METEOROLOGICAL CAUSES
OF
ANOMALOUS MICROWAVE
PROPAGATION

T. Jones

A thesis submitted in fulfilment of the requirements
for the degree of Ph.D
to the
University of Edinburgh
1993
The echoes were abnormally strong today. Instead of slicing straight on out into space as the curve of the earth fell away beneath it, the radar beam was being bent downwards by some peculiarity of the atmosphere. It was wavehopping all the way across the North Sea, bouncing off the Dutch coast, and a little more than a thousandth of a second after it had started its journey — returning along the same curving path with the secrets it had gathered.

_Glide Path_
_Arthur C. Clarke_
_1963_
Declaration

This thesis has been composed by myself and it has not been submitted in any previous application for a degree. The work reported within was executed by myself, unless otherwise stated.

July 1993
Abstract

This thesis is concerned with the influence of the weather on radio signals on surface-to-surface paths, looking particularly at the effects of fronts. The radio-meteorology of anticyclones is well understood [COST 1991], but that of fronts is less so, despite the knowledge that fronts can sometimes cause very severe radio interference through anomalous signal propagation (anaprop).

A statistical analysis is made of two years signal data from seven paths in the UK and to the Netherlands. By classifying weather conditions into 24 different types, the effects of different types of weather as causes of anaprop have been determined. The results confirm the belief [Bye 1988a] that the majority of anaprop occurs under anticyclonic conditions, and that fronts are a relatively insignificant cause of anaprop. The results for the different weather and path types are presented in a set of 'interference data sheets', allowing rapid comparison of the effects of different weather conditions on signals for land and sea paths. This analysis is one of only two that examine the effects of different weather conditions on signals, and considers a far greater amount of both signal and weather data than the other study [Spillard 1991].

To examine how fronts can cause anaprop, existing meteorological conceptual models [e.g. Browning 1985] are adapted to show where super-refractive layers occur. The models examine ana- and kata-fronts (both warm and cold), as well as warm and cold occlusions. For each type of front, qualitative predictions of the likelihood of anaprop are given.

The conceptual models are verified in two ways. Using dropsonde data from the FRONTS'87 project, three fronts are examined at resolutions far higher than can be obtained from routine observations. Super-refractive layers are found where the conceptual models predict them, and it is possible to make estimates of the location and strength of these layers. Using routine meteorological observations and signal data, it is found that, when fronts cause anaprop, the signals occur where predicted by the models. It is found, however, that only some 50% of fronts actually cause anaprop, but it is not yet clear why this is so.
Acknowledgements

I acknowledge the copyright of all the authors and organisations whose diagrams are reproduced in this work. All these are identified in the text.

I would like to thank everyone who has helped me during the course of this work, especially:

Dr. Keith Weston (Edinburgh University) and Dr. Mick Mehler (BTL) for their supervision of this thesis.

Gail Bye and Bob Howell (BTL) for their help and advice throughout the project.

Drs. Sid Clough and John McKay (Meteorological Office) for allowing me access to the FRONTS'87 data used in Chapter 5.

Special mentions to all my friends who have provided so much support and encouragement over the last few years.

This work was funded and carried out under British Telecom research contract A039339/P.

The author is now at:
Department of Mathematics
Peterhead Academy
Prince Street, Peterhead
ABERDEENSHIRE, AB42 6QQ
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Chapter 1

Introduction

The object of this thesis is to investigate the part different weather conditions, in particular fronts, play in causing interference between different parts of a telecommunications network. This chapter begins with the motivation behind this research, followed by an outline of the remainder of the thesis and finally by a summary of the main findings.

1.1 The need for this research

This work has been undertaken at the request of British Telecom Laboratories (BTL), and forms part of their continuing investigation of the effects of the Earth’s atmosphere on radio propagation. This sort of work is important since the radio and microwave regions of the electromagnetic spectrum are limited in extent and are in demand for a wide variety of uses, from broadcasting to radio astronomy. As a result there is considerable pressure to minimise ‘wastage’ of the spectrum. British Telecom, in common with most telecommunications agencies in the developed world, uses microwaves for point to point communications, beaming signals along line of sight paths typically 50 to 100 km in length. To avoid interference, nearby paths must use different frequencies and the object of BTL’s research is to minimise the coordination distance within which a frequency cannot be reused without unacceptable amounts of interference between the paths\(^1\). The coordination distance depends on both geographical factors — the geometry of the paths and the underlying terrain — and on the meteorology, through a number of interference propagation mechanisms in the atmosphere. These

\(^{1}\)“Unacceptable” amounts are difficult to quantify, but typically are when interference occurs for more than 0.1% of the year [Hall 1979 p179].
mechanisms can be divided into long-term (hence of importance when planning signal networks) and short-term (unpredictable and often producing very severe interference) mechanisms [COST 1991 p2.1].

The main long-term mechanisms are shown in Fig 1.1. Ignoring diffraction and scattering from obstacles in the signal path which are not meteorological mechanisms and therefore are outside the scope of this work, there are two major long-term mechanisms:

- **Line-of-sight propagation** is the standard propagation mechanism and, as shown in fig 1.1, it gives the required signal path between transmitter and receiver. It can be an interference mechanism when signals which spill past the receiver reach the receiver of a second path. Such interference can be avoided by careful network planning.

- **Troposcatter** has been used operationally to increase the length of signal paths but is also an interference mechanism and a control on the transmitter power on a given path.

Short term mechanisms are shown in fig 1.2 and are the main interest of this work. Short term interference cannot be overcome when planning networks unless coordination distances are very large. Four major mechanisms are defined:
Figure 1.2. Short-term mechanisms responsible for interference between signal paths. [From COST 1991 p2.2]

- **Hydrometeor scatter** is outwith the scope of this work and has been extensively studied elsewhere. It is an important interference mechanisms as hydrometeors at high levels can scatter signals over large areas [COST 1991 p2.3].

- **Enhanced line-of-sight** is responsible for higher than usual signal levels at a receiver and for increasing the distance signals will spill past a receiver. Again this mechanism is fairly well understood and is peripheral to this work.

- **Elevated layer reflection and refraction** — "ducting" — can cause signals to propagate far beyond the normal radio horizon and over terrain which blocks normal signal paths. It is thus possible to get interference between paths hundreds of kilometres apart. The physical processes that give rise to elevated layers are fairly well understood, but their occurrence within large scale weather systems is less well so.

- **Surface super-refraction and ducting** is particularly important over flat ground and over water, again allowing signals to propagate over considerable distances. In some areas it is a very severe problem, for instance surface ducts can exist for about 20% of the year over the southern North Sea [Hall & Barclay 1989 p168], causing interference between UK and Dutch signal networks. This illustrates an important point — radio interference knows no frontiers, so international cooperation is vital to allow the most efficient use of the radio spectrum.
The final two mechanisms are related, involving reflection and/or refraction from superrefractive layers in the atmosphere. It is these mechanisms which are the main interest of this work. Also, it should be remembered that these mechanisms operate together and so interactions between different mechanisms can be as important as the individual processes.

1.2 Outline of the thesis

This thesis looks at much of radio-meteorology, starting with an overview of the subject and moving to a detailed study of the radio-meteorology of fronts. There are five main chapters:

- Chapter 2 reviews the current state of knowledge of radio meteorology. It looks at the essential details of radio propagation in the Earth’s atmosphere and at how certain weather conditions can cause anomalous propagation (*anaprop*). The mechanisms responsible for anaprop are examined as is existing research on anaprop due to anticyclones and fronts.

- Chapter 3 presents the results of an analysis of signal data for a number of paths in North West Europe and correlates signal behaviour over a two-year period with the prevailing weather conditions. After a discussion of the methods used to analyse the signal and weather datasets, the results of the analysis are presented and discussed. This analysis is one of the first to look at signal statistics under *different* weather conditions rather than for a particular period, regardless of the changing weather.

- Chapter 4 looks at conceptual models of fronts. Existing meteorological models of depressions are examined and then adapted to radio-meteorology. Conceptual models of the refractivity structure and the expected anaprop around all types of fronts are presented here. These models are similar in idea to the BTL conceptual model of an anticyclone, providing a framework for the case studies of frontal anaprop in the final chapters of this work and also providing a basis for operational predictions of anomalous propagation.

- Chapter 5 uses the conceptual models to analyse the detailed structure of ana- and kata- cold fronts and an occlusion. Data have been obtained from the Meteorological Office’s FRONTS’87 project and analysed to provide the first detailed studies of the refractivity structure around these fronts.
Chapter 6 contains a number of case studies of signal behaviour as fronts interact with a short signal path in South East England. This path was selected since there is very high resolution signal data for a period when there were a number of frontal interference events and there were both upper air and surface meteorological data available. The analysis looks both at the signal data and the refractivity structure over the path. Again the conceptual models are used to interpret the findings.

1.2.1 Original material in this thesis

Being an interdisciplinary thesis, this work contains much material that has already been published. This is necessary since the work may be used both by meteorologists and by radio engineers and it is necessary to give each some background of the others subject. This material is contained in chapter 2 as well as in the early part of chapter 4

Summarising the new material for each chapter:

- Chapter 3 presents the first examination of the effects of different weather conditions on UK and Dutch signal paths. The only other work along these lines [Spillard 1991] is a study of a much more limited number of weather types and signal paths than this work.

- Chapter 4 takes existing meteorological conceptual models of fronts and adapts them to radio-meteorology. This adaptation, together with the estimated probabilities of anaprop associated with different types of fronts is entirely new.

- Chapter 5 contains entirely new material. No previous analysis of the detailed refractivity structure around weather fronts has ever been made.

- In chapter 6 the methods used to analyse the weather and signal data are not new, but the application of them to fronts is.

- The Interference Data Sheets [Appendix A] are an entirely new idea. They represent the first attempt to give path planners a way of seeing the effects of different weather conditions on the long term behaviour of anaprop.

1.3 Summary of findings

This section reviews the main results of each chapter of this thesis.
Chapter 3 looks at the statistics of anaprop in north west Europe under a wide range of weather conditions. The results confirm the generally held belief that the majority of anaprop occurs under anticyclonic conditions, but then goes further and looks at the effects of the location of the high pressure centre and at differences between seasons. Frontal conditions are found generally to give below average amounts of anaprop, but there are some exceptions. Again seasonal differences are observed, but on the whole they are less important than for anticyclonic conditions. Interactions of fronts with anticyclones are important causes of anaprop, but they are not common enough to be significant statistically.

Chapter 4 adapts meteorological models of fronts to radio-meteorology. The important features are low level super-refractive layers ahead of warm fronts and behind cold fronts. In the warm sector the refractivity structure depends on the type (ana-type or kata-type) of the front. An occlusion has characteristics of warm and cold fronts. These models are conceptual and give qualitative predictions of the likelihood of anaprop near the front. The models can be used to account for all observations of frontal anaprop in the published literature.

Chapter 5 begins the process of verifying the conceptual models, using high resolution data from the FRONTS'87 project. Although not all types of fronts can be studied, those that can be (ana- and kata-cold fronts, and an occlusion) show the features expected from the conceptual models. This allows some values to be given to the extent, position and strength of the super-refractive layers. Due to the variability of fronts, the values obtained may not be typical, but they represent a much more detailed study than has been made in the past.

Chapter 6 continues the verification of the conceptual models, linking the meteorology to anaprop. Much of the observed signal behaviour can be explained by the models and cross- and time-sections show how the refractivity structure is correlated to the signals. The range of behaviour of the signals stresses the variability of fronts and brings home the point that no front can be considered 'typical'.

An implicit, but generally unstated, goal of this work is to increase the links between the very different disciplines of meteorology and radio-science. Each has much to offer the other, and both should be willing to learn. Whether this goal has been achieved, only time will tell.
Chapter 2

Literature Survey

A considerable amount of research has been done on the links between radio science and meteorology since the development of radio early this century. This chapter examines the current state of knowledge of the field, looking at several different areas. Much of the existing research is, while interesting and important elsewhere, of little relevance to the remainder of this thesis, which concentrates on the meteorological aspects of anomalous propagation. Such material will be mentioned only in passing, with key references provided for the reader who wishes to investigate further. Material important later in the work will be explained in detail.

The literature survey begins with the basics of radio propagation and then looks at atmospheric refractivity, the major effect in radio-meteorology. This is followed by details of the meteorological mechanisms which give rise to anaprop and then by summaries of the current knowledge of the radio-meteorology of anticyclones and fronts.

2.1 Radio propagation

Radio waves (including the microwaves that are of particular interest in this work) form part of the electromagnetic spectrum, with wavelengths between millimetres and kilometres. Of most interest to this work is the short wavelength end of this range. Radio signals are vital to all forms of telecommunications, ranging from radio and TV broadcasts to point-to-point links on the Earth’s surface or between the Earth and a satellite.
Radio signals propagate according to an inverse square law. Signal strength is also affected by factors such as the type of transmitting and receiving antennae and the medium through which the signals travel. Further effects can come from terrain, which can block or scatter signals. The physics of radio propagation, antenna design and terrain effects are all outwith the scope of this research but can be found in many texts [e.g. Booker & Walkinshaw 1947, Bean & Dutton 1966, Hall 1979, Boithias 1987, Hall & Barclay 1989].

For this research, signals transmitted in a narrow beam are the only type studied. This allows us to consider the behaviour of signals as a problem in ray optics, rather than having to use mode theory, and simplifies the physics side of the problem considerably.

2.1.1 Signal attenuation

A signal propagating through the atmosphere will suffer attenuation from two causes. These are absorption by atmospheric gases and water droplets and scattering by aerosols and turbulence. Under normal circumstances this attenuation is a problem, but it is used to advantage in over-the-horizon troposcatter propagation [Spillard 1991].

At microwave frequencies atmospheric absorption is due to oxygen molecules and water vapour. Attenuation depends on frequency as well as atmospheric pressure, temperature and humidity and can vary from almost nothing to as much as 40 dB/km. The attenuation for conditions typical of a temperate climate is shown in figure 2.1 [Hall 1979 p67-69, Boithias 1987 p118-121, Bean & Dutton 1966 p270-283]. At the frequencies in current use for telecommunications (2-20 GHz), it can be seen that oxygen attenuation is negligible while water vapour absorption increases with frequency to a peak at 22 GHz. Above these frequencies water vapour absorption increases and oxygen reaches a peak absorption of 15 dB/km at 60 GHz. It is suggested [Clow 1984] that a typical 40km path at 11 GHz will lose 20% of it’s energy under normal conditions.

Attenuation can also be caused by atmospheric turbulence, when energy is scattered out of a signal path. This is an important mechanism in troposcatter propagation, but is a problem on normal paths [ibid.]. Turbulence causes rapid fluctuations in refractivity, so rays are bent away from the path. Turbulence can also affect the frequency of the signal [Ishimaru 1985] hence causing attenuation by moving energy to frequencies which the receiver cannot detect.

\(^1\)Airborne particles such as raindrops, snow, smoke and cloud water droplets.
2.1.2 Signal paths

Signal paths can be either terrestrial, between two points on the Earth's surface, or satellite, between a point on the surface and a point in space. For both operational and research purposes, terrestrial paths can be divided into a number of types, depending on the nature of the underlying terrain. The following path types are recognized by the CCIR\(^2\) [1986, Hewitt 1987a].

- Sea paths, as the name suggests, run from coast to coast over an intervening body of water. The terminals of the paths do not have to be at the water's edge since

\(^2\) The CCIR is the international body governing the use of the radio spectrum.
a path can be classified as sea type even if the terminals are a few kilometres inland, provided there is no high terrain below the path.

- Land paths are those which are entirely above a land surface (rivers, streams and minor water bodies are not enough to change the path type, but large water bodies are [Hewitt 1987a]).

- Coastal paths are the most difficult to define. In general they run over land, roughly parallel to the coastline. Further restrictions are that there should be no high ground beneath the signal path. The CCIR have an official definition of a coastal zone extending "50 km inland except where the terrain exceeds 100 metres altitude" [Bye 1988a], with all paths in this zone being coastal type. This definition is not satisfactory, and various researchers have suggested alternative definitions based on meteorological rather than geographical factors. These definitions suggest the coastal zone be defined by the furthest inland penetration of sea air [Hewitt 1987a] or from climatological humidity statistics [Bye 1988a, COST 1991]. Hewitt [1981] points out that coastal paths tend to have unique propagation characteristics, so great care should be taken when discussing them as a class.

- Mixed paths are a combination of the above types, for example most paths across the Dover Straits will be mixed land-sea paths, land-type over the UK mainland, with no coastal zone due to the height of the Downs, then sea type over the

![Specific Attenuation in Rain](image)

Figure 2.2. Attenuation of signals due to rain [From Hall & Barclay 1989 p184]
Channel. It is suggested [Hewitt 1987b] that there should be a minimum of 40 km of a second terrain type before a path can be classified as 'mixed'.

- Operational paths are ones which carry telecommunications traffic. They are generally short, typically 50 km long, with the terminals either in optical sight of each other or slightly over the optical horizon. For increased range, terminals are often located on hills or on tall buildings, the London 'Telecom Tower' being a prime example. To increase signal traffic, different polarizations may be used simultaneously [Clow 1984]. A large number of such terminals exist, covering the UK (and much of the rest of the world) in an electronic web.

- Experimental paths are generally longer than operational paths (60-1000 km). They are set up to provide data (mainly statistical) of anaprop in a region. Transmission is usually one way, with a very sensitive receiver recording signals over a wide range, from above the free space level down to the background noise level. Data are logged either as a continuous record or as some form of statistical summary. As part of the COST 210 project, a large number of experimental signal paths have been set up in North-West Europe [Figure 2.3].

Figure 2.3. Signal paths set up as part of the COST 210 project. Arrows show the direction of each path. [data from COST 1991]

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3 For the differences between optical and radio horizons, refer to section 2.2.3
2.2 Atmospheric refractivity

Just as light rays are subject to reflection and refraction, so are radio waves, and the atmospheric refractive index is the main control on anaprop.

2.2.1 The radio refractive index

Under 'typical' meteorological conditions, the atmosphere near the surface has a radio refractive index, \( n \), of about 1.00035, with a range of about ±0.0001. It is therefore more convenient to consider the atmospheric refractivity, \( N \), given by:

\[
N = 10^6(n - 1) \tag{2.1}
\]

The 'typical' refractivity is therefore about 359 N-units [CCIR 1986 p107]. In accordance with much published literature, both 'refract' and 'refractivity' are used to refer to \( N \).

The refractivity is a function of the temperature and the partial pressures of dry air, carbon dioxide and water vapour, but it has been found that, under the range of meteorological conditions found near the surface, the refractivity can be determined to an accuracy of 0.02% from temperature (in Kelvins), pressure (in mb) and vapour pressure (also in mb) by the equation:

\[
N = \alpha \frac{P}{T} + \beta \frac{e}{T^2} \tag{2.2}
\]

where \( \alpha = 77.6 \) and \( \beta = 373000 \) [Bye 1988a]. Equation 2.2 is sometimes given in the form:

\[
N = \frac{77.6}{T} \left( P + 4810 \frac{e}{T} \right) \tag{2.3}
\]

Equation 2.3 has been accepted by the CCIR as the international standard method of determining the refractivity from meteorological data [CCIR 1986 p107].

The accuracy of 0.02% quoted above assumes completely accurate meteorological measurements. Such measurements are an unobtainable ideal, particularly in the upper air observations that are of most interest to radio-meteorologists (see, for example, Hall & Gardiner [1968], Ryder et.al. [1983], Nash & Schmidlin [1987] and Thompson [1989] for discussions of the accuracy of upper air data). Typical accuracies would be:

- \( \pm 1\% \) for pressure
- \( \pm 0.5\% \) for temperature
- \( \pm 5-10\% \) for other parameters

For typical atmospheric conditions near the surface (\( P = 1000 \) mb, \( T = 288K \) and \( U = 70\% \)), the total error in RRI is given by equation 2.4 [Hall 1979 p20].

\[
\partial N = 0.27\partial P - 1.3\partial T + 4.5\partial e \tag{2.4}
\]
It can be seen that the vapour pressure is the source of most of the inaccuracy, which is unfortunate since this is also the most difficult quantity to measure accurately.

The RRI can also be measured directly using refractometers. These are very accurate (to about 0.01 N-unit) instruments [Bean & Dutton 1966 p30-7, Hall 1979 p19] and have been used very successfully in the field [e.g. Levy et al. 1991]. Refractometers are expensive instruments, so are not used for routine upper air observations, and no refractometer data have been used in the course of this work.

2.2.2 Presentation of refractivity data

As altitude increases, atmospheric pressure falls as, on average, do temperature and moisture content. The result is a systematic decrease in refractivity with height (the refractivity lapse). In a well mixed atmosphere this decrease is exponential in form and can be well represented by:

\[ N = N_s \exp\left(-\frac{z}{z_0}\right) \]  \hspace{1cm} (2.5)

where: \( N_s \) is the surface RRI,
\( z \) (sometimes given as \( h \)) is the altitude,
\( z_0 \) is a scale height.

\( N_s \) and \( z_0 \) vary with place and season, and radio-climatological maps exist showing these variations [e.g. Bean & Dutton 1966 ch 4, DNOM 1984]. The CCIR has defined a reference atmosphere:

\[ N = 315 \exp\left(-\frac{z}{7.36}\right) \]  \hspace{1cm} (2.6)

where \( z \) is in km.

Other works [e.g. Hough 1976] use the ICAN standard atmosphere with a constant relative humidity of 80% as a reference atmosphere.

Several methods have been developed to present refractivity data. All have the common aim of trying to emphasise small variations in refractivity and de-emphasise the large-scale refractivity lapse. These methods have been well documented elsewhere [e.g. Bean & Dutton 1966 p13-20] and have led to the following units used to define refractivity:

- The A-unit
- The B-unit
- The \( N_0 \)-unit

13
• The M-unit
• The K-unit

Only the latter two are of importance to this work.

The M-Unit

This method assumes that a horizontally launched ray will travel parallel to the Earth’s surface, giving a modified refractivity:

\[ M = N + 10^6 (z/a) \]  \hspace{1cm} (2.7)

where \( a \) is the Earth’s radius (6371 km). This is often written as:

\[ M = N + 157z \]  \hspace{1cm} (2.8)

A refractivity profile in M-units clearly identifies the trapping level [Section 2.2.3] as all layers where \( dM/dz \leq 0 \) [Turton et.al. 1988].

The K-unit

The K-unit, alone of all the other methods, which assume some sort of standard atmosphere, uses actual meteorological data. It is common meteorological practice to consider the potential temperature—the temperature a parcel of air would have if brought adiabatically to a standard pressure level (usually 1000 mb). This method has been applied to refractivity [Flavell 1962], allowing the preservation of the detailed structure while removing the effects of the overall lapse.

Potential temperature is given by:

\[ \theta = T \left( \frac{1000}{P} \right)^{R/C_p} \]  \hspace{1cm} (2.9)

where \( R \) is the gas constant of air \( (287 J \text{ kg}^{-1} \text{K}^{-1}) \) and \( C_p \) is the specific heat of air at constant pressure \( (1.01 \times 10^3 J \text{ kg}^{-1} \text{K}^{-1}) \)

Using the potential temperature, we can define the potential refractive index, or PRI, as the refractivity if the temperature and moisture were reduced adiabatically to 1000
mb:
\[ K = 77.6 \left( \frac{P}{\theta} \right) + 3.73 \times 10^5 \left( \frac{e_0}{\theta^2} \right) \]  \hspace{1cm} (2.10)

where \( e_0 = e(1000/P) \).

When the refractivity structure is examined in terms of the PRI, detailed structures, masked by the general refractivity lapse when the RRI profile is examined, become visible [ibid.], as can be seen in figure 2.4. Another advantage of the PRI is that values can easily be obtained from a specially adapted tephigram [Flavell 1962, 1964].

There are two drawbacks to using the PRI. The first is that, unlike all the other refractivity units discussed here, the original refractivity is not recoverable from the PRI. This was more of a problem in the 1960's than it is now, since both the RRI and PRI can easily be computed, but it is worth noting that, for atmospheric conditions typical of the British Isles, a reasonably accurate conversion (with a maximum error of about 0.5%) can be made using the equation [Flavell 1964]:

\[ \frac{K}{N} = \left( \frac{1000}{p} \right)^{0.714} \]  \hspace{1cm} (2.11)

A far more important drawback is that the PRI can only be calculated from meteorological observations, so the accuracy of RRI measurements given by a refractometer can never be achieved. Despite this, the potential refractive index remains the best method of presenting upper-air refractivity data and will be used extensively later in
2.2.3 Refractivity regimes

As mentioned earlier, it is convenient to think of tight-beam radio signals propagating as rays, similar to the treatment of light in optics. Radio rays do not normally travel in straight paths but curve, with the curvature depending on the rate of change of the atmospheric refractivity with height [Turton et al. 1988]. In a well mixed atmosphere, rays curve slightly downwards, giving a radio horizon more distant than the optical horizon [Figure 2.5]. The curvature is a consequence of the decrease in refractivity with height (the refractivity lapse rate). Because the degree of curvature depends on the refractivity lapse rate, a number of different refractivity regimes exist [ibid.].

In a well mixed atmosphere, the refractivity lapse rate is about 40 N-units/km \((dN/dz = -40)\), and the ray curvature is roughly equal to \(1/4\) of that of the earth [ibid.]. If the refractivity lapse is smaller \((dN/dz > -40)\), rays are less curved and the radio horizon is closer to the transmitter. The atmosphere is then said to be in a super-refractive state.

If the refractivity lapse rate is greater \((dN/dz < -40)\), the atmosphere is said to be in a super-refractive state. Ray curvature increases, hence radio ranges become longer. As the lapse rate increases further so do ranges, until the lapse rate reaches a critical value of 157 N-units/km \((dN/dz = -157)\). At this value, ray curvature is equal to that of the earth so horizontally launched signals travel parallel to the surface and ranges are, theoretically, infinite [ibid.].

If the lapse rate exceeds 157 \((dN/dz < -157)\) the curvature of rays is greater than that of the earth and a horizontally launched ray will intersect the surface rather than escaping to space. Such a situation is called trapping and the layer where the refractivity lapse exceeds 157 is termed the trapping layer. This leads to the phenomenon of ducting,
one of the major causes of anaprop [ibid.].

Since the atmospheric refractivity lapse, even under 'well mixed' conditions, is rarely exactly -40 N-units/km, some authors [e.g. ibid., Hall 1979] define standard refractivity when the lapse rate falls into the range \(0 \geq \frac{dN}{dz} > -80\) N-units/km. This leads to four different refractivity regimes, as shown in figure 2.6:

![Figure 2.6. Refractivity regimes. All paths are the result of a ray launched horizontally. [From Turton et.al. 1988.]](image)

- Sub-refraction
- Standard refraction
- Super-refraction
- Ducting

It should be noted that refractivity varies a great deal in the vertical, sometimes on a scale of a few metres [Spillard 1989a], so a detailed vertical section through the atmosphere is likely to exhibit a number of refractivity regimes.

### 2.2.4 Ducting

As mentioned above, a layer where the refractivity lapse rate exceeds the critical value of 157 N-units/km is termed a trapping layer and forms part of a radio duct. The trapping layer occupies the upper part of the duct, with the top of the trapping layer defining the top of the duct. The base of the duct depends on both the thickness of
the trapping layer and the altitude of its base above the surface, giving three possible types of ducts [Booker & Walkinshaw 1947, Turton et. al. 1988].

**SS ducts** Here the trapping layer extends down to the surface. Signals propagate through a combination of refraction and reflection, curving downwards towards the earth's surface and then being reflected back upwards, as shown in figure 2.7a. The base of an SS duct is the surface of the earth, so terrain features influence signal propagation.

**ES ducts** In this type the trapping layer is off the surface but the base of the duct is the surface. Between the base of the trapping layer and the surface the atmospheric refractivity lapse is less than the critical value for trapping. Again the signals propagate through a combination of refraction and reflection. In the trapping layer, rays curve towards the surface. Below the layer they begin to curve away from the surface but still hit the surface and are reflected back into the trapping layer. This is shown schematically in figure 2.7b. Again terrain has an influence on signal propagation in an ES duct.

**EE ducts** Here the base of the trapping layer is again off the surface but the duct does not extend as far as the ground. Propagation in an EE duct is by refraction.
with rays in the trapping layer being curved towards the surface and then being curved back into the trapping layer but the more ‘normal’ refractivity conditions below the base of the trapping layer. This is shown schematically in figure 2.7c. Since an EE duct is not resting on the surface, terrain has no effect on signal propagation.

The nomenclature for the three types of duct comes from one of the earliest works on radio-meteorology [Booker & Walkinshaw 1947]. The letters refer to whether the base of the trapping layer and duct are elevated or rest on the surface:

- SS duct: surface layer, surface duct
- ES duct: elevated layer, surface duct
- EE duct: elevated layer, elevated duct

This notation appears considerably simpler than the ‘simple surface duct’, ‘surface S-shaped duct’ and ‘elevated duct’ used in more recent works [e.g. Hall 1979, DNOM 1984, Turton et.al. 1988].

Associated with ducting is the phenomenon of layer reflection. This occurs when there is an extremely strong refractivity lapse (of hundreds of N-units/km). The layer acts as a ‘radio mirror’, reflecting rays off it. This can be considered as an extreme form of ducting, and will not be considered further in this work but is discussed in the various works on propagation mentioned earlier.

