Radio Science, Volume 28, Number 2, Pages 203–212, March–April 1993

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

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(Received July 23, 1991; revised July 13, 1992; accepted July 15, 1992.)

We have studied 37-MHz signals received over an 800-km temperate latitude path using 400-W continuous wave transmissions. Signals collected during a 9-day period in February 1990 on two antennas at separations of 5λ, 10λ, and 20λ were analyzed. Three signal categories were identified (overdense, underdense, and not known (NK)) and cross-correlation coefficients between the signals received by the two antennas were calculated for each signal category. No spatial variation, and in particular no decrease, in average cross-correlation coefficient was observed for underdense or NK signals as the antenna spacing was increased from 5λ to 20λ. At each antenna separation the cross-correlation coefficients of these two categories were strongly dependent on time. Overdense signals, however, showed no cross-correlation time dependency at 5λ and 10λ, but there was a strong time dependency at 20λ. Recommendations are made in regard to the optimum antenna spacing for a meteor burst communication system using spaced antenna diversity. Our measurements support the views of *Bartholomé and Vogt* [1968], who suggested that a 4λ spaced antenna diversity configuration contributed to the exceptional signal throughput of the COMET meteor burst communication system.

INTRODUCTION

Diversity is a well-accepted technique for improving the communications performance of high frequency (HF) communications systems which are often subjected to fading signals. Diversity relies on the acquisition of statistically independent samples of the channel which, when combined using a variety of techniques [e.g. *Schwartz et al.*, 1966], reduce the magnitude of the fade. One method of achieving the necessary decorrelated signals is by reception on spaced antennas. The application of diversity techniques in meteor burst (MB) communications systems has also been suggested [*Bartholomé*, 1962] as a way of overcoming intratrail fading.

Paper number 92RS02454.
0048-6604/93/92RS-02454$08.00

Multiple scattering regions, or glints [*Manning*, 1959] associated with long-lived meteor trails can serve as decorrelated signal sources which add with varying phase relationships at appropriately spaced antennas [*Manning et al.*,1952]. Other propagation modes, such as ionoscatter or sporadic *E* [*Bartholomé*, 1962 and *Shukla et al.*,1992] may also contribute a decorrelated signal at the spaced antennas. *Shukla et al.* [1992] have noted that the relative amplitude of the received signal, with reference to other weak uncorrelated signals is important in interpreting MB-spaced antenna signal correlation measurements.

MB-spaced antenna signal correlation measurements have been undertaken by a number of authors [e.g. *Ladd*, 1961; *Bartholomé*, 1962; *Shukla et al.*, 1992]. Furthermore, a spaced antenna diversity scheme has been incorporated by *Bartholomé and Vogt* [1968] in a MB communications system known as COMET, which had a remarkably high data throughput [*Cannon and Reed*, 1987]. Although *Bartholomé and Vogt*

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

1990 Day Number	Start Time UT	End Time UT	Antenna Spacing, λ
44	0926	1602	5
45	1005	1415	10
46	1019	1541	20
47	1000	1427	20
51	1003	1534	10
52	0950	1411	5

[1968] believed that the excellent system performance of COMET was primarily due to its multiple diversity schemes, the enhancement due to each of the schemes, one of which was spaced antenna diversity, was never quantified.

It is useful to review briefly the conflicting results of the MB diversity experiments performed by *Ladd* [1961] and *Bartholomé* [1962]. The experiment of *Ladd* [1961] consisted of a 1-kW transmitter operating at 35-MHz. Signals were received at two antennas separated by either 22λ or 60λ. The correlation coefficients computed for underdense, specular overdense and nonspecular overdense signals received on spaced antennas were 0.9946, 0.9819 and 0.7970, respectively, (although *Ladd* [1961] did not specify whether these values applied to 22λ or 60λ). Consequently, *Ladd* [1961] concluded that there was little advantage in using space diversity. Other work by *Manning* [1959] and *Landmark* [1958] suggests that even larger separations (>60λ) may be required to obtain signal decorrelation. *Bartholomé* [1962], who used a smaller 4λ antenna spacing (at ~40-MHz), disagreed with the conclusions of *Ladd* [1961]. When trail durations were long (>2 s) and wind distortion had led to the creation of several glints, quasi-independent time varying signal fields, implying diversity gain, were obtained at each of the separated antennas.

The conclusions of *Ladd* [1961] and *Bartholomé* [1962] are clearly in disagreement regarding the decorrelation of MB signals received at spaced antennas. Recent work by *Shukla et al.* [1992] has, however, resolved the contradictory results. These experiments consisted of 37-MHz continuous wave transmissions over an 800-km path. The signals were received on two antennas separated by 10λ, in a line perpendicular to the great circle path, a separation which is to be compared to the 22λ and 60λ spacings investigated by *Ladd* [1961] and the 4λ separation implemented by *Bartholomé* [1962]. The received signals, of duration ≥0.75 s, were categorized as "underdense," "overdense" or "not known" (NK) and cross-correlation coefficients were examined for each category as a function of elapsed time after the start of the signal. The NK category is discussed more fully by *Shukla et al.* [1992] but contains all signals which are clearly not underdense or overdense. As such, it includes nonspecular overdense signals and sporadic *E* signals.

