AN URBAN CANYON MULTIPATH MODEL FOR GALILEO

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ABSTRACT

This paper describes the development of a multipath channel model representative of a European urban canyon, as experienced by the Galileo mobile user.

The computational Electromagnetics behind the model is explained and some basic validation is presented. A tool for constructing realistic 3D urban environments is described, and the importance of accurately representing building types and surface detail is demonstrated.

A selection of results is presented and the variation of the RMS delay spread of the channel with satellite location is calculated.

Finally, the time-variant multipath channel for a receiver moving within a complex urban environment is modelled. The channel is presented in terms of power-delay profiles and Doppler shift versus delay.

INTRODUCTION

This work was carried out as part of the BNSC S@TCOM programme in association with Astrium Limited and Leeds University [1]. The overall program is aimed at signal optimisation for the Galileo mobile user and this paper concentrates on the development of the urban canyon multi-path model.

The urban canyon provides a difficult multipath environment because of the complexity of the building structures. To enable the Galileo signal structure to be designed with optimal urban performance, tools are necessary that can generate the diverse range of urban channel models, taking into account the full complexity of the surroundings.

Two such tools have been developed specifically for this application. The first is a computational electromagnetic simulator that has been adapted from a well-established and well-validated stealth-engineering tool. The second is a 3D-environment modelling tool, capable of generating realistic CAD models from photographic images or map data.

ELECTROMAGNETIC MODELLING

The computational Electromagnetics has been performed using a modified version of a stealth-engineering tool, which has been under development by Roke Manor Research since 1986. The tool is called Epsilon™ and has now been adapted for Channel Impulse Response (CIR) modelling.

Epsilon™ uses a collection of high frequency approximations to calculate the CIR. The following list gives an indication of the methods used, but it is probably reasonable to say that this whole field suffers from problems in terms of consistency of definitions.

- Physical Optics (PO) – Implemented in the most fundamental and flexible form. This uses the Kirchhoff approximation to calculate the boundary condition on surfaces, then integrates using the Stratton-Chu form of the surface integral [3].

- Physical Theory of Diffraction (PTD) – This is implemented as the Mitzner Incremental Length Diffraction Coefficient (ILDC), and when combined with PO it provides a solution sometimes referred to as the Geometrical Theory of Diffraction (GTD).

- Geometrical Optics (GO) – This is implemented as a fully automated ray tracer, which when combined with PO gives a solution sometimes referred to as GOPO. This is essential for calculating the multiple scattering within an urban environment.

- Diffuse Ray Optic (DRO) – This is a sophistication of GO and provides more accurate multiple scattering calculations.

Epsilon™ characterises the time-variant transfer function, $T(f,t)$. Three other key system functions (the time-domain function, $h(\tau,t)$, the frequency-domain function, $H(f,\nu)$, and the delay/Doppler-spread function, $S(t,\nu)$) can all be obtained from the time-variant transfer function through one or two dimensional Fourier transforms as indicated in the figure below.

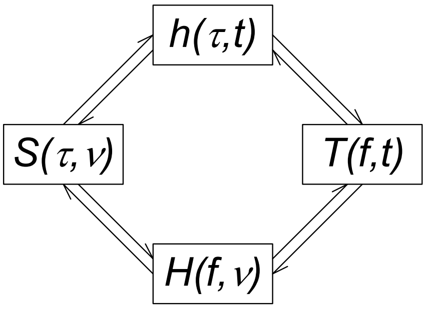

Figure 1 : Key System Functions

For the purposes of analysis the delay/Doppler-spread and the time-domain information can be most useful for gaining physical insight.

