Spaced antenna diversity in temperate latitude meteor burst systems operating near 40 MHz: Variation of signal cross-correlation coefficient with time

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The potential for meteor burst (MB) spaced antenna diversity is studied using cross-correlation techniques at a temperate latitude, using 37-MHz signals scattered over an 800-km path. Approximately 9 hours of data were analyzed from a 2-day period in February 1990, when the antenna separation was 10λ . The correlation variations with time of signals with durations ≥ 0.75 s, which were categorized as "underdense," "overdense," or "not known" (NK), were investigated. The cross-correlation coefficients of signals from underdense and overdense trails are high when correlated over their total signal envelopes, but this is not true when the signal envelope is segmented in time. NK signals are observed to be more uncorrelated than underdense or overdense signals and are, therefore, likely to be the most advantageous to a diversity system. Analysis of data from all three categories combined shows that 40% of signals with duration ≥ 0.75 s have correlation values of less than 0.6 after the first 0.25 s. The correlation-time dependency observed for NK and underdense signals is not identified for the overdense signal category. It is proposed that for underdense and NK signals the correlation-time dependency is due to the vector addition of other weak signal modes. These weak signal modes, however, have little effect on overdense signals which, typically, exhibit higher signal powers in the early stages of the signal envelope.

1. INTRODUCTION

It is mathematically convenient, when investigating meteor burst (MB) propagation, to assume that the incident wave has been scattered from idealized straight columns of ionization created by incoming meteors [Sugar, 1964]. Implicit in this formalization is a single, plane wave incident on the receiving antenna.

Mesospheric wind shears and turbulence can, however, significantly alter the initial shape of the trail and may, as a consequence, cause the formation of many scattering regions

(each known as a glint) [Manning *et al.*, 1952]. Glints may move independently and, consequently, each scattered signal experiences a different Doppler shift. Superposition of two or more discrete Doppler-shifted frequency components causes fading to be observed. Thus the aggregate wave-front is no longer plane and a time-dependent signal fading pattern will be observed at each of the antennas. These considerations indicate that it may be possible to exploit diversity [e.g., Schwartz *et al.*, 1966] techniques, similar to those used in the high frequency (HF) band, to enhance the performance of MB communications systems. A prerequisite for the successful implementation of diversity is the existence of uncorrelated fading on two or more receiving antennas. Under these circumstances a faded signal from one antenna may be compensated by the signal from another antenna. One method

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of obtaining uncorrelated signals is by reception on two appropriately spaced antennas (space diversity).

An investigation of MB space diversity on long-duration (~4 s) echoes was performed by Ladd [1961]. The experiment utilized a 1-kW transmitter with an operating frequency of 49 MHz, and signals were received on two antennas separated by either 22λ or 60λ (where λ is the signal wavelength). Signals were recorded and digitized using a sampling interval of 100 ms. The correlation coefficients were computed for underdense, specular overdense and nonspecular overdense signals. High correlations were observed (0.9946, 0.9819, and 0.7970, respectively), and Ladd [1961] concluded that little advantage could be gained using space diversity. However, fading periods on signals in this frequency band range typically between 100 ms and 1 s [Greenhow, 1950] and the 100 ms sampling period adopted would, therefore, have been too infrequent. The cross-correlation coefficients were also computed over complete signal durations. Similar analyses performed by Cannon *et al.* [1988] showed the correlation coefficient to be a function of signal decay time. In this latter work, high-correlation coefficients were reported at the start of the trail decay [Manning, 1959] with the coefficients decreasing towards the end of the signal lifetime. The measurement technique of Ladd [1961] was, therefore, flawed.

