one on which measurements were made. After this procedure the pulse scans at each station had the form in part B of Figure 4. Absolute time synchronization of the pulses, determined primarily by the initial "rough" synchronization procedure, was within 34 milliseconds. The relative pulse synchornization, determined by equating the pulse delays on the ten centimeter (ten millisecond sweep) oscilloscope scales, was within approximately 0.0004 seconds.

Transmitting and Receiving Pulses.--After pulse synchronization was established, an "ionogram" (photographic record of v rtual reflecting height versus frequency) was made. This verified pulse synchronization for all of the frequencies in the sweep cycle and gave an indication of the existing ionospheric condition. Important features of the latter were the upper and lower limits of usable frequencies and the number of available modes of propagation. To obtain the ionogram the two stations agreed on a time to start the four-minute frequency sweep cycle. The programmers were set to initiate the cycle at this time. The shutter on the Polaroid camera was opened manually just as the cycle began and was closed at the end of the cycle. A battery-powered motor potentiometer moved the time base of the B-scan oscilloscope across the oscilloscope face in the four minute interval. At the end of the cycle the exposed film was developed and examined. During the sweep cycle, the A-scope display was observed to note which frequencies providing echo pulses had high signal-to-noise ratio. It was necessary to choose such a "clear" frequency so that accurate analysis of received pulses was not impaired. Of the clear frequencies available, one was chosen for a fixed-frequency transmission to obtain signal strength variation data. These frequencies were usually within the eight to 20 Mc interval.

The movie camera and mounting attachment were fastened in front of the A-scope face. A roll of 16-mm. film was inserted into the camera and a few feet run to check the film motor drive mechanism. The film motor drive control, whose timing signals were derived from the programmer, could operate the film and shutter at one, three or five frames per second. Three frames per second was the rate used for every experiment, however. The pulse repetition frequency was switched to the 15 per second rate and the pulse synchronization checked. (If the switching operation changed synchronization, the latter was re-established.) The transmission starting time and duration were designated (ten minutes was the usual duration, although a few 20-minute runs were obtained). Enough time was allowed between the verbal time agreement and start of transmission to: (1) switch the antenna from voice-to-pulse-transmission condition, (2) align the oscilloscope time base appropriately (Georgia time base was along the bottom of the scope face while the Massachusetts time base was set along the middle of the scope face), (3) to position the pulses on the scope face in the manner previously agreed on, and (4) to control the pulse amplitudes by pulse receiver gain settings to a value small enough that the anticipated pulse height would not exceed the maximum scale on the scope face. The gain setting was then unchanged for that particular experimental trial or "run." The film was run 15 seconds before and after the transmission period limits in order to obtain film "leader." Two small bulbs were located inside the camera hood attachment, next to and on opposite sides of the scope face. These bulbs received current pulses from the programmer, one bulb actuated at ten-second intervals, the other actuated either manually or at one-minute intervals. These bulbs, when lit for about two film frame exposures, would be seen on the developed film, giving the frames a reference time. The one-minute interval bulb was manually lit at the half-way mark to give a further distinguishing time reference indication. Provision was made for examining the pulse pattern during a data gathering run by placing a hole, with tap, at the camera end of the hood attachment. At the conclusion of the run the general pulse variation was discussed and preparations were made for the next experiment. Selection of frequencies was somewhat arbitrary, except to obtain a reasonably wide range and to investigate those of unusual activity or at the extremes of the usually received values. Some frequencies were chosen at the MUF value to see what change took place as the MUF decreased below the transmitted frequency. These transmissions took place for different seasons of the year and times of the day as well as for different frequencies.

Obtaining Composite Films and Analyzing Results.--To obtain comparison of the films taken at the different stations, each film was developed in the conventional manner. The films were then superimposed so that the corresponding time marks, due to exposure of the bulbs' lights, were aligned. The ten-second and one-minute interval marks were aligned throughout after the half-way (five-minute) markers were superimposed. Since each film was taken at the same rate (three frames per second) each aligned frame shows the pulses received at opposite stations at the same instant. This in turn indicated the condition of the ionosphere at the instant the two signals' paths coincided in space. Of course it is not possible to compare each pulse with its corresponding oppositely-traveling pulse throughout the entire propagation path of each. This method does compare the condition of the ionosphere at a given point in space at discrete intervals of time. Another 16-mm. film, the "composite" photograph, was made of the superimposed films. Each frame of the composite then showed the pulse echo pattern received by the Massachusetts station on the top half of the frame, and the pulse echo pattern received at the same time as the former by the Georgia station on the bottom half of the frame. The frames were then ready for a convenient comparison of the pulses.

The composite film was put on a film viewer to enlarge each frame s image, one frame at a time. The heights of the pulses were measured, using an arbitrary linear scale, from one to 32 integral steps. The quantizing error introduced was small compared to all other amplitude differences resulting from equipment variation, recorder's errors, etc. The tabulated values for each frame were compiled on data cards, each card containing the relative pulse amplitudes for nine film frames (unless the frames contained more than two pulse echoes from each direction that were used in the analysis). (In this case a separate set of data cards was used for the additional pulses.) Each card's data then represented amplitudes of corresponding pulses for nine sampled times, 1/3 seconds apart.

From the measured pulse data, the sample correlation coefficient between two pulses propagating along the same mode (ionospheric layer or layers) in opposite directions was computed. The correlation coefficient was computed on the basis of the complete transmission interval. A graphic

"X-Y" plotter* was used to plot the signal amplitudes versus time from the card digital data. For technical reasons these plots were made for only seven minutes of transmission time, but the nature of the amplitude variation is still representative of the entire period. These signal amplitude variation charts are shown and discussed in the next chapter.

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*F. L. Mosely Co., "Autograf" two-way recorder.

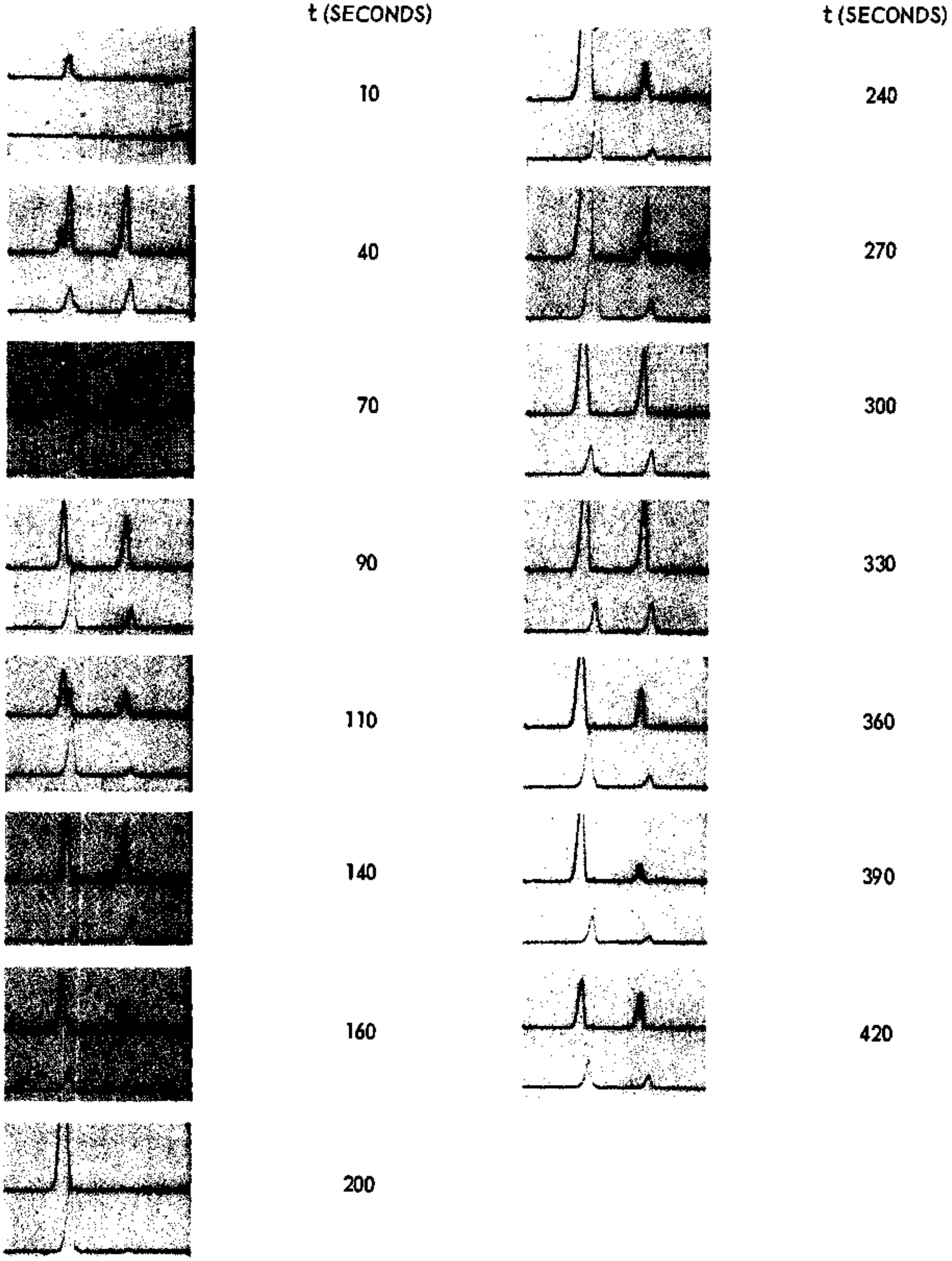

Figure 5. Pulses from Film Composites.

CHAPTER V

EXPERIMENTAL RESULTS

Description of the Data.--The film recording of the pulse amplitude variation for a transmission period sampled the logarithm of the radio signal strength at intervals of 1/3 of a second. The superimposed film strips ("composite") then provided a means for comparing the signals received simultaneously at the two stations for each sample of time. The pulse measurements for each film frame were transferred to digital data cards, from which the pulse amplitude curves were plotted and the sample correlation coefficients between oppositely-traveling pulses computed.

The correlation coefficient is a quantitative measure of the degree of association between two linearly related variables. The value of the normalized correlation coefficient lies between +1 and -1, for linearly related variables a high positive value indicating a very close association between the variables, a negative value showing an inverse relationship, and a value of zero denoting independence of the variables. An approximation to the correlation coefficient, the sample correlation coefficient, r, is given by:

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \, \Sigma(y_i - \bar{y})^2}} \qquad (3)$$

where x_i is the value of one variable

y_i is the corresponding value of the other variable

$\bar{x}$, $\bar{y}$ are the averages of x_i, y_i .

Interpretation of sample correlation coefficients in general is hazardous. The usual interpretation of ± 1 meaning complete dependence and zero denoting independence requires that no non-linear relationship exist. For instance variables dependently related by the function $x^2 + y^2 = R^2$ yield a zero sample correlation coefficient between x and y for values of x and y chosen randomly within the region of existence of x and y. In spite of this uncertainty as to the meaning of the sample correlation coefficient as applied to the data of this experiment it is felt that it does provide an indication of the property which has been defined as non-reciprocal propagation.

The relative signal strength for each propagation mode was plotted as a function of time. The form of the data contained by the cards would have made difficult the plotting of every amplitude sample. Therefore, every ninth sample, representing values three seconds apart, was plotted. Using only this portion of the data did not, however, impair the graphical picture of the signal variation as the signal fluctuations had a period longer than three seconds. The missing points would be approximately between the points three seconds apart. A continuous curve connecting the individual integral values was used to represent the Georgia-to-Massachusetts (received at Ipswich, Massachusetts) direction of transmission; the separate points represent transmission in the opposite direction. Irregularities appearing on some curves was due to the recording device "hunting" and overshooting rapid changes of value. The connection of individual points with the continuous line introduced some jaggedness. The logarithm of the received amplitudes were represented in the graphs as an arbitrary linear scale of integral values from one to 32, as measured from enlargements of the film frame's pulses. (A value of 32