Epsilon™ outputs the time-variant transfer function in the form of received field for discrete frequencies across the simulation bandwidth for discrete points in time, i.e. incremental positions, as the receiver moves through the canyon. At each frequency, the phasor vector field at the receiver is calculated as a scattering matrix. The entries in the scattering matrix represent the co-polar and cross-polar fields received when two orthogonal fields are transmitted. From these, the full linear scattering matrix can be created. For example, if the two transmitted orthogonal fields are specified as V and H, the output scattering matrix, S_L, will be,

$$S_L = \begin{bmatrix} a_{HH} & a_{HV} \\ a_{VH} & a_{VV} \end{bmatrix}$$

For Galileo, the issue of signal polarisation is particularly interesting. The transmitted signal is Right Hand Circularly Polarised (RHCP). In certain applications (e.g. a receiver in an urban canyon or a reference receiver) a RHCP receive antenna may offer advantages in terms of multipath mitigation. It is to be expected that an RHCP receiver will provide a performance enhancement by rejecting odd-order multipath signals. However, in more complex environments, particularly where Line-Of-Sight (LOS) signals may not be received and the signal polarisation tends to become random, a linearly polarised antenna may offer advantages because the first multipath signal may be the biggest signal.

Because of the interest in modelling these polarisation effects, it can be useful to produce a circular polarisation scattering matrix. The matrix S_L contains all the necessary information. Reformatting as a circular polarization scattering matrix is a simple post-processing activity.

$$S_C = \begin{bmatrix} a_{RR} & a_{RL} \\ a_{LR} & a_{LL} \end{bmatrix} = [T]\begin{bmatrix} a_{HH} & a_{HV} \\ a_{VH} & a_{VV} \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}[T]^{-1}$$

where,

$$T = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -i \\ 1 & +i \end{bmatrix}$$

S_c contains the received field values for the four possible circular polarisation combinations of transmitter and receiver. For the purposes of modelling for Galileo the value of a_{RR} is of particular interest as this models the case of a RHCP transmitter and receiver. Similarly, T may be reformed to model other configurations such as circular-to-linear transmission.

A SIMPLE VALIDATION CASE

The simple case of a receiver above a perfectly conducting ground plane is a good example to demonstrate the polarisation issues. In this example, the receiver location and elevation angle of the transmitter (located in the far-field) has been chosen such that the multipath signal travels approximately 100m further than the direct signal.

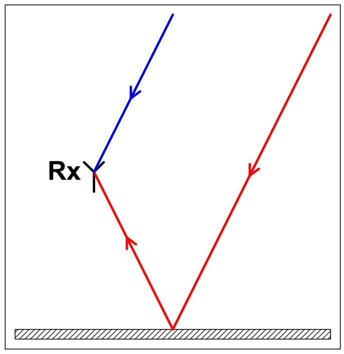

Figure 2 : Flat-Plate Validation Setup

The results of this simulation are presented below. Plots for a horizontally polarised transmitter and receiver (HH) and for a right-hand circularly polarised transmitter and receiver (RR) are given.

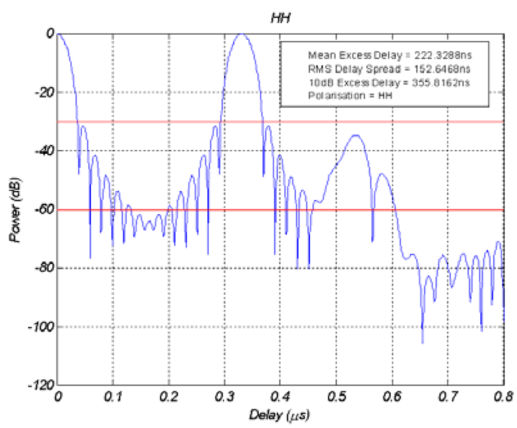

Figure 3 : Flat-Plate Validation – (Tx & Rx Horizontally Polarised)

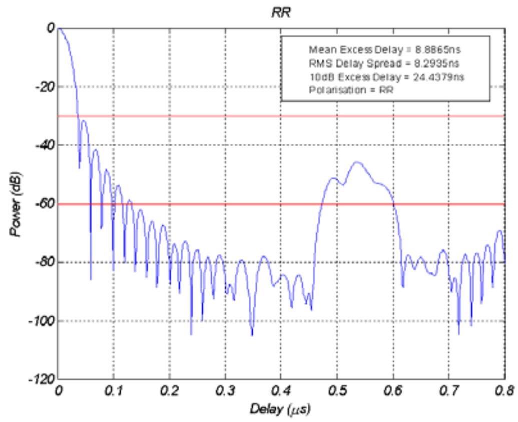

Figure 4 : Flat-Plate Validation – (Tx & Rx Horizontally Polarised)