The diagrams showing duct propagation make it clear that not all signals are trapped in the duct. Trapping depends on the angle of elevation of the ray from the horizontal, either when launched (if it starts within the duct) or when it enters the duct. The critical angle at which rays begin to be trapped is a function of the thickness of the duct and of the trapping layer [Dougherty & Hart 1979, Hall 1979 p32] and is found in practice to be $\leq \pm 0.5^\circ$ [ibid.]. As well as the critical angle, there is also a critical wavelength for trapping [Hall 1979 p30, Turton et.al.1988].

In a duct, signals are effectively trapped in two dimensions rather than three, so the theoretical signal strength decreases inversely with range, rather following the inverse square law of normal propagation [Hall 1979 p32]. Signal ranges are greatly enhanced, e.g. the radar echoes from objects several thousand kilometres distant mentioned by Durst [1947].
2.2.5 Duct meteorology

The refractivity structure of a duct is related to the meteorological conditions within it. To show this structure most clearly, it is best to use the modified refractivity, or M-unit [section 2.2.21, where a trapping layer is easily visible as any layer where $dM/dz \leq 0$. Further examination of a modified refractivity profile allows the determination of the refractivity deficit, $\partial M$, the difference in modified refractivities between the top and bottom of the trapping layer.

The refractivity deficit is a control on both the strength of the duct\(^4\) and on the thickness [Turton \textit{et.al.} 1988], although the latter also depends on the refractivity gradient below the base of the trapping layer. The base of the duct is the level where the modified refractivity is equal to that at the top of the trapping layer (or the base is on the ground, if the duct is SS or ES type). This is best illustrated schematically, so figure 2.8 shows typical modified refractivity profiles for the three types of ducts and

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{refractivity_profiles.png}
\caption{Modified refractivity profiles through (a) SS (b) ES (c) EE ducts showing the relationship between refractivity deficit and duct thickness. [From Turton \textit{et.al.} 1988]}
\end{figure}

Clearly indicates the relationships between trapping layer, refractivity deficit and duct thickness [\textit{ibid.}].

Looking at the meteorological characteristics of ducts, it is found that the refractivity lapse is a function of the lapse rates of temperature and water vapour content [Hough 1976], as might be expected from the refractivity equation. The basic conditions for trapping layer formation are a temperature inversion (temperature increasing with height) and/or a hydrolapse (water vapour content decreasing with height). The exact rates required for a trapping layer to form depend on the altitude, but near the surface

\footnote{\text{Duct strength is measured by the greatest wavelength that is trapped [Turton \textit{et.al.}1988]. This is outwith the scope of this research, so will not be investigated further.}}
a trapping layer will form if [Hough 1976]:

\[ \frac{\partial T}{\partial z} \geq +0.087K\ m^{-1} \]  
\[ \frac{\partial r}{\partial z} \leq -0.015\ kg\ m^{-1} \]  

If both the temperature and the moisture change, we find that the critical conditions for trapping layer formation become:

\[ \frac{1}{\alpha} \frac{\partial T}{\partial z} + \frac{1}{\beta} \frac{\partial r}{\partial z} \geq 1 \]  

where \( \alpha \) and \( \beta \) are the critical gradients defined in equations 2.12 and 2.13 respectively [ibid.].

The three types of ducts have typical temperature and moisture profiles, as shown in figure 2.9. It must be emphasised that these represent typical profiles, and not all cases will be similar. A trapping layer can exist if there is only a correct temperature or moisture profile, and even if the temperature or moisture is in the wrong sense for trapping layer formation provided the other gradient is sufficiently large [Hough 1976].

![Figure 2.9. Typical profiles of temperature and water vapour through (a) SS ducts (b) ES ducts (c) EE ducts. [From Booker & Walkinshaw 1947].](image)
2.3 Radio-meteorology

So far we have discussed ducts and the atmospheric conditions within them. It is now time to turn our attention to the meteorological processes which give rise to ducts or super-refractive layers. There are five major causes of ducts:

- Subsidence
- Offshore Advection
- Sea breezes (onshore advection)
- Nocturnal radiation
- Evaporation

This section will examine each mechanism briefly, giving key references where further details may be found. The survey is made from a radio-meteorological point of view, all five features are well understood meteorologically. Throughout the discussion, reference will be made to ducts resulting from each process, but it should be understood that the same conditions that lead to ducts also lead to super-refractive layers (SRLs) and that both can be a cause of anaprop.

2.3.1 Subsidence

The meteorology of subsidence has been well understood for some time and is discussed in many works [e.g. Namias 1933, McIntosh & Thom 1981 p144, McIlveen 1986 p364]. The process basically involves the descent of cold, very dry air from near the tropopause. As it descends, the air warms\(^5\). While the air subsides the mixing ratio (moisture content) of the air hardly changes, resulting in a warm and dry air parcel near the surface. Air below the base of the subsiding parcel is generally well mixed, moist and cool relative to the subsiding air. At the boundary between the two, there is both a temperature inversion and a hydrolapse, exactly the conditions that lead to a trapping layer forming. Temperature and moisture changes can be very sharp, for example a radiosonde ascent (Hemsby, 12Z, 18/8/78) showed a layer 20 mb (≈ 200m) thick exhibiting a temperature change of +5.6°C and a mixing ratio change of −4.1g kg\(^{-1}\) [DAR 1978], giving a refractivity lapse rate of approximately 225 N-units/km.

\(^5\)Descending air warms at the dry adiabatic lapse rate (9.8°C km\(^{-1}\)) less the effects of radiational cooling (1–2°C day\(^{-1}\)).
The height of the interface (the subsidence inversion) varies on daily and seasonal scales. At night, when convection in the boundary layer ceases, the inversion descends, sometimes to as low as 500m, reaching a minimum at dawn. During the day it ascends, reaching a maximum altitude at dusk [Bye 1988a]. The maximum altitude depends very much on the type of surface and factors such as the amount of cloud cover and the temperature. On a seasonal scale, inversions are generally higher in summer than in winter [Ball 1960] since hotter surfaces give a greater depth of convection.

Subsidence ducts are almost always of the EE type [Gossard 1981], giving anaprop over the entire area of subsidence. Subsidence is one of the most important mechanisms causing interference.

### 2.3.2 Offshore Advection

In meteorology, advection is defined as "the horizontal transport (of heat, mass etc.) effected by the horizontal exchange of air" [McIlveen 1986 p431]. Like subsidence, it is a well-understood phenomenon [ibid., McIntosh & Thom 1981 p94]. The form of advection that is of particular interest to radio-meteorologists is the advection of air offshore from land to sea.

When warm, dry air is advected offshore over a relatively cool sea, the lowest layers are cooled by the evaporation of moisture into them [Turton et.al. 1988]. This leads to, at the top of the modified layer, a temperature inversion and a hydrolapse, the optimum conditions for the formation of a trapping layer. An advection duct is also possible when cold, dry air is advected over a warmer sea. Here evaporation produces a hydrolapse strong enough to overcome the effects of the temperature gradient and cause super-refraction or trapping [Hough 1976]. In both cases, the resulting duct is of the SS type or occasionally of the ES type [DNOM 1984].

Both the thickness and offshore extent of the advection duct are subject to debate. The average thickness has been suggested to be as little as 25 metres [Hall & Barclay 1989 p159] or as much as 150 metres [Gough 1984, COST 1991]. It is clear that the thickness varies with distance offshore, building up to a maximum some 100 km from the coastline, then decreasing slowly [DNOM 1984]. This profile has been modelled for various parts of the world [Gossard 1982, Ko et.al. 1983, Garrett 1987, Garrett & Ryan 1989]. The extent of the duct has been said to be between 50–200 km [DNOM 1984, Turton et.al.1988] and 1000 km [Bye 1988a], obviously depending on the size of the sea area. It appears that the strength of the advection duct decreases with distance offshore [DNOM 1984, COST 1991].
Advection ducts are not as effective at trapping signals as subsidence ducts, so they do not give rise to such high signal levels as subsidence ducts [Bye 1988a].

2.3.3 Sea breeze advection

The sea breeze is a circulation set up when the land surface is at a greater temperature than the sea. This results in a heat low overland and a low level flow from sea to land [McIntosh & Thom 1981 p140]. This flow brings cool, moist air from sea to land, undercutting the warmer, drier overland air and giving the ideal conditions for ducting. Moisture gradients are particularly strong at the interface between sea and land air. The sea breeze occurs during the day, building up as the land heats and reaching a maximum in the late afternoon and early evening. Since the land must be warmer than the sea for the circulation to develop, the sea breeze is more common in summer than in winter.

The sea breeze flow is fairly shallow, only a few hundred metres thick [Mcllveen 1986 p289] so any radio ducts would be at low levels and so could have severe effects on surface paths, and can penetrate some distance inland. Simpson et.al. [1977], studying the sea breeze on the south coast of England, suggest that the sea air can regularly penetrate over 40 km inland, even over the hilly terrain of the South Downs and occasionally penetrates as far as 100 km inland. The inland penetration depends on the relative temperatures of the land and sea surfaces [ibid.] as well as on any larger scale air movements [Pearson et.al. 1983].

The association of the sea breeze with ducting was identified in the 1940's. Hatcher & Sawyer [1947], using measurements made from aircraft near Madras, India, suggest a radio duct about 1000 feet (300 m) thick, penetrating up to 15 miles (25 km) inland during sea breeze conditions, but no indication of the strength of the duct is given. The current Royal Navy document on radio-meteorology [DNOM 1984] suggests similar thicknesses and inland penetrations, pointing out that the inland penetration will be greater in low latitudes where sea breezes are more pronounced and that the sea breeze duct will occur mainly in the afternoon and early evening, when the sea breeze is most developed. An interesting observation is that the sea breeze duct extends offshore as well as onshore. This could be of importance where there is no advection. Bye [1988a] considers the sea breeze as an onshore extension of the advection duct, penetrating some 30 to 40 km inland over flat terrain.

Although not studied in detail elsewhere in this work, the author feels that there are problems with the existing treatment of the sea breeze by radio-meteorologists. Some
comments and suggestions for further work are made in the conclusions of this thesis [Chapter 7].

2.3.4 Nocturnal radiation cooling

At night, if the sky is clear, the land surface will lose heat very rapidly through long-wave radiation to space. This process, nocturnal radiation cooling, can cause anaprop on land and coastal signal paths. The meteorology of nocturnal radiation cooling is well understood [e.g. McIntosh & Thom 1983 p29] and the association with anaprop has been recognised since the 1940's [e.g. Smith-Rose & Stickland 1947, Bean & Dutton 1966 p133].

As the land surface cools, the lowest layers of the atmosphere will also cool and, if the wind is sufficiently light to inhibit turbulent mixing, a low level temperature inversion will form at the top of the cooled layer [Lochtie 1985]. There may also be a moisture inversion, since water will condense out of the cooled air as it becomes saturated, but this will depend on the initial moisture content and on the degree of cooling. If moisture does condense out, the heat released will decrease the strength of the temperature inversion, inhibiting the strength of the refractivity lapse.

The existence of a duct will depend on the strength of the temperature inversion and the presence or absence of a moisture inversion [Hall 1979 p34]. The extent of a duct will depend on the local topography, with ‘pools’ of super-refractivity trapped in areas of flat ground [Bye 1988a]. A radiation duct will be strongest at the end of the night, when the surface temperature is lowest, but may cause more severe anaprop shortly after dawn, when convection is strong enough to lift the super-refractive layer above the surface but not yet strong enough to destroy it [ibid.].

As part of their research into radio-meteorology, BTL considered ways of predicting ‘radiation nights’ from meteorological data [Lochtie 1985]. Their criteria were:

- Little or no cloud cover throughout the night.
- Calm or light winds throughout the night.
- Dry air (R.H. less than 90%).
- High pressure.

Using computer analysis of surface observations, BTL were able to correctly ‘predict’
about 80% of radiation nights identified on synoptic charts. Such analysis was considered a potential means of forecasting anaprop from meteorological data, but interest in such work appears to have diminished in recent years.

2.3.5 Evaporation ducts

The four causes of ducting that have already been considered have been directly related to synoptic scale weather systems. There is another ducting mechanism which has been observed worldwide [Turton et al. 1988] and can cover even larger areas than the advection and subsidence ducts within anticyclones. These are Evaporation Ducts which occur over water surfaces, not only the seas and oceans but also over large lakes.

As the name suggests, the ducts are formed by evaporation from the water surface creating a saturated layer at the surface with unsaturated air a few metres up. The resulting hydrolapse can be strong enough to allow a duct to form. The duct is an SS type, and is only a few metres thick, showing complex diurnal, seasonal and geographical variations [DNOM 1984]. Average thicknesses are about 5m in the North Sea [Rotherham 1974] and about 15m in the Mediterranean and Caribbean Seas [Turton et al. 1988]. Despite their small vertical extent, evaporation ducts can extend over the entire open water surface so trapped signals are able to propagate far beyond the radio horizon. The meteorology and radio-meteorology of the evaporation duct has been investigated by a number of workers, including Hall & Gardiner [1968], Hamilton & Laevastu [1973], Rotherham [1974], Gossard [1981] and Hall & Barclay [1989].

Evaporation ducts will be thickest under clear skies, during the day [Hall & Barclay 1989]. If the sea is warmer than the surface air there will be a continual upwards flux of water vapour, thus reducing the strength of the duct [Hamilton & Laevastu 1973]. If there is an ‘inversion’ with warm air over a cooler sea (which can occur in regions of upwelling or when warm air is advected offshore) the duct will be thicker. It is suggested [Gossard 1981] that the thickness of the evaporation duct depends primarily on atmospheric stability.

2.4 The radio-meteorology of anticyclones

It has been known for more than half a century that most cases of severe anaprop are associated with anticyclones. This section looks at the relationship between anticyclones and anomalous propagation, starting with an examination of the evidence for
the relationship. This is followed by a brief examination of the meteorology of anticyclones and finally by an examination of a recently produced conceptual model of the radio-meteorology of anticyclones.

2.4.1 Anticyclones and anaprop

Although the influence of atmospheric conditions on radio signals was identified during the 1920's [Appleton 1947], it was not until the extensive use of radar during World War II that the scale and severity of the problem was studied. It was quickly recognized that, in Europe at least, the majority of anaprop occurred during anticyclonic conditions. In the first ever conference on radio-meteorology, Appleton [ibid.] gave examples of greatly increased radar ranges and noted that they were due to advection, nocturnal radiative cooling and subsidence associated with high pressure systems. Smith-Rose & Stickland [1947] noted the effects of radiative cooling as a cause of high signal levels on land paths and also observed that the majority of enhanced signal levels on both land and sea paths occurred during anticyclonic conditions. Johnson [1947] noted the effects of temperature inversions, particularly those due to anticyclonic subsidence, on signals while Alexander [1947] observed that advection of warm air offshore in the circulation of a high gave increased ranges, even when the subsidence inversion was very weak. Studies of anaprop over the Arabian Sea (where anomalous radar ranges of several thousand kilometres had been observed, noted the effects of advection and the sea breeze [Durst 1947, Booker 1948]. Booker & Walkinshaw [1947], as well as making one of the first detailed studies of ducts, noted that the majority of ducts occurred during anticyclonic conditions and mentioned subsidence and nocturnal radiative cooling as the causes. Booker [1948] stated that anticyclonic subsidence was linked to the majority of anaprop, both directly and indirectly as an indicator of advection and nocturnal cooling.

In the 1960's, Flavell [1964] noted anaprop was often due to the descent of the subsidence inversion during anticyclonic conditions, while Bean & Dutton [1966 p.132-4] consider advection, radiative cooling during anticyclones and anticyclonic subsidence to be main meteorological processes responsible for ducts. Kühn & Ogulewicz [1970] note that the majority of anaprop they observed was caused by temperature inversions within anticyclones. Hough [1976] and Mulhearn [1976] give advection, anticyclonic subsidence and nocturnal radiative cooling as the meteorological conditions associated with ducting and Flavell [1978] again notes the importance of subsidence within anticyclones as a cause of long-range propagation, as does Hall [1979], although the latter author's meteorology is sometimes suspect. The importance of subsidence, nocturnal...

From the above, it is clear that a great deal of anaprop occurs during anticyclonic conditions, through the processes of subsidence, advection and nocturnal radiative cooling. Models have been developed to show how these mechanisms occur within anticyclones. Before these models are examined, it is useful to look briefly at the meteorology of anticyclones.

2.4.2 The meteorology of anticyclones

Anticyclones are the weather systems associated with regions of high pressure and, in the northern hemisphere, air flowing clockwise about the centre of the high. They are generally areas of fine and settled weather, with light winds. Anticyclones come in two main types — cold, or polar, highs and warm, or dynamic, highs, depending on the temperature in the lower troposphere. The type of most interest to radio-meteorologists is the warm anticyclone [Bye 1988a].

A warm high has a column of subsiding air from the tropopause to the top of the boundary layer, with convergence aloft and divergence below to maintain continuity. At the start of its descent the subsiding air is cold and very dry, so warms at the dry adiabatic lapse rate of $9.8^\circ C \text{km}^{-1}$, modified by radiative cooling of about $2^\circ C$ per day. Since there is little mixing, the descending air does not gain moisture, so is hot and dry as it reaches low levels. This contrasts sharply with the well mixed air in the boundary layer which is both cool and moist relative to the subsiding air. The result is a temperature inversion and a strong hydrolapse, the subsidence inversion discussed above.

The subsidence inversion, and therefore the associated super- refractive layer, is dome-shaped [Namias 1933], with the highest point over the place where the rate of increase in surface pressure is greatest [ibid.], not centred over the highest surface pressure as some works [e.g. Bye 1988a] suggest. The subsiding air descends in a clockwise spiral, taking several days over the descent, and the mean flow below the subsidence inversion is also clockwise, turned slightly away from the high pressure centre by friction. This flow is the advection described in the previous section.

Because of the overall descent and the presence of the subsidence inversion, the growth
of convective clouds is limited, so clouds will be stratiform if present. In the latter case, the clear skies allow radiative cooling at night and the formation of radiation ducts.

This very superficial examination of anticyclones has shown that three of the main causes of anaprop are linked to them. The place of the mechanisms in an anticyclone has been studied in detail by radio-meteorologists at BTL and a conceptual model of a high has been developed.

2.4.3 The BTL anticyclone model

As part of their ongoing research into anaprop, BTL have produced a conceptual model of an anticyclone, together with predictions of the anaprop it produces. The model [Bye 1988a, COST 1991 A2.4] looks at a warm anticyclone in summer as the high pressure centre develops and moves over the UK and then across the southern North Sea. The meteorology of the model is shown in figure 2.10, which shows the situation during the day and during the night. At all times the picture is dominated by the overall subsidence and the general clockwise circulation advecting air from the continent over the southern North Sea and UK mainland. During the day, there is convection above

![Diagram of anticyclone](image-url)

**Figure 2.10.** The meteorology of the BTL anticyclone model (a) during the day and (b) during the night. [From Bye 1988a]
the land surface and the model also shows shallower convection over the sea. This is likely only when the air advected offshore is cooler than the sea surface. At night convection over the land ceases, replaced by radiative cooling, but continues over the sea. The result is the nocturnal descent of the subsidence inversion to low levels, with the lowest level reached at dawn and the highest at dusk. The model assumes the inversion to be at an altitude of about 1000m during the day but no night time level is given. Although not clear from the diagrams, the model also considers the sea breeze, mainly as an extension of advection onshore over low lying ground.

The meteorology presented in the model is not new, but the model also makes predictions of anaprop during the life of the high. These are for sea, land and coastal paths, and look at the role of individual mechanisms as well as the overall picture. The predictions are purely qualitative and give the "probability of occurrence of anaprop" rather than any indication of its severity. It is assumed that different mechanisms are additive, so the total probability of anaprop will be the sum of the probabilities of individual mechanisms.

- On sea paths [Fig 2.11] the main mechanism giving anaprop is advection, which

![Figure 2.11. Predictions of anaprop on a sea path (a) total anaprop (b) individual components of the anaprop. [From Bye 1988a]](image)

lasts as long as the high, building up to a peak in the middle of the anticyclone's life and then decaying, with a slight diurnal cycle superimposed on this. Subsidence is important at night early and late in the life of the high, when the inversion is at its lowest. The sporadic anaprop late in the life of the high will be discussed at the end of this chapter.
On land paths [Fig 2.12] the only mechanisms are subsidence, as on sea paths,

![Graph showing anomalous propagation](image1)

**Figure 2.12.** Predictions of anaprop on a land path (a) total anaprop (b) individual components of the anaprop. [From Bye 1988a]

and nocturnal radiative cooling, which is most likely in the middle of the life of the high.

On coastal paths [Fig 2.13] the subsidence and nocturnal radiative cooling of a

![Graph showing anomalous propagation](image2)

**Figure 2.13.** Predictions of anaprop on a coastal path (a) total anaprop (b) individual components of the anaprop. [From Bye 1988a]

land path are supplemented by the sea breeze, which occurs each afternoon and
As part of the work for this project, the author made an examination of the BTL model. This study [Jones 1989] looked at the meteorology behind the model and made case studies of actual periods of anticyclonic anaprop which were compared with the predictions given by the model. It was found that the model was generally good, although mixed paths caused problems and some signals were observed at times when the model predicted none. These were not considered important as the model gave the probability of anaprop rather than signal levels. The study also suggested ways that the model could be extended to consider anticyclones north, south and west of the UK and in winter as well as in summer.

2.5 The radio-meteorology of fronts

Fronts have not been particularly well studied from a radio-meteorological point of view, although they have been the target of a great deal of meteorological research. An important objective of this thesis is to remedy this discrepancy, and apply some of the current meteorological understanding of fronts to their radio-meteorology.

This section will look at two aspects of the radio-meteorology of fronts. The first is the current understanding of the behaviour of radio signals at and near fronts. The second is a particular problem which has been termed sporadic subsidence, which was identified in the early 1980's as a cause of particularly severe anaprop at some fronts.

There will not be a detailed examination of the meteorology of fronts. Such a study could easily fill several volumes, and is outwith the scope of this research. The most important references on fronts are given in chapter 4, where the current meteorological models are applied to the problem of frontal anaprop.

2.5.1 Fronts and anaprop

That fronts have an effect on radio signals has been known for nearly half a century. Smith-Rose & Stickland [1947] mention 'disturbances' in signal levels as fronts cross a sea path off Wales, but they note that “at present these cases are difficult to predict since the effect is by no means uniform”. They also note problems caused by the lack of detailed meteorological data over the path, a mournful cry that will be heard many times in the course of this work. Later in their paper, they state that signal levels
decrease as a warm front passes, remain low in the warm sector and then rise sharply as the cold front passes.

Observations made in New Zealand from 1943-45 also indicated that depressions have an effect on signals, with 'unexpectedly long' radar ranges reported when the radar beam was pointing along the length of a trough [Alexander 1947]. The paper noted, however, that ranges in other directions could not be checked due to an absence of radar targets! In the USA, Randall (1947, cited by Bean & Dutton [1966 p176]) also observed signal strength changes when a cold front crossed a signal path, with high signal levels before the front arrived, then a rapid fall as the surface front reached the path.

Bean & Dutton [1966 p185-95] made a theoretical study of the refractivity structure of warm and cold fronts, using the ‘Bergen’ model of frontal structure [Chapter 4]. This work, although significant in that it was the first such study, sheds little light on the problem of anaprop at fronts. A close examination reveals that the main aim of Bean & Dutton’s work was to show how different refractivity units highlighted the discontinuity between different air masses at the frontal zone. A further study by the same authors [Bean & Dutton 1966 p195-211] uses real data, but concentrates on variations in the horizontal refractivity structure at different levels with no consideration of the potential for anaprop at the fronts. A final study [ibid. p212-223] looked at the vertical refractivity structure, both in time and space, through a cold front as it crossed the USA. The study again has no mention of super-refraction or the potential for anaprop, but a close inspection of the figures shows a strongly super-refractive layer ahead of and behind the front. The layer starts at an altitude of around 2000m, descends to about 1000m just before the front, and then ascends (and weakens) behind the front [ibid. p212].

The next reference to fronts comes from some research in Eastern Europe. Kühn & Ogulewicz [1970], studying a sea path over the Baltic, observed signal behaviour as both warm and cold fronts passed. They found that, on average, passage of a warm front was accompanied by an increase in signal level of some 30 dBf over a four hour period while passage of a cold front was marked by a fall of some 25 dBf over a two hour period. It should be noted that these represent the averages, and the authors were careful to point out that not all fronts gave rise to such large changes in level [ibid.]. It is also worth noting that the high signal levels in the warm sector are the opposite of the earlier findings of Smith-Rose & Stickland [1947].

A number of references to the effects of fronts were made during the 1980’s. Hewitt & Adams [1980] mention weather froffts “cause significant enhancements” and that the
interactions between fronts and anticyclones are an important cause of anaprop. The latter statement is followed up by a detailed analysis [Hewitt et al. 1981] which will be discussed later in this section. Hewitt & Adams [1980] mention the difficulties in using routine meteorological observations as the only source of weather data. Gossard [1981] mentions "several types of fronts effective in producing refractive index layering." These are warm fronts, cold fronts and both warm and cold occlusions, a fairly comprehensive list! Profiles of temperature and moisture near a cold front show conditions indicative of ducting, although it is not clear on which side of the front the observations were made [ibid.].

Flavell [1983], discussing long distance propagation observed in Europe, looks at the potential refractivity structure of a warm and a cold front. The latter analysis shows a super-refractive layer ahead of the front, with width, height and intensity varying considerably over the 18 hours of the survey [Figure 2.14]. The warm front study shows the frontal zone and the effects of a descending 'tongue' of warm air beneath it. The result is a super-refractive layer, sloping gently downwards towards the surface front, as shown in figure 2.15.

Clow [1984] mentions that fronts can affect signal levels, as does DNOM [1984], where it is stated that ducts may be found beneath subsided air ahead of warm fronts and behind cold fronts. Lochtie [1985] mentions the interactions between fronts and high pressure systems as a cause of large enhancements to signal levels. Juy & Spillard [1988], studying data from a path across the Channel, note slight enhancements due
to cold fronts, both alone and when passing through an anticyclone, although they state that these are not significant effects. Spillard [1989a] looks at signal statistics under different meteorological conditions, but draws no conclusions from the data. In a separate paper [Spillard 1989b] it is stated that signals are enhanced when the path is in the warm sector of a depression and, to a lesser extent, when an occluded front lies across the path.

To summarise these studies, there is a body of evidence for three features of the radio-meteorology of fronts:

- Enhanced signal levels (indicating super-refraction or ducting) in the warm sector of a depression.
- Super-refractive layers ahead of a surface warm front and behind a surface cold front. The layer ahead of a warm front appear to slope (downwards towards the surface front) and to extend over considerable distances.
- Signal enhancements due to the interaction of fronts with anticyclones.

The last of these points will be examined in more detail below, while the first two will be the subject of most of the remainder of this thesis.
2.5.2 'Sporadic' subsidence

The problem of the effects of fronts on anticyclones has already been mentioned as a cause of anaprop. These events, although few in number and of short duration, can be exceptionally severe, so have been the subject of some study.

The first reference to such events was made by Flavell [1964], who noticed periods of enhanced signals, lasting for 12–24 hours, immediately before the passage of a cold front. Analysis of the potential refractivity structure showed the enhancements were due to the formation of a strongly super-refractive layer at low levels (around 1000m). These layers appeared to be due to subsidence.

In late 1980, BTL (then the Post Office Research Laboratories) observed two severe cases of anaprop, one on a land path and the other on a sea path. The event on a land path accounted for some 80% of the signals for the whole year on the path. These events were studied in detail by Hewitt et al. [1981]. Analysis of the refractivity, both in cross section and time section, showed the formation of low level super-refractive layers (SRLs). Analysis of meteorological data showed the layers were formed through subsidence and, as this was unlike anticyclonic subsidence, the phenomenon was termed 'sporadic subsidence' [Bye 1988a]. The discussion of the events given here is the author’s interpretation of data presented by Hewitt et al. [1981].

The event on the sea path occurred when the path was in the warm sector of a depression, with an anticyclone immediately to the south giving anticyclonic curvature to the isobars over the path. The refractivity cross section [Figure 2.16a] shows the extent of the SRL, while the time section [Figure 2.16b] shows how quickly the layer descended and ascended again.

The event on the land path was longer (7 hours compared with 2) and more complex. Weather charts showed a depression with a very narrow warm sector approaching the path. For the first 4 hours, high signal levels were observed while a warm front approached the path. As the front reached one end of the path, signals fell to low levels for about 30 minutes, then rose back to high levels for about two hours more, as shown in figure 2.17. It would appear that the first period of anaprop was related to the warm front, with a gap as the front was over the path, then the second period of signals when part of the path was in the warm sector. The refractivity cross section [Figure 2.18] shows evidence of subsidence beneath the warm front, sloping downwards towards the surface front. The analysis does not appear to consider the presence of the front, probably since the frontal zone was between two observations. Possibly as a result of this, the refractivity section shows no features which could account for the signals after the
Figure 2.16. Refractivity structure of a 'sporadic subsidence' event (a) cross section (b) time section. (From Hewitt et. al. [1981])

Figure 2.17. Signal behaviour during a sporadic subsidence event on a land path. (after Hewitt et. al. [1981] with fronts added by this author)
Figure 2.18. Refractivity structure of a sporadic subsidence event on a land path. (after Hewitt et. al. [1981] with fronts added by this author)

passage of the front.