For underdense and NK signals, *Shukla et al.* [1992] reported that the signal cross-correlation coefficients decreased with elapsed time. A similar trend was not apparent for the overdense signal category. This correlation-time dependency was not identified by *Ladd* [1961] who analyzed signals over the total decay signal envelope and obtained the high correlation values mentioned above. Comparative studies between the three signal categories analyzed by *Shukla et al.* [1992] also showed that the NK signals were, on average, significantly more decorrelated than either underdense or overdense signals. It was concluded, therefore, that NK signals promise the greater diversity advantage. When all the signal categories were combined, ~40 % of the signals of duration ≥0.75 s experienced a correlation coefficient of < 0.6 after the first 0.25 s. (This correlation threshold corresponds to "useful" diversity gain under Rayleigh fading conditions [*Staras*, 1956]; it was also chosen as a reference value even when Rayleigh fading conditions did not apply).

In summary the recent results of *Shukla et al.* [1992] supported the view expressed by *Bartholomé* [1962] that diversity might be advantageous. Furthermore, *Shukla et al.* [1992] showed that it is important to consider the cross-correlation coefficients of small signal segments rather than the cross-correlation of signals over the entire signal envelope. The segmented signal approach was not adopted by *Ladd* [1961].

Having concluded that the signals received on spaced antennas are decorrelated over part of the signal envelope it is necessary to identify, for practical purposes, the "optimum" antenna spacing. As the amount of land required for the deployment of a MB spaced antenna diversity system is an important consideration when operating MB systems at relatively low frequencies between 30-50 MHz, the optimum antenna spacing is considered to be the minimum spacing that results in signal decorrelation coefficients of <0.6. None of the three studies referred to above addressed the diversity question in this way, and the optimum antenna spacing required to obtain adequate diversity remains, therefore, unanswered.

This paper determines, using cross-correlation analysis techniques, the optimum antenna spacing required for a MB space diversity system operating close to 40 MHz and at temperate latitudes. Recommendations are made concerning the optimum antenna spacing for three signal categories, i.e., underdense, overdense, and not known (NK).

EXPERIMENTAL CONFIGURATION AND ANALYSIS TECHNIQUE

The experimental configuration and the analysis technique have already been described in detail by *Shukla et al.* [1992] but are summarized here. Continuous wave 37-MHz signals were transmitted over an 800-km path from Wick, Scotland (58.56° N, 3.28° W) to Cobbett Hill Radio Station in Southern England (51.27° N, 0.63° W). Both the transmitting and receiving antennas were horizontally polarized 4-element yagis, mounted at a height of 1λ which is suitable for center path illumination at an altitude of 95-km. The transmitter power was 400-W. The two receiving antennas were sited in a