The results clearly demonstrate the effect of using circularly polarised antennas. The first reflection completely disappears as expected. This simulation was conducted using a finite ground plane. It is interesting to note the effect the edges of the plane have upon the power delay profile, although in this case, these effects are tens of dBs below the direct path signal power.

A more practical example is that of a receiver within an urban canyon. The following example compares results for HH and RR polarisations using a simple urban canyon model. These two polarsiation configurations have been chosen as interesting examples. Arguably, the case of a circularly polarized transmitter and linearly polarized receiver is an important case for the low-cost mobile user. However, these results were not available at the time of publication.

The model uses an urban canyon 24m wide by 150m long. The buildings are modelled as simple blocks with smooth plain complex faces with complex dielectric material properties. The building heights follow a Gaussian distribution with mean 25m and standard deviation of 5m.

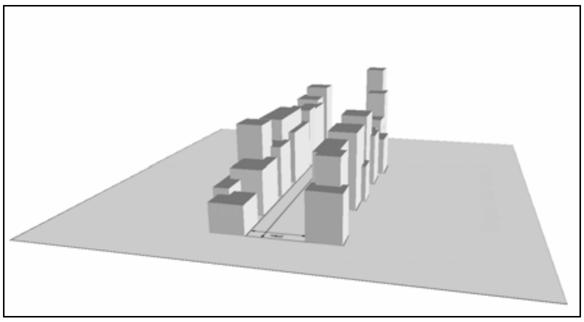

Figure 5 : Simple Urban Canyon Model

The transmitter is located in the far field with an elevation angle of 60° and an azimuth angle chosen such that the direction of incidence is perpendicular to the line of the street. The receiver is located 1m above the ground in a location with a direct line-of-sight to the transmitter.

Figure 6 shows the comparison between the HH power delay profile (dotted line) and the RR power delay profile (solid line).

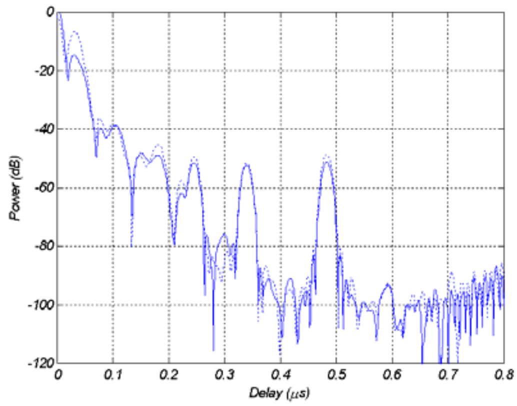

Figure 6 : RR & HH Channel Impulse Response for Simple Canyon Model

Essentially, the two CIRs have the same structure. The most significant differences occur with early delays. Clearly, the first significant multipath signal (corresponding to a reflection from the far wall of the canyon) is reduced when using circularly polarised signals compared with linearly polarised signals.

Less obvious, is the effect of the multipath reflection from the ground. As the receiver is only 1m above the ground, this limited bandwidth simulation (100MHz in this example) does not allow the direct signal and the multipath signal from the ground to be resolved. The result of this is that in the linearly polarised case, the direct and multipath signal interfere and cancel to a small extent. This effect is considerably less for the case of circularly polarised signals.

ENVIRONMENT MODELLING

To achieve high accuracy simulation results for the Satellite-to-Receiver multipath channel, it is important that the environment surrounding the receiver is accurately modelled.

To achieve this, RMRL have developed a tool specifically for creating representative urban and sub-urban environments. Photographic images (such as satellite or aerial photographs) are used as a reference to grow 3D city models. In this way street geometries and complex intersections can be easily created that are based upon a variety of real environments.

