MULTIPATH AND DIVERSITY STUDIES IN METEOR SCATTER PROPAGATION

by

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An extended experimental programme, followed by considerable data-reduction and analysis, requires the help and assistance of many personnel. To those whom I have omitted below, please accept my sincerest apologies, but also my thanks.

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Multipath and diversity studies in meteor scatter propagation

by Anil Kumar Shukla

ABSTRACT

Meteor scatter (MS) multipath and diversity is investigated using 37 MHz continuous wave transmissions. A cross-correlation technique and a modelled MS communications system are used to analyse diversity-data collected at temperate latitudes at different antenna separations and season.

Cross-correlation studies are first performed at an antenna separation of 10λ by investigating the cross-correlation variation, with time, of signals which have been categorized as "underdense," "overdense," or "not known" (NK). The cross-correlation coefficients of signals from underdense and overdense trails are shown to be high when correlated over their total signal-envelopes. This is not true, however, when the cross-correlations are performed on signal envelopes which have been segmented in time. NK signals are observed to be more decorrelated than underdense or overdense signals and, therefore, are likely to be the most advantageous to a MS communications system incorporating space-diversity. Combining the data from all three signal categories it is shown that ~40% of signals exhibiting a duration ≥ 0.75s, have correlation values of less than 0.6 after the first 0.25s of signal decay. 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 during the early stages of signal decay.

Cross correlation analysis of signals received at antennas separated by 5λ, 10λ, and 20λ shows that no spatial variation, and in particular no decrease, in average cross-correlation coefficient is observed for underdense or NK signals. At each antenna separation the cross-correlation coefficients of these two signal categories were strongly dependant on time. Overdense signals, however, show no cross-correlation time-dependency at 5λ and 10λ, but a strong time-dependency is observed at 20λ. The measurements support the view of previous workers who have suggested that a 4λ antenna separation may be useful in a MS diversity communications system.

At an antenna separation of 10λ a modelled broadcast scan-diversity and maximal-ratio diversity systems are investigated. The results show that the optimum broadcast data-block duration, in February, for a non-diversity system is ~90ms assuming a ~10ms preamble. The diversity-gain results, at a signal-to-noise (SNR) ratio of 3 dB in a 3 kHz bandwidth, show that the broadcast throughput scan-diversity gain is ~1.4 in June and ~1.18 in February. These gains are equivalent to transmitter power improvements of ~3 dB in June, and ~1.4 dB in February, assuming a simplified relationship between transmitter power and data throughput. The broadcast throughput gain achieved by a maximal-ratio diversity system in June is ~1.9 and ~1.6 in February. At the 3 dB SNR these gains are equivalent to transmitter power increases of ~ 5.8 dB and ~ 4.1 dB in June and February respectively. The summer-winter diversity gains observed are attributed to the reception of more decorrelated NK signals (e.g. sporadic-E) in June than February.

Frequency shift keying (FSK) error-probability analysis is investigated for a selection-diversity system and a maximal-ratio diversity system with antennas separated by 10λ. The results show that by using signals ≥ 3 dB SNR, ~62% fewer errors are observed in February using selection diversity than a non-diversity system, and that in June this improvement decreases to ~50%. Results obtained from the maximal-ratio diversity system show that in both February and June ~90% fewer errors are observed than a non-diversity system. By assuming 216 bit broadcast data-blocks, the results show that a non-diversity system, using signals ≥ 3 dB SNR in February, will experience an error every 8th data-block. A selection-diversity system and a maximal-ratio diversity system, however, will experience errors every 24th and 78th data-block respectively. In June every 6th, 16th and 52nd data-block will be received in error by the non-diversity, selection-diversity and maximal-ratio diversity systems respectively.
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Chapter 1    Introduction

1.1 Brief history

Meteors entering the earth's atmosphere often totally, or partially, vaporise creating long ionised columns which usually dissipate within a few seconds. Some meteors can be observed visually and are often referred to as 'Shooting Stars', the majority of meteors, however, can only be detected, via their ionised trails, using radio techniques.

Radio effects due to meteors were first reported in 1931 by Pickard, [1931] who noted that meteor showers were associated with improved radio broadcast receptions. The first comprehensive study, however, was not performed until 1947 when Hey and Stewart [1947] used British Army radar data to investigate backscatter meteor echoes. In 1946 meteor composition, heights, durations etc. were determined for the Giacobinid meteor shower using visual and radio backscatter techniques [Manning et al., 1946; Bateman et al., 1946; Prentice et al., 1947].

Bursts of signal strength enhancement on forward scatter links, lasting up to several seconds, were reported in 1948 by Allen, [1948]. These bursts, some of which were directly correlated with visual meteor observations, had a maximum and minimum rate of occurrence at 0600 and 1800 local time respectively. Even though the distances between transmitters and receivers were in excess of 2000 km, speech and music was often heard on the forward-scatter test links.

Communications system using meteor trails were first investigated in detail around 1953 [Villard et al., 1953, Eshleman and Manning, 1954]. Unfortunately,
due to the possible military applications of meteor scatter communication system [Oetting, 1980] much of the work remained classified until 1957.

The first operational meteor scatter communications link, JANET-B, was demonstrated in 1953 [Forsyth et al., 1957]. The JANET system [Davis et al., 1957] operated as a full duplex, (i.e. communications in both directions simultaneously) intermittent communications system. Amongst other systems, an air-to-ground meteor scatter system was designed by Hannum et al., [1960] and was followed, in 1966, by COMET (COMmunications by MEteor Trails) [Bartholomé and Vogt, 1968].

Commercial meteor scatter systems were not viable until the 1970's when microprocessor control units, digital signal-processing and protocol techniques had advanced significantly. At this time two large commercial networks were developed in the United States: SNOTEL, (SNOpack TELeometry) [Barton, 1977] and AMBCS, (Alaska Meteor Burst Communications System) [Johansen and Roberts, 1985]. SNOTEL uses 2 master stations to interrogate 500 remote unattended solar powered stations, and the information retrieved (i.e. precipitation, temperature, snow data) from each station is used for water resource planning. The AMBCS system consists of a single master station and is used to retrieve wind, snow and rainfall data and maintain contact with remote survey sites scattered throughout the state of Alaska.

Following a hiatus in the 1980's BLOSSOM (Beyond Line Of Sight Signalling Over Meteors) was developed at the Defence Research Agency, Farnborough (formerly the Royal Aircraft Establishment) [Cannon and Dickson, 1986]. BLOSSOM was a sophisticated experimental test-bed system designed to investigate the effects of differing communications systems operating parameters (e.g. data rates, coding techniques) and was operated over an 800 km north-south propagation path.
The four main experimental meteor scatter communications systems namely: JANET-B, Hannum, COMET and BLOSSOM, are summarised in Table 1.1 [Cannon and Reed, 1987]. The average data rates reported, with the possible exception of COMET, are approximately 15-20 bits s⁻¹. Many of the advantages of meteor scatter communications systems, such as the relatively small receiver footprint areas; the reliability of communications during ionospheric disturbances; and the cost effectiveness of communicating beyond line of sight (compared to satellite and high frequency systems), are severely compromised by these relatively low (15-20 baud) data-rates.

1.2 Physical properties of meteors

Meteors entering the earth's atmosphere are categorised as either shower meteors or sporadic meteors [Lovell, 1954]. Meteor showers occur periodically (Table 1.2), and are observed when the earth's orbit intersects the orbiting particles around the sun. These meteor showers only constitute a small fraction of the total number of incoming meteors; the remainder are sporadic meteors. The radiants of these sporadic meteors, unlike those of the showers which are well defined, appear to be random and it is estimated that ~ 10¹⁰ sporadic meteors strike the earth each day.
Table 1.1 A comparison between four meteor scatter communications systems [Cannon and Reed, 1987].

<table>
<thead>
<tr>
<th>System</th>
<th>JANET-B</th>
<th>Hannum</th>
<th>COMET</th>
<th>BLOSSOM-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>1954</td>
<td>1959</td>
<td>1966</td>
<td>1986</td>
</tr>
<tr>
<td>Simplex/Duplex</td>
<td>Duplex</td>
<td>Simplex</td>
<td>Duplex</td>
<td>Simplex</td>
</tr>
<tr>
<td>Transmitter power</td>
<td>500 W</td>
<td>5 and 8 kW</td>
<td>200 W</td>
<td>650 W</td>
</tr>
<tr>
<td>Frequency</td>
<td>40 MHz</td>
<td>50 MHz</td>
<td>36-39 MHz</td>
<td>37 MHz**</td>
</tr>
<tr>
<td>Station 1</td>
<td>4 of 5 element Yagis</td>
<td>6 of 8 element Yagis</td>
<td>See Chapter 2</td>
<td>1 of 4 element Yagis</td>
</tr>
<tr>
<td>Station 2</td>
<td>4 of 5 element Yagis</td>
<td>Dipole</td>
<td>See Chapter 2</td>
<td>1 of 4 element Yagis</td>
</tr>
<tr>
<td>Modulation</td>
<td>AM (pulse)</td>
<td>FSK</td>
<td>FSK</td>
<td>FSK</td>
</tr>
<tr>
<td>ARQ*</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Coding</td>
<td>None</td>
<td>Hamming</td>
<td>Moore 7 element ARQ</td>
<td>Various</td>
</tr>
<tr>
<td>Diversity</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Data rate</td>
<td>650 baud</td>
<td>2000 baud</td>
<td>2000 baud</td>
<td>2400 baud†</td>
</tr>
<tr>
<td>Average data rate</td>
<td>15 bits s⁻¹</td>
<td>15 bits s⁻¹</td>
<td>115 bits s⁻¹</td>
<td>15 bits s⁻¹</td>
</tr>
<tr>
<td></td>
<td>July/Aug</td>
<td>May</td>
<td>Dec</td>
<td>March</td>
</tr>
</tbody>
</table>

* ARQ; Automatic ReQuest.

** Variable in frequency range from 37 MHz to 72 MHz.

† Variable data rate from 1200 baud to 9600 baud.
Table 1.2. Meteor streams which have an hourly radio rate > 10 during their maximum date of transit [McKinley, 1961].

<table>
<thead>
<tr>
<th>Meteor shower name</th>
<th>Extreme dates</th>
<th>Date of maximum(UTC)</th>
<th>Radiant transit time (local time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrantids</td>
<td>Jan 1 - Jan 6</td>
<td>Jan 3</td>
<td>08:28</td>
</tr>
<tr>
<td>April Lyrids</td>
<td>Apr 19 - Apr 24</td>
<td>Apr 21</td>
<td>03:59</td>
</tr>
<tr>
<td>Eta Aquarids</td>
<td>May 1 May 8</td>
<td>May 4</td>
<td>07:36</td>
</tr>
<tr>
<td>Daytime Arietids</td>
<td>May 29 - June 19</td>
<td>June 8</td>
<td>09:51</td>
</tr>
<tr>
<td>Daytime e Persieds</td>
<td>Jun 1 - Jun 16</td>
<td>June 9</td>
<td>10:59</td>
</tr>
<tr>
<td>Daytime β Taurids</td>
<td>June 24 - July 6</td>
<td>June 30</td>
<td>11:12</td>
</tr>
<tr>
<td>Northern δ Aquarids</td>
<td>July 14 - Aug 19</td>
<td>-</td>
<td>02:08</td>
</tr>
<tr>
<td>α Capricornids</td>
<td>July 17 - Aug 21</td>
<td>Aug 1</td>
<td>00:00</td>
</tr>
<tr>
<td>Persieds</td>
<td>July 29 - Aug 17</td>
<td>Aug 12</td>
<td>05:43</td>
</tr>
<tr>
<td>Orionids</td>
<td>Oct 18 - Oct 26</td>
<td>Oct 22</td>
<td>04:12</td>
</tr>
<tr>
<td>Northern Taurids</td>
<td>Oct 17 - Dec 2</td>
<td>Nov 1</td>
<td>00:46</td>
</tr>
<tr>
<td>Geminids</td>
<td>Dec 7 - Dec 15</td>
<td>Dec 14</td>
<td>02:01</td>
</tr>
<tr>
<td>Ursids</td>
<td>Dec 17 - Dec 24</td>
<td>Dec 22</td>
<td>08:22</td>
</tr>
</tbody>
</table>
These more numerous sporadic meteors can be used to establish an intermittent beyond line of sight (BLOS) communications link, with shower meteors providing an additional throughput.

Meteor velocities, an important consideration along with mass in producing the ionised columns, vary between 11-72 km s\(^{-1}\) [Kaiser, 1955]. The upper velocity limit is the sum of two components; 30 km s\(^{-1}\) from the sweeping motion of the earth in its orbit around the sun, and 42 km s\(^{-1}\) associated with the escape velocity of particles leaving the solar system. The lower velocity limit of 11 km s\(^{-1}\) is the escape velocity of particles leaving the earth's atmosphere.

Table 1.3 tabulates the relationship between meteor mass, radius, number density and electron line density for sporadic meteors. The number density of incoming sporadic meteors is inversely proportional to their mass, and a function of time of day and season. The sinusoidal diurnal variation of incoming meteors, illustrated in Figure 1.1a where a third-order curve has been fitted to the data obtained from Cannon [1985], shows that the number of meteors detected maximises during the morning (0600 local time) and minimises in the evening (1800 local time). The higher morning rate is due to the sweeping action of the earth's motion around the sun (Figure 1.1b), and the lower evening rate is caused by the reduced number of meteors having sufficient velocity to overtake the earth.

The number of meteors observed also varies as a function of season. The 4:1 variation, with the maximum and minimum arrival-rates occurring in August and February respectively, results from the tilting of the earth's axis relative to the ecliptic plane [Hawkins, 1956] and is compounded by the presence and absence of meteor showers in August and February. Both the seasonal and diurnal maximum and minimum arrival-rate variations decrease with increasing latitude [Schiaparelli, 1954] due to the earth's rotational motion.
Table 1.3 The relationships between meteor mass, line density, radius, duration, and incidence rate [McKinley, 1961].

<table>
<thead>
<tr>
<th>Meteor mass (g)</th>
<th>Meteor Radius (cm)</th>
<th>Meteor trail density, (em⁻¹)</th>
<th>Theoretical meteor trail duration*</th>
<th>Average interval between meteors*</th>
<th>Number incident of this mass, or greater, per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>10³</td>
<td>4.0</td>
<td>10²⁰</td>
<td>&gt; 4 hours</td>
<td>&gt; 16 hours</td>
<td>10²</td>
</tr>
<tr>
<td>10²</td>
<td>2.0</td>
<td>10¹⁹</td>
<td>&gt; 4 hours</td>
<td>&gt; 16 hours</td>
<td>10³</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>10¹⁸</td>
<td>&gt; 4 hours</td>
<td>&gt; 16 hours</td>
<td>10⁴</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
<td>10¹⁷</td>
<td>~ 4 hours</td>
<td>~ 16 hours</td>
<td>10⁵</td>
</tr>
<tr>
<td>10⁻¹</td>
<td>0.2</td>
<td>10¹⁶</td>
<td>25 secs</td>
<td>100 mins</td>
<td>10⁶</td>
</tr>
<tr>
<td>10⁻²</td>
<td>0.08</td>
<td>10¹⁵</td>
<td>2.5 secs</td>
<td>10 mins</td>
<td>10⁷</td>
</tr>
<tr>
<td>10⁻³</td>
<td>0.04</td>
<td>10¹⁴</td>
<td>0.5 secs</td>
<td>60 secs</td>
<td>10⁸</td>
</tr>
<tr>
<td>10⁻⁴</td>
<td>0.02</td>
<td>10¹³</td>
<td>0.5 secs</td>
<td>6 secs</td>
<td>10⁹</td>
</tr>
<tr>
<td>10⁻⁵</td>
<td>0.008</td>
<td>10¹²</td>
<td>0.5 secs</td>
<td>0.6 secs</td>
<td>10¹⁰</td>
</tr>
<tr>
<td>10⁻⁶</td>
<td>0.004</td>
<td>10¹¹</td>
<td>0.5 secs</td>
<td>0.06 secs</td>
<td>10¹¹</td>
</tr>
<tr>
<td>10⁻⁷</td>
<td>0.002</td>
<td>10¹⁰</td>
<td>0.5 secs</td>
<td>0.006 secs</td>
<td>10¹²</td>
</tr>
</tbody>
</table>

* Average interval between meteors and theoretical durations are computed using a frequency of 30 MHz and a range of 150 km.
Figure 1.1 (a) The diurnal variation of incoming meteors [Cannon, 1985].
(b) The earth's sweeping motion around the sun.
1.3 Properties of meteor trails

Regions of the earth's upper atmosphere (termed the ionosphere), and their diurnal variation, are illustrated in Figure 1.2a. A typical vertical electron density profile is plotted in Figure 1.2b and shows how the electron concentration varies as a function of height, time (day and night) and solar activity (sunspot number) [CCIR, 1990].

The kinetic energy of an incoming meteor is converted into heat, light, and ionisation by collision processes in the upper D and lower E regions of the earth's ionosphere. Ionisation begins at an altitude of ~ 120 km (E region) and ends at an altitude of ~ 85 km (D region). Within this height range the neutral air density (Figure 1.3) is sufficiently high to cause the meteors to evaporate via frictional heating, as opposed to meteor evaporation via excitation of the neutral air surrounding the meteor [Manning and Eshleman, 1959].

The lengths of the ionised columns, often referred to as the meteor trails, are typically ~15 km for sporadic meteors, and the meteor trail ionisation is proportional to the mass of the particle (Table 1.3). The initially small sporadic meteor-trail radius of 0.5 - 4.0 cm [Sugar, 1964], expands rapidly by ambipolar diffusion. Diffusion coefficients vary exponentially with height from ~ 1m² s⁻¹ at 85 km to ~140 m² s⁻¹ at 115 km [Greenhow and Neufeld, 1955a] and typical sporadic meteor trail durations are ~1 s. Although recombination and attachment processes occur along the trail length, their rates are slow [McKinley, 1961] and may be neglected in comparison to diffusion effects on the short duration (~1s) trails. As the initially straight meteor trail diffuses, neutral mesospheric winds also cause the trail to distort and fragment. This aspect of trail perturbation is discussed in Chapter 2.
Figure 1.2  (a) The variation of ionospheric regions with time of day and (b) the concentration of electrons with height between sunspot maximum and minimum. [CCIR, 1990]
Figure 1.3  Composition and density of the major neutral gases in the earth atmosphere [Davies, 1990]
1.4 Scattering from meteor trails

Energy scattered from meteor trails is a function of many parameters, such as propagation frequency, trail orientation, time after trail formation, electron density etc. Useful forward scatter is produced from trails of electron line densities greater than $10^{10} \, \text{em}^{-1}$. Trails of electron density below and above a boundary of $2 \times 10^{14} \, \text{em}^{-1}$ are respectively classed as underdense or overdense trails, and the physical scattering mechanisms for each category are different. Trails of electron density $> 10^{16} \, \text{em}^{-1}$ are infrequent and, therefore, not 'useful' to a meteor scatter communications system.

Radio waves incident on underdense trails (i.e. $< 10^{14} \, \text{em}^{-1}$) pass through the trail without being reflected, but each of the electrons within the trail act as an independent scatterer. The energy received, therefore, is a summation of the energy scattered from each electron within the first Fresnel zone. Contributions from higher order Fresnel zones are negligible. A typical received envelope scattered from an underdense trail is illustrated in Figure 1.4a.

Overdense trails have high ($> 10^{14} \, \text{em}^{-1}$) electron densities and electron - electron coupling prevents complete penetration of the incident radio wave. The received energy, therefore, is primarily due to reflection, rather than scattering processes, from the first Fresnel zone of the meteor trail. Once again contributions from higher order Fresnel zones are negligible. As the overdense trails expand by diffusion, the electron density within the trail decreases. At electron densities below $10^{14} \, \text{em}^{-1}$ the incident wave is no longer reflected but scattered, and the overdense trail becomes underdense. Figure 1.4b illustrates a typical received envelope reflected and scattered from an overdense trail.
Figure 1.4  The theoretical variation of received power scattered from an
a) underdense trail and
b) an overdense trail.
1.5 'Hot spots' and footprint dimensions

'Hot spots' refer to regions in the sky where the density of favourably orientated forward-scatter meteors are greatest [Eshleman and Manning, 1954]. These 'hot spot' regions arise from the geometrical conditions (Chapter 2) required for forward scatter and from the randomly distributed meteor radiants associated with sporadic meteors. Figure 1.5 shows contours of a parameter closely related to probability density (probability duration-factor [Cannon, 1985]) on an 800 km path between Farnborough, in southern England, and Wick in Scotland. The two hot spot regions are symmetrically positioned either side of the great circle path mid-point. The probability at the mid-point is small due to the relatively low number of horizontal meteor trails which satisfy the conditions for forward scatter. Hot spot regions vary in dimensions and importance with time of day and meteor radiant. These variations, however, are usually overcome in meteor scatter communications systems by illuminating both hot spots simultaneously using wide beamwidth antennas.

Receiver footprint dimensions vary considerably between individual meteors due to different scattering geometries and system parameters (e.g. frequency). Signals scattered from long thin meteor trails, however, form elliptically shaped signal footprints at the receiver. On average, typical dimensions at 40 MHz may be 80 km by 40 km [Villard et al., 1956], with the longer length orientated along the transmitter - receiver path.

1.6 Time between meteor trails

An important parameter in considering meteor scatter communications is the interval between occurrences of individual meteors. If the more numerous
Figure 1.5  An illustration of 'Hot spots' using probability duration factors for an 800 km propagation path [Cannon and Reed, 1987].
underdense trails are considered, the waiting time \( t_w \) between each underdense meteor trail of duration at least \( t_m \) is given by [Cannon and Reed, 1987]:

\[
t_w = \frac{q_o}{HK} \exp\left(\frac{t_m}{\tau}\right) \ln\left(\frac{1}{1-P}\right)
\]

where:

- \( q_o \) is the threshold electron line density for detecting underdense trails \( (\text{em}^{-1}) \),
- \( H \) is the common area illuminated by the transmit and receive antennas, \( (\text{m}^2) \),
- \( K \) is a constant of proportionality relating the number of meteors and trail line density.
- \( \tau \) is the amplitude time constant for decay.
- \( P \) is the probability that the interval between trails is less than time \( t_w \) \((0 \leq P \leq 1)\).

This equation assumes that sporadic underdense meteors arrive randomly within the common volume illuminated by the transmitter and receiver antennas. The equation demonstrates that the waiting time increases exponentially as the wanted trail-duration increases; this relationship is also illustrated in Table 1.3. Calculations derived using a 400 km experimental data link, operated at 50 MHz, indicates that the waiting time (50% probability of occurrence) increases from 17 s for a trail duration of 0.1 s, to 35 s for a 0.2 s trail duration [Cannon and Reed, 1987]. Communications systems using meteors, therefore, must exploit not only the more numerous underdense meteor trails, but also short duration underdense trails.

1.7 **Forward scatter communications systems**

Communications systems which exploit forward scatter meteor trails can be established using frequencies within the range 20 - 120 MHz [Brown and Williams, 1977], although it is usual to use frequencies between 35 - 50 MHz. Meteor scatter
systems possess certain advantages over high frequency (HF) and satellite communications systems [Cannon and Reed, 1987]. The limited footprint dimensions created by the directional scattering characteristics of meteor trails make interception and beyond line of sight jamming difficult. Meteor systems require no frequency management, use less power than ionoscatter systems, are considerably cheaper than satellite systems and are less susceptible to degradation due to ionospheric disturbances.

The primary disadvantages of meteor scatter communication systems are their intermittent nature and their capacity to only support, on average, low data-rates (~15-20 baud) [Cannon and Reed, 1987]. These low data-rates are inherently due to the limited number of trails satisfying the geometric conditions for forward scatter, and the relatively short duration (~ 1 s) of the trails once this condition has been satisfied. These factors necessitate that digital techniques (e.g. coding, forward error correction) be used to overcome the intermittent nature of the medium by establishing a link using successive meteor trails.

A simplex meteor scatter system, where only one station transmits at any one time, is outlined in Figure 1.6 [Cannon and Reed, 1987]. The control unit, essential in any meteor scatter system, detects when a trail is available and codes (or decodes) the information for rapid data transmission (reception) via the data buffers. A primary feature of all meteor scatter systems are the data exchange protocols required between transmitter and receiver. These protocols, which are handled by the control unit, add to the sophistication of meteor scatter systems.

1.8 Aims of the Thesis

The received wavefront of signals scattered from a meteor trail are not plane. The received signals, therefore, do not decay 'smoothly' as predicted theoretically, but
Figure 1.6  A functional diagram of a simplex meteor scatter communications system [Cannon and Reed, 1987].
experience time-dependant signal fluctuations (i.e. fades, Chapter 2). These signal-fades reduce the time that signals scattered from a meteor trail are 'useful' to a meteor scatter communications system. During a signal-fade, data may be received in error and will generally contribute to the low meteor scatter data-rates observed. By reducing the effects of signal-fading the average data-rate in a meteor scatter communications systems may be improved.

Diversity, a well known technique used to reduce the effects of signal fading in high frequency (HF), troposcatter and ionoscatter systems has not been exploited, to the same extent, in meteor scatter systems. This is primarily due to the lack of experimental evidence quantifying the advantages/disadvantages of various diversity configurations and the contradictory literature (Bartholomé and Vogt [1968]; Ladd [1961]; Staras [1956]; Manning [1959]). It is the primary aim of this thesis to investigate meteor scatter fading and the possible data-rate improvements achieved by implementing diversity in a meteor scatter communication system.

This thesis investigates whether meteor scatter fading can be reduced by combining the signals received at two antennas spatially separated (space diversity) by distances of < 30\(\lambda\) at \(\sim\)37 MHz. Geographical meteor scatter space-diversity, with antenna separations of \(-\sim\)100 km, is not considered. The space-diversity signals obtained in this thesis are analysed using a cross-correlation technique and a modelled meteor scatter broadcast communications system.

Signal correlation studies will first reveal if decorrelated signals, essential for reducing signal-fading and implementing diversity techniques, can be received. Space diversity investigations will also determine the 'practical' optimum antenna spacing for a diversity system, and any seasonal dependence of the reception of uncorrelated meteor scatter signals. These studies will also clarify the
conflicting diversity results obtained by previous workers (*Bartholomé and Vogt* [1968]; *Ladd* [1961]; *Staras* [1956]; *Manning* [1959]).

The modelled broadcast meteor-scatter communications system will evaluate any diversity improvements obtained using space diversity. The analysis is performed as a function of varying communications system parameters such as data-block duration, receiver threshold etc.

Although this thesis primarily investigates meteor scatter signals it is noted that three other sources of signal propagation exist within the meteor scatter frequency range (30-50 MHz). These signal modes may add vectorially with meteor scatter signals providing the possibility of diversity gain, similar conclusion have been made by *Bartholomé* [1962]. Consequently, these other signal modes are also incorporated in this study of meteor scatter diversity.
Chapter 2  A review of meteor scatter propagation, fading and diversity

2.1 Introduction

In conventional communications systems (e.g. high frequency (HF), ionoscatter, satellite, troposcatter) the received signal-amplitude from a continuous-wave transmitted signal is non-stationary (Figure 2.1) and the fluctuating signal-amplitude is defined as fading. The characteristics of signal fading such as fading frequency, depth, and duration (Figure 2.1) depend on the causes of fading and communications system parameters. For example, at HF fading due to signal absorption may last for several hours, while fading due to the combination of two or more differing signal-polarizations may only have a fading period between 0.1 - 2 s.

Fading signals degrade the performance of communications systems by decreasing data-rates, increasing bit error rates, etc. Fades which occur slowly (i.e. over hours, days) can be overcome by changing system parameters such as transmitter power, frequency, receiver location, etc. Fading frequencies greater than a symbol period (i.e. that period which designates a '1' or '0' in a digital communications system) are difficult to combat, but are averaged in the receiving system to provide a satisfactory, if somewhat degraded, communications system. If the performance of communications systems are to be improved the detrimental effects of fading between these two extremes must be reduced.

The implementation of diversity is one method of reducing the effects of fading. Diversity techniques combine two or more uncorrelated fading signals to reduce the fade depth and frequency. The technique has been applied successfully to HF,
Observed signal fading

Expected received power from CW transmissions

Received signal power

D = Fading depth

$1/T = \text{Fading frequency}$

Time

Figure 2.1 An illustration of received signal-fading due to continuous-wave transmissions of high frequencies (HF) signals.
ionoscatter and troposcatter communications systems. It is unclear, however, if similar techniques can be applied to meteor scatter communications systems.

In this chapter meteor scatter propagation is described by first outlining the theoretical received backscatter power-equations obtained from underdense and overdense trails. These equations are then modified to describe the idealised received signal-power variations obtained on a forward scatter (i.e. communications type) link. The idealised forward-scatter signal envelopes are then compared with fading signals-envelopes obtained experimentally. Fading mechanisms and characteristics are also summarised, and the techniques commonly used to obtain uncorrelated fading-signals, and the traditional diversity combining techniques used in conventional communications systems, are also discussed. The conflicting meteor scatter diversity literature, is also reviewed.

