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Observations of Radio Wave Phase Characteristics on a High-Frequency Auroral Path

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Experimental observations of phase perturbations to continuous wave and pulse signals, over short time periods, have been carried out on a high-frequency auroral path. Statistics on phase perturbations occurring in time intervals of one to twenty milliseconds were obtained for the continuous wave signals. Pulse-to-pulse phase stability measurements were made, using one-millisecond pulses with a pulse repetition rate of 250 pulses per second. The phase of corresponding parts of successive pulses were compared continuously, and then the integrated values of phase differences during one-millisecond pulse periods were determined. Comparisons of statistics of phase perturbations for continuous wave signals and one-millisecond pulse signals indicate no significant differences for approximately four-millisecond sampling intervals and comparable fading speeds on this auroral path.

1. Introduction

A high-frequency radio signal, propagated by the ionosphere over long distances, usually arrives at the receiver via several different propagation paths and with different time delays for the various paths. Interference between the multipath signal components, along with movements of ionospheric layers and irregularities, results in phase and amplitude perturbations of the received signal. Even when one component is much stronger than the others, rapid movement of the ionosphere may still cause phase perturbations of the received signal as the phase path-length changes.

Bramley [1951] and Voelcker [1960] have considered the theoretical phase perturbations to be expected over short time periods with Rayleigh fading signals. Observations of changes in phase path lengths for high-frequency radio waves have been obtained by several workers, notably Findlay [1947], [1951], and Price and Green [1957]; however, most of the observing equipment was limited to time resolutions of the order of a second or greater. Lutz, Losee, and Ladd [1959] have suggested that the amount of multipath falling within a received signal element, and hence the phase perturbations, may be reduced by a technique of transmitting short pulses separated in time by intervals greater than the longest multipath delay times; they suggested 1-msec pulses at a repetition rate of 250 pulses per second. A phase-keyed communication system, using this separated pulse technique, would then compare the phase continuously between corresponding parts of successive pulses, the integrated value of the phase comparisons determining the signalling state.

The purpose of the observations reported in this paper is to provide some statistical information on phase perturbations occurring within a few milliseconds for continuous wave and pulse signals on a fairly long auroral path. Fast "flutter" type fading has been observed for many years on radio paths crossing the auroral zone; phase perturbations of radio waves may be expected to be quite severe under such conditions.

2. Experimental Facilities

Observations were carried out over a path from Barrow, Alaska to Boulder, Colorado during December 1959, and the first half of 1960 at frequencies of 9.9475 Mc/s, 14.688 Mc/s, and 19.247 Mc/s. The great circle distance is 4,470 km. Figure 1 shows

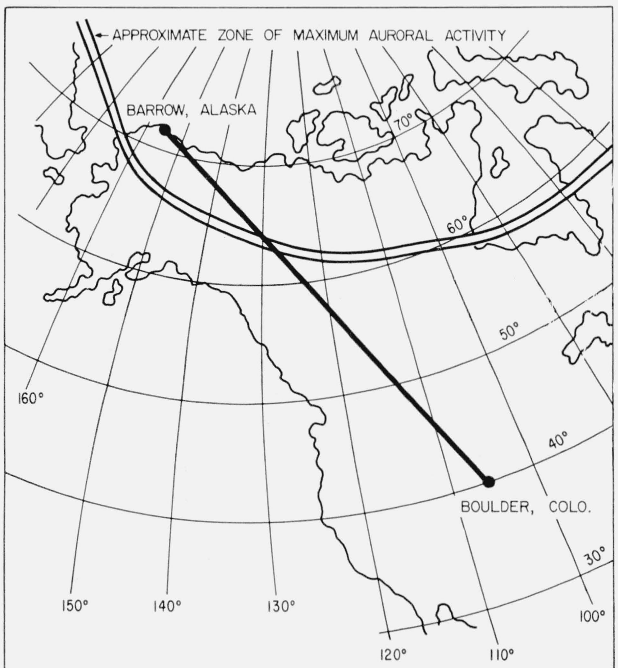


Figure 1. *Geographic locations of transmitter and receiver stations.*

the geographic location of the path relative to the undisturbed auroral Zone. A discription of the transmitting and receiving equipment is given in appendix A. The phase stability recording and analysis equipment is discussed in appendix B.