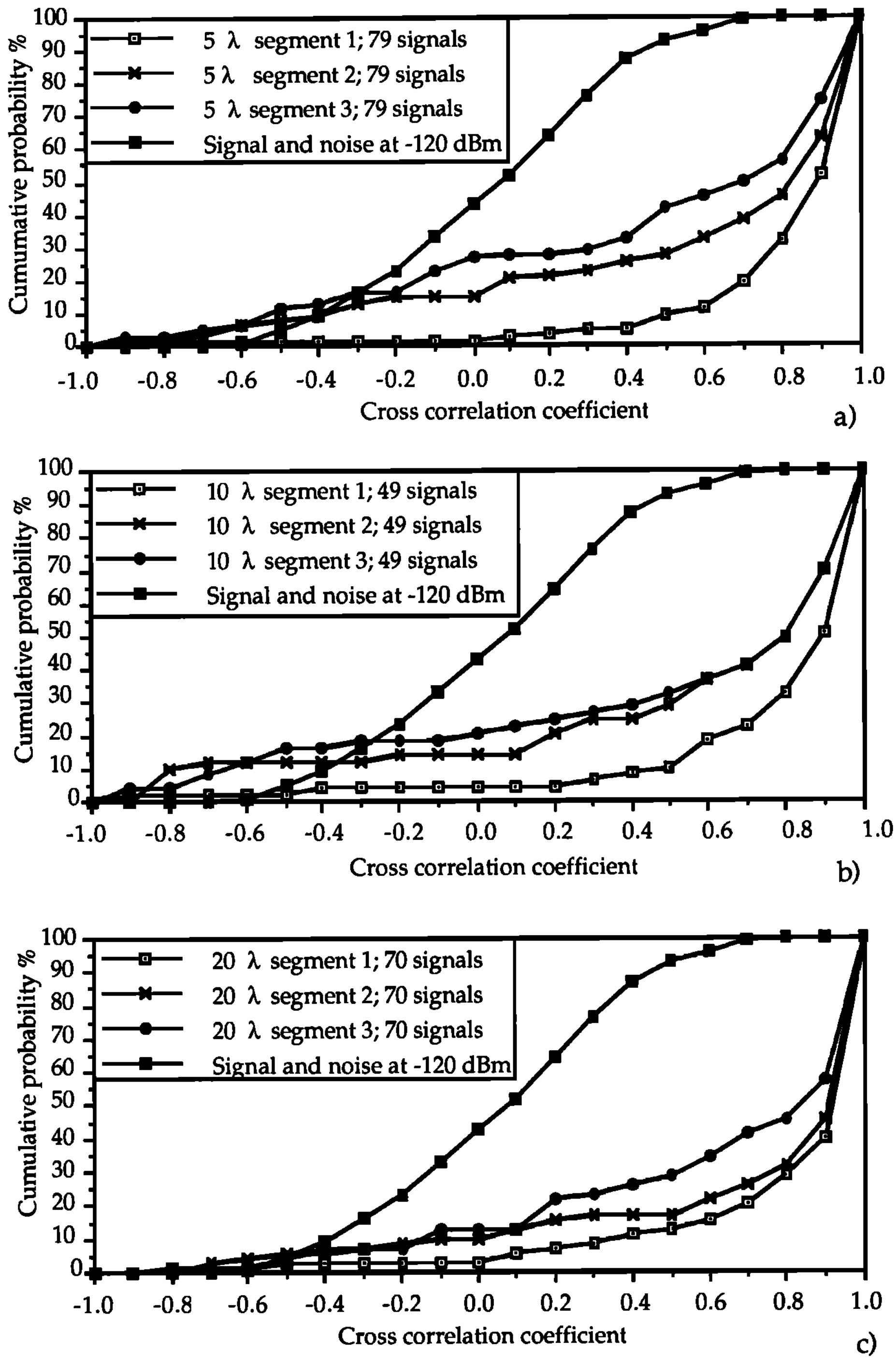

Fig. 1. Cumulative correlation probability curves applicable to underdense trails for segments 1, 2, and 3 at antenna separations of (a) 5λ, (b) 10λ, and (c) 20λ.

line perpendicular to the great circle path from transmitter to the receiver and the two outputs from the receiving system were recorded on an FM tape recorder for off line analysis. The experiment was performed in February 1990, when the incidence of sporadic E was expected to be low and morning and afternoon data were collected for three different antenna separations; 5λ, 10λ, and 20λ (Table 1).

A computer was employed to control the digitization of the analogue signals and to analyze those data. The two 25-Hz band limited signals from the dual channel recording system were sampled at 100-Hz by an 8-bit analogue to digital converter. Only signals above a minimum signal power analysis threshold of -120 dBm (which translates to a 3-dB signal-to-noise ratio in a 3-kHz channel, a typical communications system bandwidth) were analyzed.

Signals above the analysis threshold were categorized, by eye, as overdense, underdense, or NK prior to correlation analysis [*Shukla et al.* 1992]. Data within the first 0.25-s of formation were correlated, and the cross-correlation value recorded along with the trail category. Successive 0.25-s segments were windowed, and each segment was cross correlated until the end of the signal was reached. The latter is taken to be that time when both channels fall below the preset analysis threshold. The decay period is, therefore, determined by the longer duration channel. Correlation values from the first 0.25-s analysis period form the statistics for segment number 1, correlation values from the second 0.25-s analysis period form the statistics for segment number 2, and so on. Trails of duration less than 0.75-s were not analyzed.

RESULTS: SPATIAL CORRELATION VARIATION

The spatial variation of correlation values is investigated in order to determine whether signals from two antennas, separated by a few wavelengths are sufficiently decorrelated and, therefore, likely to provide diversity gain. The optimum antenna spacing for each signal category and for a MB diversity system is addressed. As a necessary part of this study the variation of correlation values with time for an antenna spacing of 10λ [*Shukla et al.*, 1992], are compared to signal correlation values obtained for 5λ and 20λ.

The effects of noise on the cross-correlation process has also been estimated and is illustrated on the cumulative probability density figures. This signal plus noise reference curve was derived by injecting CW signals from a local transmitter, at the minimum acceptable signal threshold of -120-dBm, into the two antennas. The inphase signals and approximately out-of-phase noise signals were subsequently cross correlated. The cumulative distribution from the three hundred 0.25-s segments is illustrated; the short 0.25-s window imposes a distribution of values about zero.