A cross-correlation coefficient of 0.6, or below, was adopted by Ladd [1961] as a "practical" indication of useful signal decorrelation [Staras, 1956]. Such a condition is, however, only applicable to Rayleigh fading conditions. Our studies of signal envelopes have convinced us that fading cannot always be described as Rayleigh. Interference between two, or a small number of glints (<5), resulting in a deep periodic fading envelope which approximates a rectified sine wave, is more likely than Rayleigh fading. Greenhow [1952] suggested that approximately 400 ms are required for the formation of the first glint. The applicability of the Rayleigh fading model, requiring the formation of multiple (>6) glints, is then restricted to long-enduring meteor trails. Rayleigh fading is, therefore, not generally applicable to MB diversity models. The deep periodic fading patterns resulting from two or three glints [Manning, 1959] also relies on the formation of glints each of a similar dimension. Superposition of signals from smaller scattering regions and signals from the main scattering body will cause an amplitude fluctuation as opposed to deep periodic fading.

In contrast to Ladd [1961], Bartholomé [1962] suggested that MB space diversity is a useful technique. Bartholomé [1962] performed experiments in the 38 to 41 MHz band with 400-watt transmissions using the receiver automatic gain control (AGC) voltage as a measure of the signal amplitude. The attack and decay times for these AGC measurements were 10 ms and 40 ms, respectively. An antenna separation of 4λ in a line perpendicular to the great circle path from the transmitter to the receiver was adopted. For specular reflections the diversity effect reported was small both for underdense and overdense trails. When the trails were long (>2

s), however, and wind distortion had caused several glints, quasi-independent, time-varying signals were obtained at each of the separated antennas.

The only fully developed MB communications system incorporating diversity is COMET [Bartholomé and Vogt, 1968]. The COMET system implemented space and height diversity, and signal combination was achieved using a multidetector. COMET showed a remarkably high duty cycle when compared to other MB communications systems [Cannon and Reed, 1987]. Bartholomé and Vogt [1968] believed that diversity contributed significantly to this high throughput.

In summary, the efficacy of space diversity in MB systems is unclear. MB communications systems generally provide a low average data rate, with average rates varying from a few, to generally only tens of bits per second [Cannon and Reed, 1987]. Uncorrelated signals on spaced antennas could be exploited to enhance this throughput using an appropriate diversity combiner.

Although this paper addresses meteor scatter signals, but it is also to be noted that three other sources of signal exist in the MB frequency band; namely, ionosscatter, sporadic *E* and propagation during periods of high sunspot activity via the *F2* layer. The magnitude and occurrence of signals propagated via these modes depend on mechanisms with various temporal scales and upon the radio frequency used. These other signals may add vectorially with MB signals providing the possibility of diversity gain (similar conclusions were reached by Bartholomé [1962]).

Correlation investigations of signals received on two spatially separated antennas will reveal if decorrelated signals exist which might then be exploited by MB communications systems incorporating diversity. The received signals are categorized as underdense, overdense or "not known" (NK), and the advantages of each category are examined. The "NK" category contains signals of an undefined format which may be associated with scattering from sporadic *E*, ionosscatter, or nonspecular meteor trails. Our results and conclusions apply to an 800-km, temperate latitude path at operating frequencies near 40 MHz.

2. EXPERIMENTAL TECHNIQUE

The experiment consisted of the transmission of a 37-MHz, 400-W continuous wave (cw) signal over an 800-km path. The transmitter was located in Wick, Scotland (58.56° N, 3.28° W), and signals were received at Cobbett Hill Radio Station in southern England (51.27° N, 0.63° W). To minimize the reception of sporadic *E* signals which might confuse the study of MB signals, data were collected in February 1990 when the expected occurrence frequency of these modes was at a minimum. Morning and afternoon data were collected using two antennas separated by 10λ (Table 1). This separation compares to the 22λ and 60λ antenna separation used by Ladd [1961] and the 4λ separation

TABLE 1. Timetable of Data Collected From Cobbett Hill, 1990

1990 Day Number	Data Start Time, UT	Data End Time, UT
45	1005	1107
	1111	1213
	1216	1320
	1325	1415
51	1003	1105
	1110	1213
	1217	1320
	1325	1426
	1431	1534

implemented by Bartholomé [1962]. The receiving antennas were sited in a line perpendicular to the great circle path from transmitter to the receiver. Both the transmitting and the receiving antennas were horizontally polarized four-element Yagis, mounted at a height of 1λ which provided centre path illumination at an altitude of 95 km.