2.2 Meteor scatter from underdense and overdense trails

2.2.1 Backscatter from underdense trails

To a first approximation the underdense trail is modelled as a uniform stationary column of free electrons which neither expand, diffuse or recombine. The electron concentration within the column is such that the incident wave is scattered by the free electrons and the received signal power is the sum of the energy backscattered from each electron. If the size of the first backscatter Fresnel zone is \((2\lambda R)^{1/2}\) ([Lovell and Clegg, 1948], Figure 2.2a) then the backscatter received power from an underdense trail cross-section \(\sigma\) is :-

\[
\frac{P_k}{P_T} = \frac{G_T G_R \lambda^2}{16\pi^2 R^4 \sigma}\tag{2.1}
\]

where :-

13
Figure 2.2  

a) Backscatter geometry from an underdense trail and  
b) the resulting theoretical variation of received power with time.
\( P_T, P_R \) are the transmitted and received powers respectively.

\( G_T, G_R \) are the transmitter and receiver antenna powers gains relative to an isotropic radiator in free space.

\( \lambda \) is the radio-wave wavelength in meters.

\( R \) is the distance from the transmitter to the trail in meters.

\( \sigma \) is the scattering cross-section of the trail in meters.

The scattering cross-section \( \sigma \) of the line of electrons (i.e. trail radius is 1 electron wide) can be written as [Sugar, 1964]:

\[
\sigma = \left( \sqrt{\frac{R}{2}} r_c q \right)^2 \exp \left( -\frac{32\pi^2 D}{\lambda^2} t \right)
\]  

(2.2)

where :-

\( r_c = \mu_0 e^2 / 4\pi m = 2.8178 \times 10^{-15} \text{ m}, \) is the classical radius of the electron where \( \mu_0 \) is the permeability of free space, and \( e \) and \( m \) are the charge and mass of the electron respectively.

\( q \) is the electron line density of the trail in electrons per meter.

\( D \) is the diffusion coefficient in m\(^2\) s\(^{-1}\).

\( t \) is time, in seconds, after trail formation.

This cross-section equation 2.2 comprises two main factors. The first factor, which is proportional to \( q^2 \) and \( R \), represents the scattering cross-section of the initial line of electrons. The second factor, the exponential decay term, reflects the attenuation with time as the trail expands and destructive interference occurs.

If the initial trail radius is considered to be non-zero and the electrons across this radius are assumed to be Gaussian distributed, an extra initial attenuation factor can be derived [Sugar, 1964]. By including this attenuation term in equation 2.2 and then by substituting the cross-sectional term into equation 2.1, the backscatter equation can be re-written as :-
and the time variation of received power is illustrated in Figure 2.2b. Calculations of typical theoretical variations of echo power with time using radar parameters of $G_R = G_T = (10)^{1/2}$, $\lambda = 10$ m, $P_T = 10^5$ watts, $R = 150$ km, and $D = 4\ m^2s^{-1}$, chosen for convenience, are given in Figure 2.3 [McKinley, 1961]. The figure shows that as the scattering electron density ($q$) increases from $10^{12}$ em$^{-1}$ to $10^{14}$ em$^{-1}$ the predicted duration for underdense trail increases from ~0.1 to 1 s and that the signal starts to decay immediately after trail formation.

2.2.2 Backscatter from overdense trails

Figure 2.4a details the scattering geometry and Figure 2.4b illustrates the theoretical received power variation of signals scattered by an overdense trail. The received overdense trail backscatter power can be calculated assuming that the trail is an expanding cylindrical reflector of effective radius $r_c$. After formation the scattering cross-section of the reflecting cylinder is $r_c R_c / 4$ providing $r_c < R$ [Eshleman, 1955]. If the effective radius of the expanding Gaussian distributed electron density trail, is $[Hines and Forsyth, 1957]$:-

$$r_c = \left[ 4Dt \ln \left( \frac{r_c q \lambda^2}{4\pi^2Dt} \right) \right]^{1/2}$$

(2.4)

then the received backscatter power from an overdense trail can be written as :-

$$\frac{P_R}{P_T} = \frac{G_T G_R}{64\pi^2 R^3} \left[ 4Dt \ln \left( \frac{r_c q \lambda^2}{4\pi^2Dt} \right) \right]^{1/2}$$

(2.5)

This backscatter equation 2.5 remains valid until:

$$\tau = \frac{r_c q \lambda^2}{4\pi^2D}$$

(2.6)
Figure 2.3  Theoretical variations of received signal-power with time [McKinley, 1961].
Figure 2.4  a) Backscatter geometry from an overdense trail and b) the resulting theoretical variation of received power with time.
when the logarithmic factor in equation 2.5 becomes zero. After this time the electrons are assumed to be free scatterers and the underdense transmission equation 2.3 become more applicable.

Unlike the received power from an underdense trail, which begins to decay immediately after trail formation, the received power from overdense trail initially increases as the size of the effective reflecting area increases. Typical theoretical variations of received power, based on the radar parameters used for the backscatter underdense trail, are shown in Figure 2.3. Signals scattered from overdense trails have a greater duration and received signal-power than those signals scattered from underdense trails. The figure also shows that an increase in overdense trail density \( (q) \) of \( 10^4 \) (i.e. from \( 10^{14} \) to \( 10^{18} \) \( \text{em}^{-1} \)) results in an increase in signal duration from \( \sim 0.1 \) to \( \sim 1000 \) s.

### 2.2.3 Forward scatter from meteor trails

Forward scatter equations can be derived from the backscatter radar equations by incorporating the forward link geometry illustrated in Figure 2.5. Since the scattering observed from meteor trails is approximately specular, forward scattering can only be geometrically achieved by trails which are tangential to an ellipse which has the transmitter and receiver positions as foci. By incorporating these geometrical conditions into equation 2.3, the forward scatter transmission equation for an underdense trail can be written as [Sugar, 1964]:

\[
\frac{P_R(t)}{P_T} = \frac{G_T G_R \lambda^3 q^2 r_o^2 \sin^2 \alpha}{16\pi^2 R_T R_R (R_T + R_R) (1 - \cos^2 \beta \sin^2 \phi)} \exp \left( -\frac{8\pi^2 r_o^2}{\lambda^2 \sec^2 \phi} \right) \exp \left( -\frac{32\pi^2 D_t}{\lambda^2 \sec^2 \phi} \right) \tag{2.7}
\]

where :

- \( R_T \) is the distance from the transmitter to the designated point on the trail where scattering/reflection occurs.
C = Earth’s surface
D = Plane of propagation
E = Meteor trail
F = Tangent plane
L = Length of the first Fresnel zone
β = Angle between trail axis and the plane of propagation.
ϕ = Angle of incidence.

Figure 2.5  Forward scattering geometry for a meteor trail.
$R_R$ is the distance from the receiver to the designated point on the trail where scattering/reflection occurs.

$\beta$ is the angle between the trail and the plane of $R_T$ and $R_R$.

$\phi$ is half the angle included between $R_T$ and $R_R$.

$\alpha$ is the angle between the electric vector at the meteor trail and $R_R$.

The peak received signal-power is noted to be a function of $\lambda^3$ and $q^2$.

The oblique conditions introduce two important changes to the underdense backscatter equation 2.3. First, an increase in length of the first Fresnel zone is observed which, due to the increased number of electrons directly contributing to the received signal, increases the received power. Second, due to the oblique conditions a 'sec$\phi$' term is introduced in the scattering equation.

The duration of the received signal is usually taken to be that time taken for the received power to fall by $1/e$ of its initial value. For an underdense trail this is given by:

$$\tau = \frac{\lambda^2 \sec^2 \phi}{16\pi^2 D}$$  \hspace{1cm} (2.8)$$

and shows that for forward scatter the duration increases by $\sec^2 \phi$ and is a function of $\lambda^2$.

The forward scatter equation for an overdense trail can be similarly derived by incorporating the obliquity factors. The overdense forward scatter transmission equation thus derived [Sugar, 1964] is:

$$\frac{R(t)}{R_T} = \frac{G_T G_R \lambda^2 \sin^2 \alpha}{32\pi^2 R_T R_R (R_T + R_R) (1 - \cos^2 \beta \sin^2 \phi)} \left[ \frac{4D_T}{\sec^2 \phi \ln \left( \frac{r_R \lambda^2 \sec^2 \phi}{4\pi^2 D_T} \right)} \right]^{1/2}$$  \hspace{1cm} (2.9)$$

where $R_T$, $R_R$, $G_T$, $G_R$, $\alpha$, $\phi$, $\beta$, $\lambda$ are those angles and dimensions defined earlier and in Figure 2.5.
The overdense equation 2.9 remains valid until:

\[ \tau = \frac{r_0 q \lambda^2 \sec^2 \phi}{4\pi^2 D} \]  \hspace{1cm} (2.10)

when the density of electrons is sufficiently low that signals are no longer reflected but scattered. At this time the underdense equation 2.7 become more applicable. The transitional line density, between underdense and overdense trails, can be obtained by equating the two received powers. The transitional line density obtained using this method is \( q = 0.75 \times 10^{14} \text{ em}^{-1} \).

2.3 Meteor scatter fades

The theoretical meteor scatter calculations, described above, conveniently assume that the received signal wavefront is plane and has been scattered from an idealised straight column of diffusing ionisation. It is known, however, that the ionised columns experience other forces e.g. winds [Manning, 1959; Greenhow and Neufeld, 1959b] which significantly alter their initial shape. The decaying wavefront scattered from these irregularly shaped meteor trails are no longer plane and the signals received at an antenna fluctuate (i.e. fade) as the signal-decays. Before the mechanisms causing fades are outlined, examples of meteor scatter fades, observed on a forward scatter link are described, and their impact on communications data-rates are discussed.

2.3.1 Examples of forward scatter meteor signal fades

In Figure 2.6a and 2.6b the two underdense signals above the received power-threshold of -120 dBm, used to identify a 'useful' communications signal, have comparable durations and similar peak envelope powers. In the top frame (Figure 2.6a) the signal decays linearly, in dB's, as predicted by the simple underdense transmission equation 2.7. This smooth linear decay, however,
Figure 2.6  Forward scatter meteor signals showing:
  a) an underdense signal exhibiting no fades.
  b) an underdense signal with fades.
  c) an overdense signal with fades.
contrasts with Figure 2.6b where a signal fluctuation (i.e. a fade) has significantly modified the expected linear decay. Signals scattered from overdense trails (Figure 2.6c, and Appendix A) also experience similar signal-fades.

Received signals scattered from underdense and overdense trails may also exhibit deep periodic fading. For example, in Figure 2.7a the decaying signal scattered from an underdense trail has three deep, ~10 dB quasi-periodic 1 s fades. Figure 2.7b illustrates a similar fading pattern observed on an overdense signal.

Signal fades often occur during the latter stages of signal-decay, as illustrated in Figure 2.8a (and in Appendix A). If the underdense signal-decay in Figure 2.8a is extrapolated from the peak received power to $T_1$ and onwards, the signal is predicted to drop below the threshold at $T_e$ and the signal duration is expected to be ~2.5 s. The signal fade, however, occurring after $T_1$ decreases the signal-duration by ~0.5 s (i.e. $\Delta t_s$).

In the top and lower frame of Figure 2.8b the underdense signal is considerably modified by the 'echo-overlap' event described in detail in section 2.4.5. Similar events may also be observed on overdense signals.

2.3.2 The impact of fades on meteor scatter data rates

In general the impact of meteor scatter fades are to reduce the signal duration available over which data can be transmitted, or to momentarily increase the error-rate. For example, the underdense signal in Figure 2.7a exhibits three deep fades. In this example the momentary increase in error rate associated with the three fades may result in a meteor scatter communications system interpreting the single underdense signal as three short-duration (~1s) signals. Due to the loss of valuable data transmission time, together with time lost performing repeated
Figure 2.7  Deep periodic fades observed on forward scatter meteor signals from
a) an underdense trail
b) an overdense trail
Figure 2.8  a) Signal duration decrease due to an underdense signal fade.
b) Echo-overlap signals [Berry et al, 1961] received simultaneously at two spatially separated antennas.
link establishments during the signal decay, the potential data throughput of this signal is reduced. In Figure 2.8a valuable signal transmission time \( \Delta t_s \) seconds) is lost due to the fade occurring after \( T_1 \), and in the lower frame of Figure 2.8b the communications link may be lost at \( T_2 \) and never completely re-established due to the low signal-power following the echo-overlap event.

2.4 Causes of meteor scatter fades

2.4.1 Periodic fading due to diffraction

Periodic diffraction fading, illustrated in Figure 2.9 [McKinley, 1961], occurs for a short period (< 0.5 s) before and after the sudden enhancement associated with the creation of a meteor trail. The periodic fades are a result of a moving scattering point, i.e. the meteor head, passing through successive Fresnel zones and contributing positively and negatively to the received signal-power. Oscillations of decreasing frequency and increasing amplitude occur prior to signal enhancement, and are followed by oscillations of increasing frequency and decreasing amplitude. These characteristics are associated with the moving meteor head [Browne and Kaiser, 1953] as it first approaches and then moves away from the first Fresnel zone.

The diffraction echo pattern (which is similar to a knife edge diffraction) has been used [Ellyett and Davies, 1948] to determine the velocities of incoming meteors. Most echoes, however, fail to display this diffraction fading pattern due to the slow Doppler shifts imposed on the signal scattered from improper meteor path orientations.
Figure 2.9  An illustration of diffraction fading-echoes observed on signals scattered from meteor trails [McKinley, 1961].
2.4.2 Periodic fades due to mesospheric winds

Deep (~ 10 dB) periodic fading (Figure 2.7), similar to a $|\sin(t)|$ function, can be caused by the superposition of two, or more, discrete Doppler shifted signal components [Manning et al., 1952]. In a meteor scatter fading model advanced by Manning [1959] horizontal mesospheric winds deform the initially straight meteor trail (Figure 2.10a) and cause the main scattering area, i.e. the first Fresnel zone indicated by the solid line in Figure 2.10a at $T_1 = 0$, to distort and warp (Figure 2.10b). As the scattering area warps 'Glints', normal to the receiving antenna are formed (Figure 2.10c). Since glints may be moving in different directions with different velocities, the Doppler shifts imposed on the signals scattered from each glint are unrelated. The periodic fading pattern observed, therefore, (Figures 2.7a, b) results from the beating of these Doppler shifted signal components combining in the receiver [Manning, et al., 1952].

Neutral mesospheric winds, causing meteor trail distortions, have been studied using photographic and radar techniques [JATP, 1978; Greenhow, 1954; Whipple, 1953]. The major wind components within the meteor zone (i.e. between 80 - 120 km height) vary considerably (i.e. hourly, daily and seasonally) but predominantly flow horizontally [Manning, et al., 1954] with a root mean square (rms) velocity of $\sim 50$ ms$^{-1}$. These winds are stratified in height [Aso et al, 1979; Whipple, 1953], and show no correlation between horizontal velocities separated by vertical heights of $\sim 5$ km. These mesospheric wind features satisfy those characteristics required by the fading model developed by Manning [1959].

2.4.3 Non-periodic meteor signal fades

Non-periodic meteor signal fades (e.g. Figure 2.6b, c and 2.8a) can be attributed to mesospheric winds and turbulence [Greenhow and Neufeld, 1959b]. Turbulence,
Original signal scattering area
(first Fresnel zone)

$V_1, V_2, V_3$  Mesospheric wind velocities at different heights

Favourable backscatter region

Figure 2.10 An illustration of trail distortions and glint formation by mesospheric winds.
within the meteor zone, is anisotropic and may have vertical and horizontal eddies of scale ~ 7 and 150 km respectively [Greenhow and Neufeld, 1959a]. Smaller eddies, however, of ~ 3 m have also been predicted [Balsley et al, 1979]. Although the main echoing area (the first Fresnel zone) may not be significantly deformed by the effect of mesospheric turbulence [Greenhow and Neufeld, 1959b], their impact on other scattering regions cannot be neglected.

Winds and turbulence within the meteor zone may rotate segments of the trail, some distance away from the main echoing area, through a sufficient angle to present a new scattering region. This new scattering region will then either add to, or subtract from signals scattered from the main echoing area and cause the received signal to fade.

The influence of winds and turbulence on other longer lived trails can not be neglected. McKinley and Millman [1949] have shown that some meteor signals are not received up to ten seconds after trail formation. These delayed echoes were attributed to segments of the long-duration meteor trails becoming favourably orientated for forward scatter resulting from the influence of winds and turbulence. These delayed meteor echoes may add to or subtract from the main echoing area and cause the scattered meteor signal to fades.

2.4.4 Fades due to meteor trail irregularities and 'blobs'

Some complex signal fades cannot be explained by the theories presented above and have been attributed to irregularities and variations, or 'blobs', of ionisation within the meteor trail column [McNamara and McKinley, 1959]. Although the 'blob' theory of meteor echo fading requires no wind shears, meteor blobs distorted by any wind shears present will result in greater fluctuations of the received signal.
Irregularities and variations of ionisation along the length of the meteor trail may be produced either by minor fragmentation of the incoming meteor, or by an irregularly shaped meteor. Alternatively, blobs of ionisation may be created along the meteor trail path as the meteor passes through thin stratified layers of the atmosphere within the meteor zone (i.e. between 80 - 120 km height). As the trail diffuses patches of ionisation along the irregularly ionised meteor trail may quickly fail to scatter the incident energy and cause the received signal-power to fade.

Previously non-contributing blobs of ionisation may expand, by diffusion, and form new scattering regions. Figure 2.11 illustrates this process for a backscatter system. At time T=1 only one region is orientated favourably for backscatter. As the blobs diffuse spherically, the number of favourable regions contributing to the received signal increases. As new regions begin to scatter the signal towards the receiver, the scattered signal may add or subtract to the main echoing area and result in a meteor signal fade.

2.4.5 Fades from echo overlap trails

Two (or more) meteor trails forming within the common volume illuminated by the transmit and receive antennas [Berry, et al., 1961] will also result in the reception of signal-fades. For example, in the top panel of Figure 2.8b, between T₁ and T₂ the received signal is from a single underdense trail. At T₂ a second meteor trail is formed within the common volume and the scattered signal adds constructively to the signal scattered from the first meteor trail and results in a signal enhancement at T₂. Depending on the path difference between the two trails and the receiver a reduction in signal strength may also be observed as illustrated in the lower panel of Figure 2.8b.
Figure 2.11 The formation, expansion and contribution from ionised blobs [McKinley, 1961].
2.5 Characteristics of meteor scatter fades

2.5.1 Characteristics of periodic fades.

Periodic diffraction fading exhibits frequencies up to 300 Hz [Ellyett and Davies, 1948] and fading depths decrease during the formative stages of signal decay (Figure 2.9). Approximately 10% of meteor trails exhibit this fading pattern [Greenhow, 1950], which is usually complete within the first 0.5 s of signal decay. Since diffraction fades only occur for a short period at high signal-to-noise ratios their detrimental impact on the performance of communications systems is not considered to be significant.

Periodic fading, (not associated with the diffraction phenomena) exhibits a fading period between 0.1 and 0.01 seconds [Greenhow, 1950]. Occasionally, however, fading periods of 1 s can be observed. Simultaneous observations made at 36 and 72 MHz, show that periodic fading at 72 MHz is faster than that observed at 36 MHz, and that the mean fading period at the lower frequency, is \( \sim 0.1 \) s and is independent of the meteor signal duration (Figure 2.12)

Deep periodic fading occurs on 90% of meteor signals of duration > 1.6 s [Greenhow, 1952]. Signals of duration < 0.2 s, however, show no periodic fading and Greenhow [1952] has shown that the onset of periodic signal-fading, from meteor trails which satisfy immediate specular reflection conditions, is delayed on average 0.4 s. It is concluded [Greenhow, 1952], therefore, that the time taken for the formation of a single glint is \( \sim 0.4 \) s.

Conclusions based on periodic fading data collected during different meteor showers [Greenhow 1950] have shown that periodic fading is independent of meteor trail category (i.e. underdense or overdense). This further supports the
Figure 2.12 The relationship between mean fading period and signal duration [Greenhow, 1950]
periodic fading model developed by Manning [1959] who suggested that mesospheric winds produced multiple glints since such a mechanism would affect underdense and overdense trails identically.

2.5.2 Periodic-fading frequency and time into signal-decay

The beat frequency between the discrete Doppler shifted signal components scattered from meteor trail glints is related to glint velocity and direction. As the meteor trail decays more glints are formed and the number of randomly distributed Doppler components rises [Manning, 1959]. This in turn increases the observed fading frequency. As the signal decays, the glints formed first at the ends of the echoing area cease to scatter the signal, and cause the number of glints and, therefore, the fading frequency to decrease towards zero.

If six or more independent periodic-fading signals are combined, the resulting fading signal-envelope can be described using Rayleigh statistics [Schwartz et al., 1966]. This criterion will only be satisfied by meteor signals during the central portion of meteor signal decay when the probability of obtaining 6, or more, glints is highest. Fading meteor scatter signal-envelopes, therefore, are only Rayleigh distributed for a fraction of the meteor signal decay duration.

The Doppler shifts imposed on the scattered signal, and therefore, the fading frequency observed are related to glint velocity and direction. Consequently, two glints moving in opposite directions along the transmitter-receiver path will result in faster periodic-fading frequencies than two similar glints moving in the same direction along the same path. Glints moving in a line perpendicular to the propagation path will only exhibit a small Doppler shift and may only result in slow ( ~ 1 Hz) fading.
2.5.3 Non-periodic signal fades

Greenhow [1950] has shown that wind induced fading due to glint formation from the first Fresnel zone of the single meteor trail is delayed by ~ 0.4 s following trail formation. Wind induced fades, therefore, are more likely to be observed towards the end of the signal-decay duration, than during the formative stages of signal decay. Signal fades, however, may also be caused by small movements of other scattering regions such as segments of other meteor trails originally not orientated favourably e.g. meteor blobs, regions of sporadic-E or ionoscatter.

A fade occurs when the difference in path length between the main scattering area (the first Fresnel zone) and a second scattering region is half the transmitted wavelength. At this time signals scattered from the two regions will destructively interfere causing the received signal-power to fade. At 30 MHz, for example, assuming for simplicity that two scattering regions are initially located at the mid-point along an 800 km transmitter-receiver path, (which is unlikely see sections 1.5 and 2.23), a movement of ~5 m of a scattering region (G2, Figure 2.13a) along the transmitter-receiver path will add signals destructively with the signals scattered from a stationary region G1. A displacement of ~5 m can be achieved in ~0.1 s assuming a root mean square neutral wind velocity (V1) of ~ 50 ms\(^{-1}\) (section 2.4).

If the second scattering region moves in a line perpendicular to the transmitter-receiver path (Figure 2.13b), the distance and time required before destructive interference occurs at the receiver is ~ 2 km and ~ 40 s respectively. It can be concluded, therefore, that signal fades may occur on very short time-scales (i.e. 0.1 s). Since these second scattering regions may be remnants of previous long-duration meteor trails (i.e. not a glint), signal-fades may occur at any time during a meteor signal decay.
Assuming the distance between the main echoing area $G_1$ and the receiver is $d_1$, and the distance between a second scattering region $G_2$ and the receiver is $d_2$, then destructive signal interference from the two scattering areas will occur when:

$$
\left( d_1 - d_2 \right) = \frac{n \lambda}{2} \quad n = \text{integer} \quad \lambda = \text{wavelength}
$$

If $d_1 = 400$ km, the movement required by $G_2$ for destructive signal interference is:

- a) 5 m along the propagation path at 30 MHz
- or b) 2 km perpendicular to the propagation path at 30 MHz

Figure 2.13 Movement required by a second scattering region for destructive interference and a signal fade.
Echo overlap fades are infrequent due to the small probability of two trails first entering and then being correctly orientated within the transmitter-receiver antenna common volume during each-others signal lifetime. These events have a greater probability of occurrence when the density of incoming meteors is greatest. Consequently, due to the diurnal variation of the incident meteor rate, more echo overlap trails may be expected in the morning sector than the afternoon sector. Echo overlap fades may occur on overdense or underdense signals at any time during signal-decay.

Signal fluctuations due to other weak signal propagation modes, e.g. ionoscatter, sporadic-E and propagation from the F2 layer during high sunspot activity are also possible [Bartholomé, 1962]. The magnitude and occurrence of these contributing modes depends on mechanisms of various time-scales and frequencies used.

### 2.6 Ionospheric winds and meteor trail distortions

Prevailing and tidal wind systems within the meteor zone result from solar heating of the earth's atmosphere [Forbes, 1984; Muller, 1966]. The tidal wind velocity, increases with height (Figure 2.14, Greenhow and Neufeld, 1955)), and is dominated by the semi-diurnal component. Prevailing winds, which may gust up to 100 ms$^{-1}$ [Whipple, 1953], are zonal and are sustained within the meteor region by a north-south pressure gradient which is created by the variation of solar heating with latitude.

The prevailing wind and the semi-diurnal tide can be considered independently [Greenhow and Neufeld, 1955], with the latter superimposed on the former. Although both wind systems vary considerably over short time scales (minutes-
Figure 2.14 The variation of meridonal and prevailing winds in the mesosphere with local time and height [Greenhow and Neufeld, 1956].
hours), monthly averaging of the semi-diurnal tide shows a seasonal variation [Muller, 1966]. The east to west and north to south semi-diurnal component have, on average, a lower magnitude in summer than in winter (Figure 2.15). It is difficult, however, to detect a seasonal variation on the lower velocity prevailing winds.

The semi-diurnal and seasonal variations of the mesospheric wind velocities suggest that trail distortions and, therefore, fading, may also be semi-diurnal and seasonal. Although the semi-diurnal fading relationship, with trails created in the morning being more distorted than their afternoon counterparts, have not been investigated to date, a seasonal fading relation has been detected by Landmark [1958].

2.7 Introduction to diversity

2.7.1 Conventional diversity techniques.

In conventional HF, ionoscatter, and troposcatter communications systems, system degradation (e.g. increase in error-rate, decrease in data-rate) due to fading can be reduced by implementing diversity techniques. These techniques, however, can only be successfully applied if the signal fade at two, or more, antennas is decorrelated. One method of obtaining these decorrelated fading signals is by the reception on two, or more, spatially separated antennas; this is commonly known as space diversity. Other reception techniques involve antennas at different heights, angles and polarizations [Schwartz, et al., 1966]. In principle, the number of antennas and the number of reception techniques can be unlimited. For example, diversity may be implemented with dual space (two separated antennas) and dual polarization diversity, or quad space (4 antennas) and quad angle diversity [Schwartz, et al., 1966]. The appropriate diversity
Figure 2.15 a) Monthly averages of the NS and EW semi-diurnal wind component amplitudes observed at Sheffield U.K. [Muller, 1966].
b) Monthly averages of the NS and EW steady prevailing wind observed at Sheffield U.K. [Muller, 1966].
configuration, however, is communications system and propagation mechanism dependant.

Assuming decorrelated fading-signals can be received, the effects of fading can be overcome by implementing one of four principle linear diversity combining techniques, namely: scanning, selection, maximal-ratio, or equal-gain [Brennan, 1959]. Of these four techniques, scanning diversity combination of two Rayleigh fading signals provides the least improvement to average signal-to-noise ratio and signal error-rate. This is primarily due to its lack of regard to the instantaneous signal-to-noise ratio. It is, however, the simplest technique to implement. Maximal-ratio combining provides the greatest diversity improvement in a Rayleigh fading environment, but is the most difficult to implement.

2.7.1.1 Scanning and selection combiners

A scanning combiner [Hausman, 1954] technique uses an antenna switch to scan the diversity antennas until a signal above a set threshold is detected by the receiver. Once detected only that antenna is used by the receiving system until the signal fades below the set threshold (Figure 2.16a). At this time the antennas are re-scanned for a suitable signal.

A selection combiner is similar to a scanning combiner, but the signal which has the greater signal-to-noise ratio at any instant is used by the receiving system (Figure 2.16b). This technique, however, requires signal monitoring of each of the diversity branches to ensure that the branch with the highest signal-to-noise ratio is selected and increases the complexity of the diversity system.
Output $S(t)$ of the co-phasing and summing system due to antenna signal inputs of $S_1(t), S_2(t), \ldots, S_M(t)$ is:

$$S(t) = a_1 S_1(t) + a_2 S_2(t) + \ldots + a_M S_M(t)$$

where 'a' is a weighting value for each received signal, which is proportional to the signal to noise ratio before summation.

Figure 2.17b A schematic representation of an maximal-ratio diversity combiner.
2.7.1.2 Equal-gain and maximal-ratio combiners

Equal gain and maximal-ratio techniques combine all the signals received from all the diversity branches simultaneously (Figure 2.17a and 2.17b). The two techniques rely on coherent addition of the signal with incoherent addition of the noise to improve signal-to-noise ratio, and reduce fading frequencies and fading depths. If signals are combined before they are detected by receivers, co-phasing between signals received on the different antenna branches is required. In equal gain systems the diversity branches are phase-locked and simply added. In maximal-ratio systems, however, each diversity branch is weighted in proportion to its signal-voltage to noise-power ratio before the antenna branches are summed. A maximal-ratio pre-detection combiner is the ideal combining system for maximising the average signal-to-noise ratio and minimising fade depths. This combining technique, however, may require a major instrumentation effort.