An example of such an environment created based upon imagery of a 0.5km square section of London is shown below.

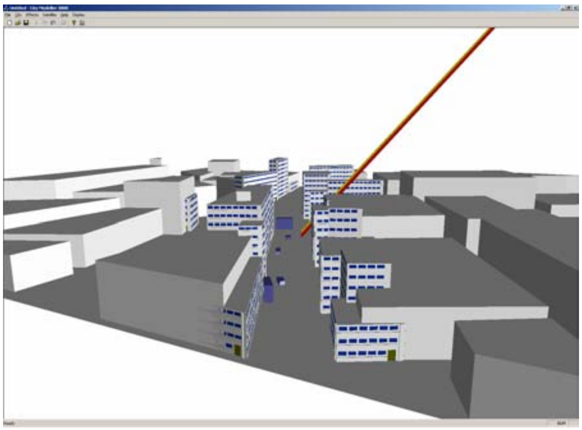

Figure 7 : Piccadilly Circus Model – View 1

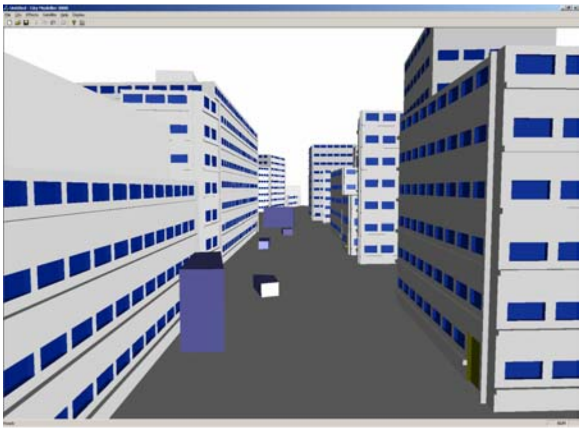

Figure 8 : Piccadilly Circus Model – View 2

The city modeller tool enables complete creation and set up of 3D environments. Building heights can be specified individually, or created randomly according to specific distributions. A library of building types is available so that a variety of different buildings can be included in the model (including a variety of building surface structures and material types).

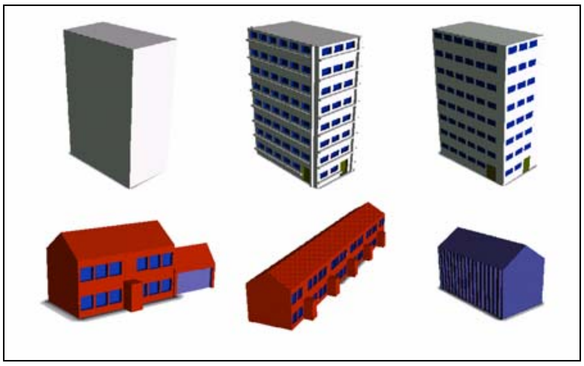

Figure 9 : A Selection of City Modeller Building Types

The significance of modelling the building surface structure and incorporating a wide variety of building types into a model is reflected in the power delay profiles, as shown later.

The city modeller software can also be used to specify receiver paths within the environment and define satellite parameters.

EXAMPLE CHANNEL ANALYSIS

The mean excess delay and RMS delay spread are two useful values to calculate from a CIR. These values are measures of the severity of a multipath environment. For a given set of multipath signal powers, *p(k)* and corresponding delays, *τ(k)*, the mean excess delay is calculated as:

$$\bar{\tau} = \frac{\sum_k p(k)^2 \tau(k)}{\sum_k p(k)^2}$$

The RMS delay spread is given by

$$\tau_{RMS} = \sqrt{\overline{\tau^2} - \left(\bar{\tau}\right)^2}$$

Where

$$\overline{\tau^2} = \frac{\sum_k p(k)^2 \tau(k)^2}{\sum_k p(k)^2}$$

Typical values for RMS delay spread for the multipath analysis performed in this work are of the order of tens of nanoseconds.