3. Phase Stability Characteristics

Regardless of the number of multipath components present in samples of the received wave, if the ionosphere is essentially fixed in characteristics and in space over the sampling interval time, there will be no phase perturbation from one sample to the next. However, movements of irregularities and of the regular layers in the ionosphere, as well as changes in ionization along the path, will cause changes in phase path lengths of the various received components and in the interference pattern between the components. Since the ionosphere is constantly in motion, and especially so in the auroral regions, it is logical to assume that phase perturbations will increase with the number of multipath components present in the samples. Therefore, one might conclude that the phase stability would be better for short pulses than for continuous wave signals, with phase sampling intervals equivalent to the pulse repetition intervals. However, if one arriving mode is much stronger than others, the pulse-to-pulse and continuous wave phase stabilities would be the same; likewise, if all of the important modes contribute energy during a received pulse period, the pulse-to-pulse phase stability is not likely to be much better than continuous wave phase stability. If pulses are used which are short enough to isolate the various multipath components, and then phase comparisons made for successive pulses of each of the most stable modes, an improvement over continuous wave phase stability should result during periods when a number of multipath components are present.

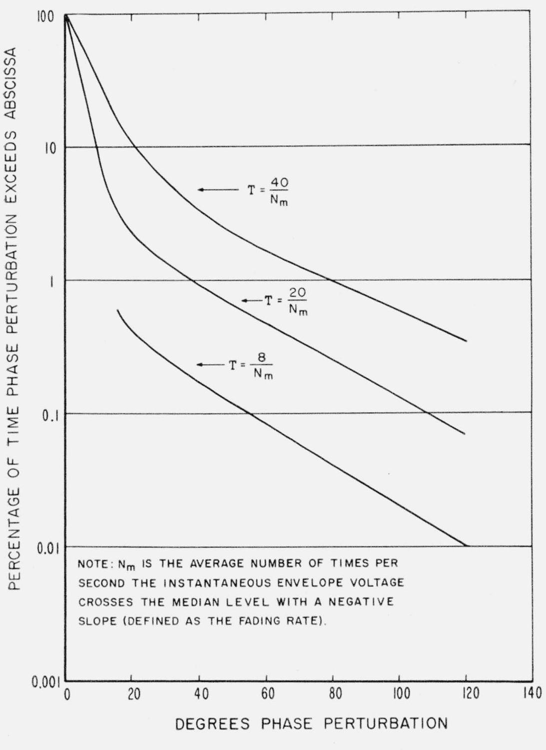


FIGURE 2. *Theoretical distributions of phase perturbations for fading CW signals for various length sampling intervals in milliseconds.*

3.1. Theoretical Distribution of Phase Varitaions

In the case of Rayleigh distributed fading of a continuous wave carrier envelope, and with the assumption of a normal-law power spectrum of the fading carrier, one may derive theoretical probability distributions of carrier phase perturbations for various length sampling intervals and fading speeds from the work of Bramley [1951] and Voelcker [1960]. The expression

$$P(|\Delta\phi|\geq\phi_i)=1-\frac{1}{\pi}\left[\phi_i+R\,\frac{\sin\phi_i\cos^{-1}(-R\,\cos\phi_i)}{(1-R^2\cos^2\phi_i)^{\frac{1}{2}}}\right],$$

obtained by integrating the expression given by Bramley [1951] for the probability density function of phase variations, is plotted on figure 2; R, the envelope of the normalized autocorrelation function of the fading carrier, is given by the expression,

$$R=\exp-(3.03N_mT10^{-3})^2.$$

In the last expression N_m is the number of times per second the envelope voltage of the fading carrier crosses the median level with a negative slope, and T is the time interval in milliseconds between sampling points. Admittedly, the envelope distribution of fading HF waves may depart considerably from a Rayleigh distribution [Koch and Petrie, 1961]; much of the time the distributions approach those for the sum of a specular component and randomly varying components. In the latter case, the phase variations should be less than those indicated by figure 2.