'Sporadic' subsidence conditions can be explained with the current meteorological understanding of fronts, and will be described later in this work [Chapter 4]. As such events are mostly confined to the warm sector of a depression, they will be termed 'warm sector subsidence', rather than 'sporadic subsidence' which suggests some unknown cause.
Chapter 3

Statistical analysis of weather and anaprop

Most studies of radio propagation rely heavily on statistics to present results and to support theories, and this work is no exception. Because most data are the result of several months or even years of analysis, some form of statistical summary is the most appropriate way of presenting them. Models of propagation processes are often formulae, in terms of easily calculated parameters, to give a close approximation to the observed statistical distribution of signals on paths of a given type.

What is exceptional about this work is that, rather than looking at the data for a given path or group of paths over a given period, the data are first classified by the meteorological conditions and then statistics produced. This allows the long term effects of different weather conditions to be compared. This information is not only important for this thesis, but also for end users, who can use this information to help plan where paths should be built. Only one previous work [Spillard 1991] has made an analysis based on weather conditions, and that is considerably more limited, both in the number of weather types and in the range of signal paths used, than the one presented here.

This chapter begins with a summary of the way signal statistics are normally presented and some of the studies made in the past. This is followed by an examination of the data available for this study and the schemes used to analyse it. The main results of the analysis are then presented. For operational use, a portfolio of “Interference Data Sheets” has been produced and supplied to BTL. These are discussed here, with the entire portfolio given in Appendix A of this thesis. The chapter closes with a discussion
of the significance of the results.

3.1 Previous work

A great deal of research into radio-meteorology and anomalous propagation has been carried out over the last half century, and many of the results have been statistical in nature. The main reasons for this are that there is too much information for any other form of non-selective analysis and that the main use of the information has been to provide long-term summaries that can be used in network planning. This is reflected in the published literature, which can be divided into statistical results and methods of predicting signal statistics.

3.1.1 Statistical analyses

Statistical analyses date back to the earliest publications on radio-meteorology. Shepard [1947] studied the relationship between signal strength and the refractivity gradient, observing a direct connection between the two. Durst [1947] gave statistics of radio ducts and correlated them with meteorological conditions for several parts of the world while Alexander [1947] presented similar results for New Zealand. Bean & Dutton [1966] give statistics of refractivity lapse rates and of surface refractivities over much of the USA, as well as correlating signal strength with meteorological variables. Much of their work was climatological in nature, and did not look at the effects of different types of weather. Hall & Comer [1969], examining data collected in the UK over a three year period, studied the refractivity structure in the lowest 1000 metres and correlated this to the temperature and moisture profiles, as well as examining seasonal and diurnal patterns. Kühn & Ogulewicz [1970] compared the results they observed in the Baltic with predictions given by the CCIR as well as studying the seasonal distributions of refractivity and signal strength. Flavell [1978] presented the results of a study of refractivity obtained from radiosonde observations, concentrating particularly on seasonal variations, while Hewitt & Adams [1981] looked at diurnal variations and at the length of anaprop events on paths in the UK and to the Netherlands.

As part of the COST 210 project a great deal of statistical data were gathered from signal paths over the UK and north-western Europe. The bulk of the results are summarised in the final report [COST 1991] but some interesting information is contained in a number of the interim publications [Hewitt 1984, Lochtie 1985, Hewitt 1985a, 1987, Hammond 1989, Diik & van Noort 1989]. Bye & Howell [1989] made an interesting
study of the refractivity lapse rate from meteorological data and found considerable
differences between coastal and inland observations.

Of most interest to this work are the results obtained by Spillard [1989a,b, 1991]. Using
signal data from the COST 210 cross channel network and ‘Daily weather report’ charts,
the studies examined the behaviour of signals under different weather conditions. An
initial study of 10 weather types and one observation a day for 9 months [Spillard
1989b] suggested that most signals were observed when an anticyclone was centred to
the east of the path with moderate enhancements when the path was ahead of a warm
front or behind a cold front. As will be shown in the next chapter, these results are in
keeping with the meteorological models developed by this author. A more detailed work
[Spillard 1991] looked at 11 weather types, using a whole year of 6-hourly observations.
Further subdivision considered the origin of the air, temperature and cloud cover. The
results showed considerable variation between weather types and between subdivisions
of each type but in most cases each category has only a few tens of hours of data, not
enough for a valid statistical analysis. This is discussed in the work and it is suggested
that use of a longer period of data and less subdivision would make the results more
meaningful. Another limitation of Spillard’s work is that data were limited to sea paths
only, rather than examining a mixture of path types.

3.1.2 Prediction methods

A number of methods have been developed to predict signal statistics from factors such
as path length and type and transmission frequency. Most of these methods produce
a cumulative distribution of some sort, showing the percentage of the time that signals
are expected to exceed a particular level. Such works include Hewitt [1987, 1988b,c],
Spillard [1991] and COST [1991]. While of great importance to radio scientists, such
models are of little importance to this work.

3.1.3 Presentation of signal data

The works mentioned in the preceding sections contain a bewildering array of ways of
presenting signal statistics. Closer inspection shows that many are similar, with the
objects either of showing how signals behave on average over the course of time or how
much of the time signals are expected to exceed a given level.

The main method used to present signal statistics is the cumulative distribution or CD.
This is a curve showing what percentage of the time signals exceed a given level. The time axis is logarithmic and will typically range from 100% to about 0.0001%, while the signal level axis ranges from the receiver noise level to some suitable maximum. CDs are used extensively in this work and examples can be seen later in this chapter.

It is often useful to examine diurnal or seasonal trends in signals and to make comparisons between levels. Such charts show either the percentage of total signals (at all levels) in a given time band or the percentage of signals recorded at a particular level. This sort of data are usually presented as a bar or line graph, sometimes accompanied by some form of average to smooth the data [e.g. Hammond 1989]. Again such charts are used extensively in this work and examples can be seen later in this chapter. Not used here, but of importance to organisations such as BTL, are event duration charts. These show the number of anaprop events for each of a number of durations. Different signal levels may be shown for comparisons to be made. Such information is of importance when planning signal networks.

3.2 Data analysis

During discussions with BTL early in this project, it transpired that little or no work had been done on the statistics of signals under different weather conditions. Since this project needed an indication of the scale of frontal anaprop, it was decided to make a detailed statistical analysis of two or three years data, looking at the incidence of anaprop under different weather conditions.

3.2.1 Selection of data

As BTL were a major contributor to the COST 210 project, they were able to make large quantities of data available to the author. Signal data from paths in the COST 210 North Sea Network for the years 1986–8 were supplied, as were the corresponding weather charts from the BTL library. 1986–8 was chosen since the signal data were the most complete — more recent material was often off site or not fully transcribed onto computers.

Due to some problems with the data for 1988 (mainly missing or corrupt data files, as well as the amount of time required to process all the data), it was decided to limit the analysis to the two years 1986–7 and only to look at signal paths within the UK mainland or to the Netherlands. The table below [Table 3.1] shows the final set of
Table 3.1. Signal paths used for statistical analysis in this work

<table>
<thead>
<tr>
<th>Path</th>
<th>Length (km)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martlesham Heath—Leidschendam</td>
<td>210</td>
<td>Sea</td>
</tr>
<tr>
<td>Martlesham Heath—Eindhoven (1)</td>
<td>298</td>
<td>Sea—Coastal</td>
</tr>
<tr>
<td>Martlesham Heath—Eindhoven (2)</td>
<td>298</td>
<td>Sea—Coastal</td>
</tr>
<tr>
<td>Martlesham Heath—Breda</td>
<td>246</td>
<td>Sea—Coastal</td>
</tr>
<tr>
<td>Martlesham Heath—Sparsholt Firs</td>
<td>200</td>
<td>Land</td>
</tr>
<tr>
<td>Martlesham Heath—London (DTI)</td>
<td>114</td>
<td>Coastal</td>
</tr>
<tr>
<td>Martlesham Heath—London (Telecom Tower)</td>
<td>114</td>
<td>Coastal</td>
</tr>
</tbody>
</table>

signal paths used.

The weather data used were the 6-hourly synoptic charts issued by the UK Meteorological Office’s Daily Weather Report (DWR), with a complete set for the two year period being supplied by BTL.

3.2.2 Weather classification

The DWR charts were chosen since they provide the highest resolution in both time (6 hour intervals) and space ($1:20 \times 10^6$) of any published data. Examples of DWR charts can be found in Appendix A of this thesis.

Weather systems were initially divided into frontal (F) and anticyclonic (A) conditions, with a further category (N) for those occasions which did not fall into either of the above categories. In view of BTL’s interest in the interactions of fronts with anticyclones [Hewitt et al. 1981], a fourth category (AF) was added. Each category except N was further subdivided, giving a total of 24 different weather types. This allowed different orientations of weather systems and signal paths to be isolated. Figure 3.1 shows the relationships between signal paths and weather conditions. It should be noted that this classification scheme is designed for paths in the UK/North Sea area, but can easily be modified to apply to other areas of the world. The 24 categories are:

Anticyclonic (A) types

A1 conditions occur when a high pressure centre is to the east of a signal path. These conditions are said [Bye 1988a] to account for most of the anaprop observed on paths in north-west Europe.
Figure 3.1. Relationship between signal paths and weather conditions for different weather types. AF conditions correspond to the appropriate F conditions but isobars have anticyclonic curvature.

The orientation of the path and the front is important only for weather types F1-6 and AF1-6. For all other types the orientations of path and front shown in the figure is unimportant.

For the weather types where orientation is important, paths are considered to be either parallel or perpendicular to the front. A path is perpendicular to the front if the angle between the path and the front exceeds 22.5°. If the angle is less than 22.5°, then the path is classified as parallel to the front. This is illustrated by the sketch:
A2 conditions are when the high pressure is centred to the west of a signal path.
A3 conditions occur when the high pressure centre is to the north of the signal path.
A4 conditions occur when the high pressure centre is to the south of the signal path.
A5 is when the high pressure is centred over or is very near to the signal path.
A6 conditions are when the path is between two highs, so pressures are higher at the ends of the path than in the middle.

Frontal (F) types

F1 conditions occur when a cold front is 'perpendicular' to a signal path, that is, moving along the path from one end to the other.
F2 conditions occur when a cold front is 'parallel' to a signal path, so the front moves over the whole length of the path at once rather than moving from one end to the other.
F3 corresponds to F1 conditions but for a warm front.
F4 corresponds to F2 conditions but for a warm front.
F5 corresponds to F1 conditions but for an occluded front.
F6 corresponds to F2 conditions but for an occluded front.
F7 conditions occur when a signal path cuts through the same front twice. The type of front is unimportant.
F8 conditions occur when a path cuts both the warm and cold fronts of a single depression, with the ends of the path ahead of and behind the warm sector.
F9 conditions occur when the entire path is in the warm sector of a depression and isobars are either cyclonically curved or straight.
F0 conditions are those where a path cuts two or more fronts, provided the weather cannot be classified as F8.

Anticyclonic-Frontal (AF) types

AF1 corresponds to F1 but with anticyclonic curvature to the isobars.
AF2 corresponds to F2 but with anticyclonic curvature to the isobars.
AF3 corresponds to F3 but with anticyclonic curvature to the isobars.
AF4 corresponds to F4 but with anticyclonic curvature to the isobars.
**AF5** corresponds to F5 but with anticyclonic curvature to the isobars.

**AF6** corresponds to F6 but with anticyclonic curvature to the isobars.

**AF9** corresponds to F9 but with anticyclonic curvature to the isobars.

**Unclassified (N) types**

N covers cases where the large scale flow is cyclonic or linear, but there are no fronts within about 100 km of the signal path. Any charts which cannot be classified as A, F or AF are put into category N.

### 3.2.3 Verification of the weather classification scheme

The weather classification scheme was developed by meteorologists but was designed to be used by non-professionals. To ascertain whether this was true, and to examine the objectivity of the analysis, two tests were carried out. For the first, the author’s supervisor used the written classification guidelines [Jones 1990] to classify a two week block of data. For the second, BTL were supplied with the same guidelines and were asked to examine another two week block of data.

The first test provided a very good correlation between the two analysis, with 93% (52/56 cases) of cases matching. The main differences were over whether some fronts should be AF or F type, but it was felt that the scheme was objective and easy for a meteorologist to use.

The second (BTL) analysis was less accurate, but still 84% (47/56) of cases agreed. Again there were differences over AF and F types, as well as some between A and N types. The problem appeared to be that meteorologists looked at the whole weather pattern, looking at the large scale flow and ignoring local behaviour of the isobars.

The guidelines were modified to deal with this, so future analysts will be requested to look at the large scale flow rather than the details.

These examinations demonstrated that the analysis scheme was objective and gave results which could be duplicated closely.
3.2.4 Data analysis

As stated earlier, signal data from the COST 210 North Sea Network were supplied by BTL. The original data covered four groups of paths — from East Anglia to the Netherlands, the UK mainland, Scandinavia and the Channel Islands, but only the first two groups had enough data available for a meaningful analysis to be made.

Signal data were supplied on disc, with compressed files each containing data for one path for a month. When decompressed, the data gave, for each hour of the month, the number of seconds of signals recorded at sixteen different levels, ranging from 60 dBf below the free space level (-60 dBf) to +15 dBf. The hourly data were divided into 6 hour blocks, each one spanning a period from three hours before to three hours after the time for a synoptic chart. This contrasts with the method used by Spillard [1991], who only looked at one hour on either side of the synoptic chart. Each method has advantages and disadvantages. Spillard’s has the advantage that the signal data is definitely related to the weather condition, whereas this not always so for the author’s, especially when conditions are changing rapidly. On the other hand, Spillard’s method does not allow diurnal variations to be examined while the author looks at signals for each hour allowing charts of diurnal variations to be produced.

Data from all paths in a group were added together and adjusted to give a common base level of -45 dBf\(^1\).

Due to the amount and complexity of the processed data, presentation was mainly graphical. Cumulative distributions and plots of diurnal and seasonal variations were produced for Dutch and for UK paths for each weather type. For the CD, the annual data were divided into two half years with a summer half year running from May to October and a winter half year running from November to April. These were based roughly on the annual cycle of sea and land temperatures.

3.3 Results of analysis

This section presents a summary of the results of the statistical analysis. More detailed information is given in an appendix to this work and results are discussed in the following section.

\(^1\)Earlier work by the author had correlated signals between different paths in a group, and had found the correlations to be statistically significant for those months examined. It was therefore safe to assume that merging data for all Dutch or all UK paths did not affect the results.
3.3.1 Expected results

From previous analyses, both by the author and by others, there are a number of expected results which should be observed here.

- Because advection is an important cause of anaprop on sea paths but not on land ones, there will be differences between UK and Dutch results. There will be more differences at lower signal levels and the differences will be more obvious for A and N weather types than for F and AF types.

- There should be differences between summer and winter half years, with more anaprop observed in summer. The differences will be more pronounced on Dutch (sea) paths than on UK paths, with the differences due to the seasonal changes in land and sea temperatures.

- Anticyclonic conditions are expected to account for the majority of signals at all levels and AF types for least. This is a consequence of the frequency with which the different types occur.

- When the significance of the signals (the amount of anaprop for a particular weather type compared with the amount of time that type is observed) is considered, anticyclonic types are expected to be the most significant, closely followed by AF types. The majority of F types and N conditions are expected not to be a significant cause of anaprop.

- A and N weather types should show a clear diurnal cycle, with more signals recorded during the night than during the day. This is due to the nocturnal descent of the subsidence inversion (if present) as well as to the formation of nocturnal radiation ducts on land and coastal paths. Advection on sea paths will modify this cycle at low signal levels, extending the maximum into the late afternoon/early evening.

- When anticyclonic conditions are examined in detail, A1 and A3 conditions are expected to cause more anaprop than A2 and A4 conditions, particularly on sea paths. This is due to the source of advected air over the signal path — for A1 and A3 conditions the air has been advected offshore from the European mainland while for A2/4 conditions the air has travelled the length of the North Sea or come from the UK.

- Because fronts could be over a path at any time of day or night, frontal conditions are generally unpredictable. Because subsidence inversions associated with fronts are expected to descend at night [Chapter 4], some diurnal cycle should be visible.
It is clear from table 3.2 that some weather types occur for a very small percentage of the time, so signal statistics for these types will have little significance. The level at which weather types become insignificant is when the occurrence is less than 0.5%, equivalent to 15 cases over the two years of observations.
The same will apply to AF conditions, although they should have some similarities with anticyclonic results.

- According to Hewitt et al. [1981], F9 and AF9 conditions (when the path is in the warm sector of a depression) should be a significant cause of anaprop.

### 3.3.2 Occurrence of different weather conditions

Table 3.2 summarises the frequency with which the different weather types were observed during the analysis period.

<table>
<thead>
<tr>
<th>Weather type</th>
<th>Dutch summer</th>
<th>Dutch winter</th>
<th>Dutch total</th>
<th>UK summer</th>
<th>UK winter</th>
<th>UK total</th>
<th>Overall total</th>
<th>Weather type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>4.77</td>
<td>6.32</td>
<td>5.55</td>
<td>5.05</td>
<td>8.15</td>
<td>6.58</td>
<td>6.06</td>
<td>A3</td>
</tr>
<tr>
<td>A4</td>
<td>5.86</td>
<td>6.12</td>
<td>5.99</td>
<td>8.08</td>
<td>9.04</td>
<td>8.56</td>
<td>7.27</td>
<td>A4</td>
</tr>
<tr>
<td>A5</td>
<td>4.63</td>
<td>1.55</td>
<td>3.09</td>
<td>4.19</td>
<td>2.37</td>
<td>3.29</td>
<td>3.19</td>
<td>A5</td>
</tr>
<tr>
<td>A6</td>
<td>0.82</td>
<td>0.92</td>
<td>0.87</td>
<td>1.09</td>
<td>0.90</td>
<td>0.99</td>
<td>0.93</td>
<td>A6</td>
</tr>
<tr>
<td>All A</td>
<td>37.02</td>
<td>36.35</td>
<td>36.69</td>
<td>42.44</td>
<td>41.85</td>
<td>42.15</td>
<td>39.42</td>
<td>All A</td>
</tr>
<tr>
<td>F1</td>
<td>10.37</td>
<td>7.71</td>
<td>9.04</td>
<td>7.27</td>
<td>5.25</td>
<td>6.26</td>
<td>7.65</td>
<td>F1</td>
</tr>
<tr>
<td>F2</td>
<td>1.98</td>
<td>2.68</td>
<td>2.33</td>
<td>2.31</td>
<td>2.28</td>
<td>2.29</td>
<td>2.31</td>
<td>F2</td>
</tr>
<tr>
<td>F3</td>
<td>7.06</td>
<td>4.49</td>
<td>5.78</td>
<td>6.13</td>
<td>5.18</td>
<td>5.66</td>
<td>5.72</td>
<td>F3</td>
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<td>1.98</td>
<td>2.13</td>
<td>2.05</td>
<td>1.29</td>
<td>1.52</td>
<td>1.40</td>
<td>1.73</td>
<td>F4</td>
</tr>
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<td>F5</td>
<td>3.14</td>
<td>3.48</td>
<td>3.31</td>
<td>2.11</td>
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<td>2.50</td>
<td>2.90</td>
<td>F5</td>
</tr>
<tr>
<td>F6</td>
<td>1.36</td>
<td>0.87</td>
<td>1.12</td>
<td>1.95</td>
<td>1.08</td>
<td>1.52</td>
<td>1.32</td>
<td>F6</td>
</tr>
<tr>
<td>F7</td>
<td>0.27</td>
<td>0.25</td>
<td>0.26</td>
<td>0.00</td>
<td>0.07</td>
<td>0.03</td>
<td>0.15</td>
<td>F7</td>
</tr>
<tr>
<td>F8</td>
<td>1.02</td>
<td>1.79</td>
<td>1.40</td>
<td>0.48</td>
<td>0.69</td>
<td>0.58</td>
<td>0.99</td>
<td>F8</td>
</tr>
<tr>
<td>F9</td>
<td>1.09</td>
<td>1.79</td>
<td>1.44</td>
<td>2.04</td>
<td>2.39</td>
<td>2.21</td>
<td>1.83</td>
<td>F9</td>
</tr>
<tr>
<td>F0</td>
<td>0.34</td>
<td>0.96</td>
<td>0.65</td>
<td>0.00</td>
<td>0.48</td>
<td>0.24</td>
<td>0.45</td>
<td>F0</td>
</tr>
<tr>
<td>All F</td>
<td>28.61</td>
<td>26.16</td>
<td>27.39</td>
<td>23.56</td>
<td>21.84</td>
<td>22.71</td>
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<td>All F</td>
</tr>
<tr>
<td>AF1</td>
<td>0.68</td>
<td>0.89</td>
<td>0.79</td>
<td>0.34</td>
<td>0.48</td>
<td>0.41</td>
<td>0.60</td>
<td>AF1</td>
</tr>
<tr>
<td>AF2</td>
<td>1.30</td>
<td>0.34</td>
<td>0.82</td>
<td>0.81</td>
<td>0.48</td>
<td>0.65</td>
<td>0.74</td>
<td>AF2</td>
</tr>
<tr>
<td>AF3</td>
<td>0.61</td>
<td>0.69</td>
<td>0.65</td>
<td>1.29</td>
<td>0.21</td>
<td>0.75</td>
<td>0.70</td>
<td>AF3</td>
</tr>
<tr>
<td>AF4</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
<td>0.54</td>
<td>0.28</td>
<td>0.41</td>
<td>0.45</td>
<td>AF4</td>
</tr>
<tr>
<td>AF5</td>
<td>0.00</td>
<td>0.27</td>
<td>0.14</td>
<td>0.00</td>
<td>0.14</td>
<td>0.07</td>
<td>0.10</td>
<td>AF5</td>
</tr>
<tr>
<td>AF6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.12</td>
<td>0.06</td>
<td>0.03</td>
<td>AF6</td>
</tr>
<tr>
<td>AF9</td>
<td>0.95</td>
<td>0.69</td>
<td>0.82</td>
<td>1.70</td>
<td>1.24</td>
<td>1.47</td>
<td>1.15</td>
<td>AF9</td>
</tr>
<tr>
<td>All AF</td>
<td>4.02</td>
<td>3.37</td>
<td>3.70</td>
<td>4.69</td>
<td>2.95</td>
<td>3.82</td>
<td>3.76</td>
<td>All AF</td>
</tr>
<tr>
<td>N</td>
<td>30.35</td>
<td>34.12</td>
<td>32.23</td>
<td>29.31</td>
<td>33.36</td>
<td>31.32</td>
<td>31.77</td>
<td>N</td>
</tr>
</tbody>
</table>
It can be seen that, for both the Dutch and UK paths, A conditions are by far the most common, followed by N, F and finally AF conditions. The only major difference between the regions is that anticyclones are about 5% more frequent on UK paths than on Dutch ones, balanced by a lower percentage of fronts. There are no obvious seasonal differences, an important point in later discussion of the occurrence of signals during each weather type. There are noticeable differences between, on the one hand, fronts roughly perpendicular to signal paths (F1,3,5) and those roughly parallel to the paths (F2,4,6). This stems from the classification scheme, which imposed stricter conditions for a front to be 'parallel' to a path than for a front to be 'perpendicular', so 'perpendicular' fronts would be expected to occur three times as often as 'parallel' fronts. This is more or less what is observed.

3.3.3 Significance of signals

One goal of this project was to provide indications of which weather types gave most interference problems. This was done using the weather data given above combined with the signal data.

The scale of the interference problem was quantified by means of the 'significance ratio' (SR). Using the signal data for -45dBf (the lowest observable level), the ratio of percentage of total signals to percentage of total weather was calculated for each weather type and season. For example, if weather type $X$ occurred for 5% of the time but accounted for 10% of total signals, the significance ratio would be $SR(X) = \frac{10}{5}$, or 2.00. If signals were produced by random processes, and not in any way dependant on the weather conditions, the SR would be expected to be close to one. If the weather conditions caused anaprop, the SR would be greater than one, and if the conditions prevented or limited anaprop, the SR would be less than one. It was found that SR's ranged from effectively zero, indicating that the weather type suppressed all anaprop, to a maximum of nearly 5, indicating the weather type as a strong cause of anaprop. These findings are summarised in figures 3.2 and 3.3.

On Dutch paths, the significance ratios are shown in figure 3.2. On almost all weather types, there are clear seasonal differences, with summer giving higher SR's than winter. Few frontal types have SR's much above one, and N has low SR's. Conversely most A and AF types have high SR's.

On UK paths, SR's are shown in figure 3.3. Again there are clear seasonal differences, with higher summer than winter values. Again, A and AF conditions show generally high SR's while F and N show low values. All these results will be discussed later in
Figure 3.2. Significance ratios for Dutch signal paths. Horizontal axis shows weather type, vertical axis shows significance ratio.

Figure 3.3. Significance ratios for UK signal paths. Horizontal axis shows weather type, vertical axis shows significance ratio.
3.3.4 Interference Data Sheets

The main method of presenting the statistical results is through a portfolio of 'interference data sheets' (IDS's). These give, for each weather type and for Dutch and UK paths:

- A cumulative distribution showing signals at all levels for winter, summer and the whole year, as well as a reference curve showing the total signals for all weather types over the whole year.

- A chart showing the variation in signals over the course of a year as a percentage of the total signals observed each month. Curves are given for three or four different signals levels, from -45 dBf up to the free space level. This chart can bring out the main seasonal influences on the anaprop but is also influenced by the variation in occurrence of the weather type.

- A chart showing the behaviour of signals throughout the course of a day, again at a number of different levels. This allows some determination of the main mechanisms responsible for the anaprop, particularly during anticyclonic conditions.

- A DWR synoptic chart for a typical example of the weather type. This aids operational use of the IDS's by giving a basis for comparison with forecast charts.

- A written summary of the results, detailing the main mechanisms likely to give rise to the anaprop as well as giving the frequency with which the weather condition occurs during the year and the significance ratios.

IDS's were produced at the request of BTL, who required statistics in a form easily used by their engineers. The data can be used for planning purposes, giving indications of which periods are most likely to be a risk from anaprop, as well as operationally, when predictions of the likelihood of anaprop can be made using forecast weather charts. The entire IDS portfolio is given as appendix A of this thesis.

3.3.5 Results for Dutch signal paths

To give an overview of the statistical results, data for all A-type conditions were merged, as were data for all F and all AF-type conditions. With the N-type conditions, this
gives four broad weather types, with CDs, annual and diurnal distributions for each. To aid comparison, charts of each type are grouped together.

The CDs [Figure 3.4] show clear differences between the four weather types. Each

![Cumulative distributions of signals on Dutch paths](image1)

![Cumulative distributions of signals on Dutch paths](image2)

**Figure 3.4.** Cumulative distributions of signals on Dutch paths (a) anticyclonic (b) frontal (c) anticyclonic-frontal (d) unclassified conditions.

shows seasonal differences, with less signals observed in the winter half-year than in the summer at all levels. These seasonal differences are not so marked for F and AF conditions as for A and N. There are also differences in the amount of signals for each weather type, with A conditions accounting for the bulk of the observed signals and AF for least.

The annual charts [Figure 3.5] show some differences between the four types. These
Figure 3.5. Monthly distributions of signals on Dutch paths (a) anticyclonic (b) frontal (c) anticyclonic-frontal (d) unclassified conditions.
are likely to reflect the incidence of different weather types as well as the seasonal differences already observed. All show more signals in the summer half-year than in the winter.

Of most interest are the diurnal charts [Figure 3.6]. Again there are differences between

![Diurnal charts](image)

Figure 3.6. Diurnal distributions of signals on Dutch paths (a) anticyclonic (b) frontal (c) anticyclonic-frontal (d) unclassified conditions.

the four types and between different signal levels within types. Anticyclonic conditions show the least range and AF conditions the most, correlating inversely with the incidence of the weather conditions. Anticyclonic and, to a lesser extent, N conditions show a cyclic pattern, with more signals observed at night than during the day. Frontal conditions show a general upwards trend throughout the day while AF conditions show little variation outside the period 22-03Z, although the large vertical scale of the chart
tends to hide small variations. The cyclic pattern for A and N conditions is expected, and the results for F and AF conditions reflect the unpredictable nature of fronts.

### 3.3.6 Results for UK signal paths

Analysing the data in the same manner as for Dutch paths, summaries were produced for the four main weather types on UK paths.

The CDs [Figure 3.7] show differences between the four types, with anticyclonic con-

![Figure 3.7](image)

**Figure 3.7.** Cumulative distributions of signals on UK paths (a) anticyclonic (b) frontal (c) anticyclonic-frontal (d) unclassified conditions.
ditions accounting for the majority of observed signals and AF for least. Of particular interest is the dominance of winter F signals at and above the free space level.

The annual charts [Figure 3.8] explain the seasonal variations, with a general lack of

![Graph a](image1)

![Graph b](image2)

![Graph c](image3)

![Graph d](image4)

**Figure 3.8.** Monthly distributions of signals on UK paths (a) anticyclonic (b) frontal (c) anticyclonic-frontal (d) unclassified conditions.

signals between January and March for all weather types.

