# Design of a Radio Channel Simulator for Aeronautical Communications

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**Abstract**

The goal of this paper is to implement a model of multipath fading in a radio channel simulator for aeronautical applications. When developing a wireless communications system, it is useful to perform simulations of the radio context in which the system has to operate. A radio link is substantially composed by three parts: transmitting segment, transmission channel and receiving segment. We focus our attention on the radio channel propagation.
We proposed two geometrical models of a territory corresponding to a determined flight area and, after importing the data needed to estimate our parameters, we compared our results with the channel soundings in literature, obtaining comparable values.

**Key Words**

Channel Model, Multipath Fading, Channel Simulator Design, Aeronautical Telemetry.

## I Introduction

In order to test the communications system quality, according to aeronautical communications requirements about the signal integrity, could be necessary to have, at the design stage, a tool that allows to simulate the radio channel and reproduce the degradation that the radio signal suffers during propagation, given the radio context.
A radio channel simulator has to provide a representation, as faithful as possible, of the propagation characteristics of the radio signals to provide useful information to ensure the implementation of good strategies to cancel or, at least, mitigate any performance degradation. We should consider the following phenomena: free space attenuation, multipath fading, Doppler effect, additive noise and interfering signals. However, in this paper, we focus our attention on the multipath fading phenomenon.
Multipath interference occurs when reflected waves of the transmitted signal arrive at main lobe of the receiver antenna. A model of an aeronautical telemetry channel, affected by multipath fading, is presented. Channel models are important to evaluate the modulation performances and the possible equalization improvement.

Channel models are usually categorized as narrowband or wideband [6, 7]. If the signal bandwidth is similar or larger than the channel coherence bandwidth, wideband channel models are used. In this case, the individual multipath reflections are resolvable in the signal bandwidth and the channel is modelled as Dirac $\delta$ impulses modulated by time-varying coefficients depending on the characteristics of the multipath.

## II Two-rays Model

Reflection, scattering, diffraction, shadowing effects and line-of-sight (LOS) path are known in mobile communications as multipath propagation. The result is the fading of the received signal due to coherent interference. We note that the real channels are time-varying. The channel impulse response depends on the physical geometry involving the aircraft, the ground station and the reflection points. As this geometry varies during the mission, also the channel impulse response varies during the flight. We assume that, over a short enough time interval, the channel does not change and it can be considered time-invariant. Thus, during a sufficiently short time interval, we could model the aeronautical telemetry channel as a linear and time-invariant system with impulse response *h(t)* and transfer function *H(f)*. Assuming that *x(t)* is system input, the channel output *y(t)* is given by the convolution of *x(t)* with *h(t)*. In the frequency domain, the input-output relationship is *Y(f)=H(f)X(f)*.
The channel is modelled as a linear and time-invariant system whose complex base-band impulse response *h(t)* is composed of *L* propagation paths, that is

$$\begin{aligned} h(t) &= \delta(t) + \sum_{k=1}^{L-1} \Gamma_k e^{j\gamma_k} \delta(t-\tau_k), \\ \gamma_k &= \alpha_k - 2\pi f_c \tau_k, \end{aligned} \tag{1}$$

where the path 0 is the line-of-sight path; $\Gamma_k$ is the gain, $\tau_k$ is the propagation delay, $\gamma_k$ is the overall phase shift of the *k*-th propagation path, $\alpha_k$ is the phase shift caused by the *k*-th reflection, and $f_c$ is the carrier frequency.
At this time, we focus on a channel model composed by two propagation paths: the line-of-sight path and a single specular reflection. Thus, we have

$$\begin{aligned} h(t) &= \delta(t) + \Gamma e^{j\gamma} \delta(t-\tau), \\ \gamma &= \alpha - 2\pi f_c \tau. \end{aligned} \tag{2}$$

We have implemented a Matlab script to evaluate, in a deterministic way, the three parameters which describe the model. We ignore the earth curvature and the refractive index variations depending on altitude. It's possible to take account of both phenomena by introducing the concept of equivalent curvature.
Moreover, when the linear dimensions of the objects in question are substantially greater than the wavelength of the transmitted signals, the geometrical optics approximations are valid.
According to geometric optics, the two-dimensional problem is solved. We assume *(x, y)* plane containing the ground antenna, the aircraft antenna and the reflection point.