3.2. Observed Phase Perturbations of CW Carriers

Observations of phase perturbations of the received continuous wave carriers were carried out in December 1959 and in February and April 1960. These observations have been analyzed to obtain statistics on phase stability of the propagating medium between sampling points separated by various length intervals.

Sample distributions of phase perturbations of the received carrier is plotted in figure 3 for phase sampling intervals spaced from 1 to 20 msec. All distributions are for a 200-sec sample of the received signal. Figure 4 shows distributions of phase

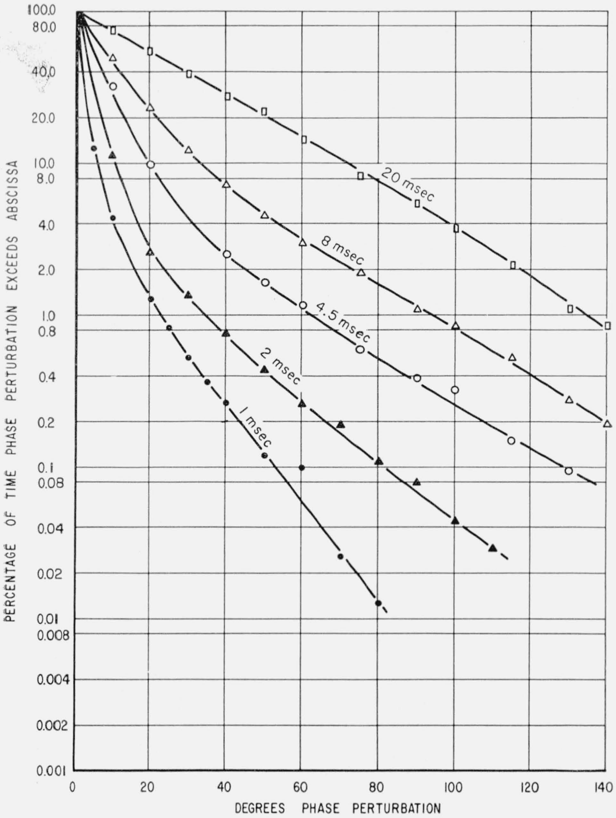


FIGURE 3. *Distributions of CW carrier phase perturbation between various length sampling intervals.*

Sampling period 200 sec
IF bandwidth 800 c/s (−6 db)
Median carrier-to-noise ratio 33 db
Average fading rate 7 c/s
19.247 Mc/s, April 25, 1960; 1456 MST

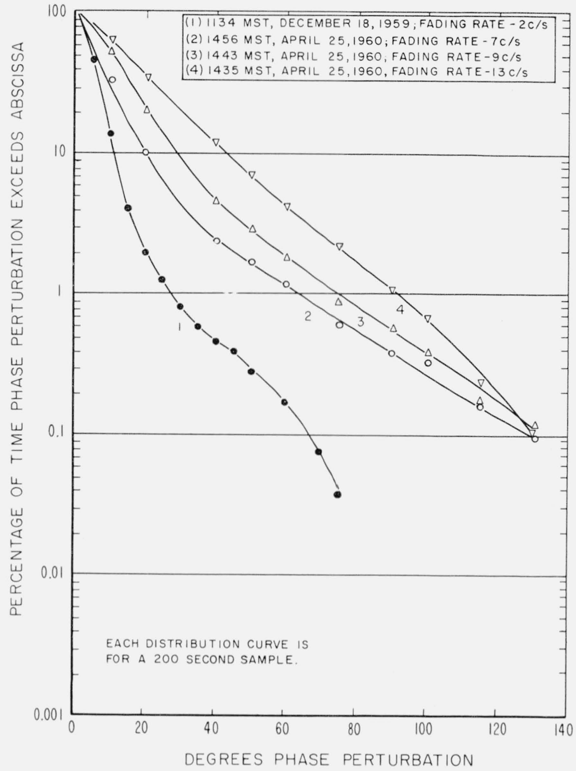


FIGURE 4. *Typical phase stability of 19.247 Mc/s CW signals between successive sampling points at 4.5 msec intervals for various fading rates.*

