Modelling and Measurement of the Diffraction of Microwaves by Buildings

C. J. Haslett

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DECLARATION

I declare that this thesis has not been, nor is currently being, submitted for the award of any other degree or similar qualification.

Signed .......................

Christopher J. Haslett
ABSTRACT

Much of the recent growth in microwave communication systems has occurred within urban areas. Private satellite and point to point microwave services have meant that microwave antennas are a common site on the roofs of offices. With the increase in system density comes the increase in the probability of mutual interference between systems sharing the same frequency band. However, the urban location of these systems means that there is also a greater possibility of a building obstructing the interference path, thus providing protection.

Because the introduction of microwave systems into an urban environment on such a scale is a relatively recent event, little information was available regarding the effect of a building on a radio path at microwave frequency. This thesis provides a procedure by which the diffracted field in the shadow of a building may be determined.

Diffraction models are developed based on Fresnel Integral methods and tested against results obtained from a measurement campaign conducted at a frequency of 11.2 GHz using real buildings as the diffracting obstacles. The diffraction model developed is extended from originally considering a two-dimensional great circle path to one which considers multiple path diffraction, typically via the roof and around the sides of the building.

It has therefore been possible to formulate procedures suitable for incorporation into CCIR recommendations whereby the presence of a building may be considered when determining coordination distance and evaluating practical interference threats on specific paths.

Finally methods by which the diffraction mechanism investigated may be incorporated into generalised signal strength prediction procedures that would consider other mechanisms, such as building scatter, are put forward.
ACKNOWLEDGEMENTS

During the seven year period of this study the University of Glamorgan has grown from having virtually no interest in radio propagation matters to the present situation where it is relatively well established as a centre for research in microwave radio propagation with four full-time research staff and two committed members of the lecturing staff. This could not have happened without the encouragement, support and trust of a number of people. Without this growth, this thesis would not have been possible.

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1.1 The Interference problem

Radio systems which coexist satisfactorily for in excess of 90% or even 99% of the time can cause mutual interference for smaller time periods due to circumstances that are generally known as "anomalous propagation conditions". Under these conditions the effect is such that the energy in the electromagnetic wave is not allowed to spread as normal but becomes trapped in a highly structured atmosphere. In this way a signal from a transhorizon transmitter, instead of being much weakened by the diffracting effect of the bulge of the earth can suddenly become enhanced such that it approaches the level which would be expected under free space conditions.

The mechanisms that lead to such enhancements in signal level are well documented in the literature (Boithias [1984], Freeman [1987], Hall and Barclay [1989], Livingston [1970]) and will be summarised here. They are commonly known as "elevated k-factor", "ducting" and "elevated layer".

Elevated k-factor:
The refractive index of the atmosphere is a function of its humidity, pressure and temperature (Bean and Dutton [1966]). There is thus a tendency for it to reduce with height above the surface of the earth. Although only a very slight refractive index gradient is normally established it is sufficient to cause a bending of the wave front such that the wave tends to follow the curve of the earth. In this way the effect of the curvature of the earth is reduced. It is accounted for by re-calculating the earth bulge on any given link using an increased value for the earths radius. The factor by which the effective earth radius is increased to account for this phenomenon is known as the k-factor. It is typically of the order of 1.3 (this means that when calculating the earth bulge an earth radius of 8280 km is used instead of the true value of 6370 km). It can however rise on
occasions to very high values. This leads to a significant reduction in the diffraction loss on a path so much so that radio paths that are normally transhorizon become effectively line of sight paths for the short time periods that such an atmospheric structure exists.

Ducting:

If the refractive index gradient continues to increase, the $k$-factor will rise to infinity (effective flat earth) and then becomes negative. Under these conditions a propagating wave is bent back towards the earth's surface from where it reflects and undergoes a further "hop" in the direction of the receiver with the energy being trapped in a layer, or "duct", typically no more than a few hundred metres high. The refractive index need not necessarily vary monotonically with height. It may undergo reversals in gradient as height increases. Thus a layer of high refractive index may be surrounded both above and below by layers of lower refractive index. These conditions have been detected by "radiosonde" balloons carrying monitoring equipment which measures parameters that allow the refractive index to be calculated as described by Lochtie and Mehler (1993). In this circumstance the energy is trapped in a duct and may propagate for hundreds of kilometres with little loss.

Elevated reflecting layer:

If, instead of gradually reducing with height, the refractive index remains approximately constant at low altitudes and then suddenly reduces at a particular altitude, the interface formed at this sudden reduction in refractive index will cause reflections of the electromagnetic wave to occur. This reflective layer will sometimes result in a receiver experiencing signal levels on transhorizon paths that are very close to the free space level. Much work has been devoted to predicting likely signal levels for small time periods (Doble [1981], Hewitt [1988], Hewitt and Adams [1980], Johns [1966], Ong [1984], Rotherham [1983]). Murphy (1982) has attempted to place a cost on interference outages and trade off these
costs against the cost of not reusing the spectrum. A minimum total cost approach is put forward whereby a small amount of interference outages are tolerated for the sake of spectrum re-use.

As more users come to share the microwave range of frequencies, the interference problem is bound to make itself more apparent, with interference generated outages occurring more often.

1.2 The site shielding solution

Obstacles in the propagation path will reduce the level of an interfering signal. Such obstacles may be naturally occurring terrain obstacles whose effect has been investigated by Boithias (1973) or purpose built screens. The most common use for purpose built screens has been to protect a satellite earth station from interfering signals from a terrestrial radio station. The fact that the earth station is pointed upwards means that it may be surrounded by a fence or even placed in a pit to provide protection from earth based interference sources. The effectiveness of such interference reduction techniques has been the subject of study by many researchers. Lucia (1970b, 1972) has investigated the possibility of placing an earth station in a pit in order to protect it from terrestrial interference. Additional artificial site shielding measures such as the building of conducting, solid or small mesh fences has been investigated by Scheeren (1988a, 1988b), Lucia (1970a) and Gould and Schmitt (1977).

The general conclusion is that obstacles do indeed lead to a reduction in the level of interference experienced in their shadow. The papers mentioned give general formulae involving the site geometry whereby the likely reduction in interference level may be predicted.

1.3 The system coordination procedure

If a new satellite earth station is to be installed at a given point on the surface of the earth, its operation must be coordinated with other users of the same frequency band. The aim of this coordination procedure is to ensure the harmonious co-existence of sharers of the
same band within the frequency spectrum. In particular the system planner must be satisfied that any interference received will be of an acceptably low level. What power level constitutes an "acceptably low level" is for the user to define. The fact that variations in the propagation medium cause the received interfering signal level to vary with time means that an absolute value of "acceptably low level" interfering signal is therefore not justified. The user of a certain radio service must specify what level of interfering signal is acceptable for a certain percentage of the time. Knowledge of the type of transmitter and antennas being used at the same frequency will allow this specification to be expressed in terms of a "minimum acceptable path loss", the path in question being from a potential interferer to the proposed earth station.

The next step in the coordination procedure as detailed in COST 210 (1991) is to identify a coordination contour. This may be performed using methodologies detailed in CCIR reports 382 and 724 (1990). The coordination contour is determined for all angles of azimuth and finally encloses an area known as the "coordination area". If conservatively large values of likely interfering transmitter power and antenna gain are used in estimating the minimum acceptable path loss then the user may be confident that no transmitter lying outside this coordination area will pose an interference problem. Figure 1.1 gives an example of a coordination contour.

An examination of the coordination area is then undertaken to locate transmitters operating at a frequency likely to cause interference. For each of these transmitters the interference path would be analysed in detail in order to determine whether a real threat of interference is posed. This detailed analysis would include details of transmitted power, antenna gains in the appropriate directions, atmospheric characteristics and the path profile.

The path profile is a two dimensional cross-section of the radio path. Procedures for using this, in conjunction with the other link parameters, to predict cumulative distribution curves of average annual interference levels may be found in CCIR report 569 (1990).
The concept of interference being of "an acceptably low level" is further complicated by the observed fact that an interfering level shows significant variation in the course of a year. The fact that an interfering signal level may be markedly higher than the annual average for a period of several weeks has led to the concept of the "worst month" as discussed in CCIR recommendation 581 (1990). It is now normal for any specification of interference levels to be quoted for the "worst month". The problem of converting from average annual levels, as may be derived from CCIR report 569, to worst month statistics has been tackled by Hewitt et. al. (1989). A method of determining the conversion factor, Q, (to convert from annual statistics to worst month statistics) is put forward and supported by 32 link years of measurements.

1.4 The need for predicting diffracted field strength in the shadow of a building.

Up until the early 1980's a procedure such as that described in CCIR report 569 would have been typically applied to the situation where an earth station was being located in a remote site away from industrially produced noise. In their review of the British Post Office microwave radio-relay network Martin-Royle and Dudley (1976) state that there were 166 microwave stations active in 1976 with a further 25 being brought into use by 1980. The probability of a building obstructing an interfering path would have been very small. Since that time rapid growth has occurred in both satellite and terrestrial microwave systems to the extent that it is now common for an earth station to be located in an urban environment with other users of the same frequency band in the vicinity. In a survey of microwave radio usage in Cardiff in 1986 the author noted a single parabolic dish antenna on the roof of the Pearl Assurance building (Cardiff's tallest building). At the time of writing there are 23 such antennas on the roof of this building. Further usage of the microwave frequency band is envisaged with the introduction of Microwave Video Distribution Systems (MVDS). The Department of Trade and Industry report (1988) on the potential for MVDS concludes that "MVDS is a feasible, and potentially competitive,
means of delivering additional TV channels." Figure 1.2 shows a typical MVDS transmission system relaying satellite TV channels by means of terrestrial microwave broadcast stations. Receivers without line of sight to the main broadcast transmitter would be serviced by an on-frequency repeater (OFR). The interference problem is recognised in the DTI report which states that "This technique requires isolation between the antennas at the OFR, and careful siting, to prevent co-channel interference." However, no advice is given as to how to "carefully site" the OFR.

In these situations accurate prediction of the diffracted field strength in the shadow of a building may greatly assist in the assessment of likely interference levels.

1.5 Relevant information in CCIR reports and recommendations.

In CCIR report 569 users are referred to CCIR report 715 (1990) in order to determine a value for diffraction loss due to a single knife edge. For multiple knife edge diffraction CCIR report 569 describes a procedure similar to that put forward by Epstein and Peterson (1953) whereas CCIR report 715 specifically refers to the approximate method of Deygout (1966) although it does additionally mention the highly accurate multiple knife edge prediction of Vogler (1982). CCIR report 715 differentiates between multiple (more than two) edge diffraction and double edge diffraction. For the case of double edge diffraction the methods of Millington, Hewitt and Immirzi (1962), Epstein and Peterson (1953) and Deygout (1966) are referred to.

Significantly, from the point of view of this thesis, no mention is made of a method for predicting the diffracted field strength where a building is the diffracting obstacle. With the growth in urban microwave systems this presents a significant lack of information available which several authors have commented on. Barclay (1988) states "The importance of having appropriate propagation predictions available when establishing the practicalities of frequency use and reuse that can be achieved for different services, in different parts of the spectrum, cannot be stressed too strongly". The CCIR itself
publishes "decisions". These decisions highlight the important future work to be undertaken by the various study groups. In decision 4-8 (1989) CCIR study group 5 notes the need to gather "propagation data relevant to the prediction of interference levels and determination of coordination distance, and propose improvements to the methods of Reports 569 and 724." Additionally in decision 102 (1989) the study group establishes a working party to study "methods of calculating the diffraction and scatter of radio waves in the presence of terrain irregularities, man-made structures and vegetation."

In the conclusion of its final report the European collaborative project COST 210 (1991) recommends the establishment of a future COST project to investigate propagation in the 10GHz - 300 GHz frequency range. This project is divided into three main areas, one of which is the investigation of "influences of the radio propagation medium and terrain features on site shielding (and other interference reduction strategies)."

A new COST project (COST 235) was established accordingly. The University of Glamorgan has been involved with these COST activities since 1987, making regular contributions in the areas of diffraction and scatter by buildings and scatter by vegetation.

1.6 Summary and interim conclusion.

The rapid growth of both satellite and terrestrial microwave radio systems has led to the need for a method of predicting the diffracted field strength in the shadow of a building. The CCIR refers only to general prediction methods of diffracted field with no specific recommendation as to the most appropriate procedure when the diffracting obstacle is a building. Thus, if a system planner is performing a coordination exercise and requires a prediction of an interference level where the path is obstructed by a building, there is no obvious procedure to adopt. The planner must conduct a literature search for a suitable method and adapt such a method according to the
prevailing circumstances. The next chapter introduces diffraction theory and derives numerical methods of giving a prediction of the diffracted field strength in the shadow of well defined obstacles. Following this, chapter 3 describes the development of equipment necessary to carry out an experimental campaign and also the selection of suitable measurement sites. These were utilised for initial experiments as described in chapter 4. Chapter 5 shows how the simple diffraction models may be developed so that diffraction by buildings may be modelled. Chapters 6 and 7 describe experimental and theoretical extensions to the study so that more than one propagation path may be considered. The models thus developed are incorporated into formal prediction procedures in chapter 8.

In chapter 9 the way in which the work described in this thesis forms part of a general site shielding study together with concurrent and proposed further work is detailed. Achievements are then summarised in chapter 10 and appropriate conclusions drawn.
Fig 1.1  An example of a co-ordination contour
Figure 1.2 MVDS Transmission System
2.1 Introduction

Electromagnetic energy at microwave frequencies propagates through space exhibiting a wave motion. Diffraction is the term used to describe the phenomenon by which energy transported by means of a wave enters the shadow of an obstacle. Diffraction effects may be explained using Huygen's principle which states that the amplitude of a wavefront may be predicted by dividing the preceding wavefront into infinitesimally small portions and regarding each of these as a point source. Each point on the next wavefront is then determined by summing phasorially the contribution of each of these point sources. If an obstacle blocks part of the wavefront then the contribution of the obstructed portion is discounted. The evaluation of the total contribution due to infinitesimally small sources requires the use of integral calculus. In determining the strength of a diffracted field the most commonly used integral is known as the Fresnel integral.

2.2 The Fresnel Integral

The Fresnel integral may be applied to the problem of predicting the diffracted field strength in the shadow of a semi-infinite absorbing half-plane. The amplitude of the diffracted wave is determined by summing the contributions due only to the unobstructed part of the wavefront. This may be done by dividing the unobstructed wavefront in the plane of the obstacle into equal portions of width $\delta h$ and summing the contributions of these from $h_1$, the height of the obstacle, to infinity (see, for example, Livingston [1970]). As the portions are of equal width their individual contributions will be of equal amplitude. (This is not quite true as there is in fact a relative amplitude decrease as the measurement point moves from the direction of propagation of any point on the advancing wavefront. However, if we
restrict ourselves to small diffraction angles, sometimes referred to as the paraxial approximation, the magnitude of error introduced by this assumption is usually negligible.) Each of these equal amplitude contributions must now be added phasorially.

Figure 2.1 shows a semi-infinite absorbing half-plane being illuminated by a plane wave. The path length from any point on the wavefront to the measurement point is

\[ r = \sqrt{x^2 + h^2} \]  

(2.1)

Now, if we are restricted to small diffraction angles,

\[ \sqrt{x^2 + h^2} \approx x + \frac{1}{2} \left( \frac{h^2}{x} \right) \]  

(2.2)

If the amplitude due to each infinitesimal portion is \( \delta E \) then its phasor contribution may be written as

\[ \delta E \cdot \exp\left[jk\left(x + \frac{1}{2}\left(\frac{h^2}{x}\right)\right)\right] \]

where \( k \) is the wave number equal to \( \frac{2\pi}{\lambda} \) (\( \lambda \) being the wavelength). This may be applied directly to the problem of determining the diffracted field in the shadow of a semi-infinite plane as shown in Figure 2.1. If the plane is of height \( h_1 \) above the receiver, (assuming the wave to be propagating horizontally), then an indication of the field strength at the receiver will be given by integrating \( \delta E \cdot \exp(jk[x + \frac{1}{2}(h^2/x)]) \) with respect to \( h \) from \( h_1 \) to infinity.

This gives,

\[
\int_{h_1}^{\infty} \delta E \cdot \exp\left[jk\left(x + \frac{1}{2}\left(\frac{h^2}{x}\right)\right)\right] dh
\]

\[ = \delta E \cdot \exp(jkx) \cdot \int_{h_1}^{\infty} \exp\left[jk\left(\frac{1}{2}\left(\frac{h^2}{x}\right)\right)\right] dh \]  

(2.3)
At this point the Fresnel parameter $v$ is introduced where,

$$v^2 = 2\left(\frac{h^2}{x\lambda}\right)$$  \hspace{1cm} (2.4)

If $\frac{1}{2}(h^2/x)$ is thought of as "excess path length" then $v^2$ may be described as "the excess path length expressed as a multiple of a quarter-wavelength". Adopting this value for $v^2$ means that

$$k[\frac{1}{2}(h^2/x)] = v^2(\pi/2)$$  \hspace{1cm} (2.5)

and the integral may be written as

$$\int_{\nu_1}^{\infty} \delta E \exp(jkx) \exp(j\nu^2(\pi/2)) d\nu$$

where

$$v_1^2 = 2\left(\frac{h^2}{x\lambda}\right)$$  \hspace{1cm} (2.6)

### 2.2.1 Numerical Evaluation of the Fresnel Integral

$\exp(jnv^2/2)$ may be expressed as the sum of a series:

$$\exp(jnv^2/2) = 1 + \frac{jnv^2}{2} - \frac{n^2v^4}{4.2!} - \frac{n^3v^6}{8.3!} + \frac{n^4v^8}{16.4!} + \frac{jn^5v^{10}}{32.5!} + \ldots$$  \hspace{1cm} (2.7)

Hence,

$$\int \exp(j\nu^2(\pi/2)) d\nu = \nu + \frac{jnv^3}{2.3} - \frac{n^2v^5}{4.5.2!} - \frac{jn^3v^7}{8.7.3!} + \frac{n^4v^9}{16.9.4!} + \ldots + C$$  \hspace{1cm} (2.8)
Letting \( x = \pi v^2 / 2 \) gives

\[
\int \exp(jv^2(\pi/2))dv = v \left\{ 1 + \frac{jx}{3} - \frac{x^2}{215} - \frac{jx^3}{317} + \frac{x^4}{419} - \cdots \right\} + C \quad (2.9)
\]

Tables exist, see for example Abramowitz and Stegun (1964), giving values for the real and imaginary parts of the Fresnel integral from \( v=0 \) to 5. The series given above, although convergent, requires computation to an excessive number of significant figures as \( v \) increases.

Thus an integral is obtained whose value may be determined by summing a series. However, in order to evaluate the definite integral with an upper bound of infinity the use of the series given above is not appropriate. The series given would be appropriate in the evaluation of the definite integral with bounds of zero and \( v \), so if the definite integral with bounds of zero and infinity could be evaluated the difference between the two definite integrals would yield the integral from \( v \) to infinity as required. Computing the sum of the real and imaginary terms for the series and plotting on a graph, as shown in figure 2.2, reveals that the value for each tends towards \( \frac{i}{2} \) giving the result

\[
\int \exp(jv^2(\pi/2))dv = \frac{i}{2}(1+jv) - v \left\{ 1 + \frac{jx}{3} - \frac{x^2}{215} - \frac{jx^3}{317} + \frac{x^4}{419} - \cdots \right\} \quad (2.10)
\]

The real and imaginary terms shown in figure 2.2 may be plotted on an Argand diagram for various values of \( v \). Figure 2.3 shows this for values of \( v \) varying continuously from -4 to +4. The spiral formed is known as the 'Cornu Spiral' and gives a graphical method of determining the diffracted field strength as a function of \( v \) relative to that received in the absence of any obstacle. The relative field strength received in the absence of any obstacle may be determined by setting \( v \) to \(-\infty\). The fact that the functions plotted in figure 2.2 are both odd leads to the result that the definite integral of \( \exp(jv^2(\pi/2))dv \) between the limits \(-\infty\) and \(+\infty\) equals \((1+j)\).
This can be seen in figure 2.3 as the length of the phasor joining the two ends of the spiral extended to \( v = \pm \pi \). The magnitude of the relative field strength for a particular value of \( v \) is the length of the phasor joining the appropriate point on the spiral to \( \frac{1}{2}(1+j) \) divided by \( (1+j) \). This graphical method will also yield the relative phase of the diffracted field.

2.2.2 Evaluating the Fresnel Integral for large \( v \).

The series developed, although absolutely convergent, does become unwieldy to use for values of \( v \) larger than about 4. An alternative approach to the Fresnel Integral yields a different series useful for evaluating

\[
G(v) = \int \exp(jv^2(\pi/2))dv
\]  
\[\text{(2.11)}\]

when \( v \) is large.

Noting that,

\[
\exp(jv^2(\pi/2)) = \frac{jv}{jv} \exp(jv^2(\pi/2))
\]  
\[\text{(2.12)}\]

and,

\[
\int jv \exp(jv^2(\pi/2))dv = \exp(jv^2(\pi/2))
\]  
\[\text{(2.13)}\]

successive integration by parts yields

\[
G(v) = \frac{\exp(jv^2(\pi/2))}{jv} \left( 1 - \frac{j}{nv^2} - \frac{3}{n^2v^4} + \frac{j \cdot 3.5}{n^3v^6} + \frac{3.5 \cdot 7}{n^4v^8} \ldots \right)
\]  
\[\text{(2.14)}\]
= \frac{j \exp(jx)}{\pi v} \left\{ 1 - \frac{j}{2x} - \frac{3}{(2x)^2} + \frac{j3.5}{(2x)^3} + \frac{3.5.7}{(2x)^4} - \ldots \right\} \tag{2.15}

where

\[ x = \frac{\pi v^2}{2} \tag{2.16} \]

It is noted that the series of equation 2.15 is not absolutely convergent. It falls into the category of what are known as asymptotic series and is suitable for large values of \( v \). An asymptotic series converges towards a fixed value as successive terms are added until the point is reached where the terms increase in magnitude and the series becomes unstable. For large values of \( v \) convergence is rapid and stability is maintained over a large number of terms.

General conclusions regarding the nature of the diffracted wave for large values of \( v \) may now be drawn.

As \( v \) becomes very large \( G(v) \) tends to \( \frac{j \exp(j\pi v^2)}{(\pi v)} \). If it is remembered that \( \pi v^2 \) is the excess path length expressed as a multiple of a quarter wavelength then \( j\pi v^2 \) is simply the phase shift normally due to such an extra path length. As the parameter \( v \) is determined by the height of the knife edge obstacle it is therefore possible to conclude that in cases where \( v \) is large the diffracted field can be considered as emanating from a line source located at the diffracting edge.

If the edge can truly be regarded as a line source then, for a fixed diffraction angle, the electromagnetic power density should vary inversely with the distance from the edge. It follows that the Fresnel parameter \( v \) should increase proportionally with the square root of this distance for large values of \( v \) as \( |G(v)| \) is inversely proportional to \( v \) when \( v \) is large.

Referring to Figure 2.1,

\[ r = \sqrt{(x^2 + h^2)} \tag{2.17} \]
and,

\[ v = h\sqrt{k/\pi x} \]  
(2.18)

\[ v^2 = \frac{h^2 k}{\pi x} \]  
(2.19)

\[ \frac{v^2}{n x} = k \cdot \frac{h}{x} \]  
(2.20)

The fact that the diffraction angle is constant means that \( (h/x) \) is constant and \( r \) is proportional to \( h \). Thus, from equation 2.20, \( v^2 \) is proportional to \( r \) which agrees with the 'line source at edge' hypothesis. The radiation pattern of this effective line source can now be determined. In order to do this, the dependence of \( v \) on the angle \( \theta = \tan^{-1}(h/x) \) with \( r \) held constant must be calculated.

Remembering the strict definition of \( v^2 \) as the excess path length due to diffraction expressed as a multiple of a quarter wavelength,

\[ v^2 = \frac{k}{\pi} \left( \sqrt{x^2 + h^2} - x \right) \]  
(2.21)

\[ \frac{v^2}{\sqrt{x^2 + h^2}} = k \left( 1 - \frac{x}{\sqrt{x^2 + h^2}} \right) \]  
(2.22)

\[ v = C (1 - \cos \theta)^{\frac{1}{2}} \]  
(2.23)

\( C \) being a constant if \( r \) is constant.

Now, \( (1 - \cos \theta)^{\frac{1}{2}} = \sqrt{2} \sin \frac{\theta}{2} \)  
(2.24)
indicating that \( v \) varies proportionally with \( \sin \theta \) if \( r \) is held constant, and hence for large \( v \) the radiated field strength varies with \( \csc \theta \) where \( \theta \) is the diffraction angle.

It should be borne in mind however that this approximation is valid only for large values of Fresnel parameter \( v \) and has the disadvantage that it leads to a prediction of infinite field strength if either \( r \) or \( \theta \) is zero, that is, at the diffracting edge or in line with the edge. Such points are known as "caustics" in diffraction theory. However the general behaviour of the diffracted field in the shadow has been determined using the Fresnel integral as a basis. The approximations derived are not valid near the shadow boundary or in the illuminated region. In such cases the full Fresnel integral should be employed.

2.3 Multiple Edge Diffraction.

Huygen's principle can again be employed to predict the diffracted field in the shadow of two parallel semi-infinite absorbing knife edges. In figure 2.4 the plane above the second (right hand) knife edge encountered by the propagating wave is divided into Huygen's sourcelets. Each sourcelet will contribute to the field strength at the receiver, \( R \). However, the path from source \( S \) to this plane is obstructed by the first (left hand) knife edge. This will introduce additional diffraction loss.