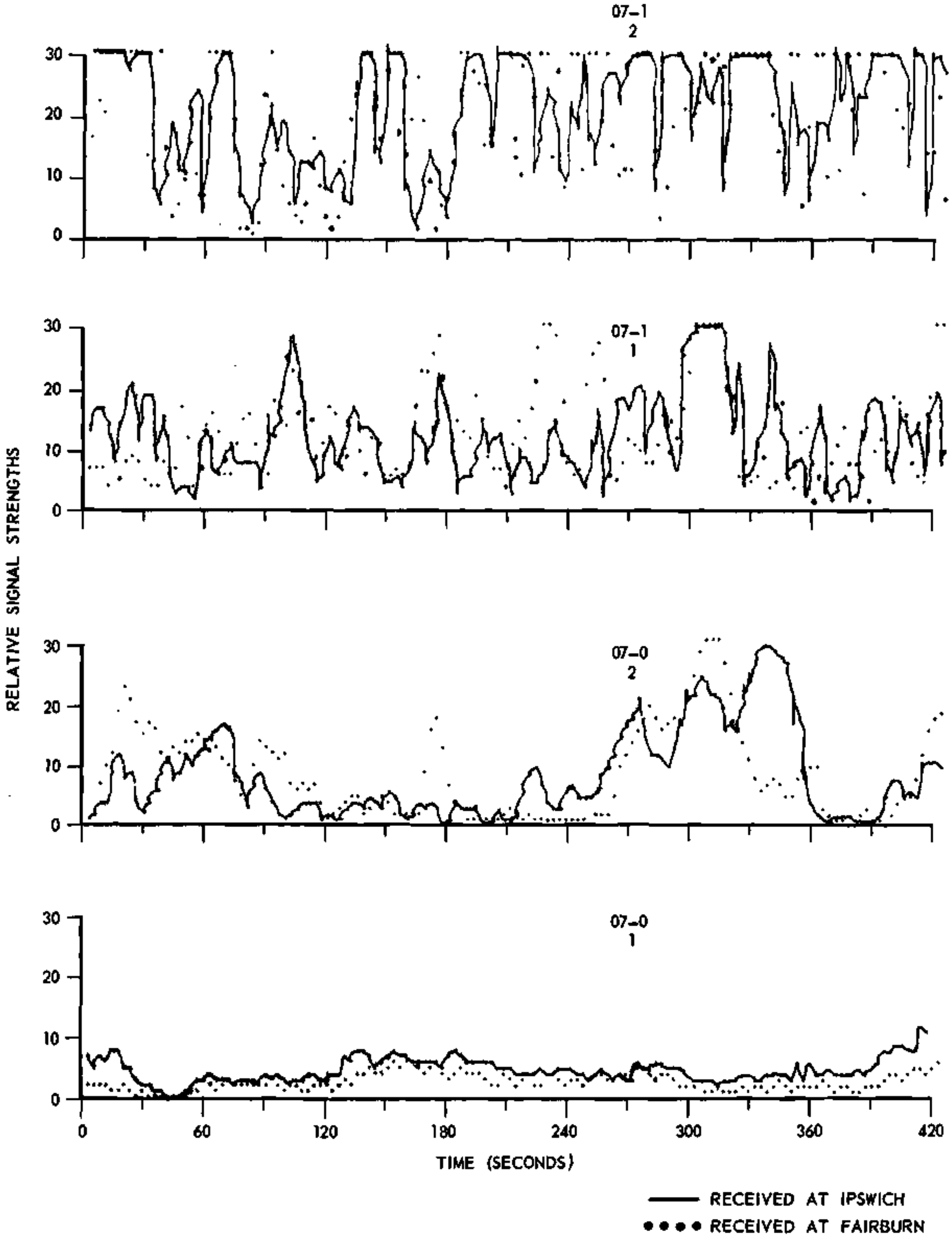

Figure 6. Relative Signal Strength Versus Time.

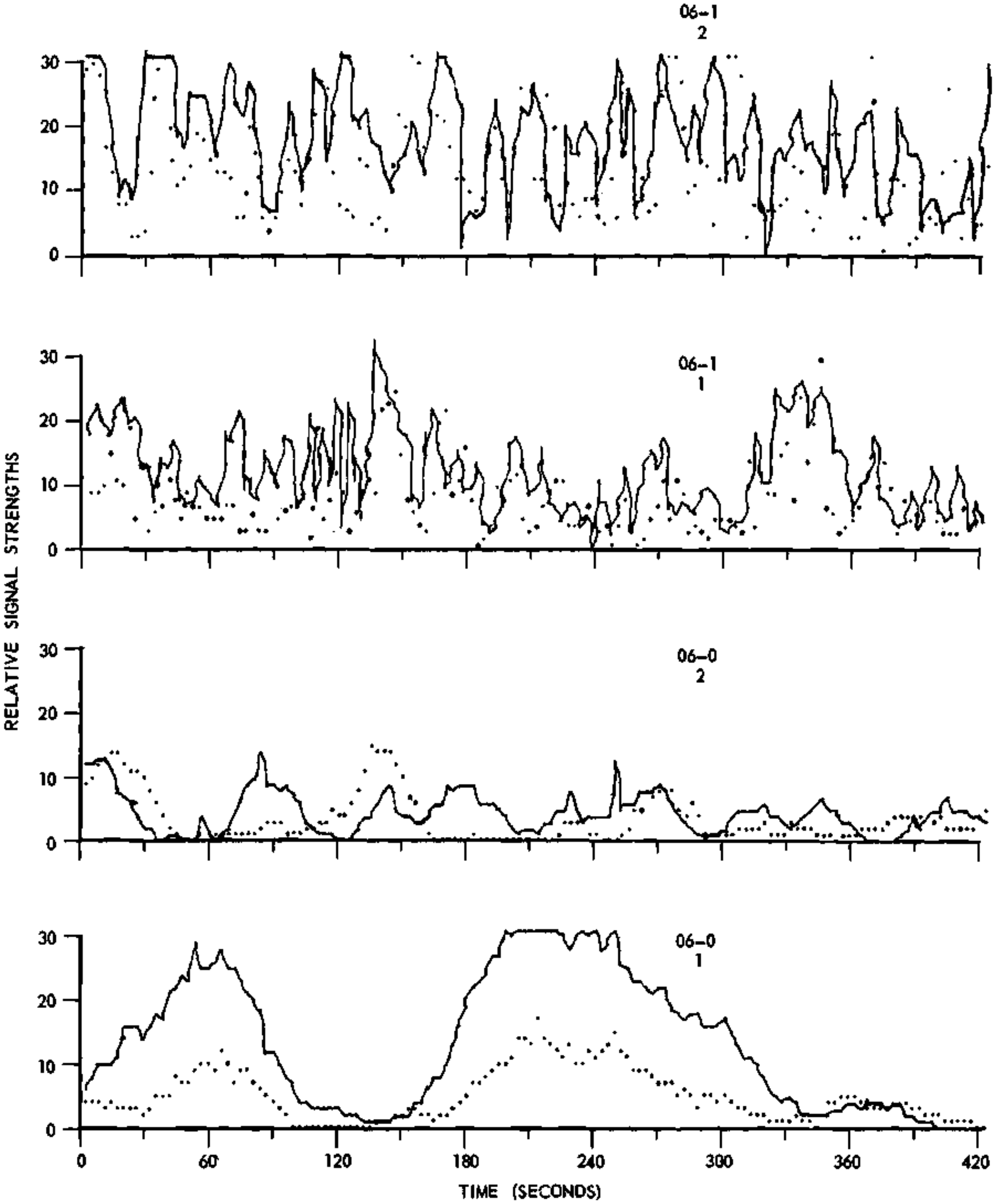

Figure 7. Relative Signal Strength Versus Time.

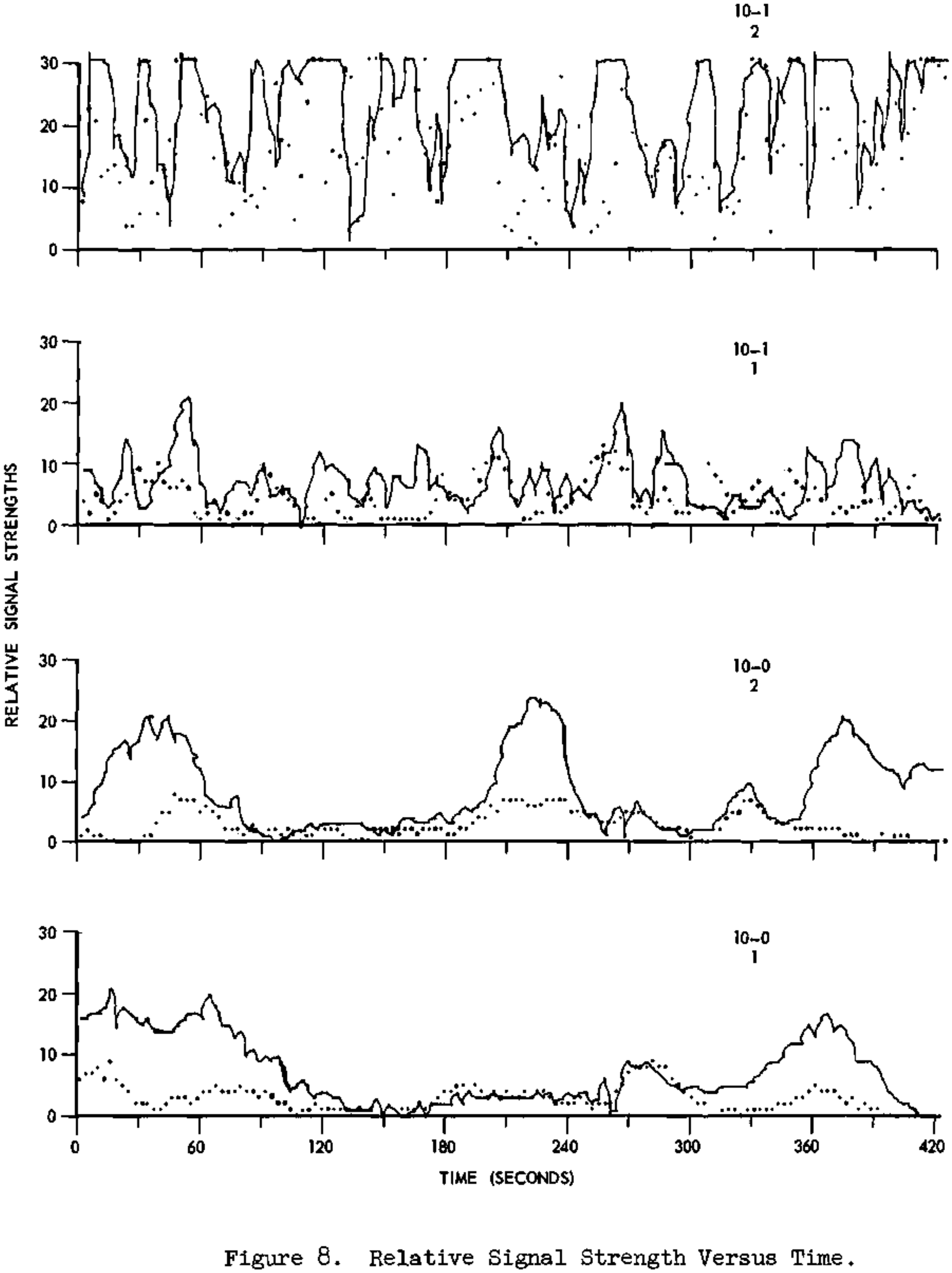

Figure 8. Relative Signal Strength Versus Time.

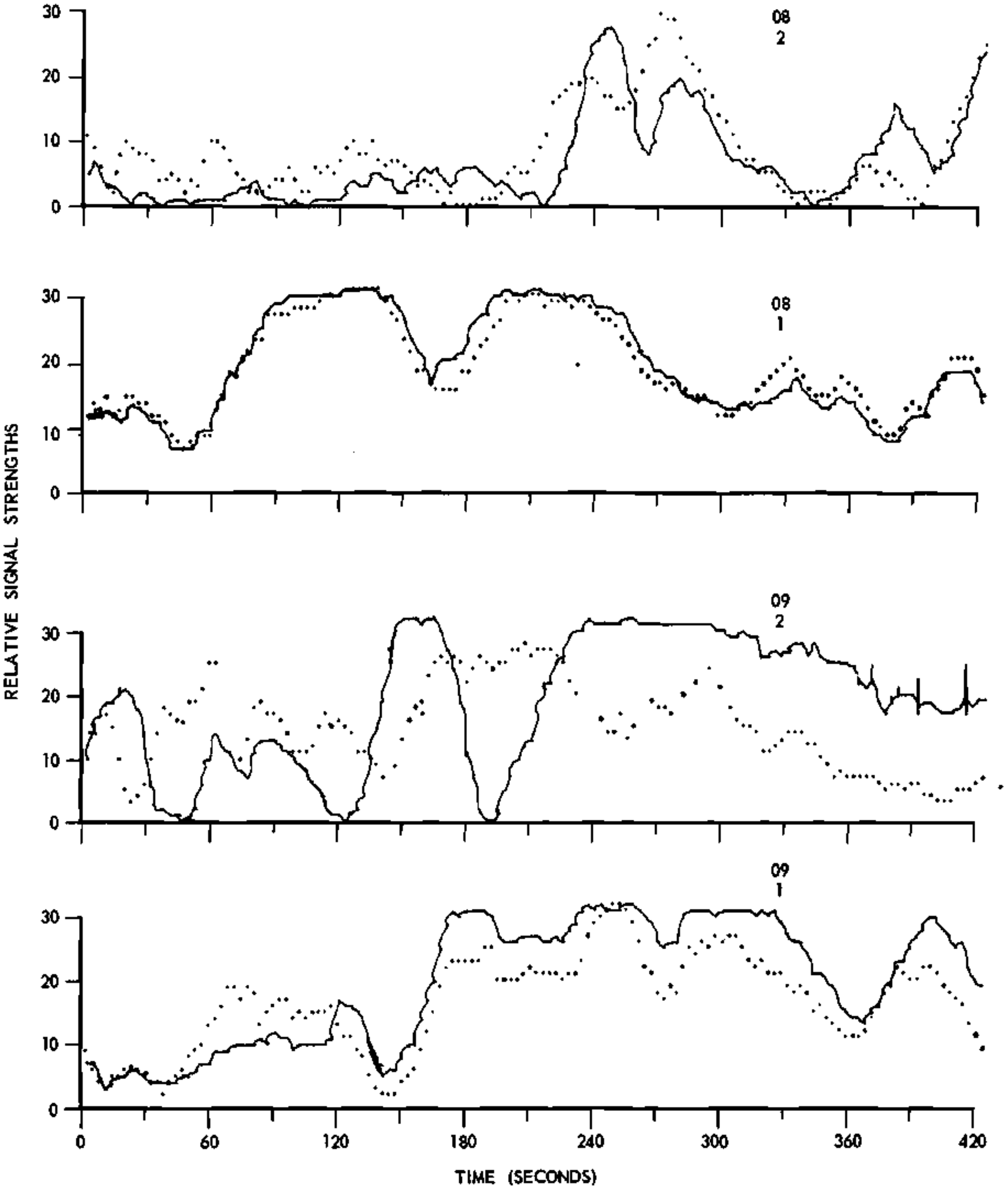

Figure 9. Relative Signal Strength Versus Time.