2.7.2 Improvements available using diversity

In a digital communications system using non-coherent frequency shift keying (FSK), which is sometimes used in meteor scatter systems, the probability that a '1' will be mistaken as a '0' or visa versa (i.e. error probability) in a Gaussian noise environment is given by [Schwartz, et al., 1966]:-

\[ P_e = \frac{1}{2} \exp\left(-\frac{\gamma}{2}\right) \]  

(2.11)

where \( \gamma \) is the carrier to noise ratio,

\[ \gamma = \frac{\text{signal energy per bit}}{\text{noise spectral density}} \]

or \[ \gamma = \frac{\text{signal power}}{\text{noise power in bit-rate bandwidth}} \]
Output $S(t)$ of the co-phasing and summing system due to antenna signal inputs of $S_1(t), S_2(t), \ldots, S_M(t)$ is:

$$S(t) = S_1(t) + S_2(t) + \ldots + S_M(t)$$

where 'a' is a weighting value for each received signal, which is proportional to the signal to noise ratio before summation.

Figure 2.17a A schematic representation of an equal-gain diversity combiner.

Output $S(t)$ of the co-phasing and summing system due to antenna signal inputs of $S_1(t), S_2(t), \ldots, S_M(t)$ is:

$$S(t) = a_1 S_1(t) + a_2 S_2(t) + \ldots + a_M S_M(t)$$

where 'a' is a weighting value for each received signal, which is proportional to the signal to noise ratio before summation.

Figure 2.17a A schematic representation of an maximal-ratio diversity combiner.
The equation shows that as the signal-to-noise ratio increases, the number of bits received in error (bit error rate) rapidly decreases (Figure 2.18). For example at a signal-to-noise ratio of 11 dB, on average, 1 bit in $10^3$ will be judged to be in error. As the ratio increases to 16 dB the probability of error decreases to 1 in $10^9$ bits.

If a fading signal envelope is assumed to be Rayleigh distributed, then the probability of error for a non-coherent FSK system can be shown to be [Schwartz, et al., 1966]:

$$P_e = \frac{1}{2 + \Gamma} \quad (2.12)$$

where :

$$\Gamma = \frac{\text{mean signal power}}{\text{mean noise power}}$$

This equation is also plotted in Figure 2.18. At a signal-to-noise ratio of ~ 9 dB the bit error-rate of a fading signal is ~1 error in $10^1$ bits transmitted; this contrasts to an error-rate of 1 in $10^2$ obtained in a non-fading environment at an identical signal-to-noise ratio.

Successful diversity schemes reduce fading, increase the average signal-to-noise ratio and enhance the system bit error rate performance. The relative merits of the three primary diversity schemes can be assessed by calculating the average signal-to-noise (SNR) ratio outputs relative to a single non-diversity receiving system. A simplified expression for the SNR improvement obtained from a scan-diversity system, however, is not available. It can be stated, however, that the SNR ratio improvement from a selection combiner will always be greater than a scan-diversity combiner. (A comparison between a dual-scan and selection combiners has been performed by Hausman [1954]). Assuming independent Rayleigh signal-fading at each of the diversity antennas, the average SNR improvement obtained from the three primary combining techniques can be shown [Brennan, 1959] to be :-
Figure 2.18  Bit error rate in a binary non-coherent FSK system with and without Rayleigh fading
Selection: \( D(M) = \sum_{k=1}^{M} \frac{1}{k} \) \hspace{1cm} (2.13)

Equal-gain: \( D(M) = 1 + \frac{\pi}{4} (M-1) \) \hspace{1cm} (2.14)

Maximal-ratio: \( D(M) = M \) \hspace{1cm} (2.15)

where \( M \) is the number of diversity branches and \( D(M) \) is the average SNR improvement obtained using diversity.

As the number of diversity branches increases, the average SNR ratio of the combined signal also rises (Figure 2.19). The relative increase, however, decreases as the number of diversity branches increases, and the greatest relative improvement to SNR is associated with only two diversity branches. During independent Rayleigh fading a dual-diversity system with a selection combiner will produce, on average, a signal-to-noise ratio gain of \( \sim 1.8 \) dB (Figure 2.19). The expected average SNR gains from equal-gain and maximal-ratio systems is \( \sim 2.5 \) dB and 3 dB respectively.

The bit-error-rate obtained using two fold selection \( (P_{e2S}) \) diversity and two fold \( (P_{e2M}) \) maximal-ratio diversity, assuming that the two signals exhibit Rayleigh distributed fading, can be evaluated [Schwartz, et al., 1966] as :-

\[
P_{e2S} = \frac{4}{(2 + \Gamma)(4 + \Gamma)}
\]

and

\[
P_{e2M} = \frac{2}{(2 + \Gamma)^2}
\]

The bit error-rates obtained using the diversity combining equations 2.16 and 2.17 and the bit error-rate obtained for independent Rayleigh fading signals (equation 2.12) are plotted in Figure 2.20. An acceptable bit error rate performance of say 1 error in \( 10^3 \) bits can be achieved with no diversity at an average signal-to-noise
Figure 2.19 Diversity improvement of average signal-to-noise ratio of independent Rayleigh distributed fading signals.
level of \(\sim 27\,\text{dB}\) (equation 2.12). The same performance, however, can be achieved using two fold selection diversity at a signal-to-ratio of \(\sim 19\,\text{dB}\) and at \(\sim 17\,\text{dB}\) using maximal-ratio diversity (Figure 2.20). The reduced signal-power of \(\sim 12\,\text{dB}\) and demonstrates the primary advantage of diversity processing. The bit error rate improvement obtained by combining the uncorrelated fading signals to 'smooth' the signal-fading is significantly greater than the \(\sim 1.8\) and \(3\,\text{dB}\) average signal-to-noise ratio improvement (Figure 2.19) obtained by signal combination using selection and maximal-ratio diversity combining respectively. The average improvement to signal-to-noise ratio could have been obtained by increasing transmitter power rather than implementing diversity; the bit error-rate improvement achieved by increasing the transmitter power by \(3\,\text{dB}\) (Figure 2.20) would only be marginal (this aspect of diversity gain is discussed further in Chapter 7).

2.8 A review of diversity meteor scatter work

2.8.1 Meteor scatter cross-correlation

Cross-correlation coefficients of signal scattered from meteor trails have been computed by several workers [Manning, 1959; Landmark, 1958; Ladd, 1961]. The cross-correlation work of Manning [1959] was performed to support his meteor scatter fading model. In the fading model glint distribution along the meteor trail length is assumed to be Gaussian. The effective re-radiating aperture of the ensemble-average meteor trail will, therefore, also be Gaussian for a Gaussian amplitude distributed wind profile. The periodic signal fading observed on two separated antennas will be different due to the path length differences from the glints within the re-radiating aperture to the receivers. The antenna separation required to reduce the fading correlation by a specified amount is then a measure of the trail aperture.
Figure 2.20  Bit error-rate in a non-coherent binary FSK system with selection and maximal-ratio diversity combining in the presence of Rayleigh distributed fading.
In the investigations performed by Manning [1959] periodic fading patterns were observed at antennas separated by 31, 46, and 62 wavelengths (λ) at 61 MHz. Time was scaled as fading cycle-number and the cross-correlation coefficient was calculated, cycle by cycle, by comparing a cycle-number of a signal from one antenna with an identical cycle-number obtained from a signal on the second and third antennas. The calculated correlation values corresponding to cycle-number multiplied by the antenna spacing were averaged over the ensemble to produce a Gaussian distributed scatter plot, which was in agreement with the Gaussian trail aperture. The results show that for periodic fading, to obtain a cross-correlation value of 0.6 for the first cycle-number an antenna separation of ~ 81 λ (~ 400 m) is required. This reduces to ~ 20 λ (~ 100 m) for the fourth cycle-number.

Landmark [1958] confirmed, using 47 MHz transmissions, the results of Manning [1959]. The standard deviation, however, of the fitted Gaussian curves obtained by Landmark [1958] were smaller in July than October, and he suggested that the analysis technique could be used to study the seasonal variation of wind shears which cause the meteor signals to fade. The results show that at 47 MHz the antenna spacing required for a signal correlation value of 0.6 for the first cycle-number is 14 λ (~ 90 m) in July and ~ 28 λ (~ 180 m) in October. For the fourth cycle-number these separations increase to 24 and 48 λ respectively.

Investigations of meteor scatter space-diversity using cross-correlation techniques were performed by Ladd [1961] on long duration (~ 4 s) meteor signals. The experiment consisted of a 1 kW transmitter operated at ~35 MHz and two five-element Yagi antennas separated from a control antenna by 22λ and 60λ in a perpendicular line across the propagation path. Received signal amplitudes from the three antennas were recorded simultaneously and digitised using a sampling interval of 100 ms. Signal cross-correlation coefficients were calculated over the
total signal duration for underdense, specular overdense and non-specular overdense signals. High correlation coefficients of 0.9946, 0.9819 and 0.7970 respectively were reported by Ladd [1961] and he concluded that due to the high signal correlation values obtained, the implementation of space diversity would result in little gain. The conclusions were based on work performed by Staras [1956] who calculated that 'useful' diversity gain could only be obtained if signals exhibited a cross-correlation coefficients of 0.6 or less. In this calculation the fading signal is assumed to be Rayleigh distributed.

Bartholomé [1962] performed experiments in the 38 to 41 MHz band with 400 watt transmissions, and used the receiver automatic gain control (AGC) voltage as a measure of the received signal amplitude. The attack and decay time of the AGC was 10 and 40 ms respectively. By using an antenna separated by 4 \( \lambda \) in a line perpendicular to the great circle path between transmitter and receiver, a small diversity gain was reported for both underdense and overdense trails. When the signals received, however, were of a long duration (~ 2 s) quasi-independent fading at each antenna was observed, indicating diversity gain.

2.8.2 Meteor scatter diversity systems

The only fully developed meteor scatter communications system incorporating diversity was COMET [Bartholomé and Vogt, 1968]. This system operated at 37 and 39 MHz, implemented space and height diversity and combined the received signals using a multi-detector. Space and height diversity were obtained by four antennas mounted on two masts spatially separated by 4 \( \lambda \). The two antennas on each mast were separated by 1.4 \( \lambda \) with the lower antenna mounted at 1.2 \( \lambda \) from the ground. The lower antennas were single 5-element Yagis and the higher antennas were twin 5-element Yagis. The transmitting antennas were twin 5-element Yagis and the transmitter power was 200 watts. The COMET system
showed a remarkably high throughput [Cannon and Reed, 1987] when compared to other meteor scatter communications systems (Table 1.1) and Bartholomé and Vogt [1968] believed that diversity contributed significantly to the improved throughput.

2.8.3 A summary of conflicting meteor scatter diversity literature

A pre-requisite for the successful implementation of diversity techniques is the existence of uncorrelated fades at two, or more receiving antennas. Under these circumstances a diversity system can compensate for a fade at one antenna by using the uncorrelated fade at another antenna.

Signal correlation studies performed by Ladd [1961] and Bartholomé [1962] are in disagreement regarding the reception of decorrelated meteor scatter signals (hence diversity gain) using spaced antennas. Ladd [1961] concluded that little advantage would be gained by meteor scatter systems implementing $22\lambda$ or $60\lambda$ space diversity due to the high (>0.6) correlation coefficients observed. Fading periods, however, on signals in his frequency band (~35 MHz) typically range between 100 ms and 1 s [Greenhow, 1950] and the 100 ms sampling interval adopted by Ladd [1961] would not have been sufficient to investigate cross-correlations of meteor scatter fading signals and diversity. 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. These high cross-correlation coefficients obtained using spaced antennas appear to be supported by the work performed by Manning [1959] and Landmark [1958]. It must be noted, however, that these workers were primarily concerned with periodic fading and glint formation as opposed to general meteor scatter fading.
The 0.6 cross-correlation coefficient calculated by Staras [1956] and used by Ladd [1961] to indicated diversity gain is based on the reception of Rayleigh fading signals. Manning [1959] has demonstrated that Rayleigh fading, which requires six or more independent signals [Schwartz, et al., 1966], may only occur for a short central period during meteor signal decay. The correlation criterion calculated by Staras [1956] and used by Ladd [1961], therefore, may not always be applicable during the decay of meteor signals.

Bartholomé [1962] suggested that space diversity was a useful technique for reducing the impact of signal fading. Experiments performed by him in the 38 to 41 MHz band using an antenna separation of $4 \lambda$, led him to conclude that diversity gain was small both for underdense and overdense trails, but when the trails were long (> 2 s) quasi-independent, time-varying signals could be obtained. The high correlation values obtained by Ladd [1961] also conflict with the diversity system, COMET, developed by Bartholomé and Vogt [1968]. The COMET system, which exhibited an excellent throughput compared to other meteor systems (Table 1.1), incorporated multiple diversity schemes. The contribution of each diversity scheme to the improved throughput, however, was not quantified and still remains unclear.

In conclusion, it remains unclear if decorrelated signals can be usefully received by meteor scatter communications systems and what antenna separation ($4, 22$ or $60\lambda$) is required for the reception of these decorrelated signals.
Chapter 3  The meteor-scatter transmitting and diversity data acquisition system

3.1 Introduction

Meteor scatter diversity and signal-fading due to multipath from glints and other scattering regions, have been investigated in this thesis by examining ~37 MHz continuous wave (cw) signal transmissions over an 800-km path (Figure 3.1). The cw transmitter was located in Wick, Scotland (58.56° N, 3.28° W) and signals were received at two spatially separated antennas at Cobbett Hill Radio Station in southern England (51.27° N, 0.63° W).

The signal strengths received at the two diversity antennas were measured and recorded using an improved receiving and recording system (termed the data acquisition system) first described by Cannon et al [1987]. The recorded diversity analogue signals were digitised and analysed (see Chapter 4) using either a cross-correlation analysis technique, or a modelled meteor scatter communications system. Both the transmitting and receiving systems were rigorously tested and evaluated to determine, and minimise, any systematic experimental errors. These errors, (e.g. attenuation differences between the two diversity receiving systems) would otherwise have masked the detection of small diversity gains.

This chapter describes the transmitting system, and the diversity data-acquisition system used throughout the meteor scatter diversity experiments. Calibration of the equipment, including the tests performed and the precautions taken to minimise experimental errors, are then detailed. The chapter concludes with a summary of the experiments performed and catalogues the diversity data recorded.
Figure 3.1 Locations of the transmitting and receiving sites
3.2 The transmitting system

The transmitting system (Figure 3.2), located in Wick, Scotland, consisted of one ~37 MHz antenna, a very high frequency (VHF) power amplifier (Plessey-DMW or Henries), a Racal signal generator and attenuator, and a digital output BIRD wattmeter. The transmitting system was controlled from Farnborough using HP 200 series computers and Racal modems. The power amplifier output-power and the power reflected from the antennas were monitored and recorded by the computer system.

The transmitting antenna was a horizontally polarized four-element Yagi mounted at a height of 1λ (at ~37 MHz) which provided centre path illumination at an altitude of 95 km. Transmitter powers at ~37 MHz between 200-400 watts were obtained using the Plessey amplifier, and higher transmitter powers, between 400 - 800 watts, were obtained using the Henries amplifier.

Tests were performed on the Plessey power amplifier, over a 48 hour period, to determine the variation of the amplifier output power with time. The results indicate (Figure 3.3) that the output power varied less than 50 watts, or <0.5 dB of the total power, over the 48 hour test period. The contribution to diversity errors, due to variations of the transmitter power, therefore, were considered insignificant, since power fluctuations were small (< 0.5 dB), and would be common to both the diversity receiving antennas.
Transmitting antenna (4-element yagi)

BIRD wattmeter

Power amplifier (e.g. Plessey)

Standby control unit

HP 9895 Disc Drive

RACAL 9084 signal generator and 9934A attenuator

GPIO

HP 200 series computer

RACAL Milgo Modem

Figure 3.2 Block diagram of the remote transmitting system
Figure 3.3 Variation of forward power from Plessey transmitter over a 44 hour period.
3.3 **The diversity data acquisition system**

3.3.1 **System overview**

The diversity data acquisition system comprised of two receiving and recording systems, channel 1 and channel 2 (Figure 3.4 and 3.5). Each channel consisted of an antenna, a down-converter, a Racal 1792 HF receiver, and a logarithmic detector. The remainder of the acquisition system included a Racal 9084 signal generator and attenuator, and a Racal Store 4DS tape recorder.

The two ~37 MHz diversity receiving antennas (Figure 3.6) were horizontally polarized, four-element Yagis, which were mounted (at Cobbett Hill, England) at a height of 1\( \lambda \), to provide centre path illumination at an altitude of ~95 km. Space diversity experiments were performed at antenna separations of 2.5, 5, 10, 20 and 30\( \lambda \) with the antennas separated perpendicular to the propagation path.

The signals received at each diversity antenna were fed, without amplification using coaxial cables, to a down-converter where the signals were amplified and converted from ~37 MHz to ~10 MHz [Dickson et al., 1987]. Input signals near 15 MHz (i.e. the image frequency) were attenuated by 35 dB at the down-converter inputs using a 15 MHz notch filter. The output from each down-converter fed signals to each HF receiver which was operated with a bandwidth of 3 kHz with the automatic gain control (AGC) turned off. The configuration of each HF receiver is detailed in Table 3.1.

The 100 kHz output intermediate frequency (I.F.) from each receiver was connected to a "logarithmic detector" [Dickson, et al., 1987] which determined the logarithm of the detected input-signal. The linear output-voltage range for each log-detector was between 1.5 and 4 V which corresponded to ~37 MHz down-
Figure 3.4  Block diagram of the meteor burst diversity data acquisition system
Figure 3.5  The diversity data-acquisition system located in the laboratory at Cobbett Hill Radio Station.
Figure 3.6 Two 4-element Yagi diversity receiving antennas separated by $2.5\lambda$ and $1\lambda$ above the ground at Cobbett Hill Radio Station.
converter input signal-powers of -130 and -94 dBm, respectively, using the HF receiver configurations detailed in Table 3.1. Typical voltage equivalent power-levels output at each log-detector, for down-converter input signals ranging from -133 to -76 dBm are plotted in Figure 3.7. The 36 dB linear dynamic range at each log-detector (i.e. signal saturation occurs below -130 and above -94 dBm) encompassed most (~95%) of the meteor signal powers detected during the diversity experiments performed.

3.3.2 Configurations of the diversity receiving system

During diversity data collection the receiving system was periodically configured to one of four receiving modes using a Hewlett Packard 200 series computer (configured for BASIC 2.1), and two computer controlled relay-control units (see section 3.2.3). These four receiving modes of data collection were: "NO DATA", "CALIBRATION", "NOISE", and "SIGNAL". The signal generator and attenuator, and the two receivers were controlled using the computer IEEE-488 bus; the relay control units were interfaced to the computer via two control lines of the General Purpose Input Output (GPIO) port. By decoding these two GPIO lines, the radio-frequency (RF) relays were switched between the down-converter (for diversity data collection) and the signal generator and attenuator (for calibration purposes).

Relay control unit "1" supplied a control voltage which was recorded, on the third track of the Store 4DS tape recorder (Figure 3.5), simultaneously with the diversity data. This control voltage was used, during data analysis, to distinguish between the four different data acquisition modes. Control voltages associated with the "NO DATA", "CALIBRATION", "NOISE" and "SIGNAL" data collection modes were 0, 1.66, 3.33, and 5 V respectively. Each of these modes was visually identifiable on the front panel of the relay control unit by one of four light emitting diodes (LED), i.e. flashing red, steady red, yellow, and green, respectively.
Table 3.1  HF receiver configurations

<table>
<thead>
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<th>Parameter</th>
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<th>Receiver 2</th>
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<td>RACAL 1792</td>
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<td>Frequency</td>
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<td>10.6776 MHz</td>
</tr>
<tr>
<td>Detector</td>
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</tr>
<tr>
<td>IF filter</td>
<td>3.0 kHz</td>
<td>3.0 kHz</td>
</tr>
<tr>
<td>AGC mode</td>
<td>Manual</td>
<td>Manual</td>
</tr>
<tr>
<td>BFO frequency</td>
<td>1 kHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>IF attenuation</td>
<td>41</td>
<td>35</td>
</tr>
<tr>
<td>digital units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF attenuation</td>
<td>8.51 V</td>
<td>8.61 V</td>
</tr>
</tbody>
</table>
Figure 3.7 Typical log-detector output voltages obtained during receiving system calibration.
The control voltages were recorded by the Store 4DS FM tape-recorder, set to a 3 V recording range, as 0, 1, 2, and 3 V. The status and configuration of the receiving system during each of the four receiving modes is summarised in Table 3.2.

The system default "NO DATA" mode (0 Volts, flashing red LED) indicated that the diversity signals being recorded were not for analysis. During this "NO DATA" mode the down-converter inputs were switched to the signal generator which was set to 1 MHz and -70 dBm (i.e. the inputs were terminated by 50 Ω). Each diversity data-tape started and ended with at least 5 s of this "NO DATA" mode. The "NO DATA" mode at the start of each data tape was always preceded by the "CALIBRATION" mode. This latter mode was used to record voltage-equivalent power-levels and enabled absolute values of signal strength, detected at the down-converters, to be derived.

System "CALIBRATION" was performed by switching the down-converter inputs to the signal generator and attenuator, tuning the signal-generator frequency to ~37 MHz, and attenuating the signal power, every 5 s by 3 dB, from -76 dBm to -133 dBm. The equivalent log-detector output voltages during each signal attenuation were recorded simultaneously with a 5 V control voltage. Typical calibration voltages recorded by the tape recorder are plotted in Figure 3.8; each receiving channel saturates below -133 dBm and above -94 dBm.

On completion of the "CALIBRATION" mode, the system was configured for "NOISE" data collection by re-setting the signal generator to 1 MHz and -70 dBm, switching the down-converter inputs from the signal generator to the receiving antennas, and by de-tuning the two HF receivers by 10 kHz. The noise voltages output at the log-detectors were recorded for 30 s following which the receivers were re-tuned for diversity "SIGNAL" acquisition.
<table>
<thead>
<tr>
<th>Voltage recorded</th>
<th>System mode</th>
<th>Relay control unit positions</th>
<th>Signal generator values</th>
<th>Receiver frequencies</th>
<th>Duration of system mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>NO DATA</td>
<td>Signal generator</td>
<td>1 MHz; -70 dBm</td>
<td>F₁</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F₂</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>CALIBRATION</td>
<td>Signal generator</td>
<td>37 MHz; -70 to -127 dBm in 3 dB steps</td>
<td>F₁</td>
<td>~ 100 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F₂</td>
<td>(5s each step)</td>
</tr>
<tr>
<td>2</td>
<td>NOISE</td>
<td>Antennas</td>
<td>1 MHz; -70 dBm</td>
<td>(F₁+10 kHz)</td>
<td>~ 30 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(F₂+10 kHz)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>SIGNAL</td>
<td>Antennas</td>
<td>1 MHz; -70 dBm</td>
<td>F₁</td>
<td>~ 29 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F₂</td>
<td></td>
</tr>
</tbody>
</table>

**Note**

* Signal power inputs to the down-convertors are further attenuated by 6 dB due to a 3 dB signal splitter and a 3 dB buffer.

† F₁, F₂ refer to tuned frequencies of receiver 1 and 2 given in Table 3.1.
Figure 3.8  Typical calibration data stored on analogue tape prior to diversity data acquisition.
The duration of the "SIGNAL" mode was 28 minutes and was preceded by "CALIBRATION" and "NOISE". Depending on the duration of the data tape, these two latter modes were either followed by "SIGNAL" or "NO DATA". Figure 3.9 illustrates the format of the diversity data recorded on each one hour data tape.

### 3.3.3 The relay control units

The two relay control units, required for the two receiving systems, operated in a master-slave configuration, with control unit 1 configured as the master unit. Using positive logic, control lines CTRL0 and CTRL1, from the HP computer GPIO port, were decoded (see Figure 3.10a) to satisfy the outputs of Table 3.3. The positive going output of the decoder was used to drive one of four (normally open) relays, which in turn switched the appropriate control voltage (5, 3.33, 1.66 or 0 V) and the corresponding LED. Control line CTRL1 was used to switch the RF Hatfield relay between (Table 3.3) the signal generator (for calibration purposes) and the receiving antennas (for diversity data collection). Although the master relay unit could be controlled manually, using the switch control-box (Figure 3.10b), diversity data-acquisition was only performed with the master unit controlled by the computer via the GPIO port.

To reduce computer generated noise coupling into the RF circuitry via the relay units, shielded cables were used to interface the master control unit to the computer, via the switch control-box. The pull up resistors required by the computer open collector outputs were located on the GPIO interface unit. High frequency noise, generated by the computer and passed down the control lines, was further reduced by inserting low pass filters between the control line inputs and the decoder circuitry (Figure 3.11). To isolate the fast switching present in the decoder, the decoder was housed separately from the RF relay and associated
Figure 3.9 The format of a one-hour analogue diversity data-tape
Figure 3.10a The 2 to 4 line decoder used to switch the appropriate control voltage and LED.

Figure 3.10b The switch control-box used for manual override of the relay control units.
Table 3.3  The 2 to 4 line decoder truth table indicating the action of the positive going output

<table>
<thead>
<tr>
<th>CTRL0</th>
<th>CTRL1</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Output voltage</th>
<th>L.E.D</th>
<th>Relay position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Flashing RED</td>
<td>Signal generator</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>Steady RED</td>
<td>Signal generator</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3.3</td>
<td>YELLOW</td>
<td>Receiver</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.6</td>
<td>GREEN</td>
<td>Receiver</td>
</tr>
</tbody>
</table>
Figure 3.11 Circuit diagram of the relay control unit.
circuitry, with each circuit having separate earth return. The circuits used low frequency switching transistors (e.g. 2N5192).

The five volts used by the decoder was derived from the 24 V supply using a 7805 regulator. Further voltage division of the 5 V was achieved, using resistors, which provided the remaining 3.33, 1.66 and 0 V control voltages required. To visually identify the current state of the relay control units, four LED were used (Table 3.3).

3.4 The analogue recording system

Two log-detector output signals, one control voltage and an audio signal were recorded on the four channels of a Store 4DS tape recorder (Figure 3.4) set to a 3V recording range. Audio signals were recorded using a direct recording (DR) channel, and all other signals were recorded using the frequency modulated (FM) recording channels. The DR channel was also used for audio inputs of the date, time, antenna separation, transmitter power etc.

The tape speed used, throughout the diversity experiments, was 3.75 inches per second, which enabled the diversity and audio signals to be recorded within a bandwidth of 0-1250 Hz, and 100 Hz - 19 kHz respectively, using the tape recorder intermediate bandwidth configuration. The duration of each diversity data recording tape, of length 1200 feet, was one hour; this conveniently resulted in three calibration periods and two signal periods per tape (Figure 3.9).

3.5 Determination and evaluation of systematic errors

It was imperative, due to the lack of information regarding the magnitude of the diversity gain expected from meteor scatter signals, to ensure that no systematic experimental errors occurred. Failure to identify and minimise these experimental
errors would otherwise have masked the detection of small diversity gains. The errors of primary concern were voltage drifts, resulting from changes in gain of the diversity receiving and recording system, and voltage offsets due to differences in attenuation between the two receiving systems.

To assist in the evaluation of experimental errors, software was developed for the HP 200 series computer which used two 8-bit Biodata Microlink analogue-to-digital converters (ADC) to nearly simultaneously sample (within 40 μs of each other) two voltages. Voltage drifts and offsets of interest were then detected by examining ten minute ADC averages obtained by sampling the voltage channels every second over long (12-24 hour) periods.

Tests were initially performed on the two 8-bit ADC units, which were identically calibrated to range from 0 - 4.5 V linearly (i.e. 0 to 255 ADC units), to ensure ADC errors and drifts were minimal. Two constant voltages of 2.5 V, supplied by a stabilised power supply, were sampled simultaneously every 1 s for 24 hours. The ten minute ADC averages obtained showed that the two voltages remained constant, within 1 ADC unit (or 0.018 V) over the 24 hours. Using the linear region of the receiving system calibration curve for log-detector 1 (Figure 3.7), a variation of 0.23 V at the log-detector corresponds to a down-converter input signal-strength change of ~3 dB. A variation, therefore, of 0.018 V (1 ADC value) is equivalent to a signal strength error of ~0.2 dB. The error detected by the ADC units was attributed to quantisation noise and noise present on the constant voltages supplied (possibly due to power supply fluctuations). The error, however, was used to define the minimum error expected, using the two ADC units, during receiving system tests.

For evaluation purposes the receiving and recording system was divided into four sub-systems (Figure 3.4) : the receiving antennas, the antenna feeder cables, the receiving system and the analogue signal-storage system (i.e. FM tape recorder).
3.5.1 Diversity antenna errors

The radiation patterns of the two receiving antennas, each mounted at a height of $1\lambda$ (at ~37 MHz) and separated by $2.5\lambda$, were modelled [Cox, 1990] above a perfectly conducting earth by the numerical electromagnetics code (NEC). The results showed that the azimuthal antenna radiation patterns (Figure 3.12) of the two antennas, separated perpendicular to the propagation path (i.e. with the antennas side-by-side Figure 3.6), were identical, and that the radiation pattern of one antenna was not modified by the proximity of the second antenna.

The effects of local features, such as the 2 m high radio-station wire fence 1 and 3 m away from Antenna 2 and 1 respectively, were also modelled using NEC. The results showed that these local features also had no effect on the antenna radiation patterns.

Noise data collected and digitised using the modelled communication system (Chapter 4) showed that the number of milliseconds that noise signals were above a defined power-threshold at each antenna, were similar (within 1%). These measurements and the antenna radiation patterns determined earlier, indicated that diversity errors, due to differences in antenna radiation patterns, would be small (< 1%).