The exact values will depend upon the environment geometry. However, care must be taken to ensure that the maximum mean delay and RMS delay spread values are not limited artificially by the simulation set up. The environment model must be sufficiently large such that all significant multipath returns are captured. The number of multipath reflections within the simulation (a parameter that can be hard limited to reduce simulation time) must be high enough that any further reflections are negligible.

Figure 10 shows an example of a CIR with calculated values for mean excess delay and RMS delay spread. For this particular simulation, multipath signals occurring after 0.7μs are negligible.

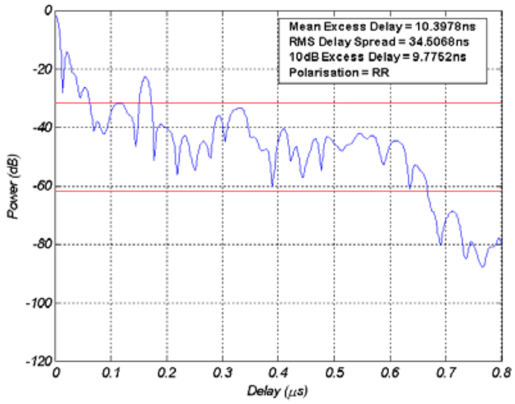

Figure 10 : Example Channel Impulse Response

IMPORTANCE OF MODELLING BUILDING SURFACE STRUCTURE

The wavelength for Galileo signals will vary between approximately 0.2 and 0.25m across the proposed frequency bands. With wavelengths of this order, the effect of building surface structure (such as ledges and recessed doorways and windows) becomes significant.

To demonstrate this, the CIR has been simulated for a receiver placed within a simple urban canyon model. For the first simulation the buildings have been given smooth concrete surfaces (Figure 5). For the second, the buildings have been given textured concrete and glass surfaces (recessed glass windows and 0.2m concrete ledges) (Figure 11). Aside from the surface detail, the two models are identical.

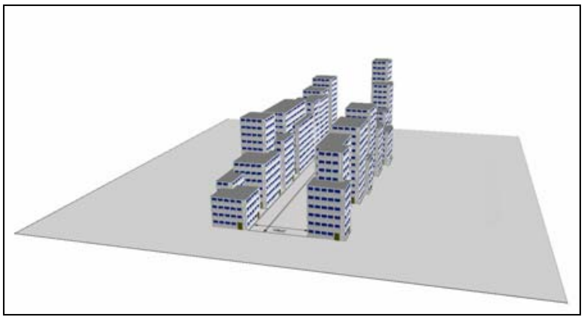

Figure 11 : Textured Simple Urban Canyon

Figure 12 compares the channel impulse response for the two simulations for RR polarisation. The dotted line is the textured surface power delay profile. The solid line is the plain surface power delay profile.

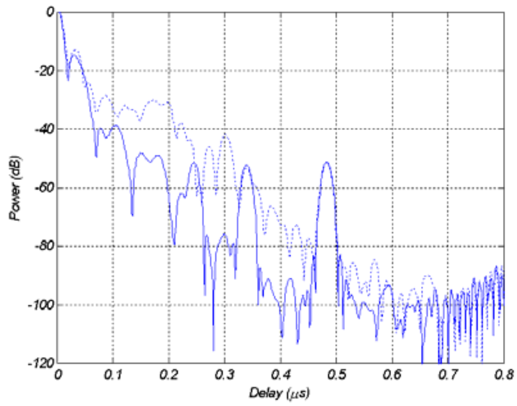

Figure 12 : Channel Impulse Responses for Smooth and Textured Canyons

There is a large difference between the two results. The underlying structure of the two responses is similar, but the textured surface simulation raises received power by up to 15dB in the 10 – 30ns delay region. One impact of this is that the mean excess delay and RMS delay spread for the channel rises from 6.5ns and 8.6ns to 8.3ns and 15.3ns respectively with the textured surface model.