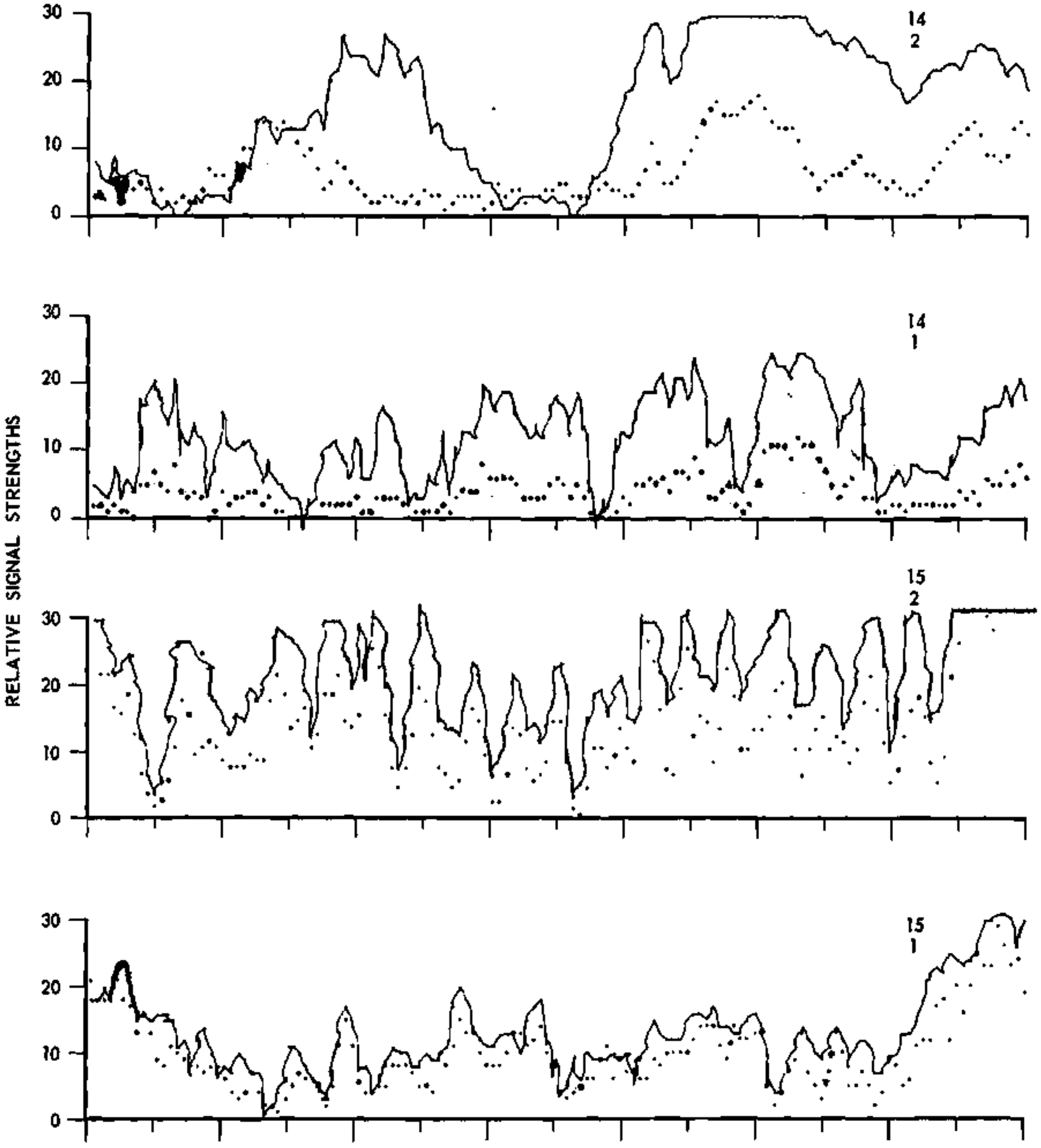

Figure 10. Relative Signal Strength Versus Time.

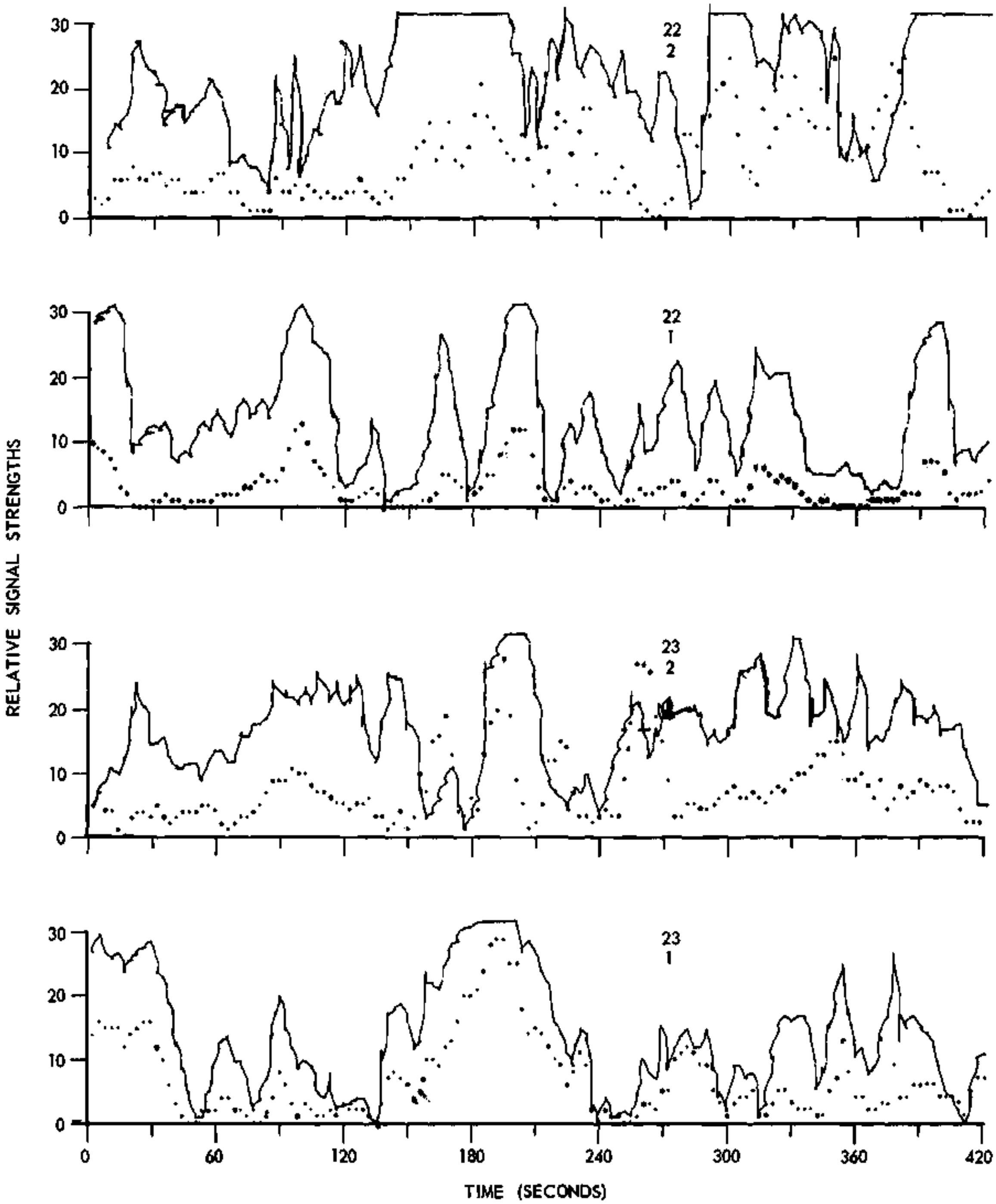

Figure 11. Relative Signal Strength Versus Time.

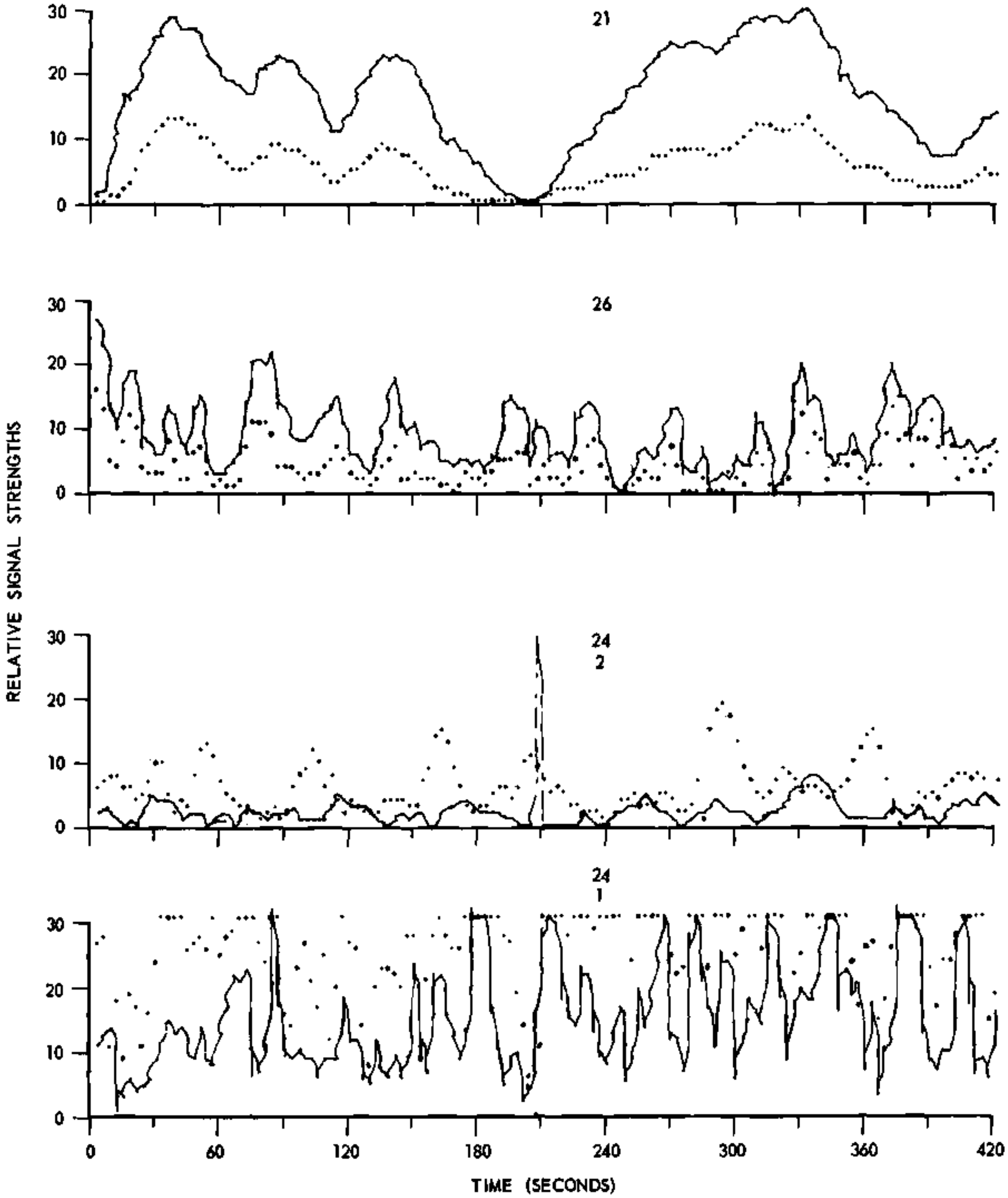

Figure 12. Relative Signal Strength Versus Time.