The diurnal charts [Figure 3.9] are interesting, especially in comparison with those for Dutch paths. Ranges are similar (to the Dutch) for F, AF and N conditions and slightly greater for A-type conditions. A day-night cycle is clearly seen for A conditions and less well for F and N conditions, where there is a high level 'peak' in the afternoon. Even AF conditions show a slightly cyclic pattern. These results for conditions with
Figure 3.9. Diurnal distributions of signals on UK paths (a) anticyclonic (b) frontal (c) anticyclonic-frontal (d) unclassified conditions.
fronts are somewhat surprising.

3.4 Discussion

During the statistical analysis, some interesting results have been observed, in some cases confirming existing expectations, and in others disagreeing with them. This section will consider the findings from the different statistical analyses.

3.4.1 Occurrence of different weather conditions

The main conclusion that can be drawn from this section is that the initial weather classification scheme was too detailed. Of the 24 weather types considered, five (F7, F0, AF4, AF5, AF6) occur so rarely that they could be omitted without any loss. This could be done in any future analysis. Comparing observations for different paths and seasons, there are few differences between winter and summer half-years, with the notable exception of A2 conditions. AF and N conditions show few differences between UK and Dutch paths, but A conditions are about 5% more frequent over UK paths than over Dutch paths, balanced by a corresponding decrease in the number of fronts.

This general lack of differences between different seasons and different geographical regions is expected from climatological studies. It is useful in that it allows the analyst to concentrate on seasonal and geographical differences in the observed signals, without having to take variations in the weather into account.

3.4.2 Significance of signals

Significance ratios have proved an important method of comparing different weather types. They provide an at a glance' summary of seasonal differences and the differences between path types.

The most obvious feature of the charts is the greater range of significances observed on Dutch paths, where several SRs exceed 4, compared with a maximum SR of 3 for UK paths. Different weather types have very different significances, too. A and AF conditions generally have above-average significances on both UK and Dutch path, while F and AF tend to have below average significance ratios. Seasonal differences
are also clear, with almost all weather types on both path groups showing higher SRs in summer than in winter.

These results confirm many of the expectations of the analysis. There are clear differences between A1/3 conditions (where advection is offshore from Europe) and A2/4 (where advection is from the UK or down the North Sea, with significant amounts of anaprop associated with the former, and below average amounts with the latter. This agrees with the view that high pressure to the East of the UK is a significant cause of anaprop [Bye 1988a]. A5 and A6 conditions are also significant causes of anaprop.

Frontal conditions can be seen to be a fairly insignificant cause of anaprop on both path types. In some cases (F7 and F0) this is due to lack of data, but for all other F weather types there is enough data for the results to be valid. F9 conditions are, as expected, more significant causes of anaprop than other types, but this is only clear on Dutch signal paths. Despite this general insignificance of frontal conditions, it must be remembered that severe anaprop can be associated with some fronts [Hewitt et al. 1981].

As expected, AF conditions are generally a significant cause of anaprop, although the rarity of some types (AF4/5/6) makes their results suspect. AF9 conditions are seen to be particularly significant on Dutch paths, but there are clear differences between summer and winter half years. N conditions are not a significant cause of anaprop.

3.4.3 Interference data sheets

Produced as a reference guide for BTL engineers, the portfolio of interference data sheets provides the statistical detail behind the summaries presented in this chapter. There is too much information to examine in full here, and each sheet includes a summary of the charts and the meteorological causes of the anaprop. It is hoped that these sheets will be useful operational tools as well as a method of correlating weather and signal data which can be used elsewhere in the world.

3.4.4 Dutch signal paths

Comparing the four main weather types (A, F, AF and N), some clear similarities are evident. These may give clues to the mechanisms causing anaprop for different weather types.

The cumulative distributions show similarities between F and AF conditions, as well as
between A and N. All four types show seasonal differences, but these are less marked for A and N than for F and AF. These seasonal effects are likely to be caused by the changing sea surface temperature during the year.

The same similarities are also visible on the diurnal charts, although not so clearly. The similarities in diurnal behaviour between A and N conditions suggest the same mechanisms at work, emphasising the message that the effects of advection, radiation cooling and subsidence are not confined to anticyclones, but can occur during any synoptic conditions. AF conditions show little variation throughout the day, with the few observable peaks likely to be due to single, severe events. This lack of variation is expected, since fronts are not constrained to any particular times of day. Frontal conditions appear to show some diurnal variation with more signals observed as the day progresses. This is surprising, as results similar to AF conditions are expected, with signals distributed equally throughout the day. These results are not observed on land paths, suggesting advection as a mechanism for the higher amounts of signals, leaving the unresolved question of why similar patterns are not observed under AF conditions.

The monthly charts show the causes of the seasonal differences on the CDs. Each weather type has a 'season' when the majority of signals are observed. It is difficult to draw any conclusions from these without corresponding monthly distributions of the weather conditions. With these, significance ratios could have been investigated in more detail to see whether, as seems likely, much of the variation between months reflects the incidence of that weather type. This is an area that could be addressed by future work in this field.

Returning to the significance ratios, A and AF conditions have almost identical SRs (around 1.7), as do F and N conditions (around 0.5). Do these SRs indicate links between the weather types, different to the links hypothesized from the CDs and diurnal charts? This and other questions are in need of answers. Can AF conditions be considered as special examples of F types, or are they more closely related to A conditions? How do the mechanisms responsible for anaprop in anticyclones interact with the mechanisms associated with fronts? Are the similarities in results for different weather conditions due only to chance? Some of these questions will be examined in the next chapter, but others will remain unanswered in this work.

### 3.4.5 UK signal paths

Once again, different weather types have similarities, suggesting common mechanisms responsible for the anaprop. The links between weather types are different to those on
Dutch paths, again raising questions to be answered.

The CDs show similarities in the results for F, AF and N conditions, with the vast majority of recorded signals in the summer half year. Anticyclonic conditions still show a difference between the seasons, but it is less marked than for the other types. Above the free space level, both F and A conditions show more signals in winter than in summer, a feature not observed on Dutch paths. Because of the small time percentages involved (less than 0.01% of the time), these are likely to be the product of a very small number of events.

Diurnal charts show similar patterns, with more signals during darkness than daylight. The variation in about the same on each chart once differences in scale are taken into account. A closer examination shows the diurnal pattern to be less pronounced during AF conditions than during the others, suggesting a mechanism independent of time as the cause. This is similar to the observations for Dutch paths, but F conditions show a very different pattern.

As on Dutch paths, it is difficult to draw any conclusions from the monthly charts without more weather data. It is clear that signals are more common in summer than in winter, but it would be necessary to produce monthly significance ratios to see how important an effect this is.

The SRs for F and N conditions are very close, as observed on Dutch paths, but A and AF conditions have very different SRs. Is this indicative of the same causes for anaprop under F and N conditions? What causes the differences between UK and Dutch results — are they all due to the effects of advection, as suggested by the BTL model, or are they purely chance. Again some of these questions will be examined later in this work, while others will remain for the radio-meteorologists of the future.

3.4.6 Conclusions

This analysis has confirmed the importance of anticyclones as a cause of anaprop as well as showing fronts to be a relatively insignificant cause. This does not mean that fronts can be ignored – they are still a problem when individual events cause severe anaprop, but they are relatively trivial for the purposes of network planning. The interactions of fronts with anticyclones are more important than fronts alone, but since they occur rarely, they also have little statistical importance.

The techniques used to analyse and correlate signal and weather data are based on the
existing tools used by radio scientists. It is hoped that further studies of the effects of weather on signals will be undertaken, so better models of the links between weather, anaprop mechanisms and signals can be developed.
Chapter 4

Conceptual models of fronts and anaprop

This chapter examines fronts and depressions through a number of conceptual models, similar to the BTL anticyclone model, which provide a physical explanation of the processes occurring in typical depressions of different types. The models are based on current meteorological knowledge, adapted to radio-meteorology. It must be stressed that the models are qualitative, not quantitative. This is due to the great variety of fronts, which can change dramatically in both the space and time scales, as well as the relatively small amount of hard data available to quantify the models. These models were developed in parallel with the case studies presented in the next two chapters, and were modified continually during the analysis process.

The chapter begins with a survey of existing work on fronts and depressions, looking in slightly more detail than usual at the conceptual models that will be used as a basis for the remainder of this chapter. This is followed by a discussion of the adaptations needed to use the meteorological models for radio-meteorology and then by a series of studies of different types of fronts—ana-type, kata-type (with and without upper cold fronts) and occlusions. For each type, there is an examination of conditions leading to anaprop, and (qualitative) predictions of the likelihood of anaprop being observed. To close the chapter, there is a brief look at warm sector subsidence and the relationship between fronts and anticyclones.
4.1 Meteorological Models of Fronts

The modern view of weather fronts and depressions can be traced back to the 1920's, when a group of meteorologists led by Bjerknes produced the 'classic' model of a depressions structure and lifecycle seen in most textbooks [McIntosh & Thom 1981 p 132, Met.O 1983 p143]. Initially fronts were identified as warm, cold or occluded but later work, involving upper air as well as surface observations, showed that warm and cold fronts could also be divided into ana- and kata-types, depending on whether the air in the warm sector was ascending or descending [Barry & Chorley 1987 p182]. Ana-fronts, with ascending air, are generally active, with deep clouds and heavy rain, particularly at the cold front. Kata-fronts, with descending air, have shallower clouds and light rain. The main features of ana- and kata- fronts are shown in figure 4.1. Occlusions

![Diagram of typical depressions with ana-fronts and kata-fronts](image)

**Figure 4.1.** Cross sections through 'typical' depressions with (a) ana-fronts and (b) kata-fronts. [From Barry & Chorley 1987 p183]

...can be either warm or cold depending on whether the warm or cold front has been lifted off the surface. The main features of each type are shown in figure 4.2.

It was also found that fronts do not retain the same characteristic throughout their length and life, also that a depression need not have warm and cold fronts of the same
Figure 4.2. (a) Warm Occlusion, with cool air behind the front overriding the cold air and lifting the fronts clear of the surface. (b) Cold Occlusion, with cold air behind the front undercutting the cool air and lifting the fronts.[From Met.O 1981 p157]

type. In particular, fronts are more likely to be kata-type away from the low, especially if the depression is on the fringes of an anticyclone. 'Weak' fronts cutting through a high are likely to be kata-type due to the overall subsidence within the high.

Although the Norwegian model is a very good device for examining the structure and evolution of depressions as a whole, it suffers from several drawbacks, most importantly that it treats a depression as a single synoptic scale feature without much consideration of the internal processes that make up the overall structure. This limitation was acceptable when the model was developed, as detailed observations of the airflows aloft were not possible [McIver 1986 p355]. Recent research on the three-dimensional mesoscale structure of fronts has led to far more detailed models.

4.1.1 'Conveyor Belt' Models

The development of 'conveyor belt' (also called conceptual) models of weather systems is relatively recent, with almost no work more than 20 years old. Recent conceptual models represent a fundamental shift in meteorological thought, from the synoptic scale to the mesoscale (i.e. an order of magnitude smaller). This shift came about through the introduction of satellite and weather radar data as an aid to analysis. For the first time it was possible to see the atmosphere as a dynamic system, in continual motion, rather than as a series of static 'snapshots' provided by 'conventional' observations. This has resulted in a far better picture of the role of frontal systems within global, synoptic and mesoscale meteorology.

Analysis using the new information sources required the development of new techniques. It was rapidly found that the Norwegian model was not really adequate and could sometimes be extremely misleading [Browning 1985]. Numerical models were
also incapable of accurately simulating mesoscale processes, so analysis had to be qualitative rather than quantitative. To give forecasters some help, conceptual models were developed to provide a framework to guide the meteorologists subjective analysis of the observed data. Hand in hand with the conceptual models came the development of 'Nowcasting'. This was a new branch of meteorology, the production of very short-range forecasts (for less than 6 hours ahead) covering small areas (less than 100 km in extent, and often considerably smaller) [Browning 1982 p ix]. Again conventional modelling proved inadequate, so forecasts were based on skill at predicting future trends from past and present data.

A depression has two 'conveyor belts' associated with it. These are broad (100—1000 km), shallow (roughly 1 km thick) belts of moving air, one warm (the WCB) and the other cold (the CCB), which rise and cross over each other, creating fronts where they do so [Figure 4.3].

![Figure 4.3. Large-scale flow in a typical mid-latitude depression, showing the warm and cold conveyor belts and the surface fronts. Numbers on conveyor belts show level (in mb) of the belt at that point. [From Mason 1983]](image)

Figure 4.3 shows the relationship between the conveyor belts and the depression as a whole, but to see how they influence fronts it is necessary to go into more detail. One
important factor is the air motion perpendicular to the fronts. Although the WCB is shown running parallel to the surface cold front, there is actually a small, but significant component across the frontal zone [Browning 1985]. This produces an ana- or kata-type cold front, depending on whether this component is rearwards or forwards relative to the cold front.

Rearwards sloping ascent of the WCB produces an ana-type front with the ascending air producing a deep convective layer and associated cumulonimbus clouds and heavy rain. The structure is shown in plan and section in Fig 4.4 [ibid.]. The vertical ascent from the surface to around 2 km is very rapid (about $5 m s^{-1}$). This zone is responsible for most of the precipitation in the frontal zone [Browning & Harrold 1970], giving a very narrow band of intense rain at the surface cold front (SCF) which can clearly be observed on weather radar images [Browning & Pardoe 1973]. Above this line convection, slantwise ascent occurs, with vertical velocities an order of magnitude lower than near the surface (about $0.4 m s^{-1}$). This ascent produces the cloud and rain behind the SCF. The figure shows that the ascending warm conveyor belt does not coincide with the frontal surface, but lies slightly above and at a steeper angle [Browning & Harrold 1970].

It has been found that maximum velocities of descending air are in the frontal zone, with a descending layer of warm air separating the front from the WCB. There is also a weak return flow (not shown on Fig 4.4) ahead of the line convection which may produce the rain ahead of the SCF shown by Browning [1985]. The line convection does not extend the whole length of the SCF, but is broken into a series of elements from 10 to 100 km long. These elements occur in zones of very strong temperature horizontal gradients across the SCF, separated by much more gentle gradients [ibid.].
Forwards sloping ascent gives a kata-cold front, with subsiding air aloft in the warm sector. The air flows are shown (again in plan and section) in Fig 4.5. This time

![Diagram of cold front](image)

**Figure 4.5.** Cold Front with forwards sloping ascent. (a) Plan showing the relationships between the surface fronts (conventional symbols), the WCB, the dry, descending air and the UCF (open cold front symbols). In this example the UCF and its associated rainband extend ahead of the surface warm front. (b) Section (along line AB in plan) showing airflows and frontal zones. (c) Wet-bulb potential temperature structure along section AB showing how the WCB and dry air are identified. [From Browning 1985]

the WCB slopes forwards and the intense line convection is absent, together with the heavy rain at the SCF. The band of recently subsided cold air (with low $\theta_w$) is split, with part sweeping behind the WCB at low levels, producing the SCF. The other part overruns the WCB, a situation that generates potential instability [Browning & Monk 1982]. This may be released as the WCB begins its ascent, giving a line of cumuliform convection and a band of moderate to heavy rain [Browning 1985]. Termed the upper cold front (UCF) [Browning & Monk 1982], as it can be considered in the same way as the SCF, the rainband marks the leading edge of the cold airflow, and lies parallel to the SCF. The whole system is often termed a split cold front. In some cases the UCF is roughly parallel to the surface warm front, appearing as a band of moderate rain behind the warm frontal rainband. This has led to some very unusual synoptic charts, which become considerably simpler when the split cold front model is applied [ibid.]. Kata-cold fronts are not always well defined by temperature observations, but appear clearly when humidity or $\theta_w$ are examined. This has led to the suggestion [Browning 1985] that they should be termed humidity fronts.

Air motions near the warm front are somewhat simpler (or perhaps less well studied)
than around the cold front. The band of cloud and precipitation ahead of the surface front (SWF) is due to the ascent of the moist WCB giving condensation. Just as the WCB marked the trailing edge of the warm sector, the CCB flows parallel to the SWF and forces the WCB to ascend over it [Mason 1983]. The slantwise ascent of the WCB can clearly be seen from the isobars on Fig 4.3 (which mark the position where the top of the conveyor belt crosses that pressure level).

The occlusion also seems to have escaped detailed analysis. Fig 4.3 shows that the line of the occluded front follows the ascending CCB before the belt turns anticyclonically and merges with the WCB [Mason 1983]. Alternatively the CCB and the cloud band of the occlusion can curve cyclonically around the surface low [Weston 1987].

The structure of depressions is considerably more complex than that outlined here. In particular the rainbands often appear in groups rather than the single bands suggested above. Convection cells also occur in groups, Mesoscale Precipitation Areas (MPA’s), containing several small convection cells [Mason 1983]. Topography can also play an important role, with orographic uplift releasing potential instability or creating low level cloud that can increases surface rainfall through the seeder-feeder mechanism [Browning & Hill 1981].

Finally it must be made clear that the system is dynamic, with changes occurring both in time and space. Although conceptual models attempt to show this, the problems of representing a four dimensional process on a two dimensional medium mean that much detail, usually temporal, is lost. The dynamic structure also means that weather systems are individuals, while the models represent either a synthesis from several case studies or a detailed analysis of a single event. It should therefore be expected that “the real atmosphere differs from the model’s predictions”!

4.2 Adaptations of models for Radio-Meteorological use

The conceptual models described in the previous section have many applications in meteorology but require some modifications before they can be used in radiometeorology. This section considers the modifications that have been made to provide usable radio-meteorological models.
4.2.1 Objectives

The models developed for this work are similar in idea to the BTL conceptual model of an anticyclone [Bye 1988a]. They show the physical processes at work and indicate the resulting potential for anaprop. A number of different models were developed, to cover as broad a range of frontal characteristics as possible. They are:

- A depression with ana-fronts [Section 4.3].
- A depression with kata-fronts and no Upper Cold Front [Section 4.4].
- A depression with kata-fronts and an Upper Cold Front [Section 4.5].
- Warm and cold occlusions [Section 4.6].

Estimates of the probability of anaprop are given for each type of depression under two sets of conditions:

- Over a warm surface (land during the day or a warm sea).
- Over a cold surface (land during the night or a cool sea).

It is felt that these options cover almost all types of fronts in sufficient detail to be usable operationally. It should be stressed that the models are based on current meteorological thinking, and no new concepts are involved. What is new, however, is their application to radio-meteorology.

4.2.2 Anaprop associated with Fronts

Many features of the radio-meteorological models are familiar from the standard conceptual models, in particular the conveyor belts and the frontal zones. To adapt the models to radio-meteorology, super-refractive layers have been added where appropriate.

Ahead of the warm front\(^1\) and behind the cold front there are super-refractive layers (SRLs), which the author has termed *leading* and *trailing edge* SRLs respectively [Fig 4.6], that slope gently upwards away from the fronts. The slope is due to the

\(^1\) *Front* refers to the surface front, while *frontal zone* refers to the front aloft.
frontal zone acting as a control on convection from the surface, which can reach greater altitudes with increasing distance from the frontal zone. Since the warm frontal zone has a shallower slope than the cold frontal zone, the leading edge SRL has a more gentle slope than the trailing edge. The height of the SRLs is controlled by two factors:

- The depth of the convection from the surface, which is dependent on the surface temperature and on the temperature profile aloft. Convection will be more vigorous over a warm surface than a cold one. This tends to lift the SRL and in extreme cases, convection may be strong enough to destroy it.

- The subsiding air in the dry zone. This tends to reduce the height of the SRL.

In both cases the strength of the SRL is controlled by the strength of the ascent and descent. Rapidly subsiding air meeting vigorous convection would be expected to give a strong refractivity lapse at the interface while weakly subsiding air meeting slight convection would produce a much weaker refractivity lapse. While the strength of convection can increase with distance from a front (since the momentum of the ascending parcel increases as it is able to ascend further), the strength of descent decreases with distance.

Within the warm sector there may be a warm sector SRL and possibly an upper cold front SRL as shown in figure 4.6. These SRLs are only expected in kata-type depressions, when the subsiding air in the warm sector meets the top of the warm conveyor belt, at an altitude\(^2\) of about 3 km. The UCF SRL only occurs if there is an upper cold front, and is found at the interface between the subsiding air and the convecting layer ahead of the UCF. The strength and altitude of these SRLs is controlled by the strength of the subsiding air and the properties of this air and the air in the WCB.

\(^2\)Based on the vertical extent of the cold front in the Browning model [Browning 1985].
It might be expected that advection ducts will form when the WCB flows over the sea. In the author's opinion these are unlikely since (for depressions affecting North West Europe) the air in the WCB typically is of tropical maritime origin and is therefore moist, compared with the classic advection duct formed when warm dry air flows over a cooler sea.

4.2.3 Effects of surface temperature

As mentioned earlier, the conceptual models cover two situations — when fronts are over warm and cool surfaces.

When fronts are over a warm surface (e.g. land during the day or when air flows over a warmer sea) there is convection beneath the leading and trailing edge SRLs. This would tend to lift and eventually disperse the SRLs, thus reducing the probability of anaprop. Over a cool surface (e.g. the land during the night or when air flows over a cooler sea) there is little convection, thus the leading and trailing edge SRLs can sink to lower levels, just as the subsidence inversion in an anticyclone descends during the night [Bye 1988a], so increasing the probability of anaprop on surface paths. This is shown in figure 4.7.

![Figure 4.7. Effects of surface temperature on the leading and trailing edge SRLs. The warm surface case is shown as a solid line while the cool surface case is shown as a broken line.](image)

It is not clear at what level the leading and trailing edge SRLs will be found. Browning [1985] shows air subsiding in the dry zones to around 1 km, so it will be assumed here that the leading and trailing edge SRLs will be found between 1 and 2 km (depending on the strength and depth of the convection), near their fronts, and at higher levels further from the fronts. Examination of data from the FRONTS'87 project (chapter 5) will provide some verification of these values.
4.2.4 A word of warning!

The conceptual models presented here represent typical depressions, but it cannot be stressed enough that 'real' weather rarely matches textbook examples. In particular the scales of depressions vary considerably. The models presented here are of typical mature depressions, but should be easy to adapt to other cases.

Since the models are qualitative, they give no indications of the strength of the SRLs, and only a vague idea of their altitude and extent. This is not a drawback since the models are intended to be a framework for the interpretation of observations which may provide the missing details.

It is assumed throughout the following material that the whole of a depression has either ana- or kata-type fronts. This is purely to make it easier to describe the SRLs and anaprop associated with given types of fronts and is not intended to imply that in 'real' depressions warm and cold fronts are always of the same type. In fact real fronts can change character along their length, and with time, but providing the characteristics of a front at a particular point are known, the models can be applied to show what SRLs and anaprop are expected.

4.3 Depressions with Ana-fronts

In a depression with ana-fronts there is general ascent in the warm sector, so any anaprop is associated with the leading and trailing edge SRLs alone.

4.3.1 Structure

A plan of a typical depression with ana-fronts is shown in figure 4.8. The line AB marks the section shown in figure 4.9. The main features to note are the trailing edge SRL immediately behind the surface cold front and the leading edge SRL starting an estimated 50–100 km ahead of the surface warm front. These are formed at the interface between the dry air descending just below the frontal zones and the convection from the surface (over a warm surface) or the turbulent boundary layer (over a cold surface). The leading edge SRL is predicted to have a width of 100–200 km, thus extending up to 300 km ahead of the surface front, while the trailing edge SRL is predicted to extend only some 50–100 km, due to the greater slope of the cold front, which allows the depth of convection to increase more rapidly with distance from the cold front than from the
Figure 4.8. Plan of typical depression with ana-fronts showing the extent of SRLs. The line AB marks the section shown in figure 4.9.

Figure 4.9. Cross section along the line AB in fig 4.8 showing the location of the leading edge and trailing edge SRLs.
warm front. The near-vertical slope of the cold front near the surface [Browning 1985] means that the trailing edge SRL starts closer to the surface cold front than the leading edge SRL does to the surface warm front (as shown in figure 4.9). These predictions will be investigated further in the next two chapters.

4.3.2 Expectations of anaprop

Figure 4.10 shows the probability of conditions leading to anaprop along a cross section through a typical depression. Two cases are shown:

- Over a warm surface when convection lifts and/or disperses the SRLs, reducing the likelihood of anaprop.
- Over a cool surface when there is no convection and therefore the SRLs are at lower levels. This increases the likelihood of anaprop.

Note that there is no anaprop at the fronts themselves. This is based on observational evidence, which suggests that SRLs do not persist through the frontal zone. This is because subsidence ceases at the front, so there are no strong temperature and humidity gradients, therefore no SRL.
4.3.3 Discussion

In a depression with ana-fronts, SRLs are expected in a relatively narrow fringe, some 100–200 km in width, ahead of and behind the surface fronts. The anaprop “footprint” reflects this configuration, with the long distance propagation possible when signals are transmitted parallel to a front, and a decreasing range as the angle between the path and the front increases. The absence of a warm sector SRL means that a depression has two periods of anaprop, separated by the passage of the warm sector. Depending on the distance of the path from the low pressure centre and on the movement and spacing of the fronts, this gap may last as long as 24 hours, or be almost non-existent.

4.4 Kata-type depressions without an Upper Cold Front

In this type of depression there is general subsidence in the warm sector, and no convection above the warm conveyor belt. Anaprop is therefore associated with leading and trailing edge SRLs together with an extended warm-sector SRL.

4.4.1 Structure

A plan of a typical depression of this type is given in figure 4.11. The line AB marks the section shown in figure 4.12. The leading and trailing edge SRLs are the same as those associated with ana-fronts, although it could be argued that the general subsidence throughout the depression enhances the subsidence in the dry zones and thus lowers and strengthens the leading and trailing edge SRLs. The cold front is severely limited in vertical extent, and there is a warm sector SRL at the interface between the top of the WCB and the base of the subsiding air. This SRL rises parallel to the WCB and may extend above the leading edge SRL, as shown in figure 4.12.

4.4.2 Expectations of anaprop

In figure 4.13 we see the expected probability of anaprop along the cross section AB. Once again, warm surface and cold surface cases are shown, and the leading and trailing edge SRLs show the same expectation of anaprop as those for ana-fronts. The warm sector SRL slopes upwards from the left to right so the probability of anaprop falls slowly as this occurs. Since this SRL is at a higher level than the leading and trailing
Figure 4.11. Plan of a typical depression with kata-fronts showing the extent of leading and trailing edge SRLs and warm sector SRLs. The line AB is the section shown in figure 4.12.

Figure 4.12. Cross section along the line AB in figure 4.12 showing airflows (relative to the fronts) and the location of SRLs.
edge SRLs, probabilities of anaprop are lower. At the fronts the SRLs stop so there is a zone with no anaprop and where the warm sector SRL exists above the leading edge SRL it is assumed that only the leading edge SRL will affect signals on surface paths. The warm sector SRL is not affected by the surface temperature, since its height is controlled by the thickness of the warm conveyor belt rather than by convection.

4.4.3 Discussion

A depression with kata-fronts has a greater potential for anaprop than one with ana-fronts. As well as the fringe of leading and trailing edge SRLs, the warm sector SRL allows anaprop over an immense area (a depression is typically 1000 km from north to south and 1000 km wide at the open end). The path-front geometry is still important, since the different heights of the warm sector and edge SRLs mean that signals are not likely to be ducted through the fronts. Anaprop from a depression with kata-fronts could last, with short breaks when the fronts pass, for up to 24 hours if the path is near the open end of the depression.

4.5 Kata-type depressions with an Upper Cold Front

In some cases there may be an upper cold front associated with a depression with kata-fronts. This is due to potential instability in the air at the top of the warm conveyor belt, which, when released, causes convection. The trailing edge of this convection marks the upper cold front. As with normal kata-fronts, there is general subsidence
throughout the warm sector, leading to a warm sector SRL between the cold front and upper cold front, as well as the usual leading and trailing edge SRLs. There is also a high level UCF SRL at the top of the convecting layer ahead of the UCF.

### 4.5.1 Structure

Figure 4.14 shows a plan through a typical depression with an upper cold front, while figure 4.15 shows a typical cross section. The cold frontal zone extends from the surface to an altitude of approximately 3 km, while the upper cold frontal zone extends from about 3 km to 7 km [Browning 1985], depending on the depth of the convection above the WCB. The leading and trailing edge SRLs are similar to the previous cases, while the warm sector SRL is limited to the zone between the surface and upper cold fronts.
Figure 4.15. Cross section along line AB in figure 4.14 showing location of SRLs.