Underdense signals

For each antenna separation a number of signals were identified and assigned a category; underdense, overdense, and NK. At 5λ, 10λ, and 20λ, 79, 49, and 70 signals respectively, of duration ≥0.75 s, and above the -120-dBm threshold were identified as underdense. Cumulative correlation distribution values, for these underdense signals, are plotted for the three 0.25-s segments at each antenna spacing in Figure 1.

At each antenna spacing, signal correlation values were found to decrease as a function of increasing segment number. At the 5λ spacing, for example, the number of signals experiencing correlation values less than 0.6 increased (Figure 2) from 12% in segment 1, to 32% and 46% in segments 2 and 3. These results confirm those obtained for a 10λ

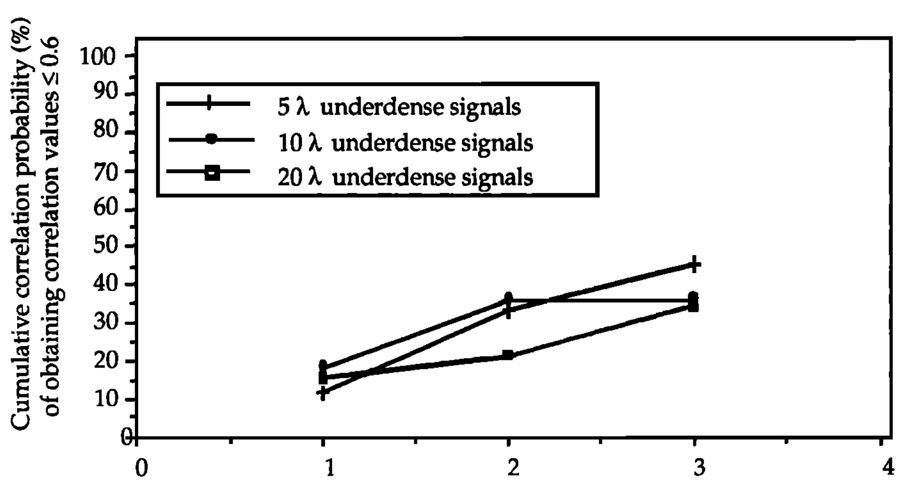

Fig. 2. Probability of obtaining correlation values of less than 0.6 for underdense signals at 5λ, 10λ, and 20λ for segments 1, 2, and 3.