Assuming completely flat ground, in this plane, the ground antenna is represented by the point *T* of coordinates *(0, $h_1$)* and the aircraft by the point *V* of coordinates *(d, $h_2$)*, where $h_1$ and $h_2$ are the ground antenna and aircraft altitude, and *d* is the ground projection distance (Figure 1).

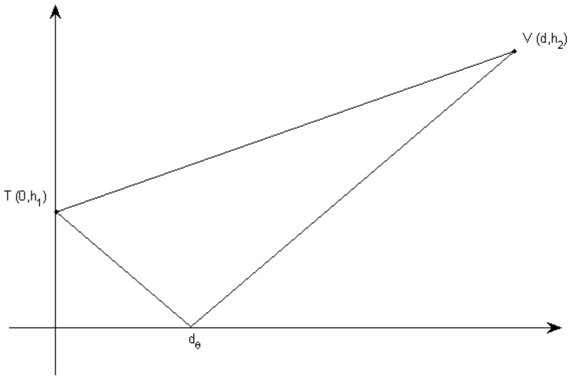


**Figure 1: Two-rays Model**

By applying Snell's law, we can determine the angle of incidence $\theta$ of the reflected path and the position $d_\theta$ of the incidence point, that is

$$\theta = arctg \frac{d}{h_1 + h_2}, \qquad d_\theta = \frac{d}{1 + h_2 / h_1}. \tag{3}$$

Known the air refractive index *n* and the difference $\Delta L$ between line-of-sight and the reflected paths, we can evaluate the delay $\tau$ by which the reflected ray reaches the aircraft respect to the direct ray, that is

$$\Delta L = \sqrt{d^2 + (h_2 + h_1)^2} - \sqrt{d^2 + (h_2 - h_1)^2}, \qquad \tau = \frac{n}{c}\Delta L, \tag{4}$$

where *c* is the light propagation speed in vacuum. Moreover, once known the characteristics of the transmitter and receiver antennas, the permittivity $\varepsilon_0$ of free space and the permittivity $\varepsilon_1$ of the reflecting media, by applying Fresnel's laws, it is possible to evaluate the gain $\Gamma$ and the phase shift $\alpha$ caused by the single reflection. In fact, we can write

$$\Gamma e^{j\alpha} = a_1 a_2 \Gamma_V + b_1 b_2 \Gamma_H, \tag{5}$$

where $a_i$ and $b_i$ are the parameters which characterize the radiation pattern and the polarization of the transmitter and receiver antennas [3] whereas the reflection coefficients for the vertical and horizontal polarizations are

$$\Gamma_V = \frac{-\cos\theta + \sqrt{\varepsilon_0/\varepsilon_1}\sqrt{1-(\varepsilon_0/\varepsilon_1)\sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_0/\varepsilon_1}\sqrt{1-(\varepsilon_0/\varepsilon_1)\sin^2\theta}},$$
$$\Gamma_H = \frac{\cos\theta - \sqrt{\varepsilon_1/\varepsilon_0}\sqrt{1-(\varepsilon_0/\varepsilon_1)\sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_1/\varepsilon_0}\sqrt{1-(\varepsilon_0/\varepsilon_1)\sin^2\theta}}. \quad (6)$$

For example, if both the antennas are isotropic and circularly polarized, we have

$$a_1 = b_1 = 1/\sqrt{2},$$
$$a_2 = b_2 = j/\sqrt{2}. \quad (7)$$

Eventually, by using the parameters *Γ*, *α* and *τ* from relations (4) and (5), it is possible evaluate the magnitude of the transfer function *H(f)*, the Fourier transform of the impulse response *h(t)*, that is

$$|H(f)|^2 = 1 + \Gamma^2 + 2\Gamma\cos(2\pi f\tau - \gamma). \quad (8)$$

Moreover, we can also consider the Doppler effect, introducing the shift frequency $f \rightarrow f - f_D$, where $f_D = nv_r f_c/c$ is the Doppler frequency and $v_r$ is the radial velocity of the aircraft, in direction of the ground antenna.

## III Geometrical Schematization

So far, we have assumed the ground perfectly flat but our aim is to model the territory corresponding to the flight area considered, by knowing the elevation profile. In the next sections, we propose two different geometrical schematizations of the territory, highlighting pros and cons of each of them. In both cases, we will consider the two-dimensional problem, using the plane passing through the ground antenna and the aircraft and orthogonal to terrain surface.