perturbations for different fading rates, all at a sampling interval length of 4.5 msec. Phase stability was, in general, a function of the fading rate, as might be expected. However, for 1 msec sampling intervals, figure 5, there appears to be very little change of phase perturbations as the observed fading rate increases above 2 c/s. The Rayleigh-fading model discussed in 3.1 compares closely with the experimental distributions only in a limited number of cases and does not explain the observations for 1 msec sampling intervals. The statistical model of a relatively constant vector plus a Rayleigh distributed vector for fast fading conditions suggested as a possible explanation for reduced depth of fading at these times [Koch and Petrie, 1961] might also be used here to explain the relatively small change of phase perturbations for very short sampling intervals as the fading rate increases. For the same fading rate there appears to be no significant difference in the distribution of phase perturbation at the various frequencies observed. It should be noted, however, that the probability of occurrence of specific fading rates is dependent upon the observed frequency [Koch and Petrie, 1961] and, therefore, the expected phase perturbations do exhibit some frequency dependence.

3.3. Observed Pulse-to-Pulse Phase Perturbations

Observations of pulse-to-pulse phase stability were carried out from June 20, 1960 through July 2, 1960. Interference from other stations was especially troublesome during this period, and much of the data had to be discarded for that reason. Reliable detection of rapid propagation-induced phase perturbations of a fading signal makes necessary a relatively low level of interference and noise. The data presented here were obtained during late afternoon and early evening hours when interference was not present at the 14.688 and 19.247 Mc/s frequencies. No reliable data were obtained at the 9.9475 Mc/s frequency.

a. Oscillograms of Pulses

Some oscillograms of typical pulse waveforms, at the 10 kc/s receiver outputs, are shown on figure 6. Oscillograms (a) through (g) were obtained at the 19.247 Mc/s frequency from 1848 to 1950 hours MST on June 28, 1960. The rapidly changing multipath conditions are evident for this period; at times there is little evidence of multipath components, and at other times multipath components are obvious within and following the main pulses. Since each of these oscillograms represent a single sweep of the oscilloscope, the changing conditions from one pulse to the next may be observed. It would appear that,