The received signals from each antenna were fed, without amplification, via coaxial cable, to the receiving and signal recording system. The 100-kHz intermediate frequency output from each receiver was connected to a "logarithmic detector," which output the logarithm of the detected input signal level. Each output was recorded on a FM channel of a tape recorder in a 1.25-kHz bandwidth. The audio output from one receiver was also recorded.

Each data tape was calibrated at 28-min intervals with signals ranging in power levels from -133 dBm to -76 dBm in 3-dBm steps. These calibration levels enabled the absolute values of the signal strength to be derived. The receiving and recording equipment was located in a temperature-controlled environment to reduce thermal drift.

3. DIGITAL ANALYSIS TECHNIQUE

3.1. Data capture

Digitization, storage and analysis of the analogue-recorded signals were conducted under computer control. Signal voltages from two channels (i.e., the analogue signals recorded from the spaced antennas), were sampled by an 8-bit analogue to digital converter. The two analogue signal channels were sampled within 40 μ s of each other to approximate simultaneous sampling. The antialiasing filter was a variable low pass filter with a 48 dB per octave roll-off.

The digitized data, which represented received signal power levels in dBm, were stored on disc. The data files were displayed as signal strength (dBm, ordinate axis) against time (seconds, abscissa) for a selection of time windows. Using a vertical sliding time cursor meteor signal envelopes, above a fixed power threshold, were visually identified (detailed in section 3.3) and categorised as underdense, overdense or "not known" (NK). The cross-correlation coefficients, power statistics and signal duration data were calculated for each signal and stored to disc.

3.2. Data analysis

Data collected were digitized according to the preceding description at a channel sampling rate of 100 Hz (10 ms) and with an antialiasing filter bandwidth of 25 Hz. This sampling rate is 10 times higher than that used by Ladd [1961]. A threshold of -120 dBm (which is equivalent to a 3-dB signal to cosmic noise ratio in a 3-kHz channel) was used for signal analysis. Cross-correlation coefficients for zero lag ($\tau = 0$) were then evaluated for these signals. Since meteor decay is a nonstationary process, cross-correlation values of $|\tau| > 0$ are invalid.

The signal correlation start time for underdense and overdense signals began at the end of the trail formation phase. The end of trail formation was identified on the recorded signals by the discontinuity on the rising edge of both the underdense and overdense signal envelopes (Figure 1). Data

Fig. 1. Signal classification: a) underdense signals, b) overdense signals, and c) not known (NK) signals.

within the first 0.25 s after formation were correlated and the cross-correlation value was recorded along with the trail category. Successive signal segments of 0.25 s duration were windowed and correlated until the end of the signal decay was reached. The latter was taken to be that time when both channels fell below the analysis threshold. The signal decay period was, therefore, determined by the longer-duration channel. The decay period incorporated the important period when only one channel was above the threshold and when diversity was expected to give its greatest improvement in channel availability.

Greenhow [1950] has shown that the frequency range of deep periodic fading from meteor trails is 1-10 Hz, and a correlation analysis segment 0.25 s was, therefore, sufficient to encompass most periodic fades. Correlation values from the first 0.25 s of the signal formed the statistics for segment number 1; correlation values from the second 0.25 s of signal formed the statistics for segment number 2 and so on (Figure 1a). Signals of duration less than 0.25 s were not cross-correlated.

The distributions of signal durations examined by Ladd [1961] are not clear. It is reasonable to assume, however, that he primarily studied long-duration signals because of his limited sampling rate of only 100 ms. Consequently, in addition to time segmentation of the signal, cross-correlation analysis was also performed over the total signal decay envelope (Figure 1b). This enables our results to be compared with those obtained by Ladd [1961].

The correlation start time for NK signals was identified by the first signal crossing of the analysis threshold (Figure 1c). Otherwise, the analysis was the same as underdense and overdense signals.