Clearly, it is impractical to model an environment to centimetre accuracy in most cases. However, if a representative channel characterisation is to be performed, attempts should be made to include a wide variety of surface detail and other clutter (such as vehicles) in the environment model. In this way, a collection of many CIRs simulated from within the model will be characteristic of that generic type of environment.

THE EFFECT OF SATELLITE LOCATION

To investigate the variation of the channel impulse response with satellite location, a set of simulations were performed with the satellite sweeping around a stationary receiver.

In the first simulation, the receiver was placed in the center of textured simple canyon model of Figure 11, 1m above the ground. The satellite was set up to sweep from 5° elevation to 90° elevation, with an azimuth direction perpendicular to the line of the canyon. Figure 13 shows the variation of RMS delay spread with elevation angle.

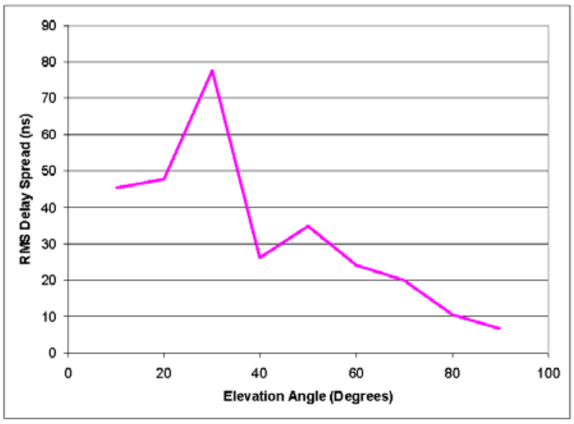

Figure 13 : Variation RMS Delay Spread With Elevation

These results compare well with measured data taken in a similar (but narrower) urban canyon in terms of both trend and magnitude [2]. There is a general trend for a decrease in RMS delay spread with increasing elevation angle. However, the pattern becomes more chaotic when line-of-sight to the satellite is lost below 40°.

In the second simulation, the satellite is swept in azimuth from 0° (looking down the line of the canyon) to 90° (perpendicular to the line of the canyon). The elevation angle was 55°. In this case, a different receiver location was chosen to ensure that line-of-sight to the satellite was maintained throughout the sweep.

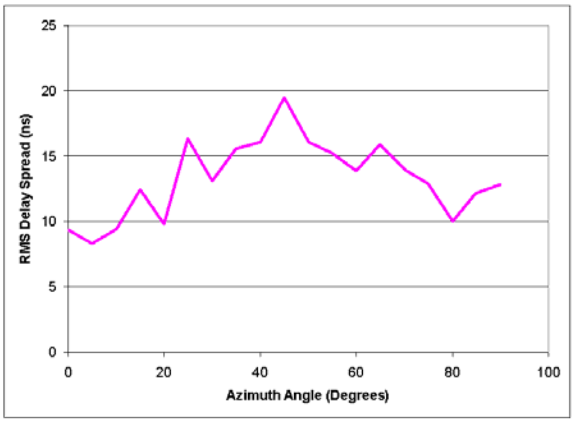

Figure 14 : Variation RMS Delay Spread With Azimuth

The variation of RMS delay spread with azimuth angle is much smaller than the variation with elevation angle. The lack of variation is largely due to the dominant line-of-sight path. A more interesting pattern may be noticeable if a non-line-of-sight version of the simulation were performed.

CHANNEL MODELLING WITHIN AN ENVIRONMENT

The Galileo multipath channel as seen by a mobile user is time varying. This results from the movement of the receiver, the transmitter and the environment itself. Here, an example is presented of a receiver moving within a complex urban environment. In this example, it is assumed that the satellite and environment are both stationary.

To characterise the time-varying channel, a receiver path is specified within the environment. It is important to sufficiently sample the receiver path to ensure that the channel is characterised and not aliased. This sampling rate can be determined by considering how Doppler spreads the signal bandwidth.