A Fresnel parameter may be assigned to each of these sourcelets by considering diffraction only at this second, right hand edge. Considering the geometry of figure 2.4, the excess path length \( \delta l \) due to a detour via a point \( h \) above the line joining \( S \) and \( R \) at the the right hand edge is given by:

\[
\delta l \approx \frac{h'^2}{2(a+b)} + \frac{h'^2}{2c} \quad \text{when } h \ll (a+b), \quad h \ll c
\]

\[
= \frac{h'^2(a+b+c)}{2(a+b)c} \quad \text{(2.26)}
\]
Thus the Fresnel parameter, \( v \) (as the square root of this excess path length expressed as a multiple of a quarter wavelength) is given by:

\[
v = h \frac{2(a+b+c)}{\sqrt{\lambda(a+b)c}} \tag{2.27}
\]

Such a Fresnel parameter could be translated into diffraction loss by the method described in section 2.1.2. However, there will be an additional diffraction loss due to the presence of the first diffracting edge.

Considering the geometry of figure 2.4, the amount by which the first (left hand) knife edge obstructs the line joining the sourcelet at height \( h \) and \( R \) is given by:

\[
h_1 = h \frac{a}{a+b}
\]

This leads to a second Fresnel parameter, \( u \), to be assigned to this diffraction path where:

\[
u = \left\{ h_1 - \frac{h a}{(a+b)} \right\} \frac{2(a+b)}{\sqrt{\lambda ab}} \tag{2.28}
\]

Thus both Fresnel parameters, \( u \) and \( v \), are dependent on \( h \) such that:

\[
\frac{\delta u}{\delta h} = \frac{a}{(a+b)\sqrt{\lambda ab}} \tag{2.29}
\]

and

\[
\frac{\delta v}{\delta h} = \frac{2(a+b+c)}{\sqrt{\lambda(a+b)c}} \tag{2.30}
\]

hence

\[
\frac{\delta v}{\delta u} = -\frac{(a+b+c)b}{ac} \tag{2.31}
\]

\( v \) and \( u \) may be plotted on orthogonal axes to form a 2-dimensional "Fresnel Surface". The area of integration must be for all values of \( h \) greater that \( h_2 \). At this point \( (h=h_2) \):

\[
u = \frac{2(a+b)}{\sqrt{\lambda ab}} h_1 - \sqrt{\frac{2 a}{\lambda b(a+b)}} h_2 \tag{2.32}
\]
\[ v = \frac{2(a+b+c)}{\sqrt{\lambda (a+b)c}} h_2 \]  

(2.33)

Noting these points and the derivative given by equation 2.31 allows an area of integration to be identified on the Fresnel surface. This area may be identified as the shaded area on figure 2.5. A more rigorous mathematical derivation leading to the same result as shown in figure 2.5 is given in the paper first describing this method by Millington, Hewitt and Immirzi (1962a).

The area of integration of figure 2.5 may be defined in terms of \( p, q \) and \( \alpha \) where:

\[ \alpha = \tan^{-1} \frac{b(a+b+c)}{ac} \]  

(2.34)

\[ q = \frac{2(a+b+c)}{\sqrt{\lambda (a+b)c}} h_2 \]  

(2.35)

and \( p \) may be determined by noting that

\[ p = u_0 \cdot \sin \alpha \]  

where \( u_x = u \) at \( v = x \)  

(2.36)

and

\[ u_0 = u_q + \frac{q}{\tan \alpha} \]  

(2.37)

\[ u_0 = \frac{2(a+b)}{\sqrt{\lambda ab}} h_1 \]  

(2.38)

Now

\[ \sin \alpha = \frac{\tan \alpha}{\sqrt{1 + \tan^2 \alpha}} = \frac{b(a+b+c)}{\sqrt{(a+b)(b+c)}} \]  

(2.39)

Hence,

\[ p = h_1 \frac{2(a+b+c)}{\sqrt{\lambda ab(c+b)}} \]  

(2.40)
2.3.1 Evaluation of the Fresnel Surface Integral

On the Fresnel surface the contribution of each infinitesimally small area is directly proportional to that area with a relative phase equal to $\pi \rho^2 / 2$ where $\rho$ is the distance from the origin. The relative field strength compared with the unobstructed field is given in terms of magnitude and phase by dividing the result of integrating the area concerned by the integral over the entire surface which is given by

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp(j\pi \rho^2) \, du \, dv = (1+j)^2 = 2j
\]

Integrals of certain shaped areas are simple to evaluate. Examples of these are given in figures 2.6, 2.7 and 2.9. The integral of an infinite sector with its apex at the origin is directly proportional to the internal angle $\psi$ and is given by $j\psi / \pi$. The integral of a finite circle radius $\rho$ centred at the origin (figure 2.7) is given by

\[
2j(1 - \exp(j\pi \rho^2))
\]

which may be envisaged as a resultant extending from the origin to a point on a circle as shown in figure 2.8. This fact poses something of a paradox regarding the nature of the Fresnel surface. Examination of figure 2.8 suggests that no matter how large the value of $\rho$, the value of the surface integral may vary significantly with a small variation in $\rho$ and not tend to any fixed value. However, it has already been determined that the integral over an infinite area is a definite value, $2j$. Perhaps the best way of coming to terms with this paradox is to imagine the circle shown in figure 2.8 not as a circle but as a spiral whose radius decreases by an infinitesimal amount with each revolution. The result is that integrating over a circle of any finite radius gives a resultant as shown in figure 2.8 whereas integrating over an infinite area would lead to the spiral reaching the centre of this circle giving a resultant of $2j$ which agrees with the expected value. The integral over a sector of a circle of finite radius, $\rho$, centred on the origin and with internal angle $\psi$ is therefore given by:
A further area for which the surface integral is simple to evaluate is an infinite rectangular strip bounded, as shown in figure 2.9, by the \( u \)-axis and a finite value of \( v \) and from a finite value of \( u \) to infinity. The value for the surface integral is given by \( F(v_0)G(u_0) \) where:

\[
F(w) = \int_0^\infty \exp(jinx^*) \, dx
\]

\[
G(w) = \int_w^\infty \exp(jinx^*) \, dx
\]

As the contribution of an elemental area is dependent only on its distance from the origin it is possible to rotate any area about the origin without affecting the result of integration. Also any area bounded by a radial from the origin will have a resultant of integration equal to that of the mirror image of the area in that radial. Bearing in mind these two facts allows the area of integration for a double knife-edge system (figure 2.5) to be divided into two sections by drawing a radial from the origin through the apex as shown in figure 2.10. One of the sections has one boundary line parallel to the \( u \)-axis whilst the other boundary line is a radial from the origin. These conditions are those specified by Millington, Hewitt and Immirzi (1962b) as necessary and sufficient for the section to be regarded as in "standard position". The second area may be mirrored in the radial and then rotated about the origin so that it, too, is in standard position. Each section may then be defined by its internal angle \( \theta \) and the distance \( \rho \) of its apex from the origin. Thus the complete surface integral may be regarded as the sum of the integrals of two sections as shown in figures 2.10 and 2.11.
The integral of a section in standard position may be regarded as the difference between the integral of an infinite sector with its apex at the origin and the sums of the integrals of regions 1, 2, and 3 as shown in figure 2.12. The evaluation of regions 1 and 3 has been discussed earlier in this chapter. A significant contribution made by Millington, Hewitt and Immirzi (1962b) is the evaluation of the surface integral of an area such as area 2 in figure 2.12, thus providing sufficient tools for an exact evaluation of the surface integral for a double knife-edge system. Considering figure 2.12 the integral of the shaded area \( G(\rho, \gamma) \) is given by

\[
G(\rho, \gamma) = \frac{j\gamma}{\pi} - \left( \frac{j\gamma}{\pi} \exp(j \pi \rho^2) \right) - G(\rho) F(\rho \sin \alpha) - H(\rho, \gamma) \quad (2.44)
\]

where \( H(\rho, \gamma) \) is the integral of area 2 in figure 2.12 and may be evaluated using the Fresnel Surface Integral (FSI) method of Millington et al. (1962b).

The normalised electric field strength is then given by

\[
\frac{E}{E_0} = \frac{\{G(\rho, \gamma_1) + G(\rho, \gamma_2)\}}{2j} \quad (2.45)
\]

where \( E_0 \) is the unobstructed field strength and \( \gamma_1, \gamma_2 \) are as shown in figure 2.10. The value yielded for the normalised electric field strength has been rigorously obtained. The only approximation made is that normally applied to Fresnel integral techniques, namely that diffraction angles should be small. The computational effort required is not prohibitive for modern computers. However, there exist approximations to the FSI method requiring less computational effort. These will now be described.
2.3.2 Approximations to the FSI double knife-edge attenuation function

These methods are variations on the single knife edge diffraction method using the Fresnel integral. The methods in chronological order were put forward by Bullington (1947), Epstein and Peterson (1953), the Japanese postal service (1957), and Deygout (1966).

2.3.2.1 The Bullington equivalent knife edge method.

This involves the replacement of the two diffracting edges by a single equivalent knife-edge at the point of intersection of the extended lines from each terminal to its nearer knife edge as illustrated in figure 2.13(a). It is clearly a rather drastic simplification of the true situation and is very difficult to apply when one of the terminals is at or near grazing incidence (often the situation for a building when the transmitter is very distant.). In those situations the two knife edges are replaced by a single knife edge of approximately the same height resulting in an underestimation of the diffraction loss.

2.3.2.2 The Epstein-Peterson method.

This method estimates the total diffraction loss for a doubly diffracted signal by treating it as two separate paths. Referring to figure 2.13(b), the two paths in question from source $S$ to edge $2$ and from edge $1$ to receiver $R$. Each of the two paths is obstructed and a diffraction loss for each path may be predicted using the Fresnel integral. The two losses (in dB) would then be added to give the total path loss.

It can be seen that there are similarities between this and the GTD approach with the diffracted wave being assumed to emanate from the first diffracting edge for the purposes of determining the loss due to the second diffracting edge. The validity of this method is high if both edges contribute significant losses and the edges are well
separated. Again, the possibility of grazing incidence, together with the fact that the edges cannot generally be regarded as well separated in the case of building diffraction, means that the appropriateness of this method for predicting the diffracted field strength in the shadow of buildings is questionable.

2.3.2.3 The Japanese method.

This is a modification of the Epstein-Peterson method whereby the contribution of the second edge is determined not by assuming the first edge to be the source when calculating the loss due to the second edge, but by extending the line joining the two edges back towards the source $S$ and placing a virtual source $S'$ the same distance from the second edge as is the actual source. This is illustrated in figure 2.13(c). This method can produce more accurate predictions than the Epstein-Peterson method but should be used with extreme care as it is non-reciprocal. Non-reciprocity (that is when different predictions are obtained depending on which terminal is regarded as the source and which as the receiver) must be regarded as a serious flaw in any proposed method.

2.3.2.4 The Deygout method

This method, illustrated in figure 2.13(d), is a variation on the Epstein-Peterson method. The first step in the procedure is to determine the Fresnel parameter for each individual knife edge as if it was the only knife edge present. The knife edge with the largest associated Fresnel parameter is then identified as the "main edge" and its associated diffraction loss calculated. The main edge then regarded as an intermediate terminal on a two hop path and the most significant edge on each hop is identified and the associated diffraction losses added to give a total predicted loss. This process continues until all diffracting edges have been accounted for.
The accuracy of this method is good when there is one dominant edge in the path. However, when two edges are of near equal significance (as is the case for a flat roofed building), a very small change in the path geometry can switch the title of "main edge" from one edge to the other resulting in large differences in predicted diffraction loss. The Deygout method must therefore be regarded as inappropriate for use with flat roofed buildings forming the diffracting obstacle.

2.4 Summary and interim conclusion

An introduction to methods of predicting the strength of an electromagnetic wave in the shadow of an obstacle has been given. In particular, the Fresnel integral has been identified as a very useful tool in predicting the diffraction field strength in the shadow of a single absorbing knife edge. This has been extended so that the diffracted field in the shadow of two parallel absorbing knife edges may be determined by means of evaluating a two-dimensional Fresnel surface integral. These two models form the basis for methods of predicting the diffracted field strength in the shadow of a building. These models are shown to be far more rigorous than some of the approximate methods found in the literature and outlined in section 2.3.

A typical building, however, differs in many aspects from the simple models examined in this chapter. In order that the applicability of any theoretical model may be trusted, comparison between predictions and measurements must be presented as supporting evidence. Chapter 3 describes the development of an appropriate measuring receiver and gives details of the experimental programme which formed an important part of the investigation.
Fig 2.1 Semi-infinite half plane diffraction

Fig 2.2 Real and imaginary terms of the Fresnel integral
Fig 2.3 The Cornu spiral
Figure 2.4 double knife-edge system
Figure 2.5  Area of integration of the Fresnel surface integral

Figure 2.6  Infinite sector
Figure 2.7  Finite circle

Figure 2.8  Resultant of integration over a finite circle

Figure 2.9  Infinite strip
Figure 2.10 Division of area by radial through the origin

Figure 2.11 Two sections in standard position
Figure 2.12  Division of sector into regions
Figure 2.13 Illustration of approximations to the FSI

- a) Bullington
- b) Epstein-Peterson
- c) Japanese Postal Service
- d) Deygout
3.1 Introduction

The desired outcome of the study was to provide methods of predicting the diffraction loss due to an obstructing building forming part of a radio path as a prerequisite for the development of a general site shielding procedure. This would allow the level of an interfering signal in the shadow of a building to be determined if the level incident on the building was known. Any methods would have to be validated by comparing predictions with measurements.

A literature survey revealed that some measurements of diffracted field strengths had been reported prior to the commencement of this study. The majority were concerned with the measurement of signal strengths in the shadow of hills and mountains (for example Deygout [1966], Meeks [1983]) which were not seen as highly valid for the testing of models in connection with diffraction by buildings.

Those experiments reported which measured the diffracted field strength in the shadow of obstacles which may be regarded as "building shaped" were generally made on small scale models. Hacking (1970) and King and Page (1972) report experimental measurements using conducting blocks as the obstacle. In both cases the transmitter was based on a HE-Ne laser giving a signal with a wavelength of 632.8 nanometres.

More recently, studies by Eliades (1991, 1992a, 1992b), van Dooren et al. (1992) and van Dooren and Herben (1993) have reported measurements of the diffracted field strength in the shadow of obstacles with dimensions of the order of a few centimetres at millimetre wave frequencies.

Experiments using scale models offer the advantage of being able to control the measurement environment so as to eliminate unwanted effects such as those due to scattered signals from adjacent obstacles. However, the appropriateness of applying measurements and models based on perfectly conducting, perfectly smooth obstacles to the prediction
of diffracted field strengths in the shadow of real buildings is questionable. This is due to the fact that it cannot be judged safe to ignore factors such as conductivity of the material of the obstacle, surface roughness and detailed profile.

In view of the lack of reported measurements of the diffracted field strength in the shadow of buildings it was decided that it would be essential to conduct and report diffracted field strength measurements taken in the shadow of real buildings to support any theoretical models. This is also in line with the CCIR requirements as indicated by Study Group 5 in the United Kingdom.

At the commencement of the study it was hoped that existing microwave transmission systems may be used as the signal source. However, the wideband nature of such transmissions and the narrow beamwidth of antennas used led to the conclusion that it would not be possible to measure any significant diffraction losses. In order to develop an experimental system with sufficient dynamic range to obtain meaningful measurements, a dedicated carrier wave transmitter was seen as highly desirable. Although a carrier wave transmission may be seen as unrealistic when results relevant to traffic carrying systems were required, models developed for single frequencies may be applied over a finite bandwidth to predict the effect of buildings on wide band systems. Additionally, the fact that a bandwidth of a few tens of Megahertz (typical of high capacity systems) is a very small percentage of the carrier frequency at microwave frequencies, means that single frequency measurements will be highly relevant to practical systems.

This chapter reports on the development of a transmitter and receiver suitable for undertaking an experimental campaign with the objective of obtaining measurements of diffraction loss in the shadow of real buildings. Also discussed in this chapter is the selection of the transmission path and receiver sites.
3.2 The choice of transmission path

Once the decision had been made to make measurements in an outdoor environment, certain extra constraints were imposed on the experimental programme. For example, licensing procedures were more stringent with regard to the frequency and output power of the carrier wave oscillator used. These were necessary to ensure that the experimental programme did not result in interference being caused on active systems. Similarly, the environment must be such that meaningful diffraction measurements could be taken where the diffracting obstacle could be clearly identified. This essentially led to the condition that the path from both the transmitter and receiver to the diffracting obstacle had to be, as near as was practically possible, a free space path.

The location of the University of Glamorgan campus bestowed a logistical advantage in this aspect. The campus is located on a sloping hillside above the river Taff. Figure 3.1 gives a detailed plan of the campus with contour lines and building heights in metres added. The Taff valley is a narrow river valley and from the University it is possible to see directly across to the hills on the eastern side of the valley. Figure 3.2 gives a view of the University from the eastern side of the valley. The advantage that the sloping ground gives is that many buildings can be seen from one viewpoint. Thus a fixed transmitter could be used to illuminate most of the campus buildings allowing the diffracted field to be measured in a variety of site geometries.

Permission was obtained to locate a small transmitter at Hawthorn comprehensive school on the eastern side of the valley. Figure 3.3 shows a map of the area indicating the position of the transmitter in relation to the campus. The path length will be observed to be approximately 1 kilometre. Following the decision regarding the location of the transmitter it was possible to identify suitable locations and buildings on the campus where the diffracted field may be measured.
3.2.1 The measurement sites

Examination of the propagation path suggested that it would be possible to make meaningful measurements of the diffracted field in the shadow of several university buildings. Making measurements at some of these sites involved moving the receiver horizontally into the shadow of a building whilst monitoring the strength of the signal diffracted around a corner of the building. At others, measurements involved moving the antenna vertically making use of an aerial platform whilst monitoring the diffracted field entering the shadow via the roof top. The sites identified are labelled on the campus plan on figure 3.4. The sites labelled H1, H2 involved horizontal movement of the antenna whereas the sites labelled V1 to V8 involved moving the antenna vertically. Having gained an insight to the propagation path it was possible to draw up a specification for a suitable transmitter and measuring receiver.

3.3 The equipment

Having identified a suitable transmission path, the next task was to produce a suitable transmitter and measuring receiver capable of providing accurate data against which any models developed may be tested.

3.3.1 The transmitter

A license was obtained to operate a 10 mW carrier wave transmitter at a frequency of 11.2GHz. As this frequency lies in the guard band between the high and low band allocations of British Telecom's national microwave network it was thought that no interference problem would be posed yet measurements obtained would be extremely relevant as this frequency band is heavily used and shared between terrestrial and satellite services. The transmitter chosen on the basis of stability, reliability, size, power supply tolerance, power consumption and price was of the "dielectric resonator oscillator" type (DRO). The DRO obtained delivered a nominal 10 mW into a 50 Ω load via a SMA output connector and required a 15V dc 75 mA power supply. An SMA to
waveguide transformer was used to connect the transmitter to either a horn antenna or to the feed of a reflecting antenna. Given the requirement to evenly illuminate the university buildings from a distance of one kilometre it was felt that the 19 degree beamwidth of a 20 dBi horn antenna was the most appropriate choice. Figure 3.5 shows the transmitter mounted on a tripod feeding into a 20 dBi horn antenna.

3.3.2 The measuring receiver

The requirement to measure the diffraction loss due to a building meant that the receiver developed would have to be much more sensitive than one which simply monitored a free space signal. For example, a receiver capable of measuring a signal attenuated by 50 dB due to an obstacle on a one kilometre path would be capable of measuring a free space signal from the same transmitter on a path over 250 kilometres in length.

Additionally, due to the fact that the measuring receiver would have to be moved both vertically and horizontally at a measurement location, the receiver would have to be mobile, portable and "self contained", that is, not requiring a mains electricity supply. Due to restricted access to areas around the buildings suitable as measurement sites, using a vehicle based receiver had to be ruled out.

3.3.2.1 Receiver specification

The apparently separate requirements of mobility and sensitivity do interact. For example, the sensitivity of the receiver may be increased by having a receiving antenna with a high gain. However, an antenna with high gain is inevitably physically large thus affecting the mobility of the receiver. Tests suggested that a realistic limit regarding the diameter of the receiving antenna would be 60 centimetres. A realistic maximum gain obtainable from a 60 cm parabolic dish operating at 11.2 GHz is 35 dBi. Assuming a transmitted power output of 10 dBm and a free space path loss (11.2 GHz ; 1.0 km) of 113
dB led to the conclusion that a free space signal level of approximately -48 dBm could be expected assuming the transmitting antenna has a gain of 20 dBi.

The transmitter in this situation is simulating an interfering signal resulting in a free space level of -48 dBm in a receiver. The objective of the experimental programme was to quantify the amount by which a building can reduce this level by acting as a diffracting obstacle. In order to test the likelihood of buildings providing significant protection from interference, it was deemed desirable for diffraction losses of up to 50 dB to be measurable. Thus the mobile receiver was required to be able to measure signals as low in power as -98 dBm.

Inspection of the measurement sites suggested that it would be possible to obtain free space signal strength measurements at the receiver locations. It would then be possible to compare diffracted field strengths with this free space signal. The linearity of the system was therefore seen as more important than absolute measurement accuracy. Given that a signal as low as 50 dB below free space would be measured, useful data would be obtained if the linearity of the system was found to be within 2 dB over the working dynamic range.

3.3.2.2 Receiver implementation

The identified task was to develop a mobile receiver capable of measuring an 11.2 GHz carrier wave signal with a linearity better than 2 dB over a working dynamic range from -48 dBm to -98 dBm. Crucial to obtaining the required specification was the system noise performance as the noise generated by the receiver when added to the thermal noise received with the wanted signal must still be significantly less than the signal power at its weakest level. Additionally the method by which the receiver would be powered could not be dismissed as a trivial problem as providing a self-contained power supply was vital to ensuring the mobility of the measuring system. These problems were dealt with in turn leading to a final design suitable for use.
3.3.2.2.1 Noise performance

The most suitable method of specifying a system noise performance is in terms of its "noise temperature". This allows the apparent internally generated noise at the input of the system to be determined as \( kT_B \) Watts where \( k \) is Boltzmann's constant \( (1.38 \times 10^{-23} \text{ J/K}) \), \( T \) is the noise temperature in Kelvins and \( B \) is the system bandwidth in Hertz. This must be added to the thermal noise entering the antenna along with the signal to give a total equivalent effective noise power at the input to the system. Although this power is a fictional power, it is an extremely valuable concept as the signal to noise ratio (SNR) at the output of the system may be determined as the ratio of the signal power at the input to the equivalent effective noise power at the input of the system. In order to keep this noise power as low as possible, the system noise temperature and the system bandwidth should be as small as possible.

The commencement of the experimental programme fortunately coincided with the availability of low cost "Low Noise Blocks" (LNB's) designed for use in domestic satellite television receivers. These operated over a frequency range of 10.95 to 11.75 GHz and incorporated a 50 dB amplifier and a 10 GHz local oscillator and mixer. Thus the output was 50 dB higher in amplitude than the input and the frequency was now in the range 950 to 1750 MHz. Most importantly the noise figure of such a device is typically less than 2 dB. The frequency down conversion allowed co-axial cable to be used to feed the signal from the LNB to the receiver. The input of the LNB was rectangular waveguide type WG17. It was normal to connect the LNB directly to the feedhorn placed at the focus of the receiving antenna. This kept losses, and hence system noise temperature, to a minimum. The desired system noise floor could be translated into a maximum system bandwidth given the above information.
Assuming:

1) Miscellaneous antenna and feedhorn losses 1 dB
2) LNB gain 50 dB
3) LNB noise figure 2 dB
4) Co-axial cable loss 4 dB
5) Equivalent noise temperature at input 290 K
6) Temperature of system 290 K

System noise temperature referred to input:

\[
Te = 75.1 + 169.6 + 438 \times \frac{0.794}{7940}
\]

\[
= 288.7 \text{ K}
\]

This must be added to the assumed equivalent thermal noise temperature of 290K to give a total effective nose temperature of 578.7K. Thus the system noise floor when referred to the input is \( K \) (578.7) B watts where \( K \) is Boltzmann's constant \( (1.38 \times 10^{-23} \text{ J/K}) \) and \( B \) is the system bandwidth in Hz. As a signal level of -98 dBm is to be measured, a total system noise when referred to the input of the receiver should be no more than -118 dBm or \( 1.6 \times 10^{-15} \text{ watts} \) in order that a minimum signal to noise ratio of 20 dB is maintained. This leads to a maximum allowable system bandwidth of 200 kHz. Spectrum analysers operating at up to 1500 MHz were available with selectable resolution bandwidths of as low as 1 kHz. The suitability of these analysers depended on their own noise floor. A -118 dBm noise floor referred to the input of the system described above would lead to a noise level at the co-axial cable output of -73 dBm. It is important that the noise added by the analyser is significantly less than this level. This requirement may impose further restrictions on the resolution bandwidth. However, making the resolution bandwidth too narrow may render the receiver unusable due to short term frequency variations (sometimes referred to as "residual FM") in the system. This could be caused by frequency variations not only in the transmitter but also in the local oscillator of the LNB. The signal tracking capability of modern spectrum analysers meant that longer term frequency drift would not
significantly affect system performance. Specifications available suggested that operation with a resolution bandwidth of 100 kHz should be achievable. Tests would be needed to ascertain whether further reductions in resolution bandwidth with associated increases in measurement dynamic range would be possible.

3.3.2.2.2 Power supply requirement

The mobility of the measuring receiver was of paramount importance. It was envisaged that receiver plus antenna would be trolley mounted, to enable movement in places with restricted access, with power being derived from a 12 Volt lead-acid battery such as that used for caravans. The power supply requirements of the receiver were two-fold

1) A 75 VA 240V ac supply to the spectrum analyser.

2) An 18V 70 mA dc supply to the LNB.