3.5.2 Antenna feeder cable errors

The "CALIBRATION" procedure of the receiving system could not compensate for signal-attenuation between the antennas and each down-converter input (Figure 3.4). Failure to ensure that feeder cable attenuations were identical would have resulted in an erroneous constant diversity gain. Cable losses, therefore, were measured, using a HP 8753C RF network analyser, and equalised to within an error
Model conditions

Frequency = 37 MHz
Max gain = 14.15 dB
Horizontal polarization
Perfect ground
Antenna 1λ above ground

Figure 3.12 Antenna radiation pattern (elevation plane) of a 4-element Yagi antenna modelled using NEC [Cox, 1990].
of ~0.25 dB, using a Hatfield attenuator and small lengths of radio feeder cables of known attenuation.

Radio cables from Antenna 1 consisted of UR 74 and UR 67, and Antenna 2 cables comprised of low loss 15/8" diameter LDF/150 cable and UR 74 cables. The total attenuation, at ~37 MHz, of the feeder cables connected from Antenna 1 to down-converter 1 was measured to be -1.78 dB. Antenna 2 feeder cables were measured to be -2.72 dB. Differences in attenuation resulted from the extra cable length (~150 m) required to separate Antenna 2 from Antenna 1 by 20λ. Both attenuation measurements were confirmed, to within an error of 0.5 dB, using a receiver and voltmeter.

Considerable precautions were taken to ensure that all connectors were carefully shielded and protected from water, which often increased the cable attenuations by ~ 1 dB. Small (~ 0.5 dB) differences in attenuation between the two diversity receiving systems were found to cause errors between 5 - 10% when the modelled communications system was used. Minor differences in attenuation caused no difficulties when the signals were analysed using the cross-correlation technique (see Chapter 4).

3.5.3 Receiving system errors

Changes in the gain of each receiving system (Figure 3.4) were evaluated by monitoring the expected constant output-voltage, at each log-detector, for constant down-converter input signal-powers. For experimental accuracy the receiving system was investigated in-situ at the receiving station (Cobbett Hill). Throughout the tests performed the down-converter input signals were -100 dBm at ~37 MHz, and the receivers were configured as shown in Table 3.1. The tests were performed over extended periods (e.g. 6 or 24 hours) and the log-detector output voltages
were sampled every second; differential receiving system drifts were then examined by plotting the ten minute ADC averages obtained (Figure 3.13).

The maximum variation of signals, over the 24 hours, is ~ 1.2 dB at log-detector 1, and ~2.5 dB at log-detector 2 and demonstrates that a calibration every 24 hours would have been impractical. The divergence/convergence of the apparent average signal strengths observed at the log-detectors (Figure 3.13) would have been interpreted as diversity gain, unless unrealistically small intervals (i.e. minutes) between calibrations were performed. For example, between 2200 and 2400 UT, the signals strength detected by log-detector 2 were greater than log-detector 1 by ~ 5 ADC units (or 1.2 dB). Between 1000 and 1200 UT, however, log-detector 1 was on average greater than log-detector 2 by ~ 0.4 dB. These receiving system fluctuations were further investigated to minimise the voltage drifts observed, and to determine the optimum time required between system calibrations which could be used to compensate for minor system fluctuations.

Apparent signal fluctuations caused by log-detectors drifts were investigated by examining ten-minute ADC log-detectors outputs, over an extended period, using known log-detector input signals (0.02 V peak to peak at the receiver I.F. of 100 kHz). The results showed that, once the detectors had been switched on for a period of ~6 hours, the output voltage of each log-detector drifted less than one ADC unit in 12 hours. The large (>4 ADC units) system drifts, therefore, could not be attributable to the log-detectors.

After considerable testing, the primary cause of the large (~ 0.18V) voltage drifts observed were traced to thermal effects within the HF receivers and downconverters, with the former contributing the greater error. The thermal effects due to the HF receivers are summarised in Figure 3.14, where the output voltage at log-detector 1, and the (root-mean-square) receiver IF voltage, are plotted as a
Figure 3.13 The output variation at the log-detector for constant down-convertor input powers.
function of increasing surface temperature of receiver 1. As the surface
temperature increases the average ADC values (averaged over one minute) and
the receiver IF output voltage (measured every minute) decrease. A change in
surface temperature from 38°C to 42°C caused an output variation of 4 ADC units
(0.072 V or -1 dB) at the log-detector.

Similar, but limited, measurements were made on the receiving system as the
temperature of down-converters circuits were increased/decreased. The
measurements indicated that the log-detector output voltage was related to the
temperature of the down-converter circuits.

To minimise thermal effects present within the down-converters, together with
any effects within the log-detectors, the thermal capacity of the material
surrounding the electronic components was increased by using polystyrene chips,
and the items were protected from local temperature fluctuations (e.g. drafts, direct
sunlight). Temperature variations within the receivers were reduced by carefully
monitoring and controlling, using heaters and cooling fans, the surface
temperatures to within 1° Celsius. Using these techniques the output variations
(for a constant ~37 MHz down-converter input signal) at each log-detector,
averaged over ten minutes during a 6 hour test, were reduced to 1 ADC unit
(Figure 3.15). A convenient interval between system calibrations was considered to
be ~30 minutes; this 30 minute period allowed three calibrations per tape
(Figure 3.9).

3.5.4 Signal recording errors

Each recording channel of the Store 4DS FM tape recorder was calibrated using the
digital voltmeter alignment procedure described in the Racal manual. Each FM
and DR channel was set to a 3 V recording range. Consequently, the output
Figure 3.14 The variation of log-detector and receiver output as a function of HF Receiver 1 surface temperature using a constant receiver signal input-power.
voltages from the master relay control unit (i.e. 0, 1.66, 3.33, or 5 V) were recorded as 0, 1, 2 and 3 V.

The voltage gain stability of the two FM recording amplifiers, used to record the output signal from the log-detectors, were tested using a constant DC input voltage of 3.5 V. The output voltages (2.1 V taken at the replay ports) from each amplifier were sampled every second, nearly simultaneously, and the ten-minute ADC value averages obtained were examined. The results showed that the two output voltages remained constant, to within 1 ADC unit error, during the 48 hour test. It was concluded, therefore, that errors of <1 ADC unit were introduced by the FM amplifiers.

The recording and replaying mechanism was tested by recording, onto tape, two DC voltages of 3.5 V for 90 minutes. The two voltages recorded were then replayed and digitised several times and the ten-minute ADC value averages obtained were examined. The results showed that each time the tape was replayed, the output voltages remained constant to within an error of 1 ADC unit, and the average ADC values were identical to those of the previous test. This demonstrated that signals could be recorded and then replayed accurately (within 1 ADC value, or 0.018 V) many times.

3.6 Noise and noise figures

The receiving station was located in a rural area, and no local VHF interference sources were observed. The median-value of the cosmic noise-power at ~37 MHz was determined to be ~17 dB above thermal noise at $T_0 = 288$ K [CCIR., 1990]. Figure 3.16 illustrates the gains and noise-figures associated with each item of receiving equipment. The noise power of each complete receiving system was calculated to
Figure 3.15 Log-detector output variations with constant down-converter input signal-power. Equipment temperature and environment controlled to within 1°C.
be 7 dB; the two diversity receiving systems, therefore, are noted to be cosmic noise limited.

The noise was also measured at the receiving antennas at ~37 MHz using a Rhode and Schwartz ESPV 20-1300 MHz test receiver. In a 3 kHz bandwidth the noise was measured to be at -124 dBm. This noise power is calculated to decrease to -134 dBm for a 250 Hz bandwidth used in the modelled communications system, and -144 dBm for 25 Hz bandwidths used during correlation analysis. These noise-powers are used, during data-analysis to enable signal-to-noise ratios to be calculated because the system-noise could not be monitored during the diversity experiments (Chapter 4).

Although hardware precautions had been taken to reduce computer generated noise, passing down the relay control unit coaxial cables from the GPIO port, precautions were also taken to use computer code which generated the least noise (e.g. careful use of BEEP commands etc.). Local computer generated noise was also reduced by carefully positioning the computer equipment relative to the down-converters and HF receivers.

3.7 Meteor scatter diversity experiments

The primary experiments performed using the diversity data-acquisition system concerned the reception of 400 W cw transmissions at antenna separations (perpendicular to the propagation path) of 2.5, 5, 10, and 20λ (at ~37 MHz). To minimise the reception of sporadic-E signals which might have confused the study of meteor scatter signals, morning and afternoon data were first collected in February 1990 (Table 3.4) when the predicted incidence of sporadic-E modes [CCIR., 1990] was at a minimum. A second experiment was performed in August, i.e. during the sporadic E season, with antenna separations of 5, 10, and 20λ (Table 3.5).
Figure 3.16 Gain and noise figure distributions within each receiving system.
Experiments were also performed during 1990-1991 at different transmitter powers, antenna heights and at a separation of ~ 30λ, and although the data were not analysed in this thesis the experiments are summarised, for information, in Tables 3.6 - 3.8. Table 3.9 outlines a 24 hour experiment performed in June 1991 with antennas separated by 5λ.

3.8 Summary

Signal strengths recorded using the diversity data acquisition system initially varied ~ 2 dB with time. The large errors were traced to thermal effects within the two HF receivers and down-converters. By carefully controlling the equipment temperature these errors were reduced, and it has been demonstrated that signal strength could be recorded within an error of (1 ADC unit) ~ 0.2 dB.

Other systematic errors, such as those introduced by the tape recorder, were also investigated and the results showed that these errors were of a similar magnitude (i.e. 1 ADC unit). The attenuation errors, of signal losses from the antennas to the down-converters, were estimated to be ~ 0.25 dB. In conclusion, by combining the three experimental errors (in a root mean square fashion) the signals detected at the two antennas could be recorded and replayed within a signal strength error of ~ 0.4 dB.
Table 3.4  Summary of data collected in February 1990: Variation with antenna separation.

<table>
<thead>
<tr>
<th>Day number 1990</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna spacing (λ)</th>
<th>Transmitter power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>0910</td>
<td>1425</td>
<td>2.5</td>
<td>400</td>
</tr>
<tr>
<td>40</td>
<td>1000</td>
<td>1540</td>
<td>2.5</td>
<td>400</td>
</tr>
<tr>
<td>44</td>
<td>0926</td>
<td>1602</td>
<td>5</td>
<td>400</td>
</tr>
<tr>
<td>45</td>
<td>1005</td>
<td>1415</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>46</td>
<td>1019</td>
<td>1541</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>47</td>
<td>1000</td>
<td>1427</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>51</td>
<td>10:03</td>
<td>1534</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>52</td>
<td>0950</td>
<td>1411</td>
<td>5</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 3.5  Summary of data collected in June 1991: Single antenna separation.

<table>
<thead>
<tr>
<th>Day number 1991</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna spacing (λ)</th>
<th>Transmitter power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>176</td>
<td>0708</td>
<td>1522</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>177</td>
<td>0812</td>
<td>1500</td>
<td>10</td>
<td>400</td>
</tr>
</tbody>
</table>
Table 3.6  Summary of data collected in July 1991: Variation with antenna separation.

<table>
<thead>
<tr>
<th>Day number</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna spacing (λ)</th>
<th>Transmitter power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>205</td>
<td>0830</td>
<td>1541</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>206</td>
<td>0830</td>
<td>1147</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>210</td>
<td>0845</td>
<td>1438</td>
<td>30</td>
<td>400</td>
</tr>
<tr>
<td>211</td>
<td>0800</td>
<td>1450</td>
<td>30</td>
<td>400</td>
</tr>
<tr>
<td>213</td>
<td>0830</td>
<td>1357</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>214</td>
<td>0725</td>
<td>1204</td>
<td>20</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 3.7  Summary of data collected in April 1990: Variation with transmitter power.

<table>
<thead>
<tr>
<th>Day number</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna spacing (λ)</th>
<th>Transmitter power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>1015</td>
<td>1515</td>
<td>5</td>
<td>800</td>
</tr>
<tr>
<td>94</td>
<td>1003</td>
<td>1323</td>
<td>5</td>
<td>600</td>
</tr>
<tr>
<td>96</td>
<td>1003</td>
<td>1331</td>
<td>5</td>
<td>440</td>
</tr>
<tr>
<td>97</td>
<td>1050</td>
<td>1405</td>
<td>5</td>
<td>200</td>
</tr>
</tbody>
</table>
Table 3.8 Summary of Data Collected in August 1991. Variation with antenna height, at an antenna separation of $5\lambda$.

<table>
<thead>
<tr>
<th>Day number</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna separation ($\lambda$)</th>
<th>Transmitter power (W)</th>
<th>Antenna height ($\lambda$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>0727</td>
<td>0829</td>
<td>5</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>225</td>
<td>1022</td>
<td>1124</td>
<td>5</td>
<td>400</td>
<td>0.5</td>
</tr>
<tr>
<td>225</td>
<td>1157</td>
<td>1259</td>
<td>5</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>225</td>
<td>1345</td>
<td>1447</td>
<td>5</td>
<td>400</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3.9 Summary of a 24 hour diversity data acquisition experiment

<table>
<thead>
<tr>
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<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna separation ($\lambda$)</th>
<th>Transmitter power (W)</th>
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</thead>
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<td>0735</td>
<td>- -</td>
<td>10</td>
<td>400</td>
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<tr>
<td>184</td>
<td>- -</td>
<td>1600</td>
<td>10</td>
<td>400</td>
</tr>
</tbody>
</table>
4.1 Introduction

Cross-correlation analysis is used in this thesis to first determine if uncorrelated meteor scatter signals can be received at the two spatially separated antennas, and then to clarify the conflicting literature outlined in Chapter 2. The analysis is performed by first identifying the different signal categories (e.g. underdense or overdense signals) received at the two antennas before cross-correlation coefficients are calculated.

A modelled meteor scatter communications system is used to evaluate whether the diversity signals recorded are advantageous to a meteor scatter communications system implementing diversity. The investigation is achieved by modelling communications systems parameters, such as the total-time available for signal transmission, error-probability etc, for a modelled communications system with and without diversity combining. A number of diversity combiners are investigated.

This chapter describes the data acquisition and analysis systems used to perform the two diversity analysis techniques outlined above. Both of these offline digital analysis techniques use the analogue diversity-data collected using the diversity receiving system described in Chapter 3.
4.2 The cross-correlation analysis system

4.2.1 Cross-correlation functions and coefficients

A cross-correlation function, $R_{xy}(\tau)$, can be derived in the time-continuous domain to describe the degree of dependence between two time-dependant signals, $x(t)$ and $y(t)$. The cross-correlation function is found by obtaining the average product between $x(t)$ at $t$, and $y(t)$ at $t = t + \tau$, over the observing period $T$ (Figure 4.1) using the equation [Bendat and Piersol, 1971]

$$R_{xy}(\tau) = \frac{1}{T} \int_0^T x(t) y(t + \tau) \, dt$$

4.1

The correlation function defined by this equation is real and either positive or negative. If the cross-correlation function is zero at a value of $\tau = 0$ (i.e. $R_{xy}(0) = 0$), then the two data sets are said to be uncorrelated. If the cross-correlation function is zero at all values of $\tau$ (i.e. $R_{xy}(\tau) = 0$) then $x(t)$ and $y(t)$ are statistically independent. A non-zero cross-correlation function indicates that the two signals exhibit a statistical dependency, with the dependency increasing with increasing correlation function value.

If the mean values of the two signals ($\mu_x$ and $\mu_y$) over the analysing period $T$ are zero, the normalised cross-correlation coefficient, may be defined as [Bendat and Piersol, 1971]

$$\rho(\tau) = \frac{R_{xy}(\tau)}{\sqrt{R_x(0)} \sqrt{R_y(0)}}$$

4.2

where $R_x(0)$ and $R_y(0)$ are the signal autocorrelation functions calculated as

$$R_x(\tau) = \frac{1}{T} \int_0^T x(t) x(t + \tau) \, dt$$

4.3

and

$$R_y(\tau) = \frac{1}{T} \int_0^T y(t) y(t + \tau) \, dt$$

4.4
Figure 4.1  Cross-correlation of two time-continuous signals $x(t)$ and $y(t)$
at $\tau=0$. The cross-correlation coefficients, defined by equation 4.2, satisfies the limits $-1 \leq \rho(\tau) \leq +1$.

A cross-correlation coefficient of +1 indicates that the two signals are identical and in-phase; a value of -1 indicates identical, anti-phase signals. For example, Figure 4.2 shows a correlogram (i.e. a plot of $R_{xy}(\tau)$ against $\tau$), obtained using the system described in section 4.2.3, of two sine-waves of frequency 10 Hz, with $\tau$ ranging between $\pm 100$ ms. Coefficient values of +1 occur at $\tau = 0$ (i.e. zero phase shift) and at $\tau = \pm 100$ ms (i.e. 360° phase shift). A correlation value of -1 occurs at $\pm 50$ ms (i.e. a 180° phase shift).

If the two time-series signals have non-zero mean (i.e. $\mu_x, \mu_y \neq 0$) due to the presence of a DC component, the cross-correlation coefficient is calculated as in equation 4.1 but with the auto-correlation functions at $\tau=0$, being calculated as

$$R_x(0) = \frac{1}{T} \int_0^T (x(t) - \mu_x)^2 dt$$

and

$$R_y(0) = \frac{1}{T} \int_0^T (y(t) - \mu_y)^2 dt$$

and with the cross-correlation function defined as

$$R_{xy}(\tau) = \frac{1}{T} \int_0^T (x(t) - \mu_x) (y(t + \tau) - \mu_y) dt$$

4.2.2 Digital calculation of the cross-correlation coefficient

Two time-continuous signals can be translated to their time-discrete form, consisting of "n" data points, using an analogue-to-digital converter (ADC) operated at a sampling rate of "h". The two time-continuous signals, $x(t)$ and $y(t)$, are then represented by the discrete data sets $x(nh)$ and $y(nh)$ respectively.
Figure 4.2 A correlogram of two 10 Hz signals obtained using the cross-correlation acquisition and analysis system.
The digital cross-correlation coefficient equation can then be written as

$$\rho(r) = \frac{R_{xy}(r)}{\sqrt{R_x(0)} \sqrt{R_y(0)}}$$  \hspace{1cm} (4.8)

where $R_y(0)$ is the auto-correlation function of the time series $y(nh)$ at $\tau=0$. The cross-correlation coefficient is calculated for a displacement "r", an integer which ranges between -m and +m such that the lead/lag times are given by $\tau_{\text{max}} = mh$ and $\tau_{\text{min}} = -mh$.

Assuming that "s" is the start-time sample number and "e" is the end-time sample number, such that the analysing period $T = (e-s)$, the cross-correlation coefficient is calculated digitally using equation 4.8 with [Bendat and Piersol, 1971]

$$R_{xy}(r) = \frac{1}{(e-s)} \sum_{n=s,e}^{r=m,-m} (x_n - \bar{x})(y_{(n+r)} - \bar{y}_r)$$  \hspace{1cm} (4.9)

where the mean value of the time-series $y(nh)$, shifted by $r$ (or by $\tau = rh$) is

$$\bar{y}_r = \frac{1}{(e-s)} \sum_{n=s,e}^{r=m,-m} y_{(n+r)}$$  \hspace{1cm} (4.10)

and where

$$\bar{x} = \frac{1}{(e-s)} \sum_{n=s,e} x_n$$  \hspace{1cm} (4.11)

The auto-correlation functions, $R_x(0)$ and $R_y(0)$, subtracting any DC offset, are calculated as

$$R_x(0) = \frac{1}{(e-s)} \sum_{n=s,e} (x_n - \bar{x})^2$$  \hspace{1cm} (4.12)

and

$$R_y(0) = \frac{1}{(e-s)} \sum_{n=s,e} (y_{(n+r)} - \bar{y}_r)^2$$  \hspace{1cm} (4.13)

These equations (4.8 - 4.13) were implemented in the data acquisition and correlation system described below.
4.2.3 Cross-correlation analysis system hardware

The cross-correlation data acquisition and analysis system is described in Figure 4.3. The system digitised and stored two voltage channels (e.g. the diversity signals recorded by the Racal Store 4DS tape recorder) and calculated the cross-correlation coefficient of the two digitally stored signals over observing periods specified by the user.

Two 8-bit Microlink ADC units were configured to convert signals between 0-3 V using a sampling rate between 1 and 100 ms. At a sampling rate of 10 ms the two ADC units were sampled within 40 µs of each other. This adjacent unit sampling time, and the sample and hold facilities available on each ADC unit, produced the effect of virtual simultaneous sampling. The Microlink unit was controlled by a Hewlett Packard (HP) 200 series computer via the IEEE-488 bus. To minimise the time-delay between samples, the ADC values were passed to the internal computer memory using a "Transfer" statement.

Anti-aliasing was achieved using a dual-channel Wavetek 852 variable low-pass Butterworth filter, which had a 48 dB per octave, per channel, roll-off. At a sampling rate of 10 ms, which was used to digitise the analogue diversity-data for cross-correlation analysis, the anti-aliasing filter was set to 25 Hz to satisfy the Nyquist theorem (i.e. that the highest sampling rate should be less than twice the highest signal frequency present).

The cross-correlation data acquisition system was semi-automated. The ADC sampling rates were automatically set using software switches, and the Racal Store 4DS tape recorder was controlled by the computer via the GPIO port. The anti-aliasing filter cut-off frequency, however, was set manually, and the calibration data values (which were used to convert the ADC signal values to signal powers)
Figure 4.3 The cross-correlation data acquisition and analysis system
were entered by the operator (see 4.2.4). The time taken to digitise 150 s of diversity signals and convert these signals, using the calibration equation, to absolute signal powers was approximately 10 minutes.

4.2.4 Software description and validation

The digital data-acquisition and analysis software was written for a HP 200 series computer in Basic version 2.1. A brief description of each of the main menu items, shown in Figure 4.4, is given in Appendix B.

Prior to analogue diversity-data digitisation, calibration-data required to convert the ADC signal samples to signal powers was entered. The calibration-data was obtained by digitising the analogue calibration voltages recorded (Chapter 3) on each tape. Figure 4.5a shows the digitised calibration voltages in ADC units (ordinate axis) against time (abscissa) for the two diversity channels. As time increases the calibration voltage decreases, by 3 dB every 5 seconds, from -76 dBm to -133 dBm. Two second averages of each ADC calibration level were assigned to known signal power-levels by the operator. A third order curve fit equation was then calculated (Figure 4.5b) and stored. This calibration equation was used to convert the 15000 ADC signal samples obtained per channel, into absolute signal power levels, which were then stored to disc for future analysis. The maximum number of samples taken per channel was 15,000 (i.e. 30,000 samples for two channels) and was defined by the maximum computer-memory array-size which must be less than 32 767 elements.

During data analysis digitised diversity signals stored on disc were first retrieved and stored in memory. Small segments (1, 5, 10 and 30s) of the diversity data were then plotted (Figure 4.6) to show signal strength values (dBm, ordinate) against
Meteor Scatter Diversity Cross-correlation
Acquisition and Analysis Program

Main Menu

- CREATE a new calibration file.
- DIGITISE and STORE a new meteor scatter data.
- DISPLAY and ANALYSE the data set.
- MERGE two $R_{xy}(0)$ data files together.
- RECALL and PRINT a $R_{xy}(0)$ data file.
- $R_{xy}(0)$ data file analysis.
- EXIT from the program.

Figure 4.4 The main menu of the cross-correlation acquisition and analysis program.
Figure 4.5 Typical computer outputs from the cross-correlation system of
a) the calibration data and
b) a third order curve fit between ADC values and dBm values.
Figure 4.6 A typical computer display output showing the diversity signals obtained from the cross-correlation system.
time (seconds, abscissa). A sliding vertical time cursor also became active and was used to define the signal durations above the user defined fixed power threshold.

The analysis software calculated the cross-correlation coefficient of the two diversity signals over a time segment specified by the user. Cross-correlation coefficients at $\tau=0$, average signal amplitudes within the analysing segments, and the duration of the signal (which is determined by the user) were stored to disc in an ASCII format. The analysis results were stored to data files which best described the signal under current investigation (e.g. an underdense or overdense signal). Since meteor signal decay is a non-stationary process, cross-correlation coefficients with $|\tau| > 0$ are invalid and, therefore, were not stored.

Validation of the cross-correlation software was initially performed by analysing the results obtained using two sine-waves of differing frequency, phase delay, amplitude and DC offset. These simple tests produced predictable results (Figure 4.2) which were easily confirmed. Further tests were performed by evaluating the cross-correlation values obtained using band-limited Gaussian noise.

The cross-correlation of band-limited white noise results in $\rho_{xy}(\tau) \neq 0$ at $\tau = 0$ [Bendat and Piersol, 1971]. A zero value, however, will occur at $\tau \leq 1/2B$, where B is the bandwidth of the noise data; for example, if $B = 25$ Hz then $\rho_{xy}(\tau) = 0$ at $\tau \leq 0.02$s. The relationship, between bandwidth and $\tau$, was confirmed for a variety of bandwidths, using noise generators and appropriate sampling frequencies and low-pass filter bandwidths.

To further validate the cross-correlation software the cross-correlation variance of band-limited Gaussian white noise was determined. Bendat and Piersol, [1971] have shown that the variance $\chi$ of the correlation value, assuming the mean values to be zero ($\mu_x, \mu_y = 0$), is:

$$\chi = \frac{1}{2B}$$
\[ \chi = \frac{1}{2BT} \left( R_x(0) R_y(0) + R_{xy}^2(\tau) \right) \]  

4.14

where \( T \) is the analysing period and \( B \) is the bandwidth. This equation, however, is only valid when the conditions \( BT \geq 5 \) and \( T \geq 10 \) are satisfied. Band-limited Gaussian noise (obtained from two noise generators) was cross-correlated over time periods which satisfied the above criteria, and the variance of each correlation value associated with each \( \tau \) was compared with the computed values. This analysis was performed for a variety of bandwidths (\( B \)) and analysis periods (\( T \)). The cross-correlation coefficients calculated, for all values of \( \tau \), were close to the theoretical values determined by the variance calculation.

The receiving system noise recorded on each data tape (Chapter 3) was not cross-correlated, during diversity signal analysis, due to non-linearities in the log-detector output near the noise level. The 10 ms sampling rate used to digitise all the diversity data, defined the anti-aliasing low-pass filter bandwidth to be 25 Hz. The system noise-power in a 25 Hz bandwidth was measured to be at -144 dBm (Chapter 3); the linear dynamic range of the log-detector, however, was between -130 and 94 dBm. Consequently, the noise displayed, which appears to be at \( \sim -133 \) dBm (see Appendix A) is artificially high due to the limited log-detector output range.

4.3 Modelled meteor scatter communications system

4.3.1 The acquisition system

A diversity communications system was modelled using the diversity throughput data-acquisition and analysis system shown in Figure 4.7. The software was written [Stocker et al., 1988] in PASCAL version 3.2 for the HP 300 series computer. Diversity signals recorded on FM channels 1 and 2 were low-pass filtered, by a
Figure 4.7  The signal-throughput data-acquisition and analysis system
dual-programmable Wavetek 552 filter, and then digitised by an Infotek AD200 12-bit analogue-to-digital converter. A control voltage, recorded on FM channel 3, which consisted of DC voltages between 0 and 3V was also digitised. The Wavetek filter and the Infotek ADC were controlled by the HP 300 computer via the IEEE-488 bus; the Store 4DS tape recorder, however, was controlled manually.

The three FM diversity channels were simultaneously sampled, within 250\(\mu\)s of each other, using a sampling frequency of 1 KHz and a low-pass anti-aliasing filter bandwidth of 250 Hz. All signals above a user defined power threshold and greater than a set duration (\(\geq 40\) ms) were digitised and stored for offline analysis.

The control voltage reflected the status of the diversity receiving and recording system (i.e. "NO DATA", "CALIBRATION", "NOISE", "SIGNAL") used to record the diversity signals (Chapter 3). This control voltage was decoded by the throughput acquisition system to identify the four different diversity receiving modes.

Each one hour diversity data-tape was digitised and stored to either hard disc or tape with header, calibration information files. The header file contained experiment information (e.g. date, time, antenna separation etc.), and the calibration file contained ADC equivalents of the system calibration voltages (Figure 4.8). The calibration data file was used as a look-up table during data analysis and converted the ADC values to signal dBm values.

4.3.2 Throughput analysis techniques

The digitised diversity signals were analysed using two main algorithms which made no differentiation between the various signal propagation modes (e.g. underdense or overdense signals) present. The analysis results, therefore,
Figure 4.8 A typical calibration curve obtained using the signal throughput analysis system (ADC values against dBm).
realistically represent a communication system which also do not make this distinction.

The first algorithm [Stocker et al., 1988] evaluated "Signal availability" by determining the total number of milliseconds (i.e. ADC units) that the received signal was greater than a specified power threshold, and therefore, available for communications. Signal availability was determined for a non-diversity communications system (e.g. using channel 1 or channel 2 only) and for a system incorporating diversity combining.

The second analysis algorithm simulated a broadcast meteor scatter communications systems which transmitted data-blocks of fixed duration. The broadcast system was modelled by repetitive and contiguous transmissions, starting at time T=0 (Figure 4.9a), of complete data-block durations, where a data-block is only transmitted if the signal amplitude is greater than the specified threshold for the total duration of the data-block. The broadcast data communications model counted the number of data-blocks transmitted for each receiving channel individually and for receiving system which implemented two channel diversity combining.