4.5.2 Expectations of anaprop

Figure 4.16 shows the expected probability of anaprop over warm and cool surfaces in a depression with an upper cold front over warm and cold surfaces. Axes as for figure 4.10.

in a depression with an upper cold front. The leading and trailing edge SRLs show the same profiles as the other types of front, but this time the warm sector SRL is limited to the zone between the cold and upper cold fronts. The high level UCF SRL is assumed not to cause any anaprop on surface paths. This is because it is at an altitude of about 7 km, far above any terrestrial path. The probability of anaprop is lower in the warm sector since the warm sector SRL is higher than the edge SRLs (around 3 km compared with 1-2 km). This is in keeping with the effects of inversion height on the probability of anaprop given in the BTL model [Bye 1988a].
4.5.3 Discussion

Since low level (less than 3-4 km altitude) SRLs extend over a smaller area in a kata-type depression with an UCF than in one without, anaprop is a less serious problem than before, although more so than in a depression with ana-fronts. Three separate periods of anaprop are expected, associated with the leading, warm sector and trailing edge SRLs respectively. If the path is near the open end of the depression, there may be a considerable gap between the leading edge and warm sector SRLs while if the path is near the low pressure centre there may be only a short break as the warm front passes. Since all three SRLs are relatively narrow, the path/front geometry is important, with signals transmitted at small angles to the fronts propagating over far longer distances than those transmitted nearly perpendicular to the front.

4.6 Occluded depressions

As a depression becomes occluded, the warm sector is squeezed upwards, leaving a weak occluded front extending down to the surface. The formation of a warm or cold occlusion depends on the relative temperatures of the air masses ahead of and behind the occlusion. If the air behind the occlusion is warmer, it will override the air ahead, lifting the cold front. If the air ahead is warmer, the cold air behind will undercut it, resulting in the warm front being lifted [Figure 4.2]. As a consequence of this, either the leading or trailing edge SRL is lifted considerably, while the other SRL is lifted only slightly (if at all), resulting in anaprop on one side of the front only.

4.6.1 Warm occlusions

In a warm occlusion, air behind the depression is warmer than the air ahead of it. When the warm sector is squeezed out, the trailing airmass rises up the occluded front, which is effectively a weak warm front [Figure 4.17]. The trailing edge SRL has been lifted by the ascending air and is too high to cause anaprop on surface paths. The leading edge SRL has also been lifted slightly, due to the ascent of the cold conveyor belt once it is clear of the WCB [Figure 4.3]. Probabilities of anaprop are therefore lower than for the leading edge SRL ahead of a warm front. The resulting expectations of anaprop over warm and cool surfaces are shown in figure 4.18.
4.6.2 Cold occlusions

In a cold occlusion the situation is reversed. Air behind the occlusion is cooler than the air ahead of it, so the latter is lifted, together with the warm front, and the occluded front is effectively a weak cold front extending to the surface [Figure 4.19]. The leading edge SRL has been lifted considerably, so anaprop is unlikely ahead of the occlusion, while the trailing edge SRL remains at low levels. Unlike the case in a warm occlusion, the trailing edge SRL is unlikely to be higher than at a normal cold front, so the probability of anaprop is not reduced from that for a normal trailing edge SRL. The expected probability of anaprop in a cold occlusion is shown in figure 4.20.
Figure 4.19. Section through a typical cold occlusion showing the location of SRLs.

Figure 4.20. Expected probability of anaprop in a cold occlusion
4.6.3 Discussion

Since the SRLs associated with both types of occlusion are narrow, the path/front geometry is important when considering anaprop. As usual, long range propagation is possible when signals are transmitted parallel to the front.

4.7 Warm sector subsidence

As discussed earlier [Chapter 2], cases of very severe anaprop have been observed when a signal path is in the warm sector of a depression as it skirts the edge of a high. For this reason, the statistical analysis investigated the interactions of fronts and anticyclones and found that, though rare, they gave rise to above average quantities of anaprop. Initially termed 'sporadic subsidence' by BTL [Hewitt et.al. 1981, Bye 1988a], these periods of anaprop appear to occur in the warm sector of a depression and have been renamed 'warm sector subsidence' in this work.

Warm sector subsidence can be considered to be an extreme example of the models of kata-fronts presented here. The large scale subsidence associated with the high pressure system brings the frontal SRLs down to low levels, leading to higher probabilities of anaprop. The dry, warm descending air will increase the strength of the inversion, giving a bigger refractivity lapse rate and thus higher signal levels.

With the overall subsidence, the fronts will almost certainly be kata-type, since the vigourous ascent at ana-fronts will not occur. It is unclear whether upper cold fronts will occur, but it is likely that they will when potential instability is great enough.

It appears that warm sector subsidence is an extreme example of frontal anaprop, and can be explained in terms of the mechanisms identified in this chapter. This helps to confirm the statistical links hypothesized between frontal and anticyclonic-frontal conditions in the previous chapter.
Chapter 5

Refractivity analysis
I—FRONTS’87

One of the most detailed studies of fronts in the last decade was the FRONTS’87 project. This was a series of intensive studies, made by the UK Met Office and the French Meteorological Service, of depressions approaching the south west of England. Data from these studies were made available to the author and have been used to develop and verify the conceptual models presented in the preceding chapter.

This chapter begins with an overview of the project, looking at some of the reasons it was undertaken and at the data it has produced. This is followed by a discussion of the studies selected to verify the models and the data which have been used.

Three case studies follow—of ana and kata cold fronts and of an occlusion. These allow most aspects of the conceptual models to be verified, with the exception of warm fronts (although these are, to a certain extent, considered with occlusions). In each case an attempt is made to partially quantify the qualitative models.

5.1 The FRONTS’87 Project

The FRONTS’87 project has provided some of the most detailed studies of fronts in recent years. It forms the observational element of the Mesoscale Frontal Dynamics Project (MFDP), which, in turn, forms the British contribution to a larger European programme on mesoscale meteorology [Clough 1987, Clough & Testud 1988].
MFDP has three specific objectives [*ibid.*]:

- To obtain an improved dynamical understanding of synoptic, mesoscale and smaller-scale interactions within cold-frontal systems.
- To acquire mesoscale data sets and use them for the further development of numerical models.
- To describe the structure and evolution of mesoscale features in cold fronts and to derive conceptual models of value in nowcasting.

Preparations for the projects began in 1985, and the observations were made during the winter of 1987-8, with a full analysis of the results expected to take several more years.

### 5.1.1 The field experiment

As stated above, FRONTS'87 was the field experiment to provide data for the MFDP. It was decided to concentrate on fronts approaching the English Channel from the Atlantic, to make full use of the various sources of data and also to allow dropsondes to be used over as large an area as possible. Use of a sea area also reduced topographic effects [Clough 1987]. To achieve the aim of studying interactions between different scales, data had to be obtained at all these scales. This was achieved by defining three nested zones in the observational area [Fig 5.1]:

- **An outer zone**, covering most of England, Ireland and France. Within this area, routine observations, supplemented by some extra radiosonde ascents at 6 hourly intervals, provided the data needed to study the synoptic scale.

- **An inner zone**, covering south-west England and north-west France. Here a number of special radiosonde sites, with ascents made every three hours, were set up to provide mesoscale data. In the western part of this zone an aircraft operations area was defined. Here the MRF (Meteorological Research Flight) Hercules was used to provide dropsonde profiles through the front.

- **A central area**, around a number of radar and sodar installations in Brittany. Together with surface observations, sonde ascents at 90 minute intervals and airborne observations, this area was the main source of data on small scale structures and processes.
5.1.2 The Intensive Observational Periods

Since it was expected that a front would take about 24 hours to cross the outer zone, the FRONTS'87 programme was divided into a number of Intensive Observational Periods (IOPs). These each lasted for 36 hours, after which special data collection ceased. Since aircraft operations required some advance notice, IOPs had to be identified some 48 hours before data collection started. This was done on the basis of numerical forecasts (in the UK and in France). The forecasts were used to identify the approximate location of the front, which was then refined as the IOP began and more detailed data became available.

In all, eight IOPs were selected, spread over a three month period from October 1987 to January 1988 [Table 5.1].

The fifth IOP was aborted when the main radar in Brittany became unservicable. Data were still obtained from the radiosondes but aircraft operations were cancelled. During the sixth IOP no dropsonde observations were made due to Air Traffic Control problems. For further details on the data collected and the movement of the fronts, refer to Machin [1988].

Figure 5.1. The FRONTS'87 experiment area showing the zones referred to in the text. See legend for an explanation of symbols. [From Clough 1987]
Table 5.1. The FRONTS'87 Intensive Observational Periods [Machin 1988]

<table>
<thead>
<tr>
<th>IOP No.</th>
<th>Start</th>
<th>End</th>
<th>Type of Front</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18/10/87</td>
<td>20/10/87</td>
<td>Ana-cold</td>
</tr>
<tr>
<td>2</td>
<td>11/11/87</td>
<td>12/11/87</td>
<td>Ana-cold</td>
</tr>
<tr>
<td>3</td>
<td>19/11/87</td>
<td>20/11/87</td>
<td>Ana-cold</td>
</tr>
<tr>
<td>4</td>
<td>13/12/87</td>
<td>14/12/87</td>
<td>Warm Occlusion</td>
</tr>
<tr>
<td>5</td>
<td>17/12/87</td>
<td>aborted</td>
<td>Ana-cold</td>
</tr>
<tr>
<td>6</td>
<td>5/1/88</td>
<td>6/1/88</td>
<td>Ana-cold</td>
</tr>
<tr>
<td>7</td>
<td>9/1/88</td>
<td>10/1/88</td>
<td>Ana-cold</td>
</tr>
<tr>
<td>8</td>
<td>12/1/88</td>
<td>13/1/88</td>
<td>Kata-cold</td>
</tr>
</tbody>
</table>

5.1.3 Instruments

Details of the instruments used are given in the works cited above [Clough 1987. Clough & Testud 1988, Machin 1988]. The main instrument of interest in this work is the NAVAID Dropsonde, developed by the UK Met Office in the late 1970's specifically for projects like FRONTS'87 [Ryder et.al. 1983]. The sonde makes the same measurements as a conventional radiosonde—pressure, temperature and humidity, as well as wind through tracking of the sondes position. The sonde, weighing 3.5 kg, has a parachute to limit the fallspeed to 12 ms⁻¹. Careful design of the parachute ensures that the sonde does not ‘fly’ relative to the air it is falling through, so any horizontal motion is due solely to the wind [ibid.]. Position determination using the LORAN navigational aid allows wind velocities to be measured to an accuracy of about 1 ms⁻¹ over the entire North Atlantic.

Temperature is measured by a thermistor (with a time constant of 1s) to an accuracy of less than 0.5°C. Humidity is measured using a carbon hygristor, accurate to ±5% over the range 30% to 95% [ibid.]. Pressure is measured, to an accuracy of ±0.2 mb, by an integrated circuit pressure transducer. Readings are made at approximately 1 second intervals, giving a vertical resolution of about 10 m.

Data are received by the MRF Hercules and recorded by an onboard computer system. The aircraft can carry up to 80 sondes and has the facility to receive data from up to five sondes simultaneously, an important feature when drops are being made every 20-30 km [ibid.].
5.2 Radio-Meteorological Studies

Since the MFDP did not examine the refractivity structure of the FRONTS'87 data, the Met Office were happy to supply Edinburgh University with the entire FRONTS'87 dataset for refractivity research\(^1\). The dataset included dropsondes, radiosondes and mesoscale model data, but it was decided at the beginning that the dropsonde data should be the primary source. To study the widest possible range of conditions, three IOPs were selected for analysis. These were:

- IOP 7, to examine an ana-type (rearwards sloping) cold front.
- IOP 8, to examine a kata-type (split, or forwards sloping) cold front.
- IOP 4, to examine an occlusion and, to a lesser extent, a warm front.

No studies were possible for IOPs 5 and 6, since no dropsonde observations were made, and IOPs 1–3 had less data available than IOP 7, so they were rejected as ana-front studies.

5.2.1 Data Processing

All the data were supplied on magnetic tape which was read into the Edinburgh University EMAS system and then transferred to the Meteorology Department's UNIX network. Data were supplied in a coded format with one file per drop, a total of 206 files from all the IOPs. Initial processing—to extract height, pressure, temperature and humidity—was then carried out.

It was initially decided that only four quantities were required for the analysis, to which a fifth was later added. They are:

- The Potential Refractivity, \( K \), calculated as shown below.

\[
K = 77.6 \frac{1000}{\theta} + 3.73 \times 10^5 \frac{e_0}{\theta^2} \quad (5.1)
\]

where \( \theta \) is the potential temperature (defined in equation 5.7).

\( e_0 = e(1000/P) \) (P is the pressure in mb) and \( e \) is given by:

\(^1\)The author would like to take this opportunity to thank Drs S Clough and J McKay for their help in supplying and decoding the data. Without their assistance none of the FRONTS'87 work would have been possible.
Potential refractivity is the main quantity used to verify the conceptual models.

- The Refractivity, $N$, given by:
  \[ N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \]  
  where $P$ is the pressure (in mb), $T$ is the temperature (in K) and $e$ is the vapour pressure in mb (as defined above).

- The Equivalent Potential Temperature, $\theta_e$, given by:
  \[ \theta_e = \theta + 2.45r \]  
  where:
  \[ r = \frac{5}{8} \frac{e}{p} \times 1000 \]

- The Potential Temperature, $\theta$, given by:
  \[ \theta = T \left( \frac{1000}{P} \right)^{0.286} \]

- The Dewpoint Depression, $T - T_d$, where $T_d$ is given by:
  \[ T_d = \frac{237.3 \alpha}{1 - \alpha} \]  
  and:
  \[ \alpha = \frac{\ln \left( \frac{e}{6.11} \right)}{17.27} \]  

This quantity was selected to aid in the location of fronts by indicating the location of clouds and dry air.

The distance of each drop along the run was calculated from the plots given by Machin [1988], with positions accurate to ±3km. No account was taken of the movement of the sondes due to the wind. This was because the horizontal displacements were relatively
small (less than 10 km) and determining the exact position of the sonde at any height would have required a vast amount of additional data processing. Instead it is assumed that the sondes fell vertically.

Each IOP was divided into a number of runs, typically four, with the first to locate the exact position of the front, and the remainder to gather more useful data. Processed data for all the drops during a run were merged into a single file for contouring. For this purpose, it was assumed that all drops on a run occurred at the same time, instead of over a period of about 1 hour. Ideally each drop would have been related to the position of the front when the drop was made but this was not possible since the contour plots were used to locate the front. This, together with the earlier assumption about vertical descent, gives horizontal distances an inaccuracy of at most 20 km.

Contouring was performed on the departmental UNIX network, using the UNIRAS package. The effectiveness of the interpolation routines was assessed by comparison with plots produced by the Met Office [Machin 1988]. Such a comparison, between the $\theta_e$ profiles for IOP 8 Run 3 is shown in figures 5.2 & 5.3. Ignoring the differences in scale and the different contour values, it is clear that the computer analysis is very close to the human interpretation. This, and similar examples, were taken as verification that the interpolation routines were suitable for this work. With the exception of IOP 4 Run 1 (omitted since three drops did not provide enough data for the interpolation process), charts of the five quantities were produced for each run in the three selected

Figure 5.2. Met Office analysis of $\theta_e$ structure along Run 3 of IOP 8. Isopleths are at 2°C intervals. Distances along run and approximate heights have been added to aid comparison. [From Machin 1988]
The process of contouring can both hide and exaggerate features in the original data. Since super-refractive layers can be very thin, they can be lost between isopleths. Equally, close packed isopleths may suggest the refractivity gradient is greater than it actually is. To attempt to overcome these problems, some care was taken in the location of SRLs on the sections. SRLs were located using the refractivity (N) data rather than the potential refractivity (K) and attempts were made to check subjective analyses. Initially SRLs were located by eye and their existence checked by examining tabulated refractivity gradients (dN/dx) for individual drops. Because this was a very time-consuming process, not all drops could be checked, but the author feels that the SRLs shown on the profiles are a good approximation to the real structure. The table below shows those runs (not drops) for which calculations of dN/dx were made:

<table>
<thead>
<tr>
<th>Run 1</th>
<th>IOP 7</th>
<th>IOP 8</th>
<th>IOP 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2</td>
<td>Most drops</td>
<td>Some</td>
<td></td>
</tr>
<tr>
<td>Run 3</td>
<td>Most drops</td>
<td>Some</td>
<td>None</td>
</tr>
<tr>
<td>Run 4</td>
<td>Some drops</td>
<td>Some</td>
<td>None</td>
</tr>
</tbody>
</table>

It is the opinion of the author that the potential refractivity profiles that follow show the location of major SRLs accurately. It is probable that small SRLs exist which are not shown, but this should not diminish the validity of the analysis nor the conclusions.
Figure 5.3. Analysis of $\theta_e$ structure along Run 3 of IOP 8 produced by UNIRAS contouring routines. Horizontal scale is distance (in km) from the Western end of the run, vertical scale is the altitude in m. Isopleths are at 2 K intervals, fronts have been added based on Met Office analysis.

IOPs.

Analysis concentrated initially on the location of frontal zones, cloudy regions and intrusions of dry air. The last two were determined by the plots of dewpoint depression, cloud was assumed where this was less than 2°C while a dry intrusion was expected where it exceeded 6°C. Analysis to locate frontal zones from the $\theta_e$ plots was performed (separately) by Dr Keith Weston and by the author and close agreement was generally obtained. Where other information on the vertical structure of the fronts was available (for example in Machin [1988]), this was used to guide the analysis. After this initial stage, the fronts were plotted on the Potential Refractivity profiles and these were interpreted in terms of the conceptual models.

5.3 IOP 7 Case Study

This IOP examined a typical example of an ana-type cold front, approaching the observation area from the North-West. The period began at 0001Z on 9/1/88 and ended, 36 hours later, at 1200Z on 10/1/88. The positions of the surface front for the first half of this period are shown in fig 5.12. Four dropsonde runs were made [Table 5.21 and are shown on fig 5.12 later in this section.
Table 5.2. IOP 7 Dropsonde runs [Machin 1988]

<table>
<thead>
<tr>
<th>Run</th>
<th>Direction</th>
<th>Drops</th>
<th>Start time</th>
<th>Finish time</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SE–NW</td>
<td>10</td>
<td>0722</td>
<td>0831</td>
<td>24000 ft</td>
</tr>
<tr>
<td>2</td>
<td>NW–SE</td>
<td>7</td>
<td>0848</td>
<td>0955</td>
<td>26000 ft</td>
</tr>
<tr>
<td>3</td>
<td>SE–NW</td>
<td>19</td>
<td>1024</td>
<td>...</td>
<td>26000 ft</td>
</tr>
<tr>
<td>4</td>
<td>NW–SE</td>
<td>11</td>
<td>1202</td>
<td>1306</td>
<td>26000 ft</td>
</tr>
</tbody>
</table>

5.3.1 Run 1

The $\theta_e$ structure along this run is shown in fig 5.4, together with the position of the front and dry and moist regions. The rearward slope of the front is clearly visible, as is the tongue of dry air descending behind it. This was also visible on the Meteosat Water Vapour image of the front [Machin 1988].

The potential refractivity structure [Fig 5.5] reflects the $\theta_e$ structure. The effects of the dry air can clearly be seen in the descent of the isopleths behind the frontal zone, with a trailing edge SRL (AA in figure) some 60-80 km wide immediately behind the front. This SRL, at an altitude of about 600 m has a strong refractivity lapse of about 100 N-units/km. The layer slopes (about 800 m in 100 km) and weakens with distance from the front, as expected from the conceptual model [Fig 4.9].

5.3.2 Run 2

Here the situation is similar to the previous run. The front again slopes rearwards, with a deep moist zone marking the line convection at the surface front expected from the meteorological models [Browning 1985]. This is shown in figure 5.6.

The potential refractivity structure is shown in figure 5.7. Again there is clear evidence of the subsidence-induced trailing edge SRL (AA on figure), but this time at around 1500 m altitude between 100 and 300 km behind the surface front, with a strength of about 100 N-units/km. Nearer the front a weaker SRL is found at the 500 m level (BB on figure) but it is not clear whether the layer slopes from one to the other. Again this is broadly in keeping with the model.
Figure 5.4. Equivalent potential temperature section along IOP 7 Run 1 (isopleths at 2 K intervals). Horizontal scale is distance (in km) from NW end of run, vertical scale is altitude (in m). Approximate location of the frontal zone, moist and dry air are also shown.

Figure 5.5. Refractivity structure along IOP 7 Run 1. Scales and position of frontal zone as in Fig 5.4, isopleths at 5 K-unit intervals. Features referred to in text marked. Dashed lines indicate position of drops.
Figure 5.6. $\theta_e$ structure along IOP 7 Run 2. Scales and contours as in Fig 5.4. Frontal zone, dry and moist regions as indicated.

Figure 5.7. Refractivity structure along IOP 7 Run 2. Scales and position of frontal zone as in Fig 5.4, isopleths at 5 K-unit intervals. Features referred to in text marked.
5.3.3 Run 3

With 19 sondes along this run, the profiles are considerably more detailed than the previous two runs. The $\theta_e$ profile [Fig 5.8] shows dry air descending to very low levels (sometimes below 1 km) behind the front and the moist convection at the surface front is also clear.

The potential refractivity [Fig 5.9] shows the trailing edge layer (AA, BB and CC) on at levels between 500 m (near the front) to 1500 m (300-400 km behind the front). Again it is difficult to see whether the layer slopes or is in a number of segments (this may be an artefact of the interpolation process). The layer appears to be dispersed near the 200 km point, possibly due to an area of more vigorous convection than usual. This also appears on the $\theta_e$ profile as a bulge on the top of the moist layer and along the 293 K isopleth. Again the refractivity structure is in broad agreement with the models.

5.3.4 Run 4

On this run the $\theta_e$ profile [Fig 5.10] is similar to the earlier runs. Again there is a moist layer of convective cloud above the surface front and an extensive dry region behind the frontal zone. On the potential refractivity profile [Fig 5.11] the trailing edge SRL is clearly visible (AA on figure), extending for some 300 km behind the surface front, at a level of about 1000 m. Again there is evidence in the refractivity of the subsidence behind the front and ascent at it. Once again this is broadly in keeping with the conceptual models.

5.3.5 Summary

All four runs showed SRLs behind the cold front. Their positions (relative to the front at 09Z) are shown in figure 5.12, which also shows the dropsonde runs. To show the SRLs in more detail, figure 5.13 combines the SRLs for all four runs and, for comparison, shows the relevant parts of the conceptual model of frontal anaprop.

There is clear evidence of the trailing edge SRL, although far broader than the 100 km that the model assumes. The SRL appears to have a strength of 100 N-units/km or more and to range from 500 to 1500 m altitude, somewhat lower than the model assumed. The slope of the SRL has not been confirmed—while there is some evidence for a gradient of about 1:100 from Run 1, the other runs do not confirm this. As
Figure 5.8. $\theta_e$ structure along IOP 7 Run 3. Scales and contours as in Fig 5.4. Position of front, dry and moist regions shown.

Figure 5.9. Refractivity structure along IOP 7 Run 3. Scales and position of frontal zone as in Fig 5.4, isopleths at 5 K-unit intervals. Features referred to in text marked.
Figure 5.10. $\theta_e$ structure along IOP 7 Run 4. Scales and contours as in Fig 5.4.

Figure 5.11. Refractivity structure along IOP 7 Run 4. Scales and position of frontal zone as in Fig 5.4, isopleths at 5 K-unit intervals. Features referred to in text marked.
Figure 5.12. IOP 7 dropsonde runs and frontal positions. Positions of the front at 3 hour intervals are shown, together with the aircraft run and drop points [after Machin 1988]. Positions and altitude of SRLs shown on each run relative to the front at 07Z.

Figure 5.13. (a) SRLs observed during IOP 7, giving position and height of each SRL (b) conceptual model of an ana front.
indicated earlier, this may be due to the interpolation process.

As a result of this analysis, it appears that the model could be amended to give a trailing edge SRL, with a constant refractivity lapse of 100 N-units/km, extending from an altitude of 500-750 m immediately behind the surface front to 1500 m at a distance of 300 km behind the surface front.

5.4 IOP 8 Case Study

This IOP examined a kata-type cold front, approaching the observation area from the West. Since FRONTS'87 concentrated on active cold fronts (normally ana-type), this front does not exactly follow the Browning model of a kata-cold front, but it is close enough to the ideal to allow the conceptual models to be tested reasonably. The IOP began at 0600Z on 12/1/88 and ended at 1800Z on 13/1/88. The positions of the surface front at 6 hour intervals are shown in figure 5.22 later in this section, as are the four dropsonde runs, with further details given in table 5.3.

<table>
<thead>
<tr>
<th>Run</th>
<th>Direction</th>
<th>Drops</th>
<th>Start time</th>
<th>Finish time</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E-W</td>
<td>6</td>
<td>1719</td>
<td>1811</td>
<td>24-26000 ft</td>
</tr>
<tr>
<td>2</td>
<td>W-E</td>
<td>9</td>
<td>1833</td>
<td>1930</td>
<td>26000 ft</td>
</tr>
<tr>
<td>3</td>
<td>E-W</td>
<td>18</td>
<td>1955</td>
<td>2143</td>
<td>26000 ft</td>
</tr>
<tr>
<td>4</td>
<td>W-E</td>
<td>6</td>
<td>2220</td>
<td>2321</td>
<td>26000 ft</td>
</tr>
</tbody>
</table>

5.4.1 Run 1

This run was planned to locate the front, so ended almost as soon as this was done. As a result the front is very close to the western end of the run and little detail behind the front is visible. The Equivalent Potential Temperature section is shown in figure 5.14, together with the approximate location of the frontal zone and the dry and moist regions. At this point on the front there is little evidence of the large scale subsidence in the warm sector that characterises a kata-type depression.

The potential refractivity structure [Fig 5.15] is relatively uniform ahead of the frontal zone but there is some evidence of subsidence and the presence of a trailing edge.
Figure 5.14. Equivalent potential temperature section along IOP 8 Run 1 (isopleths at 2 K intervals). Horizontal scale is distance (in km) from W end of run, vertical scale is altitude (in m). Approximate location of the frontal zone, moist and dry air are also shown.

Figure 5.15. Refractivity structure along IOP 8 Run 1. Scales and position of frontal zone as in Fig 5.14, isopleths at 5 K-unit intervals. Features referred to in text marked.
SRL behind the front (AA on figure). There is not really enough information for a quantitative analysis, however.

5.4.2 Run 2

On this run the $\theta_e$ structure [Fig 5.16] shows the split structure of the front clearly. The frontal zone extends from the surface to about 4000m, somewhat higher than expected, but in keeping with the active nature of the front.

The Potential refractivity structure [Fig 5.17] shows a trailing edge SRL (with a strength of about 70 N-units/km) immediately behind the surface cold front (AA), extending some 150 km to the rear. Whether the layer is sloped or not is not clear from the analysis. Between the surface and the upper cold front there is some evidence of a weak SRL (BB) at an altitude of about 3500m. This is in the correct position for the UCF SRL expected from the model.

5.4.3 Run 3

This is the most detailed run, and most clearly shows the split nature of the cold front, as well as a warm front [Machin 1988]. This is shown in the $\theta_e$ section [Fig 5.18]. The location of fronts have been taken from the Met Office analysis shown in figure 5.2. Now the surface cold front is limited to the lowest 1000 m, with an UCF extending to 6000 m. The warm front is also visible on the analysis as an intrusion of cold air ahead of the warm sector. Three regions of major subsidence are visible, as expected from the models.

The refractivity structure [Fig 5.19] also shows the features expected in the model. Subsidence behind the surface cold front results in a very strong trailing edge SRL at about 1200m (AA). Refractivity gradients exceed 200 N-units/km, indicating fully developed ducting and the layer is some 150 km wide. There is also evidence of a weak warm sector SRL (BB) and of a weak high level UCF SRL (CC). This profile agrees closely with those expected from the models.
Figure 5.16. $\theta_e$ structure along IOP 8 Run 2. Scales and contours as in Fig 5.14. Frontal zone, dry and moist regions as indicated.

Figure 5.17. Refractivity structure along IOP 8 Run 2. Scales and position of frontal zone as in Fig 5.14, isopleths at 5 K-unit intervals. Features referred to in text marked.
Figure 5.18. $\theta_e$ structure along IOP 8 Run 3. Scales and contours as in Fig 5.14. Position of front (taken from the Met Office analysis [Machin 1988]), dry and moist regions shown.

Figure 5.19. Refractivity structure along IOP 8 Run 3. Scales and position of frontal zone as in Fig 5.14, isopleths at 5 K-unit intervals. Features referred to in text marked.
5.4.4 Run 4

This run is somewhat less detailed than the two preceding it, but still there is useful information to be obtained. The $\theta_e$ section [Fig 5.20] clearly shows the surface cold front and the warm front, although the position of the upper cold front is less obvious. The warm sector is about the same width as in Run 3 (it is interesting to note that the synoptic charts [Fig 5.22] do not show the warm front although the sections produced by the Met Office do).

The refractivity structure [Fig 5.21] shows a very strong leading edge SRL (AA) at an altitude of about 500 m, beginning some 50 km ahead of the surface warm front and extending for at least 100 km (after which it runs off the chart). Refractivity gradients are in excess of 100 N-units/km. There is also evidence of a weaker trailing edge SRL (BB) at about 2000 m altitude, stretching for some 100 km behind the surface cold front. Warm sector and UCF SRLs are not observed.

5.4.5 Summary

Figure 5.22 shows the position and height of all the SRLs relative to the front at 18Z, as well as the dropsonde runs. All four runs show SRLs behind the surface cold front, while two runs show SRLs ahead of the front [Fig 5.23].