By knowing the position of the aircraft, it will be possible to identify the data from the elevation profile that will be used for the geometric schematization. At best, the plane, previously considered, will intersect the ground surface at points located along the diagonal of a square subgrid of our data. In all other cases, it will be necessary to perform a preliminary interpolation.

Thus, the territory, corresponding to the flight zone, is schematized with points of coordinates $(x_i, h_i)$, where $h_i$ is the $i$-th height obtained from the elevation profile. At this point, it is possible to choose between two types of schematization, producing two different models. We can approximate the ground with horizontal segments (Bar Model) or obtain a polygonal (Poly Model) by joining the points of the elevation profile.

## IV Bar Model

In this section we propose our first geometrical model. If we approximate the ground with horizontal segments (Figure 2), the points $(x_i, h_i)$ have abscissa $x_i=(2i+1)d/2N$, where $N$ is the number of the known points and $i$ belongs to interval $(0, N-1)$. To determine the multipath, our algorithm provides some *if* statements that allow to find in which segments the Snell's law occurs and any shadowing effects.

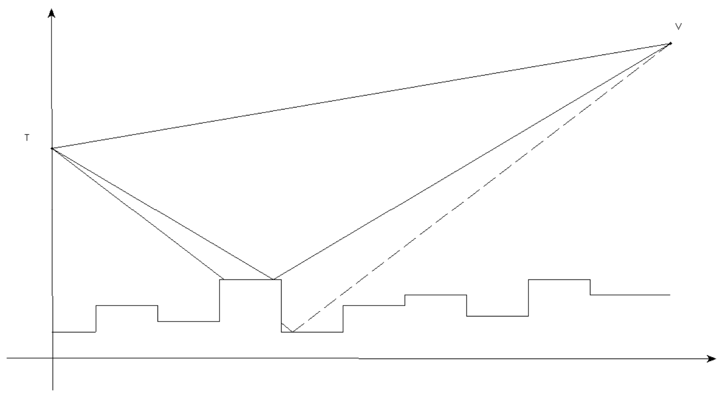


**Figure 2: Bar Model**

However, it is possible to demonstrate that for the schematization adopted at the most for a single segment can be achieved the conditions just mentioned. Consequently, we can determine if there is only the direct ray or there is also a reflected ray and which are its features, known the elevation profile.
The limit of this model, therefore, is that there is no more than a single reflected ray, even if, often, in the aeronautical field, a model with only two rays is already sufficiently accurate to describe the radio propagation channel. In the next section, we propose a model that removes this limit but presents, anyway, a limitation.

## V Poly Model

Instead of using the horizontal segments, in this section, we will model the territory, corresponding to the flight area, with a polygonal joining the points obtained from the elevation profile (Figure 3).

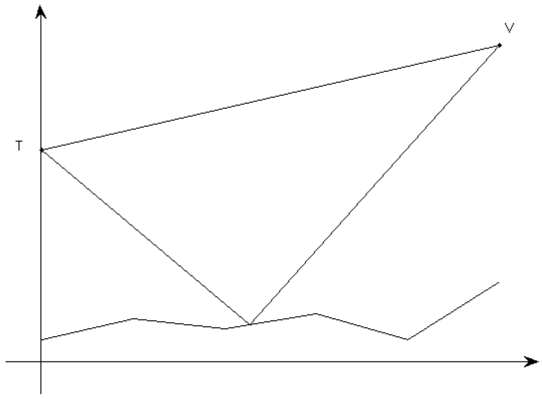


**Figure 3: Poly Model**

These points have abscissa $x_i=iD/N$, where $D>d$ is the maximum distance covered by the elevation profile, $N$ is the number of the known points and $i$ belongs to interval *(1, N)*.
With this schematization is more difficult to individuate the segments that contribute to the multipath, however, with an appropriate series of *if* statements, it is possible to find where the Snell's law occurs and any shadowing effects. Thus, the Poly Model allows having more than one reflected ray, but it is not always the best solution because the Bar Model often describes most effectively the properties of radio channel. For example, for particular elevation profiles, the Poly Model, unlike the Bar Model, only provides the direct ray. The best way to proceed is to compare the two models for a correct evaluation of the obtained results.