A block duration mode (Figure 4.9b) was also implemented by Stocker et al., [1988] although it was not used in this thesis. The mode, which may be used to form the basis of a half duplex type (i.e. communications in one direction only at any time) meteor scatter communications model, operated using the non-diversity and diversity channels.
Figure 4.9  An illustration of a) the broadcast mode and 
b) the block duration mode, modelled by the communications system.
4.3.3 **Diversity combining techniques investigated**

Of the possible four common diversity combining techniques (Chapter 3) the signal-availability and the broadcast throughput were modelled for a scanning and maximal-ratio type diversity system. The signal-availability and broadcast throughput for the scan-diversity technique were determined by accumulating the number of ADC samples, or data-blocks transmitted, when one "OR" the other signal channel was above the threshold. This scanning diversity model assumed that signal-detection and antenna switching could take place within 1 ms; i.e. the antenna scanning frequency was 1 KHz.

Before the signal-availability and the broadcast system could be modelled for the maximal-ratio type combiner, the output expected from a maximal-ratio combiner were determined. In a maximal-ratio type combiner, the combiner output signal-to-noise ratio is evaluated \[Brennan, 1959\] from the sum of the individual power ratios of each diversity channel, i.e.

\[
P_m = \sum_{k=1,2} P_k \tag{4.15}
\]

where \(P_k\) are the output power ratios of each diversity channel, \(k\), (\(k\) in this diversity experiment was 2). In modelling this technique, it is assumed that co-phasing (e.g. using phase-locked loops) of the signals prior to diversity combination has taken place. *Brennan* [1959] has shown that phase differences less than 37.5° will only result in a degradation of signal-gain of \(\sim 1\) dB in maximal-ratio or equal-gain combiners.

The maximal-ratio type combining technique was modelled assuming that the voltage induced, on channel 1, across a resistor (R) of 50 \(\Omega\) due to a received signal of power of \(P_1\) (watts) was
\[ V_1 = (P_1 R)^{1/2} \]

and similarly the voltage induced for channel 2 was,

\[ V_2 = (P_2 R)^{1/2} \]

then the maximal-ratio detector output voltage was determined as

\[ V_E = V_1 + V_2 \]

which is calculated in dBm as

\[ P_E = 20 \log (V_E) \]

The average signal-to-noise ratio gain obtained over a single receiving system will be 3 dB if the signals are locally coherent and if the noise on each channel is independent and uncorrelated. For example, if \( V_1 \) and \( V_2 \) are both 2 V and the root mean square (RMS) noise is 1 V (i.e. signal-to-noise ratio is 6 dB), then the combiner output will be 4 V for signal, with noise voltage increasing in an RMS manner to 1.414V. The non-diversity 6 dB signal-to-noise will increases, by 3 dB, after maximal-ratio combining to 9 dB.

The maximal-ratio type diversity channel was obtained via an offline conversion program. This program combined the signals on channel 1 and 2, using the technique described above, and re-stored the maximal-ratio output power and the output-power for non-diversity system under a new filename. Since noise signal-powers could not be recorded by the receiving system (section 4.2.4) the noise power measured using a Rhode and Schwartz ESPV measuring receiver (i.e. -134 dBm in the 250 Hz bandwidth, Chapter 3) was used to define the receiving system noise-floor for the non-diversity system. In a maximal-ratio diversity system, the system noise is modelled to increase by 3 dB. Consequently, the noise floor at the output of the maximal-ratio combiner was assumed to be -131 dBm in the 250 Hz bandwidth.
4.3.4 Modelled Frequency shift keying error probabilities

The non-coherent frequency shift keying (FSK) error probabilities (Chapter 2) were modelled, by the analysis system described above, for a non-diversity system and a selection and maximal-ratio diversity system. The error-probability ($P_e$) for a single non-diversity system is determined digitally for "d" signal samples above a specified receiver threshold by evaluating (Chapter 2):

$$P_e = \frac{1}{2d} \left[ \sum_{n=1, d} \exp \left( -\frac{\gamma(n)}{2} \right) \right]$$

(4.16)

where $\gamma(n)$ is the signal-to-noise ratio of signal sample "n" above the specified receiver threshold 't'. During the evaluation of error-probabilities the system noise was assumed to be constant at -134 dBm for the 250 Hz bandwidth non-diversity system (Chapter 3). For the non-diversity system error-probabilities the signal power samples used are obtained from receiving channel 1. For a selection diversity system the error-probability is determined using equation 4.16 and samples from whichever channel experiences the (instantaneous) greatest signal power. The maximal-ratio diversity errors were calculated using the signal output modelled by the maximal-ratio combiner assuming that the noise-floor was -131 dBm (i.e. the measured noise-floor plus 3dB).

4.4 Summary

This chapter has described two analysis systems used for the investigation of diversity signals recorded on FM tape. Both analysis systems digitised the analogue recorded signals using HP computers.

The cross-correlation analysis system digitises the diversity-data using a sampling rate of 10 ms and an anti-aliasing, low-pass, filter bandwidth of 25 Hz. The system
enables signals above a pre-defined threshold to be displayed, categorised and
cross-correlated over periods defined by the operator.

The modelled communications system digitises signals at a sampling rate of 1 ms and an anti-aliasing, low-pass, filter bandwidth of 250 Hz. The system models a single communications system and a communications system which incorporates diversity combining, and determines whether the analogue diversity signals recorded are advantages to a communications system incorporating diversity.

FSK error probabilities for a non-diversity, selection-diversity and maximal-ratio diversity systems, are also modelled by the communications system model. The system noise floor, required to calculate the FSK error-probability in the 250 Hz analysis bandwidths used, was assumed to be -134 dBm for the non-diversity system and the selection diversity system, and -131 dBm for a maximal-ratio diversity system.
Chapter 5  Cross-correlation investigation of meteor-scatter space diversity signals received at 10λ

5.1 Introduction

This chapter reports the cross-correlation investigations of 400 Watt cw transmissions (Chapter 3) received on two antennas spatially separated by 10λ (at ~37 MHz) in February. The two days of data analysed (Table 3.4 and 5.1) were collected in February when the incidence of sporadic E, which may have confused the investigation of meteor scatter signals, was predicted to be at a minimum [CCIR., 1990].

The results will reveal if decorrelated signals (an indication of diversity gain) exist, and clarify previous conflicting literature (Chapter 2) published by Ladd [1961] and Bartholomé [1962]. The antenna separations used by Ladd [1961] were 22λ or 60λ at ~35 MHz, and the cross-correlation coefficients of 0.9946, 0.9819 and 0.7970 computed for underdense, specular overdense and non-specular overdense signals respectively, were obtained using a 1-kW transmitter. The no-diversity gain conclusions of Ladd [1961] conflict with the results of Bartholomé [1962] who, using 400 W transmissions and an antenna separation of 4λ, predicted meteor scatter diversity gain.

The received signals analysed in this Chapter are categorised as "underdense", "overdense" or "Not Known" (NK) to determine which category, on average, exhibits the greater decorrelation. The NK category contains signals of an undefined format which may be associated with scattering from sporadic E, ionosscatter, or non-specular meteor trails. The contents of this chapter appear in a more concise format in Shukla et al. [1992].

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Table 5.1  Timetable of data analysed from Cobbett Hill in February 1990

<table>
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<tr>
<th>Day Number</th>
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<th>Data End time (UT)</th>
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</tr>
<tr>
<td></td>
<td>13:25</td>
<td>14:26</td>
</tr>
</tbody>
</table>
5.2 Data analysis

The received signals from each antenna were recorded (Chapter 3), in a 1.25 kHz tape recorder bandwidth, and digitised in a 25 Hz bandwidth for correlation analysis (Chapter 4). The 10 ms sampling interval used was ten times shorter than that used by Ladd [1961].

A threshold of -120 dBm (equivalent to a 3 dB signal to system noise ratio in a 3 kHz channel) was used for signal analysis. The cross-correlation coefficients for zero lag ($\tau=0$) were evaluated for the "underdense," "overdense," and "Not Known" (NK) signal categories. Since meteor decay is a non-stationary 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 signal by the discontinuity observed on the rising edge of both the underdense and overdense signal envelopes (Figure 5.1). Data 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 is taken to be that time when both channels fell below the analysis threshold value. The signal decay period was therefore, determined by the longer duration channel and incorporated the important period when only one channel was above the threshold. It is during this period that 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. The correlation period (0.25 s) adopted, therefore, was sufficient to encompass most periodic fades and enabled sufficient samples to be
Figure 5.1 Signal classifications:

- a) underdense signal
- b) overdense signal
- c) not known (NK) signal
taken for cross-correlation analysis (see 4.2.4). Signals of duration less than 0.25 s, therefore, were not cross-correlated in this study. A cross-correlation value of a segmented signal was only stored for further analysis if 50% of the segment signal was above the analysis threshold (i.e. -120 dBm).

Correlation values from the first 0.25 s segment of each signal category were grouped together and formed the statistics for segment number 1. Correlation values from the second 0.25 s segment formed the statistics for segment number 2, and so on (Figure 5.1a). Implicit in this grouping was the assumption of an average ionisation height and location. This ignored the differing geometrical factors which would affect the decay of meteor trails occurring within the common volume illuminated by both antennas.

The distributions of signal durations examined by Ladd [1961] were not clear. It is reasonable to assume, however, that he primarily studied long (> 1 s) duration signals due to his limited sampling interval 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 5.1b). This latter envelope technique was similar to that used by Ladd [1961] and enabled new results to be compared with those results obtained by Ladd [1961].

The correlation start time for NK signals is identified by the first signal crossing of the analysis threshold (Figure 5.1c). Otherwise the analysis was the same as for underdense and overdense signal categories.

5.3 Received signal categorisation.

Appendix A shows examples of underdense, overdense and NK signal categories. Similar signal categorisation has been performed by Østergaard et al. [1985], and
the characteristics used to identify the different signal categories are summarised below.

Signals scattered from an underdense trail were characterised by a fast (~ 0.1 s) rising increase in signal strength followed by a slower linear decay (in dB) which started immediately after the envelope had reached its maximum amplitude.

A specular overdense signal (Figure 5.1b) was also characterised by a fast (~ 0.1 s) rise in signal strength until the first Fresnel zone was formed. This was followed by a period of slowly increasing signal strength, resulting in a rounded top to the received envelope, followed by the decay of the signal. Overdense decay durations and received signal strengths are usually greater than those from underdense trails.

Signals not of the above format were categorised as 'not known' (NK). Figure 5.1c shows a highly uncorrelated waveform which is categorised as a NK signal. Signals which suffered from echo-overlap decorrelation [Berry et al. 1961] (Figure 5.2) were also categorised as NK

5.3.1 Examples of diversity gain signals.

In the underdense signal illustrated in Figure 5.1a, the decay duration on channel 1 is greater than on channel 2 by an amount $\Delta t$. In this example a simple diversity antenna switch (i.e. a scan diversity system) would effectively increase the meteor scatter signal duration by the amount $\Delta t$ s. This example of diversity gain contrasts with the overdense signal example in Figure 5.1b, where a diversity antenna switch would not increase the effective signal duration and would not, therefore, be advantageous in a meteor scatter (MS) system.
In the NK signal example (Figure 5.1c) 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 MS system for this NK signal example. The echo-overlap signal illustrated in Figure 5.2, would also be advantageous to a diversity processing system. The deep fade occurring just after $T_2$ on channel 2, could be compensated by the signal on channel 1, and the average duration may be increased by $\Delta t$ s due to channel 2.

Figures 5.3a and 5.3b illustrate deep periodic fading. In the first example, underdense signal fades received at the two antennas are approximately correlated, and diversity processing would not be advantageous. In the second example, however, the periodic fading pattern observed on the overdense signal is uncorrelated and diversity processing would be of clear advantage.

5.4 Results

5.4.1 Signal decorrelation with time: signal durations $\geq 0.75$ s

Preliminary space diversity studies Cannon, et al. [1988] indicated a dependence of meteor scatter signal correlation values with time from the start of the trail decay. New data are presented for three signal categories which are examined as a function of time from the start of the signal decay envelope (i.e. segment number). A repeat of the analysis technique, used by Ladd [1961], which is only briefly described by Ladd [1961], is also attempted by investigating signals correlation values calculated over total signal decay durations. Segmented and unsegmented signal correlation values are then compared.
Figure 5.2  An example of an echo-overlap signal
Figure 5.3  Deep periodic fading observed on: a) an underdense signal and b) an overdense signal.
Firstly, the distribution of signal decay durations are examined. Signals scattered from underdense trails are, as expected, shorter (Figure 5.4) in decay duration than those from overdense signals. Only 15% of the underdense signals have a duration greater than 0.75 s, this compares to 42% for the overdense signal category. NK signals, however, experience durations which are more similar to overdense than underdense signals. The short duration of these NK signals leads us to suspect that a majority of these NK signals may be of a meteoric origin.

Greenhow [1952] has suggested that the onset of meteor signal fading is delayed by ~0.4 s after trail formation. The time-dependency of cross-correlation values, therefore, was investigated by examining signals of a minimum duration of 0.75 s. This ensured that at least three 0.25 s correlation segments for each signal category were above the analysis threshold, and that short-duration low-power meteor signals were not compared with longer duration higher-power meteor signals. This data-selection criterion assisted in ensuring that the signals analysed were, on average, 'similar' in each signal category. For illustrative purposes, segments 4 and 5 were examined, at a 0.6 cross-correlation threshold level, by examining minimum signal durations of 1 s and 1.25 s respectively; these two segments, however, were not analysed in further detail.

5.4.1.1 Underdense signal correlation values

Forty nine signals of duration ≥ 0.75 s were identified as underdense from the two days of data collected (Table 5.1). This sample number decreased to 29 and 21 for signal durations of ≥ 1 s and ≥ 1.25 s respectively. Cumulative correlation distribution values obtained from the first three 0.25 s signal segment are plotted in Figure 5.5, along with values calculated from the total, unsegmented, signal decay envelope. Segment 4 and 5 values at the 0.6 threshold level are illustrated in Figure 5.6a.
Figure 5.4  Signal-duration probability for the three signal categories
Figure 5.5 Cumulative correlation probability curves applicable to 49 underdense signals of duration $\geq 0.75$ s
Figure 5.6  Cumulative cross-correlation value at the 0.6 threshold for:

a) underdense signals,
b) overdense signals,
c) not known signals.
In Figure 5.5 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] for underdense trails, although it is unclear if his 0.9946 is a median or a mean. The high correlation values obtained from the unsegmented envelope appear to support the hypothesis that space diversity, using underdense trails, will provide little gain in meteor scatter systems. This conclusion, however, will be shown to be 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 5.5). However, the segmented signal correlation probabilities, below the 0.6 threshold, increase from 20% for segment 1, to 35% for segments 2 and 3. At the 0.6 threshold level the cumulative cross-correlation probabilities for segment 4 and 5 (obtained by analysing signal durations ≥ 1 and ≥1.25 s) are 56% and 48% respectively and support the trend towards decorrelation observed with increasing segment number (Figure 5.6a). On average, 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 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.
5.4.1.2 Overdense signal correlation values

Sixty eight signals of duration $\geq 0.75$ s were identified as scattered from overdense trails. Cumulative correlation distributions were evaluated for unsegmented trails and for segmented trails (Figure 5.7). Cumulative probabilities for segments 4 (50 signals) and 5 (41 signals), obtained by analysing signal durations $\geq 1.0$ s and $\geq 1.25$ s respectively, at the 0.6 threshold level are plotted in Figure 5.6b.

High correlation values are observed for the total unsegmented overdense signal decay envelope (Figure 5.7). Only 4 % of the total unsegmented overdense signals have correlation values of 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, a conflict between correlation values calculated over the unsegmented total signal envelope and the and those calculated from a segmented signal is found.

If the correlation values from segmented signals are considered, it is found that the correlation distributions (Figure 5.7) for segments 1, 2 and 3 are very similar (within 10 %). This similarity is also apparent for segments 4 and 5, for 50 and 41 overdense signals, respectively. The correlation probabilities at the 0.6 threshold level are 27 %, 34 % and 23 % for signal correlation segments 1, 2 and 3 respectively, and 30% for segment 4 and 37 % in segment 5. The lack of any significant trend towards decorrelation with increasing segment number (Figure 5.6b) is in contrast to the time-dependant correlation values observed for underdense signals (Figure 5.6a).

It is usual to attribute received signal amplitude fluctuations to perturbations of the trail by mesospheric winds. Consequently, both overdense and underdense
Figure 5.7 Cumulative correlation probability curves for segments 1, 2, and 3, applicable to 68 overdense signals of duration ≥ 0.75 s.
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 for the underdense and overdense signal categories suggest, however, that the amplitude fluctuation mechanism is trail dependent. It is suggested that the differences can be attributed to the typically greater received signal strength observed from overdense trails. Examination of the received signal-power (Figure 5.8) between segments 1 to 5, shows that the median received power in each segment for overdense signals only changes by approximately 2 dB between segments 1 and 3. This contrasts to a 5 dB change for the underdense signal category.

It is proposed that meteor signal decorrelation occurs via two mechanisms. The first mechanism may be attributed to with the creation of secondary scattering regions by mesospheric winds [Manning, 1959, Villard et al., 1956] as described earlier (see chapter 2). The second mechanism arises from weak (less than -120 dBm) signals from other modes (e.g. sporadic-E and ionoscatter) signals which add to the received MS signal in an uncorrelated fashion at the two antennas. The latter mode will particularly affect low power underdense and NK signals (Figure 5.8). It is suggested that the decreasing correlation value observed in both segments 2 and 3 (and supported by segments 4 and 5) 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 would be expected to have relatively little affect 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 will only contribute to signal decorrelation as the signal strength decays. It remains somewhat surprising that no trend towards decorrelation is apparent by segment 5 for the overdense
Figure 5.8  Average median power present between segments 1 to 5 in the three signal categories.
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, therefore, be due to inadequate antenna separation.

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

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

5.4.1.3 NK signal correlation values

The NK signal category, as well as containing ionoscatter and sporadic-E signals, also contains signals of meteoric origin; for example, echo overlap trails, and scattered signals which do not exhibit the characteristic rise time and envelopes necessary to identify the other two categories. The 112 NK signals, of duration \(\geq 0.75\) s are, on average, of a lower received power than those of the other two signal categories (Figure 5.8). The received signal power in segments 4 and 5 (from 75 and 56 signals respectively) also exhibit signal powers similar to segments 1, 2 and 3. Due to the low received signal-power, significant decorrelation is anticipated for all 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 5.9). The median and mean values are 0.66 and 0.52 respectively. A comparison of the cumulative distribution curves for the first three segments from the three signal categories (Figures 5.5, 5.7, and 5.9) indicates that NK signals are generally less correlated than underdense or overdense signals.

NK signals exhibit a trend towards 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, and then to 54 and 70% for segments 4 and 5 (Figure 5.6c).

5.4.1.4 Combined underdense, overdense and NK signal correlation values

Although it is useful to categorise the received signals in order to clarify fading mechanisms etc., a meteor scatter communications system cannot distinguish between overdense, underdense and NK signals. Consequently, all the correlation values from the three different signal categories are combined together. Cumulative distribution curves for correlation values calculated over total signal envelopes, and those calculated for segments 1, 2 and 3, are presented in Figure 5.10. Approximately 25% of the signals in segment 1 have correlation values less than 0.6; this probability increases to approximately 40% for segment 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 have a median of 0.84 and mean of 0.7.
Figure 5.9 Cumulative correlation probability curves for segments 1, 2 and 3 applicable to 112 not known signals of duration \( \geq 0.75 \) s.
Figure 5.10  Cumulative correlation probability curves for segments 1, 2 and 3 applicable to all received signals of duration $\geq 0.75$ s.
5.4.2 Signal decorrelation with time: signal durations ≤ 0.25 s

In Figure 5.11 the short duration underdense signal has a greater duration on Channel 2 than Channel 1 by an amount Δt s; the signal also appears to be uncorrelated towards the latter stages of signal decay. Although, these short duration signals were not analysed, due to the insufficient sampling rate, the figure indicates that short duration underdense signals may also be decorrelated and possibly useful to a diversity system.

These short duration trails support the fading theory discussed above, where other weak signal modes add to weak underdense signals to cause the fade observed. Meteor scatter communications systems which exploit these short duration underdense trails, therefore, may also gain from diversity processing.

5.4.3 Signal decorrelation with time: signal durations ≥ 10 s

Signals of duration > 10 s are also observed (Figure 5.12), although they are infrequent, these signals often experience deep (~ 10 dB) fading. Although it is unlikely that this example signal is of a meteor origin, these long duration signals exhibit regions of signal decorrelation.

Long duration, non-meteoric signals, can be exploited by meteor scatter communications systems. Reducing the impact of fading on these long duration signals, by implementing diversity, can only enhance the exploitation of these long-duration signals. These long-duration signals were not analysed further, due to their infrequent occurrence.
Figure 5.11. Short duration (~ 0.25 s) underdense signal indicating signal decorrelation

Figure 5.12. A long duration (> 10 s) NK signal showing regions of signal decorrelation.
5.4 Summary

This chapter 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 firstly 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]. 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.

Correlation conclusions based on the total decay envelope correlation method used by Ladd [1961] have been shown to be wrong. Correlation values obtained using the total decay envelope are high and similar to those correlation values obtained over segment 1 using the signal segmentation analysis method (Table 5.2). The unsegmented total decay correlation values are dominated by the time decaying signal envelope assuming that the perturbation of 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, therefore, that the correlation-time dependency is, partly, a result of the relatively low power received signals, i.e. underdense or NK, combining with other weak power signal modes. These weak modes, however, have little effect on the overdense signals which, typically, have a 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 (Table 5.2). NK signals, therefore, promise the greater diversity advantage. When all the received signals are combined together to model signals received by a MS system, 40% of the signals of duration $\geq 0.75$ 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 was expected, 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 may also be expected. 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, it has been shown that the high correlation values calculated by Ladd [1961] were a consequence of the measurements based upon signals analysed over their whole duration. 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].

Attention is also drawn to the work of Staras [1956], which contributed to the conclusions of Ladd [1961], concerning the degree of decorrelation required before the signal is 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 MS channel. The work of Staras [1956] is not, therefore, always applicable to MS signal fading.
Table 5.2  Probabilities of obtaining cross-correlation values less than 0.6

<table>
<thead>
<tr>
<th>Trail category</th>
<th>Cumulative probability at the 0.6 correlation threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Segment 1</td>
</tr>
<tr>
<td>underdense</td>
<td>18.4</td>
</tr>
<tr>
<td>overdense</td>
<td>26.5</td>
</tr>
<tr>
<td>not known (NK)</td>
<td>26.8</td>
</tr>
<tr>
<td>Combined signals</td>
<td>24.9</td>
</tr>
</tbody>
</table>
In conclusion, the results presented in this Chapter show that decorrelated meteor scatter signals can be detected. The signal-decorrelation further suggests that the implementation of space diversity may be advantageous, especially when NK signals propagate. A diversity contribution, however, can also be expected from overdense and underdense trails particularly towards the end of their trail lifetimes when significant decorrelation occurs.
Chapter 6  **Signal cross-correlation investigations as a function of antenna separation and season**

6.1 **Introduction**

The modest $4\lambda$ antenna spacing implemented by Bartholomé and Vogt [1968] contrasts with the $10\lambda$ spacing investigated in Chapter 5 and the larger $22\lambda$ and $60\lambda$ spacings used by [Ladd, 1961]. Other work by Manning [1959] and Landmark [1958] suggests that even larger separations ($> 60\lambda$) may be required to obtain signal decorrelation. The 'optimum' antenna spacing required to obtain decorrelated signals remains unanswered. For practical purposes, therefore, the 'optimum' antenna spacing, i.e. the minimum antenna spacing required to obtain adequate diversity signal decorrelation, must be determined. The amount of land required for the deployment of a meteor scatter space-diversity system, an important consideration when operating at relatively low frequencies between 30-50 MHz, can then be minimised.

The first section of this Chapter determines, using the cross-correlation analysis technique, the optimum antenna spacing required for a ~37 MHz meteor scatter space diversity system operating at temperate latitudes. Recommendations are made concerning the optimum antenna spacing for the signal categories analysed, i.e. underdense, overdense and not known (NK). The spatial diversity results presented in this chapter appear in a more concise form in Cannon et al. [1993].

The proportion of NK signals might be expected to increase during the summer solstice periods when the incidence of sporadic-E peaks. A decorrelation trend, therefore, should be apparent with signals received in summer being, on average, more decorrelated than those received in winter. In the second section of this Chapter the winter-summer (or seasonal) variation of signal decorrelation is
investigated for each signal category by comparing the results obtained in February with those obtained in June.

6.2 Experiment and analysis technique summary

The spatial decorrelation data analysed was collected in February 1990, (i.e. during predicted low incidence of sporadic-E and NK signals) and morning and afternoon data were collected at three different antenna separations of 5λ, 10λ and 20λ (Table 6.1). The winter-summer correlation variation was investigated by analysing the 10λ antenna separation data (Table 6.2) collected in June 1991, when the incidence of sporadic-E and NK signals was expected to be high. The analogue data recorded was digitised, categorised and analysed identically to that described in Chapter 5 (see sections 5.2, 5.3).

6.3 Results- spatial variation of cross-correlation coefficients

6.3.1 Signal duration and the cross-correlation of noise at -120 dBm

The duration of each signal category above the analysis threshold of -120 dBm (i.e. 3 dB signal to system-noise threshold in 3 kHz bandwidth) is plotted for each antenna separation in Figure 6.1. The signal duration of each individual category is similar at each antenna separation. NK signals, on average, have a greater duration than underdense signals, but a shorter duration than overdense signals (see also Figure 5.4). This again suggests that NK signals may be of a meteoric origin, and possibly due to long duration overdense signals not originally orientated favourably for forward scatter.

The effects of noise on cross-correlating signals received at a threshold of -120 dBm are illustrated on each of the cumulative probability density figures
Table 6.1  Timetable of Data Collected, at Cobbett Hill, in February 1990

<table>
<thead>
<tr>
<th>Day number</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna spacing (λ)</th>
</tr>
</thead>
<tbody>
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<td>44</td>
<td>09:26</td>
<td>16:02</td>
<td>5</td>
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<tr>
<td>45</td>
<td>10:05</td>
<td>14:15</td>
<td>10</td>
</tr>
<tr>
<td>46</td>
<td>10:19</td>
<td>15:41</td>
<td>20</td>
</tr>
<tr>
<td>47</td>
<td>10:00</td>
<td>14:27</td>
<td>20</td>
</tr>
<tr>
<td>51</td>
<td>10:03</td>
<td>15:34</td>
<td>10</td>
</tr>
<tr>
<td>52</td>
<td>09:50</td>
<td>14:11</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 6.2  Timetable of Data Collected, at Cobbett Hill, in June 1990

<table>
<thead>
<tr>
<th>Day number</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna spacing (λ)</th>
</tr>
</thead>
<tbody>
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<td>177</td>
<td>08:12</td>
<td>09:15</td>
<td>10</td>
</tr>
<tr>
<td>177</td>
<td>09:20</td>
<td>10:20</td>
<td>10</td>
</tr>
<tr>
<td>177</td>
<td>10:35</td>
<td>11:20</td>
<td>10</td>
</tr>
<tr>
<td>177</td>
<td>11:46</td>
<td>12:47</td>
<td>10</td>
</tr>
</tbody>
</table>
Figure 6.1 Signal duration probability curves received at 5λ, 10λ, and 20λ for the three signal categories a) underdense, b) overdense, c) not known.
referred to in this section. The results demonstrate the worst case impact of noise on the cross-correlation of signal received at the analysis threshold of -120 dBm.

The signal plus noise reference curves were obtained by injecting CW signals, from a local transmitter, at the minimum acceptable signal threshold of -120 dBm. If no noise was present, the cross-correlation coefficient would have been zero (since the DC level is ignored in the cross-correlation, see section 4.2). The coefficient would also have been zero provided that the noise was uncorrelated and a long analysis window (e.g. seconds) was taken. In a 250 ms segment, however, the cross-correlation coefficient deviates from zero due to the small analysis window.

The cumulative distribution of noise obtained (e.g. Figure 6.2a) using 0.25 s segments shows a distribution of values about zero. The noise curves represent a reference from which the signal cross-correlations must deviate to ensure that the coefficients are obtained from decorrelating signals rather than noise. For example, at the +0.6 threshold level the cumulative correlation probability of noise is ~90 % (Figure 6.2a). For underdense signals the correlation probability in segment 3 at the 0.6 threshold is ~46% (Figure 6.2a), almost half the noise correlation value. As the signals become more decorrelated they approach the noise correlation curve, which indicates the increasing influence of noise on the signal.

6.3.2 Cross-correlation of underdense signals

At 5\(\lambda\), 10\(\lambda\) and 20\(\lambda\) seventy-nine, forty-nine and seventy signals, respectively, of duration \(\geq 0.75\) 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
Figure 6.2 Cumulative correlation probability curves applicable to underdense signals for segments 1, 2 and 3 at antenna separations of: a) $5\lambda$, b) $10\lambda$, c) $20\lambda$. 
6.2 along with the mean of three hundred 0.25 s correlation values of noise received at -120 dBm.