Cross-correlation values for each segment were grouped together and analyzed. Implicit in this analysis technique is the assumption of an average ionization height and location. This averaging ignores the differing geometrical factors which affect the decay of meteor trails occurring within the antenna common volume.

3.3. Trail categorization

Signals were assigned to one of three signal categories: underdense, overdense or "not known" (NK) (Figure 1). A similar signal categorization was performed by Østergaard *et al.* [1985].

Signals scattered from an underdense trail are characterized by a fast (~ 0.1 s) rising increase in signal strength followed by a slower linear decay (in decibels) which starts immediately after the envelope has reached its maximum amplitude. An underdense signal is illustrated in Figure 1a where the decay duration on channel 1 is greater than channel 2 by an amount Δ . In this example a simple diversity antenna switch would effectively increase the signal duration by the amount Δt , an increase in duration which may be advantageous in a MB system.

A specular overdense signal (Figure 1b) is also characterized by a fast rising increase in signal strength until the Fresnel zone is formed. This is followed by a further period of slowly increasing signal strength, resulting in a rounded top to the received envelope, before the signal decays. Overdense decay durations and received signal strengths are usually greater than those from underdense trails. In the overdense signal example (Figure 1b) a diversity antenna switch would not increase the effective signal duration and would, therefore, not be advantageous.

Signals not of the above format were categorized as "not known" (NK). Figure 1c shows a highly uncorrelated waveform which was categorized as a NK signal. In the example we note that during the period included by the dashed vertical lines, the received power on channel 1 is above the threshold but that on channel 2 is below the threshold. A diversity antenna switch would be advantageous to a MB system for this NK signal example.

Signals which suffer from echo-overlap decorrelation [Berry *et al.*, 1961] were also categorized as NK. These echo-overlap signals occur when two trails form within the lifetime of each other and within the antenna common volume (Figure 2). Between times T_1 and T_2 a single underdense trail exists but at T_2 a second meteor trail forms. The signals scattered from the two trails add or subtract at the antennas, depending on their relative path difference, resulting in the envelopes seen in Figure 2. These trails are grouped in the NK category because of their unusual and rare nature.

Fig. 2. An example of echo overlap signal.

Figures 3a and 3b illustrate the deep periodic fading due to [Manning, *et al.*, 1952] two (or more) Doppler-shifted components beating together to produce a $\cos t$ modulation pattern. The total decay duration of the underdense signal (Figure 3a) is ~ 2.6 s. In a conventional communications system, however, this single trail might be interpreted as three shorter (< 1 s) trails because of the three deep (~ 10 dB) fades present during the signal decay. The potential data throughput from such a signal is then not fully exploited because of the time lost reestablishing the link after each signal fade. In this particular example of a fading underdense signal, diversity

Fig. 3. Deep periodic fading observed on a) underdense signal and b) overdense signal.

would not be advantageous because of the coherency of the deep fades at the two antennas. Although a similar fading pattern is observed for the overdense signal in Figure 3b, in this example there is a fade time delay between the signals recorded on the two channels. Diversity systems can exploit this fade delay by combining the signals to reduce the fade depth. The combined channel signal decay may then be used more efficiently, thereby increasing the system data throughput.

4. RESULTS: DECORRELATION WITH TIME

Correlation investigations of signals received on two spatially separated antennas will reveal if decorrelated signals exist which might then be exploited by MB communications systems incorporating diversity. The three signal categories, described earlier, are analyzed to determine which signal type provides the greatest decorrelation and hence the greater potential contribution to any diversity gain.

Preliminary space diversity studies [Cannon *et al.*, 1988] indicated a dependence of MB signal correlation value with time into the trail decay. New data are presented for three signal categories which are examined as a function of time into the signal decay envelope (i.e., segment number). A repeat of the analysis technique employed by Ladd [1961] is also attempted, based on our limited knowledge of that experiment, by investigating signal correlation values calculated over the total unsegmented signal decay envelope.