A 12 V dc to 240 V ac inverter with a maximum load capacity of 200 VA was acquired with the 18 V dc for the LNB being derived from the 240 V ac supply. The inverter was therefore supplying a maximum of 100 VA with a quoted efficiency of 50%. Thus a current of approximately 16 Amps was drawn from the battery. A fully charged battery in good condition could maintain operation for 1½ - 2 hours. The method by which the dc voltage was fed to the LNB was not straightforward. It had to be supplied on the coaxial cable along which the signal would pass. In order that the signal should be guided to the spectrum analyser and not to the power supply it was vital that the power supply should appear as a high impedance at 1.2 GHz and a low impedance at dc. A 100 mH inductor in series with the dc supply achieved this. However even with the inductor inserted it was possible that a mismatch could be caused. The length of cable from the junction with the signal cable to the 100 mH inductor should be an exact integer multiple of half wavelengths. As the wavelength in the cable was approximately 17 centimetres it was found that the best way of minimising losses was to experiment using slightly different cable lengths until a maximum signal level was received by the spectrum analyser.
The receiver with antenna was mounted on a trolley to form a self contained measuring unit. This system, being both novel and containing a number of unique features, implements an extremely economic method of producing a sensitive microwave measuring receiver. Figures 3.6 and 3.7 show a photograph and a block diagram of the trolley mounted receiver respectively. A further development allowed simultaneous measurements of horizontal and vertical polarisations using a single spectrum analyser to be made. In fact, a further development, subsequently implemented, allowed co-polar and cross-polar measurements of simultaneous transmissions of vertically and horizontally polarised signals to be made. These developments, however, are not directly relevant to this thesis which concentrates on co-polar measurements of the diffracted field.

3.3.2.3 Receiver calibration

Once the appropriate equipment had been acquired, the next task was to assemble it for use as a measuring receiver and calibrate it with known power levels entering the low noise block. The measuring receiver was calibrated as a complete unit in the configuration in which it would be assembled in the field.

It was first necessary to establish the minimum resolution bandwidth required for successful operation. This was determined by reducing the resolution bandwidth until the signal level recorded started to become inconsistent. That is, successive sweeps yielded noticeably different measured values of the signal level. Tests revealed that the system operated successfully under a variety of environmental conditions provided that the resolution bandwidth was not reduced below 10 kHz. At this resolution bandwidth the noise floor of the spectrum analyser with the input terminated in 50 Ω was measured as -87 dBm. The total noise floor level displayed on the analyser with the LNB actuated was measured as -81 dBm suggesting that the measurement of diffraction loss in excess of 50 dB should be possible on a 1 kilometre path using a 20 dBi horn transmit antenna and a 60 cm parabolic dish receive antenna.
In order to calibrate the measuring receiver, the transmission path loss of between 60 and 110 dB was simulated using precision waveguide attenuators to reduce the power from the DRO oscillator to measurable levels. The waveguide attenuators are driven by a micrometer screw mechanism such that attenuation levels may be repeated with great precision.

The first procedure was to vary the path loss whilst measuring the received power with a calibrated microwave spectrum analyser. In this way it was possible to note attenuator settings that would produce power levels of between -50 dBm and -90 dBm. Relevant specifications indicated that the levels were measured to an accuracy of better than 1 dB. Replacing the spectrum analyser by the measuring receiver it was possible to repeat the attenuator settings and hence compare power levels measured by the measuring receiver with those measured by the spectrum analyser under the same conditions. The resulting calibration curve is given in figure 3.8. This reveals a nearly constant difference of 48 dB between the two readings, suggesting that measurements of diffraction loss taken directly from the measuring receiver would be of acceptable accuracy. The measuring receiver was thus deemed ready for use in diffraction measurements. From the calibration curve of figure 3.8 measurements made by the spectrum analyser may be converted into the power gathered by the antenna to within an accuracy of 2 dB.

3.4 Summary and interim conclusion

Suitable sites for making diffraction measurements were identified on the University of Glamorgan campus. A transmitter and mobile measuring receiver suitable for this purpose were developed. In the next chapter, the measurement procedure is explained in detail and measured results are given.
Note: transmitter is 70m above sea level
contours given in metres above sea level
approximate roof heights are given in metres above ground level

Figure 3.1 University of Glamorgan Campus
showing ground and building heights
Figure 3.2  University of Glamorgan viewed from eastern side of Taff valley
Figure 3.3 Location of transmitter and University campus
Figure 3.4 Campus plan showing locations of measurement sites
Figure 3.5  11.2 GHz transmitter and 20 dBi horn antenna mounted on tripod
Figure 3.6  Measuring receiver assembled on trolley
Figure 3.7 Block diagram of the measuring receiver
Figure 3.8 Measuring receiver calibration chart
DIFFRACTION MEASUREMENTS MADE ON THE UNIVERSITY CAMPUS

4.1 Description of environment

The 10 mW, 11.2 GHz transmitter was installed one kilometre from the University campus. Whilst the 19 degree beamwidth of the horn antenna meant that it was possible to evenly illuminate any particular campus building, some re-directing of the antenna was necessary for measurements involving buildings located at different areas of the campus. The immediate environment of the buildings involved dictated that the measurements would have to be made with the receiver extremely close (within 100 metres) of the obstructing building. Whilst this had the advantage of allowing one diffracting edge to be clearly identified it represented a definite limitation which would have to be examined closely before any general method may be proposed on the basis of results obtained.

The location of sites indicated on figure 3.4 was largely determined by the requirement of being able to move the mobile measuring receiver on its trolley horizontally for a suitable distance (usually a few tens of metres) at locations H1 and H2. Locations V1 to V8 had to be accessible to the aerial platform and have a level area to accommodate the base of the platform whilst it was elevated. The maximum height of the platform was 9 metres. This was not sufficient to allow measurements to be made in the shadow of the tallest campus buildings which are some 20 metres in height. It was, nevertheless, possible to identify eight suitable sites for which results are reported.

4.2 Experiments involving horizontal movement of the receiver

The steeply sloping ground on which the University of Glamorgan is built offered the advantage of illuminating many buildings from the transmitter site without the incident signal being obstructed by intervening buildings. This created the possibility that significant measurements may be made of diffraction around the side of the
buildings by moving the measurement trolley horizontally. These would complement measurements made involving vertical movement of the receiving antenna.

4.2.1 Measurement of the diffracted field in the shadow of 'G' Block

'G' Block is the largest building on the University campus and was expected to be capable of providing a high degree of protection. To its advantage as a measurement site it can be seen from figure 3.4 that a car park is located on the opposite side of the building from the transmitter (measurement location H1). This facilitated movement of the mobile measuring trolley. Measurements were taken moving the receiver along three lines as shown in detail in figure 4.1. Measurements made along each of the three lines are displayed graphically in figure 4.2 with diffraction loss being the difference between the measured signal strength in the shadow and the free space level. Also added onto each of the measurement curves is a prediction of diffraction loss based on a perfectly absorbing single knife edge model, as described in section 2.2.

4.2.2 Measurement of the diffracted field in the shadow of a University hall of residence

Again open space on the opposite side of the buildings to the transmitter facilitated receiver movement (measurement location H2 in figure 3.4). Details of the measurement site are given in figure 4.3. Although the close proximity of the building to the lines of measurement meant that the diffracting edge was often in the near field of the antenna, it was considered that the measurement made in the building shadow would serve as a useful indication of protection afforded in such circumstances. Results obtained are displayed in figure 4.4 with single knife edge predictions again being added to allow comparisons to be made.
4.2.3 Discussion of measurements made moving the receiver horizontally

The results displayed in figures 4.2 and 4.4 reveal that there is a definite similarity between the measured results and single knife edge prediction up to a certain value of diffraction loss. This would appear to suggest that diffraction around the corner of a rectangular building may be modelled by a single absorbing knife edge. Above this value of diffraction loss, the measured value of diffraction loss is less than the predicted value. An investigation revealed that the receiving antenna was receiving not only the diffracted signal but also the scattered signal from various surrounding structures. Figure 4.5 gives examples of paths by which a significant signal reached the receiving antenna for the 'G' block site (location H1 in figure 3.4). It can be seen that the receiving antenna may see more than one apparent signal source with little angular separation between them. This made it impossible for the receiving antenna with its 3 degree beamwidth to discriminate between the components. Even when the angular separation was considerably more than 3 degrees, a scattered signal of greater strength than the diffracted signal could render accurate measurement of the diffracted signal strength an impossible task.

The measurements presented cannot therefore be said to give conclusive evidence for validating diffraction models when applied to real buildings at microwave frequencies. However useful information can be drawn from these results:

i) Scatter from buildings and vegetation is a significant propagation mechanism at microwave frequencies. A scattered signal from an adjacent building will often be larger than a diffracted signal when deep in the shadow of a diffracting obstacle. Diffraction models when applied to geometries such as those investigated will predict very high levels of diffraction loss (greater than 70 dB in some cases). The results revealed that it is unsafe to suggest to system planners that such high amounts of extra protection from interference may be offered by a diffracting building in an environment where potential scatters exist.
The fact that what has been created is an artificial multipath environment means that all the various signals incident on the measuring antenna should exhibit a high level of coherence. This will cause a spatial interference pattern to exist. Analysis of this interference pattern should allow the individual signals to be identified and quantified. If successful, adoption of a means of measuring and processing the interference pattern should extend the dynamic range of measurements of the diffracted field in a multipath environment. As a result of this, separate studies were commenced to investigate methods of predicting the strength of signals scattered by buildings and vegetation. It also soon became apparent that the development of techniques to resolve the multipath interference pattern was worthy of a research study in its own right.

The purpose of the experimental study described here was to provide data on the strength of the diffracted field. It was therefore necessary to conduct measurements in an environment where multipath signals caused by significant scattered signals were unlikely to be found. The solution was found to be an investigation of roof-top diffraction with movement of the receiving antenna being in a vertical direction by means of an aerial platform. In this way the receiving antenna was pointed well away from any scattering obstacles and hence any scattered signal should be much lower in level than when the receiving antenna was pointed horizontally.

4.3 Experiments involving vertical movement of the receiver

The sites identified as likely to provide meaningful data whilst still being accessible to the aerial platform and sufficiently level so that the platform could be safely raised are indicated as sites V1 to V8 in figure 3.4. Sites V1, V2 and V3 are in the shadow of the halls of residence. These buildings have a wedged roof. Sites V4, V5 and V6 are in the shadow of one of the newer buildings which are of concrete construction with a less solid roof coated with tar and stone chippings. Sites V7 and V8 are in the shadow of one of the older university buildings being brick built with a flat concrete roof.
4.3.1 Measurements made in the shadow of wedged-roof buildings

It was possible to raise the aerial platform above the roof height at locations V1, V2 and V3 in order that the free space signal level could be recorded. It was then possible, by visual inspection from the aerial platform to position the receiving antenna so that the direct path from the source to the receiver grazed the diffracting edge. This was taken as a reference point for the movement of the antenna with the receiving antenna height being quoted relative to this position. Throughout the measurement procedure, the receiving antenna maintained a clear view of the diffracting edge. The measurements made are displayed in figure 4.6. The horizontal distance to the diffracting edge is quoted for each location and once more a prediction for the diffracted field based on a perfectly absorbing knife edge is added for comparison purposes.

4.3.2 Measurements made in the shadow of flat roofed buildings

The path geometry where the diffracting obstacle is a flat roofed building is slightly more complicated than the wedged roof building case. The path parameters measured are given in figure 4.7. The reference point for the receiving antenna is taken as the roof height. Measured results are given in figures 4.8 to 4.12 with the four fixed parameters \( a', b', c' \) and \( \theta \) quoted for each case. The prediction curve in this case is based on a single absorbing knife edge located at the centre of the building.

4.3.3 Discussion of measurements made moving the receiver vertically

The effect of extraneous scattered signals is noticeably reduced with the signal level now varying monotonically with receiver height. It may be seen from figure 4.6 that where the diffracting obstacle has a
wedged roof then the single absorbing knife edge model gives a very good prediction of the diffracted field strength where both transmitter and receiver have a clear view of the diffracting edge.

Figures 4.8 to 4.12 show that a single absorbing knife edge model consistently overestimates the strength of the diffracted field by several dB with the error increasing with movement into the shadow. From figures 4.8 to 4.12 it can be seen that it was possible to perform four of the five measurements for both vertical and horizontal polarisations. From the results obtained, a slight polarisation dependence may be observed with a higher diffracted field strength being recorded for vertically polarised transmissions. The difference between measurements for the two polarisations does, however, vary and is typically only one or two dB. The significance of this polarisation dependence may not therefore be judged high from the viewpoint of site shielding effects.

4.4 Summary and interim conclusion

Measurements of the diffracted field have been made in the shadow of buildings on the University of Glamorgan campus. The first measurements involved moving the antenna horizontally with a vertical corner of a building acting as the diffracting edge. The data provided were however influenced by scattered signals from adjacent buildings. Moving the antenna vertically whilst monitoring the diffracted field entering the shadow via the roof top of the building reduced the likelihood of the data being corrupted by the scattering mechanism. The existence of the scattered signals, although undesirable when attempting to measure a diffracted signal will of course occur in practical site shielding situations. Thus, by carrying out the experiments in a realistic environment it was possible to obtain information regarding the level of protection from interference that may be expected in the shadow of buildings.

The measurements involving roof top diffraction show that the single absorbing knife edge model described in chapter 2 gives a good prediction of the diffracted field in the shadow of a wedged-roof
building whereas the same model seriously overestimates the diffracted field strength in the shadow of a flat-roofed building. A slight polarisation dependence was noted for the diffracted field in the shadow of flat roofed buildings with a higher diffracted signal strength being noted where the transmissions were vertically polarised.

The next chapter develops the simple diffraction models described in chapter 2 so that a model suitable for predicting the strength of the diffracted field in the shadow of building shaped geometries is produced.
Figure 4.1 'G' Block measurement site (location H1)
1 - Measurements
2 - Single knife-edge approximation

Note: for site geometry details see figure 4.1

Figure 4.2 Measurements in the shadow of 'G' Block
Figure 4.3 Hall of residence measurement site
(location H2)
Figure 4.4 Measurements in the shadow of hall of residence
Figure 4.5  Multiple path propagation at 'G' Block measurement site
Figure 4.6 Diffraction measurements in the shadow of wedged-roof buildings (locations V1, V2 and V3)
Figure 4.7  Path parameters for measurements in the shadow of flat roofed buildings
Figure 4.8  Measurements taken at location V4
Figure 4.9 Measurements taken at location V5
Figure 4.10 Measurements taken at location V6
Figure 4.11 Measurements taken at location V7
Path parameters: $a' = 800\text{m}$, $b' = 25\text{m}$, $c' = 84\text{m}$, $\theta = 0.42^\circ$

Figure 4.12 Measurements taken at location V8
5 MODELS SUITABLE FOR PREDICTING DIFFRACTION BY BUILDINGS

5.1 Introduction

Chapter 2 introduced diffraction theory and gave details of methods by which the diffracted field in the shadow of a perfectly absorbing knife edge may be predicted. This was extended to the case where the incident field was doubly diffracted by two parallel absorbing knife edges. However, neither of these geometries may be described as representative of typical buildings. Experimental results reported in chapter 4 show that the single knife edge approximation appears appropriate for predicting the field strength in the shadow of wedge roofed buildings whereas it seriously overestimates the field strength where a flat roofed building of appreciable thickness forms the diffracting obstacle. The work detailed in this chapter provides theoretical support for these observations using the models described in chapter 2 as a base. These models are extended to shapes similar to those of two dimensional outlines of buildings, namely a wedge and rectangular slab. The main difference between these and the simple absorbing knife edge models is the addition of reflecting surfaces which require adding contributions at the receiving point due to the source plus its virtual image in these surfaces. One principle which will be shown to be extremely valuable as a tool for predicting the contribution due to the image of the source is known as Babinet's principle (see, for example, Hecht [1987] p. 458) which will now be explained.

5.2 Babinet's Principle

Certain obstacles may be said to be complementary. For example, consider the two configurations shown in figure 5.1. Each shows a knife-edge obstacle in between the same source, S, and receiver R. The apexes of the obstacles are coincident. The normalised electric field strength may be evaluated for each configuration in terms of magnitude...
and phase. Babinet's principle states that the sum of the two normalised electric field strengths must be unity. The two obstacles shown are complementary.

Thus when presented with an obstructed path geometry, the normalised electric field strength may be evaluated either by computing the normalised electric field strength for the obstacle as shown or by evaluating the normalised electric field strength for its complement and subtracting that from unity. This gives the user a choice of geometries to evaluate. For example the sum of the integrals of the shaded and unshaded areas of figure 2.5 must add to 2\(\pi\) thus evaluating the integral of one of these areas yields the integral of the other. Babinet's principle is used extensively in this chapter and in particular a double inverted knife-edge geometry is reduced to the difference between a single knife-edge and an erect double knife-edge geometry as shown in figure 5.2. In this case Babinet's principle is applied to the left hand knife-edge whilst the right hand knife-edge remains constant for the three situations illustrated. The normalised field strength for configuration (A) in figure 5.2 may be solved as the difference between the normalised field strengths for configurations (B) and (C). This leads to the inverted double knife-edge system being reduced to a form where it may be solved directly using the method of Millington, Hewitt and Immirzi (1962a, 1962b).

5.3 Diffraction by buildings with wedged roofs

The initial model used to simulate a building with a pitched roof is a perfectly smooth, perfectly reflecting wedge with sloping sides of infinite extent. The effects of practical "imperfections" namely, imperfect reflection, surface roughness and the non-infinite extent of the sloping sides are then discussed. General conclusions are drawn regarding a practical method of predicting the strength of the diffracted field in the shadow of a building with a pitched roof.
5.3.1 The perfectly reflecting, smooth, infinite wedge

The diffracted field in the shadow of a perfectly smooth, infinite wedge may be predicted using the "four-ray model". This prediction model may be envisaged as the sum of components from the transmitter, plus its virtual image, to the receiver, plus its virtual image - a total of four possible paths as illustrated in figure 5.3. To each path a Fresnel parameter \( v \) is assigned, and the function \( G(v) \) evaluated where

\[
G(v) = \int_{-\infty}^{\infty} \exp(j \frac{1}{2} \pi x^2) \, dx
\]

(5.1)

If the reflection coefficient at the wedge surface can be assumed to be \(-1\) the resultant electric field strength \( E_n \), normalised to the free space level, is given by

\[
E_n = \frac{(G(v_1) - G(v_2) \exp(-j \phi_2) - G(v_3) \exp(-j \phi_3) - G(v_4) \exp(-j \phi_4))}{(1+j)}
\]

(5.2)

where
- \( v_1 \) is the Fresnel parameter for path \( SR \)
- \( v_2 \) is the Fresnel parameter for path \( S'R \)
- \( v_3 \) is the Fresnel parameter for path \( SR' \)
- \( v_4 \) is the Fresnel parameter for path \( S'R' \)

The phase terms in equation 5.2 account for the fact that the free space path lengths \( SR, S'R, SR' \) and \( S'R' \) of figure 5.3 are not equal. However, the four diffracted paths are of equal length and, for values of \( v \) greater than about 1, the apparent source of the diffracted wave is coincident with the diffracting edge (King and Page [1973]). In such cases equation 5.2 may be simplified to give

\[
|E_n| = \{|G(v_1)| - |G(v_2)| - |G(v_3)| + |G(v_4)|\}
\]

(5.3)

5.3.2 Predictions obtained using the four-ray model

Equation 5.2 has been used to predict the diffracted field strength in the shadow of wedge-roofed buildings for a variety of path geometries. Figure 5.4 gives predicted diffraction loss as a function of internal
wedge angle when the diffraction angle is 100 milliradians at frequencies of 1 GHz, 10 GHz and 100 GHz. As the internal wedge angle decreases, so the diffraction loss tends towards the single knife edge value. Figure 5.4 reveals that the diffraction loss will not significantly exceed the single knife edge value unless the internal wedge angle exceeds 160 degrees. This is apparently true regardless of frequency. The implication of this finding is that in cases where the apex of a wedge-shaped roof forms the diffracting edge, and the internal wedge angle is less than 160 degrees, a single knife edge model is sufficiently accurate for most practical purposes.

5.3.3 The effect of practical differences from the ideal model

Practical pitched buildings differ from the ideal model in a number of ways. In particular the surface will not be perfectly reflective, will not be perfectly smooth, nor will the sloping sides be of infinite extent.

Investigating first the fact that the reflection coefficient will not, in general, equal -1 leads to a modification to be made to the original equation 5.3 to give

\[ |E_n| = \{|G(v_1)| + \Gamma|G(v_2)| + \Gamma|^2|G(v_3)| + \Gamma^3|G(v_4)|\} \]  (5.4)

Where \( \Gamma \) is the reflection coefficient at the surface of the wedge. Upon examination of equation 5.4 it can be seen that, as practical values of \( \Gamma \) will often be considerably less than unity, the magnitude of the first term will dominate. This term represents the value of normalised electric field strength for a single knife-edge diffraction case. Thus the effect of imperfect reflectivity would be to make the diffracted field strength tend towards the value predicted for a single knife edge. Indeed, a perfectly absorbing wedge would yield a diffracted field strength equal to that for a single knife-edge.
predicting the effect produced by an uneven surface is more difficult. It is possible to integrate reflected components for very small portions of the roof which can be assumed to be locally planar (Beckmann and Spizzichino [1963]). The overall effect of surface roughness is to make the reflected components more random in nature tending to reduce the magnitude of the resultant of these components. Thus the effect of surface roughness is to make the first term of equation 5.4 dominate leading to a prediction for the diffracted field strength tending towards that for a single knife-edge.

The fact that the sloping sides are not of infinite extent can be accounted for by regarding the reflected components not as undergoing a single knife-edge diffraction but rather undergoing a multiple knife-edge diffraction as some radiation from the source is not reflected towards the roof apex but rather is incident on the side walls of the building. Considering the ray path which undergoes reflection in the left hand surface only, this may be accounted for by evaluating the diffracted field due to the mirror image of the source in this left hand surface. The non-infinite extent of this surface may then be modelled by obstructing the path to the roof apex at the surface boundary. This situation is illustrated in figure 5.5(a). Where the ray undergoes reflection in both surfaces, mirror images of both source and receiver must be considered with the path from each to the apex obstructed at the appropriate surface boundary as shown in figure 5.5(b). $S'$ and $R'$ show the positions of the virtual images of the source and receiver respectively, reflected in the appropriate surfaces.

The main problem in evaluating the diffracted field strengths for the configurations shown in figures 5.5(a) and 5.5(b) stems from the fact that the three knife-edges are not all in the same sense. That is, one of them is inverted relative to the other two. Babinet's principle may be used to reduce these into configurations where all knife-edges are in the same sense. Figures 5.6 and 5.7 show how this may be done for the configurations of figures 5.5(a) and 5.5(b) respectively. The "final configurations" B and C in figure 5.7 both contain inverted knife edges. They may both be further modified using the methods illustrated in figures 5.2 and 5.6 respectively to give configurations
containing only erect knife-edges. It will be observed that in order to solve this exactly it is necessary to use the method developed by Vogler (1982). However, it is possible to generalise that the diffracted field strength will be less than if only the central knife-edge was present. Thus the effect of the non-infinite rather than infinite extent of the sloping sides will generally be to reduce the value of the reflected components which will again lead to the first term of equation 5.4 dominating.

Consideration of all three practical differences from the ideal model suggest that each will result in the diffracted field strength tending towards the value for a single knife-edge. The simulations carried out using the ideal model show that the predicted level of diffracted field strength in the shadow of the wedge is virtually the same as in the shadow of a knife edge if the internal wedge angle is less than 160 degrees. As the internal angle of most pitched roofs is less than 160 degrees and all the effects of practical differences from the ideal model result in the field strength tending towards that for a single knife-edge it seems reasonable to conclude that a single knife-edge model is an adequate method for predicting the diffracted field strength in the shadow of a pitched roof building where the apex of the roof forms the common horizon between the transmitter and receiver.

5.3.4 Summary of wedged roof diffraction

Analysing an ideal wedge and then modifying the prediction method to account for practical differences between real pitched roof buildings and the ideal model suggests that a single knife-edge model is valid for predicting the diffracted field strength in the shadow of such buildings. This suggestion is strongly supported by the experimental results detailed in section 4.3. It should be noted however that the model is valid only if both the transmitter and receiver have a clear line of sight to the roof apex. Validity can be maintained if the transmitter is over the horizon and ducting conditions prevail but not if the receiver is near to or below the line of the sloping roof having an obstructed path to the roof apex. This condition requires the use of a double diffraction analysis and will be discussed in section 5.4.7.
5.4 Diffraction by buildings with flat roofs

In this section an analysis of diffraction by buildings with flat roofs is described. The building is visualised as two knife edges connected by a flat reflecting surface. The path geometry is illustrated in figure 5.8. The problem is to evaluate the field distribution along plane $y$ as a result of that at plane $x$ and hence determine the resultant field strength at $R$. Previous models (King & Page [1973], Whitteker [1990]) have considered this resultant field strength as the sum of the two components: one undergoing a double knife-edge diffraction and the other suffering an additional reflection in the roof surface. In this section the method put forward by the author (Haslett & Al-Nuaimi[1991]) is described in detail.

Computation is simplified if the reflected component is visualised as that due to a virtual source undergoing an inverted double knife-edge diffraction as shown in figure 5.9. The virtual source $S'$ in figure 5.9 is the reflection of $S$ of figure 5.8 in the line of the roof. It can then be seen that the field distribution in plane $x'$ of figure 5.9 is the mirror image of that in plane $x$ of figure 5.8. To calculate the resultant at $R$, the magnitude of source $S'$ should be multiplied by the surface reflection coefficient as appropriate. The contributions due to $S$ in figure 5.8 undergoing a straightforward double knife edge diffraction and $S'$ in figure 5.9 undergoing an inverted double knife-edge diffraction must be summed phasorially to give the resultant field strength at $R$.