At each antenna spacing signal correlation values were found to decrease as a function of increasing segment number. At the $5\lambda$ spacing, for example, the number of signals experiencing correlation values less than 0.6 increased (Figure 6.3) from 12% in segment 1, to 32% and 46% in segments 2 and 3 respectively. (The noise correlation at the 0.6 threshold is ~90% indicating that three segments were not influenced by the correlation of noise). The increasing decorrelation trend confirms those results obtained for a $10\lambda$ separation obtained in Chapter 5.

In Figure 6.2 there is no systematic trend relating decorrelation and antenna spacing and no clearly favourable antenna spacing (in the 5-20$\lambda$ range) is observable (Figure 6.2) for the reception of decorrelated underdense signals. At the 0.6 cross-correlation level (selected for comparative reasons, see Chapter 5) it is noted that signals received at a $10\lambda$ spacing are less correlated than those received at a $20\lambda$ antenna spacing (Figure 6.3). It is further observed that since the $5\lambda$ correlation values cross the other two curves no trend towards decorrelation with antenna separation is observed for underdense signals.

6.3.3 Cross-correlation of overdense signals

Between 68 and 118 signals $\geq 0.75$ s were identified as overdense at each antenna spacing and the cumulative correlation distribution values are plotted for the three segments at each antenna separation in Figure 6.4. Early in signal decay lifetimes (i.e. segment 1) overdense signals are more decorrelated than underdense signals (Figure 6.5). This is not entirely unexpected since small underdense trails scatter coherently: this does not occur with overdense trails which tend to act as relatively large signal sources [Sugar, 1964].
Figure 6.3 Probability of obtaining correlation values of less than 0.6 for underdense signals at 5 $\lambda$, 10$\lambda$, and 20$\lambda$, for segments 1, 2 and 3.
Figure 6.4. Cumulative correlation probability curves applicable to overdense signals for segments 1, 2 and 3 at antenna separations of: a) 5\(\lambda\), b) 10\(\lambda\), c) 20\(\lambda\).
Figure 6.5  Comparison of cumulative correlation probabilities for overdense and underdense signals at antenna separations of: a) $5\lambda$, b) $10\lambda$, c) $20\lambda$, for segment 1.
In Chapter 5 it was concluded that high amplitude overdense signal decorrelation was primarily caused by mesospheric wind distortions of the meteor trail. Consequently, a trend towards decorrelation with time had been expected. In that Chapter only results from an antenna spacing of $10\lambda$ were addressed and no trend to decorrelation with time was noted. A comparison between Figures 6.4a, 6.4b, and 6.4c demonstrates that the $10\lambda$ separation was insufficient to measure the wind-induced signal decorrelation. The $5\lambda$ antenna spacing shows little to no correlation dependency on time. For a $10\lambda$ separation there is still no clear dependency although the curves are diverging. When the spacing reaches $20\lambda$, however, there is a clear trend of decorrelation with time (illustrated in Figure 6.6 at the 0.6 level), a trend which is identical to that shown by both the underdense and NK trail categories (section 6.2.2 and 6.2.4) at the three antenna separations of 5, 10 and $20\lambda$.

It is concluded that with an antenna spacing of $20\lambda$ the influence of the multiple scattering regions (e.g. glints) is noticeable whereas their effect is not apparent at smaller ($<10\lambda$) antenna spacings. In these data the tendency to decorrelate with time has also resulted in higher decorrelation coefficients in segment three at $20\lambda$. The spatial correlation values and variation suggests that an antenna separation of $>10\lambda$ (e.g. $\sim20\lambda$) is needed for the reception of decorrelated overdense signals.

### 6.3.4 Cross-correlation of NK signals

At each antenna spacing NK segment 1 signals (Figure 6.7) are, generally, less correlated than underdense or overdense signals (Figures 6.2 and 6.4). At the $5\lambda$ 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 $10\lambda$ and $20\lambda$ antenna spacings.
Figure 6.6  Probability of obtaining correlation values of less than 0.6 for overdense signals at $5 \lambda$, $10 \lambda$, $20 \lambda$ for segments 1, 2 and 3.
Figure 6.7  Cumulative correlation probability curves applicable to NK signals for segments 1, 2 and 3 at antenna separations of: a) 5 λ, b) 10 λ, c) 20 λ.
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 6.8) the trend towards decorrelation, as a function of segment number, at antenna spacings of $5\lambda$ and $20\lambda$ confirms a similar trend reported in Chapter 5 at the $10\lambda$ separation.

In this data the $5\lambda$ spacing is the most favourable for the reception of uncorrelated NK signals (Figure 6.7 and 6.8). This is surprising as it might be expected small separations, i.e. $5\lambda$, to show the highest correlation values. We have examined the $5\lambda$ data and find that it is subject to considerable low amplitude ($\leq -120$ dBm), multipath propagation which cause 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 categorisation 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 the diversity gains obtained at separations of $5\lambda$, $10\lambda$ or $20\lambda$ would be similar to each other.

6.3.5 Discussion and summary:-- spatial correlation variation

This section reports an investigation of the decorrelation of 37 MHz scattered signals received on two separated antennas spaced at $5\lambda$, $10\lambda$ and $20\lambda$. 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 minimum duration of 0.75 s.

Overdense signals from two antennas separated by $5\lambda$ and $10\lambda$ did not decorrelate with time. At a separation of $20\lambda$, however, there was a decorrelation dependency
Figure 6.8  Probability of obtaining correlation values of less than 0.6 for NK signals at 5λ, 10λ, 20λ for segments 1, 2 and 3.
with 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 production of multiple glints and a separation of a least $20\lambda$ was needed to
measure this. Logistical constraints precluded extending this study to separations
$>20\lambda$.

In contrast to the above both underdense and NK signals from two antennas
separated by $5\lambda$, $10\lambda$ and $20\lambda$ decorrelated with time; no relationship between
correlation coefficient and increasing antenna separation was, however, observed
for either category. It is believed that the decorrelation observed 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 $5\lambda$
separation. Underdense trails are smaller signal sources [Sugar, 1964] than
overdense trails and the signals from underdense trails were sufficiently coherent
that any significant decorrelation effects were not detected. NK signals, on the
other hand, almost certainly derive from a spatially distributed signal source such
as a wind distorted trail or a region of sporadic-E. Consequently, a separation of
only $\sim 5\lambda$ was sufficient 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 meteor
scatter communications system using space diversity. The proportion of
underdense, overdense and NK signals used by a meteor-scatter 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 meteor-scatter 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 it is recommend that a diversity antenna separation of $20\lambda$ (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 $5\lambda$ spacing is sufficient.

On the basis of these measurements, and those presented in Chapter 5, the $4\lambda$ space diversity antenna separation implemented by Bartholomé and Vogt [1968] in COMET would probably have contributed to the excellent system performance. The moderate powered COMET system (~ 200 W) would have passed much of its traffic over overdense signals and consequently a spacing of $20\lambda$ would have been more advantageous than the $4\lambda$ antenna separation which was used. The $4\lambda$ separation, however, would have provided a useful degree of signal decorrelation. Our results, therefore, partly explain the high average data rates achieved by the COMET system.

6.4 Results - winter-summer variation of cross-correlation coefficients

Winter and summer cross-correlation values obtained from the three signal categories were examined to determine which (if any) signal category decorrelated as a function of season, and which category could contribute to a seasonal diversity gain. In order to minimise the time consuming analysis technique, the winter-summer (or season) cross-correlation variation was investigated by analysing four hours of data collected in February 1990 (day 45, Table 6.1, and 5.1) at an antenna separation of $10\lambda$, and comparing it with four hours of data obtained in June 1991 (day 177, Table 6.2) at the identical antenna separation. The
10\(\lambda\) antenna separation was selected to enable the cross-correlation values and conclusions obtained to be compared with those of Chapter 5.

In order to ensure that a four hour data set would be adequate for analysis, the results and conclusions obtained earlier in February for a nine hour data set (day 45 and 51, Table 5.1) were compared with those obtained from a four hour data set (day 45). The results obtained from the smaller data-set are plotted in Figures 6.9, 6.10, and 6.11, and the results obtained from the nine hour data-set are plotted in Chapter 5. A comparison between signal duration statistics (Figure 5.4 and 6.9), cumulative correlation distributions (see Figures 5.5, 5.7, 5.9 and Figure 6.10), and median signals-powers (Figure 5.8 and 6.11), demonstrate that the conclusions formulated in Chapter 5, regarding the temporal variation of cross-correlation values for each signal category, were identical to the results obtained from the shorter four-hour analysis period.

6.4.1 February-June correlation variation of underdense signals

The duration distribution of the underdense signals observed over four hours in June is plotted in Figure 6.12. The duration distribution is similar to the distribution plotted in Figure 6.9 which was obtained in February, at the identical antenna separation of 10\(\lambda\).

The four hours of data analysed in June resulted in 41 underdense signals of duration \(\geq 0.75\) s. In February, analysis of a similar four hour period resulted in 30 underdense signals of duration \(\geq 0.75\) s. The segmented cumulative correlation distribution curves for the underdense signals (Figure 6.13a) observed in June, show a similar trend towards decorrelation with time (segment number) to the segmented correlation values obtained in February (Figure 6.10a). The total decay envelope correlation values and those values obtained over segment 1, for the
Figure 6.9 Signal duration probability curves for four hours of data collected in February.
Figure 6.10  Cumulative correlation probability curves for a) 30 underdense b) 39 overdense and c) 36 NK signals of duration ≥ 0.75 s observed over 4 hours in February.
Figure 6.11  Median power present in each signal category as a function of segment number. Signal duration \( \geq 0.75 \) s, observed over 4 hours of February data.
Figure 6.12 Signal duration probability curves for three signal categories analysed from 4 hours of data collected in June.
Figure 6.13  Cumulative correlation probability curves for a) 41 underdense b) 40 overdense and c) 234 NK signals of duration ≥0.75 s observed over 4 hours in June.
two analysis periods (i.e. February and June), are also similar. In June, however, segments 2 and 3 are, on average, more decorrelated than segments 2 and 3 in February.

In Chapter 5 the trend towards decorrelation of underdense and NK signals was attributed to weak signals (e.g. sporadic-E and ionoscatter) adding to the low-power underdense and NK signal in an uncorrelated fashion at the two antennas. The NK and underdense signal categories observed in June have similar low-powers (Figure 6.14) to the signals observed in February (6.11). Consequently, additive weak-signals will also cause the underdense and NK signal categories to decorrelate in June. During summer solstice periods, however, the incidence and average received power of these sporadic-E signals increases [CCIR, 1990]. It is suggested that this results in the underdense signal segments 2 and 3, being more decorrelated, on average, in June than February.

6.4.2 February-June correlation variation of overdense signals

Forty signals of duration ≥ 0.75 s were categorised as overdense in June, and thirty nine overdense signals were observed in February. The segmented cumulative correlation probability curves, obtained in June, (Figure 6.13b) for segments 1, 2 and 3 are similar to those segmented correlation values observed in February (Figure 6.10b). No clear trend towards decorrelation with time (segment number) can be observed for the overdense signals detected in June or February. These observations confirm the view that the 10λ antenna separation may be inadequate to observe the trend towards decorrelation with time (see 6.2.1.3).

The total signal-envelope correlation values calculated for the overdense signals identified in June are, on average, more decorrelated than those obtained in February. In June ~15% of the signals have correlation values less than 0.6,
Figure 6.14 Average power present in each signal category. Signals of duration ≥0.75 s observed over 4 hours in June.
which contrasts with a value of <1% in February. The signal duration distribution of overdense signals observed in June (Figure 6.12) is similar to the duration distribution obtained in February (Figure 6.9). The increased total envelope decorrelation values observed in June, therefore, are due to an enhanced decorrelation observed during the latter stages of the overdense signal decay. This enhanced decorrelation may be attributed to the seasonal increase in the rms (root-mean-square) value of the random wind velocity as suggested by Landmark [1958]. Unsegmented underdense signals fail to show a February-June decorrelation trend due to their short decay duration (Figure 6.12).

6.4.3 February-June correlation variation of not-known signals

Figure 6.12 shows that a greater number of NK signals are observed in June than February and that the average duration of the NK signals in June is also greater than the average duration in February (Figure 6.9). These increases may be attributed to a greater seasonal incidence of non-meteoric mode signals (e.g. short duration sporadic-E) and a greater number of overdense signals originally not suitable for forward scatter.

In June 234 NK signals of duration ≥ 0.75 s were observed at the 10λ antenna separation. The cumulative distribution of the total-envelope correlation values for NK signals (Figure 6.13c), shows that signals observed in June are more decorrelated than those observed in February. For example, ~22% of the signals have correlation values less than 0.6 in February, which contrasts to ~52% in June. The winter-summer variation of total-envelope correlation values for NK signals may be due to a greater incidence of weak-mode signals in June (e.g. sporadic-E) and the seasonal increase in the rms random wind velocity [Landmark, 1958].
The trend towards decorrelation with time (i.e. segment number) is also observed for NK signals detected in June. The segmented correlation values are, on average, more decorrelated in June than February. This winter-summer variation of the segmented correlation values may be due to the increased incidence and increased average-power of the weak signal-modes, which add to the low-power (Figure 6.14) NK signals in an uncorrelated fashion.

6.4.4 Combined underdense, overdense, and NK signals

All signals, of duration $\geq 0.75$ s observed over 4 hours in June, were combined and compared with all signals of duration $\geq 0.75$ s observed during 4 hours in February (Figure 6.15). The trend towards decorrelation with segment number, discussed in Chapter 5, is again confirmed for the data observed in June. The increase in the number of scattering events of duration $\geq 0.75$ s by a factor of $\sim 3$ in June, can be attributed to an increase in uncorrelated NK signals.

The segmented correlation values observed in June are more decorrelated, on average, than signals observed in February (Figure 6.15). In June approximately 45% of the signals in segment 3 have correlation values less than 0.6. This compares to $\sim 32\%$, for segment 3, in February. The total unsegmented envelope decorrelation values show a winter-summer trend. In February the correlation probability (at the 0.6 threshold) is $\sim 14\%$ and increases to $\sim 42\%$ in June.

6.4.5 Discussion and summary:- February-June correlation variation

Four hours of data obtained in June and February, over similar periods and at identical antenna separations of 10$\lambda$, have been compared. The conclusions obtained from the two four hour periods support the seasonal correlation variation trend hypothesised in Chapter 5. The results show that underdense
Figure 6.15  Cumulative probability curves applicable to all received signals of duration $\geq 0.75$ s for a) February b) June.
and overdense signal durations in June and February, are similar. The NK signals, however, exhibit a greater average duration in June than February.

Segmented underdense and NK signals show a winter-summer decorrelation trend, with those observed in June, on average, being more decorrelated than those detected in February. The winter-summer trend of the segmented correlation values can be attributed to the increased incidence and average power of the decorrelating weak signal modes (i.e. sporadic-E and ionoscatter).

Overdense segmented signals show no winter-summer variation in correlation values. This is not in conflict with the weak signal mode fading mechanism discussed earlier for the low-power underdense and NK signals. The typically higher powers of overdense signals, during the formative stages of signal decay (Figure 6.14), are not decorrelated by the weak signal modes.

Unsegmented overdense and NK signal-envelopes are more decorrelated in June than February. The winter-summer decorrelation trend may be attributed to the seasonal increase in the rms value of the random mesospheric wind velocity as suggested by Landmark [1958]. Unsegmented underdense signals fail to show a seasonal trend due to their short duration.

The greatest contribution to diversity gain results from the uncorrelated NK signals (Chapter 5). The increased incidence of the uncorrelated NK signals and their greater decorrelation observed in June, suggests that their contribution to diversity will increase in June, and result in a seasonal diversity gain. A smaller seasonal contribution can also be expected from underdense signals which have greater segmented decorrelation values in June than February. The overdense signal category, which is also more decorrelated in June than February, during latter stages of signal decay, may also enhance any diversity gain detected.
Chapter 7 Modelled meteor scatter communications system implementing diversity

7.1 Introduction

In this Chapter communications-diversity gains are investigated using the modelled meteor scatter communications system described in detail in Chapter 4. The diversity gains are investigated by analysing typical communications systems parameters such as broadcast data-block duration, FSK error, average baud-rate etc. for a non-diversity and diversity systems.

The analogue diversity data analysed in this Chapter are summarised in Table 7.1. The diversity signals are sampled simultaneously using a sampling frequency of 1 kHz and an anti-aliasing filter bandwidth of 250 Hz (Chapter 4). The system noise-floors for the non-diversity, scan-diversity and selection-diversity systems are measured to be -134 dBm (Chapter 3) in the 250 Hz bandwidths. For the maximal-ratio diversity system the noise-floor at the output of the signal combiner is 3 dB higher at -131 dBm. The 14 and 20 dB receiver-thresholds used throughout the analysis are equivalent to signal-to-noise ratios of 3 and 9 dB in a typical 3 kHz communications bandwidth.

The total-time in ms that the signal is available for communications (i.e. signal-availability, Chapter 4) is determined first for a single non-diversity system (also referred to as a single channel system, or channel 1), and then for a scan-diversity system and a maximal-ratio diversity system. A broadcast communications system (Figure 7.1) is modelled for a single channel system, a scan-diversity system, and a maximal-ratio diversity system as a function of increasing receiver threshold.
<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Data start time (UT)</th>
<th>Data end time (UT)</th>
<th>Antenna spacing (λ)</th>
<th>Transmitter power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>February</td>
<td>45</td>
<td>1005</td>
<td>1415</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>1991</td>
<td>June</td>
<td>177</td>
<td>0812</td>
<td>1357</td>
<td>10</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 7.1 Summary of data analysed
Figure 7.1 Simulation of a non-diversity broadcast meteor scatter system
FSK error-probabilities are also evaluated for a modelled non-diversity system, a selection-diversity system and a modelled maximal-ratio diversity system for all signals greater than a minimum signal detection threshold (i.e. receiver threshold).

Diversity gains are first computed for the data obtained in February at the $10\lambda$ antenna separation, and then for the data obtained in June at an identical antenna separation. The results will show if the decorrelating signals detected in Chapters 5 and 6 are useful to meteor scatter communications systems implementing diversity processing.

7.2 Analysis of space-diversity signals obtained in February at $10\lambda$

7.2.1 Signal-availability gain using scan-diversity

The signal-availability (ms, ordinate axis) results for the four hour data-period analysed are plotted in Figure 7.2a as a function of increasing receiver threshold above the measured system noise in a 250 Hz bandwidth (i.e. -134 dBm). Meteor scatter signal-durations, above a defined power threshold, decrease as the signal threshold increases; consequently the diversity and non-diversity signal-availabilities are observed to decrease for increasing receiver threshold. At the 14 dB threshold the non-diversity system is "available" to a communications system for $\sim 4.5 \times 10^6$ ms. Using scan-diversity, however, the availability increases to $\sim 5 \times 10^6$ ms at the identical threshold.

The signal-availability ratio for the two non-diversity channels does not deviate more than $\sim 5\%$ of the expected ratio of '1' at all receiver thresholds (Figure 7.2b). This demonstrates that the two non-diversity systems were well matched. In contrast the modelled scan-diversity ratio decreases with increasing receiver
Figure 7.2 4 hours of data collected at 10λ in February showing
a) non-diversity and scan-diversity signal-availability (ms)
b) non-diversity and scan-diversity signal-availability ratio
threshold. At the 14 dB receiver threshold the scan-diversity system shows a signal-availability improvement of ~ 1.15 (i.e. 15%) compared to a non-diversity system. As the receiver threshold increases to 20 dB the availability-ratio decreases to ~1.11 (11%). The decreasing trend with increasing receiver threshold is consistent with the correlation studies reported in Chapter 5 and 6, which showed increasing decorrelation values with increasing segment number (i.e. time into signal decay) and decreasing received signal-power.

7.2.2 Maximal-ratio diversity signal-availability gain

The signal-availability obtained using the modelled maximal-ratio diversity system, for the four hours of February data, is plotted in Figure 7.3a as a function of increasing receiver threshold above the combiner system noise-floor (i.e. -131 dB in the 250 Hz bandwidth). At the 14 dB threshold the maximal-ratio signal-availability increases by ~58% with reference to the single non-diversity system.

Between receiver thresholds of 10 and 16 dB, the maximal-ratio signal-availability ratio (Figure 7.3b) decreases and then between 16 and 20 dB the ratio increases. The decreasing trend in signal-availability ratio is consistent with the increasing correlation values observed in Chapter 5 and 6. The increasing trend at first sight is unexpected, an explanation for the increase, however, is offered below.

The increasing signal-availability ratio, at receiver thresholds of >16 dB, may be attributed to overdense signals. The overdense signal-availability improvement obtained using maximal-ratio diversity at high receiver thresholds (e.g. >16 dB) will be greater than that achieved from underdense signals; this is illustrated in Figure 7.4. At low receiver thresholds (<16 dB), when the overdense signal-decay is similar to that observed for an underdense signal, the overdense signal-availability improvement obtained using maximal-ratio diversity may be similar
Figure 7.3  Four hours of data obtained at 10X in February showing
a) non-diversity and maximal-ratio diversity signal-availability
b) non-diversity and maximal-ratio diversity signal-availability ratios
Figure 7.4  An illustration of the increase in maximal-ratio signal availability from
a) underdense signals
b) overdense signals
to that obtained from the underdense signals. At high receiver thresholds (Figure 7.4) the overdense signal-availability improvement ($\Delta t_2$) should be greater than that available from an underdense signal ($\Delta t_1$). The increased contribution to signal-availability from overdense signals can also be illustrated using the duty-cycle ($D_c$) equation [Cannon and Reed, 1987]

$$D_c \propto P_R^x$$  \hspace{1cm} 7.1

assuming that the received signal-power $P_R$ is proportional to the transmitter power $P_T$, and assuming (based on experimental evidence [Sugar, 1964]) that $x \sim 0.5$ for underdense signals, and $x \sim 2$ for overdense signals. As $P_R$ increases by 3 dB (e.g. the power doubling expected from ideal maximal-ratio combining of two perfectly correlated signals), the underdense signal duty-cycle will increases by 1.4 ($\Delta t_1$, Figure 7.4a). This improvement contrasts with a duty cycle increase in of $\sim 4.0$ ($\Delta t_2$, Figure 7.4b) obtained from maximal-ratio combining of a perfectly correlated overdense signal.

7.2.3 Broadcast diversity gain in February

An increase in diversity signal-availability does not guarantee an improvement in data throughput using a broadcast diversity system. For example, the signal-availability improvements observed, using diversity, may be of low signal-power (resulting in a high error-probability) or distributed in small periods (e.g. smaller than a data-block duration) and not 'useful' to a broadcast communications system. The broadcast throughput and error-probability, therefore, were investigated for non-diversity and diversity systems. First, the optimum data-block duration was evaluated and that optimum-duration was used in the broadcast throughput model to determine the broadcast-diversity gain.
7.2.3.1 Optimum scan-diversity data-block duration

In a broadcast meteor scatter communications system a period of housekeeping or preamble overhead, 'P', is associated with each received data-block of duration 'B'. The 'information' duration of each received data-block, therefore, is (B-P) and the optimum broadcast data-block duration is that duration commensurate with a maximum number of received information bits.

The average information baud-rate ($B_I_s$) achieved at a receiver threshold 's', for data-blocks of duration 'B', over a time period (T) of 4 hours, is determined as:

$$B_I_s = \frac{(B-P) \cdot N_s \cdot D}{T}$$

where 'D' is the data-rate (typically 2400 bits per second [Dickson et al., 1987]) and $N_s$ is the number of data-blocks received of duration 'B' at threshold 's' modelled by the broadcast simulation algorithm (Chapter 4). The average information baud-rates were calculated, as a function of increasing broadcast data-block and preamble duration, at the 14 dB receiver threshold.

For both a non-diversity system (Figure 7.5a) and a scan-diversity system (Figure 7.5b) the results show that at receiver thresholds of 14 dB above the system noise (i.e. -134 dB) the information baud-rate first rapidly rises and then slowly decreases for all preamble durations. The steep baud-rate increase for data block durations between 0-100 ms, is due to the decreasing impact of the preamble (or protocol) duration, [Cannon and Dickson, 1991], on the broadcast data-block duration. The slowly decreasing baud-rate, following the peak, occurs due to the small number of long duration signals which can carry the long data-blocks [Cannon and Dickson, 1991].
Figure 7.5  The average information data rate for increasing data block and preamble duration, at a receiver threshold of 14 dB in February, for a) single non-diversity system  
b) scanning diversity system
As the average information baud-rate for both the non-diversity system and the scan-diversity system decreases (Figures 7.5), local baud-rate maxima are observed, e.g. at data-block durations of 400 and 500 ms. These maxima result from increasingly efficient usage of the received signal by the broadcast system as illustrated in Figure 7.6. The illustration shows that when the preamble duration (P) is 10 ms (a reasonable duration for header information) and the data-block duration is 350 ms, the total information-time (i.e. (B-P).N) due to 5 received blocks is 1700 ms. As the data-block duration increases to 400 ms the received meteor-scatter signal is used more efficiently and the information-time, due to 5 received blocks, increases to 1950 ms; i.e. an improvement of 250 ms. As the data-block duration increases further to 450 ms the number of blocks, which can be fit, decreases to 3, and the information time decreases to 1320 ms.

The scan-diversity information data-rate (Figure 7.5b) is greater than that observed for the non-diversity system (Figure 7.5a) for all identical data-block and preamble durations. At a data-block duration of 100 ms and preamble duration of 10 ms, the modelled scan-diversity broadcast data-rate is ~49 baud, in contrast to ~ 42 for the single channel non-diversity system. The averaged information data-rate curves (Figure 7.5) show how the data-block duration and preamble duration may be traded to obtain a specified average information-rate. For example, an average baud-rate of >40 baud may be achieved using a broadcast non-diversity system (Figure 7.5a) with data-blocks of duration of 100 ms and 10 ms preambles. By using scan-diversity, however, >40 baud (Figure 7.5b) may be achieved using a 100 ms data-block and a 20 ms preamble; i.e. more header information may be transmitted for the same data-rate.

As the preamble duration increases, the data-block duration commensurate with the maximum average information data-rate (i.e. the optimum data-block duration) also increases. For a preamble duration of 20 ms, the optimum data-
Signal power

Analysis threshold

Received signal

350ms data blocks

400ms data blocks

450ms data blocks

Time

Figure 7.6 An illustration of how an increase in broadcast data-block duration can increase the average information data-rate.
block duration is ~100 ms for the non-diversity (Channel 1) system. As the preamble increases to 40 ms and then to 80 ms the optimum data-block duration increases to ~200 ms and 250 ms respectively. The optimum data-block duration for a non-diversity and scan-diversity is ~90 ms for a 10 ms preamble. For these conditions the information data-rate for the single channel and scan-diversity system is ~40 and 50 baud respectively (Figures 7.5).

7.2.3.2 The optimum maximal-ratio broadcast data-block duration

The average maximal-ratio diversity information baud-rate, calculated using equation 7.2 at the 14 dB threshold, is plotted as a function of increasing data-block and preamble duration in Figure 7.7. The figure shows that the optimum data-block duration is at ~90 ms for a 10 ms preamble duration and results in an average baud-rate of ~67 baud. This contrasts to a baud-rate of ~40 and ~50 baud observed for a single non-diversity system and a scan-diversity system respectively (Figure 7.5).

As the data-block duration increases the maximal-ratio diversity information baud-rate, as expected, decreases (Figure 7.7). The first local baud-rate maxima occurs at a data-block duration of 500 ms; ~100 ms greater than the first local maxima observed for the single or scan-diversity broadcast systems (Figure 7.5). The data-block increase may be attributed to the average increase in signal duration achieved using maximal-ratio diversity. For example, combining two perfectly correlated (i.e. $R_{xy}(0) = 1$) underdense signals using a maximal-ratio combiner, will results in the combined signal being 3 dB greater than either of the non-diversity input signals. The 3 dB increase in received signal-power will result in a 1.4 increase in signal duration (see section 7.2.3.3)
Figure 7.7 The average information data-rate for a maximal-ratio diversity system, as a function of data-block and preamble duration, at the 14 dB threshold in February.
The information data-rate curves (Figure 7.7) once again show how the data-block and preamble duration may be traded to obtain a particular information rate. For example, a single non-diversity system average baud-rate, at the 14 dB receiver threshold, of ≥40 baud can be achieved using a data-block duration of 100 ms and a 10 ms preamble (Figure 7.5a). Using a maximal-ratio diversity system, however, a data-rate >40 baud may be achieved (Figure 7.7), at the 14 dB threshold, with a 100 ms data-block duration and a 20 ms preamble-duration. The increased preamble duration may enable greater housekeeping information to be sent for no penalty in data-rate.

7.2.3.3 Broadcast diversity-gain in February

The average information baud-rates for the diversity and non-diversity systems, calculated using equation 7.2, are plotted in Figure 7.8a, as a function of increasing receiver threshold above the system noise. The broadcast throughputs are modelled for the non-diversity system optimum data-block and preamble durations of 90 ms and 10 ms respectively. At the 14 dB threshold the non-diversity broadcast baud-rate is ~40 baud and decreases to ~18 baud at the 20 dB threshold. A scan-diversity system, however, exhibits an increased baud-rate of ~50 and ~20 baud at the 14 and 20 dB thresholds respectively. The baud-rate is further enhanced, to ~67 baud at the 14 dB threshold and ~30 baud at the 20 dB threshold, using maximal-ratio diversity.