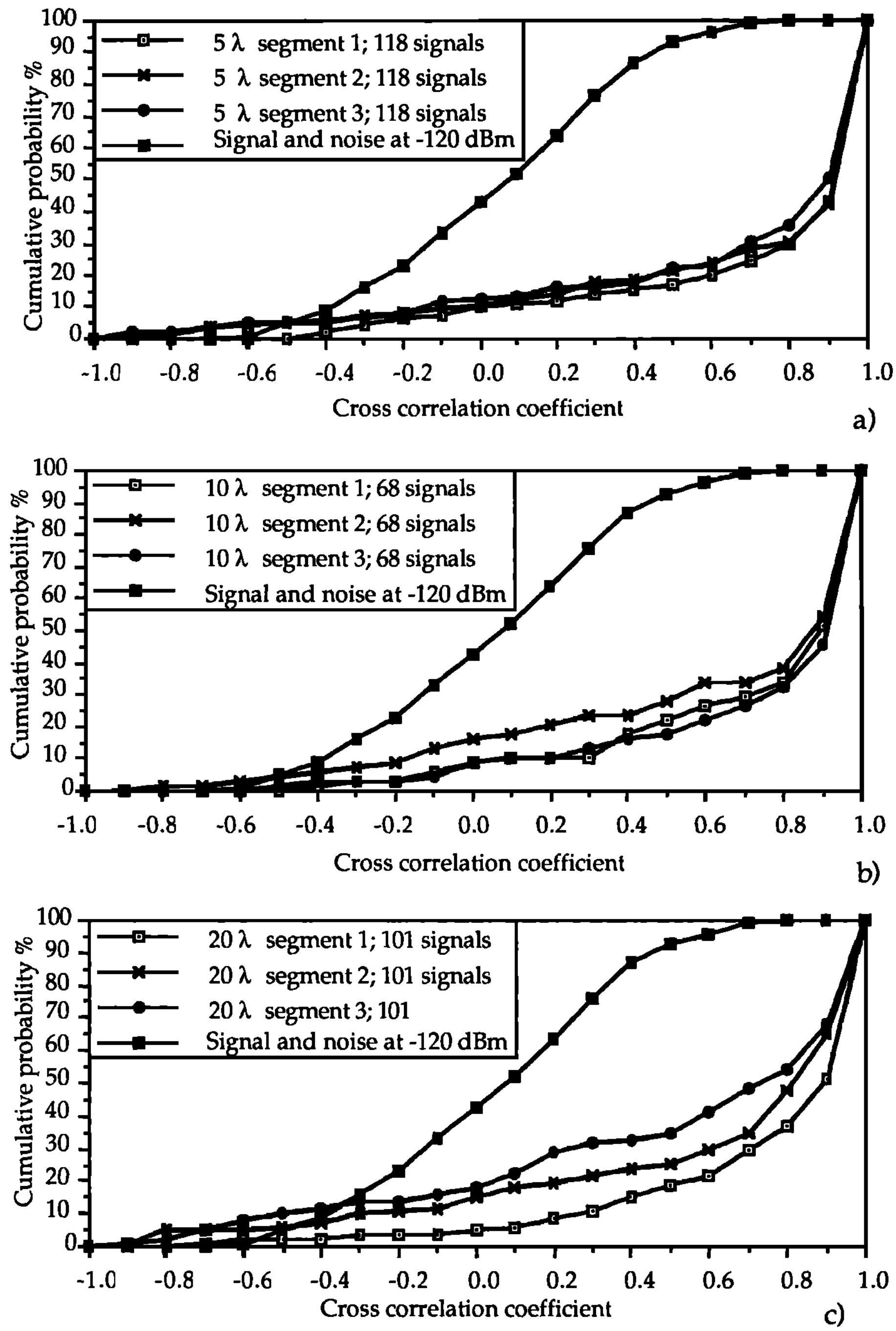

Fig. 3. Cumulative correlation probability curves applicable to overdense trails for segments 1, 2, and 3 at antenna separations of (a) 5λ, (b) 10λ, and (c) 20λ.

separation [*Shukla et al*, 1992]. No clearly favorable antenna spacing is observable (Figure 1) for the reception of decorrelated underdense signals, nor is there any systematic trend relating decorrelation and antenna spacing. Taking the 0.6 level as illustrative (Figure 2), it is seen that signals for a 10λ spacing are less correlated than those for 20λ. It is further observed that the 5λ correlation values straddle the other two curves.