Visualising the reflected component as in figure 5.9 allows Babinet's principle to be used in its solution. The reflected component is the difference between two further components: a double knife edge diffraction and a single knife-edge diffraction as shown in figure 5.2. Thus the entire problem may be solved by evaluating the diffracted field strength for the two double knife edge systems and one single knife edge system.
5.4.1 Conversion of path parameters for evaluation of diffracted field strength

Comparison of figures 4.7 and 2.4 reveals significant differences between the geometry used in the analysis of Millington, Hewitt and Immirzi and that which is most easily obtained by measurement on a radio path obstructed by a flat roofed building. In order to apply the method of Millington, Hewitt and Immirzi it is necessary to express \( a, b, c, h_1 \) and \( h_2 \) of figure 2.4 in terms of \( a', b', c', h \) and \( \theta \) of figure 4.7.

Figure 5.10 combines the two geometries thus allowing conversions to be made from one set of parameters to the other. Assuming \( a', b', c', h \) and \( \theta \) are known:

From the diagram,

\[
\phi = \arctan \left( \frac{a'tan\theta - h}{a' + b' + c'} \right) \tag{5.5}
\]

\[
h_1 = a'\tan(\theta - \phi) \tag{5.6}
\]

\[
a = a'\sec\theta + h\tan\phi \tag{5.7}
\]

thus

\[
h_1 = a'\tan(\theta - \phi)\sec\theta + h\tan\phi\tan(\theta - \phi) \tag{5.8}
\]

hence

\[
h_1 = \frac{a'\tan(\theta - \phi)\sec\theta}{1 - tan\phi\tan(\theta - \phi)} \tag{5.9}
\]

and

\[
a = \frac{h_1}{\tan(\theta - \phi)} \tag{5.10}
\]

similarly

\[
h_2 = (c'tan\phi + h)\cos\phi \tag{5.11}
\]

\[
c = c'\sec\phi - h^2\tan\phi \tag{5.12}
\]

Finally \( b \) may be determined by noting that

\[
a + b + c = (a' + b' + c')\sec\phi \tag{5.13}
\]

The system parameters may therefore be converted from site measurements to the form required for application of the method of Millington, Hewitt and Immirzi.
It is therefore possible, given the parameters of the path geometry of figure 4.7 to determine values for $\rho, \gamma_1$, and $\gamma_2$ as shown in figure 2.10. Hence the normalised electric field strength $E_n'$ for the component undergoing a straightforward double knife edge diffraction, eg from source $S$ in figure 5.10 without reflection is given by

$$E_n' = \frac{G(\rho, \gamma_1) + G(\rho, \gamma_2)}{2j} \quad (5.14)$$

### 5.4.2 The path geometry for the reflected ray

As stated previously, the normalised field strength of the component undergoing a reflection may be determined by evaluating the difference between a double knife edge diffraction and a single knife edge diffraction. In order to compute the necessary double knife diffraction it is first necessary to again express $a, b, c, h_1$, and $h_2$, in terms of $a', b', c', \theta$ and $h$. Figure 5.11 illustrates the situation. $S'$ in figure 5.11 is the reflection of source $S$ of figure 5.10 in the line of the roof. Thus $\theta$ has the same value in figures 5.10 and 5.11. However $\phi'$ in figure 5.11 is significantly different from $\phi$ in figure 5.10, in fact

$$\phi' = \arctan \left| \frac{a \tan \theta + h}{a' + b' + c'} \right| \quad (5.15)$$

A similar procedure to that given earlier yields

$$h_1 = -\frac{a' \tan(\theta - \phi') \sec \phi'}{1 - \tan \phi' \tan(\theta - \phi')} \quad (5.16)$$

$$a = \frac{-h_1}{\tan(\theta - \phi')} \quad (5.17)$$

$$h_2 = (h - c' \tan \phi') \cos \phi' \quad (5.18)$$

$$c = c' \sec \phi' + h_2 \tan \phi' \quad (5.19)$$

Negative values of $h_1$ and $h_2$ will give rise to negative values of $p$ and $q$. This in turn will lead to the necessary area of integration changing from that shown in figure 2.5 to that as shown in figure 5.12. The surface integral of the shaded area may be evaluated by noting that the integral over the entire surface is $2j$. Thus the integral over the
shaded area in figure 5.12 is \((2j-G(\rho, \gamma_3)-G(\rho, \gamma_4))\). It should however be noted that what is required is not just the value of this integral but the difference between this and the integral for a single knife edge located in the position of the right hand wall of the building. Now the parameters \(p\) and \(q\) as used in the method of Millington, Hewitt and Immirzi are simply Fresnel parameters, \(p\) being the Fresnel parameter for the left hand knife edge taken alone and \(q\) being this parameter for the right hand knife edge taken alone. The area of integration for the right hand knife edge taken alone is shown in figure 5.13. The horizontal boundaries of the two areas (figures 5.12 and 5.13) are coincident. Thus the difference between the areas of integration may be determined graphically. This difference is illustrated in figure 5.14. The shaded area of figure 5.14 therefore represents the field strength of the component which undergoes a double knife edge diffraction plus reflection in the roof. The shaded area is not in standard position. However examination of figure 5.14 shows that the integral of the shaded area may be evaluated as the difference between two areas which may be manoeuvred to be in standard position. The normalised electric field strength, \(E_{n''}\), of the component undergoing a reflection in the roof is given by

\[
E_{n''} = \frac{G(\rho, \gamma_4)-G(\rho, \gamma_5)}{2j}
\]  

(5.20)

5.4.3 Determining the resultant electric field

The resultant normalised electric field strength in the shadow of the flat roofed building, \(E_n\) is then given by

\[
E_n = E_{n'} + \Gamma E_{n''} \exp(j2\pi\delta l/\lambda)
\]  

(5.21)

In equation 5.21 \(\Gamma\) represents the reflection coefficient and \(2\pi\delta l/\lambda\) represents a phase shift. It should be noted that \(E_{n'}\) and \(E_{n''}\) are the ratios of the received electric field strength in both magnitude and phase for the geometries of figures 5.8 (ignoring roof reflection) and 5.9 respectively. It can be seen that the free space path lengths (SR
in figure 5.8 and $S'R$ in figure 5.9) are not generally equal. Considering figures 5.8 and 5.9 and assuming that $(h+a'tan\theta)\ll (a'+b'+c')$ the path length difference $\delta l$ is given by the equation

$$\delta l = \frac{2a'htan\theta}{a'+b'+c'}$$

(5.22)

5.4.4 Comparing predictions with experimental measurements

One problem experienced in applying equation 5.21 to a practical situation is determining a suitable value for $\Gamma$, the reflection coefficient of the surface of the roof. The reflection coefficient experienced by an electromagnetic wave incident on a smooth plane surface depends on the electrical characteristics of the surface, the angle of incidence, the polarisation and frequency of the wave.

Kerr (1988) building on standard theory such as described by Stratton (1941) derives the reflection coefficient for both vertical and horizontal polarisations over a horizontal surface. The reflection coefficient for vertically polarised transmissions being given by

$$\Gamma_v = \frac{ksin\phi - \sqrt{(k - cos^2\phi)}}{ksin\phi + \sqrt{(k - cos^2\phi)}}$$

(5.23)

where: $k$ is the complex dielectric constant of the reflecting surface;

$\phi$ is the grazing angle

and for horizontally polarised transmissions, the reflection coefficient is given by

$$\Gamma_h = \frac{sin\phi - \sqrt{(k - cos^2\phi)}}{sin\phi + \sqrt{(k - cos^2\phi)}}$$

(5.24)

For a perfectly conducting surface the complex dielectric constant assumes infinite magnitude, hence $\Gamma$ would be +1 for a vertically polarised wave and -1 for a horizontally polarised wave travelling over a horizontal roof. Adopting values of +1 and -1 for the reflection
coefficient allows the two possible extremes of diffracted field strength to be predicted. In figures 5.15 to 5.19 the experimental results reported in chapter 4 for diffracted field measurements in the shadow of flat roofed buildings are compared with predictions given by equation 5.21 for the relevant path parameters. Predictions are made for assumed values of \( \Gamma \) of +1, 0 and -1. An assumed reflection coefficient of zero gives the prediction for a double knife edge system with no connecting reflecting surface.

Examination of figures 5.15 to 5.19 reveals that the polarisation dependence of the measured diffracted field is virtually insignificant compared with that predicted for the case where the connecting surface was a perfect conductor. Indeed, the prediction for the situation where the assumed reflection coefficient is zero appears to give a credible estimate of the diffracted field with the majority of errors tending to overestimate the strength of the field. This represents a highly significant finding as, when attempting to predict interference levels, it is generally thought best practice if any errors in models used tend to overestimate the interfering signal strength. If this finding can be supported it would therefore be possible to recommend the double knife edge model when predicting the diffracted field in the shadow of a flat roofed building.

The likely effects of practical differences from the ideal slab model exhibited by practical buildings will now be examined in order to lend theoretical support to the experimental measurements.

5.4.5 The effect of practical differences from the ideal slab model

A perfectly smooth, perfectly conducting, rectangular slab is obviously an idealised model which may be used only as a basis from which to attempt to model practical buildings. If the roof material is a poor conductor then the magnitude of the reflection coefficient will be less than unity making the prediction for the resulting electric field to tend towards that for a double knife edge system. Surface roughness will tend to reinforce this effect by reducing the coherence of the
wave undergoing reflection. An inspection of building roofs reveals that most roofs should appear smooth to centimetre wavelength incident signals but rather tend to vary from a different initial assumption for the slab model, namely that the roof profile is a straight line connecting the two side walls. All roofs slope at various angles for drainage purposes. Many are surrounded by parapet walls a metre or so in height. The fact that the roof lies below the height of the side walls will result in different predictions for the diffracted field strength. It will now be shown how the slab model developed may be extended to allow predictions to be made where the reflecting roof is sunk below the side walls.

5.4.6 Extension to the parapet wall situation

The model so far has dealt with the situation where the reflecting surface is at the height of the side walls. It is quite common for this surface to be below the side walls, for example when the roof is surrounded by a parapet wall. This may be accounted for by lowering the left hand knife edge in figure 5.9 so that it extends below the line joining the top of the side walls by an amount equal to twice the height of the parapet wall. As the virtual source $S'$ is the source $S$ reflected in the line of the roof (which is now not the same as the line joining the side walls) $S'$ will also be lowered by an amount equal to twice the height of the parapet wall. This situation is illustrated in figure 5.20. The effects of doing this are twofold; first, the magnitude of the reflected component reduces and, secondly, the phase relationship between the two components changes. The first effect leads to the signal level tending towards that for a double knife edge. The second effect means that it is possible for the phase relationship between the "direct doubly diffracted" and the "reflected diffracted" waves to reverse so that it is possible for the diffracted field with a reflecting surface present to be greater than that for a perfectly absorbing building even when there is a negative surface reflection coefficient.
Figure 5.21 predicts the diffraction loss as a function of parapet wall height for a typical site shielding geometry with building thicknesses of 10m, 40m, 70m, and 100m. A surface reflection coefficient of -1 is assumed in this instance. It can be seen that the diffracted field strength varies most rapidly for the narrower buildings. Comparing the path lengths from apex to apex in figures 5.9 and 5.20 the difference is given by

\[ \sqrt{(b'^2 + y^2)} - b' \]

which is approximately equal to \( y^2 / 2b' \) where \( y \) is equal to twice the parapet wall height. If \( y/2 = \sqrt{\lambda b' / 4} \) then the path length difference from apex to apex of the direct and reflected rays will equal half a wavelength thus reversing the phase relationship between them. This suggests that the parapet wall height expressed as a multiple of \( \sqrt{\lambda b'} \) is critical in determining whether the phase relationship of the direct and reflected rays has been significantly altered from the situation where the reflecting surface is at the same level as the side walls. In fact if the parapet wall height is greater than approximately \( \sqrt{\lambda b' / 10} \) the diffracted field strength will be closer to that for a perfectly absorbing building than a perfectly reflecting one. This allows certain guidelines to be drawn regarding the significance of the height of a parapet wall for different building thicknesses and different operating frequencies. Table 5.1 shows the value of parapet wall height above which the phase of the reflected ray will be significantly altered thus rendering the slab model illustrated in figure 5.8 invalid. Under these circumstances the double erect knife edge model should be used.
5.4.7 Application of double knife-edge diffraction to buildings with a wedged roof

The conclusion of section 5.3 is that a single knife-edge model is appropriate for predicting the diffracted field strength if the transmitter and receiver both have a clear view of the roof apex. This proviso may not always be adhered to, most notably where the receiver is close to the building and well below the roof apex as illustrated in figure 5.22. Diffraction by the left hand edge of this building may be regarded as insignificant but diffraction by both the apex and the right hand edge of the building must be considered. Figure 5.23 shows how the parameters of a path including a wedge roofed building may be converted to those necessary for implementation of the method of Millington, Hewitt and Immirzi.

Considering the geometry of figure 5.23 and assuming that $a'$, $b'$, $c'$, $\varepsilon$, $\theta$ and $h$ are known and $h_1$, $h_2$, $a$, $b$ and $c$ are to be calculated it can be seen that

\[
\phi = \arctan \left( \frac{(a' + ib') \tan \theta - h}{a' + b' + c'} \right) \tag{5.25}
\]

\[
h_1 = a \tan(\theta - \phi) \tag{5.26}
\]

\[
a = (a' + ib') \sec \phi \tan(\theta - \phi) \tag{5.27}
\]

thus

\[
h_1 = \frac{(a' + ib') \sec \phi \tan(\theta - \phi)}{1 - \tan \theta \tan(\theta - \phi)} \tag{5.28}
\]
and
\[
a = \frac{h_1}{\tan(\theta-\phi)} \tag{5.29}
\]
\[
h_2 = (c'\tan\phi + h - \frac{1}{2}b'\tan\varepsilon)\cos\theta \tag{5.30}
\]
\[
c = c'\sec\phi - h_2\tan\phi \tag{5.31}
\]
Finally, \( b \) may be determined by noting that
\[
a+b+c=(a'+b'+c')\sec\phi \tag{5.32}
\]
If the receiver is gradually lowered from grazing a transition occurs from the situation where diffraction by the apex only may be regarded as significant to the case where double knife edge diffraction must be considered. This area of transition may be judged intuitively but a more complete picture is achieved if the diffraction by the second (lower) knife edge is considered throughout. For the near-grazing case the parameter \( q \) is negative whereas \( p \) is positive. This leads to an area of integration on the Fresnel surface as shown in figure 5.24. It can be seen from figure 5.24 that the appropriate surface integral may be evaluated as the difference between two areas in standard position as discussed in section 2.2. Using the parameters shown in figure 5.24 the normalised electric field strength \( E_n \) is given by
\[
E_n = \frac{G(p,\gamma_6) - G(p,\gamma_7)}{2j} \tag{5.33}
\]
In order to illustrate the transitional effect as double knife-edge diffraction becomes significant, figure 5.25 shows the predicted diffracted field strength in the shadow of a wedged roof building when it is illuminated from a distance of 1000 metres by a source at the same height as the building apex. The building is assumed to be symmetrical and of 10m thickness with its roof sloping at an angle of 20 degrees to the horizontal. The receiver is taken to be 10m from the building (15m from the apex) and its height varies from grazing to 10m below this level. A comparison is given between the single and double knife-edge models. It can be seen from figure 5.25 that the single knife edge model is reasonably valid if the receiver is above the line joining the two knife edges. Below this level, however, the second knife edge has a significant effect on the strength of the diffracted field and thus should be considered when predicting the field strength in the shadow of a building with a wedged roof.
5.4.8 An investigation in the validity of approximations to the FSI double knife edge attenuation function

Section 2.3.2 describes four procedural approximations to the FSI method of determining the diffracted field strength in the shadow of two parallel absorbing knife edges. These were first developed for use in predicting the diffracted field in the shadow of mountain ridges rather than buildings. They are all unsuitable for extension to include the presence of a reflecting surface but, as the double erect knife edge model appears to give a credible estimate of the diffracted field strength, these approximations may yield an acceptably accurate prediction whilst being less costly on computing time. Figure 5.26 gives a comparison of predictions for the five methods for the case where two knife edges of equal height are illuminated with grazing incidence. The transmitter is taken to be 10 kilometres distant and the separation of the knife edges is 10 metres for the predictions shown in figure 5.26(a) and 100 metres in 5.26(b). The receiver is located 200 metres the other side of the knife edges and is varied in height from grazing to 20 metres below this level. The wavelength is taken to be 30 millimetres.

It is of note that the Deygout and Japanese methods give the same prediction for these path geometries, each predicting a constant 6dB extra diffraction loss compared with the Bullington equivalent knife edge model. The problem of using the Epstein-Peterson method when there is little separation between the knife edges is clearly shown in figure 5.26(a) with a diffraction loss prediction less than that for the single knife edge. The FSI solution (Millington et al.) tends towards the single knife edge (Bullington) value for small diffraction angles and the Japanese/Deygout prediction for large diffraction angles. The Japanese/Deygout prediction is close to the exact solution for both geometries for large diffraction angles, but a small increase in the height of the first edge would result in a switch of "main edge" for the Deygout model leading to a prediction very nearly equal to the Epstein-Peterson prediction. The non-reciprocity of the Japanese method means that, if transmitter and receiver were interchanged, it too would give a prediction very close to the Epstein-Peterson method. It is
therefore concluded that only the FSI method may be used with confidence when predicting the diffracted field strength for a double knife edge system.

5.4.9 Summary of flat roof diffraction

A method has been developed whereby the diffracted field strength in the shadow of a smooth slab may be predicted, given the value of the surface reflection coefficient. In order to apply this method to practical buildings the effect of imperfections must be considered. It can be seen from table 5.1 that the parapet wall heights required to render the slab model invalid are not great. Indeed many of the heights stated would be present as variations on a "flat" roof for drainage purposes. If one adds to this the fact that the effect of surface roughness and imperfect reflection is to make the resulting field strength tend towards that for an absorbing slab then the conclusion which can be drawn is that, unless the nature and profile of the reflecting surface are accurately known, the perfectly absorbing slab (or double knife-edge) model is the most appropriate for predicting the diffracted field strength in the shadow of a flat roofed building. Due to the typically small separation between the two diffracting edges, compared with the path dimensions, it is important that the Fresnel surface integral method is used to predict the diffracted field strength rather than an approximation such as the Epstein-Peterson method.

Nevertheless, the possibility of error always exists. Whilst a case has been put forward for regarding a flat roofed building as a double knife edge system, the reality of the situation is that the effective reflection coefficient at the surface of the roof may lie anywhere between -1 and +1. The range of predictions assuming these two extremes will depend on the building width and the values of the Fresnel parameters $p$ and $q$. Figures 5.15 to 5.19 include the effect of varying the surface reflection coefficient from -1 to +1. From this it can be seen that the maximum value for a reflection coefficient of +1 is only a few dB greater than that for zero reflection coefficient. Combining this with the fact that positive values of effective reflection
coefficient approaching unity are expected to occur only rarely (with vertically polarised transmissions over surfaces with extremely high conductivity) results in the conclusion that the probability of seriously underestimating diffracted field strength by using the double knife edge model is small. Figures 5.15 to 5.19 suggest that the double knife edge system will yield generally acceptable predictions of the diffracted field strength with any errors tending to overestimate the strength of the field; a correct philosophy for interference level prediction.

5.5 Summary and interim conclusion

The observation that if a wedged roof forms the diffracting obstacle, and is clearly viewed from both transmitter and receiver, then a single absorbing knife-edge model produces an acceptably accurate prediction of the diffracted field strength has been given theoretical support. It therefore seems appropriate to recommend this model for use in predicting the diffracted field in the shadow of buildings with wedged roofs. Analysis of the flat roof building geometry for the purposes of predicting diffracted field strength has been shown to be considerably more involved. Analysis has concentrated on firstly considering a perfectly conducting, perfectly smooth rectangular slab and then extending this to consider practical "imperfections" of real buildings. The conclusion reached was that, unless the electrical characteristics and detailed profile of the roof are known, then a double erect knife edge model is most appropriate for use.

It is of note that analyses so far have been restricted to the two dimensional path profile assuming a single propagation path. This is appropriate when one dominant diffraction path can be identified as is usually the case when the receiver is extremely close to the obstructing building. This becomes less appropriate when the receiver - building distance increases such that diffraction around the sides of the building and via the roof top must be considered. The next chapter describes an extension to the experimental programme such that the diffracted field in the shadow of buildings located a considerable distance from the receiver was measured.
Figure 5.1 Complementary knife-edge obstacles
Figure 5.2 Babinet equivalent of inverted knife-edge

\[ A = B - C \]
Figure 5.3 Wedge system showing four ray model

Figure 5.4 Variation of diffraction loss with internal wedge angle
Figure 5.5 Knife-edge systems for single and double reflections
Figure 5.6 Babinet equivalent for the system shown in figure 5.5(a)

$A = B - C$
A = B - C

Figure 5.7 Babinet equivalent for the system shown in figure 5.5(b)
Figure 5.8 Flat roof geometry

Figure 5.9 Illustration of equivalent diffraction path for reflected wave
Figure 5.10 Comparison of double knife-edge and flat roof building geometries

Figure 5.11 Comparison of geometries for the reflected ray
Figure 5.12 Area of integration for negative values of $p, q$

Figure 5.13 Area of integration for a single knife-edge
Figure 5.14 Difference between areas of integration of figures 5.12 and 5.13
Figure 5.15 Comparison between measurements taken at location V4 and the slab model
Figure 5.16 Comparison between measurements taken at location V5 and the slab model
Figure 5.17 Comparison between measurements taken at location V6 and the slab model
Figure 5.18 Comparison between measurements taken at location V7 and the slab model
Figure 5.19 Comparison between measurements taken at location V8 and the slab model.
Figure 5.20  Inverted knife-edge geometry considering parapet wall

Figure 5.21  Diffraction loss as a function of parapet wall height
Figure 5.22  Diffraction by a wedge-roofed building
(receiver has no line of sight to the apex)

Figure 5.23  Comparison of double knife-edge and
wedge roof building geometries
Figure 5.24 Area of integration for positive $p$, negative $q$

Figure 5.25 Diffraction loss as a function of movement into shadow (building with wedged roof)
Figure 5.26 Comparison of predictions using different models

a) edge separation = 10 metres  
b) edge separation = 100 metres
EXPERIMENTS INVOLVING MULTIPLE PATH DIFFRACTION

6.1 Introduction

It is common for signal strength prediction models to consider only the two dimensional great circle path profile. In any environment there is potential for errors to be introduced due to the fact that lateral profile variations are ignored. Assis (1973) has reported that errors of ± 10 dB may result over typical irregular terrains whereas Bachynski and Kingsmill (1962) have investigated the diffracted field strength in the shadow of knife edge obstacles whose profile varies laterally. In an urban environment the potential for error is much greater than over irregular terrain. It is possible for the most significant diffraction path to be around the side of a building rather than over the roof. In general it is not uncommon to be able to view a large building from a distance of a few kilometres. In this situation, diffracted fields from both sides of the building and over the roof may be of a significant magnitude. Clearly, considering only the two dimensional path profile is inappropriate in this situation.

In this chapter experiments are described where the obstructing building was a considerable distance from both transmitter and receiver. This meant that, given the angular beamwidth of the antennas employed, no single dominant diffraction path could be identified. The results would therefore be expected to reveal the effects of multiple path diffraction.

6.2 Experimental equipment

The same transmitter and receiver as for the measurements made on the University of Glamorgan campus were used for these experiments. It was no longer viable, however to leave the mobile receiver mounted on its trolley. Most of the measurements described were made in city streets and it was necessary to elevate the antenna above "foreground clutter" such as fences or trees. The measuring receiver was installed in a van.
equipped as a mobile measuring laboratory. A telescopic mast was mounted onto the van. This mast would allow the receiving antenna to be raised to a height of 10 metres above ground level. At the head of the mast was an electrically steerable platform allowing the azimuth and elevation of the receiving antenna to be varied. It was thus possible to move along the roadside and monitor the strength of the received signal at intervals of distance whilst keeping the receiving antenna pointed at the obstructing building. The 20 dBi horn antenna used with the transmitter has a 3 dB beamwidth of approximately 20°. As the maximum angle subtended by either of the buildings investigated when viewed from the transmitter was less than 2°, the building and relevant surrounding space were assumed to be nearly uniformly illuminated.

6.3 Measurement sites

Additional site parameters were required in order to define the propagation path where more than one diffraction path was involved. Figure 6.1 shows a plan view of a rectangular building and gives details of the site geometry measurements made. Additionally, the height of the roof and the receiving antenna were recorded using the transmitter height as a zero reference. The path lengths involved meant that a flat earth approximation was justified. Referring to figure 6.1, measurements were made keeping \( d_1, d_2 \) and \( \theta \) constant with the receiving antenna being moved horizontally so that dimension \( x \) of figure 6.1 varied.

The first building investigated was a fire station practice tower. The small horizontal dimensions (4 metres by 3 metres) may be somewhat unrealistic but the building offered the advantages that the site geometry could be accurately measured and also that it was in an isolated position. This meant that the likelihood of measurements being corrupted by signals scattered by adjacent obstacles was small. Referring to figure 6.1 the site geometry for building 1 is defined below.
The second building used as a diffracting obstacle was an office block in a city centre location which was felt to be more typical of an urban environment where building diffraction models would be required. In this location the possibility of receiving signals scattered from adjacent tall buildings was considerably greater than for the first building.

The third building was a block of flats in a residential area. Although the area did not have the density of tall buildings as was the case in the vicinity of building 2, the possibility of receiving scattered signals was still judged to be considerable.
site geometry for building 3
w: 23 metres
t: 23 metres
θ: 90 mrad
\(d_1\): 1790 metres
\(d_2\): 520 metres
Tx height: 0 metres
Rx height: -35 metres
Roof height: -5 metres

6.4 Results

The results for the three buildings investigated are displayed graphically in figures 6.2 to 6.4. The dimension \(x\), against which diffraction loss is plotted, is indicated on figure 6.1. The measurement points are joined by straight lines so that any "interference pattern" due to the existence of three propagation may be detected.