## VI Filter Design

With regard to equation (2), we realized a FIR (Finite Impulsive Response) numerical filter, sampling the continuous impulsive response derived from the Two-Rays Model.
When the sample time is $T_s=\tau$, the sampling of the continuous ideal impulsive response return 0 value everywhere. Thus, by using the *sinc* function instead the Dirac $\delta$ impulse, we obtain the impulse response below

$$\hat{h}(t) = \operatorname{sinc}(t/\sigma) + \Gamma \exp(j\gamma)\operatorname{sinc}((t-\tau)/\sigma), \qquad (9)$$

where the width of the *sinc* main lobe depends on $\sigma$. In this case, FIR coefficients will be

$$\hat{h}(n) = \text{sinc}(nT_s/\sigma) + \Gamma\exp(j\gamma)\,\text{sinc}((nT_s - \tau)/\sigma),\quad n \in [0, N-1], \tag{10}$$

where $N$ is the number of the filter coefficients. By using this impulsive response, the transfer function becomes

$$\hat{H}(f) = \sigma\Pi(\sigma f)[1 + \Gamma\exp(j\gamma)\exp(-j2\pi\tau f)]. \tag{11}$$

Note that the equation (11) is the same of the ideal model transfer function less than the window effect of the $\Pi$ function, that is

$$\Pi(x) = \begin{cases} 1 & -1/2 < x < 1/2 \\ 0 & otherwise \end{cases} \tag{12}$$

The best choose is $\sigma=1/(2f_s)$, where $f_s$ is the sample frequency. At this way, we can select all the useful spectrum of sampled signal.
For example (fixed $\Gamma=0.8$, $\gamma=0.7$ *rad*, $\tau=40$ *ns*, $f_s=80$ *MHz*), by using a FIR filter composed by $N=20$ elements (Figure 4), we can obtain the transfer function represented below (Figure 5).

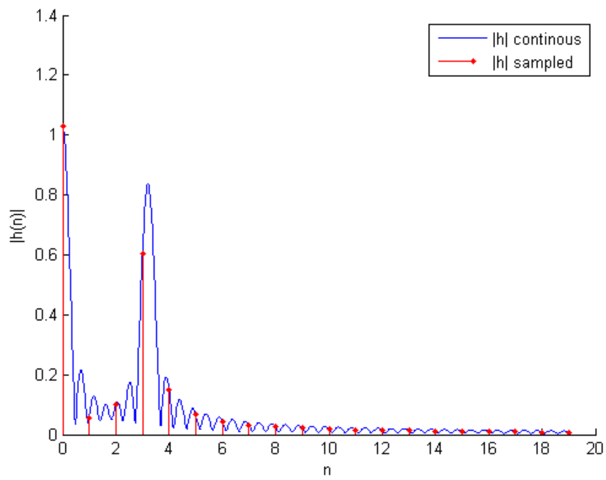


**Figure 4: Sampled Impulsive Response**

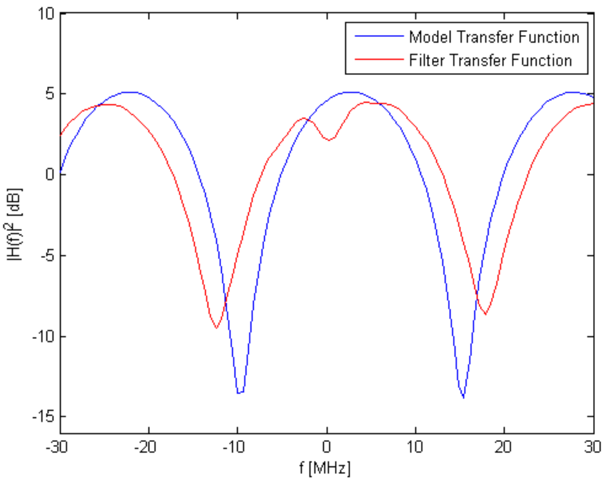


**Figure 5: Transfer Functions**

If we observe the last figure, we note that the transfer function obtained by the Fourier transform of the FIR filter coefficients, is a good approximation of the transfer function given by our Two-rays Model.