Once again, the data from this IOP are in good agreement with the conceptual models. The trailing edge SRL is clearly visible along the length of the front, although considerably narrower (about 100-150 km) than at an ana-front. This is possibly due to the forward slope of the front which does not act as a 'lid' on convection in the way that the rearward-sloping ana-cold front does. The strength of the trailing edge SRL seems to be slightly greater than at an ana-cold front, probably due to the greater amount of subsidence. The height of the trailing edge layer is more variable this time, ranging between 500 m and 2 km instead of around 500 m. Two examples are not enough to say which is more typical. The leading edge SRL has also been observed, at very low levels (less than 500 m). The expected gap between the surface warm front and the leading edge layer has also been observed but there is not really enough data to quantify the feature. As before, it is not clear whether the leading and trailing edge SRLs are sloped.

There is less good evidence for the warm sector and UCF SRLs. Subsidence induced descent of the refractivity isopleths is seen in most profiles but it is not obvious whether
Figure 5.20. $\theta_e$ structure along IOP 8 Run 4. Scales and contours as in Fig 5.14.

Figure 5.21. Refractivity structure along IOP 8 Run 4. Scales and position of frontal zone as in Fig 5.14, isopleths at 5 K-unit intervals. Features referred to in text marked.
Figure 5.22. IOP 8 dropsonde runs and frontal positions. Positions of the front at 6 hour intervals are shown, together with the aircraft runs and drop points [after Machin 1988]. Position and altitude of SRLs shown relative to front at 18Z.

Figure 5.23. (a) Summary diagram showing position and altitude of SRLs for IOP 8. All distances are shown relative to the surface front (b) conceptual model of kata-fronts.
the isopleths are packed together to give a super-refractive layer. This suggests that SRLs in the warm sector of a depression are weak and so not likely to be a significant cause of anaprop.

5.5 IOP 4 Case Study

IOP 4 was the only one to study an occluded front—a warm occlusion approaching the observation area from the South-West. The IOP began at 0001Z on 13/12/87 and ended at 1200 on 14/12/87. The positions of the surface front at 6 hour intervals, together with the dropsonde runs, are shown later in this section [Fig 5.30] Four runs were made [Table 5.4] of which the last was a zig-zag profile across the front [Fig 5.30].

<table>
<thead>
<tr>
<th>Run</th>
<th>Direction</th>
<th>Drops</th>
<th>Start time</th>
<th>Finish time</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NE–SW</td>
<td>4</td>
<td>1431</td>
<td>1500</td>
<td>24000 ft</td>
</tr>
<tr>
<td>2</td>
<td>SW–NE</td>
<td>7</td>
<td>1519</td>
<td>1614</td>
<td>26000 ft</td>
</tr>
<tr>
<td>3</td>
<td>NE–SW</td>
<td>13</td>
<td>1628</td>
<td>1720</td>
<td>26000 ft</td>
</tr>
<tr>
<td>4</td>
<td>SW–NE</td>
<td>9</td>
<td>1739</td>
<td>1940</td>
<td>26000 ft</td>
</tr>
</tbody>
</table>

For the purposes of this analysis this has been converted to a straight run, with drops at appropriate positions along the mean line of the run, as shown in figure 5.30. Since there were only three datafiles for Run 1, not giving enough points for the interpolation to be successful, this run was not analysed.

5.5.1 Run 2

On this profile the cold front aloft is clearly defined, with the warm front near the surface less well so [Fig 5.24]. Since the main aim of the research was to study cold fronts this is to be expected. Dry air subsiding behind the cold front is clearly visible but subsiding air ahead of the warm front is not observed.

The potential refractivity structure [Fig 5.25] shows the effects of this subsidence in an elevated trailing edge SRL at around 2 km altitude, as expected from the model.
Figure 5.24. Equivalent potential temperature section along IOP 4 Run 2 (isopleths at 2 K intervals). Horizontal scale is distance (in km) from NW end of run, vertical scale is altitude (in m). Approximate location of the frontal zone, moist and dry air are also shown.

Figure 5.25. Refractivity structure along IOP 4 Run 2. Scales and position of frontal zone as in Fig 5.24, isopleths at 5 K-unit intervals. Features referred to in text marked.
5.5.2 Run 3

Once again the cold front aloft is the main feature of the $\theta_e$ profile [Fig 5.26] although the warm front near the surface can also be seen. Again there is subsidence behind the cold frontal zone.

The refractivity profile [Fig 5.27] is very similar to the previous run, although somewhat more detailed due to the greater number of dropsondes providing data. The elevated trailing edge SRL is at about 1500-2500 m altitude (AA) and about 100 km in width. The abrupt descent of the low level isopleths beneath the warm frontal zone is possible evidence for a leading edge SRL but the run ends before this can be confirmed.

5.5.3 Run 4

On this run the $\theta_e$ profile [Fig 5.28] shows the cold front aloft clearly but the warm front is beyond the eastern edge of the chart. Moist convective air immediately ahead of the front and dry subsiding air behind it are clearly seen.

The refractivity profile [Fig 5.29] shows two main super-refractive layers. One (AA) is immediately behind the cold front, at about 2500 m altitude and with a width of about 100 km. This is likely to be an elevated trailing edge SRL. Some 200 km further back there is a narrower SRL (BB) at about the same altitude. This may be associated with a shallow cold front shown on the Met Office analysis [Machin 1988].

5.5.4 Summary

Figure 5.30 shows the positions of all SRLs observed during IOP 4 relative to the front at 18Z. Figure 5.31 shows the positions of all SRLs and compares them with the relevant sections of the conceptual model.

The data from this IOP goes part of the way towards confirming the conceptual model of a warm occlusion. The elevated trailing edge SRL appears as expected, at an altitude of around 2500 m and with a width of about 100 km. The leading edge SRL is not observed through lack of data, so there is no evidence to disprove its presence. All in all the data are easily fitted into the model's framework.
Figure 5.26. $\theta_e$ structure along IOP 4 Run 3. Scales and contours as in Fig 5.24. Position of front, dry and moist regions shown.

Figure 5.27. Refractivity structure along IOP 4 Run 3. Scales and position of frontal zone as in Fig 5.24, isopleths at 5 K-unit intervals. Features referred to in text marked.
Figure 5.28. $\theta_e$ structure along IOP 4 Run 4. Scales and contours as in Fig 5.24.

Figure 5.29. Refractivity structure along IOP 4 Run 4. Scales and position of frontal zone as in Fig 5.24, isopleths at 5 K-unit intervals. Features referred to in text marked.
Figure 5.30. IOP 4 dropsonde runs and frontal positions. Positions of the front at 6 hour intervals are shown, together with the aircraft runs and drop points [after Machin 1988]. Positions and altitudes of SRLs shown relative to the front at 18Z.

Figure 5.31. (a) Summary of SRLs from IOP 4 showing altitude and position. All distances are relative to the surface front (b) Section of conceptual model of warm occlusion.
5.6 Discussion

The FRONTS’87 project has proved an invaluable source of data for this research. The data allows the refractivity structure around cold fronts to be studied in far more detail than conventional radiosonde ascents would allow, both in the horizontal, with dropsondes every 20–100 km compared with a minimum of 200 km between radiosondes, and in the vertical, with readings every 10 m compared with 500-1000 m for smoothed radiosonde data.

Since the FRONTS’87 project concentrated on the structure of active cold fronts it was not possible to verify all the models. However, a large amount of evidence supporting certain features of the conceptual models has been gathered, which goes a long way to suggest that the other, important, features are indeed correct. The FRONTS’87 data has also allowed a certain amount of quantification of the (previously only qualitative) models, although there is still a long way to go on this front.

The main finding from the FRONTS’87 dataset has been confirmation of the existence of the trailing edge SRL, together with some indications of its height and strength. It was found that the layer is considerably wider when the front is ana-type than when a kata-front is present, but the strength remains similar, at about 100 N-units/km, indicating a strongly super-refractive layer. The difference in width appears to be due to the rearwards slope of the ana-cold front acting as more of a limit to convection than the forward sloping kata-cold front. In the latter case only the subsiding air acts to limit the vertical extent of convection while in the former case both the front and the subsiding air limit convection.

The study of a kata-cold front failed to show strong warm sector and UCF SRLs, although there was evidence for a slightly super-refractive atmosphere. Since the models did not predict the strength of the layers and also since the front was an ‘active’ one, this may be a feature of the front rather than a major flaw in the models. Evidence supporting a leading edge SRL was seen, with the gap between the layer and the surface front visible. The study of the occlusion was not able to confirm the presence of a low level leading edge SRL (due to lack of data). The trailing edge layer was found to be higher than usual for a cold front, as expected from the models.

As has been mentioned before, the FRONTS’87 analysis has not contradicted any features in the models, although not all the features have been observed. Possible extensions to this work would include the analysis of detailed data from other programmes to study warm fronts and occlusions in greater detail.
Chapter 6

Refractivity analysis II—Gt
Baddow

Although the previous chapter [5] has provided much evidence supporting the conceptual models of frontal radio-meteorology [chapter 4], there has not yet been any examination of the signals produced when a front intersects a path. This chapter attempts to remedy that. Detailed signal data have been obtained for an experimental path in south east England, together with routine surface and upper air observations. This has provided the information for an extended case study of signals and weather for a three month period in summer 1989. Two types of analysis have been made:

- A simple correlation of time series signal data with the position of the surface front as it approaches, crosses and recedes from the path.
- A more detailed comparison of signal time series with potential refractivity profiles derived from radiosonde ascents.

Use of routine weather observations to identify periods of frontal anaprop was of lead to ways of using forecast data (either surface or upper air) to make short range predictions of anaprop associated with fronts.

The chapter begins with a survey of the signal path, the meteorological data available and some of the reasons for the choice of path and dates. This is followed by a short examination of the data processing. The signals produced by different types of fronts are considered in an attempt to find characteristic 'signatures' of frontal anaprop. Finally some examples of refractivity sections and their relation to signals are examined.
6.1 Sources of Data

When it was decided that an attempt should be made to link the conceptual models to signal behaviour, it was clear that the hourly summaries supplied for the statistical analysis would not be sufficient. BTL were approached and agreed to supply time series data collected as part of the COST 210 project. This information, in the form of 10 second averages of signal levels recorded once per second, could be supplied on disk. Data of this type were only available for a limited number of paths, and most easily available for a coastal path in SE England, the Martlesham Heath–Great Baddow path\(^1\). BTL therefore supplied the author with data for a three month period (July to September 1989).

The Gt Baddow path is officially classified as coastal type according to the CCIR definition. It is just over 66km long, running from Gt Baddow (in Essex) to Martlesham Heath (in Suffolk). The path is shown in figure 6.1 together with a section showing terrain along it. Transmitter and receiver are at such a height that a direct line of sight exists under normal atmospheric conditions.

Weather data for the analysis were in the form of 6 hourly “Daily Weather Report” charts, purchased from the Met Office. These provided surface analyses and some upper air information, as well as a satellite image that occasionally proved useful when locating fronts. In addition, the 12 hourly radiosonde ascents, plotted on tephigrams, were obtained from the weather facsimile broadcasts put out by the Met Office. These upper air charts, considered vital to the project, were only available from late June 1989.

BTL had notified the author that “the summer of 1989 was a particularly good time for anomalous propagation”\(^2\), so it was decided to use signal data for a three month period, starting almost as soon as upper air data were available. July, August and September 1989 were therefore selected as suitable and signal data were sent to the author.

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\(^1\)It was hoped that data could be obtained for a longer sea/land path from Köln (in what was then West Germany) to Martlesham Heath or from the sea/coastal Eindhoven–Martlesham path. This, however, proved impossible.

\(^2\)Presumably this means that it was a bad time for anaprop on operational networks, but good for the experimental ones!
6.2 Data analysis

Weather data for the three month period were available from the Daily Weather Report, which included synoptic charts for midnight, 0600, 1200 and 1800 GMT, and from tephigrams (for midnight and 1200 GMT) received by fax from the Met Office. Signal data were received from BTL on disc, with a separate file for each day's signals. These gave 8640 values, each an average signal level for a 10 second period, for each day.

6.2.1 Signal data analysis

To reduce the size of the data files, the signals were processed to give mean, maximum and minimum levels for every five minutes throughout the day. This reduced each day's data to 288 records and made graphs much easier to interpret, as well as speeding up data processing and analysis. Because the weather charts were every six hours, the change from 10 second to 5 minute averages did not affect the results.
6.2.2 Weather data analysis

The weather data were analysed several times during the course of this research. Each examination had different goals and used the previous analyses as a starting point.

An initial analysis used the same classification scheme as the statistical results produced for chapter 3 of this thesis. The aim was to identify the times fronts were recorded over the signal path, as well as their type. The table below [6.1] shows the number of fronts affecting the Gt Baddow path, July—September 1989.

<table>
<thead>
<tr>
<th>Type of Front</th>
<th>Code</th>
<th>No. of ‘F’ cases</th>
<th>No. of ‘AF’ cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Front Perpendicular (A) F1</td>
<td>1</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Cold Front Parallel (A) F2</td>
<td></td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td>Warm Front Perpendicular (A) F3</td>
<td></td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Warm Front Parallel (A) F4</td>
<td></td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Occluded Front Perpendicular (A) F5</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Path in Warm Sector (A) F9</td>
<td></td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Path cuts 2 fronts (F0)</td>
<td></td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

chairs that showed each type of front over or near the path. (See chapter 3 for more information on the classification scheme.)

The second stage of the analysis looked in more detail at the passage of fronts over the path. By looking at the position of surface fronts on a sequence of DWR charts, the movement of the front could be determined. This required a number of assumptions to be made.

- The position and type of fronts on the DWR charts is correct. This is not always the case, since some sequences of charts show a front changing from occluded to cold or warm as the analysts change shift, but it is a necessary assumption for this work. If other forms of data had been available, ‘suspect’ charts would have been re-analysed, but no such data could be obtained.

- The width of the surface front is small compared with the uncertainty in position. This means that the surface front can be considered a line rather than a band.

- Fronts move at a constant velocity between charts, so the position of the front at some intervening time can be found by linear interpolation.

With these assumptions, the time that a front passed over a particular point could be
found to a reasonable degree of accuracy\textsuperscript{3}. This allowed fronts to be marked on the signal level charts, either as a time the front moved from one side of the path to the other (for fronts parallel to the path) or as the time it reached each end of the path (for fronts perpendicular to the path).

A further stage of analysis was used for the more detailed cross-section studies. As well as information from surface charts, tephigrams were used to produce refractivity sections, both in time and in space. Because of the small scale and poor quality of the tephigrams, it was not possible to read temperatures or dewpoints to an accuracy better than ±1°C, nor pressures (except at standard pressure levels) to better than ±10mb. Calculated refractivities were therefore accurate to ±5 K-units [section 2.2]. Using synoptic charts as guides to the type and location of fronts, the refractivity sections were contoured by hand.

6.3 Correlation of surface data with signals

Once the position and motion of fronts had been established, they were correlated with the signal charts. This detailed analysis looked at three types of fronts.

- Cold fronts parallel to the signal path
- Cold fronts perpendicular to the signal path
- Warm fronts in any orientation

These categories are a reflection of the number of fronts of each type, and each will be examined separately.

The aim of this analysis was to (if possible) identify patterns of signal behaviour which could be considered a 'signature' of frontal anaprop of different types, and also to identify features of surface observations and synoptic charts which could be used to predict which fronts would cause anaprop.

\textsuperscript{3} Reasonable is not easy to define, and depends on individual cases, but it has been assumed for the rest of this chapter that times of passage are accurate to ±1 hour.
6.3.1 Cold fronts parallel to the path

From the conceptual models, it is expected that ana- and kata-type cold fronts will cause two distinct types of anaprop.

- Ana-type cold front have a trailing edge SRL, so anaprop (higher than normal signal levels) is expected after the front has passed over the path [Fig 4.9]. Evidence from the FRONTS'87 work [Chapter 5] suggests that the trailing edge SRL is some 100 or more kilometres in width, so anaprop is likely to occur for two or more hours after the front passes (based on typical speeds of cold fronts). As the front is passing, SRLs will be broken up, so a drop in signal levels is expected. Since there is no warm sector SRL, signal levels before the front passes are expected to be low.

- A kata-type cold front has the same trailing edge SRL as the ana-type, and the same ascent at the front. At and after the frontal passage, there is not expected to be any difference between kata- and ana-fronts. Ahead of the surface front, however, the warm sector SRL on top of the warm conveyor belt means that a peak in signal levels is expected before the front passes. The duration of this anaprop will vary considerably depending on the width of the warm sector, but could last for half a day or more.

The analysis showed 15 cases of cold fronts parallel to the Gt Baddow path. Three different patterns of signal behaviour were observed.

- No anaprop (7 cases)
- Anaprop only after the front has passed (3 cases)
- Anaprop before and after the front has passed (4 cases)

An example of an event with no anaprop is shown in figure 6.2. It is clear that signal levels do not change as the front moves from one side of the path to the other. The synoptic chart shows light winds and heavy cloud cover. The other cases with no anaprop have similar signal behaviour, and the synoptic charts show light winds, and heavy cloud cover. Two of the charts show the front to be stationary, or reversing direction over the path. Since anaprop is not expected at the surface front, the lack of signals in these two cases may be due to the front persisting over the path.

4A fourth case of this type is missing data for the period before the front passes.
Figure 6.2. Cold front parallel to path with no anaprop: (a) Signal behaviour as cold front crosses path; (b) Synoptic chart

A cold front with signals after the front has passed is shown in figure 6.3. The surface front reaches the path at about 04Z, and signal levels rise some 10 dB for a short period immediately afterwards. Signal levels do not appear to fall when the front is over the path and the rise at 01Z appears to be due to a warm front moving away from the path. The synoptic chart shows a slight anticyclonic curvature to the isobars, light winds and cloud cover decreasing from 00Z to 06Z. These and similar events are consistent with the results predicted for an ana-cold front by the conceptual models.

A cold front with signals both before and after the front crosses the path is shown in figure 6.4. The pre-frontal peak as the front approaches is followed by a drop as the front passes, then three peaks over about six hours as the front moves away from the path. The synoptic chart shows very light winds and cloud cover decreasing from 06Z to 18Z. Other cases show similar conditions. These observations are in keeping with the predictions of the conceptual model for kata-cold fronts, while the separate peaks after the front has passed agree with the broken trailing edge SRLs observed in the FRONTTS’87 results.

6.3.2 Cold fronts perpendicular to the path

Since the synoptic conditions are the same, it is expected that anaprop associated with a cold front approaching the path from the end will be similar to that observed when
Figure 6.3. Cold front parallel to path with one period of anaprop: (a) Signal behaviour as cold front crosses path; (b) Synoptic chart

Figure 6.4. Cold front parallel to path with two periods of anaprop: (a) Signal behaviour as cold front crosses path; (b) Synoptic chart
it approaches from the side with ana- and kata-cold fronts giving different amounts of anaprop.

The main difference between parallel and perpendicular fronts is in the length of time the front is over the path. A parallel front will cross from one side of the path to the other quickly, so signals will be inhibited by the front for a short period. A perpendicular front moves from one end of the path to the other, so anaprop is likely to be inhibited for the whole time this is occurring — a few hours rather than an hour or less.

Only seven cases of cold fronts perpendicular to the path were observed, with the same three patterns of signal behaviour observed previously.

- No anaprop (3 cases)
- Anaprop after the front had passed (1 case)
- Anaprop before and after the front passed (3 cases)

Figure 6.5 shows a typical example of a front which did not cause anaprop. The synoptic chart shows the front extending into a ridge of high pressure, and anticyclonic anaprop is seen during the night. As the front approaches the path, signal levels fall very rapidly (this may also be related to the lifting of the subsidence inversion after
dawn) and remain at low levels until the front is well clear of the path. The synoptic chart shows light winds, clearing skies and high surface temperatures. Other instances where no anaprop was observed have similar conditions.

The single case where signals are observed after the front has passed is shown in figure 6.6. A slow moving front cuts through the edge of a high, and is over the path for several hours, just clearing the path at 18Z. During the time the front is over the path signal levels remain constant, but there is a small peak after the front is clear. The drop after this occurs when another front approaches rapidly from the west, probably crossing the path just before midnight (the analysis does not make the position of this front entirely clear). The signal peak occurs at the right time to be due to a trailing edge SRL.

The final pattern of signals has peaks before and after the front reaches the path. Figure 6.7 shows such an event. A fast moving front near the centre of a depression moves along the path, reaching Martlesham at about 07Z. The signals show a clear drop in level between 06 and 07Z, corresponding reasonably with the time the front was over the path. The initial peak could therefore be explained as a warm sector SRL, with the second peak as a trailing edge SRL. Although not studied further in this work, this event merits further investigation to determine the movement of the front more accurately.
6.3.3 Warm fronts

During the observation period, warm fronts were considerably rarer than cold ones. Six examples were found, four with the surface front parallel to the path and two when they were perpendicular.

From the conceptual models, it is expected that ana- and kata-warm fronts will give different types of signals. Both should have anaprop as the warm front approaches the path, due to the leading edge SRL, and a kata-front should give anaprop after the front has passed, from the warm sector SRL. An ana-front will not cause anaprop after the front has passed since there is no warm sector SRL. As with cold fronts, the only differences between ‘perpendicular’ and ‘parallel’ fronts will be the length of time the front is over the path and inhibiting anaprop.

Of the fronts parallel to the path, two showed no anaprop for several hours on either side of front’s passage while two showed signals before the front passed. One of these [Figure 6.8] showed high signal levels for several hours before the front passed, falling to normal some two hours before the front reached the path. Signal levels did not rise when the path was in the warm sector, but there was a noticeable rise in signal levels after the cold front passed. This is in agreement with the expected results for ana-fronts.

Neither of the two fronts perpendicular to the path showed any sign of elevated signal
6.4 Correlation of refractivity sections with signals

As well as examining the signal data alone, radiosonde data were used to produce potential refractivity sections and an attempt was made to relate these to the signal data. A number of case studies were made but, while some interesting features were observed, the results were generally inconclusive. This section presents two analyses, a cross section through a front and a time section for a period when several fronts affected the path.

6.4.1 Selection of case studies

Selection of these case studies required much thought. Several events were analysed roughly, both in time and cross section, after which the two presented here were selected for more careful analysis and interpretation. Initial selection was on the basis of available upper air data, as missing or incomplete data increased the problems (discussed below) of the wide spacing of radiosonde ascents. Final selection of the two events presented here was based on a number of criteria.
• The cross section study was chosen from the cold fronts (since there was insufficient data for meaningful studies of a warm or occluded front) studied earlier, allowing comparison between the time series analysis and the refractivity section. Analysis of a cold front also allowed comparison with the FRONTS'87 studies. The event of 1/7/89 was eventually selected since a non-standard radiosonde ascent was made from Larkhill, giving extra resolution. This case study was also part of the author's presentation at the ICAP'91 conference [Jones 1991].

• The time section studies each covered a period of 5 to 7 days with a number of fronts passing in that time. The period 5–11/8/89 was eventually selected since a range of frontal types (three cold fronts parallel and one perpendicular to the signal path, together with one or two warm fronts) affected the path during that period and there was only one missing radiosonde ascent.

Routine radiosonde ascents are made every twelve hours (00 and 12Z), from nine sites in the British Isles. Two other sites make occasional ascents at irregular times. Since most of the anaprop that seems to be associated with fronts lasts for considerably less than 12 hours, it is not possible to make refractivity cross sections for many cases of presumed frontal anaprop. Similarly the space scale of about 200km between radiosonde stations means that many features of the atmosphere are not observed because an ascent does not pass through them.

Interpolation using a computer graphics package proved impossible since the contouring routines did not have enough data for good interpolation. Instead contours were drawn by hand, aided by calculated positions of the 10 K-unit isopleths on each ascent, giving a linear interpolation. Minor isopleths were entirely hand drawn. Some obviously incorrect data values were omitted from the interpolation scheme. Surface pressures were not easily extracted from the tephigrams, so were ignored. This did no affect the validity of the analysis.

6.4.2 Analysis of a refractivity cross section

The cold front of 1/7/89 was an example of anaprop before and after the front crosses the path. The signal chart [Figure 6.9] shows these peaks. Note that the time axis has been reversed to allow easy comparison with the refractivity structure [Figure 6.10]. As well as the position of the radiosondes, the profile also shows the approximate time w.r.t. the passage of the surface front over the path, allowing correlation with the signal chart. This assumes that the refractivity section moves with the front, not a valid assumption meteorologically, but a useful approximation for this type of analysis.
Figure 6.9. Signal behaviour for the Gt Baddow path for the cold front of 1/7/89. Time axis has been reversed to allow easy correlation with the refractivity section. Features referred to in text marked.

Figure 6.10. Potential refractivity structure over southern England for 12Z on 1/7/89 showing approximate position of front. Horizontal axis shows position of radiosonde ascents as well as 'time' scale w.r.t frontal passage over signal path. Features referred to in text marked.
The profile shows descent of the isopleths behind the upper cold front, with signs of a warm sector SRL (A). Ahead of the UCF, the ascent of the isopleths occurs where ascent due to the release of potential instability is expected (B). Behind the surface cold front there is a low level trailing edge SRL (C), with evidence of subsiding air in the descent of the isopleths. All of these features are in keeping with the conceptual models.

The two SRLs account for the two periods of anaprop. The earlier period (A) is due to the warm sector SRL, while the later period (C) is due to the trailing edge SRL, in keeping with the conceptual models. Although the models give a lower probability of anaprop in the warm sector, they cannot make prediction of signal levels, so the similar levels observed for each SRL are not anomalous.

It must be stressed that the refractivity section cannot reveal all the features that are likely to be present. Even so, features are observed to account for the signals, showing the potential of this type of analysis as a means of studying anaprop.

6.4.3 Analysis of a refractivity time section

The time section shows signal behaviour and compares it with the refractivity structure during a period when an anticyclone decayed and was replaced by a series of depressions. Figure 6.11 shows the signals during the period, with the time and type of fronts indicated. The decay of the high pressure system is reflected in the decay of the nocturnal signal maximum during the period. Looking at the effects of the fronts on signals, a number of features are seen.

A A warm front, perpendicular to the path, which can be considered to show either anaprop before (leading edge SRL) and after (warm sector SRL) the front passes or the front breaking up the subsidence inversion and causing a drop in signal levels for a short period.

B A cold front, parallel to the path, which causes no anaprop.

C A probable warm front (the weather charts do not make it clear how far south the front extends, so it is not clear if the front is over the path) with anaprop before the front passes (leading edge SRL) but not afterwards.

D A cold front parallel to the path, with anaprop before (warm sector SRL) and after the front has passed (trailing edge SRL). This case has already been examined in this chapter [Figure 6.4].
E A very narrow frontal depression with anaprop in the warm sector (warm sector SRL) and possibly anaprop due to leading and trailing edge SRLs.

The refractivity section [Figure 6.12] uses data from Hemsby radiosonde, some 100km from the signal path. Six super-refractive layers are seen (I-VI), corresponding with periods of anaprop. One period of anaprop does not relate to features on the refractivity section. This is when cold front D crosses the path. As this front (at 08Z) is between two radiosonde ascents, it is likely that the SRLs do exist, but the data are not of high enough resolution to reveal them.

It is difficult to relate most of the profile to fronts, but two features (II and VI) can be interpreted as evidence of leading edge SRLs.

These results will be discussed in the next section.

6.5 Discussion

The analysis of data from the Gt Baddow—Martlesham signal path has produced a number of interesting results, but in many ways has been disappointing. It was initially hoped that a method of identifying when fronts were likely to cause anaprop could be developed, but it was found that fronts have too much variability for this to be achieved.

6.5.1 Surface analysis

The correlation of signals with surface charts has shown that fronts have a range of effects on signals, from no visible modification of signal levels to signal enhancements of more than 20 dB. There appears to be no property visible on the surface charts used that determines whether a particular front will or will not cause anaprop, further emphasis that “no front may be considered typical”. In general the results confirm the belief that, while fronts are generally insignificant causes of anaprop, some may give rise to severe anaprop [Hewitt et.al. 1981, Bye 1988a].

On a positive note, anaprop, when observed, occurred at the times and places indicated by the conceptual models. This allows predictions of signal level enhancements to be added to the predictions of SRL widths made from the FRONT'S87 data. The case studies here suggest that an enhancement of at least 10 dB is likely for the time the path is anywhere in an SRL, with 'normal' signal levels when the front is over any
Figure 6.11. Signal behaviour for 5–11/8/89. Fronts and features referred to in text marked.

Figure 6.12. Refractivity structure for 5–11/8/89. Fronts and features referred to in text marked.
part of the path. It must, however, be stressed that this has not been investigated for any paths other than Gt Baddow—Martlesham Heath and also that only about 50% of fronts, regardless of type, give rise to anaprop.

It would be useful to make further investigations of the relationship between signals and features obtained from surface observations. Some suggestions for such work will be made in the next chapter.

6.5.2 Refractivity analysis

As well as providing additional data on the behaviour of signals as fronts move over a path, both of the upper air analyses have provided useful results, confirming some of the findings from the FRONTS'87 data. The data are of much lower resolution than that in the preceding chapter, so not all of the expected features have been observed. Those that have, however, are fully in keeping with the conceptual models.