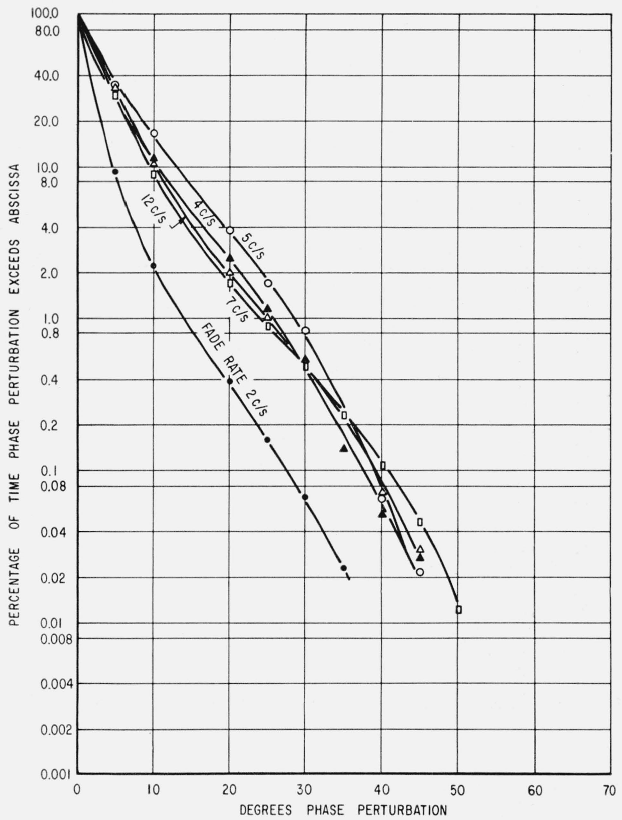
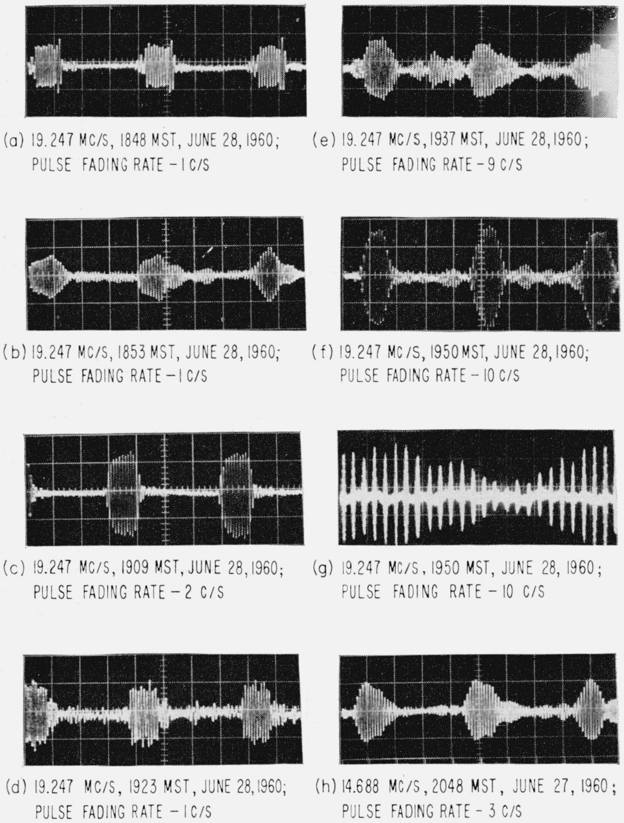


FIGURE 5. *Phase perturbations between 1 msec sampling points for various average fading rates (CW carrier).*

Sampling period 200 sec
If bandwidth 800 c/s (−6 db)
Median carrier-to-noise ratio 22 to 37 db
14.688 Mc/s, December 1959; midday



NOTE:
ALL OSCILLOGRAMS EXCEPT (g) HAVE SWEEP–TIME OF ONE MILLISECOND PER MAJOR SCALE DIVISION;
OSCILLOGRAM (g) HAS SWEEP TIME OF TEN MILLISECONDS PER MAJOR SCALE DIVISION.

FIGURE 6. *Single-sweep oscillograms of received 1 msec pulses.*

Note: All oscillograms except (g) have sweeptime of 1 msec per major scale division;
Oscillogram (g) has sweeptime of 10 msec per major scale division.

at times, multipath effects are quite variable for successive pulses, and hence pulse-to-pulse phase perturbations would be quite significant part of the time.

b. Distribution of Pulse-to-Pulse Phase Perturbations

Distributions of phase perturbations of the received pulse signals were obtained for data samples of 200 sec in length. Sample results of the 19.247 Mc/s observations of pulse-to-pulse phase stability for good signal-to-noise ratios are given in figure 7 for several different pulse fading rates. The median pulse signal-to-noise ratios were 16 to 24 db for these observations. The results at 14.688 Mc/s showed no significant difference for comparable fading rates.