It should be noted that the measurements for buildings 1 and 2 entailed horizontal movement of the receiving antenna from grazing incidence on one side of the building to just beyond grazing incidence on the other side. Where building 3 formed the diffracting obstacle it was not possible to move the receiving antenna through the required distance and the last measurement was made deep in the shadow of the building.

Examination of figures 6.2 to 6.4 reveals that the signal strength varies considerably with small horizontal movement of the receiver. This is probably evidence of an interference pattern caused by a significant diffracted field being incident on the receiver from more than one direction. These results demonstrate the need to consider more than one diffraction path, especially as the obstacle-receiver distance increases.
6.5 Summary and interim conclusion

The experimental work has been extended so that it is no longer limited to the situation where the receiver is extremely close to the obstructing building. Results have been obtained that will now allow a general building diffraction model to be tested. When the obstacle receiver distance is large the results demonstrate the need to extend the theoretical model beyond considering only the two-dimensional great circle path. The nature of the variation of electric field strength with distance in the shadow of the building suggests that large variations in signal over small distances will be the norm at large distances from the obstacle. Consideration must therefore be given to the most suitable way of describing the field strength in the shadow. Simply predicting the field strength at a point will not be sufficient. It may be that the average signal strength over a small distance either side of a fixed point will be the most appropriate indication of signal strength when interference prediction procedures are carried out.

In the next chapter the theoretical model is extended to include the possibility of multiple path propagation. Theoretical predictions are tested against the results reported. The complete model is then compared with other diffraction models developed concurrently with this study at other institutions.
Figure 6.1  Site geometry measurements as viewed from above
Figure 6.2 Measurements made in the shadow of building 1
Figure 6.3 Measurements made in the shadow of building 2
Figure 6.4 Measurements made in the shadow of building 3
EXTENSIONS TO DIFFRACTION MODELS

7.1 Introduction

It is clear from the results displayed in figures 6.2 to 6.4 that a two-dimensional model considering only the great circle path is inappropriate for use where the receiver is at such a distance from the building that a significant diffracted field may arrive via more than one route. Leaving the judgement of such a situation to intuition is obviously potentially unsafe. If a general model included contributions from all three potential diffracting edges then there would be no need to rely on intuitive judgement. If the diffracted field strength via a particular edge was negligible then it would be revealed as such in the complete analysis.

This chapter gives details of an extension to the two-dimensional FSI model such that multiple path diffraction may be considered. Comparisons are given between predictions made and the measured results detailed in chapter 6.

Recent work on microwave frequency diffraction has not been exclusive to the University of Glamorgan. During the period of this study, separate methods capable of dealing with similar situations have been developed at other institutions. Of particular relevance are models developed at Eindhoven University of Technology (Netherlands) utilising the Uniform Theory of Diffraction (UTD) and models developed at the Rutherford-Appleton Laboratory (United Kingdom) and Alcatel-Telettra (Italy) involving the Parabolic Equation (PE) method. Both these additional models are capable of predicting the diffracted field strength in the shadow of buildings at microwave frequencies.

The UTD and PE methods are described in this chapter. Additionally, a test case is described whereby all three methods (FSI, UTD, PE) are used to predict the diffracted field strength in the shadow of a perfectly conducting rectangular block at 1 GHz for both vertical and horizontal polarisations.
7.2 Extending the FSI model

Considering the plan view of a rectangular building such as shown in figure 6.1, it is possible to define parameters for the diffraction paths around the sides of the building in a similar manner to the path over the roof. Parameters $a$, $b$, $c$, $h_1$, and $h_2$ are indicated on a plan view of a rectangular building in figure 7.1. The FSI method may be used to predict the diffracted field strength at point $R$ for that diffraction path. The relevant parameters for diffraction via the other side of the building and via the roof may be determined in a similar manner.

In this way, the three-dimensional diffraction problem is separated into three two-dimensional paths, each of which may be solved by the FSI method. The three predicted normalised field strengths must then be added phasorially to produce a resultant normalised field strength at point $R$. The three two-dimensional paths are not, however, separate. They do, in fact, have regions of overlap as indicated in figure 7.2. The contribution of the wavefronts passing through these regions will be considered twice when predicting the resultant diffracted field. Ideally, the contribution due to these regions should be determined and then deducted from the resultant of the separate predicted fields to give a more accurate prediction. The determination of this contribution is not straightforward but, due to the orthogonal nature of the overlapping two-dimensional systems, it may be approximated by the product of the normalised field strengths predicted for these two-dimensional systems. This approximation is exact (subject to the approximations of the Fresnel integral) for a zero thickness screen but becomes slightly less accurate as the thickness of the building increases. However, the contribution of the overlapping regions is only significant where the straight line joining the source and receiver passes near to the corner of the building.

The same uncertainties regarding the electrical characteristics and detailed profile of the reflecting surface apply to the three diffraction path situation as applied to the single path model. It may again be judged appropriate to ignore reflections and use a double absorbing knife edge model for each of the three paths.
7.3 Comparison between predictions and measurements

In figures 7.3 to 7.5 the measurements of field strength made in the shadow of the buildings detailed in chapter 6 are compared with theoretical predictions. The prediction method used is the three dimensional extension to the FSI method in its simplest form. Surface reflections are ignored, corner diffraction terms are not considered making this procedure very straight forward to implement using well established procedures.

Figure 7.3 compares predictions with results for the isolated building. The similarity between predictions and measurements is very encouraging in this instance. It is clear that the predicted interference pattern is observed in practice. There is a slight tendency for the diffracted field strength to be overestimated suggesting that there is a negative effective reflection coefficient at the building surface. In the case of the other two buildings, the agreement with measurements is less convincing. The predicted interference pattern is of a very small spatial wavelength such that it would not be detected by making measurements at 90 centimetre intervals as was the case. However, certain observations may be made from figures 7.4 and 7.5. There is a similarity between prediction and measurements near the shadow boundary, that is for small values of diffraction loss. Deep in the shadow of the building some measurements record a field strength in excess of any predicted level. It is of note that this occurs only in the shadow of the buildings for which neighbouring buildings represented potential scatterers. It may be that, deep in the shadow of buildings located in an urban environment, scatter from adjacent buildings forms the dominant propagation mechanism.

It is therefore fortunate that one of the buildings (building 1) was in an isolated position where diffraction was likely to be the dominant propagation mechanism for all receiver locations. The comparison given in figure 7.3 suggests that the simplest extension of the FSI method to the three dimensional situation is appropriate for predicting the signal strength in the shadow of practical buildings.
7.4 Alternative methods of predicting diffracted field strength

As stated in section 7.1, concurrent work at separate institutions has concentrated on similar problems. These studies have yielded two alternative methods for determining the diffracted field strength in the shadow of buildings. They utilise the Uniform Theory of Diffraction (UTD) and the Parabolic Equation (PE) methods respectively. These two methods will now be described and predictions obtained compared with those obtained from the FSI method.

7.4.1 The Uniform Theory of Diffraction

UTD is in fact an extension of another diffraction prediction procedure known as the Geometric Theory of Diffraction developed by Keller (1962). In section 2.2 it was noted that, deep in the shadow of a single knife edge obstacle, the diffracted field strength may be determined by regarding the source of this field as a line source located at the diffracting edge with a radiation pattern that varies with \( \csc \theta \), \( \theta \) being the diffraction angle. If this is taken to be correct then computation of the diffracted field strength becomes much faster than employing the integral methods described in section 2.2. The additional speed will become more apparent when multiple knife edge diffraction is considered. This is the basis of GTD. A problem occurs as the diffraction angle reduces and in fact GTD in its simplest form produces a discontinuity in predicted field strength at the shadow boundary. If an edge is illuminated by a plane wave then, well above the edge in the illuminated region the wave will still be a plane wave whereas deep in the shadow it will be a cylindrical wave centred at the diffraction edge. In between these two extremes (in the vicinity of the shadow boundary) the nature of the wave is neither plane nor cylindrical. This region is known as the transition region. UTD overcomes the discontinuity problem experienced with GTD by formally defining the transition region. If \( |v| \) (where \( v \) is the Fresnel parameter for the diffraction path under investigation) is less than a particular value then the field strength should be determined by use of Fresnel Integral techniques. If it is greater than this value then GTD
may be used. James (1986) suggests a value of approximately 3 for \( |v| \) is appropriate. A locus of points with a fixed value of \( |v| \) describes a parabolic cylinder in two-dimensional space as shown in figure 7.6. If the observation point of interest is within the area defined by the parabola then the Fresnel integral method should be used. Outside this region then the asymptotic approximations of GTD may be regarded as valid. By allowing GTD to be applied only when \( |v| \) exceeds a certain value, UTD produces predictions that are virtually indistinguishable from those produced by Fresnel integral methods, whilst still allowing considerable computational savings to be made.

7.4.1.1 Multiple edge diffraction utilising UTD

A further assumption of GTD methods is that the diffracted field strength is dependent only on the strength of the field incident at the diffracting edge. For multiple edge diffraction therefore the diffracted field strength may be predicted by considering the first edge as the signal source for the second edge (where the second edge lies deep in the shadow region of the first edge) or regarding the original source as the signal source for the second edge (where the second edge is clearly illuminated by the source) If, however, the second edge lies in the transition region of the first edge then no apparent source can be identified which causes a difficulty in predicting the diffracted field in the shadow of the second edge. This difficulty may be overcome to an acceptable degree of accuracy by employing what are known as "slope diffraction terms". These terms are additional to the incident field on the diffracting edge and are based on the first derivative of the incident field at the edge (see James [1986] pp. 138-143).

The value of slope diffraction terms becomes apparent if the two geometries of figures 5.8 (ignoring the reflecting surface) and 5.9 are considered. The diffraction angles are the same for both situations and therefore GTD would yield the same prediction for the diffracted field strength in the shadow of the second (right hand) edge. However, the derivative of the incident field is in the opposite sense for the two situations yielding slope diffraction terms of opposing signs. Thus UTD
can be used to show that the two configurations would give different
diffracted fields as one would expect intuitively. This configuration
is, of course, a requirement for determining the diffracted field in
the shadow of obstacles involving reflecting surfaces such as flat
roofed buildings.

A further possibility is that the second diffracting edge lies in the
transition region of the first edge and the observation point lies in
the transition region of the second edge. This is the most difficult
situation to solve using UTD/GTD methods whereas it is ideal for
solution using the FSI method implying that diffraction angles would be
small.

7.4.1.2 The application of GTD/UTD to
diffraction by buildings

The most relevant work in applying GTD/UTD to the prediction of the
diffracted field strength in the shadow of a building has been carried
out recently at the Eindhoven University of Technology in the
Netherlands. Building on the work of Kouyoumjian and Pathak (1974),
of predicting the diffracted field strength behind a finite-width
screen has been put forward (van Dooren et. al. [1992]). The screen
model has been extended so that the diffracted field in the shadow of a
rectangular block may be predicted (van Dooren and Herben [1993a]) and
the theoretically predicted polarisation-dependence of the diffracted
field in the shadow of a highly conductive block is demonstrated by
means of small-scale experiments. Further experiments (van Dooren and
Herben [1993b]) have demonstrated that the diffracted field exhibits
little polarisation dependence where the block is made from absorbing
material. The paper gives details of an heuristic extension to the UTD
method to deal with imperfect reflectivity in the obstacle surface.
Predictions are again favourably compared with results of small scale
experiments. The geometry of the experimental arrangement was chosen
such that the problem associated with overlapping transition regions
did not materialise.
7.4.2 The Parabolic Equation (PE) method

The Parabolic Equation method was first introduced into radio wave propagation by Fock (1946) but the large computational requirement has meant that it has not been exploited until recently. It has now been shown to be a powerful tool for modelling propagation in the troposphere. Methods available draw on experience developed using the PE method to model underwater acoustics. Its application to predicting the nature of radio propagation over irregular terrain has been explained in depth by Craig (1988), Levy (1990) and McArthur (1991).

The PE method is distinctly different from the FSI and UTD methods which have entailed defining the exact location of source and receiver. All the link parameters have been determined by the position of any obstacles relative to those two points. The result of any calculation is a prediction of the power density at the point receiver relative to that in the absence of any obstacle. The PE method differs from this in as much as the transmitter only is defined as a starting point. Moreover, it is not a point source but an aperture with a defined power distribution. Taking this as an initial condition, the method is used to predict successive wavefront power distributions taking into account any obstacles and terrain reflections. Field strength is computed along a line normal to the direction of propagation by operating on the field strength distribution of the previous line. The line being computed is "marched" across the area of interest resulting in a two-dimensional picture of the power density at all points on a grid. The PE method has the additional advantage that atmospheric structure may be included along with terrain details. This allows the effects of anomalous propagation, such as ducting, to be analysed.

McArthur (1991) has compared predictions from the PE method for a double knife edge system with those obtained from the FSI method and found them to be indistinguishable.

One problem with using the PE method is that computer run time is usually several minutes on a desk top computer as opposed to less than one second for a single path using the FSI method. Several minutes run time might be acceptable but it may be that the user wishes to observe
the effect of varying a link parameter such as the height of one edge or the height of a connecting roof. In such cases a few hundred "runs" are often required making the difference in computational effort required for the two methods much more marked.

The PE method must however be acknowledge as an extremely powerful propagation tool capable of tackling propagation problems that no other method can tackle satisfactorily, most notably the incorporation of atmospheric structure into the propagation path.

Until recently, the PE method could be applied only to 2-dimensional radio paths. However, Levy (1993) and Saini (1993) have both reported extensions whereby, instead of the PE method being used to march a line of field strengths across a two dimensional grid, it is used to march a surface through three dimensional space thus making it suitable to model diffraction by building shaped obstacles.

7.5 A test case

The UTD, PE and FSI methods all have a sound scientific base. It would however allow any of the methods to be used with greater confidence if they could be shown to give similar predictions for the same site geometry.

Accordingly, collaboration was arranged between the University of Glamorgan, the Rutherford-Appleton Laboratory and Eindhoven University of Technology (van Dooren, Haslett and Levy [1993]). The situation investigated entailed predicting the diffracted field strength in the shadow of a perfectly conducting block for both vertical and horizontal polarisations. Figure 7.7 gives a plan view of the site geometry. The source $S$ was taken to be fixed at a height 1 metre below the height of the top surface of the block. The receiver $R$ moved so as to vary dimension $x$ from $-15m$ to $+15m$ whilst keeping its height fixed at 5 metres below the top surface of the block.
The predictions for all three methods are shown for both polarisations at a frequency of 1 GHz in figure 7.8. The predictions for vertical polarisation is offset by 20 dB for the purpose of clarity. Agreement is very good except for vertical polarisation in the region 4m < x < 6m where there are slight differences that are probably due to the treatment of corner diffraction. All models predict the same average level of the received field in the shadow region behind the obstacle, as well as the strong polarisation dependence. It may therefore be concluded that, despite their very different basis, the three methods show remarkably good agreement for the predicted field strength behind the obstacle.

During the collaborative exercise it became apparent that the FSI method represented an easy to implement, flexible means of determining the diffracted field strength. It could deal with geometries involving near grazing diffraction angles and large diffraction angles with equal ease. Near grazing angles involve overlapping transition regions posing difficulties to the UTD method whereas large diffraction angles entail a rapid expansion of the computational domain required for the PE method resulting in an increased computational requirement.

7.6 Summary and interim conclusion

The two dimensional FSI procedure has been extended so that it may be used in situations where more than one significant diffraction path exists. Predictions have been favourably compared with measurements made in the shadow of an isolated building. However, deep in the shadow of a building located in a cluttered urban environment, scatter from adjacent buildings appears to form the dominant propagation mechanism.

Methods developed at other institutions utilising UTD and PE methods have been briefly described. All three methods have been compared for a test situation and good agreement has been shown to exist.
It therefore appears that, given the uncertainties inherent in the modelling of practical buildings, the FSI method forms a flexible, efficient means of determining the diffracted field strength in a building's shadow.

An aim of the study is to provide system planners with procedures suitable for use where a building forms part of the propagation path such that its effect on coordination distance and on likely interference levels may be determined. The next chapter shows how this may be achieved using the FSI method as a basis. The effect of simplifications (to make predictions more rapid) such as a single knife edge approximation are investigated together with the benefits they provide to the prediction procedure.
Figure 7.1 Plan view showing path parameters for double knife edge system model
Figure 7.2  Block shaped obstacle showing overlap of two-dimensional systems
Figure 7.3 Comparison between measurements and prediction for building 1
Figure 7.4 Comparison between measurements and prediction for building 2.
Figure 7.5  Comparison between measurements and prediction for building 3
Figure 7.6  Parabolic transition region around a knife-edge obstacle
Figure 7.7    Test case geometry (plan view)
Figure 7.8 Comparison of FSI, UTD and PE methods
The aim of the project reported in this thesis has been to provide system planners with useful guidelines and procedures to deal with the presence of an obstructing building in a radio path.

Theoretical work has used the Fresnel surface integral (FSI) method as a basis for developing a slab model. Extensions to the basic slab model have revealed that, particularly at microwave frequencies, small variations in the profile of the reflecting surface will cause large differences in the strength of the diffracted field. Thus, although the slab model could accurately predict the diffracted field strength in the shadow of a perfectly conducting, perfectly smooth slab, this did not simulate a practical situation. It was concluded that, unless the profile and electrical characteristics of the reflecting surface were known, a building outline could best be modelled as a double knife edge system. This model needs only readily made site geometry details to be available.

Experimental work at 11.2 GHz has shown that predictions made using this model are of generally acceptable accuracy. In this chapter the double knife edge system model is used as a basis for developing procedures in the frequency range 1-40 GHz. The procedures may be separated into two areas. Firstly, incorporating building diffraction into the determination of coordination distance is felt to be a useful contribution. Additionally, the quantifying of the effect of the presence of a building on the levels of interference from a transmitter potentially causing an interference threat (i.e. lying within the coordination area) is achieved.

In the determination of coordination distance, it is acknowledged that obtaining what may be regarded as readily available site geometry details would be too onerous a task. For example, the measurement of building thickness and orientation for all buildings in sight of a proposed receiver location at 1° intervals may be regarded as too time consuming.
It is therefore of benefit for the effect of simplified procedures without the prerequisite for this requirement to be investigated. This is done in the following section and a formal procedure for the incorporation of building diffraction in the determination of coordination distance is stated. This procedure requires that only data obtainable using a modern theodolite located at the proposed receiver site are available.

In predicting the effect of a building on interference levels due to a specified transmitter, the model in its most sophisticated form is used. However, recommendations must be made on its appropriate use in different situations. For example, where the interference is trans-horizon or line of sight. Additionally, an engineering model is suggested for use in the situation where multiple diffraction paths cause an interference pattern to be produced with the diffracted field varying greatly over small distances.

8.1 Incorporating building diffraction into the determination of coordination distance

CCIR report 724 is entitled "Propagation data required for the evaluation of coordination distance in the frequency range 1-40 GHz". It enables the user to establish a distance in any given direction within which a transmitter may pose an interference threat. Any transmitters which are located within this distance would then be subjected to a more detailed examination. The fact that an error in coordination distance can mean either that an unexpected interference situation arises or that excessive work was performed in assessing interference threats means that accurate estimation of the coordination distance is highly desirable.

Report 724 investigates two modes of propagation:

i) Mode 1 - Great circle propagation mechanism.

ii) Mode 2 - Scattering from hydrometeors.
This proposed method deals exclusively with propagation mode 1 - great circle propagation mechanisms.

Section 8.1.1. gives a brief outline of the method by which coordination distance is determined. This allows the sensitivity to errors in path loss prediction to be determined so that the seriousness of any errors may be assessed.

In its present form report 724 states that shielding from man-made structures, except those specifically built for shielding purposes, should not be considered when determining coordination distance. Ignoring obstructing buildings will lead to a longer coordination distance than necessary being determined. This will lead to unnecessary work investigating potential interfering transmitters. This section proposes a method whereby the shielding by buildings may be estimated rapidly for the purpose of determining coordination distance.

This method relies on comparisons being made with sophisticated diffraction models discussed in chapter 2 of this thesis and in published material (Haslett[1991,1993], Haslett and Al-Nuaimi[1991]). The effect of simplifications necessary to make the evaluation sufficiently rapid for coordination purposes is examined. The outcome of this is a proposal which the author believes is a best compromise between speed and accuracy.

8.1.1 Path loss determination in CCIR rep 724

The coordination distance may be regarded as the distance above which the transmission path loss can be assumed to be large enough so that the signal from any potential interferes lying outside this distance will be sufficiently attenuated so that no interference threat will be posed. The method in the report 724 is based on a user defined quantity known as "minimum permissible basic transmission loss". This quantity will be dependent on the receiver for which the coordination distance is being determined.
Once the minimum permissible basic transmission loss, \( L_b(p) \), has been established, this may be related to coordination distance by the following expression:

\[
L_b(p) = A_o + \theta d_i + A_h \quad \text{dB}
\]

(8.1)

in which:

\[
A_o = 120 + 20 \log f \quad \text{dB}
\]

with:

\( \theta \): rate of attenuation (dB/km);
\( d_i \): coordination distance for propagation Mode 1 (km);
\( A_h \): horizon angle correction (dB);
\( f \): frequency (GHz).

The rate of attenuation, \( \theta \), is a function of frequency, the time percentage under consideration and also of the climatic zone in which propagation takes place. The earth is divided into four climatic zones for the purposes of evaluation of coordination distance:

- Zone A1: coastal land and shore areas;
- Zone A2: land, other than coastal and shore areas;
- Zone B: "cold" seas, oceans and other large bodies of water;
- Zone C: "warm" seas, oceans and other large bodies of water.

8.1.2 Sensitivity of coordination distance estimation to transmission loss errors

The determination of \( \theta \) for each zone and for various time percentages will indicate how errors in transmission loss predictions will affect the coordination distance estimation. Table 8.1 indicates the sensitivity (in km/dB) to error for time percentages of 1% and 0.01% for all four climatic zones at frequencies of 1 GHz, 4 GHz, 12 GHz and 40 GHz.
<table>
<thead>
<tr>
<th>Zone</th>
<th>f=1 GHz</th>
<th>f=4 GHz</th>
<th>f=12 GHz</th>
<th>f=40 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p=.01%</td>
<td>p=1%</td>
<td>p=.01%</td>
<td>p=1%</td>
</tr>
<tr>
<td>A1</td>
<td>14.9</td>
<td>8.3</td>
<td>10.1</td>
<td>4.9</td>
</tr>
<tr>
<td>A2</td>
<td>10.8</td>
<td>6.6</td>
<td>6.5</td>
<td>3.9</td>
</tr>
<tr>
<td>B</td>
<td>25.0</td>
<td>13.4</td>
<td>13.4</td>
<td>7.7</td>
</tr>
<tr>
<td>C</td>
<td>26.2</td>
<td>15.9</td>
<td>16.4</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Table 8.1 Sensitivity of coordination distance to errors in path loss (km/dB)

Three general conclusions may be drawn from Table 1:

i) The sensitivity is greater at lower frequencies.

ii) The sensitivity is greatest in zone C.

iii) The sensitivity is greater when a small time percentage is considered.

8.1.3 Incorporating building diffraction into "horizon angle correction"

The purpose of this section is to comment on one factor in the coordination distance determination procedure, namely, horizon angle correction. This is the factor which accounts for diffraction loss protection afforded by an obstacle. The horizon angle correction angle is quoted as a function of frequency and elevation angle only and as such is a simplification. The result of the simplification is that the coordination distance calculation is fast to execute requiring a minimum of surveying work at the earth station site.

The horizon angle correction, $A_h$, is an additional path loss assumed according to the following formula:

$$A_h = 20 \log(1+4.5f^2\xi) + f^{1/3}\xi \quad \text{dB} \quad (8.2)$$
for $\varepsilon > 0$ where $\varepsilon$ is the horizon elevation angle in degrees and $f$ is the frequency in GHz. It can be shown to be a good approximation to the diffraction loss deep in the shadow of a horizontally illuminated obstacle of radius of curvature 10 metres situated 500 metres from the site in question. CCIR report 724 makes some additional conditions:

i) "The maximum value of $A_h$ shall be 30dB"

ii) "Man made structures ............. shall not be considered".

It is not suggested that the 30dB limit should be changed. However, ignoring the presence of a building which would obviously provide some protection from interference will result in an over-estimation of the coordination distance and, consequently, unnecessary work assessing interference threats.

This section investigates the possibility of incorporating buildings as providers of protection in the evaluation of coordination distance. The models thus far developed are used to evaluate the horizon angle correction formula for various configurations at frequencies of 1, 4, 12 and 40 GHz. Discrepancies in diffraction loss prediction are converted into discrepancies in coordination distance so that their significance may be revealed.

Equation 8.2 suggests that the maximum assumable loss of 30dB will occur when the diffraction angle is only 0.65 degrees at $f=40$ GHz and 4.1 degrees at $f=1$ GHz. The fact that obstacle distance and radius of curvature are assumed fixed is a source of concern regarding accuracy. Indeed, the application of the "radius of curvature" concept to buildings is not established. Figure 8.1 shows the variation of diffraction loss with diffraction angle (considering greater circle path only) for a building of 20 metres thickness at distances of 20, 100, 500 and 2500 metres from the obstacle. These are compared with predictions from equation 8.2. The model used for comparison purposes is the two dimensional double knife edge system put forward in chapter
5. This approximates to a perfectly absorbing building model and has been extensively tested using real buildings as described in chapter 4.

It can be seen that equation 8.2 gives a good approximation to the double knife edge system prediction at a distance of 500 metres but is at variance for other distances. It must be borne in mind that if an upper limit of 30 dB protection is assumed then comparisons need only be made where diffraction loss predictions are less than 30 dB.

From the graphs of figure 8.1 the fact that diffraction loss increases with distance for a given diffraction angle is clearly demonstrated. The angle correction formula of CCIR report 724 was produced with terrain diffraction rather than building diffraction in mind. In the terrain diffraction situation 500 metres may be seen as a plausible minimum distance to an obstacle. Equation 8.2 would then lead to a generally conservative estimate of diffraction loss. Where the obstacle is a building it is quite common for it to be located at less than 500 metres from the proposed receiver site.