Consider the spectrum of a signal prior to Doppler spreading:

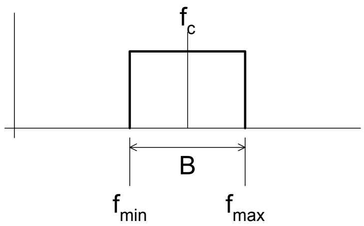

Figure 15 : Spectrum prior to Doppler Spreading

where, f_c is the signal carrier frequency, and,

$$f_{\min} = f_c - \frac{B}{2}$$

$$f_{\max} = f_c + \frac{B}{2}$$

The Doppler frequency shift for any frequency, f, given a receiver velocity of V is,

$$f_D = \frac{Vf}{c}$$

where, c is the speed of light.

Therefore, the bandwidth of the signal after it has passed through the channel will be spread as indicated in the figure below.

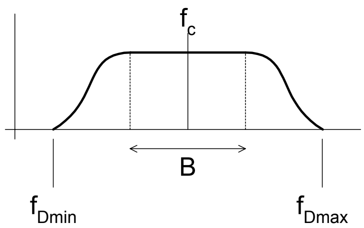

Figure 16 : Spectrum after Doppler Spreading

where,

$$f_{D\min} = f_{\min} - \frac{vf_{\min}}{c}$$

$$f_{D\max} = f_{\max} + \frac{vf_{\max}}{c}$$

Therefore, the total additional bandwidth caused by Doppler spread is given by

$$\begin{aligned} B_D &= \frac{Vf_{\min}}{c} + \frac{Vf_{\max}}{c} \\ &= \frac{V}{c}\left(f_{\min} + f_{\max}\right) \\ &= \frac{V}{c}\left(f_c - \frac{B}{2} + f_c + \frac{B}{2}\right) \\ &= \frac{2Vf_c}{c} \end{aligned}$$

In order to fully capture the Doppler-spread signal, it is necessary to sample at the rate given by the additional Doppler bandwidth (remembering that Epsilon™ produces data for both amplitude and phase). Therefore, the spacing of the samples in time, Δt, must be,

$$\Delta t = \frac{c}{2Vf_c}$$

Given that the vehicle velocity is V, the spacing of the samples in position, Δs, can also be calculated,

$$\begin{aligned} \Delta s &= V \times \frac{c}{2Vf_c} \\ &= \frac{c}{2f_c} \\ &= \frac{\lambda}{2} \end{aligned}$$

It is interesting to note that when characterising the time-variant channel, samples must be taken every half-wavelength, independently of receiver velocity.

It must be remembered that this calculation does not consider motion of the satellite.

As an example, Figure 17 shows the simulation set-up for a receiver moving within a complex urban environment. Direct lines from the satellite to the receiver have been drawn within the model. This helps to visualise whether a particular receiver location has direct line-of-sight or non-line-of-sight to the satellite.

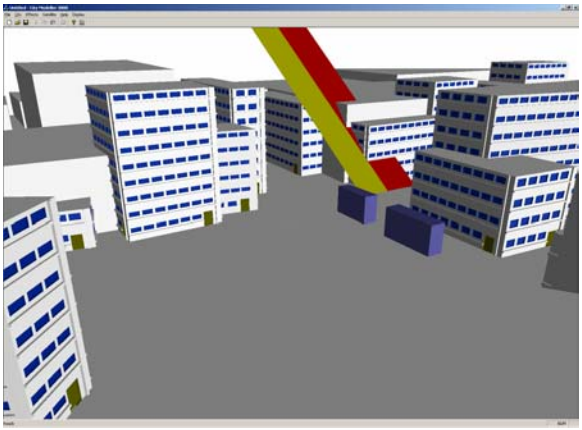

Figure 17 : Receiver Path Within an Urban Environment

The receiver moves from a deep urban canyon, where there is no line-of-sight path to the satellite, to an open intersection with direct line-of-sight. The environment model includes a variety of building types as well as a small number of all-metal vehicles.

Simulations were performed, sampling the receiver every half wavelength in distance (approximately every 9.5cm for a carrier frequency of 1575MHz). The total distance traveled by the receiver in this simulation was 17m.