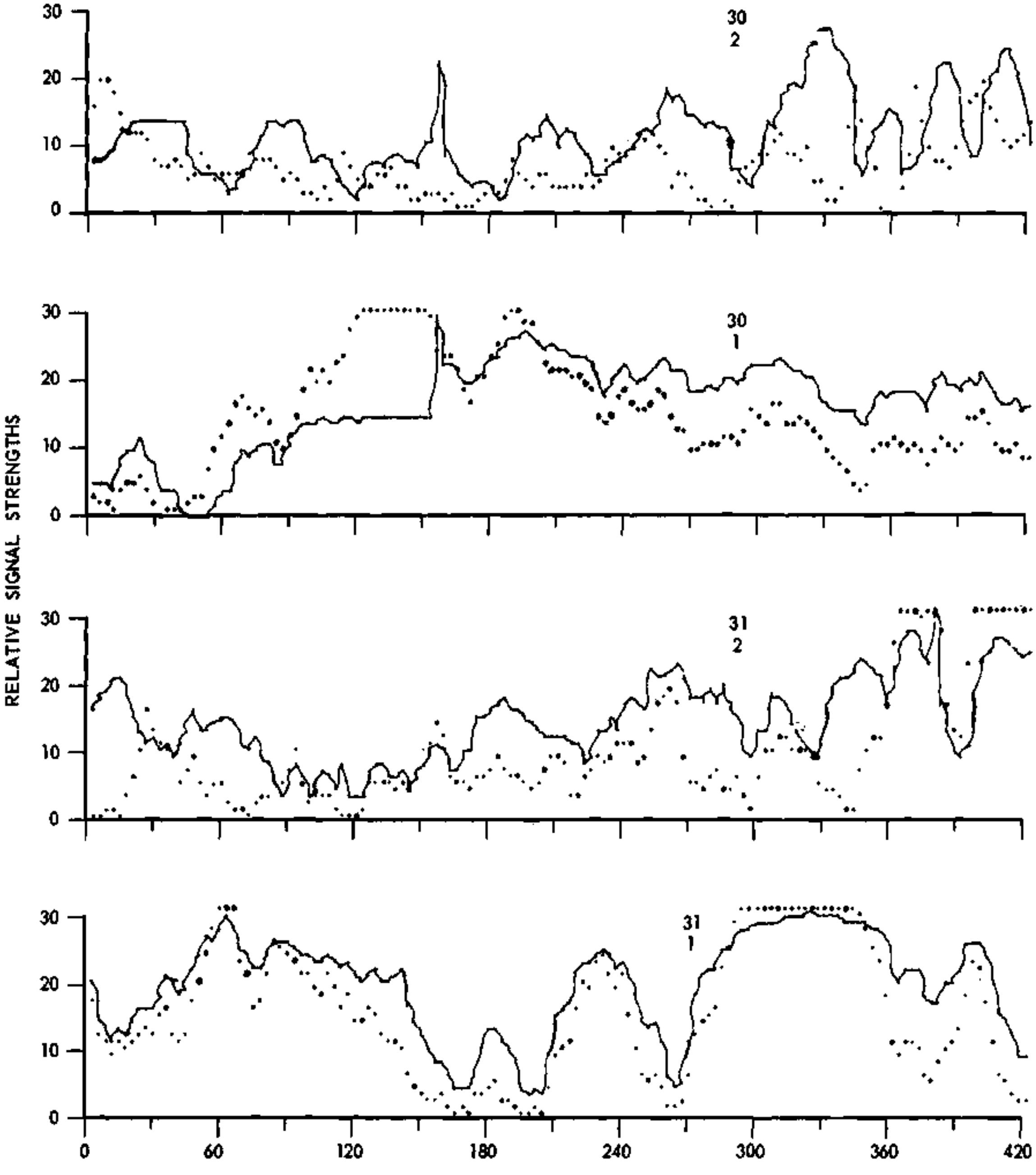

Figure 13. Relative Signal Strength Versus Time.

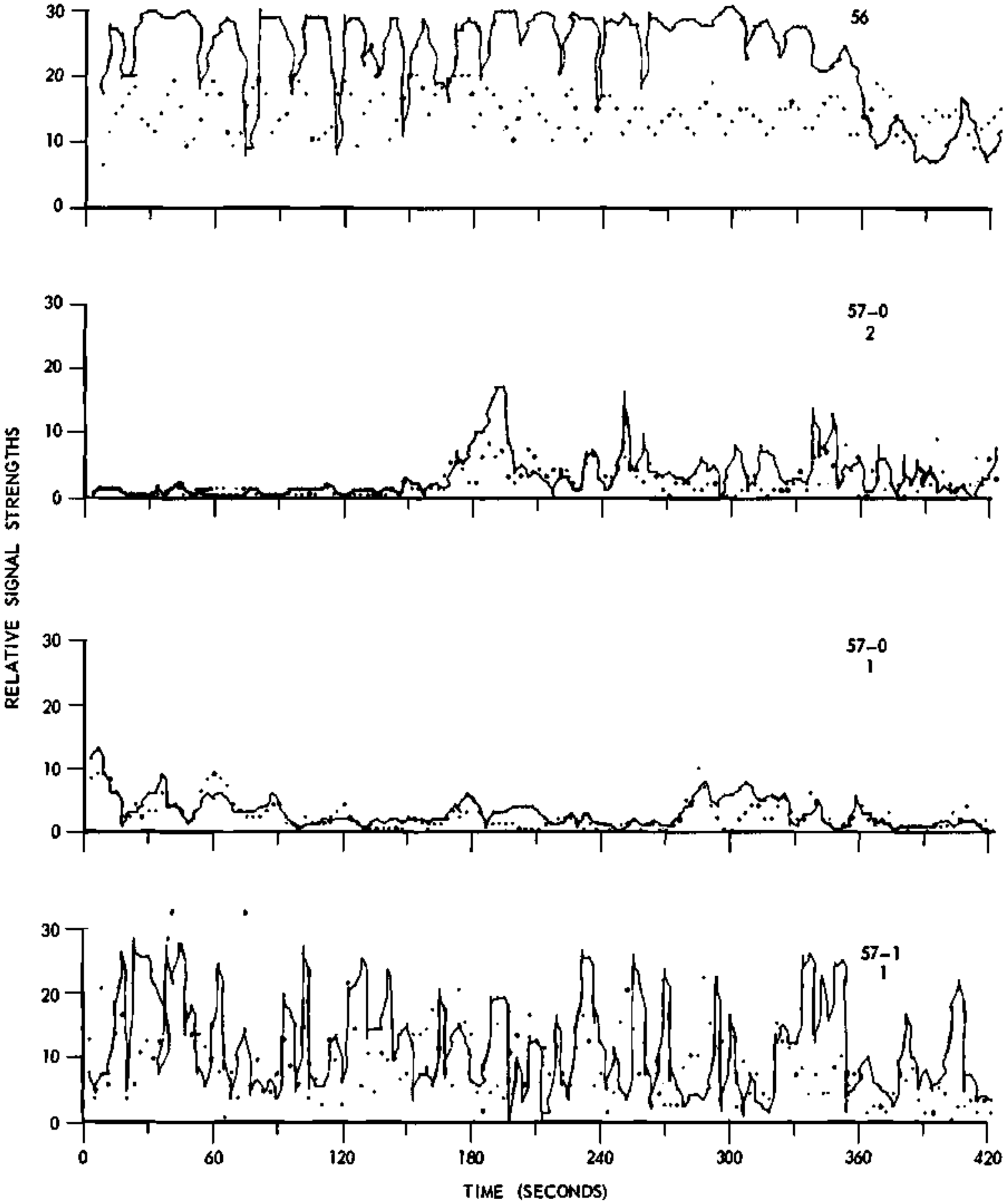

Figure 14. Relative Signal Strength Versus Time.

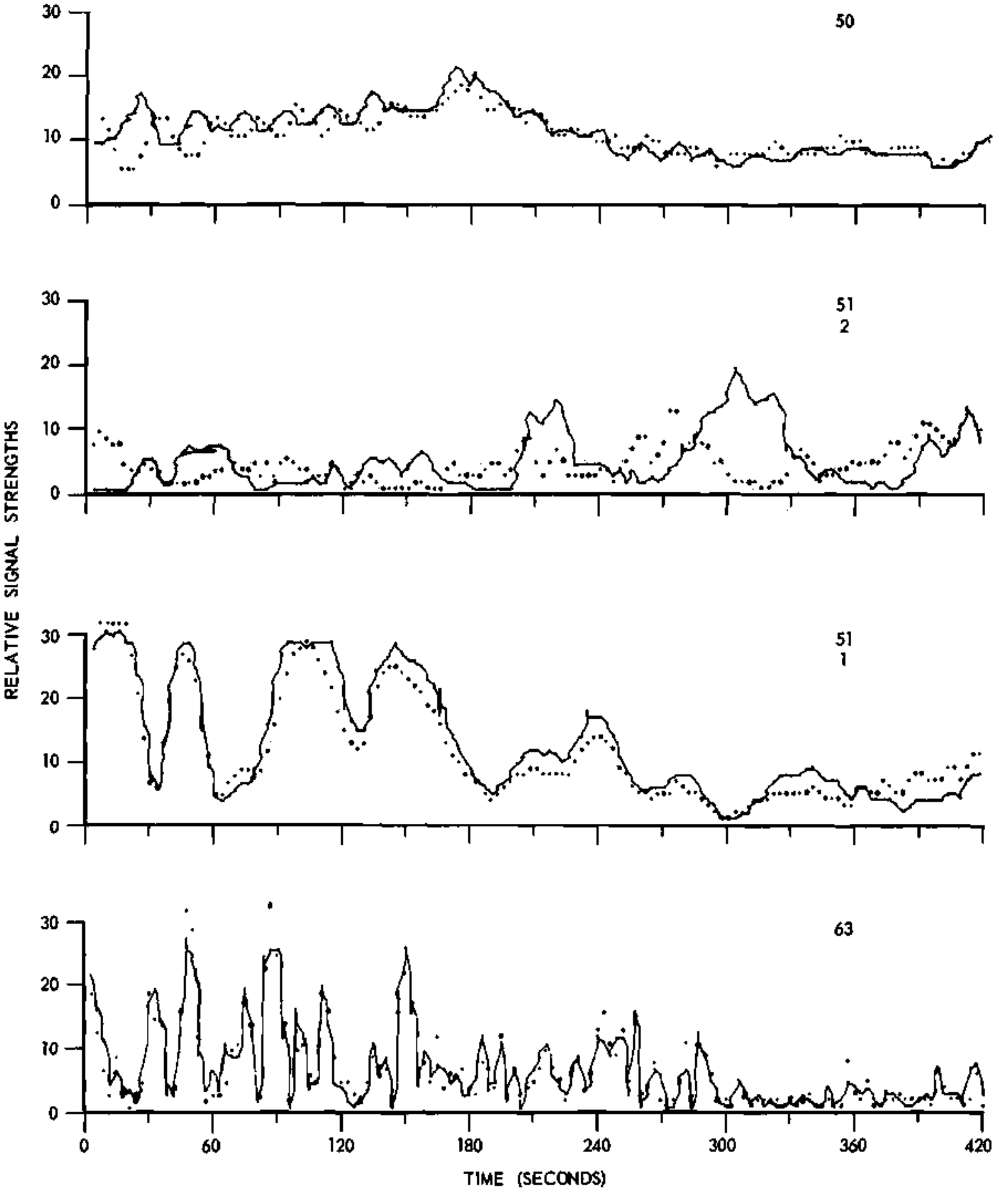

Figure 15. Relative Signal Strength Versus Time.

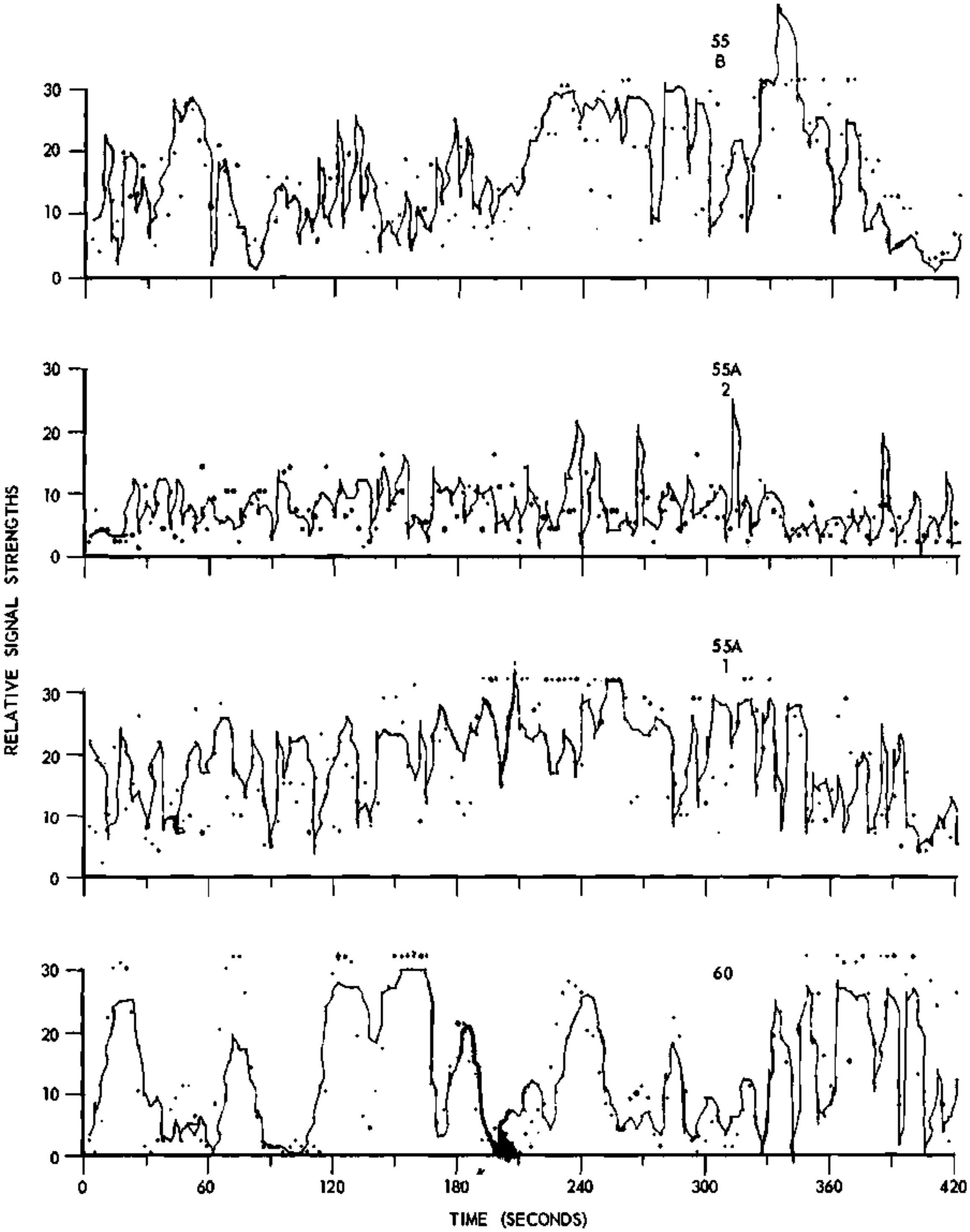

Figure 16. Relative Signal Strength Versus Time.