As an example, let us consider the situation where the diffraction angle is 5° and the obstacle-receiver distance is 100 metres. This is equivalent to the obstructing building being approximately 9 metres higher than the receiver. At 1 GHz the prediction of equation 8.2 is that the diffraction loss would be 30 dB whereas the curve corresponding to an obstacle-receiver distance of 100 metres in figure 8.1 suggests that a diffraction loss of 22 dB would be more accurate. Thus the protection would be overestimated by approximately 8 dB (more if the building had a wedged roof rather than a flat one).

As frequency is increased, the 30dB limit is reached for both predictions. At 12 GHz for example the 30dB limit for equation 8.2 is reached when the diffraction angle is 1.5 degrees. This corresponds to difference in height between the obstacle and receiver of only 2.6 metres. Nevertheless at this point the difference in diffraction loss prediction is approximately 8dB. As frequency increases the diffraction angle required to produce 30dB diffraction loss reduces. However, at this angle, the CCIR report 724 prediction over-estimates diffraction
loss by approximately 8dB at all frequencies in the range 1-40 GHz if
the obstacle is 100 metres from the receiver. Similarly it would
underestimate diffraction loss by approximately 6 dB in the frequency
range if the building was 2500 metres from the obstacle (it must be
noted, however, that multiple path diffraction will almost certainly be
significant when the building is at such a distance).

Taking the data of table 8.1 it is possible to assess the effect of
overestimating diffraction loss by 8dB (obstacle distance = 100m) or
underestimating it by 6dB (obstacle distance = 2500m). In producing
table 8.2 it is assumed that the "correct" coordination distance is 300
kilometres. The effect of under-estimating or over-estimating the
diffraction loss due to a building would lead to different coordination
distances being obtained. The appropriate figures are inserted.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Distance to obstacle</th>
<th>f=1 GHz p=.01%</th>
<th>f=4 GHz p=.01%</th>
<th>f=12 GHz p=.01%</th>
<th>f=40 GHz p=1%</th>
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<tr>
<td>A1</td>
<td>100m</td>
<td>181</td>
<td>234</td>
<td>241</td>
<td>261</td>
</tr>
<tr>
<td></td>
<td>2500m</td>
<td>389</td>
<td>350</td>
<td>361</td>
<td>329</td>
</tr>
<tr>
<td>A2</td>
<td>100m</td>
<td>214</td>
<td>247</td>
<td>248</td>
<td>269</td>
</tr>
<tr>
<td></td>
<td>2500m</td>
<td>365</td>
<td>340</td>
<td>339</td>
<td>323</td>
</tr>
<tr>
<td>B</td>
<td>100m</td>
<td>100</td>
<td>193</td>
<td>193</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td>2500m</td>
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<td>380</td>
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</tr>
<tr>
<td>C</td>
<td>100m</td>
<td>100</td>
<td>173</td>
<td>169</td>
<td>226</td>
</tr>
<tr>
<td></td>
<td>2500m</td>
<td>457</td>
<td>395</td>
<td>398</td>
<td>355</td>
</tr>
</tbody>
</table>

Table 8.2 Coordinad distance predictions from CCIR rep 724 for
obstacle at 100m and 2500m distance (km). (Correct value=300km)

The fact that the errors are greatest at low frequencies may seem to be
surprising. This is due to the fact that the point under consideration
is when the predicted diffraction loss (by either of the two methods)
reaches 30dB. Although this point refers to different diffraction angles depending on the frequency, the difference between the predictions of the two models used is generally frequency independent. The smaller difference in distance required to account for this difference in level at higher frequencies means that the errors in coordination distance will be smaller for a given error in path loss prediction.

The over-estimation of coordination distance when the building is at a large distance from the receiver may go some way to allow for the effect of a signal diffracting around the side of a building. Of more concern is the fact that the coordination distance is under-estimated at shorter obstacle-receiver distances (less than 500m) as diffraction around the side is still likely and will further exacerbate the error. A predicted value of 100km instead of 300km may well be judged unacceptable.

As a first method of reducing the error in diffraction loss prediction, a more accurate formula from CCIR report 569 [1990] is used (equation 8.3):

$$A_h = 20 \log(1 + 6.3 \varepsilon (fd_h)^{1/2}) + 0.46 \varepsilon (fC_r)^{1/3} \text{ dB}$$

(8.3)

for $\varepsilon > 0$

where:

- $\varepsilon$ is the horizon elevation angle (degrees)
- $f$ is the frequency (GHz)
- $d_h$ is the horizon distance (km)
- $C_r$ is the obstacle radius of curvature (m)

The radius of curvature is replaced by building thickness to produce the predictions illustrated in figure 8.2. It is acknowledged that building thickness is not measurable from the receiver site and therefore would be accepted as a necessary parameter by users with reluctance.
It is observed from figure 8.2 that once the predicted diffraction loss reaches significant levels (greater than about 10 dB) equation 8.3 overestimates diffraction loss for all obstacle distances. The effect is greatest at higher frequencies (greater than about 10 GHz) where the errors are approximately equal to those obtained using equation 8.2. Thus using the more sophisticated equation of CCIR report 569 has afforded little improvement in prediction accuracy. Clearly the equating of building thickness to effective radius of curvature is questionable.

Two facts are now clear. Firstly, the measurement of building thickness is a time-consuming activity. Secondly, the inclusion of an assumed "effective radius of curvature" affords little if any improvement in accuracy. The fact that the errors involved always appear to lead to an overestimation of diffraction loss suggests it may be prudent to assume that the building is a knife-edge. This would lead to a simplification of equation 8.3 as shown below.

\[ A_n \approx 20 \log \left( 1 + 6.3 \sqrt{\frac{\pi}{2}} \right) \text{ dB} \]  

(8.4)

The effect that this would have on the prediction accuracy is shown in figure 8.3. The error is now reduced to a maximum of approximately 4 dB if the limit of 30 dB is still imposed. It must be remembered that the building from which curves 1 to 4 in figure 8.3 are produced is assumed to have a flat roof and a thickness of 20 metres. If the building was less thick or had a wedge-shaped roof then the error would be smaller.

The fact that the error deep in the shadow has been reduced means that the most significant discrepancies in figure 8.3 occur where the diffraction angle is very small. In fact the term \( 6.3 \sqrt{\frac{\pi}{2}} \) of equation 8.4 is equal to \( \sqrt{2\pi} \v nu \) where \( \nu \) is the Fresnel parameter (see section 2.1). \( 20 \log(\sqrt{2\pi} \nu) \) dB is a well-known approximation to single knife edge diffraction loss for large \( \nu \) (it is better known in the form \( 12.95 + 20 \log(\nu) \) dB). Therefore equation 8.4 can only be expected to be a close approximation when \( \nu \) is large.
The unity term has been added in equations 8.2, 8.3 and 8.4 to prevent negative values of diffraction loss resulting for small values of ε, but nevertheless, when ε is zero equations 8.2, 8.3 and 8.4 yield a zero result whereas 6.02 dB is the true value of diffraction loss by a knife edge obstacle under grazing conditions. A building of non-zero thickness would yield a greater diffraction loss.

A better approximation to single knife-edge diffraction loss is given in CCIR report 715-3 [1990] taken from a paper by Boithias [1984]:

\[ A_h = 6.9 + 20 \log\left(\sqrt{(v-0.1)^2+1} + v - 0.1\right) \] (8.5)

which translated into the parameters used in equation 8.3 yields

\[ A_h = 6.9 + 20 \log\left(\sqrt{(1.4 \varepsilon(f_d h)^{1/2 - 0.1})^2+1} + 1.4 \varepsilon(f_d h)^{1/2 - 0.1}\right) \] (8.6)

It is expected that use of equation 8.6 instead of equation 8.4 would reduce errors for small diffraction angles. Figure 8.4 shows that this is indeed the case with the general situation appearing to be that diffraction loss is underestimated by a few dB due to the building thickness not being considered. It is felt that the additional accuracy afforded justifies the requirement of measuring the distance to the obstacle. Equation 8.6 is recommended for use as providing an appropriate compromise between simplicity of use and accuracy.

However, it is quite possible to find that the receiver is in the shadow of a building such that the angle of elevation of the building exceeds the angle subtended by the building horizontally (in azimuth). In such cases it can be expected that a significant diffracted signal will be received around the sides of the building. This situation is now given further consideration.
8.1.4 Multiple path diffraction

Considering only the 2-dimensional building profile is often not sufficient to predict the diffracted field strength in the shadow of a finite width obstacle such as a building. The diffracted field around the side of the building must also be considered. A phasor summation of the relevant fields leads to an interference pattern in the shadow in which the field strength varies rapidly with distance. (van Dooren and Herben [1993], Haslett [1993]).

Where a practical building is the obstacle, it has been shown (Haslett and Al-Nuaimi [1991], Haslett [1993]) that, as neither details of the electrical characteristics nor detailed profiles of the reflecting surfaces are known, then the effect of reflections should not be considered.

In producing the interference pattern shown in figure 8.5, the three diffraction paths (roof top plus two sides) were considered as a double knife edge system with the resultant computed as a phasor sum of the three. Figure 8.5 investigates the diffracted field in the shadow of a building 50 metres square at its base and 30 metres in height relative to the receiver. The building is assumed to be illuminated by a uniform plane wave at normal incidence at a frequency of 12 GHz. The receiver is assumed to be 1000 metres from the building and to move horizontally parallel to the building from grazing incidence on one side to grazing incidence on the other.

The predicted interference pattern leads to the possibility of extremely high levels of protection being estimated in point to point analyses. However, examination of this pattern shows that when this is the case the signal level varies greatly with distance. Variations of several dB over a few centimetres are possible. It would thus be unsafe to expect such high levels of protection as are predicted by the nulls of the interference pattern to be attainable, especially as the existence of the interference pattern is a narrowband phenomenon. The model developed would be of more practical use if the interference pattern could be smoothed out to give a median level of protection in a given location. One possibility is to sum the power densities due to
each of the three diffraction paths rather than to phasorially sum the fields. Figure 8.5 shows the smoothing out effect this has on the interference pattern whilst still giving a credible estimate of the diffracted field.

One major effect of accepting the "power sum" approximation is to allow the use of equation 8.6 to compute the individual power densities and hence predict the total diffracted field. This then provides an extremely rapid method of estimating the strength of the diffracted field. Again, building thickness is ignored. However, the error introduced due to this is probably small in most cases as if the interfering signal is not incident normally then the corners of the building present to the signal what approximates to a knife edge. If this is not assumed then the need exists to determine the orientation of the building, a time consuming activity for a first analysis. The procedure is therefore to firstly compute the three components:

\[
A_{h_i} = 6.9 + 20 \log \left\{ \sqrt{\left(1.4 \varepsilon_1 (f \delta_h)^{1/2} - 0.1\right)^2 + 1} + 1.4 \varepsilon_1 (f \delta_h)^{1/2} - 0.1 \right\} \\
\text{for } i=1, 2, 3
\]

where: \( \varepsilon_1 \) is the angle of elevation to the building roof
\( \varepsilon_{2,3} \) is the difference in azimuth between the direction under consideration and the sides of the building.

From this the relative power densities may be determined:

\[
P_{d_i} = \text{Antilog}_{10}(-A_{h_i}/10)
\]

The diffraction loss, \( A_b \), may then be computed

\[
A_b = -10 \log \sum_{i=1}^{3} P_{d_i} \text{ dB}
\]

Results from this method are compared with the power sum approximation of figure 8.5. A comparison is presented in figure 8.6 for frequencies of 1, 4, 12 and 40 GHz. In this case a uniform plane wave is assumed to be normally incident on a building 50 metres square at the base and 30 metres in height relative to the receiver. The receiver is moved along
a horizontal line parallel to the building from grazing incidence on one side of the building to grazing incidence on the other side. It should be noted that this represents something of a worst case scenario as the incident wave is normal to the building.

The similarity of the predictions shown is encouraging especially as this represents a worst case. The 50 metre thickness of the building has little effect on the diffracted field strength when the receiver is 1000 metres from the building. The effect of building thickness generally increases as the receiver is moved closer to the obstacle. Figure 8.7 presents results of investigating a similar situation to figure 8.6 but with the receiver now only 100 metres from the building. The error is seen to be only slightly increased with strength of the diffracted field still being over estimated deep in the shadow of the building. The size of the error would be reduced if the orientation of the building was changed.

As an example of the effect of building orientation, a prediction in presented in figure 8.8 for a building with a 35 metre square base oriented at 45° to the incoming wave. The silhouette of the building as viewed from the receiver will be virtually the same as for figure 8.6. Again the receiver is 100 metres from the building and the prediction is given assuming horizontal movement perpendicular to the direction of the incident wave from grazing incidence on one side of the building to grazing on the other. The difference between the two predictions is now smaller. However a slight over estimation of the diffracted field deep in the shadow is inevitable. Nevertheless the simplified model can be seen to give useful predictions, especially considering its relative simplicity.

8.1.5 The effect of height gain

Modelling of diffraction situations under non-uniform illumination has suggested that the diffracted field is mostly influenced by the field
incident at the diffracting edge (Haslett and Wille [1993]). The phenomenon known as height gain whereby the field strength incident varies with height leads to two further problems.

Firstly, it is not possible to directly equate "diffraction loss" with "protection from interference" under these conditions. It is possible for the field incident at roof height to be a few tens of dB's greater in strength than that which would be incident at the receiver in the building's absence.

Secondly, when considering multiple path diffraction, the field strength incident on each edge under consideration may be different. This will distort the predictions made under these conditions.

However, it is vital that height gain is clearly defined. There exist methods of predicting the field strength as a function of height when various path parameters have been defined (for example CCIR report 715). These methods apply only under well mixed atmospheric conditions. But when coordination distances are being determined, the time percentages being considered are small. The propagation conditions prevailing whilst the received signal level is in its highest single percentile are not those of a well mixed atmosphere. Generally speaking ducting conditions will be present with the signal level no longer gradually increasing with height, but rather varying in a manner difficult to predict.

The CCIR in report 569 [1990] examines the likely signal level for small time percentages on trans-horizon propagation paths. The prediction methods put forward, both current and proposed, do not include height in the calculation. This suggests that signal levels for small time percentages on trans-horizon links are not strongly height dependent with high signal strengths being almost equally likely at low and high level receiving points. There will naturally be a transition stage as time percentage increases to a point where height dependence becomes significant. However it appears that the only option open when time percentages as small as 1% are being considered is to consider height gain to be zero. This, of course, is a happy conclusion at which to arrive as it lends validity to the models put forward thus far.
8.1.6 Formal statement of proposed method

If the models developed are accepted then it allows a formalised procedure for determining the extra "building loss" which may be taken into consideration when determining coordination distance. This may be stated as follows:

When a building is identified whose roof has a positive elevation when viewed from the receiver, four parameters should be noted:

- \( \epsilon \) the angle of elevation to the roof (degrees)
- \( \theta_1 \) the lower azimuth direction of a side of the building (degrees)
- \( \theta_2 \) the higher azimuth direction of a side of the building (degrees)
- \( d_h \) the building-receiver distance (kilometres)

The building loss \( A_b(\theta) \) is then given as a function of azimuth, \( \theta \):

\[
\text{If } \theta < \theta_1 \text{ or } \theta > \theta_2 \text{ then } A_b(\theta) = 0
\]

\[
\text{If } \theta_1 < \theta < \theta_2 \text{ then:}
\]

\[
A_b(\theta) = -10 \log \sum_{i=1}^{f=3} P_{d_i} \quad \text{dB} \quad (8.10)
\]

where:

\[
P_{d_i} = \text{Antilog}_{10}(-A_{h_i}/10)
\quad (8.11)
\]

and:

\[
A_{h_1} = 6.9 + 20 \log(\sqrt{(1.4(\theta - \theta_1)(fd_h)^{1/2-0.1})^2 + 1}) + 1.4(\theta - \theta_1)(fd_h)^{1/2-0.1}
\quad (8.12)
\]

\[
A_{h_2} = 6.9 + 20 \log(\sqrt{(1.4(\theta_2 - \theta)(fd_h)^{1/2-0.1})^2 + 1}) + 1.4(\theta_2 - \theta)(fd_h)^{1/2-0.1}
\quad (8.13)
\]
\[ A_h = 6.9 + 20 \log \sqrt{[1.4 \epsilon (f d h)^{1/2} - 0.1]^2 + 1} + 1.4 \epsilon (f d h)^{1/2} - 0.1 \]  

(8.14)

where \( f \) is the frequency in GHz.

The building loss \( A_b(\theta) \) may then be used in place of the horizon angle correction factor, \( A_h \), of CCIR report 724.

8.2 Analysing potential interference paths

Once the coordination distance has been determined in all directions of azimuth, an appropriate coordination area may be drawn on a map. This area is then investigated in order to determine whether or not any potentially interfering transmitters lie within it. If such a transmitter is found then the likely level of interference from this transmitter is determined. The outcome of this is a predicted cumulative distribution of signal levels at the receiver.

The procedure now described allows the effect on interference levels of an obstructing building to be predicted. It is not a complete interference level prediction procedure as it assumes that well established methods (CCIR rep. 569 [1990], Hewitt et. al. [1989]) allow for the interference levels to be predicted ignoring the presence of the building. The building diffraction model developed is used to incorporate the building into the radio path. Rather than simplify the model for the purpose of rapid execution as was the case in the coordination distance determination procedure, the most accurate practical model available is utilised where individual paths are investigated.

8.2.1 Determination of the site shielding factor of a building

In determining the site shielding factor (SSF) it is recommended that three diffraction paths for a building are considered as a matter of course. This negates the need to develop rules whereby the number of diffraction paths to be considered may be ascertained. If, for example, only one diffraction path needed to be considered then the
contribution of the other paths to the resultant field strength would be revealed as insignificant by the subsequent analysis of the three paths.

The types of paths which may require analysis can be broadly divided into two main types:

i) Short distance "line of sight" paths. These paths, which will generally be located in an urban environment, will show little variation of signal strength with time.

ii) Trans-horizon paths. Such paths will generally only pose an interference threat for small time percentages. In such cases a cumulative distribution of the signal level would reveal the level exceeded for various time percentages. The effect of a building on this cumulative distribution needs to be interpreted as a form of SSF.

The two path types are now investigated separately.

8.2.1.1 Analysis of SSF on short paths.

On a short path (perhaps with the transmitter in the same city as the receiver) the interfering signal will be always present showing little variation with time. The level of this interfering signal needs to be determined so that its effect on the operation of the receiver may be predicted. Building diffraction may be relied on to provide protection from interference which may be additionally reduced from its maximum possible level only by the directivity and pointing direction of the antenna concerned.

In predicting the strength of the diffracted field, three diffraction paths should be considered. Each of these three paths should be analysed so that the relevant double knife edge system geometry may be identified. It may be that a single knife edge model in sufficient for one or more of the edges; for example where the diffracting building has a wedged roof.
Once the parameters have been identified, a normalised electric field strength may be determined using the method of Millington et. al. (1962a, 1962b). Figure 8.5 shows the result of adding the normalised field strength on a phasor basis or adding the normalised power densities linearly. Examining the two possible outputs shows that the power density sum is a much smoother curve which does not predict very low signal strengths at points where phasor cancellation occurs. The interfering signal will generally not be at a spot frequency but rather occupy a finite bandwidth. This will lead to a reduction in the variation of the interference pattern, making the power density sum option more attractive. There are points, however, where the "phasor addition" model predicts a higher field strength that "power density addition". The user may therefore feel unsafe in accepting the power density addition as a suitably safe estimate of the likely interfering signal strength. A third option exists whereby a safe estimate may be determined. That is to assume that the three diffracted fields add in phase at all points. Figure 8.9 is a reproduction of figure 8.5 but with a "sum of moduli" prediction added.

It is clear from figure 8.9 that the "sum of moduli" option produces a smooth curve joining the peaks of the interference pattern. It therefore will yield a conservative estimate of the amount of protection offered by a building. This is seen as a correct philosophy in interference prediction methods.

8.2.1.2 Analysis of SSF in longer paths.

When the interference path is longer, especially when it is trans-horizon, the value of a simple point-to-point analysis considering the diffracting building is questionable. Additionally, quantifying a single SSF for a building, and even defining what is meant by SSF, when the original strength is varying with time is not a simple task.

The term site shielding factor (SSF) is defined in a number of ways in the literature (COST 210 [1990], van Dooren and Herben [1993], Vyncke and Vandervorst [1993]). The definition used in the short path, time invariant, analysis is that the SSF is the ratio of the strengths of
the interfering electric field with and without the obstacle present. Under ducting conditions the field incident on the obstacle is non-uniform. An analysis of this situation (Haslett and Wille [1993]) reveals that the SSF is not constant under such conditions. Thus SSF requires re-defining when being applied to trans-horizon paths. Of importance on such paths is the cumulative distribution of signal strength. The effect of an obstructing building on such a cumulative distribution may be seen as analogous to the SSF. Of vital importance is the SSF when the incident signal at the diffracting edge is greatly enhanced relative to its average value. This usually occurs during ducting conditions where constructive reflections within the duct cause a signal strength enhancement. The nature of such an interference pattern is that it approximates to the form \((1+r.\exp(j\theta))\) (this is discussed more fully in chapter 9) where \(r\) is the relative magnitude of the interfering signals and \(\theta\) is the phase difference between them. The peaks of such a pattern tend to be broad and flat suggesting that, under the highly relevant conditions of signal enhancement, the incident field will be quite uniform in nature thus rendering the diffraction model valid. It is acknowledged that this is so only for roof top diffraction and that the field incident on a side diffracting edge may well vary along this edge. However, it is felt extremely unlikely for the field incident on the side diffracting edge to be greater than that incident on the roof top under enhanced signal strength conditions.

Therefore the best procedure to recommend is that the relative field strength in the shadow of a building is predicted for conditions of uniform illumination to yield a value for the diffraction loss. The signal level observed for small time percentages will be reduced by this amount causing the cumulative distribution to be shifted accordingly. Whether or not it is permissible to refer to such a diffraction loss as the SSF of the building is of secondary importance. It is the effect of the building on the cumulative distribution of the received signal strength that is of direct concern to the user when trans-horizon interference paths are being considered.
8.2.1.3 Approximations to the model

It is possible that the model as described may be too time consuming to implement where rapid approximate estimations of the protection from interference afforded by a particular building are required. Again, the silhouette model, whereby the thickness of the building is ignored provides a rapid method of arriving at a slightly conservative estimate of this protection. Figure 8.10(a) gives a side view of the obstructed radio path with figure 8.10(b) giving a plan view of the same path.

Using the parameters given in figure 8.10 three Fresnel parameters may be determined. For the situation where the transmitter and receiver are both close to the diffracting obstacle the Fresnel parameter \( v_1, v_2 \) and \( v_3 \) for each diffraction path are (CCIR rep. 715 [1990]):

\[
\begin{align*}
    v_1 &= \sqrt{2(d_1+d_2)a_1.a_2/\lambda} \\
    v_2 &= \sqrt{2(d_3+d_4)a_1.a_2/\lambda} \\
    v_3 &= \sqrt{2(d_5+d_6)a_5.a_6/\lambda}
\end{align*}
\] (8.15-8.17)

\( a_n \) is in radians, \( d_n \) and \( \lambda \) are in metres.

Where the transmitter is greatly removed from the receiver (for example, in the case of transhorizon radio paths) then the above formulae are not suitable as \( d_1, d_3 \) and \( d_5 \) tend to infinity with \( a_1, a_3 \) and \( a_5 \) tend to zero. More appropriate formulae are:

\[
\begin{align*}
    v_1 &= a_2\sqrt{2d_2/\lambda} \\
    v_2 &= a_4\sqrt{2d_4/\lambda} \\
    v_3 &= a_6\sqrt{2d_2/\lambda}
\end{align*}
\] (8.18-8.20)

The diffraction loss \( J(v_n) \) on each path is then given in dB using the formula of Boithias (1984).

\[
J(v_n) = 6.9 + 20\log_{10}(\sqrt{(v-0.1)^2 + v_n +1} + v - 0.1) \text{ dB} \] (8.21)
This may then be converted to a normalised power density $P_n$.

$$P_n = \text{Antilog}_{10}[-0.1J(v)]$$  (8.22)

This may be performed using all three Fresnel parameters to yield values for $P_{n1}$, $P_{n2}$ and $P_{n3}$ respectively. An overall figure for the diffraction loss, $A_b$, due to the building may then be determined.

$$A_b = -10.\log_{10}(P_{n1} + P_{n2} + P_{n3}) \text{ dB}$$  (8.23)

8.2.2 The upper limit of SSF in practical situations.

The models used can lead to very high predictions of diffraction loss. Indeed, measured values of diffraction loss as high as 65 dB have been recorded (chapter 4). Measurements made in cluttered sites (chapters 4 and 6) have shown that scattered signals may be much stronger than the diffracted signal under such circumstances. Methods exist whereby the strength of the scattered signals from buildings (Bramley and Cherry[1973]), Al-Nuaimi and Ding [1993]) and vegetation (Al-Nuaimi and Hammoudeh [1993]) may be predicted. These require quite accurate site geometry measurements to be made in order to obtain reliable predictions. If the user is prepared to do this then there is no reason why the high value of diffraction loss due to the obstructing building should not be taken in conjunction with scattered signals to provide a combined prediction for the interfering signal strength.

The existence of scattered interfering signals, although more time-consuming to predict than the diffracted signal, should not be ignored. If an accurate prediction of these scattered signals is not carried out then it must at least be noted that high values of diffraction loss do not necessarily translate to a corresponding reduction in interference level.