The cross section shows SRLs in the places expected from the model, and clearly indicates the relationship between periods of anaprop and particular SRLs. Some indications of air flows near the front can be determined by looking at the behaviour of refractivity isopleths. Because of the low resolution of the upper air data, it is difficult to determine strength, height and width of SRLs with any great degree of accuracy. This could be partially overcome by using unprocessed radiosonde data, or even the original processed data rather than using values extracted from a small, poor quality tephigram. This would deal with the vertical resolution, and give a better guide to the height and strength of the SRLs, but it is not possible to overcome the low horizontal resolution using standard observations. If the cold front examined here had not crossed the signal path close to the time of a routine radiosonde ascent, such analysis would not have been possible. Despite these limitations, it is possible that analysis of this type using output from numerical models could be used to predict anaprop on an operational basis.

The time section suffers from the same problems in resolution as the cross section. Again, vertical resolution could be improved by using raw, rather than processed data, but the temporal resolution cannot be improved using routine observations. If only the Met. Office could see the value of making radiosonde ascents at three (or even six) hour intervals...

The signals show the behaviour expected from the conceptual models, and the influence of anticyclonic conditions on signals is clear—anaprop is much more severe during the
first three days of the analysis, than at the end, when the weather had become cyclonic. The refractivity section shows that almost all the anaprop can be ascribed to different SRLs, but it is less easy to see which of the SRLs are frontal in origin. This is (again) a result of the low resolution of the data. Despite the negative tone of this discussion, the analysis of the Gt Baddow data has provided much qualitative evidence in support of the conceptual models. The determination of the variability of frontal anaprop has also been useful, and provides many hints as to where further study may be fruitful.
Chapter 7

Conclusions

To bring this work to a close, this chapter provides a final overview of the thesis. It begins with a chapter by chapter summary of the main findings, bringing the various sections into a coherent whole. This is followed by a number of suggestions for further research and finally by a personal evaluation of the whole project.

7.1 Summary of findings

Excluding the literature survey, which, although vital to the research, does not contribute anything to the results, each chapter of this thesis contributes important results. Most of the findings are linked by the conceptual models [Chapter 4], which provide a framework for interpreting observational results.

Chapter 3 examines the effects of different weather conditions as causes of anaprop. The results can be summarised in the significance ratios, the amount of anaprop caused by a given weather type as a ratio of the amount of time that type occurs for [Figures 7.1 & 7.2]. These, and other results, confirm the expectation that anticyclones are the most important cause of anaprop [Bye 1988a], with fronts as a relatively insignificant source of interference propagation, statistically speaking. This does not stop some fronts causing very severe anaprop [e.g. Hewitt et.al 1981].

This work is one of only two to study the effects of different weather conditions on anaprop, and uses a far more detailed classification scheme and greater range of signal paths than the other work [Spillard 1991]. Results for each weather type have been used
to create a set of interference data sheets [Appendix A], allowing easy comparison of different weather conditions and types of paths. These use the presentation techniques already familiar to radio scientists, and may prove useful for planning new signal paths in southern England and to Europe.

Chapter 4 is the heart of the remainder of this work. Existing meteorological models of fronts [e.g. Bennetts et al. 1988, 1989] have been adapted for radio-meteorological use. The adapted models show where the super-refractive layers (SRLs) which give rise to anaprop are located and make predictions of the probability of anaprop (but not signal levels) in different parts of depressions. The most important features of the adapted models are the leading and trailing edge SRLs (ahead of the surface warm front and behind the surface cold front respectively) in all types of depression and the SRLs in the warm sector found where fronts are kata-type. There may be a warm sector SRL on top of the warm conveyor belt and, if an upper cold front is present, an upper cold front SRL ahead of the UCF. Occlusions are considered to have characteristics of warm or cold fronts, with either a leading or a trailing edge SRL. These conceptual models can be used to explain all references to anaprop at fronts in the published literature. They were also used, successfully, to explain some “anomalous” results presented at the ICAP’91 conference [Levy et al. 1991]. To verify and quantify the conceptual models, a number of detailed case studies were made.

Using dropsonde data from the FRONTS’87 project, three case studies were made [Chapter 5], of ana- and kata-type cold fronts and of a warm occlusion. The dropsonde data allowed the refractivity section to be displayed to an extremely high resolution (10m in the vertical and 20-60km in the horizontal [Thorpe & Clough 1991]). Each of the case studies gave the results predicted from the conceptual models, as shown in the following figures, which compare the real and expected location of SRLs. The similarity between real and expected results can only be described as astounding! Although not all features of the models could be observed (since the FRONTS’87 project concentrated on cold fronts), those that were have provided some quantitative data to add to the qualitative models.

Chapter 6 compares real signal data with weather data interpreted by the conceptual models. It is found that only about 50% of the fronts studied produced anaprop, but where they did, the results were fully in keeping with the conceptual models. It was hoped that features could be found on surface and forecast charts that would indicate which fronts caused anaprop, but this proved impossible. It is possible that other techniques may be developed to predict anaprop from surface observations—some suggestions on this are given later in this chapter.
Figure 7.3. Real and expected SRLs at an ana-cold front

Figure 7.4. Real and expected SRLs at a kata-cold front
Looking at refractivity sections obtained from routine radiosonde ascents provided further evidence to support the conceptual models. Anaprop on signal charts could easily be related to SRLs on refractivity sections and, in some cases, the refractivity structure could be related to the conceptual models. This was not always possible, since the resolution of the data was poor in both time and space. (Compare 500-1000m in the vertical and 200-300km in the horizontal with the resolution of the FRONTS'87 data.)

All the studies of fronts showed how variable they can be, and how difficult it is to draw general conclusions from a limited number of case studies. Through the conceptual models, however, it is now possible to make useful predictions of the extent and, to a certain degree, of the severity of frontal anaprop. These predictions may be of use to BTL when operating their telecommunications network.

7.2 Further work

As with any piece of work, this thesis has raised questions as quickly as it has answered them. This section considers some of the unresolved problems that have been found during the work. Since this research was sponsored by industry, further work will depend on the need industry perceives for it. From the author's viewpoint, there are several areas that provide scope for further work.
• The statistics of anaprop presented here show significant differences between different weather conditions but in some cases the analysis is hampered by lack of data. As with any statistical analysis, adding further data will improve the accuracy. Such data are available from the COST 210 project and it would not be a difficult task to add at least two more years to the two years already studied.

• The statistical analysis is confined to signal paths in the UK-Netherlands region, so it is not known how valid the conclusions are for other parts of the world. Radio-climatological maps could possibly give some indication of similar regions, but it would be useful to produce IDS portfolios for other regions where good signal data are available.

• The conceptual models of fronts used by meteorologists are continually changing in the light of new research, so it would be useful to update the models presented here on a regular basis.

• The Meteorological Office are planning to follow up the FRONTS'87 project with further detailed studies of fronts. These could provide further verification of the conceptual models presented here, and perhaps extend the verification to more types of fronts. It would be particularly useful to set up signal paths in the area of any new project, allowing a very detailed look at the relationships between signals and the structure of fronts. Such a project would be a major undertaking and would require a great deal of co-operation between the Met Office and the researchers involved.

• Although the examination of surface charts and signal data from the Gt Baddow path did not reveal any features that determined whether a front would produce anaprop, it is possible that such features could be found. By examining hourly or three-hourly surface observations, and by applying a scheme similar to that used by BTL to predict radiation nights [Lochtie 1985], it might be possible to identify which fronts produce anaprop.

• Many further case studies similar to those on the Great Baddow path could be made. It would be useful to compare the effects of fronts in the UK and on similar paths in Europe. It would also be useful to re-analyse some of the events to take more account of the speed of the front. This would allow better comparison of 'similar' events. It would also be useful to try to understand why some fronts cause anaprop while others don't appear to. This could be a consequence of the direction the front approaches the signal path from or due to upper air features of the fronts.

• The effects of the sea breeze on anaprop over coastal regions appears in need of further investigation. Of particular importance is the relationship between the
sea breeze and offshore advection. On the downwind coastline, the sea breeze could be considered as an extension of the advection duct onshore as far inland as the terrain allows, but what happens on the upwind coast? If advection is weak, the sea breeze may bring moist air inland, giving the possibility of anaprop in the coastal zone, but how does this affect the formation of the advection duct? If advection is stronger, the inland penetration of the sea breeze must be limited to some extent but again the formation of the advection duct is bound to be affected. These, and related, questions could possibly be answered through the use of a relatively simple two-dimensional model of the transport of moisture and heat between land and sea. Such a piece of research should be a very fruitful field for further study.

- A potentially interesting field of study is the energy spectrum of anaprop. Meteorological studies [Stull 1988 p32] show that energy is mainly concentrated in the synoptic scale (periods between 10 and 100 hours) and in the turbulent scale (periods less than 0.1 hour), with an 'energy gap' between them. It would be interesting to perform a spectral analysis of high resolution signal data and correlate it with the energy spectra of different meteorological variables, particularly those of pressure, temperature and moisture, that control the refractivity.

7.3 Evaluation

This brief, and personal, evaluation of the whole research is a welcome opportunity for me to switch from the third to the first person.

When I began this work, the goals were to determine the cause, effects and scale of frontal anaprop, and to put it into place in the wider field of radio-meteorology. With the aid of some judicious shifting of the goal-posts, all this has been achieved. As well as these explicit goals, I felt from the beginning of the project that an unwritten, but very important, goal was to increase the links between meteorology and radio-science, but whether this has been achieved, only time will tell. The need for such links was, for me, highlighted by reactions to my contribution to the ICAP'91 conference, where I was asked many questions about conceptual models of fronts and how they could be applied to different aspects of radio propagation. That such knowledge should be familiar to meteorologists for more than a decade but unfamiliar to the majority of radio-meteorologists seems to me to be indicative of the need for more links between the disciplines. Meteorologists, too, may be able to learn from the wealth of data collected by radio scientists on the detailed structure of the lower atmosphere.
I would like, again, to thank everyone who has helped me during the course of this work. A full list would be too long to print, but you all know who you are! Special thanks, though, to all my friends, both old and new, who have stood by me over the last few years. Without your support, none of this would have seen the light of day. Thanks, also, to the legions of previous workers in meteorology and radio-science whose researches I have drawn on. As Sir Isaac Newton so truly said,

“If I have seen further, it is because I have stood on the shoulders of giants.”
Appendix A

Interference data sheets

The following material is a copy of the full portfolio of interference data sheets produced during this work.

Interference data sheets

Interference data sheets (IDSs) provide a summary of signal behaviour under different weather conditions. A total of 24 different weather types have been defined and for classification purposes paths have been divided into ‘Dutch’ (running from Martlesham Heath (in East Anglia) to the Netherlands) and ‘UK’ (running from Martlesham Heath to other point on the UK mainland) types. This classification is discussed further in this thesis. Each IDS has the same format:

1. A cumulative distribution showing summer, winter and whole year signals for the weather type, as well as the total for all weather types. Summer refers to the half-year from May to October, while winter refers to the half year running from November to April. The percentages are the amount of signals at a given level relative to the total amount of signals observed. The CD indicates seasonal differences as well as the importance of signals produced by each weather type.

2. A chart showing the behaviour of signals in the course of a year at three different levels (45, 30 and 15 dB below the free space level). The chart shows the percentage of the total years signals for that weather type and level received during each month. This again shows seasonal differences, giving more detail than the
3. A chart, in the same format as the annual chart, showing the diurnal behaviour of signals. The percentages are of the total years signals for the weather type and level received during each hour. This chart can give indications of the anaprop mechanisms at work, particularly for anticyclonic weather types, using conceptual models such as Bye [1988].

4. A synoptic chart from the Daily Weather Report [HMSO 1986-7] showing a typical example of the weather type. This chart, by comparison with forecast charts, allows some predictions of anaprop to be made.

5. A written summary, including: The frequency of the weather type as a percentage of the entire summer and winter; The significance ratio for summer and winter. This is the percentage of total signals recorded for the weather type divided by the percentage of the time for which that the type occurs. An SR of 1 indicates average amounts of signals for the weather type. SRs greater than 1 denote above average amounts of signals, indicating the weather type is a significant cause of anaprop while SRs less than 1 signify below average amounts of signals, indicating the weather type inhibits anaprop.

A summary of the main features of the charts and an indication of the mechanisms responsible for the anaprop. These mechanisms are based on work by BTL [Bye 1988] and by the author.

When using the IDSs, it is worth noting the following points. Firstly, weather systems can be very variable, so particular events may well give results quite different from the statistical summaries shown here. Secondly, some weather types do not have enough data to make the analysis meaningful. These cases, typically giving data for one or two signal producing events, are indicated on the sheets. One weather type, AF6 on Dutch paths, has no recorded cases. For completeness, a blank IDS is given for this type.
Anticyclone east of Dutch signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for A1 conditions

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Summer: 8.49%</th>
<th>Winter: 13.13%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance Ratio</td>
<td>Summer: 3.08</td>
<td>Winter: 1.94</td>
</tr>
</tbody>
</table>

This is the single most important weather type for causing anaprop, with high significance levels and the CD showing little seasonal differences below the free space level. The annual chart shows a number of peaks at all levels, with the majority of signals occurring in April and May. The diurnal chart shows patterns typical of anticyclonic anaprop [Bye 1988], with an early morning peak due to subsidence and a maximum in the afternoon/evening due to advection.

The main mechanisms responsible for anaprop are advection of warm air offshore from mainland Europe (particularly in summer) and subsidence. On coastal parts of the paths, if the topography allows, nocturnal radiative cooling may cause anaprop, as may the sea breeze.
Anticyclone west of Dutch signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for A2 conditions

Frequency

Summer: 12.45%
Winter: 8.32%

Significance Ratio

Summer: 0.94
Winter: 0.11

This common weather type is not significant in winter and of average significance in summer. The CD shows large seasonal differences, as does the annual chart, where the majority of signals at all levels are seen to occur in September. The diurnal chart shows low level signals are more common in the afternoon and at night, although signals do occur throughout the day. At higher levels there is a major peak in the evening, probably due to advection offshore from the UK.

The main mechanisms responsible for anaprop are advection of warm air offshore from the UK (particularly in summer) and subsidence. On coastal parts of the paths, if the topography allows, nocturnal radiative cooling may cause anaprop, as may the sea breeze.
Anticyclone north of Dutch signal paths

Summary for A3 conditions

Frequency
Summer: 4.77%  
Winter: 6.32%

Significance Ratio
Summer: 4.25  
Winter: 1.10

A3 conditions are significant all the year round, but particularly so in summer. The CD shows clear seasonal differences, visible on the annual chart as an 'A3 season' from April to July at all levels. The diurnal chart shows variability throughout the day, with a minimum between 06Z and 08Z. It is difficult to determine particular mechanisms for the anaprop, but the early morning peak can be ascribed to subsidence, with the late afternoon maximum due to advection. Some of the variation may be due to different tracks of advected air, sometimes offshore from the Netherlands to the UK, at other times offshore from Denmark, parallel to the European coast.

The main mechanisms responsible for anaprop are advection of warm air offshore from mainland Europe (particularly in summer) and subsidence. On coastal parts of the paths, if the topography allows, nocturnal radiative cooling may cause anaprop, as may the sea breeze.
Anticyclone south of Dutch signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for A4 conditions

Frequency
- Summer: 5.86%
- Winter: 6.12%

Significance Ratio
- Summer: 0.91
- Winter: 0.51

A4 signals are not significant in either winter or summer. The CD shows little seasonal differences below -25 dBf, but the annual chart shows a concentration of signals in April and May, with very few signals between October and February. The diurnal chart shows variability at all levels, with a late afternoon maximum, probably due to advection, and a smaller peak in the early hours, due to subsidence.

The main mechanisms responsible for anaprop are advection of warm air offshore from the UK (particularly in summer) and subsidence. On coastal parts of the paths, if the topography allows, nocturnal radiative cooling may cause anaprop, as may the sea breeze.
Anticyclone centered over Dutch signal paths

Summary for A5 conditions

Summary for A5 conditions

- **Frequency**
  - Summer: 4.63%
  - Winter: 1.55%

- **Significance Ratio**
  - Summer: 3.29
  - Winter: 1.25

This is a significant type in both summer and winter, but considerably more so in summer. There are marked seasonal differences, clear on the CD and on the annual chart, where there are almost no recorded signals between November and March. The diurnal chart shows variability at all levels, with a noticeable, and surprising, peak between 12Z and 20Z at higher levels.

Anaprop is the result of subsidence, advection (to a limited extent, since there is little air movement near the centre of a high) and radiative cooling and sea breeze effects on coastal parts of the paths.
A6 is a significant weather type, particularly so in summer, but only a limited number of occasions have been observed. There are clear seasonal differences, with the majority of signals occurring in July as a result of a single severe incident. The diurnal chart reflects this, with a peak at 21Z from this occasion. At low levels, signals are spread through the afternoon and night, with no signals observed between 09Z and 14Z.

The main mechanisms responsible for anaprop are advection of warm air offshore from mainland Europe or the UK (depending on the configuration of the two highs) and subsidence. On coastal parts of the paths, if the topography allows, nocturnal radiative cooling may cause anaprop, as may the sea breeze.
Cold front perpendicular to Dutch signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Typical Synoptic Chart

Summary for F1 conditions

Frequency: Summer: 10.37% Winter: 7.71%
Significance Ratio: Summer: 0.44 Winter: 0.09

Like most frontal types, these conditions are not a significant cause of anaprop. The CD shows marked seasonal differences, which are also clear in the annual chart, here the majority of anaprop occurs between May and July. The diurnal chart shows day-night differences at all levels, but clearest at -30 dB, a feature probably due to the nocturnal descent of SRL's.

The main mechanisms causing anaprop are trailing-edge SRL's behind the surface front and sometimes warm sector SRL's ahead of the surface front. The SRL's are relatively narrow bands (100-200 km wide) along the length of the surface front.

Since fronts can move rapidly (up to 60 kph), anaprop can appear and disappear rapidly.
Cold front parallel to Dutch signal paths

Summary for F2 conditions

Frequency:
- Summer: 1.98%
- Winter: 2.68%

Significance Ratio:
- Summer: 1.10
- Winter: 0.07

F2 conditions are not a significant cause of anaprop in winter, but are just significant in summer. This is clear on both the CD, with very marked differences at all levels between winter and summer, as well as on the annual chart. The diurnal chart shows the majority of high level signals to be concentrated in the early afternoon, while at low levels, there are both afternoon and nocturnal maxima.

The main mechanisms causing anaprop are trailing-edge SRL's behind the surface front and sometimes warm sector SRL's ahead of the surface front. The SRL's are relatively narrow bands (100-200 km wide) along the length of the surface front.

Since fronts can move rapidly (up to 60 kph), anaprop can appear and disappear rapidly.
Warm front perpendicular to Dutch signal paths

Summary for F3 conditions

Frequency: Summer: 7.06% Winter: 4.49%
Significance Ratio: Summer 0.89 Winter: 0.36

F3 conditions are not a significant cause of anaprop on Dutch signal paths. Seasonal differences are visible on the CD, but less pronounced than for some frontal types. On the annual chart, it can be seen that signals are concentrated in the spring (March-May) and summer (July-September) at all levels. The diurnal chart shows high level signals to be concentrated in the afternoon and night (14-23Z), with a similar pattern at low levels.

The main anaprop-causing mechanism is the leading edge SRL, ahead of the surface warm front. This is wide (about 1000 km) and slopes gently downwards towards the surface front. Anaprop would therefore be expected to build up slowly, but decay rapidly just before the passage of the surface front.
F4 conditions are a significant cause of anaprop in summer, but are not significant in winter. This is clearly indicated on the CD as well as in the annual chart. The diurnal chart shows the majority of signals occurring between 09 and 00Z, with a peak at high levels around 21Z.

The main anaprop-causing mechanism is the leading edge SRL, ahead of the surface warm front. This is wide (about 00 km) and slopes gently downwards towards the surface front. Anaprop would therefore be expected to build up slowly, but decay rapidly just before the passage of the surface front.
Occluded front perpendicular to Dutch signal paths

Summary for F5 conditions

Frequency:
- Summer: 3.14%
- Winter: 3.48%

Significance Ratio:
- Summer: 0.39
- Winter: 0.31

F5 conditions are not significant in either summer or winter. The CD shows a small seasonal difference above -35 dBf, but little below this level, while the annual chart shows signals concentrated between February and July. Signals are concentrated in the middle of the day, especially at high levels, while at -45 dBf signals are spread through most of the day. These signals suggest anaprop is related to the front alone, rather than to advection or subsidence.

Occlusions have either a leading edge or trailing edge SRL associated with them, so anaprop is expected to occur either ahead of or behind the surface front. Without detailed meteorological information, it is difficult to determine which type of SRL is present. If the SRL is behind the front, anaprop is expected to last for a shorter time than if the SRL is ahead of the front.
Occluded front parallel to Dutch signal paths

Summary for F6 conditions

| Frequency | Summer: 1.36% | Winter: 0.87% |
| Significance Ratio | Summer: 0.48 | Winter: 1.41 |

This is not a significant type in summer, but significant in winter. Unusually, the CD shows winter has more signals than summer, also clear from the annual chart. Since there is only limited data for this weather type, results are not statistically significant.

Oclusions have either a leading edge or trailing edge SRL associated with the them, so anaprop is expected to occur either ahead of or behind the surface front. Without detailed meteorological information, it is difficult to determine which type of SRL is present. If the SRL is behind the front, anaprop is expected to last for a shorter time than if the SRL is ahead of the front.
Dutch signal paths cut same front twice

Summary for F7 conditions
Frequency: Summer: 0.27% Winter: 0.25%
Significance Ratio: Summer 0 Winter: 0

This is a totally non-significant weather type, with very limited data making the statistics worthless. All the charts represent a single event which gave rise to a very short period of anaprop.

Anaprop mechanisms would depend on the type of front involved.
Dutch signal path cuts depression

**Summary for F8 conditions**

- **Frequency:**
  - Summer: 1.02%
  - Winter: 1.79%
- **Significance Ratio:**
  - Summer: 0.27
  - Winter: 0

This weather type is not significant in summer and winter, clear on the CD and annual chart. Signals are mainly observed late at night, but this is probably an artefact of a limited number of interference-producing events.

Interference mechanisms will mainly be warm sector SRL's.
**Dutch Signal paths within warm sector**

**Cumulative Distribution**

- Total
- F9 Winter
- F9 Summer
- F9 Annual

**Annual Variations**

- -45 dBm
- -30 dBm
- -15 dBm

**Diurnal Variations**

- 45 dBm
- 30 dBm
- 15 dBm

**Summary for F9 conditions**

**Frequency:**
- Summer: 1.09%
- Winter: 1.79%

**Significance Ratio:**
- Summer: 3.09
- Winter: 0.09

F9 is not a significant weather type in winter but highly significant in summer, again clearly seen in the CD and annual chart. Signals occur throughout the day at low levels, with two clear peaks at higher levels.

The main mechanisms causing anaprop will be warm sector SRL's, sometimes combined with warm sector (sporadic) subsidence. The latter mechanism occurs when the path is near the periphery of a high and subsidence causes the rapid descent of the inversion layer to low levels, leading to very severe, but short term, anaprop.
Dutch signal paths cut two or more fronts

Summary for F0 conditions

Frequency: 
- Summer: 0.34%
- Winter: 0.96%

Significance Ratio: 
- Summer: 0
- Winter: 0.08

This is an insignificant weather type throughout the year, without enough data to give a meaningful statistical analysis.

Interference mechanisms will depend very much on the types of fronts.
Cold front perpendicular to Dutch paths (anticyclonic isobars)

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for AF1 conditions
Frequency: Summer: 0.68% Winter: 0.89%
Significance Ratio: Summer: 2.04 Winter: 1.48

AF1 conditions are a significant cause of anaprop throughout the year, with little seasonal differences visible on the CD and signals observed in most months. The diurnal chart shows interference to be restricted to the period 18-05Z, although this is probably the result of a limited number of cases.

Anaprop mechanisms are a combination of the anticyclonic ones, particularly subsidence, with warm sector and trailing edge SRL's. As with AF9 conditions, periods of very severe, but short term, interference may occur during this weather type.
Cold front parallel to Dutch paths (anticyclonic isobars)

**Cumulative Distribution**

- Total
- AF2 Winter
- AF2 Summer
- AF2 Annual

**Annual Variations**

- -45 dB
- -30 dB
- -15 dB

**Diurnal Variations**

- 45 dB
- 30 dB
- 15 dB

**Typical Synoptic Chart**

19 AUG 87 AT 0600

**Summary for AF2 conditions**

- Frequency: Summer: 1.30% Winter: 0.34%
- Significance Ratio: Summer: 1.64 Winter: 0

This is a significant weather type in summer but not in winter, with obvious seasonal differences on both the CD and the annual chart, where almost all interference is observed between August and October. Signals are spread throughout the day at low levels, but at higher levels, they are concentrated between 19-00Z and from 06-07Z.

Anaprop-producing mechanisms are a combination of anticyclonic and cold frontal.
Warm front perpendicular to Dutch paths (anticyclonic isobars)

Summary for AF3 conditions

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0.61%</td>
<td>0.69%</td>
</tr>
<tr>
<td>Significance Ratio</td>
<td>1.43</td>
<td>1.17</td>
</tr>
</tbody>
</table>

AF3 is a significant cause of anaprop in both summer and winter, with little seasonal difference at the lowest signal level. The annual chart reflects this, with signals observed throughout the year. The diurnal chart shows two main maxima - between 04 and 09Z and from 16-21Z.

Anaprop mechanisms are a combination of the leading edge SRL and anticyclonic mechanisms, particularly subsidence. The result is descent of the inversion layer and the potential for severe interference. Because of the gentle slope of the warm front, periods of anaprop may be quite long (12 to 24 hours duration).
Warm front parallel to Dutch paths (anticyclonic isobars)

Cumulative Distribution

Annual Variations

Diurnal Variations

Typical Synoptic Chart

Summary for AF4 conditions

Frequency

Summer: 0.48% Winter: 0.48%

Significance Ratio

Summer: 1.84 Winter: 0.33

This weather type is significant in summer but not in winter, with some seasonal differences at low levels on the CD. Signals (from a limited number of events) occur mainly in February and August. The diurnal chart has signals at all levels spread throughout much of the day, with a peak, representing a single event, in the late evening.

Anaprop mechanisms are a combination of leading edge SRL's and the anticyclonic mechanisms.
IDS AF5 D  Occluded front perpendicular to Dutch paths (anticyclonic isobars)

Cumulative Distribution

Annual Variations

Diurnal Variations

Typical Synoptic Chart

Summary for AF5 conditions
Frequency
Summer: 0%
Winter: 0.27%
Significance Ratio
Summer: 0
Winter: 0.51

AF5 conditions do not have enough data to give statistically meaningful results. The data shown here are for a single event.

Anaprop is expected to be due mainly to the anticyclonic mechanisms, with a contribution from the SRL associated with the occluded front. Occlusions have either a leading edge or trailing edge SRL associated with them, so anaprop is expected to occur either ahead of or behind the surface front. Without detailed meteorological information, it is difficult to determine which type of SRL is present.
Occluded front parallel to Dutch paths (anticyclonic isobars)

Summary for AF6 conditions

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Summer: 0.00%</th>
<th>Winter: 0.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance Ratio</td>
<td>Summer: 0.00</td>
<td>Winter: 0.00</td>
</tr>
</tbody>
</table>

This weather type has not been observed on Dutch signal paths.
Dutch signal paths in warm sector (anticyclonic isobars)

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for AF9 conditions

Frequency: Summer: 0.95% Winter: 0.69%
Significance Ratio: Summer: 4.67 Winter: 0.23

This weather type, as with its companion, F9, is highly significant in summer, but relatively insignificant in winter, as both the CD and the annual chart clearly show. The diurnal chart shows little variation over the course of a day at low levels, with the high level peak at 01Z is likely to be due to a single event.

The mechanisms responsible for anaprop are a combination of warm sector SRL's with anticyclonic subsidence, resulting in very rapid descents of the inversion layer to low levels. This may cause extremely severe interference, although this is not likely to be of long duration.
Indeterminate weather type over Dutch signal paths

Frequency: Summer: 30.35% Winter: 34.12%  
Significance Ratio: Summer: 0.79 Winter: 0.27

This weather type is not significant and, since it is a 'catch all' for weather that does not fit into other classes, leaves little room for discussion.

The main anaprop-poducing mechanisms are likely to be the anticyclonic ones - subsidence and advection, as well as radiation and sea-breeze SRL's where topography permits. The diurnal chart shows a pattern typical of anticyclonic conditions.
Anticyclone east of UK signal paths

Summary for A1 conditions

Frequency
- Summer: 9.30%
- Winter: 11.73%

Significance Ratio
- Summer: 2.62
- Winter: 1.86

This is the most important weather type on UK paths, accounting for about 25% of all observed signals. This importance is demonstrated by the high significance ratios. The CD shows little difference between winter and summer and the annual chart shows signals spread throughout the year, with little differences between levels. The diurnal chart shows a cyclic pattern with a maximum at dawn and a minimum around midday at all levels.