The broadcast throughput-gain, G, achieved using diversity is determined by the quotient between the diversity and non-diversity average baud-rates. These gains are plotted in Figure 7.8b for the non-diversity, scan-diversity and maximal-ratio diversity systems. The gain obtained from the two non-diversity systems does not deviate more than 5% from the expected value of 1 (i.e. both non-diversity systems are well matched). The broadcast gain obtained using scan-diversity, however,
Figure 7.8 Results from a diversity and non-diversity broadcast model assuming 90ms data block durations and 10ms preambles showing a) the broadcast baud rate, averaged over 4 hours in February, and b) the broadcast throughput ratio of 4 hours of broadcast data.
shows a decreasing trend with increasing receiver threshold. This decreasing trend is consistent with the cross-correlation studies performed earlier (Chapter 5 and 6), which demonstrated increasing decorrelation values with increasing segment number. The maximal-ratio diversity gain initially decreases, between 10 and 16 dB, and then increases with increasing receiver threshold (Figure 7.8b). The decreasing trend may be attributed to increasing decorrelation values with segment number, and the increasing trend may be attributed to the enhanced throughput achieved from overdense signals (see section 7.2.2) at the higher receiver thresholds.

At the receiver threshold of 14 dB the broadcast throughput gain (G) achieved using scan-diversity is ~1.18; as the threshold increases to 20 dB, G decreases to ~1.15. For the maximal-ratio diversity system G ~ 1.6 and ~1.7 at thresholds of 14 and 20 dB respectively. Eshleman [1954] has shown that, for a non-fading meteor scatter signal-envelope, in a fixed bandwidth and data-rate system, the information rate (I_e) is related to the effective transmitter power by,

\[ I_e = \lambda^2 (P_T)^{\frac{k}{2}} \]

where \( \lambda \) is the signal wavelength, \( P_T \) is the transmitter power and 1≤k≤1.2 for underdense signals, and k≥2 for overdense signals. Assuming data reception at the 14 dB threshold is dominated by underdense signals (i.e. k=1) the effective transmitter power gain is proportional to \( G^2 \). The scan-diversity gain of 1.18, therefore, implies an increase in effective transmitter power of ~1.39 (or ~1.4 dB). As the receiver threshold increases to 20 dB the data throughput contribution from underdense signals decreases (i.e. k=1.2) and the effective transmitter power gain proportionality is assumed to be \( G^{5/3} \). Consequently, the scan-diversity gain of ~1.15 observed at 20 dB may be equivalent to a ~ 1.26 (or ~1 dB) increase in effective transmitter power.
If the signals at the two antennas at the 14 dB threshold are assumed to be perfectly correlated underdense signals, then by implementing a maximal-ratio combiner the signal-to-noise ratio of the received underdense signals will increase by 3 dB. Using equation 7.3 for k=1, a 3 dB increase in received signal-power is equivalent to a 1.4 broadcast throughput gain (G). Maximal-ratio gains of ≥ 1.4, therefore, may be due to decorrelated underdense signals.

At the 14 dB (k=1) threshold for the maximal-ratio diversity system, the broadcast-gain of -1.6 indicates an improvement in effective transmitter power of -2.6 (or -4.1 dB). At a threshold of 20 dB (k=1.2), however, G-1.7 and the increase in predicted effective transmitter power decreases to -2.5 (or -3.9 dB).

The effective transmitter power gains predicted using the relationship developed by Eshleman [1954] fail to consider the impact of meteor signal-fading, and should, therefore, be considered with caution. In a full-duplex meteor scatter system exhibiting non-reciprocal fading, the increases in transmitter powers predicted may, in the extreme, double.

7.3 February-June variation of diversity gain

Space diversity signals obtained at an antenna separation of 10λ in June 1991 were, on average, more decorrelated than those signals, obtained at an identical antenna separation in February (Chapter 6). This winter-summer decorrelation trend suggested a seasonal trend in meteor scatter broadcast diversity-gain. This seasonal trend is investigated by comparing 4 hours of data obtained in June with 4 hours of data collected in February (Table 7.1).
7.3.1 February-June variation of signal-availability

In June the signal-availability (Figure 7.9a) for a single channel system at 14 dB above the measured system noise of -134 dB, is $\sim 10^6$ ms; approximately 2.8 times greater than that observed in February (Figure 7.2). The increased availability can be attributed to a seasonal increase of low-power NK signals (e.g. sporadic-E) and a seasonal increase in meteor-rate (Chapter 2). As the receiver threshold increases, the contribution from low-power NK signals decreases and the seasonal-availability improvement decreases to $\sim 2$ at the 20 dB threshold.

The signal availability-ratio between the two non-diversity systems in June (Figure 7.9b) does not deviate more than 5% of the expected value of 1. The scan-diversity availability-ratio, however, decreases from 1.31 at the 14 dB threshold to 1.25 at 20 dB. This decreasing trend in scan-diversity availability-ratio, with increasing receiver threshold, is again consistent with the increasing decorrelation observed with increasing segment number (Chapter 5 and 6). The 1.31 and 1.25 scan-diversity ratios observed in June are greater than the 1.15 and 1.11 ratios observed in February at identical thresholds (Figure 7.2b) and indicate a seasonal broadcast diversity gain.

In June the maximal-ratio diversity signal availability-ratio is $\sim 1.8$ at 14 dB above the system noise of -131 dB, and $\sim 1.88$ at the 20 dB threshold (Figure 7.9a). The decreasing and increasing trend in diversity-ratio for the maximal-ratio diversity system is similar to that observed in February (Figure 7.3b), and may be attributed to increasing decorrelation values observed with increasing segment number (Chapter 5, 6), and the greater signal-availability improvement obtained by combining overdense signals (see section 7.2.2). The availability-ratios of $\sim 1.8$ and $\sim 1.88$ observed in June are greater than the $\sim 1.58$ and $\sim 1.65$ availability-ratio improvements observed, at identical thresholds, in February (Figure 7.3b).
Figure 7.9 Four hours of data obtained in June at an antenna separation of 10λ showing
a) Signal availability for non-diversity and diversity systems, and
b) the signal availability ratio for the non-diversity and diversity systems
7.3.2 The optimum broadcast data-block duration in June

The average information baud-rate, calculated using equation 7.2 for the data obtained in June, at a receiver threshold of 14 dB is plotted as a function of increasing data-block duration for the non-diversity and two diversity systems in Figures 7.10. For all three systems the average information baud-rate is greater than that observed in February, at all preamble durations. For example, using a 100 ms data-block duration and 10 ms preamble, the information-rate, averaged over four hours in June, is ~80, 115, and 160 baud for the single system, the scan-diversity system and maximal-ratio diversity system respectively. These baud rates respectively compare to ~ 40, 50 and ~67 baud observed in February over the similar four hour period (Figure 7.5 and 7.7).

The modelled optimum data-block duration for a single non-diversity system in June occurs at ~100 ms for the 10 ms preamble duration. In February the optimum data-block and preamble duration were ~ 90 ms and 10 ms respectively. The increased data-block durations observed in June may be attributed to the average increase in NK signal duration (Chapter 6) detected in June. Optimum data-block and preamble durations observed for the scan-diversity and maximal-ratio diversity systems (Figure 7.10b and 7.10c) are for a data-block duration of 100 ms and a 10 ms preamble.

The first local maxima, caused by efficient usage of the signal by the broadcast system (see section 7.2.3.1), occurs at a data-block duration of 500 ms for all three broadcast systems (Figure 7.10b and 7.10c). This data-block duration is ~100 ms greater than that observed in February at an identical threshold and the increase may be attributed to the average increase of NK signal-durations observed in June (Chapter 6).
Figure 7.10 Average information baud rate obtained in June as a function of data-block and preamble duration for
a) single system
b) scan-diversity system
c) maximal-ratio diversity system
7.3.3 February-June variation of broadcast diversity gain

The modelled average broadcast baud-rate for June was examined and compared with the broadcast results obtained in February. For both periods equation 7.2 was used to model the broadcast throughput. The data-block duration and preamble duration of 90 and 10 ms were used for both the non-diversity systems and the diversity systems.

In June the average information baud-rate is approximately twice that observed for the similar four hour period in February. At the 14 dB and 20 dB thresholds the average baud-rate for a single non-diversity system in June is ~85 and ~29 baud respectively (Figure 7.11). This contrasts with the 40 and 18 baud observed for a non-diversity system in February (Figure 7.8a) at identical thresholds. In June the modelled scan and maximal-ratio diversity systems indicate a broadcast throughput of ~120 and ~170 baud respectively at the 14 dB threshold, and ~35 and ~50 baud at the 20 dB threshold.

The diversity to non-diversity average baud-rate gain (G), for the data analysed in June, is plotted in Figure 7.11b. The gain obtained using two non-diversity systems does not exceed the expected value of '1' by more than 5% (i.e. no gain). The scan-diversity gain, however, decreases from ~1.4 at 14 dB to ~1.27 at 20 dB. These gains are greater than the 1.18 and 1.15 broadcast scan-diversity gains observed in February (Figure 7.8b) at identical receiver thresholds. Using the relationship developed by Eshleman [1954] between effective transmitter power and information-rate (equation 7.3) for qualitative comparisons, the increase in effective transmitter power predicted for a broadcast scan-diversity gain of G ~ 1.4 at the 14 dB threshold (k=1) is ~ 3 dB. At the 20 dB threshold with k=1.2 the 1.27 scan-diversity broadcast-gain indicates a ~1.7 dB improvement in transmitter
Figure 7.11 Results from a diversity and non-diversity broadcast model assuming 90ms data block durations and 10ms preambles showing
a) the broadcast baud rate, averaged over 4 hours in June, and
b) the broadcast baud rate ratio of 4 hours of June broadcast data
power. These effective transmitter power improvements contrast with the ~1.4 dB and ~1 dB increases predicted for the scan-diversity system in February at identical receiver thresholds.

For a maximal-ratio diversity system in June, the 1.95 broadcast-gain observed at the 14 dB threshold (Figure 7.11b) is equivalent to a ~5.8 dB increase in effective transmitter power assuming k=1. As the receiver threshold increases to 20 dB (k=1.2), the broadcast maximal-ratio gain is ~2 and indicates a ~5 dB increase in transmitter power. It must be noted that these transmitter power improvements predicted by Eshleman [1954] should be treated with considerable caution.

7.4 Improvements in FSK error probabilities obtained using diversity

7.4.1 An illustration of diversity error-probabilities gains

In conventional high frequency (HF) and troposcatter scatter communications systems the diversity gain achieved by improving the average signal-to-noise ratio, by a few dB's, and increasing the signal-availability by a few-percent, may be relatively unimportant compared to the reduction obtained in the variance of the diversity signal envelope [Schwartz, et al., 1966]. By reducing the variance of the signal envelope, the error-probability, i.e. that a '1' is mistaken as a '0' and vice-versa, (Chapter 2) can be significantly reduced; this is illustrated in Figure 7.12.

The three deep uncorrelated fades (fade depth ~10 dB) observed in the stationary received signal-envelopes (Figure 7.12a, b), e.g. from HF non-diversity receiving systems, cause the mean signal-to-noise ratio in each non-diversity system, over the time period 'T' (e.g. 1 min) to be ~19 dB. By combining the two uncorrelated fading signal-envelopes (Figure 7.12c), using selection-diversity, the average signal-to-noise ratio increases to ~20 dB. If the minimum signal-to-noise ratio
Figure 7.12 An illustration of a short period of uncorrelated signal fading for
a) two non-diversity systems and
b) a selection-diversity system
required by the receiving systems was 15 dB, the signal-availability gain achieved using scan-diversity will also be minimal (< 10 % in this illustrative example). The average signal-to-noise ratio gain of ~1 dB observed using selection-diversity may easily be obtained by just increasing the transmitter power.

The error-probability $P_e$, for a non-fading FSK system is (Chapter 2)

$$ P_{FSK} = \frac{1}{2} \exp\left( -\frac{\gamma}{2} \right) $$  \hspace{1cm} (7.4)

where $\gamma$ is the instantaneous signal-to-noise ratio. In the non-diversity illustrative example (Figure 7.12a,b), equation 7.4 integrated over the time period T', results in an error-probability of ~10^{-3}. The integrated value is dominated by the error-probabilities ($P_e = 10^{-3}$) during the three deep fades. The error-probability for the non-fading selection-diversity system (Figure 7.12c) however, will be ~10^{-23}; an error-rate improvement otherwise only achievable by a non-diversity system by improving the average signal-to-noise ratio of the fading signal (e.g. by increasing the transmitter power) by ~10 dB. The dominating fades will then occur at a signal-to-noise ratio of ~20 dB and the integrated non-diversity error probability over the time period T' will be ~10^{-23}. In the simplified illustration the error-probability gain is demonstrated to be of greater significance than either the signal-availability gain or the average improvement in signal-to-noise ratio.

7.4.2 Error-probabilities for Rayleigh signal-fading and meteor scatter systems

In conventional communications systems (e.g. HF, troposcatter) the FSK error-probabilities due to stationary fading signal-envelopes are calculated by evaluating [Schwartz, et al., 1966]:

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\[ P_e = \int_{0}^{\infty} P_{FSK}(\gamma) \cdot P_{e} \, d\gamma \] 7.5

where \( P_e \) is the probability density function (pdf) of the fading signal-envelope and \( P_{FSK} \) is defined by equation 7.4. This error-probability expression can easily be calculated [Schwartz, et al., 1966] for non-diversity systems assuming the fading is Rayleigh distributed, and for a dual-diversity systems assuming the two Rayleigh fading signal-envelopes are independent (i.e. uncorrelated, \( R_{xy}(\tau)=0 \)). Uncorrelated Rayleigh signal-fading, however, may not always be achievable by the diversity system (e.g. due to limited antenna separation), the impact of correlated (i.e. \( R_{xy}(\tau) \neq 0 \)) Rayleigh fading signals, however, can be calculated [Schwartz, et al., 1966]. This is achieved by first evaluating an expression for the joint probability density function of the two correlated signal envelopes in terms of the cross-covariance [Davenport and Root, 1958]. This expression has been used by Staras [1956] to conclude that most of the advantages of diversity can be obtained with signals of correlation value \( \sim 0.6 \). This correlation value has erroneously been used by Ladd [1961] to indicate the lack of diversity gain in meteor scatter systems (Chapter 5).

In meteor scatter diversity systems the received signal-envelopes are not stationary, may not be uncorrelated, and the signal-fading observed may not be Rayleigh distributed (Chapter 5). Conventional (i.e. HF or troposcat) theoretical diversity analysis techniques, therefore, are not easily applicable to meteor scatter systems and these theoretical techniques are not investigated further in this thesis. The error-probabilities, however, are determined experimentally using the FSK error-probability algorithm described in Chapter 4. These error-probabilities are evaluated for a non-diversity system, a selection-diversity system (as opposed to a scan-system previous analysed) and a maximal-ratio diversity system as a function of minimum detectable signal threshold, (i.e. the minimum signal a broadcast system may detect) and season.
7.4.3 Average FSK selection-diversity error-probability in February

For a four hour period of non-diversity data the average error-probability from signals greater than, or equal to, the 14 dB detector-threshold is $\sim 6 \times 10^{-4}$ (Figure 7.13a). A selection-diversity system, however, experiences an error probability of $\sim 2 \times 10^{-4}$; this error-probability can also be achieved by a non-diversity system at the 15.5 dB threshold. As the detection threshold increases the error-probability, as expected, decreases for the non-diversity and scan-diversity system. For example, for signals $\geq 20$ dB detector-threshold the error-probability decreases to $\sim 3 \times 10^{-6}$ for a single non-diversity system and $\sim 8 \times 10^{-7}$ for a selection-diversity system.

Error-probability ratios for a non-diversity and selection-diversity system are plotted in Figure 7.13b. The single channel error-ratio, as expected, does not deviate more than 5% from the expected value of '1'. The selection-diversity to non-diversity error-probability ratio, however, decreases with increasing receiver threshold. For signals $\geq 14$ dB detector-threshold, the error-probability ratio is 0.38; i.e. selection-diversity is predicted to experience ~62% fewer errors than the non-diversity system. The impact of the improved error-probability obtained using selection-diversity is illustrated by the following example. For signals $\geq 14$ dB detector-threshold the non-diversity error probability of $\sim 6 \times 10^{-4}$ implies an error every $\sim 1666$ bits; for a selection diversity system, however, an error-probability of $\sim 2 \times 10^{-4}$ indicates in an error every $\sim 5000$ bits. In a broadcast communications system using data-blocks of duration 90 ms and a data-rate of 2400 bits per-second [Cannon and Reed, 1987] a data-block is 216 bits long. In a non-diversity system, therefore, an error is predicted every eighth data-block. In a selection-diversity system, however, every 24th data-block is predicted to be in error, i.e. sixteen more data-blocks are received correctly using selection-diversity than a non-diversity system.
Figure 7.13  a) Meteor scatter FSK error probabilities obtained with and without selection-diversity in February at an antenna separation of 10λ.  
b) FSK error probability ratio for a meteor scatter selection-diversity system in February.
In a simplex or duplex system the ~62% improvement in error-probability obtained using selection-diversity, will not only reduce the number of blocks received in error, but also decrease the number of protocol exchanges.

7.4.4 Average maximal-ratio diversity FSK error-probability in February

The modelled average maximal-ratio diversity FSK error-probability and the modelled non-diversity error-probability, for the four hours of data collected in February at 10λ, are plotted in Figure 7.14a. The error-probability observed using maximal-ratio diversity is, as expected, smaller than that obtained using either a single non-diversity system or a selection diversity system. The non-diversity system error probability for signals ≥ 14 dB detector-threshold is ~6 × 10^-4. The maximal-ratio diversity error, however, at the same threshold is ~6 × 10^-5 (Figure 7.14a). As the detector threshold increases the error-probability, as expected, decreases. For signals ≥ 20 dB detector-threshold the error-probability decreases to ~3 × 10^-8 for the maximal-ratio diversity system and to ~3 × 10^-6 for the non-diversity system.

The error-probability ratio for the maximal-ratio diversity system, referenced to the non-diversity system (Figure 7.14b), decreases as the detector threshold increases. For signals ≥ 14 dB detector-threshold the ratio is ~0.1, that is ~90% fewer errors are observed using maximal-ratio diversity than a single non-diversity system. The ratio decreases with increasing detector threshold and for signals ≥ 20 dB detector-threshold, ~98% fewer errors are observed using maximal-ratio diversity than the non-diversity system. The decreasing trend may be attributed to the decreasing impact of low-power signals as the detector threshold increases, together with the increase in average receiver signal-power obtained at the output of the maximal-ratio combiner (see section 7.2.2).
Figure 7.14  a) Meteor scatter FSK error probabilities obtained with and without maximal-ratio diversity in February at an antenna separation of 10\lambda.  
b) FSK error probability ratio for a meteor scatter maximal-ratio diversity system in February.
In a maximal-ratio diversity system the error rate, at the 14 dB threshold, of
\(-6 \times 10^{-5}\), implies an error every \(-16666\) bits, as opposed to every \(-1666\) bits for a
single non-diversity system. Assuming 216 bit broadcast data-blocks (i.e. data-rate
of 2400 bits per-second, and a 90 ms data-block duration) an error will occur every
78th received data-block in a maximal-ratio diversity system, and every 8th data-
block for a non-diversity system The number of data-blocks received in error,
therefore, may be significantly reduced using maximal-ratio combining.

7.4.5 February-June variation of diversity FSK error-probabilities

The seasonal variation of diversity error-probability was investigated by
comparing a four hour period in June with a similar four hour period in February
(Table 7.1). The modelled error-probabilities for the single non-diversity system,
the selection diversity system and the maximal-ratio diversity system in June are
plotted in Figure 7.15a as a function of increasing minimum signal detector-
threshold; those FSK errors obtained in February are plotted in Figure 7.13a. The
results show that more errors are observed in June than February. For example, at
the 14 dB threshold the error-probability for a non-diversity system is \(-8 \times 10^{-4}\) in
June which contrasts to an error probability of \(-6 \times 10^{-4}\) observed in February.

The error-probability ratios obtained in June are plotted in Figure 7.15b and the
selection-diversity ratio of \(-0.5\), at all receiver thresholds, indicates that a selection-
diversity system will experience, on average 50% fewer errors than a non-diversity
system. In June, as the detector threshold increases, the error-probability ratio
remains close to 0.5, in contrast to the decreasing trend observed in February
(Figure 7.13b). The nearly constant ratio in June implies that the impact of fading is
present at all signal detection levels. This may be due to periodic fading observed
on long duration (> 10 s) signals (e.g. fading sporadic-E).
Figure 7.15 Error-probabilities obtained over a four hour period in June for a non-diversity system, selection-diversity and a maximal-ratio diversity system showing
a) the FSK error-probability
b) the FSK error-probability ratio
The seasonal error-probability ratio (i.e. errors observed in June and February, Figure 7.16) of 1.37 for a single non-diversity system indicates that, on average, ~37% more errors are observed in June than February. The higher error-probability in June may be attributed to the reception of a greater number of weak signals (i.e. NK signals, Chapter 6). The seasonal selection-diversity error-ratio increases as a function of increasing receiver threshold from ~1.8 at 14 dB to ~ 2.1 at 20 dB (Figure 7.16). This increasing trend may be due to an enhanced contribution from long-duration fading signals (e.g. sporadic-E) observed in June. The seasonal maximal-ratio diversity error-ratio shows that, on average, ~35% more errors are observed in June than February, and that no trend is observed with increasing detector threshold. The seasonal degradation in the error performance observed for both non-diversity and diversity systems indicates that the seasonal broadcast throughput gain presented earlier (see section 7.3) is associated with a seasonal increase in the error-probability.

For signals ≥ 14 dB detection-threshold the maximal-ratio diversity system error-ratio in June is 0.1; that is 90% less errors are observed using maximal-ratio diversity. The ratio is observed to decrease as the detector threshold increases; a similar trend is observed in February (Figure 7.14).

Assuming a data-block is 216 bits long then, in June, for signals ≥14 dB detector-threshold every sixth data-block will be in error in a non-diversity system. Using selection and maximal-ratio diversity systems, however, every 16th and 52nd data-block, respectively, will be in error. In February errors were predicted to occur every 8th, 24th and 78th data-block for the non-diversity system, selection diversity system and the maximal-ratio diversity system respectively.
Figure 7.16 A comparison of FSK error-probabilities obtained over a four hour period in June and February for selection-diversity, maximal-ratio diversity and a non-diversity systems.
7.5 Summary

Meteor scatter diversity data has been analysed using the modelled communications system described in Chapter 4. A modelled broadcast system, using scan-diversity and maximal-ratio diversity has been investigated as a function of receiver threshold and season. The latter was performed by comparing four hours of data obtained in February with 4 hours of diversity data obtained in June at an identical antenna separation of 10λ. FSK error-probabilities have been modelled for a meteor scatter system with and without selection or maximal-ratio diversity as a function of minimum signal detector-threshold and season.

The results obtained by the modelled broadcast systems are summarised in Table 7.2, and the modelled FSK error probability results are summarised in Table 7.3. The system noise, based on measured values (Chapter 4), for a non-diversity, scan-diversity and selection-diversity systems were taken to be -134 dB. For a maximal-ratio diversity system the noise was set 3 dB higher at -131 dB. Analysis performed at a 14 and 20 dB receiver thresholds above the system noise in 250 Hz bandwidths, were, therefore, equivalent to a 3 and 9 dB receiver thresholds in a 3 kHz communications bandwidth.

At an antenna separation of 10λ in February the optimum data-block duration, assuming a 10 ms preamble, was ~90 ms for a single non-diversity system, ~100 ms for a scan-diversity system, and ~100 ms maximal-ratio diversity system. In June, however, the optimum data-block duration was ~100 ms for an increased preamble duration of ~10 ms.

The modelled broadcast throughput diversity-gain at the 14 dB threshold in February, assuming a 90 ms data-block and a 10 ms preamble, was ~1.18 (Table 7.2) with a scan-diversity system and ~1.6 using a maximal-ratio diversity system. As
<table>
<thead>
<tr>
<th>Modelled diversity analysis parameter</th>
<th>Modelled diversity system</th>
<th>February at 14 dB receiver threshold</th>
<th>February at 20 dB receiver threshold</th>
<th>June at 14 dB receiver threshold</th>
<th>June at 20 dB receiver threshold</th>
</tr>
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<tbody>
<tr>
<td>Optimum broadcast data-block and preamble duration (ms)</td>
<td>Non-diversity</td>
<td>~90 / 10 ms</td>
<td>-</td>
<td>~100 / 10 ms</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Scan-diversity</td>
<td>~100 / 10 ms</td>
<td>-</td>
<td>~100 / 10 ms</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Maximal-ratio diversity</td>
<td>~100 / 10 ms</td>
<td>-</td>
<td>~100 / 10 ms</td>
<td>-</td>
</tr>
<tr>
<td>Average broadcast baud-rate assuming 90ms data-blocks and 10ms preambles</td>
<td>Non-diversity</td>
<td>~40 baud</td>
<td>~18 baud</td>
<td>~85 baud</td>
<td>~29 baud</td>
</tr>
<tr>
<td></td>
<td>Scan-diversity</td>
<td>~50 baud</td>
<td>~20 baud</td>
<td>~120 baud</td>
<td>~35 baud</td>
</tr>
<tr>
<td></td>
<td>Maximal-ratio diversity</td>
<td>~67 baud</td>
<td>~30 baud</td>
<td>~170 baud</td>
<td>~50 baud</td>
</tr>
<tr>
<td>Broadcast throughput gain (G)</td>
<td>Scan-diversity</td>
<td>~1.18</td>
<td>~1.15</td>
<td>~1.4</td>
<td>~1.27</td>
</tr>
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<td></td>
<td>Maximal-ratio diversity</td>
<td>~1.60</td>
<td>~1.7</td>
<td>~1.95</td>
<td>~2</td>
</tr>
<tr>
<td>Transmitter gain predicted by Eshleman [1954]</td>
<td>Scan-diversity</td>
<td>~1.4 dB</td>
<td>~1 dB</td>
<td>~3 dB</td>
<td>~1.7 dB</td>
</tr>
<tr>
<td></td>
<td>Maximal-ratio diversity</td>
<td>~4.1 dB</td>
<td>~3.9 dB</td>
<td>~5.8 dB</td>
<td>~5 dB</td>
</tr>
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Table 7.3 Summary of FSK error-probability

<table>
<thead>
<tr>
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<th></th>
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<td>FSK error probability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-diversity</td>
<td>~ 6 x 10^{-4}</td>
<td>~ 3 x 10^{-6}</td>
<td>~ 8 x 10^{-4}</td>
<td>~ 5 x 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>Selection-diversity</td>
<td>~ 2 x 10^{-4}</td>
<td>~ 8 x 10^{-7}</td>
<td>~ 4 x 10^{-4}</td>
<td>~ 2 x 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>Maximal-ratio diversity</td>
<td>~ 6 x 10^{-5}</td>
<td>~ 3 x 10^{-8}</td>
<td>~ 9 x 10^{-5}</td>
<td>~ 4 x 10^{-8}</td>
<td></td>
</tr>
<tr>
<td>FSK error probability ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selection-diversity</td>
<td>~ 0.38</td>
<td>~ 0.3</td>
<td>~ 0.5</td>
<td>~ 0.5</td>
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</tr>
<tr>
<td>Maximal-ratio diversity</td>
<td>~ 0.1</td>
<td>~ 0.02</td>
<td>~ 0.1</td>
<td>~ 0.02</td>
<td></td>
</tr>
<tr>
<td>First broadcast data block to be received in error assuming data-block is 216 bits long</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-diversity</td>
<td>8</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Selection-diversity</td>
<td>24</td>
<td>-</td>
<td>16</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Maximal-ratio diversity</td>
<td>78</td>
<td>-</td>
<td>52</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
the receiver threshold increased to 20 dB, the scan-diversity gain decreased to ~1.15 and the maximal-ratio diversity gain was ~1.7. In June the broadcast scan-diversity gain (assuming 90 ms data-blocks and 10 ms preambles) improved to ~1.4 at 14 dB and 1.27 at 20 dB. The maximal-ratio gain in June was 1.95 and 2.0 at the 14 and 20 dB thresholds respectively.

If the relationship developed by Eshleman [1954], between transmitter power and data throughput, was used for qualitative comparisons, the scan-diversity broadcast throughput gain $G \sim 1.4$, observed in June at the 14 dB threshold, was equivalent to a transmitter power increase of ~3 dB. In February, the increase in transmitter power predicted using the Eshleman [1954] relationship at the 14 dB threshold was ~1.4 dB. In a maximal-ratio diversity system the broadcast gains observed of ~1.6 and ~1.95 in February and June respectively, were equivalent to improvements of effective transmitter power of 4.1 dB in February and 5.8 dB in June. In a full-duplex system (i.e. simultaneous communications between transmitter and receiver) experiencing non-reciprocal fading, the gains observed, in the extreme, may double. These conversions between broadcast throughput gain, $G$, and effective transmitter power [Eshleman, 1954], however, must be treated with considerable caution.