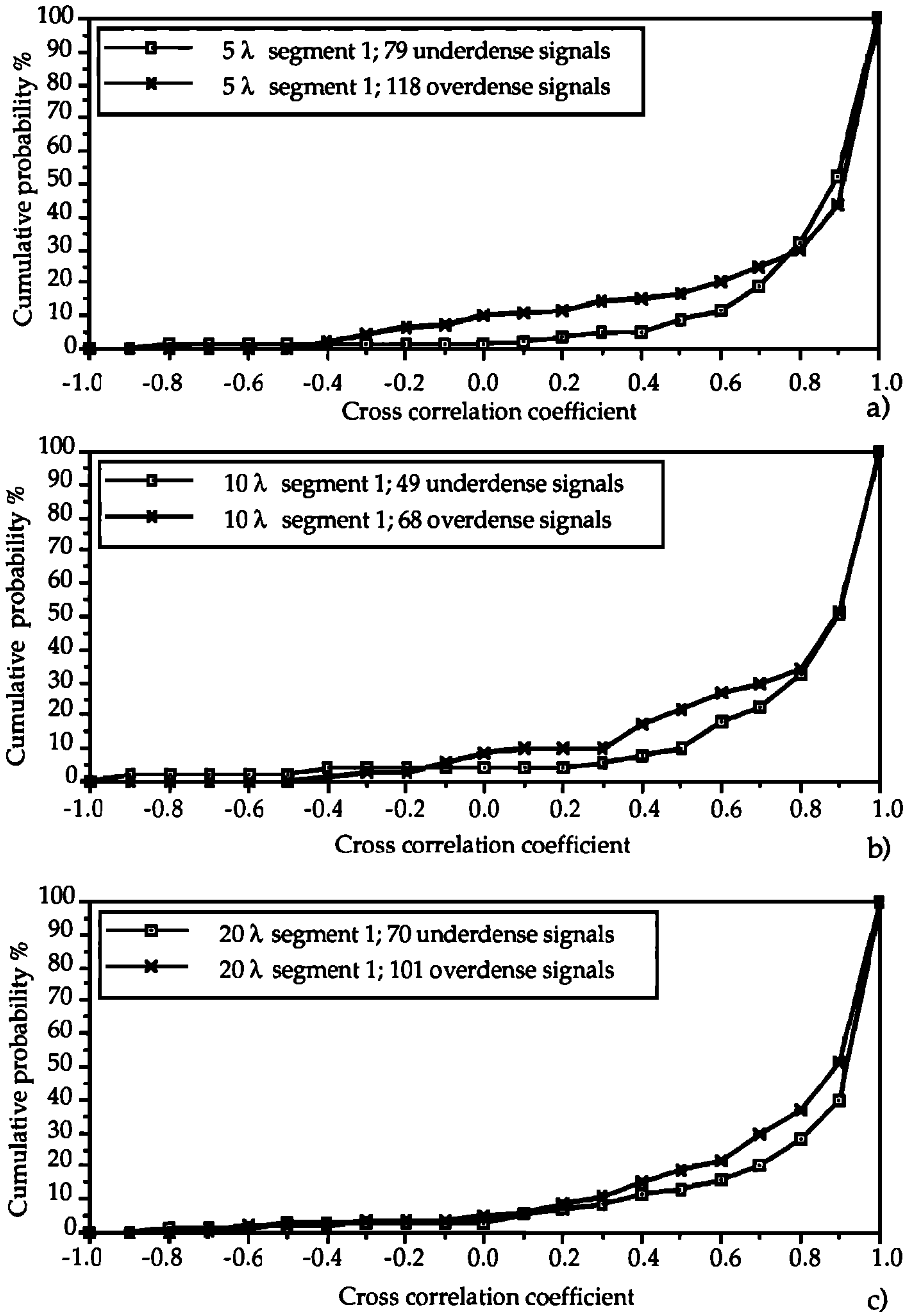

Fig. 4. Comparison of cumulative correlation probabilities for overdense and underdense signals at the three antenna spacings for segment 1.

Overdense signals

At 5λ, 10λ, and 20λ the number of overdense signals with durations above 0.75-s were 118, 68, and 101, respectively. The cumulative correlation distribution values are plotted for the three segments at each antenna separation in Figure 3. Early in signal decay lifetimes (i.e., segment 1), overdense signals are more decorrelated than underdense signals (Figure 4). This is not entirely unexpected since small underdense trails scatter coherently; this does not occur with overdense trails which are physically larger signal sources [*Sugar*, 1964].

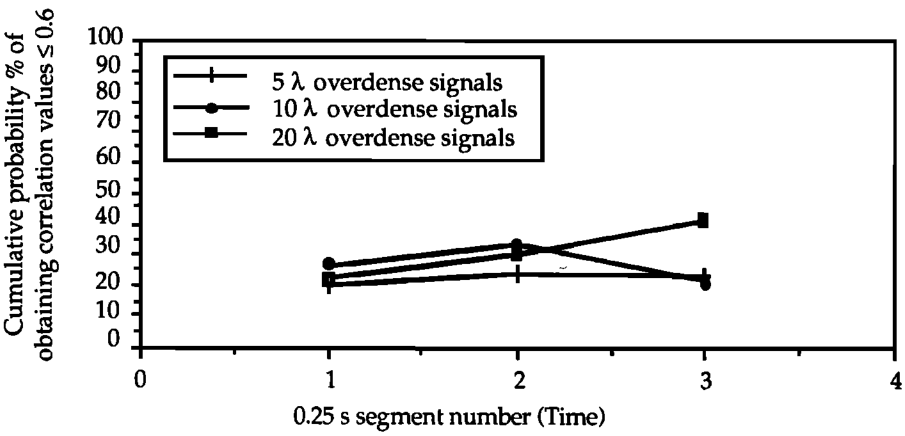

Fig. 5. Probability of obtaining correlation values of less than 0.6 for overdense signals at 5λ, 10λ, and 20λ for segments 1, 2, and 3.

In a previous paper, *Shukla et al.* [1992] commented that high-amplitude overdense signal decorrelation was primarily caused by mesospheric wind distortions of the meteor trail. Consequently, a trend toward decorrelation with time had been expected. In that paper, only results from an antenna spacing of 10λ were addressed, and no trend to decorrelation with time was noted. A comparison between Figures 3a, 3b, and 3c shows that the 10λ separation was insufficient to measure the wind-induced signal decorrelation. The 5λ antenna spacing shows little to no correlation dependency on time. For a 10λ separation there is still no clear dependency, although the curves are diverging. When the spacing reaches 20λ, however, there is a clear trend of decorrelation with time (illustrated in Figure 5 at the 0.6 level), a trend which is identical to that shown by both the underdense and NK trail categories at 5, 10, and 20λ.

We conclude that with an antenna spacing of 20λ that the influence of the multiple glints in overdense trails is noticeable, whereas their effect is not apparent at smaller antenna spacings. In these data the tendency to decorrelate with time has also resulted in higher decorrelation coefficients in segment 3 at 20λ. The spatial correlation values and variation suggest that at least 20λ is needed for the reception of decorrelated overdense signals. Greater separations above 20λ may lead to further decorrelation of the signals.

NK signals

At each antenna spacing NK segment 1 signals (Figure 6) are, generally, less correlated than underdense or overdense signals (Figures 1 and 3). At the 5λ spacing, for example, 49% of segment 1 NK signals have correlation values less than 0.6, compared to 11% and 20% for underdense and overdense signals. Similar observations can be made at the 10λ and 20λ antenna spacings.