Figure 18 presents the time-varying CIR for this simulation.

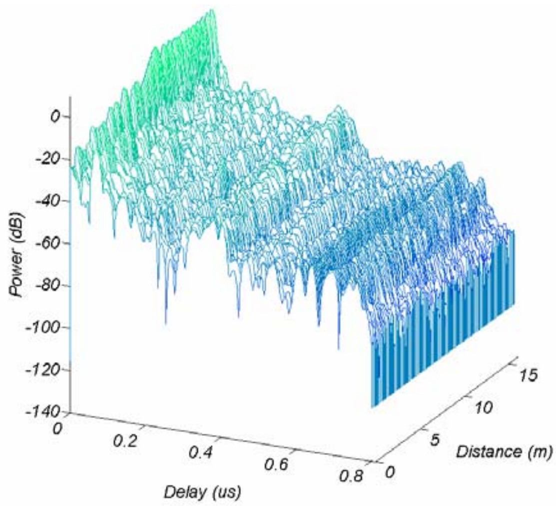

Figure 18 : Power Delay Profile Versus Distance Travelled

The time varying CIR clearly shows the transition from non-line-of-sight to the satellite to line-of-sight. In the non-line-of-sight region, the receiver is within a canyon and suffers from severe multipath. As the receiver progresses into the open intersection, the line-of-sight signal dominates and the later time multipath signals become less significant.

Figure 19 presents the Doppler-delay plot for the simulation.

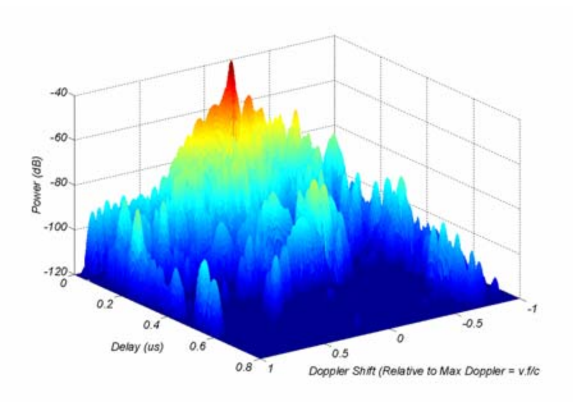

Figure 19 : Doppler-Delay Plot

An early-delay spike with very little Doppler shift dominates the Doppler-delay plot. This is characteristic of the receiver moving almost tangentially to the satellite. Later delays demonstrate a wider range of Doppler spreads.

A large series of simulation runs are currently underway at Roke Manor, with the aim of producing a comprehensive set of multipath channel data for a wide range of environments. It is hoped to group these into sets of data for generic environments. This data will be presented in a later publication.

Within the context of the BNSC S@TCOM programme, this data is being used for the analysis of signal structure and optimising receiver architectures specific to Galileo.

HOSTS AND EXECUTION ISSUES

Epsilon™ is a parallel application designed to execute on a heterogeneous network of PCs running NT/Windows2000 and various UNIX machines with a Windows based GUI front end.

Epsilon™ is written in C++ and uses a proprietary communications harness for worker/driver communications. The required hardware communications network is Ethernet, making Epsilon™ suitable for use in most engineering establishments, without special computing resources.

The execution speed of Epsilon™ will scale almost linearly with the number of compute nodes, provided the parallel machine is kept compute bound. That is, it is inefficient to use large networks of machines on small problems.

The computation load to generate a comprehensive channel model can run into several days on a modest parallel machine.

CONCLUSIONS

It has been shown that a sophisticated computational Electromagnetics tool with a pedigree in the defence field has been adapted for CIR applications.

When combined with an environment modelling package, the result is a very powerful multipath channel analysis tool.

The selection of results presented in this paper demonstrate the importance of accurately modelling the environment and the impact of using circularly polarised signals.

In the near future, it is planned to combine the electromagnetics simulation capability and the city modelling software into a single tool. It is also hoped that extensions to the current work will help in providing further validation data for the tool.

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