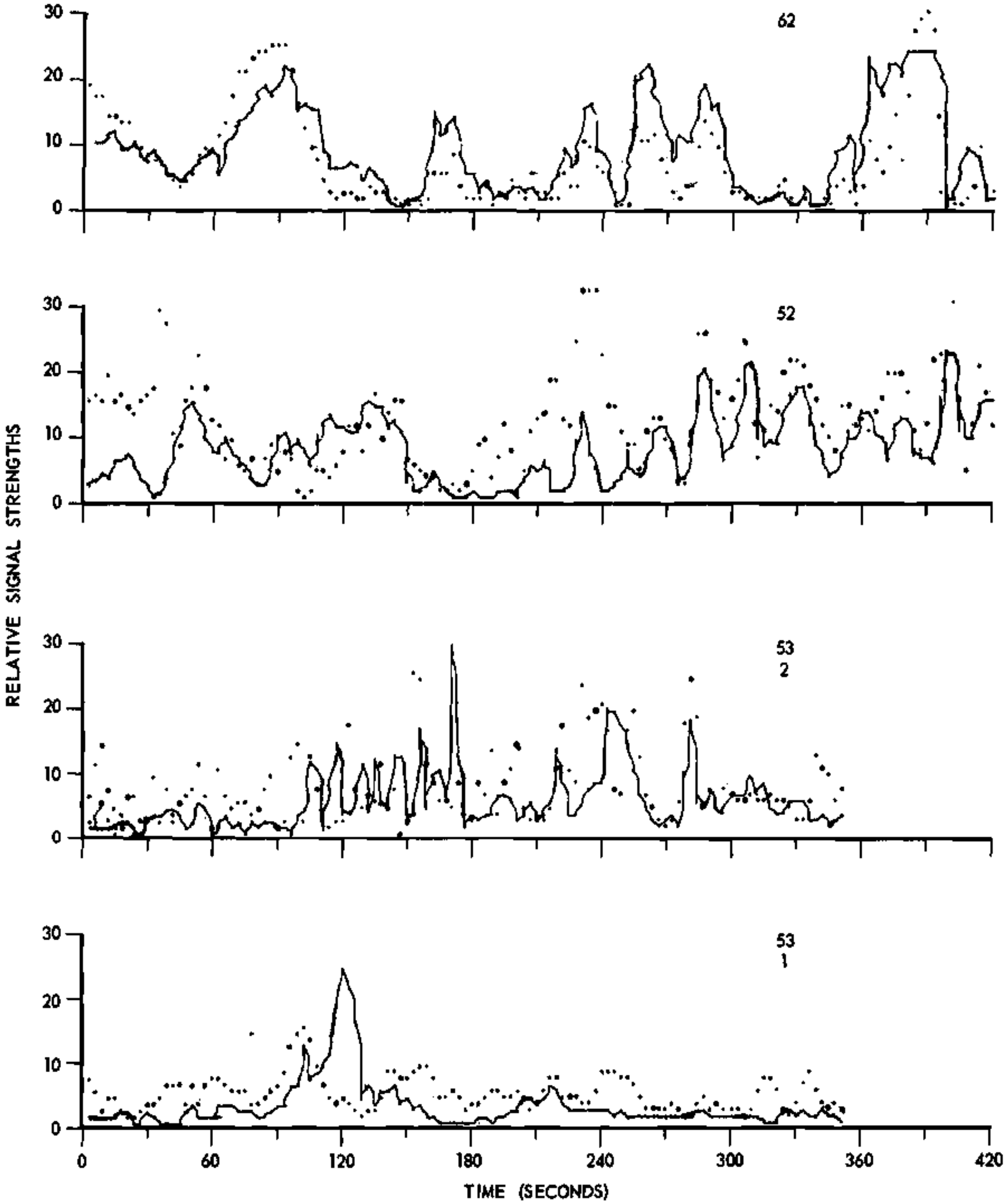

Figure 17. Relative Signal Strength Versus Time.

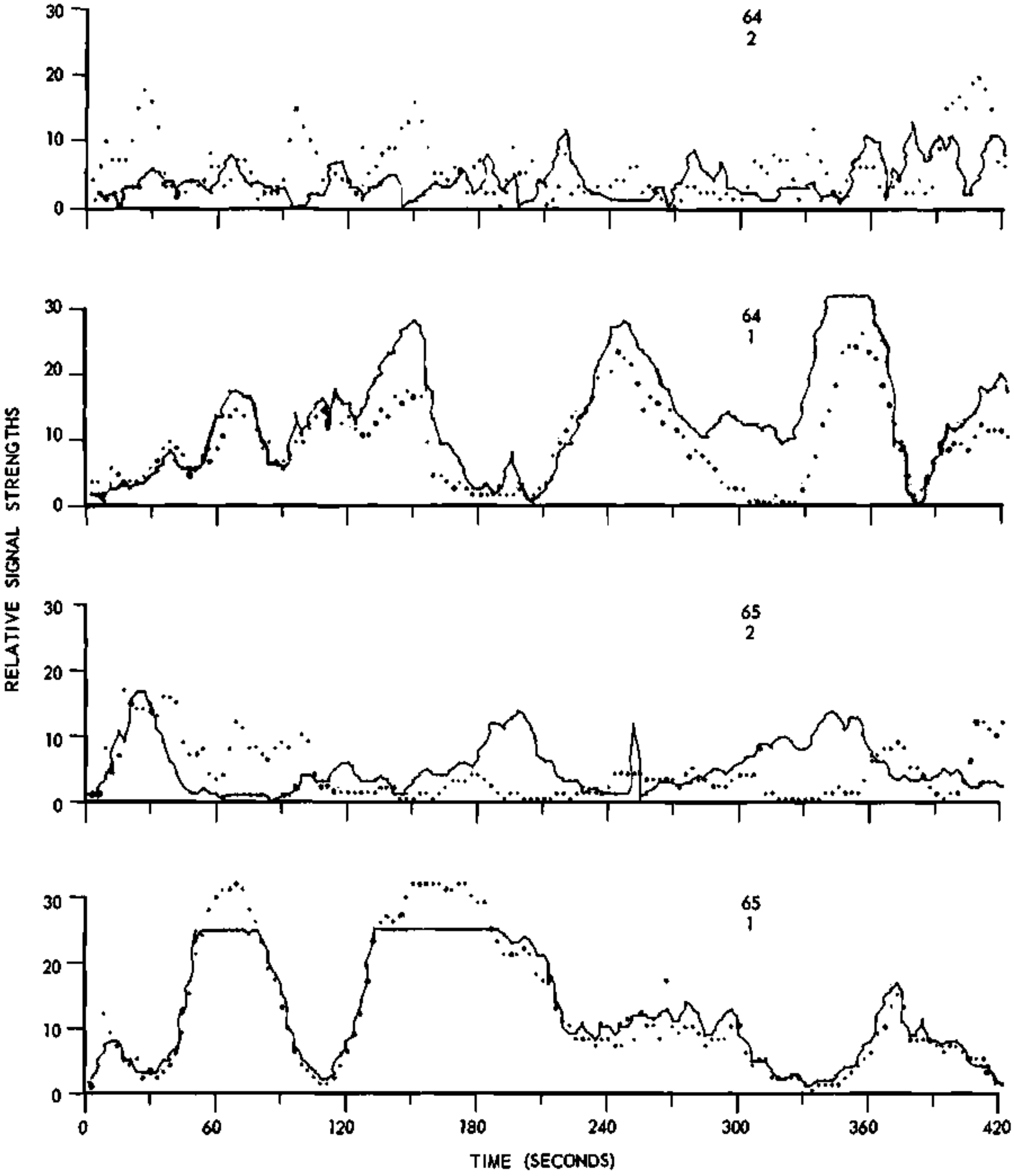

Figure 18. Relative Signal Strength Versus Time.

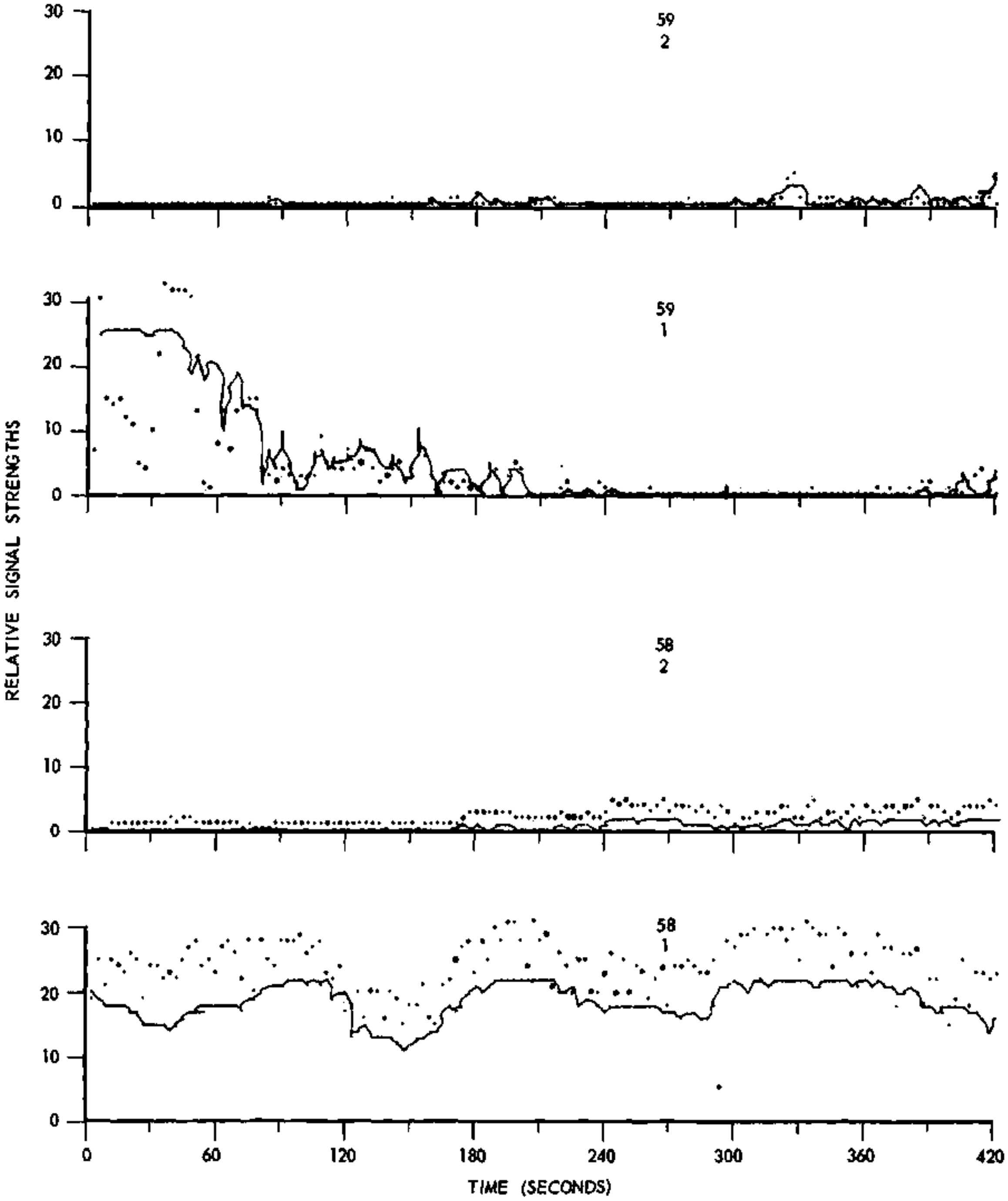

Figure 19. Relative Signal Strength Versus Time.

corresponded to a pulse height of approximately 1-5/8 inches on the oscilloscope display.) For convenience of material organization, the experimental trials ("runs") were plotted for only seven minutes duration. Since the periods of signal variation observed in the experiments were much less than seven minutes, the duration plotted gives a representative picture of the typical variation. Omission of the last three minutes of propagation, therefore, did not distort the results. The same scale, seconds, was used for every plot and each plot contains a run identification and a mode designation number. Figure 5 shows the form of the pulses taken from the film frames for the indicated times. The last pulse of each frame for this example is plotted as Run No. 21, Figure 12. Figures 6 through 19 show the plots of relative logarithmic signal strength versus time. Table 1 lists the experiment identification information and the sample correlation coefficients, based on all of the logarithmic amplitude samples taken for each transmission.