Segmented and unsegmented signal correlation values are compared.

First, we examine the distribution of signal decay durations. Signals scattered from underdense trails are, as expected, shorter (Figure 4) in decay duration than those from overdense signals. Only 15% of the underdense signals have a duration

Fig. 4. Signal duration probability curves for the three trail categories analyzed. Antenna separation is 10λ .

greater than 0.75 s; this compares to 42% for the overdense signal category. NK signals, however, experience durations more similar to overdense than underdense signals. This similarity leads us to suspect that a majority of these NK signals may be of a meteoric origin.

The time dependency of the cross-correlation value was investigated by analyzing signals of duration ≥ 0.75 s above the analysis power threshold of -120 dBm. This results in at least three 0.25 s correlation segments for each signal above the analysis threshold.

4.1. Underdense trails

Forty-nine signals of duration ≥ 0.75 s were identified as underdense from the two days of data collected. Cumulative correlation distribution values obtained from each 0.25 s signal segment (numbers 1, 2 and 3) are plotted in Figure 5, along with values calculated from the total, unsegmented, signal decay envelope.

Less than 12% of the correlation values calculated over the complete unsegmented signal decay envelope are less than 0.6 (chosen as a threshold for comparative reasons). The median and mean correlation values for the total signal envelope are 0.93 and 0.85, respectively. The former value is similar to the value of 0.9946 presented by Ladd [1961], although it is unclear if this 0.9946 value is a median or a mean. Our high correlation values obtained from the unsegmented envelope appear to support the hypothesis of Ladd [1961] that space diversity, using underdense trails, will provide little gain in MB systems. This conclusion, however, will be shown to be

Fig. 5. Cumulative correlation probability curves applicable to 49 underdense signals of duration ≥ 0.75 s.

questionable when the correlation values obtained from segmented signals are analysed.

The correlation values obtained from the unsegmented total decay envelopes have a similar cumulative correlation distribution to those values obtained from cross-correlating segment 1 (Figure 5). However, the segmented signal correlation probabilities, below the 0.6 threshold, increase from 20% for segment 1, to 35% for segments 2 and 3. We find that underdense signals exhibit a correlation-time dependency with the correlation values decreasing towards the end of signal decay.

Conclusions concerning the contribution of underdense trails to diversity, based on correlation analysis, must, therefore, account for the time-dependent nature of the correlation values observed. The conclusion drawn by Ladd [1961], that underdense trails have little to offer in regard to diversity, is only true for the first 0.25 s (segment 1) of signals lasting ≥ 0.75 s.

4.2. Overdense trails

Sixty-eight signals of duration ≥ 0.75 s were identified as signals scattered from overdense trails. Cumulative correlation distributions were evaluated for unsegmented and segmented trails and are plotted in Figure 6.

Fig. 6. Cumulative correlation probability curves applicable to 68 overdense signals of duration ≥ 0.75 s.

High correlation values are observed for the total unsegmented overdense signal decay envelope (Figure 6). Only 4% of the correlation values, calculated over unsegmented overdense signals, are less than 0.6. The median (0.95) and the mean (0.90) correlation values are similar to the 0.9819 correlation value given by Ladd [1961] for overdense trails. His conclusion that overdense trails provide little diversity advantage, therefore, appears to be confirmed. Once again, however, we find a conflict between correlation values calculated over the unsegmented signal envelope and those calculated from a segmented signal.

If we consider correlation values from segmented signals, we find that the correlation distributions for segments 1, 2 and 3 are similar (within 10%). Correlation probabilities at the 0.6 threshold level are 27%, 34% and 23% for segments 1, 2 and 3, respectively. The lack of any significant trend towards decorrelation with segment number (time) is in contrast to the time-dependent correlation values observed for underdense signals between segments 1, 2 and 3.