Sweep-frequency oblique-incidence ionograms, obtained by Tveten [1960] on the Barrow-Boulder path near the times when pulse phase stability observations were made indicated that at all times multipath components arrived with a delay of about 100 μsec with respect to the first received component, and only occasionally did significant multipath components arrive with a delay that exceeded 1 msec at either of the two frequencies used for phase observations. Transmitted pulses of the sweep-frequency equipment were 100 μsec in width. Careful examination of the sweep-frequency records and the phase observations indicated that at certain times when a number of discrete multipath components were observable on the ionograms (all within one millisecond delay), the phase perturbations were less than at other times when the received sweep-frequency pulses were simply smeared out to 200 μsec in width. Thus it would appear that the most significant short interval phase perturbations on this path are a function of very rapid moving ionospheric irregularities. This observation also indicates that the occurrence of many multipath components does not itself produce phase perturbation.

3.4. Comparison of Continuous Wave and Pulse-to-Pulse Phase Stability

From the discussion in the previous section, one surmises that most of the multipath components causing large phase perturbations over short time intervals were well within a delay of 1 msec with respect to the first arriving component. It might, therefore, be expected that the pulse-to-pulse stability with 1-msec pulses, and continuous wave

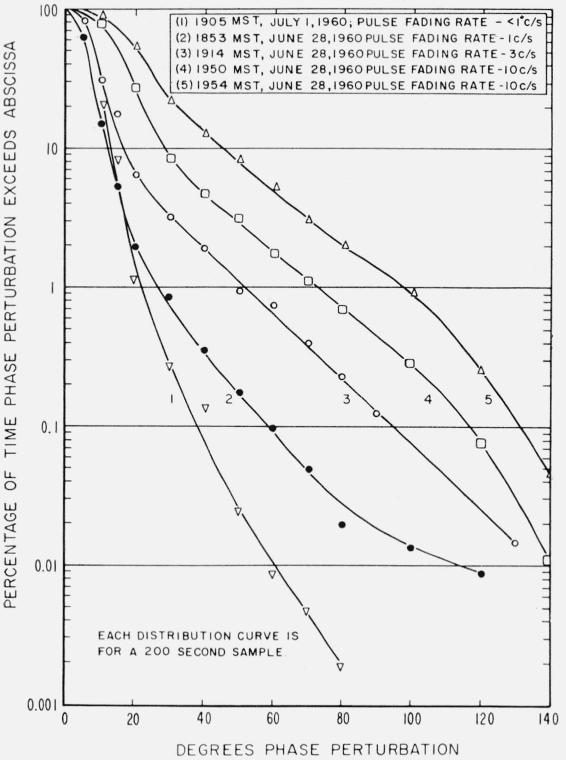


FIGURE 7. *Typical pulse-to-pulse phase stability at 19.247 Mc/s for various fading rates.*

phase stability for sampling intervals equivalent to the pulse repetition interval, would not be appreciably different. Comparison of figure 7 with figure 4 does, in fact, indicate that for approximately 4-msec sampling intervals and comparable fading speeds, pulse-to-pulse and continuous wave phase perturbations are not significantly different on this path.

4. Conclusions

The statistics derived from the phase stability observation show an expected correlation with fading rate for the 4.5 msec sampling interval, but are relatively uncorrelated with fading rate changes above 2 c/s for the 1 msec sampling interval on this auroral path. The observed phase perturbations are not adequately described by the Rayleigh-fading model a large part of the time. The probability of occurrence of large phase perturbation are less for the experimental distributions that predicted from the Rayleigh-fading model. The experimental distributions approach the distribution that would be obtained if the received signal consisted of the sum of a specular component and randomly varying components. The theoretical distribution derived from the Rayleigh fading model can be used to bound the actual phase perturbation distributions, that is, the probability of occurrence of a specific phase perturbation should not exceed the value given by the Rayleigh-fading model.

Although the use of separated pulses for phase-keying applications would appear to have some merit as compared with continuous wave phase-keyed systems, there does not seem to be much advantage to the technique, as presently evolved, for an aurorally-disturbed propagation medium. The rapidly changing ionospheric characteristics cause severe phase perturbations for a small percentage of the time on the path investigation for both separated pulses and continuous wave signals. Phase-keying systems requiring 4-msec phase stability do not appear to be practical on such a path. The use of pulses much shorter than a millisecond to separate the modes, together with phase information from only the most stable modes, may provide an improvement, although this has not been investigated.