From these graphs, two general types of non-reciprocal behavior were noted. One type occurs when one signal increases while the other signal simultaneously decreases. If the two signals are different in value but are not changing, this is not considered to be non-reciprocity in this study since the ten minute runs were too short to allow a quantitative determination of long time non-reciprocal behavior. Laver and Stanesby (30) as noted in Chapter II found evidence of long time non-reciprocal behavior persisting as long as two hours. Presumably the unequal amplitude observed in some runs of the present study represent long time non-reciprocity since the preliminary adjustments made during the time synchronization procedure included gain equalization for the two directions of propagation. Unfortunately the data obtained does not clearly resolve this aspect of the signal behavior. The other observed type of non-reciprocity is characterized by a somewhat parallel variation of signals that are out of phase by a few seconds. The summed durations of the first type were measured from the graphs and the total accumulated time tabulated under t_1 in Table 1. The corresponding accumulated duration for the latter type is listed under t_2 in the same Table. The measurement of t_1 and t_2 are mutually exclusive.

In order to investigate what effect, if any, different ionospheric conditions or frequencies of propagation had on non-reciprocal behavior results of experiments for certain common conditions were grouped together. For each group, the correlation coefficients and duration of non-reciprocal behavior (both types) were averaged and listed in Table 2. The ionospheric condition groups considered were Winter-day,[*] Summer-day, Summer-night,[**] and Summer-sunrise-sunset (or transition). The frequency groups were not chosen on theoretical grounds but because the frequencies used in all of the experiments fell into certain separate categories. The subdivisions were the 8.35 - 8.45 Mc, 10.55 - 11.85 Mc, 16.55 - 16.95 Mc, and greater-than-20 Mc groups. For brevity, these will be indicated by the 8.35, 10.55, 16.55, and 20 Mc groups, respectively. Table 2 lists the averages of the correlation coefficients and durations (within the seven minute transmission) of non-reciprocity for each of these groups.

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[*] Winter is taken to be the time during which the sun is below the celestial equator, or between September 22 and March 21. During these periods the sun's zenith angle is low, resulting in a lower level of ionization in winter daytime than in summer daytime.

[**] The summer-night and winter-night conditions do not differ significantly.

Presentation of the Data.--With regard to the constant power output of each transmitter during a fixed-frequency transmission, the relative signal strength curves indicate that ionospheric propagation changes to a large degree in short intervals of time. One such type of variation is that in which the signal has no prevailing magnitude but jumps throughout values about 20 (relative logarithmic magnitudes) units apart in a time of the order of ten seconds. Runs 06-1-1 of Figure 7, 07-1-1 of Figure 6, 24-1 of Figure 12, and 57-1 of Figure 14 are included in this type. Another general type of variation noticed is that in which the signals have a prevalent high value with sudden dips in value for a few seconds. This effect suggests an ionosphere of a uniform composition except for patches, similar to heavy clouds, which blot out the sun's rays except at isolated "holes." Examples of this type are runs 07-1-2 of Figure 6, 10-1-2 of Figure 8, 56 of Figure 14, and 55A-1 of Figure 16. Runs in which the signal amplitudes vary to an extreme degree but in a smooth, prolonged time (of the order of a minute) are those like 06-0-1 of Figure 7, 09 of Figure 9, 21 of Figure 12, and 65-1 of Figure 18. For some runs, the signal amplitudes varied but little throughout the transmission period; runs 07-0-1 of Figure 6, 58 of Figure 15, and 50 of Figure 19 are of this category. Understandably, no two runs are the same; the factors that determine the ionosphere's composition are many, and some of them change in a random fashion. An examination of the curves showing the least variation reveals that these runs, with the exception of No. 50, were made in the 8.35 Mc group.

There are extremes in the degree of reciprocity. Run 21, Figure 12, displays slowly varying signals with only six seconds duration of non-reciprocity. Its correlation coefficient, r, is 0.88. Run 23-1,

Figure 11, shows that rapidly varying signals may still remain in close correspondence. Its duration of non-reciprocity is 48 seconds and its r is 0.88. An example of the other extreme is run no. 56, Figure 14, whose coefficient is -0.03 and with non-reciprocal behavior totaling 186 seconds. This coefficient indicates a considerable degree of non-reciprocity. Run 09-2, Figure 9, had the poorest degree of association, with a coefficient of -0.07. Much of this was due to out-of-phase fading. Every experiment displayed some non-reciprocity.

For the winter-daytime experiments, the results are listed in Table 2. The average coefficients are 0.77 for 1E, 0.28 for 1F1, and 0.43 for 1F2. The average total non-reciprocal durations are, respectively, 42, 97, and 51 seconds, demonstrating the expected order of relationship to the coefficients (e.g., longest duration for lowest coefficient).*

For the summer daytime experiments the average correlation is 0.82 for 1E, 0.46 for 1F1, and 0.40 for 1F2. The 1E and 1F1 coefficients are higher than those for the winter experiments, but the 1F2 coefficient was lower. The difference in non-reciprocal durations is insignificant for 1E but appreciable for 1F1 and 1F2. The average non-reciprocal durations exhibit the expected order of relationship for the winter propagation conditions also.

The night-time propagation conditions are not significantly different in summer than in winter. A few hours after sunset the recombination of ions will take place at a rate depending on the density of

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*The duration of non-reciprocity and the correlation coefficient are not always in a direct correspondence since the correlation coefficient also takes into account the magnitudes of the non-reciprocal differences, which were not tabulated. There is, however, a general correspondence between the two.

particles present. The summer night-time average correlation for 1E is lower than the corresponding values for summer and winter daytime conditions. The F1 and F2 layers combine at night to form a single F layer. For this combined, or 1F region, the average coefficient is higher than for either the 1F1 or 1F2 layers for both winter and summer, but lower than the 1E night-time value. Some signal returns believed to be 2F were obtained during some of the night-time experiments. This is the most likely period for such reception since the absorbing D layer, through which the signal would have to pass four times, disappears at night. Furthermore the E layer, which contributes to attenuation of signals, has a decreased ionization level at night. Hence there is good reason to believe the 2F reception is greatly enhanced at night. Its average coefficient is lower than either the night-time 1E and 1F values.

The sunrise-sunset (summer) transition period had the lowest 1E coefficient, 0.19. The 1F1 coefficient for this period was 0.48, between the values for the summer day and summer night conditions. The non-reciprocity durations for the two paths during this period were approximately equal.

For the 8.35 Mc category, the coefficients were 0.58 for 1E, 0.37 for 1F1, and 0.42 for 1F2. Most of the experiments at this frequency were conducted during the winter (see Table 1). For the 10.55 Mc and 16.55 Mc groups, the coefficients were highest for 1E, lower for 1F1, and lowest for 1F2. For runs at frequencies above 20 Mc, the coefficient for 1E was only slightly higher than for 1F2, and their average non-reciprocal durations were the same. The highest average coefficient for 1E occurred in the 16.55 Mc trials, while highest of 1F1 and 1F2 occurred during the 10.55 Mc and 20 Mc runs, respectively.

Approximately five or six runs were used in obtaining the average of the correlation coefficients and the non-reciprocity durations. It is quite reasonable that any one run used was not typical for that transmission condition but was subject to abnormal ionospheric activity. Had this been the case, its correlation coefficient could have been much different than its typical value. Such a difference, when averaged with only a few other values, would have affected the average of the correlations in at least the second significant digit. Along with all the other possible errors of the experiment and the analysis of results, this fact makes the accuracy of the second significant digit of the average correlation coefficient (and the average non-reciprocal duration) appear doubtful. Hence the values for the summer-day and winter-day 1E made correlation coefficients, 0.77 and 0.82, are not significantly different. Similarly, the 1F2 made averages for winter and summer 0.43 and 0.40 do not differ appreciably.

Discussion of Results.--The most consistent result is the fact that the 1E coefficients are higher than for the other paths with the exception of the sunrise-sunset condition. The 1E signal does not remain in the ionosphere as long nor is subject to as many variation effects as the 1F1 and 1F2 signals. For example the 1F2 must pass completely through the E and F1 layers twice and through the F2 layer where it is refracted. Of course the earth's magnetic field is present in all of these layers. Furthermore, the relative signal strength variation graphs indicate that the later-arriving signals undergo more extreme and rapid variation, on the average, than the earlier-arriving signals. Since the F1 and F2 layers both introduce additional effects on the two signals, it would be expected that the signals passing through the 1E region only would exhibit a closer relationship. For the sunrise-sunset condition the reason for the much lower 1E coefficient is uncertain although it probably results from the rapidly changing level of ionization due to the large change in sunlight present. The effect would not be so noticeable for the F region since the much smaller molecular density prevents large increases of ionization during sunrise and large decreases of ionization due to recombination at sunset.

While the 1E propagation mode coefficient is larger than that of either the 1F1 and 1F2 in summer and in winter, the 1F1 coefficient is smaller than that of the 1F2 in winter and larger in summer. This result also follows the trend of ionization intensity. It is recalled that the F2 ionization is stronger than the F1 in winter, and less strong in summer. The summer 1E and 1F1 coefficients are larger than their respective winter values. Here again it is recalled that the ionization levels of the E and F1 layers are higher in summer than in winter. The 1E average coefficient is smaller at night than either the winter day or summer day coefficient. The E ionization level of course is less at night than during the daytime.

On examination of the results for different frequencies used, one characteristic is the same as for the previously mentioned conditions. This characteristic is that the 1E correlation is higher than both the 1F1 and 1F2 for every frequency category. Likewise, the 1F1 correlation is higher than the 1F2 value for every category except the 8.35 Mc one. This latter exception is expected however, since the majority of the 8.35 Mc experiments were conducted during the winter when the F2 ionization level was higher than the F1 level. Hence the indication is that for a given frequency of propagation, the earlier-arriving two-way signal (the one traveling through a lower layer) will have a higher degree of reciprocity than a later-arriving signal.

With regard to the behavior of a signal through a given layer for different frequencies, no definite trend was shown. The highest correlation for the 1E was for the 16.95 Mc group experiments, while the highest for the 1F1 and 1F2 were for the 10.55 Mc and 20 Mc categories, respectively. It was generally observed that lesser non-reciprocity occurred close to, but about one megacycle below, the MUF. The observed MUF values for the transmission times were not complete enough to examine this aspect thoroughly. This choice of frequencies, rather than the absolute frequency groups used, may have shown a relation between frequency and non-reciprocity.

The average durations of each non-reciprocal variation lasted for approximately six to 15 seconds and the typical values for phase differences was of the order of ten seconds.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--It has been shown by carefully designed and conducted experiments that some non-reciprocity of identical radio wave pulses, traveling in opposite directions over the same ionospheric transmission path, does exist. Some previous experimental investigations (35), (36) and theoretical treatments (37), (38) had verified the existence and basis of non-reciprocity. The previous experiments, however, did not give much information regarding the duration or extent of the non-reciprocity.

This study examined propagation conditions for different seasons of the year, times of day, and frequencies of transmission. The least degree of non-reciprocity, as determined by the averages of the correlation coefficients for the period, was found to occur during the summer daytime conditions for the 1E and 1F1 modes of propagation. The least non-reciprocity for the 1F2 mode took place during winter daytime, while the average correlation of the night-time combination of the F1 and F2 layers was greater than either the daytime 1F1 and 1F2 values. For all propagation condition categories listed with the exception of the summer sunrise-sunset (transition) period, the non-reciprocity was higher for the later-arriving signals than for the signal propagated via 1E.

The trend of non-reciprocity observed in these tests followed very closely the relative ionospheric activity, i.e., higher reciprocity for the more stable E region. The non-reciprocity is higher for the later arriving signals than for the earlier received ones except for the 1F1 and 1F2 during winter daytime conditions (when the F2 ionization density is higher than that of the F1) and during sunrise-sunset periods, during which time the ionosphere undergoes rapid changes. Observed also was a relation between relatively low correlation (high non-reciprocity) and relatively low level, or intensity, of ionization.

There was no observed dependence of the amount of non-reciprocity on frequencies of propagation, however this result is not conclusive. The relative degree of non-reciprocity for the various modes of transmission showed no preference for frequency range but the 1E reciprocity was highest for all frequency groups considered.

Every experimental trial displayed non-reciprocity though some contained a total of only six seconds duration for a seven minute transmission period. Some runs displayed non-reciprocity for a total of three minutes out of the seven minute period. The average duration of each occurrence of non-reciprocity was of the order of five to ten seconds. As expected, the average of the total non-reciprocal duration is roughly inversely proportional to the average of the correlation coefficient for each condition examined.

Recommendations.--It was assumed in this study that the oppositely-traveling signal pulses passed the midpoint of the transmission path at the same instant. While there may be some deviation from this, it is relatively slight. Vertical-incidence soundings at the midpoint of the transmission path synchronized with the oblique-incidence transmissions would give useful information regarding the behavior of the ionosphere at the vicinity of the signal's crossing. Comparison of the vertical-incidence signal variations would assist in the determination of the region where the signals experienced the greatest disturbance.

Another source of information possibly adding to the explanation of the signal variation is the record of sunspot and sudden ionospheric disturbance data. Periods of high sunspot or violent ionospheric activity could be checked with oblique-incidence experiments to investigate dependence of non-reciprocal conditions on such activity.

Other features worthy of investigation, examined to a limited extent by personnel at Lincoln Laboratory of the Massachusetts Institute of Technology, are the changes of flight time and phase relationships of the various signals. Experiments that simultaneously record the many parameters of wave propagation, while requiring a major coordinated effort, would obtain valuable data concerning the effects of the ionosphere on radio propagation.