It is usual to attribute received signal amplitude fluctuations to perturbations of the trail by mesospheric winds. Consequently, both overdense and underdense trails would be affected identically after trail formation. The two trail types would then be expected to decorrelate within similar time scales. The contrasting time-dependent correlation results between the underdense and overdense categories suggest, however, that the amplitude fluctuation mechanism is trail-dependent. We suggest that the differences can be attributed to the typically greater received signal strengths observed from overdense trails. Received signal power analysis (Figure 7) shows that the average received power in each segment for overdense signals only changes by approximately 1-dB between segments 1 and 3. This contrasts to a 5-dB change for the underdense signal category.

We propose that meteor signal decorrelation can occur via two mechanisms. The first is concerned with the creation of secondary scattering regions attributed to mesospheric winds [Manning *et al.*, 1952] as described earlier. The second mechanism arises from weak (less than -120 dBm) signals from other modes (e.g., sporadic E and ionosscatter) which add to the received MB signal in an uncorrelated fashion at the two

Fig. 7. Average power present in the three signal categories for signals of duration ≥ 0.75 s. Antenna separation is 10λ .

antennas. The latter mode will particularly affect low-power underdense and NK signals (Figure 7). We suggest that the decreasing correlation value observed in both segments 2 and 3 for underdense signals and NK signals (discussed below) is primarily due to the second mechanism, where the weak uncorrelated signals have a significant effect on the low-power underdense and NK signals. Conversely, however, the weak uncorrelated signals have relatively little effect on the typically higher received signal power levels characteristic of overdense trails in segments 1, 2 and 3. The stronger overdense signals rely on mesospheric winds to cause the decorrelation observed in these segments and the second mechanism only contributes to signal decorrelation as the signal strength decays. It remains somewhat surprising that no trend towards decorrelation is apparent by segment 3 for the overdense signals. *Greenhow* [1952] has suggested that wind induced trail distortion is expected after 0.4 s (i.e., late into segment 2), and since our analysis covers the first 750 ms of signal decay, wind-induced signal decorrelation should be apparent. The absence of any firm trend towards overdense signal decorrelation with time might, however, be due to inadequate antenna separation.

In conclusion, the contribution to diversity from overdense trails cannot be determined by only considering the correlation values calculated over the total unsegmented signal decay envelope, and a segmented approach is required. For a 10λ antenna spacing we measure, however, no strong tendency towards decorrelation with time.

Due to the different correlation-time dependency results between underdense and overdense signals, it is considered unwise to combine the correlation data from the underdense and overdense signal categories to increase trail statistics. The preliminary results of *Cannon et al* [1988] were in error in this regard.

4.3 NK signals

The NK signal category, as well as containing ionosscatter and sporadic *E* signals, also contains signals of meteoric origin, for example, echo overlap trails, and scattered signals which do not exhibit the characteristic fast rise-time necessary to identify the other two categories. The 112 NK signals, of duration ≥ 0.75 s are, on average, of a lower received power than the other two signal categories (Figure 7), for all three signal segments analyzed. Significant decorrelation is, therefore, anticipated for all three segments and for the total signal envelope.

The cumulative cross-correlation distribution for the total unsegmented NK signal duration shows that 45% of the signals exhibit correlation values of less than 0.6 (Figure 8). The median and mean values are 0.66 and 0.52, respectively. A comparison of the cumulative distribution curves from the three signal categories (Figures 5, 6, and 8) indicates that NK signals are generally less correlated than either underdense or overdense signals.

Fig 8. Cumulative correlation probability curves applicable to 112 Not Known signals of duration ≥ 0.75 s.

NK signals exhibit a trend toward decorrelation with increasing segment number (time). For segment 1, 28% of the correlation values are below 0.6, and this cumulative probability increases to approximately 48% for segments 2 and 3.

4.4 Underdense, overdense and NK signals

Table 2 summarizes the decorrelation probabilities at the 0.6 correlation threshold for overdense, underdense and NK signals when the separation between the antennas is 10λ .