Appendix A. Transmitting and Receiving Equipment

The transmitting station was at the camp of the Artic Research Laboratory, Barrow, Alaska. Three (3) kilowatt transmitters were used with precise carrier frequency control and frequency stability to better than one part in 10^8 per day. A quarter-wave vertical antenna and radio wire groundplane were used with each transmitter.

For the continuous wave observations, the transmitters were operated without modulation. For the pulse-to-pulse phase observations, the radio frequency drive for the transmitters was gated "on" and "off" with a precise pulse generator. The "on" periods were 1 msec in length, with a pulse repetition frequency of 250 c/s, providing an "off" time of 3 msec between the end of one pulse and the start of the next pulse.

The receiving station was located at the NBS Table Mesa field site near Boulder, Colo. Receiving equipment consisted of high quality communication type receivers with external heterodyne oscillators. The oscillator stability was within one part in 10^8 per day. Automatic gain control (AGC) of the receivers was deactivated during phase stability observation periods. The receiver carrier frequencies were translated down to 2.5 kc/s and 10 kc/s for continuous wave and pulse-to-pulse observations, respectively. Receiving antennas consisted of half-wavelength horizontal dipoles at a height of one wavelength above the ground.

Appendix B. Phase Stability Recording and Analysis Equipment

For the continuous wave phase stability observations the receiver 2.5 kc/s output was connected to a phase detector for comparison with a precise frequency standard. The output voltage of the phase detector was recorded on frequency modulated channel of a tape recorder. Phase perturbations between various length sampling intervals, ranging from 1 to 20 msec, were analyzed from the reproduced phase detector recordings. At the beginning of each sampling interval the voltage output of the phase detector was clamped to zero reference; at the end of the sampling interval the change of the phase detector output voltage (representing the phase perturbation between the beginning and end of the interval) activated gate circuits which had threshold levels equal to or below this voltage, allowing associated decade counters to register one count. The percentage of time that the phase perturbation exceeded the phase angle associated with each threshold level is therefore registered on the respective decade counter. Calibration of the phase detector was performed before each recording, using an external oscillator and phase shifter.

For the pulse-to-pulse phase observations the received signals, translated to 10 kc/s, were recorded on magnetic tape. The signals from the magnetic tape reproducer were fed to the inputs of two channels, one of the two channels incorporating a 4-msec magnetostrictive delay line. The pulse modulated 10 kc/s outputs of the two channels were compared in a phase detector. Continuous relative phase information of the carrier for two consecutive pulses, over the 1 msec pulse periods, was provided by the phase detector. The instantaneous phase information was integrated for 1 msec periods, and the resultant integrated voltage was proportional to the integrated phase differences for the two consecutive pulses. The integrated output of the phase detector was sampled at the end of each 1 msec integrating period by amplitude discriminators for a set of decade counters. Thus, the distribution of phase perturbations between consecutive pulses was obtained from the counter indications for an observing period. Calibration of the phase detector and associated circuitry was accomplished before each analysis period with the aid of an auxiliary oscillator, adjusted precisely to the recorded carrier frequency, and a calibrated phase shifter in one of the channels.

The experimental study of phase perturbations, reported herein, was sponsored by the U. S. Air Force Wright Air Development Division, Wright-Patterson Air Force Base, Ohio. The assistance of the Arctic Research Laboratory, Office of Naval Research, Point Barrow, Alaska, is gratefully acknowledged for providing facilities and housing for transmitter operation. Special thanks are due L. H. Tveten of NBS for providing sweep-frequency ionograms, and M. Nesenbergs of NBS for integrating the theoretical probability density function of phase variations. Othe NBS personnel contributing substantially to the project include W. B. Harding, G. E. Wasson, G. G. Ax, and J. L. Workman (Barrow, Alaska).

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