Table 1. Identification of Experimental Data

Experiment Identification Number	Date	Time (EST)	Frequency (Mc)	Mode of Propagation	Total Duration of Non-Reciprocity (Seconds)		Sample Correlation Coefficient
					t_1	t_2	
07-0,1	Feb. 26, 1959	1525	8.45	1E	24	0	.86
07-0,2	Feb. 26, 1959	1525	8.45	$1F_1$	39	27	.41
07-1,1	Feb. 26, 1959	1525	8.45	$1F_2$ lo*	27	9	.31
07-1,2	Feb. 26, 1959	1525	8.45	$1F_2$ hi	33	15	.49
08, 1	Mar. 5, 1959	1405	16.95	1E	6	15	.97
08, 2	Mar. 5, 1959	1405	16.95	1E	48	57	.69
09, 1	Mar. 5, 1959	1420	16.95	1E	15	90	.92
09, 2	Mar. 5, 1959	1420	16.95	1E	90	63	-0.07
06-0,1	Mar. 5, 1959	1535	8.35	1E	18	0	.89
06-0,2	Mar. 5, 1959	1535	8.35	$1F_1$*	54	36	.22
06-1,1	Mar. 5, 1959	1535	8.35	$1F_2$ lo*	33	12	.52
06-1,2	Mar. 5, 1959	1535	8.35	$1F_2$ hi*	36	39	.37
10-0,1	Mar. 5, 1959	1550	8.35	1E	15	42	.27
10-0,2	Mar. 5, 1959	1550	8.35	$1F_1$*	39	33	.15
10-1,1	Mar. 5, 1959	1550	8.35	$1F_2$ lo*	33	36	.26
10-1,2	Mar. 5, 1959	1550	8.35	$1F_2$ hi*	21	24	.46
14,1	Mar. 10, 1959	1150	16.95	1E	18	12	.74
14,2	Mar. 10, 1959	1150	16.95	$1F_2$ lo	24	21	.41
15,1	Mar. 10, 1959	1403	23.45	1E	21	18	.75
15,2	Mar. 10, 1959	1403	23.45	$1F_2$ lo	24	18	.63

(Continued)

*Modes consisting of two or more superimposed pulses.

Table 1. Identification of Experimental Data (Continued)

Experiment Identification Number	Date	Time (EST)	Frequency (Mc)	Mode of Propagation	Total Duration of Non-Reciprocity (Seconds) t_1	t_2	Sample Correlation Coefficient
21	Mar. 24, 1959	1531	11.35	$1F_1$	6	0	.88
22,1	Mar. 24, 1959	1129	16.75	1E	12	21	.85
22,2	Mar. 24, 1959	1129	16.75	$1F_1$	45	30	.35
23,1	Mar. 24, 1959	1155	16.75	1E	9	39	.88
23,2	Mar. 24, 1959	1155	16.75	$1F_1$	75	36	.06
24,1	Mar. 31, 1959	1545	8.45	1E	33	27	.63
24,2	Mar. 31, 1959	1545	8.45	1E	57	15	.27
26	Apr. 7, 1959	1054	23.85	$1F_2$	12	0	.87
30,1	Apr. 21, 1959	1422	16.55	1E	21	27	.67
30,2	Apr. 21, 1959	1422	16.55	$1F_2$	114	45	.07
31,1	Apr. 21, 1959	1434	16.55	1E	12	0	.90
31,2	Apr. 21, 1959	1434	16.55	$1F_2$	42	24	.73
65,1	July 9, 1959	1253	10.75	$1F_1$	6	0	.97
65,2	July 9, 1959	1253	10.75	$1F_2$	87	42	.17
63	July 21, 1959	1347	24.75	$1E_s$	15	0	.84
64,1	July 21, 1959	1043	11.85	1E	21	9	.81
64,2	July 21, 1959	1043	11.85	$1F_1$*	63	15	.22
62	Aug. 27, 1959	0614	10.55	1F	18	15	.79

(Continued)

Table 1. Identification of Experimental Data (Continued)

Experiment Identification Number	Date	Time (EST)	Frequency (Mc)	Mode of Propagation	Total Duration of Non-Reciprocity (Seconds)		Sample Correlation Coefficient
					t_1	t_2	
56	Sept. 1, 1959	1838	11.35	1F	150	36	-.03
57-0,1	Sept. 1, 1959	2033	4.15	1F lo	27	9	.75
57-0,2	Sept. 1, 1959	2033	4.15	1F hi	30	6	.77
57-1	Sept. 1, 1959	2033	4.15	2F*	42	45	.36
59,1	Sept. 1, 1959	2100	6.65	1F lo	30	12	.67
59,2	Sept. 1, 1959	2100	6.65	1F hi	33	0	.48
60	Sept. 1, 1959	2155	11.35	1E	27	24	.76
58,1	Sept. 1, 1959	2325	8.35	1E	63	0	.64
58,2	Sept, 1, 1959	2325	8.35	1F hi	15	0	.96
55-A, 1	Sept. 10, 1959	0336	4.25	1F lo*	36	15	.53
55-A, 2	Sept. 10, 1959	0336	4.25	2F*	39	9	.54
55-B	Sept. 10, 1959	0400	11.25	1F lo*	24	15	.87
52	Sept. 10, 1959	0523	7.85	1F	33	27	.66
53,1	Sept. 10, 1959	0722	8.45	1E*	63	36	.19
53,2	Sept. 10, 1959	0722	8.45	1F*	51	21	.20
50	Sept. 10, 1959	0804	16.95	1F	39	21	.80
51,1	Sept. 10, 1959	1044	16.95	1E	6	0	.97
51,2	Sept. 10, 1959	1044	16.95	1F$_2$	63	15	.17

Table 2. Averages of Correlation Coefficients and Durations of Non-Reciprocity.

	Winter-Day			Summer-Day			Summer Night			Summer-Sunrise, Sunset			8.35 - 8.45 Mc			10.55 - 11.85 Mc			16.55 - 16.95 Mc			> 20 Mc		
	r	t_1	t_2	r	t_1	t_2	r	t_1	t_2	r	t_1	t_2	r	t_1	t_2	r	t_1	t_2	r	t_1	t_2	r	t_1	t_2
1E	.77	17	25	.82	16	15	.70	45	12	.19	63	36	.58	36	17	.78	24	17	.86	12	26	.80	18	9
1F1	.28	54	43	.46	30	23	.58	35	15	.48	58	24	.37	43	22	.61	45	15	.37	59	41			
1F2	.43	29	22	.40	64	25							.42	31	19	.45	65	28	.35	61	26	.75	18	9
2F							.45	41	27															

$\bar{t}_1$ and $\bar{t}_n$ are in seconds.

$\bar{t}_1$ and $\bar{t}_n$ are the averages of the summed durations of the two types of non-reciprocity in the seven minute (420 second) runs.

T is $\bar{t}_1 + \bar{t}_n$.

APPENDICES

APPENDIX I

FORMATION OF THE IONOSPHERE

When an electron moves from one energy level to an energy level below it (closer to the nucleus), it emits a quantum of energy in the form of electromagnetic radiation. Conversely, if an atom is irradiated with electromagnetic radiation of the proper frequency, an electron may absorb a quantum of radiation energy and move to a higher energy level (away from the nucleus). If there is a range of frequencies in the illuminating radiation, then the electron will be able to absorb a quanta of the proper energy to become completely disassociated from the atom. In this case the atom becomes "ionized." The ionized atom and electron are each unbalanced electrical charges. An atom may also become ionized if it collides with a fast-moving particle such as a proton or electron. If the particle has enough energy, it may knock one of the outer electrons out of the atom. Both processes contribute to ionization in the upper atmosphere but radiation is by far the predominant ionizing agent. This electromagnetic radiation includes ultraviolet light, X-rays, gamma rays, and cosmic rays, with ultraviolet light being the major source of ionization.

The simplest type of ionized layer that can be predicted on theoretical grounds is the so-called "Chapman layer." Suppose ultraviolet or X-ray radiation of a single wavelength capable of producing ionization of an atmospheric constituent is incident upon an atmosphere whose density, and therefore its absorption coefficient, vary exponentially with altitude.

As the radiation penetrates more deeply into the absorbing atmosphere, its intensity is decreased. At a sufficiently low altitude the greater part of the radiation is absorbed, and a lower bound is formed to the region of ionization produced by the radiation. Since the rate of ionization production is dependent on the density of ionizable constituent at any height, as well as on the radiation intensity, the upper part of the layer will exhibit a rate of ionization production which decreases with height in the same manner as does the air density. The actual ionization density present at any time will represent a balance between the rates of production, accumulation, and loss.

The rate of change of ion density is given by the equation

$$\frac{dN}{dt} = q - aN^2 \tag{4}$$

where N = the number of ion pairs

q = the rate of production

a = the coefficient of recombination.

For equilibrium conditions, $q = aN^2$.

Applied to a plane-stratified ionospheric region, the theory of layer formation upon the preceding assumptions leads to the following expression for the electron distribution function:

$$N = N_o \exp \frac{(1 - z - \epsilon^{-z} \sec x)}{2} \tag{5}$$

where N_o = the electron density at the reference height where $z = 0$; z is height normalized by the scale height and is zero at the height of the layer maximum for $x = 0$; x = the solar zenith angle. The atmospheric density is assumed to be proportional to ϵ^{-z}.

The height at which the maximum electron density appears is

$$z_{max} = \ln \sec x$$

where z is taken as zero for $x = 0$.

For the plane earth case, the ionization density of a layer maximum varies with solar zenith-angle according to the relation

$$N_{max} = N_o \sqrt{\cos x} \qquad (6)$$

where N_o is the value of N_{max} for $x = 0$.

APPENDIX II

PROPAGATION OF ELECTROMAGNETIC WAVES IN AN IONIZED ATMOSPHERE

Since ordinary air is an insulator the electric field of a radio wave does not set up any current of electrons. The changing electric field sets up a "displacement current" by which the wave travels. In an ionized atmosphere, however, the electric field is able to set the free electrons into motion, thus establishing an actual conduction current. The current now set up is out of phase with the displacement current and cancels, in part, the latter, so that the rate of change of the electric and magnetic fields of the wave is changed. Thus change results in the phase of the wave at a given point in the ionized region being shifted, so that the wave appears to speed up. As a wave sets up a convection current, therefore, its phase velocity increases. Since the ion density increases with altitude the effect of the convection current will become more pronounced as the wave penetrates further into the ionized region and the wave (phase) velocity will become greater. The speed at which the signal as a whole travels is not the wave velocity, but is the group velocity, V_g, given by

$$V_g = C\,n = \frac{C^2}{V_p} \qquad (7)$$

where C is the velocity of the wave in free space,

n is the refractive index of the medium, and

V_p is the phase velocity.

As n is less than unity in the ionosphere, the group velocity is decreased in the ionosphere and further, the greater the phase velocity, the smaller the group velocity. Hence the signal is retarded and the group velocity of a vertically traveling wave will become zero when the refractive index is reduced to zero. The wave then proceeds downward with gradually increasing group velocity until it leaves the ionized region, at which time it resumes the free space velocity.

In the absence of the earth's magnetic field, the refractive index of the ionosphere is given by

$$n = \sqrt{1 - \frac{Ne^2}{\pi m f^2}} \tag{8}$$

where N is the electron density, f is the frequency of propagation,

e is the charge on an electron, and

m is the mass of an electron.

The group velocity is then

$$V_g = C\,n = C\sqrt{1 - \frac{Ne^2}{\pi m f^2}} \;. \tag{9}$$

The condition for reflection at vertical incidence is that $n = 0$, or

$$N = \frac{\pi m f^2}{e^2} \tag{10}$$

The latter equation specifies the ion density N required for the reflection of the frequency f. This equation is sometimes written in the form

$$n = \sqrt{1 - \frac{f_N^2}{f^2}} \tag{11}$$

where f_N, having dimensions of frequency, is defined by

$$f_N = \sqrt{\frac{Ne^2}{\pi m}} \quad . \tag{12}$$

The value of f_N, depending only on the ion density N and called the "plasma frequency," is a convenient way of expressing ion density in units of frequency.

In the presence of the earth's magnetic field the situation becomes much more complex. The electrons experience a new force perpendicular to both the magnetic field and the direction of movement, so that the electron rotates about the field. The rate of rotation, called the gyro-frequency, depends only on the strength of the field, H, and is given by

$$f_H = \frac{He}{2\pi m} \quad . \tag{13}$$

The expression for the refractive index in the presence of a magnetic field, neglecting particle collisions, is (39):

$$n = \sqrt{1 - \frac{f_N{}^2/f^2}{1 - \dfrac{f_T{}^2/f^2}{2(1 - f_N{}^2/f^2)} \pm \dfrac{f_T{}^4/f^4}{4(1 - f_N{}^2/f^2)^2} + \dfrac{f_L{}^2}{f^2}}} \tag{14}$$

where f = the wave frequency, f_N is the plasma frequency, f_H is the gyro-frequency, $f_L = f_H \cos \theta$, $f_T = f_H \sin \theta$, θ being the angle between magnetic field and direction of propagation.

Setting $n = 0$ to solve for the conditions of reflection yields, for the case where $f > f_H$:

$$f_{N_1}{}^2 = f^2 - ff_H \tag{15}$$

$$f_{N_2}{}^2 = f^2 \tag{16}$$

$$f_{N_3}{}^2 = f^2 + ff_H \quad . \tag{17}$$

One of the values of frequencies for reflection, $f_N = f_1$ does not depend at all on the magnetic field and the same reflection condition is derived as for the case of no magnetic field. This is called the "ordinary" ray. The reflection at the lower frequency given by equation (15), is called the "extraordinary" ray. The ray reflected at the frequency given by equation (17) has little chance of reaching the higher level of greater electron density required for reflection and is usually not seen. If $f<f_H$, only the extraordinary ray given by equation (17) is reflected.