NK signal correlation values for segment 1 are always more correlated than those of segment 2 and 3 at any one antenna separation. At the 0.6 correlation threshold (Figure 7) the trend toward decorrelation, as a function of segment number, at antenna spacings of 5λ and 20λ confirms a similar trend reported earlier by *Shukla et al.* [1992] at the 10λ separation.

In our data the 5λ spacing is the most favorable for the reception of uncorrelated NK signals (Figures 6 and 7). Intuitively, this is surprising as we might expect the 5λ measurements to show the highest correlation values. We have examined the 5λ data and find that it is subjected to considerable low-amplitude (~<-120 dBm) multipath which has caused decorrelation of the NK signals. In contrast this multipath has had little impact on the analysis of underdense or overdense signals due to the stringent categorization requirements for those signals. The absence of any systematic variation in NK correlation values as a function of distance and the trend to decorrelation with time at all distances suggests that separations of 5λ, 10λ, or 20λ would provide similar diversity gain.

CONCLUSIONS

This paper has investigated the decorrelation of 37-MHz scattered signals received on two separated antennas spaced at 5λ, 10λ, and 20λ. The spatial variation of correlation values, a parameter important for diversity system design, has been investigated. All of the following conclusions relate to signals of duration ≥0.75 s.

Overdense signals from two antennas separated by 5λ and 10λ did not decorrelate with time. At a separation of 20λ, however, there was a strong decorrelation dependency on time. Since overdense signals are generally of higher amplitude than the other signal categories, they are less affected by low-amplitude signals propagating via other modes; overdense signal decorrelation is thus primarily dependent on the