In the determination of coordination distance, CCIR report 724 (1990) places an upper limit of 30 dB on the horizon angle correction factor. Measurements made at highly protected sites (described in chapter 9) suggest that this may be a suitable limit to impose on the SSF of the
building. Such a limit is, by its nature, somewhat arbitrary. Some scattered paths have very little loss and would make this limit unachievable. An accurate prediction of the interfering signal level can only be achieved in an urban situation by identifying the diffracting and scattering propagation paths and evaluating them in turn.

8.3 Summary and interim conclusion

The work presented in this chapter shows how the diffraction models developed may be used in two procedures:

i) the determination of coordination distance
ii) the prediction of the signal level on a specific path.

In determining the coordination distance it was acknowledged that the amount of data required for a full evaluation would be too onerous. Accordingly, well established approximations to Fresnel integral methods of determining diffracted field strengths were evaluated. In particular, they were compared with a double knife edge model of a building of typical dimensions. A procedure by which the diffracted field strength in the shadow of a building may be estimated using only the horizontal angle subtended by the building, elevation angle to the roof of the building, the distance to the building and the frequency of operation as parameters has been formally stated. This allows the diffracted field to be rapidly predicted thus rendering the method suitable for use in the determination of coordination distance.

Currently the CCIR recommends that man made structures should not be considered when determining coordination distance (CCIR rep. 724 [1990]). It is recommended that the method explained here is incorporated into the coordination distance determination procedure allowing a "building loss factor" to replace the "horizon angle correction factor" in appropriate cases.
For the purposes of investigating specific paths, the model in its most sophisticated form may be used. A method for using the model on both short and transhorizon paths is stated. Approximations to the model considering only single knife edge diffraction are developed. The fact that the model considers only diffraction paths must be borne in mind. It is quite possible for scatter from buildings or vegetation to form the dominant propagation mechanism in a cluttered environment.

The next chapter identifies diffraction as one of several propagation mechanisms influencing the strength of an interfering signal. Suggestions of methods by which these mechanisms may be combined to provide a general site shielding procedure are put forward.
Figure 8.1 Comparison of CCIR rep 724 formula with double knife-edge system model
Figure 8.2 Comparison of CCIR rep 569 formula with double knife-edge system model
Figure 8.3 Comparison of modified reg 569 formula with double knife-edge system model.
Figure 8.4 Comparison of Boithias' SKE model with double knife-edge system model.
Figure 8.5  The smoothing effect of computing the power sum rather than phasor sum.
Building is 50 metres square at base, 30 metres high. Receiver is 1000 metres behind building.

1. Double knife edge model
2. Single knife edge model

Figure 8.6 Comparison between double knife-edge system power sum and Boithias' single knife-edge approximation power sum.
Building is 50 metres square at base, 30 metres high. Receiver is 100 metres behind building.

1. Double knife edge model
2. Single knife edge model

Figure 8.7 Comparison between double knife-edge system power sum and Boithias' single knife-edge approximation power sum.
Building is 35 metres square at base, 30 metres high. Receiver is 100 metres behind building.

1. Double knife edge model
2. Single knife edge model

Figure 8.8 Comparison between double knife-edge system power sum and Boithias' single knife-edge
Figure 8.9  Comparison of three methods of predicting diffracted signal strength in a multiple path situation
Figure 8.10 Side and Plan views of diffracting obstacle
9.1 Introduction

The work reported in this thesis forms a part of a programme aimed at providing users of the radio spectrum with sufficient information to confidently predict the level of interference that will be experienced from sharers of the same frequency band in an urban environment. In this study the amount of protection afforded by a building which obstructs the interference path has been investigated and appropriate diffraction models developed.

In this chapter doubts are raised as to the universal validity of the models developed. In particular three questions are responded to:

1. The experimental programme and the diffraction models developed consider the situation where both the receiver and transmitter have a clear view of the obstructing building. Can the validity of the model be assumed when the transmitter is situated at a great distance from the building and anomalous propagation conditions exist?

2. The existence of scatter paths from adjacent buildings and vegetation has been observed to severely reduce the amount of protection afforded by an obstructing building. How may this best be incorporated into a general interference prediction procedure?

3. The model has assumed that no electromagnetic energy is transmitted through the building. Can this be assumed for all buildings?

Some of these questions have been partly answered by further experiments reported in this chapter. Others, in particular question 3 above, will form the subject of further work at the University of Glamorgan.
9.2 Predicting the diffracted field on transhorizon paths

The GTD/UTD and Fresnel-Kirchhoff methods described make the assumption that both transmitter and receiver have a clear view of the obstacle in question. This is not always the case. Indeed, from the point of view of evaluating the likelihood of interference, the situation requiring most intensive investigation is that of distant transmitters posing a threat for only a small time percentage. During this small time percentage, the signal is greatly elevated from its average level. This is usually due to the presence of ducts in the atmosphere. Ducting occurs when the variation in the refractive index with height is sufficiently large to cause the wavefront to bend downwards and reflect off the terrain back into the atmosphere where it is bent down once more. In this way the energy is trapped within a layer of the atmosphere and can propagate long distances with relatively little loss. Under ducting conditions the incident signal strength at the front of an obstacle due to a transhorizon transmitter can rise to within a few dB of free space level and even, on rare occasions, exceed this level.

The PE method has the advantage over the other methods being presented for tackling this situation as it is possible to define atmospheric structure along with the terrain profile. It is therefore possible to enter the atmospheric conditions required for ducting to prevail. However, the evaluation of interference is performed on a statistical basis on transhorizon systems. So, although the PE method can predict the diffracted field strength for a specified circumstance, in order to simulate a variety of anomalous conditions a great many situations would have to be defined. This would be a time consuming matter.

As an example of signal levels which may be experienced on transhorizon paths, figure 9.1 presents predictions made using the PE method on a 50 kilometre sea path. The transmitter is assumed to be 35 metres above sea level with vertical polarisation used at a frequency of 11.2 GHz. Predictions are given for standard atmospheric conditions and for two types of ducting situation. The effect of any obstructing building would be of little interest, from the interference reduction viewpoint,
under standard atmospheric conditions as the incident signal level is so low. It is of considerable interest, however, under the two ducting situations where the incident signal level is predicted to be elevated to the region of the free space level. It may be observed that the signal strength is not uniform with height under these circumstances. Rather, it exhibits a lobing structure characteristic of reflections within the duct. To a first approximation the lobing structure may be simulated by two coherent plane waves with appropriate angular separation and relative amplitudes.

Taking the surface duct as an example, the spatial wavelength of approximately eight metres corresponds to an angular separation of 3.8 milliradians at 11.2 GHz. It is therefore possible to predict the diffracted field strength in the shadow of a building under ducting conditions as the summation of the diffracted fields due to two plane waves with an appropriate angular separation. Each of these diffracted fields may be predicted by the FSI method making computation much faster.

In line with our policy to verify any theoretical models with measurements in environments corresponding to the situation being investigated, a long term measurement programme has been initiated monitoring the diffracted field in the shadow of a flat roofed building on a 50 kilometre transhorizon path. The building thickness in this case is 21 metres. The monitoring antenna is 35 metres behind the building and 1.6 metres below roof height. For comparison purposes, the signal strength was also monitored on the front of the building at the roof top and 1.6 metres below this. The signal received by the lower antenna is the closest it is possible to approximate the signal that would be incident at the antenna in the shadow if the building was not there. The difference between these two signals therefore indicated the site shielding factor of the building.

The signal received by each antenna may now be predicted for the case where a surface duct exists producing an incident field profile as indicated in figure 9.1. The situation is envisaged where tidal variations cause the "interference pattern" to move up the front of the building with time. Additionally, various depths of null may be
considered. Figure 9.2 shows the predicted fields for three different null depths using the FSI double knife edge model and considering the incident profile to be produced by two coherent sources with an angular separation of 3.8 mrad. The time axis has not been given units as this will depend on the speed at which the interference pattern moves up the building face.

From figure 9.2 it may be seen that, where the incident signal level is enhanced then the signal strength in the shadow is consistently approximately 24 dB below the level incident at the front of the building. This agrees with the predicted diffraction loss for a single source at grazing incidence.

However, when the incident signal becomes depressed, it is noticed that the signal in the shadow is most closely correlated with that incident at the roof height and also that the signal strength in the shadow varies by less than the incident signal level. This effect becomes more noticeable as the depth of null increases. Indeed, under extreme conditions the incident signal is actually predicted to be less than that at the front of the building resulting in a negative value for the site shielding factor for a short period of time. This negative site shielding factor is not due to an enhancement of the diffracted field strength but rather due to the diffracted signal being depressed by less than the incident signal. The important conclusion from the interference prediction viewpoint is that, under enhanced signal conditions the FSI model should prove robust despite the non-uniform nature of the incident signal.

The practical study naturally requires the long term monitoring of the signal. This is the subject of a further study being carried out at the University of Glamorgan. The experiment has been established and initial results have been reported (Haslett and Wille [1993]). Further monitoring is required before any definite conclusions can be made but so far the validity of the analysis put forward appears to hold.
9.3 Consideration of the effect of adjacent buildings and vegetation

Several of the measurements made observed that, deep in the shadow of a building, scattered signals were so strong as to prohibit the accurate measurement of the diffracted field strength. The prediction of the levels of signals scattered from building and vegetation has formed separate studies at the University of Glamorgan and procedures for predicting the strength of such signals have been put forward (Al-Nuaimi and Ding [1993], Al-Nuaimi and Hammoudeh [1993]). Ideally, in order to predict the level of interference experienced by a receiver, all signal paths (direct, scattered and diffracted) should be considered so that the intensity and direction of incidence of interfering signals as viewed by the receiver may be predicted. The resulting signal level may then be predicted giving due consideration to the receiving pattern of the antenna. This is to be the subject of further work at the University of Glamorgan.

At present the CCIR recommends that a limit of 30 dB is placed on diffraction loss for coordination prediction purposes. An experimental programme has been carried out on the University of Glamorgan campus aimed at determining what levels of signal may be expected at sites that appear to be extremely well protected. The results of these experiments are of interest in the context of commenting on the maximum likely protection that will be obtained.

9.3.1 Measurements made in highly protected sites

In cases where the receiver is close to the obstructing building the models developed predict, and indeed measurements reveal, that significant levels of protection will be afforded even when the receiving antenna is only a metre or two in the shadow of the building. This suggests that as the receiver is moved deeper into the shadow the amount of protection afforded will become very large indeed. Whilst, in the strictest sense, the diffraction loss due to the building may reach very high levels (80 dB or more), the early results obtained for horizontal movement of the receiving antenna at ground level (see
section 4.2) suggest that it would be unsafe for system planners to equate "diffraction loss" with "reduction in interference level" in these circumstances. In order to obtain a practical limit to the amount of interference reduction that may be assumed due to the presence of a diffracting obstacle, an investigation was undertaken to determine interference levels at sites that would be expected to offer a very high degree of protection on the basis of diffraction loss caused by a building located in between the transmitter and receiver.

Eight sites on the university campus were chosen for investigation. In order that the results obtained had relevance, and the receiver was not so well protected in all directions as to make it totally unsuited to receive any wanted transmissions, it was ensured that each site had a good view of the geostationary arc so that it had the potential to be used as an earth station site for which interference protection data is highly relevant.

The experimental procedure was to transmit from Hawthorn comprehensive school, as before, and then scan around with the receiving antenna noting the level of any measurable diffracted or scattered signals. Additionally the antenna was pointed in an elevated direction so as to point at the geostationary arc and the level of "interfering" signal received was again noted. Typical results obtained, from one site, are given in diagrammatic form in figure 9.3. It should be noted that a recorded scatter level of, for example, -46 dBf means that the signal level measured was 46 dB below that which would be received under free space conditions with the antenna pointed directly at the transmitter.

Examining the measurements in figure 9.3, it can be seen that although the diffracted signal was very small (63 dB below free space) substantial scattered signals were received from surrounding buildings. The strength of the scattered signals is such that, when the antenna was pointed away from the transmitter and the scatterers and elevated towards the geostationary arc, a clearly detectable signal was recorded. Of additional interest is the fact that a significant scattered signal was received from a building (halls of residence) some 400 metres distant. The same general conclusions can be drawn from measurements made at all sites.
The following statements were true of all eight sites:

1/ Measured diffraction loss was in excess of 50 dB.

2/ No signal was detected due to transmission through the obstructing building.

3/ Significant scattered signals were recorded from surrounding buildings and/or vegetation.

4/ Elevating the antenna towards the geostationary arc resulted in the "interfering" signal being detected.

The highest measured signal whilst the antenna was pointed at the geostationary arc was 55 dBf. Given that in the absence of the diffracting obstacle the signal would be only approximately 30 dBf, due to the directional properties of the receiving antenna, the additional protection provided by the building is only 25 dB despite the diffraction loss due to the presence of the building being well in excess of 50 dB.

Interference levels in any given situation will depend on the scattering paths and the characteristics of the receiving antenna. However, the message from this experiment is clear: as well as considering diffracted signals, the level of signals scattered from vegetation and buildings must be assessed before any likely interference levels may be predicted. As has been stated earlier, the investigation of signals scattered from buildings and vegetation is the subject of separate research studies at the University of Glamorgan.

9.4 The transmission of signals through buildings

None of the experimental programmes conducted led to signals being measured that could be attributed to penetration through an obstructing building. However, it is felt unsafe to conclude that transmission through buildings will be an insignificant propagation mechanism in all cases. This is because none of the buildings was of the "open-plan"
type where it was possible to see through the building due to the presence of windows on either side. A more extreme case would be where the obstructing building was a multi-storey car park with a very open structure. It is possible to envisage transmission through such a building forming the dominant propagation mechanism in such circumstances.

Recently there has been much interest in propagation within buildings in order to obtain coverage predictions for mobile radio purposes (Turkmani and de Toledo [1993], Matthews and Abu Bakar [1993], Damosso et. al. [1993]). The transmission of microwaves through buildings appears to have been somewhat neglected. A further study is therefore proposed with the aim of incorporating transmission through buildings into the interference prediction model. This would entail conducting an experimental programme. The outcome would be the provision of information that would allow users to identify buildings likely to allow transmission and also of procedures by which the level of such signals may be predicted.

9.5 Making use of computer stored terrain data

It is possible that the location of an earth station is not defined exactly but rather any specific place within a given urban area may be deemed acceptable.

In an urban area the propagation characteristics may vary greatly for a small change in location. The evaluation of coordination distance and the prediction of interference levels would have to be carried out for each proposed location. This would be somewhat time consuming. Much relevant information regarding the environment of the United Kingdom is becoming available in the form of computer databases. Ground height information at 50 metre horizontal intervals is to be available and of specific interest to this study is the fact that many cities are being digitally mapped with building locations and heights included. Similar information has been utilised to predict the coverage for mobile radio systems (Sharpees and Mehler [1993]). It would be possible to extract the information required for the implementation of the procedures...
described in chapter 8 from such databases. This would then allow potential sites to be evaluated for interference levels with acceptable speed.

It is likely to be many years before sufficient information is available so that the use of databases may be regarded as generally applicable. One possible method of speeding up the evaluation of potential earth station sites, without assuming the availability of comprehensive database information, is to characterise urban areas on the basis of parameters such as building density and average building height. It may then be possible to predict the likely protection from interference afforded by such buildings as a function of the height of a potential receiver location. Such a prediction would inevitably be based on statistics derived from models and experiments.

Such modelling and experiments form the subject of a further proposed study at the University of Glamorgan aimed at providing methods of rapidly assessing the likely interference levels experienced at urban locations to an acceptable level of accuracy.

9.6 Summary and interim conclusion

This chapter has shown how the achievements of the study carried out may be used in conjunction with other work so that progress may be made towards a generalised site shielding procedure. Further work has been proposed in two main areas, one aimed at assessing the amount of microwave energy which may be transmitted through buildings and, secondly, to allow interference levels to be predicted by characterising an urban area using statistical information of the immediate environment. In the next, final, chapter the achievements of the study are summarised and conclusions drawn.
Figure 9.1 Incident signal strength predictions using PE method
Figure 9.2 Diffracted signal strength under conditions of varying null depths
Figure 9.3  Example of measurements made in a highly protected site
10 SUMMARY AND CONCLUSIONS

10.1 Summary

The desirability of making tools available by which system planners may assess the effect of a building on a propagation path was established in chapter 1. The recent growth in microwave frequency systems particularly in urban areas has had the effect of making interference problems more likely and increasing the probability of a building obstructing an interference path under investigation. The fact that this rapid growth has largely taken place within the last decade has meant that comparatively little work has been carried out investigating the interaction between electromagnetic waves at microwave frequency and buildings. The need was identified for models to allow the diffracted field strength in the shadow of a building to be predicted. As most diffraction experiments prior to this study had been carried out either at near optic or millimetre wave frequencies using small scale models or at much lower (VHF/UHF) frequencies over mountains, it was felt necessary that any models developed would require validating by the execution of experiments using real buildings as the diffracting obstacle.

Chapter 2 reviews well established diffraction theory and gives a detailed derivation of the way in which the diffracted field strength in the shadow of a single knife edge obstacle may be numerically predicted. This was extended to encompass the situation where the obstacle consisted of two parallel knife edges which was thought to be more relevant to the situation where a building forms the diffracting obstacle. This utilised the Fresnel Surface Integral (FSI) method. Approximations to the double knife edge model were also described.

Chapter 3 describes the selection of sites on the University of Glamorgan campus suitable for making diffraction measurements in the shadow of buildings. Additionally the development of a suitably sensitive mobile microwave measuring receiver is described. Measurements made of campus are described in chapter 4. Initially these entailed moving the trolley mounted receiver horizontally and measuring
the field diffracted around a vertical edge of the building. Many of these measurements, however, were corrupted by scatter from adjacent buildings - an observation which spawned a separate study. It was found that the effect of scatter may be virtually eliminated by moving the receiving antenna vertically whilst pointing it at the rooftop of the obstructing building and thus measuring the strength of the field undergoing rooftop diffraction. A significant amount of measured data was compiled for which results are compared with single knife edge predictions. From this it was clear that, whilst the single knife edge model yielded an acceptably accurate prediction of the diffracted field strength in the shadow of a wedged roof building, it led to significant overestimation of this field where the diffracting obstacle was a flat roofed building. Accordingly, in chapter 5, the theory introduced in chapter 2 was extended to produce diffraction models suitable for practical buildings. These used perfectly smooth, conducting obstacles as a starting point and then assessed the likely effect of practical variations from this ideal model. It was concluded that the single knife edge model was the most appropriate for predicting the diffracted field in the shadow of a wedged roof which was clearly viewed by both transmitter and receiver, whereas a practical flat roofed building was best modelled by a double knife edge system solved by the FSI method.

All the models discussed up to this point had assumed that one significant diffracting edge could be identified. In a typical environment, particularly as the distance from the building to the receiver increases, more than one significant diffraction path needs to be considered. For example, via the roof of the building and around the sides. Chapter 6 gives details of experiments made using buildings outside the University of Glamorgan campus in situations where significant diffracted signals may be expected via more than one path. The results obtained were significantly different from the situation where only one diffraction path existed with large variations in field strength observed for movement over very small distances. In chapter 7 the diffraction model developed was extended so that contributions from more than one diffraction path could be incorporated. This was shown to give good agreement with results for an isolated building but when the obstacle was in a cluttered, urban environment, scatter from adjacent buildings appeared to form the dominant propagation mechanism deep in
the shadow of the obstacle. The model developed was compared with two separate models developed concurrently at other institutions which utilised the Uniform Theory of Diffraction and the Parabolic Equation method. The three models were seen to give remarkably good agreement regarding the prediction of the field strength in the shadow.

At this stage, sufficient confidence had been gained in the prediction models to address the problem of incorporating the results into planning procedures such as those recommended by the CCIR. Chapter 8 gives details of methods by which building diffraction may be incorporated into the determination of coordination distance and into interference assessment procedures. Suitable simplifications to the model are put forward and likely errors analysed. It must be acknowledged however that diffraction represents only one propagation mechanism in an urban environment with signals scattered from adjacent buildings assuming large significance deep in the shadow of the diffracting obstacles. In chapter 9 further work is proposed aimed at producing a general site shielding model whereby the effect of all buildings in the vicinity of the receiver is included whether they obstruct the signal in question or provide an additional scattering path. Additionally, the question of how much microwave energy can be transmitted through a building is proposed as worthy of a further study.

10.2 Conclusion

10.2.1 Contribution to theoretical models

Reviewing available models led to the adoption of Fresnel integral techniques in order to predict diffracted field strength. These were chosen in preference to GTD methods because of their better accuracy, particularly where multiple diffraction occurs with one edge in the transition region of the other. Additionally the simplicity of the geometry under investigation did not make the use of Fresnel integral
methods prohibitively complicated. It is in situations where the path geometry is very complicated that GTD becomes the only realistic choice.

Initially two roof profiles were analysed, namely, wedge roofed and flat roofed. The author acknowledges that diffraction models for wedges and slabs have been known for some time. King and Page (1972) discuss both types of model and give a few experimental results at 632.8 nm wavelength. Whitteker (1990) describes the slab model in more detail and outlines the derivation of formulae stated in the King and Page paper. Predictions are compared with measurements made by Hacking (1970) again using a He-Ne laser at 632.8 nm wavelength.

This thesis extends both these works by evaluating their relevance to diffraction by real buildings at microwave frequencies. In the case of the wedge model it is important to assess the effect of surface roughness, imperfect reflection and non infinite extent of the sloping sides. This then led to an evaluation of the appropriateness of the wedge model from the viewpoint of using it to predict the diffracted field in the shadow of a wedge roofed building. It became apparent that, where both transmitter and receiver had a clear view of the diffracting apex, a single knife edge model was adequate. Where either did not have a clear view of the diffracting apex then a double knife edge system model was required. In either case the original wedge model which, at first, had seemed the obvious choice was either not necessary or inappropriate. The slab model was extended by pointing out a different method of determining the additional component of the diffracted field due to reflection in the connecting surface of the slab. This has the advantage of making the derivation of the extra phase term much simpler. It also allows the effect of variations in roof profile to be simplified. In particular the effect of the connecting roof not being at the height of the sidewalls was analysed. This is a very common phenomenon with a parapet wall often surrounding a flat roof. The predicted results at microwave frequencies are that, for comparatively small parapet wall heights, the predicted diffracted field strength is often closer to the predicted value for a double knife edge system than for a slab. Analysis suggested a threshold
figure of $\sqrt{\lambda b/10}$ for the parapet wall height where $\lambda$ is the wavelength and $b$ is the building width. Parapet wall heights above this figure render the slab model completely invalid.

At microwave frequencies, and with typical building dimensions, the value $\sqrt{\lambda b/10}$ often represents very small heights. Certainly smaller than it would be reasonable to expect a system planner to investigate. This knowledge, coupled with the uncertainty over the reflective qualities of the roof material, meant that any specific assumption regarding the nature of the component undergoing reflection was prone to error. A study was undertaken regarding the range of possible diffracted field strengths assuming extreme conditions for reflection coefficient of +1 and -1. The outcome of this was the conclusion that it would generally be safe, from the interference prediction viewpoint, to assume zero reflection coefficient. That is, the flat roofed building should be treated as a double knife edge system. Using this method, the diffracted field strength may be predicted rapidly using the method of Millington et.al. and the probability of seriously underestimating the diffracted field strength is very small. There remains the possibility of overestimating the diffracted field strength but this thesis argues that the amount of detail, regarding the electrical characteristics and exact profile, required in order to identify the situations where this would be the case would render investigation prohibitively lengthy.

The aim of this thesis throughout has been to enable system planners to confidently estimate a reduction in interference levels due to the presence of an obstructing building. In order to achieve this aim it was necessary to be able to comment on the validity of the model developed under realistic interference conditions. A "realistic interference" situation is usually taken to mean elevated signal levels being received from a transhorizon transmitter due to anomalous propagation conditions. Simulations using the parabolic equation (PE) method predict that under ducting conditions the incident field is highly non uniform with the signal strength varying rapidly with height. The theoretical model has been adapted so that the diffracted
field strength may be predicted under such circumstances. The model suggests that the diffracted signal will have a maximum dependence with the signal incident at the roof top.

The simulation also reveals that a time varying signal incident at the diffracting edge will cause the diffraction loss due to the building to be time varying also. In fact, at times it is predicted to be of a very low value. However this does not mean that there will be an interference threat at these times because the low value of diffraction loss is due to the incident signal dropping in level rather than the signal in the shadow increasing.

A further extension to the theoretical model allows multiple path diffraction to be considered. This is seen as an important extension as it will sometimes not be possible to identify a single diffraction path. The Fresnel surface integral (FSI) method was again used as a basis from which to develop such a model. This was seen to be straightforward in its implementation although this type of geometry would perhaps be thought of as more suited to GTD/UTD methods.

Recently a sophisticated UTD model has been developed by van Dooren and Herben (1992, 1993) of the University of Eindhoven. In this model the diffracted field in the shadow of an ideal smooth perfectly conducting rectangular block has been investigated. The theoretical model is validated by a small scale experiment in an anechoic chamber using a 50 GHz source. Additionally, extensions to the two-dimensional parabolic equation (PE) method has been recently shown to allow the diffracted field strength to be predicted in the shadow of a rectangular block considering multiple path diffraction. Use of the FSI model to simulate the same building characteristics and path geometry reveals that UTD, PE and FSI models may be used as a basis for multiple path diffraction predictions around buildings (van Dooren, Haslett and Levy [1993]).
10.2.2 Contribution to measured data.

A major element of the work entailed the development of the mobile measuring receiver. This proved to be an extremely economic and sensitive receiver capable of detecting signals as low as -125dBm in level. This receiver was used to conduct the experiments described in chapter 4 and formed the basis of the receivers used in further experimental programmes conducted at the University of Glamorgan (Al-Nuaimi and Ding [1990, 1993], Haslett and Wille [1993], Al-Nuaimi and Hammoudeh [1993].

The experimental work undertaken, and reported in chapters 4 and 6, used exactly the type of diffracting obstacle for which the theoretical models were intended, namely buildings of typical dimensions.