In the graphical solution of oblique-incidence maximum usable frequencies by the transmission curve method (40), it is seen that most of the curves intersect the F2 layer portion of the virtual height versus frequency in two places. These two values correspond to "low wave" and "high wave" frequencies (not related to the ordinary or extraordinary waves) at the indicated wave frequency of the parametric curve. At the MUF for a certain path, the high and low waves converge to form one wave.

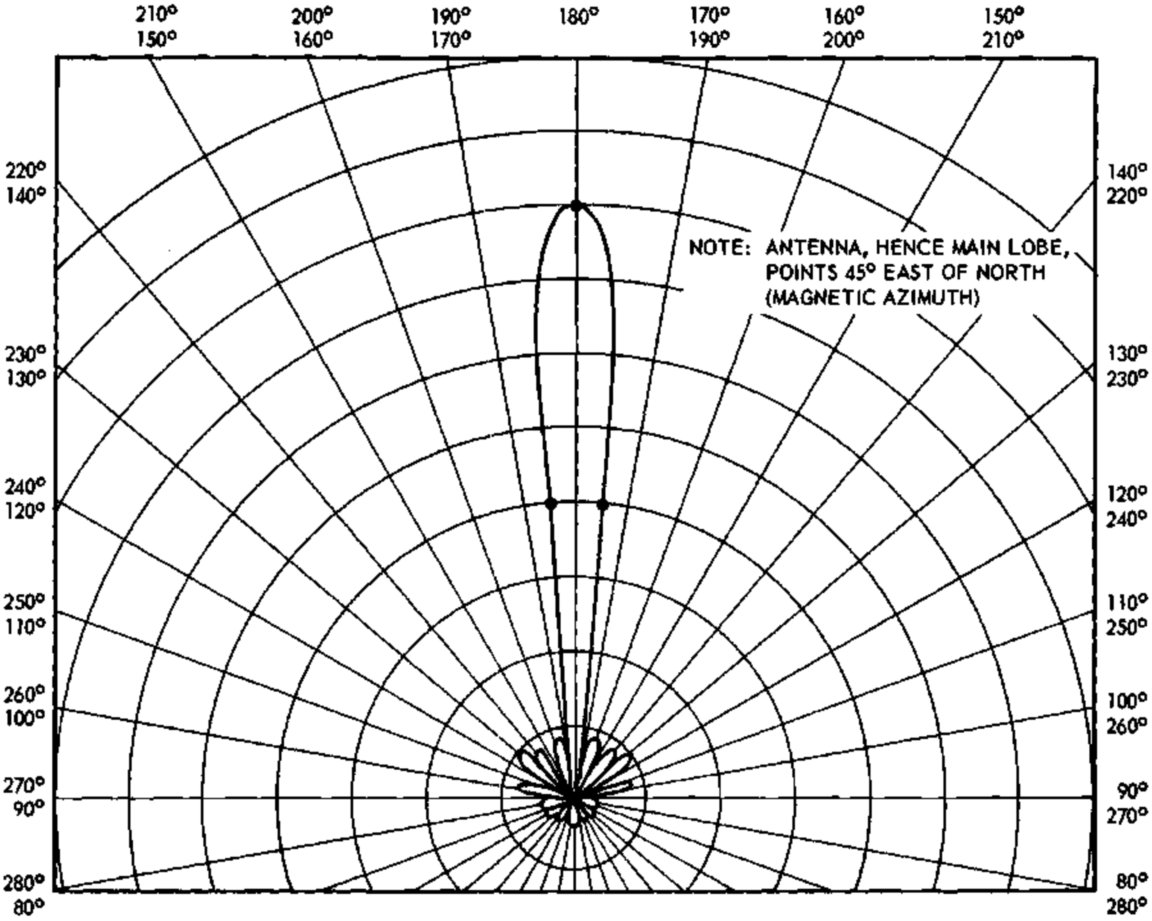

Figure 20. Horizontal Antenna Radiation Pattern.

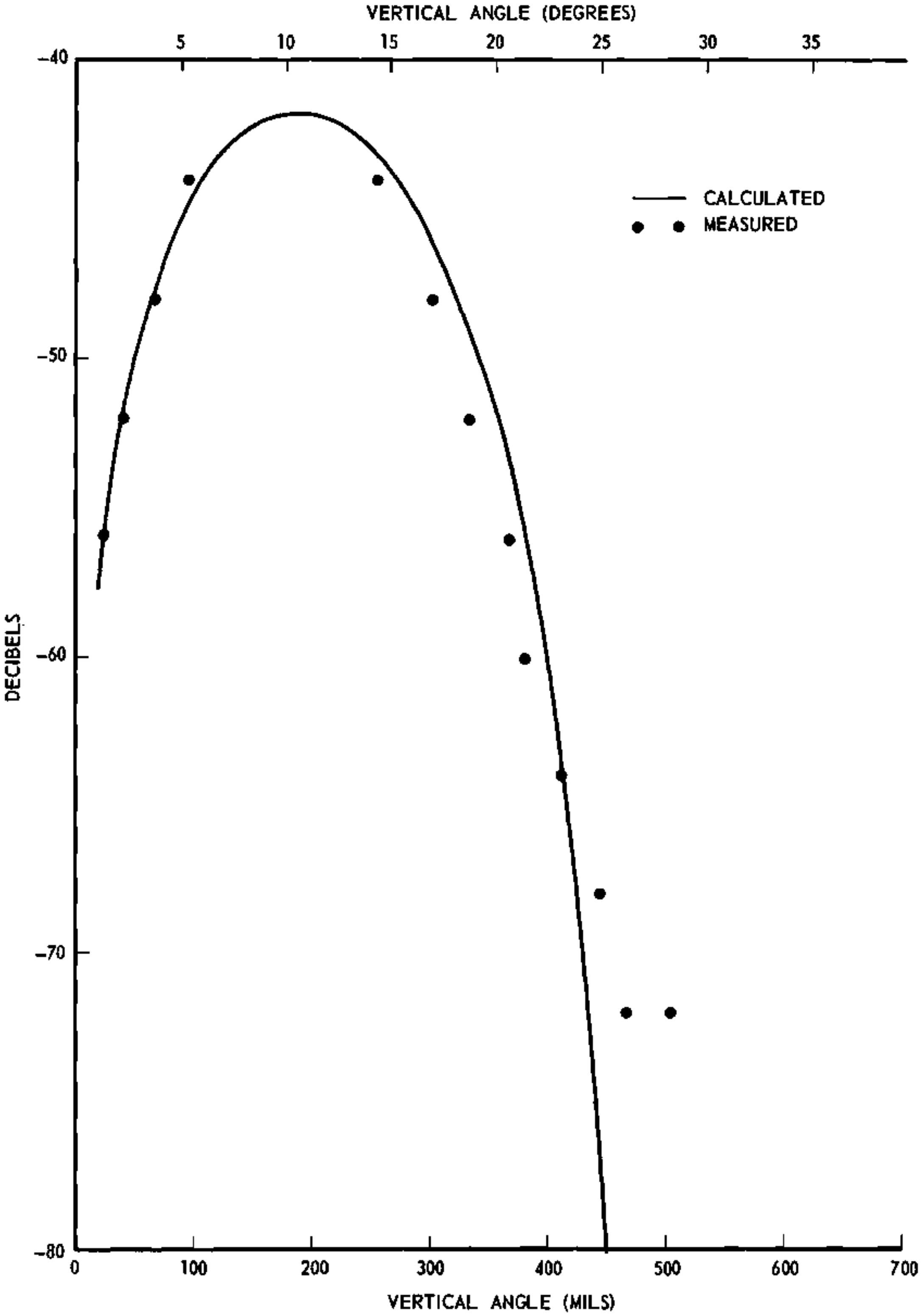

Figure 21. Vertical Antenna Radiation Pattern.

BIBLIOGRAPHY

1. Stewart, Balfour, "Terrestrial Magnetism," Encyclopedia Britannica (Ninth Edition), Vol. 16, 1902, p. 181.

2. Mitra, S. K., The Upper Atmosphere (Second Edition), Calcutta, India: The Asiatic Society, 1952, p. 177.

3. Eccles, W. H., "On the Diurnal Variations of the Electric Waves Occurring in Nature, and on the Propagation of Electric Waves Round the Bend of the Earth," Proceedings of the Royal Society, Vol. A, 87, 1912, p. 79.

4. Larmor, J., "Why Wireless Electric Rays Can Bend Round the Earth," Philosophical Magazine, Vol. 48, 1924, p. 1025.

5. Breit, G. and Tuve, M. A., "A Test of the Existence of the Conducting Layer," Physical Review, Vol. 28, 1926, p. 554.

6. Jordan, E. C., Electromagnetic Waves and Radiating Systems, Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1950, p. 657.

7. Ibid, p. 658.

8. Mitra, op. cit., p. 177 (Figure 1).

9. Wright, J. W., Knecht, R. W., and Davies, K., "Ionospheric Vertical Soundings," Annals of the International Geophysical Year, I.G.Y. Instruction Manual, Vol. 3, 1957-1958, p. 4.

10. Mitra, op. cit., p. 236.

11. Ibid, Chapter VI.

12. Wright, Knecht, and Davies, op. cit., secs. 3.2 and 3.7.

13. Ibid, p. 47.

14. Ibid, pp. 54-58.

15. Ibid, p. 55, Figure 40.

16. Martyn, D. F., "Propagation of Medium Radiowaves in the Ionosphere," Proceedings of the Physical Society, Vol. 47, 1935, p. 332.

17. Smith, N., "Extension of Normal-Incidence Ionospheric Measurements to Oblique-Incidence Radio Transmission," U. S. National Bureau of Standards Journal of Research, Vol. 19, July - Dec., 1937, p. 89.

18. Appleton, E. V. and Benyon, W. J. G., "The Application of Ionospheric Data to Radio Communication Problems," Part II, Proceedings of the Physical Society, Vol. 59, 1947, p. 58.

19. Millington, G., "The Relation Between Ionospheric Transmission Phenomena at Oblique Incidence and Those at Vertical Incidence, Proceedings of the Physical Society, Vol. 50, 1938, p. 801.

20. Benyon, W. J. G., "Propagation of Radio Waves-Measurements with Oblique Incidence on the Ionosphere," Wireless Engineer, Vol. 25, 1948, p. 322.

21. Cox, J. W. and Davies, K., "Oblique-Incidence Pulse Transmission," Wireless Engineer, Vol. 32, 1955, p. 35.

22. Chapman, J. H., Davies, K., and Littlewood, C. A., "Radio Observations of the Ionosphere at Oblique Incidence," Canadian Journal of Physics, Vol. 33, 1955, p. 713.

23. Carson, J. R., "Reciprocal Theorems in Radio Communication," Proceedings of the Institute of Radio Engineers, Vol. 17, 1924, p. 952.

24. Strutt, J. W., Baron Rayleigh, Theory of Sound (Second Edition), Vol. 1, London: Macmillan and Co., Ltd., 1929, p. 155.

25. Carson, J. R., "A Generalization of the Reciprocal Theorem," Bell System Technical Journal, Vol. 3, July, 1924, p. 393.

26. Budden, K. G., "A Reciprocity Theorem on the Propagation of Radio Waves via the Ionosphere," Proceedings of the Cambridge Philosophical Society, Vol. 50, Part IV, 1954, p. 604.

27. Eckersley et al., "Report on Measurements Made on Signal Strengths at Great Distances During 1922 and 1923 by an Expedition Sent to Australia," Journal of the Institution of Electrical Engineers, Vol. 63, October, 1925, p. 933.

28. Eckersley, T. L., Falloon, S. Farmer, F. J., and Argar, W. O., Letters to the Editors, "Wireless Propagation and the Reciprocity Law," Nature, Vol. 145, 1940, p. 222.

29. Meadows, R. W., "An Experiment to Test the Reciprocal Radio Transmission Conditions over an Ionospheric Path of 740 kilometers," Proceedings of the Institute of Radio Engineers, Vol. 103, Part B, 1956, p. 224.

30. Laver, F. J. M., and Stanesby, H., "An Experimental Test of Reciprocal Transmission over Two Long-Distance High-Frequency Radio Circuits," Proceedings of the Institute of Electrical Engineers, Vol. 103, Part B, 1956, p. 227.

31. Kraus, John D., *Antennas*, New York: McGraw-Hill, 1950, pp. 408-412

32. "Training Manual on Antennas," Philco Service Manual AN-150A, Dec. 1948, pp. 163-164, 111

33. Chapman, Davies, and Littlewood, *op. cit.*

34. Bowker, A. H., and Liberman, G. J., *Engineering Statistics*, Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1959, pp. 273-4.

35. Meadows, *op. cit.*

36. Chapman, Davies, and Littlewood, *op. cit.*

37. Budden, *op. cit.*

38. Archer, D. H., "On the Reciprocity of Rays Propagated Through a Horizontally Stratified Ionosphere," Massachusetts Institute of Technology, Lincoln Laboratory Technical Report No. 168, December, 1957.

39. Wright, Knecht, and Davies, *op. cit.*, p. 28.

40. *Ionospheric Radio Propagation*, National Bureau of Standards Circular 462, June, 1948, p. 69.