## VII Results

To verify the validity of our models, we compared the results of our simulations with the channel sounding performed in [6, 7], after importing the data needed to estimate our parameters. In particular, by using our Two-rays Model, we compared the parameters $\Gamma$, $\gamma$, $\tau$ of the single reflection ray and we obtained comparable values.
We got our results from several runs of simulations, by varying the geometrical and electromagnetic parameters for reproducing, as much as possible, the different scenarios described in these papers. At this way, we have found the gain $\Gamma$ in a range between *0.65* and *0.85*, the angle $\gamma$ in a range between *0.7* and *1.3 rad*, and the delay $\tau$ in a range between *45* and *70 ns*. For a comparison, the corresponding values obtained in a test performed in [7] are: $\Gamma=0.8$, $\gamma=1.3$ *rad*, $\tau=55$ *ns*.
Eventually, the Bar and Poly Models were compared for evaluate their correspondence with the territory schematized.

## VIII Future Developments

Soon, we will perform tests under static conditions, realizing ad hoc configurations of the data link system to have as much control as possible of the radio context in exam. Later, once known the elevation profile and the electromagnetic properties of a territory corresponding to a given navigation area, flight test sessions will be provided.
Talking about future developments, we are interested in completing the multipath model by introducing a random component based on physics optics and the statistical properties of the terrain. The first step is to define an electromagnetic scattering model in which the reflected waves

should depend on the electromagnetic characteristics, the surface of terrain and, obviously, the incident electromagnetic field.
If we consider a space region $\Omega'$, characterized by the electromagnetic proprieties $\varepsilon_0$ and $\mu_0$, and the generic source $\underline{f}(\underline{r})$, the incident electric field $\underline{E}_i$ must verify the Helmholtz equation below [4]

$$\begin{aligned} &\nabla^2 \underline{E}_i(\underline{r}) + \beta_0^2 \underline{E}_i(\underline{r}) = \underline{f}(\underline{r}), \qquad \forall \underline{r} \in \Omega' \\ &\beta_0 = 2\pi f_c \sqrt{\varepsilon_0 \mu_0}. \end{aligned} \tag{13}$$

Introducing an obstacle $\Omega$ in the scene, we can define the total electric field $\underline{E}$ as follows

$$\underline{E}(\underline{r}) = \underline{E}_i(\underline{r}) + \underline{E}_s(\underline{r}), \tag{14}$$

where $\underline{E}_s$ is the scattered field that must verify a similar Helmholtz equation, that is

$$\begin{aligned} &\nabla^2 \underline{E}(\underline{r}) + \beta^2 \underline{E}(\underline{r}) = \underline{f}(\underline{r}), \\ &\beta = \beta(\underline{r}) = 2\pi f_c \sqrt{\varepsilon(\underline{r}) \mu(\underline{r})}. \end{aligned} \tag{15}$$

Assuming $\mu(\underline{r}) \approx \mu_0$, we have

$$\begin{aligned} &\nabla^2 \underline{E}_s(\underline{r}) + \beta_0^2 \underline{E}_s(\underline{r}) = -\beta_0^2 \chi(\underline{r}) \underline{E}(\underline{r}), \\ &\chi(\underline{r}) = \frac{\varepsilon(\underline{r}) - \varepsilon_0}{\varepsilon_0}, \end{aligned} \tag{16}$$

where $\chi$ is the reflectivity profile of scene. It is possible to show that for equation (16), there is an integral solution [4].
We should model the terrain surface like a stochastic process. In literature, several approaches about natural surface representation are studied. In particular, there are classic models and the fractal based models [5]. Our idea is to statistically characterize the reflection coefficients, by using the synthetic statistical parameters of the terrain.

## IX Conclusions

In this paper, we describe some geometrical schematizations of a territory corresponding to a given flight area, for evaluate, in a deterministic way, the characteristics of the multipath fading caused from radio context. We propose three schematizations: Two-ray Model, Bar Model and Poly Model. We compared the results of our simulations with the channel sounding performed in [6, 7] and, by using the Matlab scripts of our models, we obtained comparable values.
Moreover, the Bar and Poly Models were compared for evaluate their correspondence with the territory schematized and for highlight strengths and weaknesses of each of them.
We have made a digital filter using the technique of sampling of the continuous-time impulse response. The results obtained show that the frequency response of such FIR, accurately schematizes the ideal frequency response obtained from our Two-Rays Model.

In the future developments, we propose an approach to complete the multipath model by introducing a random component based on physics optics and the statistical properties of the terrain. Eventually, the goal of a radio channel simulator is to provide the channel transfer function. This information could be used in future works to realize an equalization filter to be integrated into a digital baseband receiver in order to increase the performances of a data link system.

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