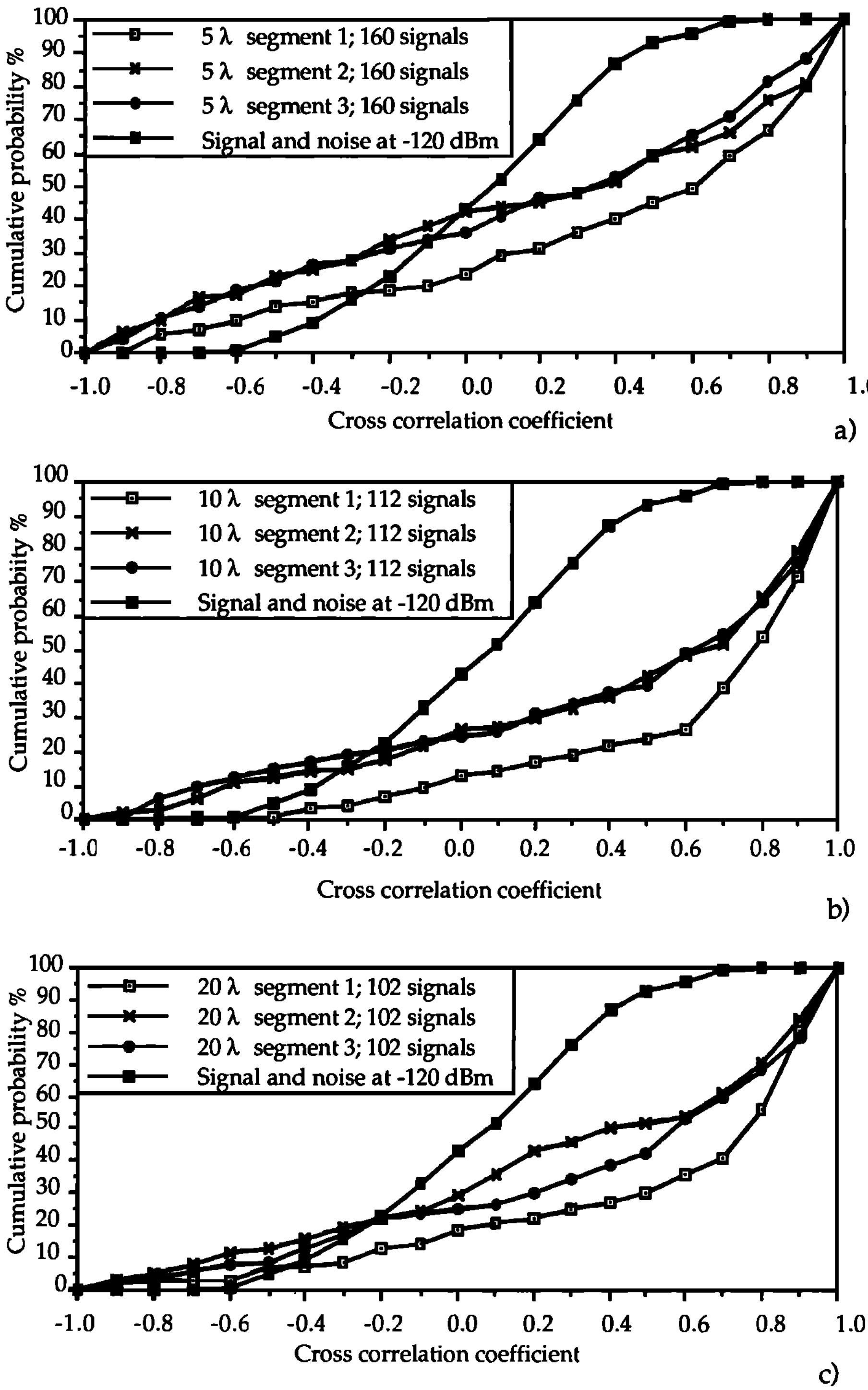

Fig. 6. Cumulative correlation probability curves applicable to NK signals for segments 1, 2, and 3 at antenna separations of (a) 5λ, (b) 10λ, and (c) 20λ.

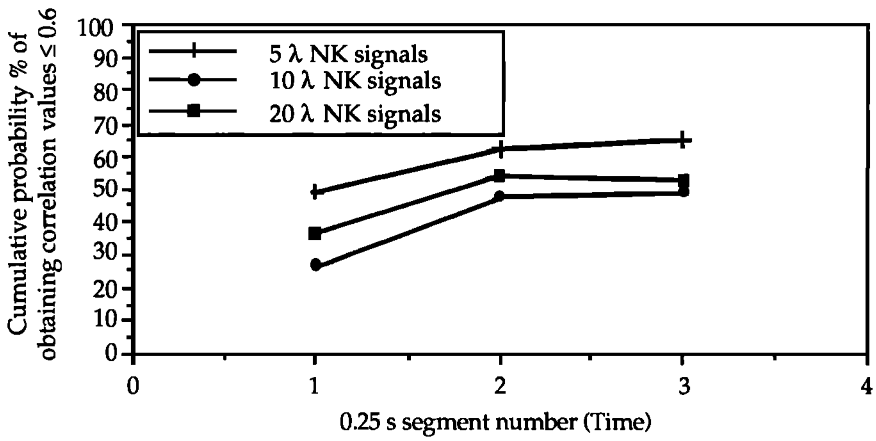

Fig. 7. Probability of obtaining correlation values of less than 0.6 for NK signals at 5λ, 10λ, and 20λ for segments 1, 2, and 3.

production of multiple glints, and a separation of a least 20λ was needed to measure this. Logistical constraints precluded extending this study to separations >20λ, where it is possible that further signal decorrelation would have been measured.

In contrast to the above both underdense and NK signals from two antennas separated by 5λ, 10λ, and 20λ decorrelated with time; no relationship between the variation of correlation coefficient and increasing antenna separation was, however, observed for either category. We believe that the decorrelation that did occur was primarily due to the effects of the low-amplitude additive, but uncorrelated, ionoscatter and sporadic *E* modes. These additive effects were apparent even at a modest 5λ separation. Underdense trails are relatively smaller than overdense trails, and the signals from underdense trails were sufficiently coherent that we were unable to measure any significant decorrelation effects. NK signals, on the other hand, almost certainly derive from a spatially distributed signal source such as a wind distorted trail or a cloud of sporadic *E*. Consequently, only a small separation of ~5λ was needed to achieve significant decorrelation. There was little or nothing to be gained by separating the antennas further.

It is pertinent to discuss the implications of these measurements for a MB communications system using space diversity. The proportion of underdense, overdense, and NK signals used by a MB communications system is dependent on a number of system factors such as effective isotropic radiated power, receiving system antenna gain, operating frequency and electromagnetic noise level. Consequently, no universal recommendations can be made regarding the optimum antenna separation for a MB system implementing spaced antenna diversity. For commonly available contemporary systems which incorporate simple error codes, 4- or 5-element yagi antennas and a transmitter power of a few hundred watts, overdense and NK signals will probably account for a large proportion of the signal throughput. As such, we recommend a diversity antenna separation of 20λ (or more) which will enhance the data throughput contribution made by both NK and overdense signals. If, however, most of the signal traffic is passed via underdense and NK trails (for example in a system using a few kilowatts of transmitter power) a 5λ spacing is sufficient.

On the basis of our measurements here and those presented in an earlier paper [*Shukla et al.*, 1992], the 4λ space diversity antenna separation implemented by *Bartholomé and Vogt* [1968] in COMET would probably have provided a useful performance improvement. That moderate powered system would have passed much of its traffic over overdense and NK trails, and consequently a 20λ spacing (or higher) would have been optimum. Not withstanding that, 4λ would have provided a useful degree of signal decorrelation between the two diversity channels. Our results, therefore, partly explain the excellent performance of that system.

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