Non-coherent FSK error probabilities have been modelled for a non-diversity system, a selection diversity system and a maximal-ratio diversity system. The modelled results provide relative improvements in FSK error probabilities using diversity. Theoretical diversity FSK error probability calculations were not within the scope of this thesis. Modelled FSK error-probabilities (relative to a non-diversity system) show that in February, for signals $\geq 14$ dB detector-threshold, 62% fewer errors were observed using selection-diversity, and 90% fewer errors were observed using the maximal-ratio system. Assuming a data-block is 216 bits long (i.e. data-rate 2400 bits per second and 90 ms data-block durations) a non-diversity system would receive an error every 8th data-block. Using selection-diversity and maximal-ratio diversity, however, every
24\textsuperscript{th} and 78\textsuperscript{th} data-block, respectively, were predicted to be in error. In June the error probabilities increase and results showed that, assuming a data-block of 216 bits, an error would occur every 6\textsuperscript{th}, 16\textsuperscript{th}, and 52\textsuperscript{nd} data-block for a non-diversity system, a selection-diversity system and a maximal-ratio diversity system respectively. The modelled FSK error-probabilities showed that although the broadcast throughput diversity-gain was greater in June than February, the diversity-gain observed would be associated with an increase in the FSK error-probability.
Chapter 8 Summary of conclusions and suggestions for further work

8.1 Introduction

Meteor scatter diversity and multipath has been investigated using $\sim$37 MHz continuous-wave signals and two antennas separated in a line perpendicular to the propagation path (Chapter 3). The diversity data obtained was analysed using a cross-correlation technique and a modelled meteor scatter communications system implementing diversity (Chapter 4).

The cross-correlation analysis system digitised the diversity-data using a sampling rate of 10 ms and an anti-aliasing, low-pass, filter bandwidth of 25 Hz. The analysis system enabled the received diversity signals, above a defined signal-power threshold, to be categorised as "underdense", "overdense" or "not known" (NK). The received signals in each category were then correlated using a signal segmentation method, and a method similar to that favoured by Ladd [1961].

Signals received at an antenna separations of $10\lambda$ were first analysed using the cross-correlation technique to determine which of the received signal categories were decorrelated (Chapters 5) and, therefore, potentially advantageous to a meteor scatter communications system implementing space diversity. The optimum antenna separation, for the reception of decorrelated signals, was then investigated by analysing signals received at antenna separations of $5\lambda$, $10\lambda$ and $20\lambda$ (Chapter 6).

The modelled diversity communications system was used to determine if communications diversity gain could be achieved. The modelled communications system (Chapter 4) digitised the received signals at a sampling rate of 1 ms using an anti-aliasing, low-pass, filter bandwidth of 250 Hz. The broadcast-gain (Chapter 7)
was determined for a non-diversity system, a modelled scan-diversity system and a modelled maximal-ratio diversity system. Modelled FSK errors were calculated for a non-diversity system, a selection-diversity system and a maximal-ratio diversity system. Both the broadcast throughput-gain, and the FSK error-probabilities were investigated as a function of season by comparing the results obtained in February with those obtained in June.

8.2 Cross-correlation analysis of meteor scatter signals received at 10λ

Cross-correlation analysis of meteor scatter signals, received at two antennas separated by 10λ (Chapter 5), showed that conclusions based on the total-decay signal-envelope correlation method used by Ladd[1961] were incorrect. Correlation values obtained using this method were high and similar to those correlation values obtained over the first 0.25 s segment (segment 1) using the signal segmentation analysis method used in this thesis. The unsegmented total-decay correlation values were dominated by the time-decaying signal envelope, given that the perturbation of the decaying signal envelope, by multipath, was small.

Underdense and NK signals were shown to decorrelate with increasing segment number (i.e. time into signal decay). This trend towards decorrelation was not detected in the overdense signal category. It was suggested, therefore, that the correlation-time dependency was, partly, a result of the relatively low-power underdense or NK signals, combining with other weak power signal propagation modes (e.g. sporadic-\(E\), ionoscatter). These weak signal-modes would have little effect on the overdense signals which, typically, have higher received signal-powers.

Comparative studies between the three signal categories over the three 0.25 s correlation segments, showed that NK signals were significantly more
decorrelated, on average, than either underdense or overdense signals. NK signals, therefore, promised the greater diversity advantage. When all the received signals were combined together, to model the signals received by a meteor scatter communications system, 40% of the signals of duration ≥ 0.75 s experienced correlation value of less than 0.6 in segments 2 and 3.

In conclusion, the decorrelated meteor scatter space diversity signals received at the antenna separation of 10λ suggested that diversity may be advantageous to a meteor scatter communications system; especially when NK signals were present. A diversity contribution could, however, also be expected from underdense signals, particularly towards the end of their signal lifetimes when significant decorrelation could occur.

8.3 Spatial correlation variation of meteor scatter signals

The spatial variation of correlation values, a parameter important for diversity system design, was investigated using signals received at antenna separations of 5λ, 10λ and 20λ (Chapter 6). All of the following conclusions relate to signals of duration ≥ 0.75 s obtained in February when the incidence of NK signals was expected to be at a minimum.

Overdense signals from two antennas separated by 5λ and 10λ did not decorrelate with time. At a separation of 20λ, however, a decorrelation dependency with time was observed. Since overdense signals were, on average, of higher signal-amplitude than either underdense or NK signals, overdense signals were less affected by weak signal-modes (e.g. sporadic-E, ionoscatter); overdense signal decorrelation, therefore, primarily depended on the production of multiple scattering regions (glints), and a separation of at least 20λ was needed to detect this
fading. Logistical constraints precluded extending the study to antenna separations >20λ.

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 observed for either signal category. The observed decorrelation 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 the modest 5λ antenna separation. Underdense trails are relatively smaller scattering sources than overdense trails and the signals from underdense trails were sufficiently coherent that any significant decorrelation effects were not measurable. 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.

For commonly available contemporary meteor scatter communications 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, a diversity antenna separation of 20λ (or more) will be required to receive decorrelated overdense signals and enhance the data throughput achieved using space-diversity. If, however, most of the signal traffic is passed via underdense and NK signals (for example in a system using a few kilowatts of transmitter power) a 5λ diversity antenna spacing is sufficient to receive decorrelated signals.

On the basis of the correlation measurements made in this thesis, the 4λ space diversity antenna separation implemented by Bartholomé and Vogt [1968] in
COMET would probably have contributed to the excellent system performance via
the reception of uncorrelated signals. That moderately powered system would
have passed much of its traffic over overdense and NK trails and consequently a
spacing of 20λ would have been advantageous. Not withstanding that, 4λ would
have provided useful signal decorrelation between the two diversity channels.
Our results, therefore, partly explain the high average data rates achieved by the
COMET system.

8.4 February-June correlation variation

The correlation variation of meteor scatter diversity signals obtained in June and
February, at identical antenna separations of 10λ, were investigated in Chapter 6.
The results showed that in June segmented underdense and NK signals were, on
average, more decorrelated than those detected in February. The results indicated
a seasonal decorrelation trend as suggested in Chapter 5. The seasonal trend of the
segmented correlation values could be attributed to the seasonal increased
incidence and increased average signal-power of the decorrelating weak signal
modes (e.g. sporadic-E). Overdense segmented signals exhibited no seasonal
variation in correlation values. This is not in conflict with the weak signal mode
fading mechanism discussed earlier for the low-power underdense and NK
signals. The typically higher powers of the overdense signals, during early stages
of signal decay, are not decorrelated by the weak signal mode.

Due to the seasonal trend in NK and underdense signal decorrelation values, the
diversity throughput gain detected in June was predicted to be greater than the
gain observed in February. A seasonal contribution to the throughput diversity
gain may also be expected from the longer duration overdense signals particularly
during the latter stages of signal decay which were more decorrelated in June than
February.
8.5 Meteor scatter broadcast gain using space-diversity

A modelled broadcast system, using scan-diversity and maximal-ratio diversity combining was investigated as a function of receiver threshold and season (Chapter 7) using the space diversity signals recorded at 10λ. The broadcast gain achieved using diversity are summarised in Table 8.1. The 14 and 20 dB thresholds, used during data analysis in the 250 Hz bandwidth, are equivalent to 3 and 9 dB receiver threshold in a 3 kHz communications bandwidth (Chapter 4).

At an antenna separation of 10λ in February, when the number of NK signals is expected to be at a minimum, the optimum data-block duration commensurate with maximum data-rate, for a non-diversity system was ~90 ms for a 10 ms preamble at the 14 dB threshold (Chapter 7). In a selection-diversity system and maximal-ratio diversity system the optimum data-block duration increased to ~100 ms for a 10 ms preamble duration. In June the optimum data-block duration for the non-diversity, scan-diversity system and the maximal-ratio diversity system was determined to be ~100 ms for a 10 ms preamble.

The broadcast diversity-gain (G), at the 14 dB threshold in February, using a 90 ms data-block and a 10 ms preamble, was ~1.18 with a scan-diversity system. At the 20 dB threshold, the broadcast scan-diversity gain in February decreased to ~1.15. In June, however, the scan-diversity gain increased to ~1.4 at 14 dB and ~1.27 at 20 dB.

For a maximal-ratio diversity system the broadcast diversity-gain (G), in February, at the 14 dB threshold (above system noise of -131 dB) was ~1.6 and was ~1.72 at the 20 dB threshold. In June, however, the gain (G) was observed to increase to ~1.93 and ~2.0 at the 14 and 20 dB thresholds respectively.

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### Table 8.1 Summary of broadcast diversity gains

<table>
<thead>
<tr>
<th>Diversity analysis Parameter</th>
<th>Modelled diversity system</th>
<th>February at 14 dB receiver threshold</th>
<th>February at 20 dB receiver threshold</th>
<th>June at 14 dB receiver threshold</th>
<th>June at 20 dB receiver threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average broadcast baud-rate assuming 90ms data-blocks and 10ms preambles</td>
<td>Non-diversity</td>
<td>~40 baud</td>
<td>~18 baud</td>
<td>~80 baud</td>
<td>~29 baud</td>
</tr>
<tr>
<td></td>
<td>Scan-diversity</td>
<td>~50 baud</td>
<td>~20 baud</td>
<td>~120 baud</td>
<td>~35 baud</td>
</tr>
<tr>
<td></td>
<td>Maximal-ratio diversity</td>
<td>~67 baud</td>
<td>~30 baud</td>
<td>~170 baud</td>
<td>~50 baud</td>
</tr>
<tr>
<td>Broadcast throughput gain (G)</td>
<td>Scan-diversity</td>
<td>~1.18</td>
<td>~1.15</td>
<td>~1.4</td>
<td>~1.27</td>
</tr>
<tr>
<td></td>
<td>Maximal-ratio diversity</td>
<td>~1.60</td>
<td>~1.70</td>
<td>~1.95</td>
<td>~2.00</td>
</tr>
<tr>
<td>Transmitter gain predicted by <em>Eshleman</em> [1954]</td>
<td>Scan-diversity</td>
<td>~1.4 dB</td>
<td>~1.0 dB</td>
<td>~3.0 dB</td>
<td>~1.7 dB</td>
</tr>
<tr>
<td></td>
<td>Maximal-ratio diversity</td>
<td>~4.1 dB</td>
<td>~3.9 dB</td>
<td>~5.8 dB</td>
<td>~5.0 dB</td>
</tr>
</tbody>
</table>
A relationship between effective transmitter power and data throughput, developed by Eshleman[1954], was used for qualitative comparisons. Using this relationship the broadcast scan-diversity gain of G~1.4, observed in June at the 14 dB threshold, was equivalent to a transmitter power increase of ~3 dB. In February the smaller broadcast scan-diversity gain of ~ 1.18, at the identical threshold, was equivalent to a smaller increase in transmitter power of ~1.4 dB. For the maximal-ratio diversity systems the equivalent transmitter power gain predicted, at the 14 dB thresholds, in June and February were ~6 dB and 4.1 dB respectively.

In a full-duplex meteor scatter communications system implementing diversity and subject to non-reciprocal fading, the improvements observed may, in the extreme, double (e.g. in June a broadcast scan-gain at the 14 dB threshold of 2.8, or a 6 dB increase in transmitter power). It has been stressed that conversions between broadcast throughput gain, G, and the improvement in effective transmitter power using the Eshleman [1954] relationship, must be treated with considerable caution due to the lack of consideration of fading in the model developed by Eshleman[1954].

8.6 Meteor scatter FSK error-probability gain using space-diversity

FSK error-probabilities were determined (Chapter 7) for a non-diversity system, a selection-diversity system and a maximal-ratio diversity system. The error-probabilities were evaluated as a function of minimum signal detection threshold and season, and the results are summarised in Table 8.2.

In February, for signals ≥ 14 dB threshold, the FSK error-probability ratio of 0.38 and 0.1 for the selection-diversity and maximal-ratio diversity systems (Table 8.2) indicate that 62% and 99% fewer errors were observed using selection or maximal-ratio diversity, respectively, than a non-diversity system. Assuming the broadcast

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Table 8.2 Summary of diversity error-probability gains

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FSK error probability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-diversity</td>
<td>~ $6 \times 10^{-4}$</td>
<td>~ $3 \times 10^{-6}$</td>
<td>~ $8 \times 10^{-4}$</td>
<td>~ $5 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Selection-diversity</td>
<td>~ $2 \times 10^{-4}$</td>
<td>~ $8 \times 10^{-7}$</td>
<td>~ $4 \times 10^{-4}$</td>
<td>~ $2 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Maximal-ratio diversity</td>
<td>~ $6 \times 10^{-5}$</td>
<td>~ $3 \times 10^{-8}$</td>
<td>~ $9 \times 10^{-5}$</td>
<td>~ $4 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td><strong>FSK error probability ratio</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selection-diversity</td>
<td>~ 0.38</td>
<td>~ 0.3</td>
<td>~ 0.5</td>
<td>~ 0.5</td>
<td></td>
</tr>
<tr>
<td>Maximal-ratio diversity</td>
<td>~ 0.1</td>
<td>~ 0.02</td>
<td>~ 0.1</td>
<td>~ 0.02</td>
<td></td>
</tr>
<tr>
<td><strong>First broadcast data-block to be received in error assuming a data-block is 216 bits long</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-diversity</td>
<td>8</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Selection-diversity</td>
<td>24</td>
<td>-</td>
<td>16</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Maximal-ratio diversity</td>
<td>78</td>
<td>-</td>
<td>52</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
data-blocks comprised of 216 bits (i.e. data-rate 2400 bits per second and 90 ms data-block durations) the error-probability results showed that every eighth data-block in a non-diversity system would be in error. Using selection-diversity and maximal-ratio diversity, however, every 24th and 78th data-block, respectively, would be in error.

In June the probability of an FSK error, using signals above the 14 dB detector-threshold, increased and results showed that for a non-diversity system ~ 35% more errors were predicted in June than February. This increase in error-probability resulted in an error occurring every 6th data-block in a non-diversity system (assuming 216 bit data-blocks). For a selection-diversity system and maximal-ratio diversity system in June, the error-probability results showed that every 16th, and 52nd, respectively, would be in error. The seasonal increase in FSK error-probability may be attributed to a seasonal increase in low-power uncorrelated signals (e.g. sporadic-E). The error-probability and broadcast gain results demonstrate that although a seasonal broadcast diversity-gain variation occurs, the gain is associated with a seasonal variation in FSK error-probabilities.

To conclude, meteor scatter communications systems implementing space diversity should experience an improvement in broadcast data-throughput and a reduction in FSK error-probability. The ease of implementation of scan or selection diversity, suggests that these diversity configurations may be implemented to reduce the impact of signal-fading and enhance the performance of meteor scatter communications systems. Significant advantages may also accrue using maximal-ratio diversity combining. The advantages of this diversity system result from not only decreasing the impact of signal-fading, but also increasing the signal-to-noise ratio by 3 dB. Assuming that the sophistication required to implement maximal-ratio diversity can be tolerated, significant advantages may be obtained by its implementation in meteor scatter communications systems.
8.7 Further work

A meteor scatter communications system incorporating space-diversity should be constructed. It is suggested that, due to its ease of implementation, the meteor-scatter diversity communications system should incorporate two antenna space-diversity and scan (or selection) combining. The receive antennas should be separated by at least 10λ in a line perpendicular to the transmit and receiver path.

Although a trend in diversity gain with season has been detected, time precluded the detection of a diurnal diversity gain. Such an experiment could also be performed as a function of season. The gains detected would then impact on the operational parameters (e.g. data-block duration) required by the meteor scatter communications systems as a function of local-time and season.

Diversity and non-diversity broadcast-gains should be investigated as a function of increasing transmitter power. The results would reveal, experimentally, the increase in transmitter power required to achieve the throughput gain observed using diversity. Alternative diversity techniques should also be investigated, e.g. height, polarisation, frequency diversity. The exploitation of height and frequency diversity may further minimise the space required by a diversity system.

An important caveat to the results presented in this thesis relate to the geographical latitude of the experiments performed. At high latitudes, in particular, where anomalous propagation modes are more common, different conclusions may be obtained. Consequently, diversity experiments should be performed as a function of latitude, and since north-to-south and east-to-west propagation paths exhibit differing throughput characteristics, these paths should be investigated simultaneously.
Appendix A  

Examples of meteor signal-envelopes

Introduction

During cross-correlation analysis (Chapter 5 and 6) the digitised diversity-data is plotted to show signal strength values (dBm, ordinate) against time (seconds, abscissa), and the received signal-envelopes, above a set threshold of -120dBm, are categorised as either 'Underdense', 'Overdense' or 'Not Known'. Examples of each of these signal categories, obtained from an antenna separation of 10λ in June ('D' data filenames) or February ('T' filenames) are plotted below. The examples of interest are bounded by vertical lines which denote the total-decay envelope used during analysis (Chapter 5). Due to the limited log-detector dynamic range, the signal-noise is ~10 dB greater than that determined experimentally. A similar signal categorisation has been performed by Østergaard et al.[1985].

Signals scattered from an underdense trail were characterised by a fast (~0.1 s) rising increase in signal strength followed by a slower linear decay (in dB) which started immediately after the envelope had reached its maximum amplitude. Examples of underdense signals are plotted on pages A2-A4.

A specular overdense signal was also characterised by a fast (~ 0.1 s) rise in signal strength until the first Fresnel zone is formed. This is followed by a period of slowly increasing signal strength, resulting in a rounded top to the received envelope, which is followed by the decay of the signal (see pages A5-A7).

Signals clearly not of the above format were categorised as 'Not Known' (NK) and examples are plotted on pages A8-A10. Echo-overlap signals are also included in this signal category.
Underdense signals

Threshold is \(-120\) dBm
Data Filename = T1443b9
Time window is 5 secs

Threshold is \(-120\) dBm
Data Filename = D199la9
Time window is 5 secs

Threshold is \(-120\) dBm
Data Filename = T14636
Time window is 5 secs
Underdense signals

Threshold is -120 dBm
Data Filename - T14841
Time window is 5 secs

Threshold is -120 dBm
Data Filename - T148311
Time window is 5 secs

Threshold is -120 dBm
Data Filename - T148311
Time window is 5 secs
Underdense signals

Threshold is -120 dBm
Data Filename = TI4428
Time window is 10 secs

Threshold is -120 dBm
Data Filename = TI4806
Time window is 5 secs

Threshold is -120 dBm
Data Filename = TI4804
Time window is 5 secs
Overdense signals

Threshold is -128 dBm
Data Filename = T1483b3
Time window is 5 secs

Threshold is -128 dBm
Data Filename = D1993b7
Time window is 5 secs

Threshold is -128 dBm
Data Filename = D1993a10
Time window is 5 secs
Overdense signals

Threshold is -120 dBm
Data Filename = D1993b15
Time window is 5 secs

Threshold is -120 dBm
Data Filename = D1993b12
Time window is 5 secs

Threshold is -120 dBm
Data Filename = D1993b10
Time window is 5 secs
Overdense signals

Threshold is -120 dBm
Data Filename - T140411
Time window is 5 secs

Threshold is -120 dBm
Data Filename - T14402
Time window is 5 secs

Threshold is -120 dBm
Data Filename - D19914
Time window is 5 secs
NK signals

Threshold is -120 dBm
Data Filename: D1991b7
Time window is 5 secs

Threshold is -120 dBm
Data Filename: D1991b8
Time window is 5 secs

Threshold is -120 dBm
Data Filename: D1993b1
Time window is 5 secs
NK signals

Threshold is -120 dBm
Data Filename = T14422
Time window is 5 secs

Threshold is -120 dBm
Data Filename = D199a2
Time window is 5 secs

Threshold is -120 dBm
Data Filename = D199a4
Time window is 5 secs
NK signals

Threshold is -120 dBm
Data Filename = D1391b9
Time window is 5 secs

Threshold is -120 dBm
Data Filename = D1391b3
Time window is 5 secs

Threshold is -120 dBm
Data Filename = D1391b4
Time window is 5 secs
Appendix B  The cross-correlation analysis program

Introduction

The cross-correlation analysis system and technique has previously been described in Chapter 4. The general cross-correlation analysis software, which can also be used to analyse non-meteor scatter signals, is described below by outlining the function of each main menu item (Figure B.1). The software is written in HP BASIC version 2.1 for the Hewlett Packard 9836 computer and the 9 softkeys available are extensively used to display sub-menu options. Throughout the software description Channel 1 and Channel 2 refer to the two space-diversity recording systems (Chapter 4). The software developed is stored on one eight-inch floppy disc and is automatically loaded and executed when the computer is switched on. The computer system must have available at least 1 Mbyte of RAM before the software is loaded. To control the Store 4DS tape recorder a HP General Purpose Input Output (GPIO) interface card must also be installed.

CREATE a new calibration file.

During data acquisition each receiving system is calibrated every 28 minutes using down-converter input signal-powers of -76 dBm to -133 dBm in 3 dB steps. The duration of each calibration level is ~5 s (Chapter 4). These analogue calibration voltages are digitised and a third-order curve fit equation, relating the analogue-to-digital (ADC) value to the down-converter input signal-power, is calculated and stored. The calibration equations are used, during diversity data digitisation, to convert the ADC values obtained into signal-power levels (dBm) prior to data storage.

Calibration equations are obtained by selecting the 'CREATE a new calibration file' option from the main menu. The option samples the calibration voltages every 10ms
Meteor Scatter Diversity Cross-correlation
Acquisition and Analysis Program

Main Menu

- CREATE a new calibration file.
- DIGITIZE and STORE a new meteor scatter data.
- DISPLAY and ANALYZE the data set.
- MERGE two $R_{xy}(0)$ data files together.
- RECALL and PRINT a $R_{xy}(0)$ data file.
- $R_{xy}(0)$ data file analysis.
- EXIT from the program.

Figure B.1 The main menu of the cross-correlation acquisition and analysis program.
Figure B.2 Typical computer outputs during calibration showing
a) the ADC calibration voltages between -76 dBm (t~ 1 s)
   and -133 dBm (t~ 100 s)
b) a plot of the third-order calibration equation obtained
and stores the ADC values in buffer memory. Once the final calibration voltage has been sampled, digitisation is halted, and the ADC values (Y-axis) are plotted (Figure B2) against time (X-axis). By using a sliding vertical time-cursor an ADC calibration voltage level can be assigned to a dBm value starting at -76 dBm (t-1). Each ADC level decrements by 3 dB every 5 seconds and the last ADC-to-dBm assignment is at -133 dBm (t~100 s). Once all the ADC levels have been assigned to a signal-power value, a third-order-curve fit equation is calculated and plotted (Figure B2). If the operator is satisfied with each calibration curve the calibration equation is stored to disc and the program returns to the top level menu (Figure B1).

**DIGITISE and STORE new meteor scatter data**

This menu item digitises the analogue diversity data and converts the ADC values obtained into signal-powers (dBm) using the calibration equation specified by the operator. Two modes of digitisation are available; 'MANUAL' and 'AUTOMATIC'. When digitisation is performed using the 'AUTOMATIC' mode the operator defines the sampling rate and the calibration file to be used. By controlling the Store 4DS tape recorder 'REMOtELY' using the computer GPIO port, upto 12 data-blocks, each consisting of 15,000 samples per channel, can be digitised and stored automatically to floppy disc.

During 'MANUAL' digitisation the operator enters the sampling rate and the calibration file to be used before to each data block is digitised. The Store 4DS tape-recorder is controlled manually following prompts provided by the software.

The sampling-rate is set using soft-switches but the filter bandwidth must be set manually. 15,000 ADC values per channel are initially stored in buffer memory during digitisation. The samples are then converted to signal-powers (dBm) utilising the
calibration equations obtained using the CREATE menu option. The time taken to digitise one data block at a sampling rate of 10 ms is ~8 minutes.

Time-contiguous data-blocks, each of 15,000 samples per channel, are stored under sequentially number filenames. Each data file is tagged with the time, date, aliasing filter bandwidth, sampling-rate and the filename of the calibration data file used. An eight-inch floppy disc stores a maximum of 4 signal data files.

**DISPLAY and ANALYSE the data set**

The time contiguous-data blocks stored on floppy disc can be re-called displayed and analysed using the 'DISPLAY and ANALYSE' menu option. If diversity data is to be displayed and then analysed, appropriate ASCII data files are created on the 5 inch internal floppy discs. The analysis data (i.e. signal category, signal duration, cross-correlation values and average signal-powers) are stored to disc until the operator 'EXITS' from signal analysis. During analysis six data files may be created for the three signal-categories (underdense, overdense, or NK) and the two primary analysis results (average signal power and cross-correlation values).

Each entry to the cross-correlation data file comprises of the signal-duration, and 11 possible cross-correlation values. The first 10 cross-correlation value locations are reserved for the cross-correlation values obtained from the first 10 segments. Location 11 is for the cross-correlation value for the total signal decay (i.e (signal start-time) - (signal end-time). Signal-power statistics (i.e average signal power, maximum and minimum signal-power and standard deviation) are stored in a similar data-format to the correlation-values. The average signal-power is calculated for each segment and for an unsegmented signal.
Figure B.3 A typical computer display showing the two diversity signal channels and the softkey menu options available.
The duration of each analysis segment is defined in the 'X-CORREL' subroutine. During meteor scatter analysis the cross-correlation lead-lag time, (defined in 'X_CORREL' subroutine) is set to zero (i.e \( \tau = 0 \)), but can easily be redefined to range between \( \pm T_{ms} \). Meteor signal cross-correlation values at \( \tau \neq 0 \) are invalid because meteor signal decay is a non-stationary process.

To perform signal analysis the operator defines the signal duration by locating the signal-start time (using the sliding vertical time-cursor) and signal-end time. The software automatically divides the signal-duration defined into the appropriate number of segments and then calculates the segmented and unsegmented correlation and signal-power statistics. The results obtained are stored to a signal-category data file specified by the operator.

If the data is only to be displayed no data files are created and any signals analysed are not stored to disc. This option may be used to obtain hard copies of the signals displayed. A HP thermal printer and a HP 7470A graphics plotter are supported by the software, although the latter device must be selected by a minor modification to the software.

The data files requested by the operator are displayed as signal-strength (dBm ordinate axis) against time (seconds abscissa) and a selection of time windows are available (e.g. 0.5, 1, 5, 10 and 30 s Figure B3) For reference a horizontal power threshold, at a level specified by the operator, is also drawn on each time-frame. The diversity data displayed can be advanced by one time-frame using the upper four softkeys \( k_0 - k_4 \). The time-frame displayed can be advanced, or retarded (by the duration currently displayed) using 'SHIFT LEFT' (\( k_4 \)) or 'SHIFT RIGHT' (\( k_0 \)) softkeys. The 'NEW START TIME' enables the operator to display data from other data files without exiting the program.
Embedded within the analysis routines are other non-primary sub-routines (e.g. calculation of the decay meteor scatter decay gradients, correlation variance) which were developed during correlation-analysis and software evaluation. Although these are currently not recalled in the main menu, or from any of the sub-menus, a minor modification to the software can make these non-primary sub-routines active.

**MERGE two $R_{xy}(0)$ data files**

Multiple cross-correlation data files stored on disc, for example obtained from different analysis sessions, can be 'merged' into one data file to ease statistical analysis. Since any two correlation-data files may be merged, care is required when using this menu option to ensure that correlation-data from different signal categories are not combined in error. This error, however, may be overcome by using the '$R_{xy}(0)$ data file analysis' option which can separate the error data-file into two files.

**RECALL and PRINT a $R_{xy}(0)$ data file**

This option enables the operator to print the data stored in a specified correlation data file. The data is printed to the VDU screen, or to a thermal printer if it has been previously selected.

**$R_{xy}(0)$ data file analysis**

Statistical analysis of the cross-correlation and signal-amplitude data can be achieved using the data file analysis option. On selection of the option, a data analysis software suit is loaded and enables the data files stored to be manipulated (i.e merged, deleted, separated) and analysed. Data stored in each data file can be analysed by calculating statistical parameters (i.e average, median, maximum, minimum) for each segment.
number and by plotting cumulative probability distributions functions for each segment.

The general analysis suit can be used to analyse either the signal-power data files or the cross-correlation data files. Data analysis is performed on signals of duration $\geq T$ (where $T = 0.75$ in chapters 5 and 6) and the data is first recalled from floppy disc and stored in buffer memory. The operator is then able to select the data to be analysed (e.g. cross-correlation values, signal-duration,) and which analysis routine is to be used (median, maximum, minimum, average and standard deviation). Results can be output to a thermal printer or to an ASCII data file if required.

Re-entry to the cross-correlation acquisition and analysis software is performed by re-booting the system.

EXIT from program.

This enables the operator to EXIT the cross-correlation software suit.
References


Davies, K. D., Ionospheric Radio, Peter Peregrinus, IEE electromagnetic waves series 31, 1990.


Schiaparelli, G. V., Meteor astronomy, Oxford University Press, 1954.