The measurement programme led to reliable results being obtained which could be used to assess the validity of the theoretical models.

10.2.3 Contribution to the published literature

Details of significant developments that were felt to make a new addition to published material were made public as follows:

i) The extension of the slab model to deal with the situation where the roof is surrounded by a parapet wall was published in "Electronics Letters" (Haslett and Al-Nuaimi [1991])

ii) The extension to include the method by which the diffracted field may be predicted under condition of non-uniform illumination was presented at the fifth international conference on Antennas and propagation (ICAP '93) (Haslett and Wille [1993])

iii) The method by which the diffracted field strength may be predicted when more than one diffraction path exists was published in "Electronics Letters" (Haslett [1993])
iv) Comparisons between predictions made using the FSI method and the PE and UTD methods assuming the diffracting obstacle to be a perfectly conducting rectangular block were published in "Electronics Letters". (van Dooren, Haslett and Levy [1993]).

Additionally a report on the experimental programme and the two dimensional model was placed in the public domain as a research note of the National Radio Propagation Programme (Haslett [1991]). As well as these formal contributions regular technical reports have been presented to the management committees of COST programmes 210 and 235 on which the author is a co-opted expert. These committee papers are not publications as such but rather form the basis of the final reports of the programmes. The final report of COST 210 [1990] cites work performed at the Polytechnic of Wales (now University of Glamorgan). It is expected that the final report of COST 235 will reference work reported in this thesis. Further to this, results of work have been reported to study group 5 of the CCIR. It is this study group that produces the recommendations and reports of the CCIR for radio propagation in non-ionised media. Some adjustments were made to report 569 (1990) as a result of preliminary work performed at the University of Glamorgan. The custom of publishing on a four yearly basis has now ceased, reports now being issued not under the flag of the "CCIR" but directly under the "ITU" when material is deemed worthy of publication. The intention of this is to keep users informed of the latest developments in recommended procedures.

10.3 General Conclusion

A need was identified for a procedure whereby the diffracted field strength in the shadow of a building may be predicted. Multiple edge diffraction models were investigated with the Fresnel Surface Integral (FSI) method being selected as the most appropriate. Ideal geometries were investigated initially but attention was paid to the effect of likely discrepancies between ideal models and practical buildings resulting in a model that yielded acceptably accurate predictions.
whilst being mindful of the fact that the electrical characteristics and detailed profile of the building surface would not be known in the majority of cases.

The models were validated by a measurement campaign devised by the author using real buildings as the diffracting obstacle. This utilised a mobile measuring receiver commissioned by the author. The experimental results confirmed the validity of the theoretical model.

As a result of the work reported, a substantial amount of new information is available to users, so that the diffracted field strength in the shadow of a building may be predicted with greater confidence.
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Recommendation 581: "The concept of worst month", (in volume V)
APPENDIX

PUBLICATIONS BY THE AUTHOR

RELEVANT TO THIS THESIS
Prediction of diffracted field strength in the shadow of a flat roofed building

Introduction: Predicting the level of an interfering signal in a situation where a building lies in between the interferer and receiver requires a method of calculating the diffracted field strength in the shadow of such a building. King and Page\(^1\) and Whitteker\(^2\) have put forward models whereby the diffracted field strength may be evaluated in the shadow of a flat topped terrain obstacle. This is done by solving the Fresnel surface integral using the method proposed by Millington, Hewitt and Immirzi.\(^3\) This Letter shows how this may be modified in such a way as to simplify the computation and also allow factors, such as imperfect reflectivity and the existence of a parapet wall around the roof of a practical building, to be considered. Additionally, results from a measurement programme conducted at 11.2 GHz are submitted.

Slab model: The profile of a flat roofed building between source and receiver is given in Fig. 1. The problem is to evaluate the field distribution along plane \(Y\) as a result of that at plane \(X\) and hence to determine the resultant field strength at \(R\). Previous models\(^1,2\) have considered this resultant field strength as the sum of two components: one undergoing a double knife edge diffraction and the other suffering an additional reflection in the roof surface. Computation is simplified if the reflected component is visualised as that due to a virtual source undergoing an inverted double knife edge diffraction as shown in Fig. 2. The virtual source \(S_i\) in Fig. 2 is the reflection of \(S\) in Fig. 1 in the line of the roof. It can then be seen that the field distribution in plane \(X'\) of Fig. 2 is the mirror image of that in plane \(X\) of Fig. 1. To calculate the resultant at \(R\) the magnitude of source \(S_i\) should be multiplied by the surface reflection coefficient (-1 for a perfect conductor) as appropriate.

Visualising this component as in Fig. 2 allows Babinet's principle to be used in its solution. The reflected component is the difference between two further components: double knife edge diffraction and a single knife edge diffraction as shown in Fig. 3. Thus the entire problem may be solved by evaluating two double knife edge components and a single knife edge component.

Fig. 1 Path profile

\begin{align*}
\text{Fig. 2 Inverted knife-edge geometry} \\
\text{Fig. 3 Babinet equivalent of inverted knife edge}
\end{align*}

The method of Millington, Hewitt and Immirzi yields a value for the relative field strength, \(E/E_0\), where \(E_0\) is the unobstructed field strength, in terms of magnitude and phase. An examination of Figs. 1 and 2 reveals that path lengths \(S\) and \(S'R\) are not generally equal. Although the magnitude of \(E_0\) will not be significantly affected by this, the phase difference introduced must be considered when evaluating the total phase difference between the diffracted field strengths of the two components. Using the geometry of Fig. 1, the path length difference \(\delta l\) is given by the equation

\[
\delta l = \frac{2ah \tan \Theta}{a + b + c}
\]

Special case of tangential illumination: It is common for an interfering source to be over the horizon from the viewpoint of the receiver with an interference problem only being posed under ducting conditions. In such cases the angle of incidence of the signal with the building is assumed to be tangential with the roof surface (\(\Theta = 0\)). In this situation the position of source \(S\) in Fig. 1 coincides with that of its virtual image \(S^\prime\) in Fig. 2. Examination of the Babinet equivalent (Fig. 3) of the inverted knife edge diffraction leads to the conclusion that determining the resultant field strength at \(R\) requires the calculation of only one double diffraction and one single diffraction. If \(E'/E_0\) and \(E''/E_0\) are the relative field strengths at \(R\) for the single edge and double knife edge cases, respectively, then the resultant relative field strength is

\[
\frac{2E''/E_0}{E'/E_0} - \frac{E'/E_0}
\]

assuming perfect reflectivity at the roof surface.

Extension to parapet wall situation: The model so far has dealt with the situation where the reflecting surface is at the height of the side walls. It is quite common for this surface to be below the side walls, for example when the roof is surrounded by a parapet wall. This may be accounted for by lowering the left hand knife edge in Fig. 2 so that it extends below the line

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Inverted knife-edge geometry considering parapet wall

joining the top of the side walls by an amount equal to twice the height of the parapet wall. This situation is illustrated in Fig. 4. The effects of doing this are twofold; first, the magnitude of the reflected component reduces, and, secondly, the phase relationship between the two components changes. The first effect leads to the signal level tending towards that for a double knife whereas the second effect means that it is possible for the diffracted field with a reflecting surface present to be greater than that for a perfectly absorbing building. A signal strength 1.5 dB greater than for a perfectly absorbing building has been measured. This occurred when a perfectly reflecting roof surface was surrounded by a parapet wall of height \((w/4)^{1/2}\), where \(w\) is the building thickness.

Results of experimental programme: Buildings have been illuminated from a distance of 1 km with an 11.2 GHz CW source. The measuring receiver was mounted on an aerial platform and the diffracted signal measured in the shadow of the building. The graph of Fig. 5 compares measurements with predictions assuming a reflection coefficient of 0, -0.5 and -1. It can be seen that an assumed reflectivity of between 0 and -0.5 would produce the best prediction. This agrees well with measurements of roof reflection loss of approximately 15 dB.

Conclusion: A model has been developed that can predict the diffracted field strength in the shadow of a flat roofed building where the roof reflectivity is specified and the level of the roof below the side walls is known. If such details are not known a perfectly absorbing building model will give a reasonable prediction of diffracted field strength.

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C. J. HASLETT
M. O. AL-NUAIMI
Department of Electronics and Information Technology
The Polytechnic of Wales
Pontypridd, Mid Glamorgan CF37 1DL, United Kingdom

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Multiple Path Diffraction by Rectangular Buildings

J. Haslett

Indexing terms: Modelling, Radiowave propagation, Mobile radio systems

Consideration of only the two dimensional great circle path is insufficient to determine the diffracted field strength in the shadow of a finite width obstacle such as a rectangular building. A simplified absorbing slab model based on Fresnel integral methods is proposed as an appropriate model for determining the diffracted field strength in such cases. Predictions are compared with experimental results obtained at 11.2 GHz using an isolated building and a building in a cluttered urban environment as diffracting obstacles.

Introduction: When predicting likely radio interference levels at a receiver, it is frequently required that the diffracted field strength in the shadow of a building be estimated. A previous model [1] considers only the two-dimensional building line. It concludes that, because at microwave frequencies all profile variations lead to large phase uncertainties in the reflected ray, a double knife edge model is the most appropriate model for a flat-roofed building. In this Letter the method intended to allow diffraction around the sides of the building to be considered. An experiment involving measuring the diffracted field in the shadow of real buildings at a frequency of 11.2 GHz is also reported.

Theoretical model: The solution to the double knife edge model for flat-roofed buildings described in Reference 2 provides a highly accurate prediction of the diffracted field strength. The model used regards the diffraction path from each of the sides of a rectangular building as further knife edge systems. Fig. 1 shows a plan view of a rectangular building and indicates how parameters a, b, c, h, h1, h2 would be determined so that the method of Millington et al. [3] may be used directly. Once these parameters have been determined for all three paths the relative field strength at the receiver is predicted for each path. The resultant is obtained as the phasor sum of the three individual contributions. Reflections at the surface of the building are ignored so the model approximates to a perfectly absorbing rectangular slab. The model may be modified to include the effect of reflections but it is found that the large variations in predicted field strength due to very small changes in surface profile would be of little benefit in practical situations.

Experimental programme: The transmitter consisted of an 11.2 GHz carrier wave oscillator which delivered 10 mW into a 20 dB horn antenna. Transmissions were vertically polarised. This antenna has a 3 dB beamwidth of approximately 3°. As the maximum angle subtended by either of the buildings investigated when viewed from the transmitter was less than 2°, the building and relevant surrounding space were assumed to be nearly uniformly illuminated. The receiver consisted of a 20 dB horn which fed a satellite television low noise block (LNB). The output of the LNB was fed into a spectrum analyser.

The first building investigated was a fire station practice tower. The small horizontal dimensions (4 × 3 m²) may be somewhat unrealistic but the building offered the advantages that the site geometry could be accurately measured and also that it was in an isolated position. This meant that the likelihood of measurements being corrupted by signals scattered by adjacent obstacles was small.

The second building used was in a city centre location which was felt to be more typical of an urban environment where building diffraction models would be required. In this location the possibility of receiving signals scattered from adjacent tall buildings was considerably greater than for the first building.

Fig. 2 gives details of the site geometry measurements made. Additionally the height of the roof and the receiving antenna were recorded using the transmitter height as a zero reference. The short path lengths involved meant that a flat earth approximation was justified.

Measurements were made keeping d1, d2 and θ constant with the receiving antenna being moved horizontally so that dimension x of Fig. 2 varied. The variation of diffraction loss with x is shown in Fig. 3 for the first building and in Fig. 4 for the second. Predicted results using the model described are added for comparison purposes.

\[ \theta = 120°, \text{Rx height} = 79°, \text{roof height} = 8.0 \text{m} \]

\[ \text{predicted} \]

\[ \text{measured} \]

\[ \text{predicted} \]

\[ \text{measured} \]

\[ \text{predicted} \]

\[ \text{measured} \]
Discussion of results: Fig. 3 suggests that the model developed is of acceptable accuracy for most practical purposes. The interference pattern due to phasor summation of the three fields is clearly in evidence. The tendency for the diffracted signal to be slightly weaker than predicted is probably due to the reflecting surface of the building having a negative effective reflection coefficient in this case. In Fig. 4 the measured results are quite close to those predicted near the shadow boundary. Deep in the shadow, however, the signal measured is considerably greater than that predicted. This could be due to the increased significance of any scattered signals from adjacent buildings as the diffracted signal becomes weaker. If only two-dimensional roof top diffraction was considered, the predicted diffraction loss would be largely independent of $x$ at approximately 28.0 and 26.2 dB for the cases of Figs. 3 and 4, respectively. This is clearly a generally unacceptable over-estimation of diffraction loss demonstrating the need to consider the true diffraction paths.

Conclusions: A model has been put forward whereby the diffracted field in the shadow of a rectangular building may be predicted. Measurements indicate that the model is of acceptable accuracy where the diffracting building is in an isolated location. From results made in a cluttered urban environment it appears that fields scattered from adjacent buildings could form the dominant propagation mechanism deep in the shadow of the diffracting building.

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C. J. Haslett (Department of Electronics and Information Technology, University of Glamorgan, Pontypridd, Mid Glamorgan CF37 1DL, United Kingdom)

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THE EFFECT OF NON-UNIFORM ILLUMINATION ON SITE SHIELDING FROM BUILDINGS AT MICROWAVE FREQUENCY

C J Haslett, V Wille
University of Glamorgan, United Kingdom

ABSTRACT
Predicting the diffracted signal strength behind an obstacle is valuable in estimating the obtainable site shielding factor (SSF), where the SSF is defined as the difference between unobstructed and diffracted signal levels. Presently, the majority of models by which diffracted field strength may be predicted assume that the diffracting obstacle is clearly illuminated by the transmitter. For the case where a building is being relied on to provide protection from microwave frequency interference it is more common for the interference path to be trans-horizon. In this situation a threat is posed on the receiver only under anomalous propagation conditions.

In this paper a flat roofed building is treated as a double knife edge system and the exact, surface integral method of determining diffracted field strength is extended so that it may be applied to conditions of non-uniform illumination. Additionally, results from an experiment involving the long term monitoring of site shielding on a 50km trans-horizon path at 11.2GHz are presented.

INTRODUCTION
Haslett and Al-Nuaimi (1) have shown that the diffracted field strength in the shadow of a flat roofed building may be predicted by regarding the building as a double knife-edge system and using the Fresnel Surface Integral of Millington et al. (2,3). However, the assumption is made that there exists an unobstructed path from the transmitter to the obstacle. It is of interest to system planners to know how such diffraction models cope with the situation where a transmitter is over the horizon from the viewpoint of the obstacle.

EXPERIMENTAL WORK
A 50km trans-horizon link was established with a 10mW, 11.2GHz CW transmitter being located on a disused farm building in East Quantoxhead, Somerset and a monitoring receiver located on a school building at Newport, Gwent. Over 90% of the path is across the Bristol Channel. The likely existence of both surface and evaporation ducts as well as the very large tidal variation means that this link provided a great variety of incident fields at the receiver.

The building whose site shielding properties were examined was 10m high and 15m thick. The angle of incidence of the signal was 45° from normal to the building. The transmitting antenna consisted of a 90cm parabolic dish. Three antennas were located at the receiving point; two 25dBi horns receiving an unobstructed signal (one at roof top and one at the height of the antenna in the building shadow) and a 60cm parabolic dish antenna mounted some 21m behind the building and 1.6m below the roof top.

The measuring receiver was connected to a data logger so that the signal level received from each of the three antennas was recorded in turn with each signal level being recorded once every 1.5 seconds. Graphical outputs from the data logger took the form of a simulated chart recorder, a cumulative distribution of the three measured signals and a cumulative distribution of the SSF.

THEORETICAL WORK
The path profile of the 50km path was inserted into the parabolic equation (PE) programme developed at the Radio Communication Research Unit of the Rutherford-Appleton Laboratory. The incident field was predicted for various types of atmospheric structure: standard atmosphere; surface duct; evaporation duct. Simulation results using the PE method are shown in figure 1. It may be seen that under standard atmospheric conditions the incident field strength becomes greater with increasing height at a rate of approximately 0.6dB/m. This continues until the free space path loss of 147dB is reached. Where ducting conditions have been simulated, the signal strength is predicted to be much stronger than under standard atmospheric conditions. However, a definite lobe structure may be identified with deep nulls present. The double knife-edge system model was employed on a "split-step" basis to predict the diffracted field strength under standard atmospheric conditions. This revealed that no significant difference in diffracted field strength would be expected from the situation where the incident
field was uniform at the level incident at the roof top.

The lobe structure under ducting conditions was simulated by the use of two coherent sources. For example, the surface duct simulation of figure 1 reveals that the incident field will contain nulls at intervals of approximately 8m. In this case the sources were assumed to be 50km distant from the receiver with a vertical separation of 180m.

The short run time of the double knife edge model allowed the effect of varying null depth and null height relative to building height to be examined. Figure 2 shows the predicted signal strength at the three monitoring points of the experimental set-up when nulls of various depths move up the face of the building (the time scale is dependent on the speed at which the null moves). The simulation reveals that the diffracted signal is most strongly correlated with the signal at the roof top and also that the depth of null experienced in the shadow is significantly less than that incident at the roof top. This leads to the instantaneous short term value of SSF dropping perhaps to negative values. The statistical significance of these simulations from the viewpoint of the prediction of interference levels will be revealed by examining results of the monitoring programme.

EXPERIMENTAL RESULTS

The variation with time of the signal at the front and in the shadow of the building was monitored. As expected a great variety of signal behaviour was observed of which two examples are given.

Examination of figure 3 clearly shows the influence of the tide on the signal strength. All three signals monitored can be seen to exhibit the same characteristics under these circumstances. Figure 4 gives a cumulative distribution (cd) of the difference in signal levels (the recorded SSF) and figure 5 gives the cd of the three measured signals. It should be mentioned here that, although levels were recorded every 1.5 seconds, each point of figure 3 is the average of 144 consecutive readings. However every measurement is used in the production of the cd curves. An instantaneous SSF of as low as 12dB is noted in figure 4 but figure 5 shows the cd of the signals to be parallel with a constant difference of 27dB. The cd curves for the three signals (figure 8), however, are again shown to be parallel with a constant difference of 27dB. Indeed, figures 5 and 8 are almost identical. This means that the cause of the very low values of SSF observed must be a very low level incident on the roof top antenna rather than a high level in the shadow. Therefore the low value of SSF is of little significance when predicting interference levels in the building shadow.

The parallel nature of the cd curves however, means that the statistics of the signal in the shadow may be obtained from statistics of the unobstructed signal.

CONCLUSIONS

Theoretical modelling supported by experimental results suggests that the diffracted field in the shadow of a building is most strongly correlated with that incident at the roof top. The cumulative distributions of incident and diffracted field measurements are shown to be very nearly parallel even when taken for periods as short as one day under different propagation conditions. These facts support the hypothesis that the site shielding factor of a building (in dB) equals diffraction loss (dB) minus height gain (dB). "Diffraction loss" is the predicted difference in incident and diffracted signal strength for uniform illumination and "height gain" is the predicted difference in incident signal strength between the roof top and (unobstructed) receiver height.

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Figure 1: PE prediction of incident field strength

Figure 2: Signal strength under conditions of varying null depth

Figure 3: Signal variation with time at 'standard atmosphere'

Figure 4: cd of site shielding factor at 'standard atmosphere'
Figure 5: cd of signal level at 'standard atmosphere'

Figure 6: Signal variation with time under 'ducting conditions'

Figure 7: cd of site shielding factor under 'ducting conditions'

Figure 8: cd of signal level under 'ducting conditions'
DIFFRACTION BY A RECTANGULAR BUILDING: COMPARISON OF THREE FIELD-STRENGTH PREDICTION TECHNIQUES

G. A. J. Van Dooren, C. J. Haslett and M. F. Levy

Indexing terms: Electromagnetic fields, Geometrical theory of diffraction

A comparison is made between three methods to calculate the electromagnetic field diffracted by a perfectly conducting block-shaped obstacle. The models, that are first briefly described, include a ray-based model (uniform theory of diffraction) and two wave-based models (Fresnel surface integral and parabolic equation method). A test case is analysed with all methods resulting in good agreement between the predicted results for both linear orthogonal polarisations.

Introduction: The problem of field strength prediction has gained renewed interest in recent years. Applications lie in the field of mobile and personal communications and interference reduction, the latter being one of the research topics of the European project COST 235 [1].

Accurate field-strength predictions are required to account for diffraction of electromagnetic waves by buildings. In this Letter we compare three diffraction models based, respectively, on the uniform theory of diffraction (UTD) [2], the Fresnel surface integral (FSI) [3] and the parabolic equation (PE) [4].

The geometry considered is shown in Fig. 1. The positions of S(source) and Obs(ervation point) are given in a Cartesian co-ordinate system. The source S emits a signal that is either horizontally ($\sigma$) or vertically ($\pi$) polarised. The electric field $E_{\sigma}$ will be calculated for $-15 \leq x \leq 15$, at $y = 120$ m and a frequency of 1 GHz. The obstacle has its top face at $z = 1$, m, and $y = 100$, m, $x = -150$, $x = 150$, $z = 1$, $z = -5$. It is also assumed that the obstacle extends indefinitely in the $-z$ direction. The parameter $\Delta z$ is used to denote $z_{obs} - z_{o}$.

UTD prediction model: Using UTD, the resulting field $E_{obs}$ at the observation point position is given by

$$E_{obs} = E^{60} + \sum_{p} E^{p} + \sum_{q} E^{q} + \sum_{k} E^{k}$$

where $E^{60}$ is the geometrical optics field, $E^{p}$ is the field singly diffracted at the obstacle, $E^{q}$ is the doubly diffracted field, and $E^{k}$ are higher order diffracted fields. Note that $E^{60}$ is included only for observation points in lit space. The summatations in eqn. 1 extend over the number of ray paths originating from S to Obs having one (singly diffracted) or more (doubly/higher order diffracted) points located on the slab. It was found from numerical analyses that multiple-diffraction contributions should be taken into account up to order $k^{-3/2}$, where $k = 2\pi/\lambda$ with $\lambda$ being the wavelength [5]. The contributions of this order correspond to waves undergoing both corner and edge diffraction.

Recently, the performance of this prediction model has been experimentally verified for scaled obstacles at a frequency of 50 GHz using a vector network analyser. Excellent agreement in detail between theoretical and measured results was obtained for conducting obstacles with various geometries [5].

The main advantage of the UTD model is that it provides a clear physical insight into the diffraction process at buildings, and that diffraction at an obstacle and an antenna may be analysed in a combined way. It is very well suited for the description of diffraction phenomena near the observation point.

FSI prediction model: In this model initially three waves are considered: one propagating over the top face and two around each side. Each of these paths is regarded as a two-dimensional system with a line source as the transmitter. The obstacle outline on each two-dimensional system may be likened to a flat-topped terrain obstacle. It entails evaluating the relative electric field strength due to a double knife edge system and adding it to that for the wave undergoing a reflection in the connecting surface. When the model is extended to three dimensions, the two-dimensional systems are found to overlap so that it would be incorrect to simply add the three relative field strengths together. Rather the resultant relative electric field is given more accurately by

$$E_{obs} = E_1 + E_2 + E_3 - E_1 \cap E_2 - E_1 \cap E_3$$

where $E_1$ is the relative electric field strength for the top face, $E_2$ for the left hand edge of the building and $E_3$ for the right hand edge of the building. The terms $E_1 \cap E_2$ and $E_1 \cap E_3$ represent the overlapping portions of the two-dimensional systems.

In predicting the diffracted field for a vertically polarised wave in the shadow of a conducting slab an effective reflection coefficient of $+1$ is assumed for the top face diffraction component and $-1$ for the side components. These are reversed for a horizontally polarised wave. It should be noted that only reflections in the surface connecting the two edges are considered. Additionally, the pattern of the antenna at $obs$ is not modelled.

The main advantage of this method is that it may be rapidly implemented using well established methods.

PE prediction model: PE techniques provide a numerical full-wave solution to radio propagation problems. PE methods have been applied successfully to propagation over irregular terrain [4] and more recently to urban environments [6].

In three dimensions, a function $u$ slowly varying in range $y$ is associated with a field component $E_{obs} = \exp(ik)u(x, y, z)$. $u$ then satisfies approximately the outgoing wave PE:

$$\frac{\partial u}{\partial y} = -ik\left[1 - \sqrt{\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}\right)}\right]u$$

The parabolic nature of this partial differential equation (it is of first order in $y$) allows the solution to be transferred from one transverse vertical plane to the next. It can be solved by two-dimensional split-step FFT techniques or by finite difference methods.

The results presented here have been obtained with the two-dimensional FFT approach, using a simple image model for reflections in the obstacle faces. This works well for a block-shaped obstacle with faces parallel to the axes, which is either perfectly absorbing or perfectly conducting, using the appropriate polarisation-dependent boundary conditions. Extension to a finitely conducting obstacle or an obstacle of more complicated shape is not straightforward using split-step techniques. It will probably require the development of a finite difference algorithm.

The three-dimensional split-step method is straightforward to implement and is valid in the shadow region as well as the transition region.
Comparison of results: Typical results of the three methods discussed are shown in Fig. 2 for both vertical (V) and horizontal (H) polarisation and for Δz = −5 m. The results for vertical polarisation are lowered by 20 dB for legibility. Agreement is very good except for vertical polarisation in the region 4 ≤ |x| ≤ 6, where there are slight differences, probably due to the treatment of corner diffraction. All models predict the same average level of the received field in the shadow region behind the building, as well as the strong polarisation dependence observed. Comparisons for other values of Δz give similar results.

Conclusions: Three diffraction models have been described and compared for the case of diffraction by a perfectly conducting block-shaped obstacle using a frequency of 1 GHz and a realistic building geometry. Despite their very different nature, the three methods show remarkably good agreement for the predicted field strength behind the obstacle and confirm the strong polarisation dependence of the diffracted field.

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