Because these results are from coastal and land paths, the main mechanism causing the anaprop is subsidence, with nocturnal radiation cooling and the sea breeze having an effect where the local topography allows.
IDS A2 U

Anticyclone west of UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for A2 conditions

Frequency
Summer: 14.74%  Winter: 9.66%
Significance Ratio
Summer: 1.56  Winter: 0.52

A2 conditions show noticeable seasonal differences, visible on both the CD and annual charts. Signals are observed through most of the year, with noticeable maxima in summer and little difference between levels. The diurnal chart shows a clear day-time minimum and nocturnal maximum, indicating subsidence as the main interference mechanism, particularly at high levels.

The main mechanisms responsible for anaprop are subsidence, together with sea breeze and nocturnal radiative cooling where the terrain allows. The minor peak around 20Z may be due to the sea breeze.
A3 conditions are highly significant in summer but not significant in winter. These seasonal differences are clear on the CD, which shows the difference increasing with signal level, and on the annual chart, which shows the majority of signals are recorded during May and June. The diurnal chart shows a marked day-night contrast, most clearly at high levels.

Anaprop is mainly due to anticyclonic subsidence, together with nocturnal radiative cooling and sea breeze effects where the terrain allows. These mechanisms fit well with the observed diurnal pattern.
Anticyclone south of UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for A4 conditions

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Summer: 8.08%</th>
<th>Winter: 9.07%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance Ratio</td>
<td>Summer: 1.02</td>
<td>Winter: 0.74</td>
</tr>
</tbody>
</table>

These conditions are barely significant in summer and not significant in winter. The CD shows almost no seasonal differences, as does the annual chart, which shows signals throughout the year. The diurnal chart shows a day-night pattern at all levels, with an unexpected maximum at 10Z, probably representing a single case of warm sector subsidence or some artificial source.

Because these results are from coastal and land paths, the main mechanism causing the anaprop is subsidence, with nocturnal radiative cooling and the sea breeze having an effect where the local topography allows.
IDS A5 U

Anticyclone centred over UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for A5 conditions

Frequency
Summer: 4.19%
Winter: 2.37%

Significance Ratio
Summer: 2.93
Winter: 1.06

A5 is a highly significant weather type in summer, but barely significant in winter. There are clear seasonal differences seen on the CD and also on the annual chart, which shows an 'A5' season between May and October. The diurnal chart shows a clear day-night contrast at all levels.

Because these results are from coastal and land paths, the main mechanism causing the anaprop is subsidence, with nocturnal radiative cooling and the sea breeze having an effect where the local topography allows.
IDS A6 U

UK signal paths between two anticyclones

Cumulative Distribution

Annual Variations

Diurnal Variations

Typical Synoptic Chart

Summary for A6 conditions

Frequency
Summer: 1.09%  Winter: 0.90%
Significance Ratio
Summer: 2.98  Winter: 1.26

A6 conditions are highly significant in summer and significant in winter, with a small seasonal difference seen on the CD and on the annual chart, which shows two main periods of signals. The diurnal chart shows an extended maximum between 16Z and 10Z, considerably longer than for other anticyclonic conditions. The -15 dBf 'spike' at 16Z may represent a short period of warm sector subsidence or some artificial source.

Because these results are from coastal and land paths, the main mechanism causing the anaprop is subsidence, with nocturnal radiative cooling and the sea breeze having an effect where the local topography allows.
Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for F1 conditions

Frequency

Summer: 7.27%  
Winter: 5.25%

Significance Ratio

Summer: 1.05  
Winter: 0.35

F1 conditions are not a significant cause of anaprop in winter and are barely so in summer. Seasonal differences are clear in the CD, increasing with signal level, while the annual chart shows the bulk of signals at all levels to be concentrated between April and July. At low levels, the diurnal chart shows signals to be spread throughout the day, with a nocturnal maximum. At higher levels, signals are limited to the night, possibly due to the nocturnal descent of SRL’s.

The main mechanisms responsible for anaprop are trailing edge SRL’s behind the surface front and sometimes warm sector SRL’s ahead of it. Because the trailing edge SRL is relatively narrow (100-200 km wide), anaprop can be expected to be of relatively short duration.

Since cold fronts can be very fast moving features, anaprop can be expected to commence and cease suddenly.
Cold front parallel to UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Typical Synoptic Chart

Summary for F2 conditions

<table>
<thead>
<tr>
<th></th>
<th>Summer: 2.31%</th>
<th>Winter: 2.28%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2.31%</td>
<td>2.28%</td>
</tr>
<tr>
<td>Significance Ratio</td>
<td>0.61</td>
<td>0.11</td>
</tr>
</tbody>
</table>

These conditions are not significant in either summer or winter. The CD shows clear seasonal differences, while the annual chart shows signals concentrated between July and September. The diurnal chart shows signals spread fairly evenly throughout the day at low levels, with a high level peak at 04Z representing a single anaprop event.

The main mechanisms responsible for anaprop are trailing edge SRL's behind the surface front and sometimes warm sector SRL's ahead of it. Because the trailing edge SRL is relatively narrow (100-200 km wide), anaprop can be expected to be of relatively short duration.

Since cold fronts can be very fast moving features, anaprop can be expected to commence and cease suddenly.
Warm front perpendicular to UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for F3 conditions

Frequency
Summer: 6.13%
Winter: 5.18%

Significance Ratio
Summer: 1.05
Winter: 0.25

F3 conditions are barely significant in summer and not significant in winter. These seasonal differences are visible on both the CD and on the annual chart, which shows a clear 'F3 season' between June and August. The diurnal chart shows a clear day-night pattern at all levels, but most obviously at higher levels. This fits well with the nocturnal descent of the leading edge SRL.

The main mechanism producing anaprop is the leading edge SRL, extending up to 1000 km ahead of the surface front. This layer slopes gently downwards towards the surface front, so anaprop can be expected to increases slowly and reach a peak perhaps 100 km ahead of the surface front, decaying rapidly before the front passes. Because of the width of the SRL, periods of anaprop can be expected to be quite long (up to 24 hours).
Warm front parallel to UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Typical Synoptic Chart

Summary for F4 conditions

Frequency
Summer: 1.29%
Winter: 1.52%

Significance Ratio
Summer: 1.01
Winter: 0.17

These conditions are barely significant in summer and not at all so in winter. The CD and the annual chart show clear seasonal differences. The diurnal chart shows a clear difference between day and night, with signals falling off rapidly at about 03Z and increasing rapidly after 21Z. This fits well with the nocturnal descent of SRL's.

The main mechanism producing anaprop is the leading edge SRL, extending up to 1000 km ahead of the surface front. This layer slopes gently downwards towards the surface front, so anaprop can be expected to increase slowly and reach a peak perhaps 100 km ahead of the surface front, decaying rapidly before the front passes. Because of the width of the SRL, periods of anaprop can be expected to be quite long (up to 24 hours).
Occluded front perpendicular to UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Typical Synoptic Chart

Summary for F5 conditions

Frequency
Summer: 2.11%  
Winter: 2.90%

Significance Ratio
Summer: 1.22  
Winter: 0.40

F5 conditions are significant in summer, but not so in winter, although the CD shows little seasonal difference below -35 dB. Surprisingly winter signals are more severe above this level. The annual chart shows the majority of signals are concentrated between April and July. The diurnal chart shows a small day-night variation at low levels, considerably more pronounced at high levels.

Occlusions have either a leading edge or trailing edge SRL associated with them, so anaprop is expected to occur either ahead of or behind the surface front. Without detailed meteorological information, it is difficult to determine which type of SRL is present. If the SRL is behind the front, anaprop is expected to last for a shorter time than if the SRL is ahead of the front.
Occluded front parallel to UK signal paths

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for F6 conditions

<table>
<thead>
<tr>
<th></th>
<th>Summer:</th>
<th>Winter:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1.95%</td>
<td>1.08%</td>
</tr>
<tr>
<td>Significance Ratio</td>
<td>0.48</td>
<td>0.47</td>
</tr>
</tbody>
</table>

These conditions are not significant in either summer or winter, with the CD showing little difference between the seasons. The annual chart shows the majority of signals above -45 dBf occur in December, while the diurnal chart shows that these represent a single, very short event. At lower levels, signals occur in several months and are spread through most of the day, with a maximum around 04Z.

Oclusions have either a leading edge or trailing edge SRL associated with them, so anaprop is expected to occur either ahead of or behind the surface front. Without detailed meteorological information, it is difficult to determine which type of SRL is present. If the SRL is behind the front, anaprop is expected to last for a shorter time than if the SRL is ahead of the front.
UK signal paths cut front twice

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for F7 conditions

Frequency
Summer: 0.00%  
Winter: 0.07%

Significance Ratio
Summer: 0.00  
Winter: 0.00

F7 conditions do not have enough data to give any meaningful statistical results. All the data here represents a single event.
UK signal paths cut depression

Summary for F8 conditions

Frequency
- Summer: 0.48%
- Winter: 0.69%

Significance Ratio
- Summer: 1.00
- Winter: 0.06

F8 conditions are average in summer and virtually non-existent in winter, as shown on both the CD and on the annual chart. At low signal levels, signals are spread throughout much of the day, but are concentrated around dawn at higher levels, representing a single event.

Anaprop is probably due mainly to warm sector SRL's, with a contribution from the leading edge and trailing edge SRL's.
IDS F9 U

UK signal paths within warm sector

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for F9 conditions

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Summer: 2.04%</th>
<th>Winter: 2.39%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance Ratio</td>
<td>Summer: 0.95</td>
<td>Winter: 0.08</td>
</tr>
</tbody>
</table>

Unlike F9 conditions on Dutch paths, they are not a significant cause of anaprop on UK paths. The CD shows considerable differences between summer and winter and the annual chart shows that the bulk of signals at all levels occur in May and September. The diurnal chart shows that low level signals have a definite day-night pattern, as do signals at higher levels. The -15 dBf 'spike' at 20Z represents a single event.

The main mechanisms causing the anaprop is the warm sector SRL descending to lower than usual levels due to anticyclonic subsidence. This can result in short periods of severe anaprop, occurring with little or no warning.
UK signal path cuts two or more fronts

**Cumulative Distribution**

**Annual Variations**

**Diurnal Variations**

**Typical Synoptic Chart**

**Summary for F0 conditions**

<table>
<thead>
<tr>
<th></th>
<th>Summer:</th>
<th>Winter:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0.00%</td>
<td>0.48%</td>
</tr>
<tr>
<td>Significance Ratio</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

This weather type does not have enough data to give a meaningful analysis. The data here represent three events only.
Cold front perpendicular to UK signal paths (anticyclonic isobars)

Summary for AF1 conditions

- Frequency: Summer: 0.34% Winter: 0.48%
- Significance Ratio: Summer: 0.88 Winter: 0.38

AF1 conditions are not significant in either season. The CD shows significant differences between summer and winter, while the annual chart shows the majority of signals occur in September, representing a single signal-producing event. This is also clear from the diurnal chart. At low levels, there is a noticeable day-night contrast, indicating subsidence as a major cause of anaprop.

Anaprop is due to a combination of anticyclonic subsidence with warm sector and trailing edge SRL's.

It appears that this weather type does not represent a large number of events, so all analysis must be treated with caution.
Cold front parallel to UK signal paths (anticyclonic isobars)

Summary for AF2 conditions

<table>
<thead>
<tr>
<th></th>
<th>Summer: 0.81%</th>
<th>Winter: 0.48%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significance Ratio</td>
<td>1.44</td>
<td>0.00</td>
</tr>
</tbody>
</table>

AF2 conditions are significant in summer but not in winter. This is clear on the CD and on the annual chart, where all observed signals are in summer. At low signal levels, the diurnal chart shows ananprop to be spread throughout most of the day, except for a period between 04 and 09Z, effectively ruling out anticyclonic subsidence alone as a cause of ananprop. At high levels, signals represent two events only.

Ananprop is due to a combination of warm sector and trailing edge SRL's, brought to lower levels than usual by the overall subsidence in the high.

It appears that this weather type does not represent a large number of events, so all analysis must be treated with caution.
Warm front perpendicular to UK signal paths (anticyclonic isobars)

Summary for AF3 conditions

Frequency

Summer: 1.29%  
Winter: 0.21%

Significance Ratio

Summer: 1.48  
Winter: 0.19

AF3 conditions are significant in summer, but there is not enough data to say whether they are significant in winter. The CD shows these seasonal differences, as does the annual chart, which shows the vast majority of the signals to be concentrated between May and October. At low levels signals are spread throughout the day, with slight traces of day-night differences, but at higher levels signals are confined to the period 20-23Z.

Anaprop is through a combination of anticyclonic subsidence with leading edge SRLs. The level of the subsidence inversion decreases as the front gets closer, resulting in an increase in severity of the anaprop.
AF4 conditions are significant in both summer and winter, with very little difference between the half-years on the CD. The annual chart shows signals limited to December, August and October, representing a limited number of signal producing events. The diurnal chart shows a clear day-night pattern at high and low levels.

Anaprop is through a combination of anticyclonic subsidence with leading edge SRLs. The level of the subsidence inversion decreases as the front gets closer, resulting in an increase in severity of the anaprop.
IDS AF5 U  Occluded front perpendicular to UK signal paths (anticyclonic isobars)

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for AF5 conditions

Frequency  Summer: 0.00%  Winter: 0.14%
Significance Ratio  Summer: 0.00  Winter: 1.48

Data for AF5 conditions represents a single, significant, event. It is not enough to allow meaningful analysis.

Anaprop under AF5 conditions is through a combination of anticyclonic subsidence with the leading or trailing edge SRL associated with the occluded front.
Occluded front parallel to UK signal paths (anticyclonic isobars)

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for AF6 conditions

Frequency
Summer: 0.00%
Winter: 0.12%

Significance Ratio
Summer: 0.00
Winter: 2.28

There are insufficient data to draw any meaningful conclusions from these results. Signals are only observed in winter and represent a single event lasting about 12 hours.
UK signal paths in warm sector (anticyclonic isobars)

Cumulative Distribution

Annual Variations

Diurnal Variations

Summary for AF9 conditions

Frequency
Summer: 1.70%
Winter: 1.24%

Significance Ratio
Summer: 1.23
Winter: 0.02

AF9 conditions are not significant in winter and marginally significant in summer. The CD shows this, as does the annual chart, where the bulk of the signals are seen to occur in July and August. The diurnal chart shows almost no signals between 09 and 21Z, so all signals are observed at night or shortly after dawn. This suggests nocturnal descent of inversion layers as a major anaprop-producing mechanism.

Anaprop is due to a combination of warm sector SRL's and anticyclonic subsidence. This can cause very rapid descent of the inversion layer to extremely low levels, hence very intense anaprop. These events are of short duration, but start and stop with little warning.
**IDS N U**

**Indeterminate weather type over UK signal paths**

### Typical Synoptic Chart

15 APR 86 AT 0600

### Cumulative Distribution

- **Total**
- **N Winter**
- **N Summer**
- **N Annual**

### Annual Variations

- -45 dBf
- -30 dBf
- -15 dBf

- **Frequency**
  - Summer: 29.31%
  - Winter: 33.36%

- **Significance Ratio**
  - Summer: 1.35
  - Winter: 0.34

N-type conditions are significant in summer but not in winter, with clear seasonal differences visible on the CD. The annual chart reflects this, with a minimum between December and February at all levels. The diurnal chart shows a day-night cycle at low levels, but at higher levels signals are observed during the early afternoon (13-15Z), contrary to expectations. These may be due to a single severe subsidence event.

### Diurnal Variations

- **Frequency**
- **Significance Ratio**

It is difficult to ascribe particular anaprop mechanisms to these conditions. Any of the 'anticyclonic' mechanisms may operate, as may leading edge SRL's (trailing edge SRL's are narrower and so unlikely to affect N-type conditions). The diurnal pattern (with the exception of the afternoon signals) bears a close resemblance to A1 conditions, suggesting similarities between N and A type conditions.

Summary or N conditions

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>29.31%</td>
<td>33.36%</td>
</tr>
<tr>
<td>Significance Ratio</td>
<td>1.35</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Appendix B

Publications and reports

B.1 Reports

This section lists (chronologically) all reports written by the author during the research for this thesis and gives a short summary of each. Reports are unpublished unless otherwise indicated and in all cases copies are available from:

Department of Meteorology
Kings Buildings
University of Edinburgh
EDINBURGH
EH9 3JZ
SCOTLAND

or from:

Antenna and Spectrum Management Group
BTL
Martlesham Heath
IPSWICH
IP5 7RE
ENGLAND
April 1989
Meteorological Causes of Anomalous Microwave Propagation
This report is a survey of the literature relating to radio-meteorology, anticyclones and weather fronts.

August 1989
Meteorological Influences on the Anomalous Propagation of Radio Signals
(1989 Annual Report)
This report, based on a paper at the 1989 departmental conference, summarises progress made over the preceding year and sets out goals for the next year.

November 1989
An examination of the BTRL Anticyclone Model
This report looks in detail at the conceptual model of anticyclonic anaprop [Bye 1988] developed at BTL and makes suggestions for enhancements.

March 1990
Weather Data: Classification and Analysis
(Research Note 1/90)
This report presents a scheme for the classification of weather conditions over NW Europe using 6 hourly weather charts.

Signal Data: Classification and Analysis
(Research Note 2/90)
This report presents a preliminary method of analysing signal data from the COST 210 database.

May 1990
The Relationships between Signal and Weather Data
(Research Note 3/90)
This report gives preliminary results of an analysis of signal data under differing weather conditions.

August 1990
Anomalous Microwave Propagation under Differing Weather Conditions
(1990 Annual Report)
This report is a summary of work since the previous annual report.
April 1991
The Role of Fronts in Anomalous Microwave Propagation
Paper presented at Seventh International Conference on Antennas and Propagation (ICAP'91)
York University, April 1991
A copy of this paper is given immediately after this section.

August 1991
Conceptual Models of the Radio-Meteorology of Fronts
This report (effectively chapter 4 of this thesis) presents the conceptual models of fronts.

December 1991
Draft Final Report
This report, for BTL, gives the final state of the different goals of the research contract and presents chapters 4 and 5 of this thesis.

January 1993
Interference Data Sheet Portfolio
This is identical to the set of IDSs presented in appendix A of this thesis.

B.2 Published Papers
The following is a copy of a paper by the author presented at ICAP'91 and published in the conference proceedings. The author would like to thank the Institute of Electrical Engineers for permission to reproduce the work.
THE ROLE OF FRONTS IN ANOMALOUS MICROWAVE PROPAGATION

T Jones
University of Edinburgh, UK

INTRODUCTION

The weather has an important influence on radio communications links, both when choosing a suitable path for a new link and when a link is operational. A good understanding of the effects of different atmospheric conditions on signal propagation is therefore vital to telecommunications organisations. The mechanisms that lead to anomalous propagation (anaprop) - mainly through ducting - are well understood, as is the occurrence of anomalous propagation during anticyclonic conditions (1). Since anaprop is not confined to anticyclones, it is necessary to look at the effects of other weather conditions on propagation, in particular that of weather fronts and the interactions between fronts and anticyclones.

This paper examines these relatively unstudied aspects of radio-meteorology in several ways. A brief account of previous work on the radio-meteorology of fronts is followed by a statistical analysis of their effects on propagation on a number of links in NW Europe. A conceptual model of the radio-meteorology of fronts is presented as are some case studies of signal behaviour under a variety of weather conditions. This work has been approached from the point of view of a meteorologist, so should offer a different approach to the study of anomalous propagation.

This work is carried out under contract to British Telecom Research Laboratories (BTRL). Acknowledgement is made to the Director of Research and Technology Department of British Telecom for permission to publish this paper.

FRONTS AND PROPAGATION

In the past, most radio-meteorologists have concentrated on the mechanisms responsible for anaprop, or on its occurrence during anticyclones, with relatively little attention being paid to fronts. Given the transitory nature of fronts, and the resulting difficulty in obtaining good data on the refractivity structure aloft, this is not unreasonable. Several authors, however, have mentioned that fronts have some effect on signals, but have not gone into much more detail.

Bean & Dutton (2) cite an earlier study that showed a rapid drop in signal levels when a cold front moved over a link. This is supported by Kuhn & Ogulwi (3) which found that signal levels increased with the passage of some warm fronts and decreased when some cold fronts passed. The work only examined the most severe instances of frontal anaprop, supporting the differences between ana- and kata-type fronts discussed later in this work.

Bean & Dutton’s analysis of surface refractive index charts (2) showed higher levels in the warm sector than ahead and behind the depression, but again this was only a single case study. Cross sections through a cold front (2) showed that refractivity isopleths were lower immediately ahead of the front than behind or further ahead of it. A similar analysis (4) looked at two exceptionally severe events, involving interactions between fronts and anticyclones. As they coincided with routine upper air observations, detailed examinations of the refractivity structure were possible. It was found that the anaprop was due to the abrupt descent of a subsidence inversion (and the associated duct) from its usual level near 2000m to as low as 500m, albeit for a short period. This phenomenon, termed ‘sporadic sub- ducting’. The observed results for anticyclonic conditions are clearly a major cause of anaprop, but there are considerable differences between the A1 and A3 classes on the one hand and the A2 and A4 ones on the other. This is due to the location of the paths, in the former case air arrives over the links after an overland path, thus advection ducting is an important part, while in the latter case, air has a long track over the North Sea, minimising advection ducting. The observed results for anticyclonic conditions could thus not be expected to apply to regions other than NW Europe.

Frontal conditions appear to cause less than average amounts of anaprop, although there is a large variation between different types. There are no obvious patterns to the frontal interference, probably due to the large differences between individual fronts which cannot be captured in routine weather observations. The AF classes appear to follow the F classes, although significant percentages are higher, as if the anticyclonic circulation provides a ‘background’ with frontal effects superimposed on it. There are, however, relatively few cases of AF conditions, so the results given and the corresponding AF9 classes do appear to be significant, particularly on the sea paths to the Netherlands. The statistical significance of these results is currently being investigated.

According to the presence of anticyclones and fronts using the scheme illustrated in Fig 2. The anticyclonic (A) weather classes are based on the BTRL conceptual model of anticyclonic anaprop, extended to take account of different plausible states for the final weather classes relative to the link. Frontal (F) weather classes 1 to 6 are based on the conceptual model presented here and F9 is based on the ‘sporadic sub-
A CONCEPTUAL MODEL OF FRONTS

Although conceptual models lack the 'glamour' of numerical models, they are an important tool for understanding the processes involved in any phenomenon. They also provide a framework for the interpretation of results and as a basis for more complex models. In meteorology there are two conceptual models of the structure and processes of fronts and depressions. The Bergen model was developed in the 1920's and gave a picture of a frontal depression found in most meteorology texts (e.g. 6). The model is essentially static, giving 'snapshots' of a depression at different stages in its development. It also led to the idea of ana- and kate-type fronts, where air is ascending or subsiding relative to the front respectively. The second model is the Browning model, developed since the 1970's (7). This model is dynamic, considering the airflows around depressions, and how their interactions lead to fronts.

This work takes elements of both the Bergen and Browning models and uses them to indicate the location of ducts near fronts. It is assumed that an unsheared air will have a duct (or at least a super-refractive zone) at its base. The depressions shown here (Figs 4a,b) are good examples of ana- and kate-type fronts, but it must be stressed that few depressions are as clear-cut as these, and that individual fronts may exhibit both ana- and kate-type behaviour at different places.

The model suggests that both ana- and kate-fronts have ducts immediately ahead of the surface warm front (WF) and just behind the surface cold front (CF). These are due to the 'dry zone' caused by subsiding air just beneath the frontal surface (6). Away from the surface fronts the ducts are high, but nearer the front the altitude is limited by the presence of the front, so the ducts slope gently downwards towards each front. Rain associated with the fronts is indicated on the diagrams since, although it has minimal effects at around 1 GHz, it may be important for work at other frequencies.

Kata-fronts are marked by a general subsidence in the warm sector, so a duct may exist over much of the depression. The duct is limited by the top of the warm conveyor belt (7), so as this rises up the WF, the duct is lifted. Some kate-type depressions have an upper cold front (UCF) formed when instability in air in the warm conveyor belt causes convection. In this case the duct is broken into two sections at different heights (Fig 4b) while if no UCF is present, the duct is continuous.

Clearly kata-fronts are more likely to cause anaprop than ana-fronts since there is a greater area of duct to intercept signals, so AF9 weather conditions, with subsidence in the warm sector due to the anticyclonic subsidence, would enhance the expectations for a high incidence of anaprop (as the statistics showed). Some anaprop may be caused by ana-fronts, over short distances perpendicular to the fronts, as signal bounce off the duct to a receiver, and over longer distances parallel to the fronts as signals are trapped in the duct. Due to the speed with which fronts move (typically 10 to 20 m/s), such anaprop is likely to be of relatively short duration, while kata-fronts may cause longer periods of interference.

CASE STUDIES OF FRONTAL INTERFERENCE

A number of case studies are being made of events on a 66 km coastal link in SE England. Signal levels are sampled at 10s intervals to a resolution of 0.1 dbf, from which 5 minute means, maximum and minimum levels have been extracted. Weather data are available in the form of 6 hourly synoptic charts, as well as 12 hourly upper air observations. The studies cover a three month period in summer 1989 when a considerable amount of anaprop was observed. Two cases are examined in this work, the first shows enhanced signal levels apparently associated with the passage of a cold front while the second shows a particularly severe event that occurred during AF9 conditions.

During the CF event a front moved rapidly over the path and two periods of enhanced signals, each lasting some three hours, were observed. They are shown on Fig 5, together with the distance of the front from the transmitter. The data can be interpreted using the conceptual model of a kate front, although it is stressed that this interpretation has not yet been rigorously checked. The first period of enhancement (marked A on Fig 5) can be ascribed to the subsidence in the warm air ahead of the front. The drop in signal levels coincides with the passage of the surface front, while the second enhancement (B) is consistent with a duct in the 'dry zone', behind the surface front. The gradual decrease in signal levels towards the end of the 'B' enhancement could be due to the gradual increase in height of the inversion. This 'double peak' in signals as a cold front passes over a link has been observed on another link. Another interesting feature of the chart is the noticeable divergence of signal maxima and minima from the mean between 01 and 03Z. This feature has been observed on other occasions, but no causal mechanism has yet been found for it.

The 'sporadic subsidence' event [Fig 6] was particularly severe, with signals above the free space level for several hours. It is associated with F9 or AF9 weather conditions with the link to the south of the warm sector of a depression and a weak anticyclonic circulation. The strong signals observed earlier in the day appear to be due to a sea breeze duct or the lifting and then break up of a nocturnal radiation inversion. The rapid increase in signal levels at about 19Z appears to coincide with the movement of the warm sector over the link, but the weather charts do not make it clear if this is in fact the case.

Both the cases presented here represent preliminary analyses, and much further work is planned. In particular, cases of similar weather conditions will be compared by overlaying signal level charts, after suitable scaling to take account of fronts and fronint speeds. If similar features are observed on several occasions, further investigation of the physical causes will be merited, but if similar weather conditions give widely differing signals, it must be assumed that the behaviour is more or less random. The analyses will be enhanced through the use of upper air observations, allowing a crude picture of the refractivity structure aloft to be produced. The low resolution of upper air observations, both in space and time, precludes any detailed analysis of the refractivity structure over this link.

Detailed upper air data have been obtained from the UK Meteorological Office for a number of cold fronts to the SW of the UK. Analysis will produce a detailed picture of the refractivity structure near the front, but since there are no suitable signal data available, correlations between refractivity structure and signals will not be possible. Instead it is hoped that the detailed refractivity data will be used to considerably improve the conceptual models presented here.

CONCLUSIONS

Fronts are not a severe problem on a long term basis, so little attention needs to be paid to them when planning new links. Cases of frontal/anaprop interference are relatively uncommon, at least in NW Europe, so they are also unimportant in the long term.

In the short term, fronts may cause problems on operational links, especially when F9/AF9 conditions occur. Due to the great variety of fronts, it is not possible at this stage to predict their short term effects on signals, although the conceptual models presented here make a start on that process. The use of upper air observations and possibly output from weather forecasting models may provide a way of predicting signal levels, but using surface analyses this will never be possible. It is hoped that comparisons of case studies similar to those presented here will allow signal 'signatures' for different types of front/link configurations to be produced, but due to the influences of local topography and the regional geography and meteorology, these 'signatures' may not be applicable to other links.

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Fig 1 - 1.3 GHz Signal Paths used in the statistical analysis. All links use the Martlesham Heath transmitter.

Fig 2 - Weather Types

Fig 2 - Weather types used for the statistical analysis. AF types match the corresponding F type but isobars have anticyclonic curvature.

Fig 3a - Significant %ages - Dutch Paths

Fig 3a - Results of the statistical analysis showing the percentage of cases of each weather type that are significant. For reference, the average significance (for the entire period) is shown as a line.

Fig 3b - Significant %ages - UK Paths

Fig 3b - Results of the statistical analysis showing the percentage of cases of each weather type that are significant. For reference, the average significance (for the entire period) is shown as a line.
Fig 4 - Conceptual models of ana- and kata-type fronts with the possible locations of radio ducts shown. Arrows show air movement relative to the fronts.

Fig 5 - Five minute mean, maximum and minimum signal levels (dB) for the Gt Baddow link (7/7/89). Position of front relative to Martlesham Heath is also shown.

Fig 6 - Five minute mean, maximum and minimum signal levels (dB) for the Gt Baddow link (5/8/89).
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