Although it is useful to categorize the received signals in order to clarify the fading mechanisms, a MB communications system cannot distinguish between overdense, underdense, and NK signals. Consequently, we combined together all the correlation values from the three different signal categories. Cumulative distribution curves for correlation values calculated over total signal envelopes, and those calculated for segments 1, 2, and 3 are presented in Figure 9. Approximately 25% of the signals in segment 1 have correlation values less than 0.6, this probability increases to approximately 40% for segments 2 and 3.

Correlation values from the unsegmented signal envelopes are comparable to those values obtained from segment 1. Approximately 25% of unsegmented signals have correlation values of less than 0.6. The unsegmented correlation values, which have a median of 0.84 and mean of 0.7, are again recognized to be misleading.

TABLE 2. Probabilities of Obtaining Cross-Correlation Values Less Than 0.6

Trail Category	Cumulative Probability at the 0.6 Correlation Threshold			
	Segment 1	Segment 2	Segment 3	Total Decay Envelope
Underdense	18.4	36.7	36.7	12.2
Overdense	26.5	33.8	22.1	2.94
Not Known (NK)	26.8	48.2	49.3	44.6

Fig. 9. Cumulative correlation probability curves applicable to all received signals of duration ≥ 0.75 s. Antenna separation is 10λ .

5. SUMMARY

This paper has investigated the cross-correlation coefficients of signals scattered at 37 MHz and received on two antennas separated by 10λ . Three signal categories were identified, and the signals were cross-correlated over their total decaying envelopes using a technique similar to that used by Ladd [1961]. The signals were also cross-correlated over 0.25 s signal segments using the segmentation process favoured by Cannon *et al.* [1988]. All of the following conclusions relate to signals of duration ≥ 0.75 s, but essentially similar conclusions regarding the temporal evolution of the signal decorrelation are expected for signals of shorter duration.

Conclusions based on the total decay envelope correlation method used by Ladd [1961] have been shown to be misleading. Correlation values obtained using this technique are high and similar to those correlation values obtained over segment 1 using the signal segmentation analysis method. The unsegmented total decay correlation values are dominated by the time decaying signal envelope assuming that the perturbation to the decaying signal envelope, by multipath, is small.

Underdense and NK signals become more decorrelated with increasing segment number (i.e., time). This trend towards decorrelation is not detected in the overdense signal category. It is suggested that the correlation-time dependency is partly a result of the relatively low-power underdense and NK signals combining with other weak signal modes. These weak modes, however, have little effect on the overdense signals which are, typically, of higher received power.

Comparative studies between the three signal categories over the three correlation segments show that NK signals are significantly more decorrelated, on average, than either underdense or overdense signals. NK signals, therefore, promise the greater diversity advantage. When all the received signals were combined together to model signals received by a MB system, 40% of the signals of duration ≥ 0.75 s experience correlation values of less than 0.6 in segments 2 and 3.

During the period of this experiment, relatively little sporadic E propagation occurred. The proportion of NK signals might be expected to increase during summer solstice periods when the incidence of sporadic E peaks. A diurnal diversity gain variation would also be expected at that time. An important caveat to this work relates to the geographical latitude of the experiment. At high latitudes in particular, where anomalous propagation modes are more common, different conclusions may be obtained.

In regard to the conflicting conclusions in the literature regarding the advantages of space diversity, we have shown that the high correlation values calculated by Ladd [1961] were due to measurements based upon signals analyzed as a whole. That author should have segmented the signal to derive results similar to those presented here, which substantiate the views of Bartholomé [1962] and Bartholomé and Vogt [1968].

We also draw the reader's attention to the work of Staras [1956], which contributed to the conclusions of Ladd [1961], concerning the degree of decorrelation required before the signals are considered to be useful in a diversity system. The theoretical basis of the calculations is the joint probability density function of two Rayleigh fading channels which is often not applicable to the MB channel.

In conclusion, the results presented in this paper suggest that space diversity may be advantageous, especially when signals propagate via NK trails. A diversity contribution can, however, also be expected from overdense and underdense trails, particularly towards the end of their trail lifetimes when significant decorrelation occurs.

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