FLIGHT SIMULATION WITH DYNAMIC AERONAUTICAL CHANNEL MODEL

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ABSTRACT

This paper includes the design, modeling and analysis of the aeronautical channel which includes the dynamics of flight simulation. For any given flight path scenario in the cruise state it is well understood that the channel is fitted by a 2 ray model. The dynamics of this model can be generated using the two-ray ground reflection model which is based on the position, velocity, and direction of the aircraft. The dynamic aeronautical channel model includes Doppler shift and delay spread for each path of a channel model. This paper shows how each parameter is created for modelling the dynamic channel. The design of such channel model will help the telemetry community to incorporate channel dynamics in computer simulation to improve the accuracy of flight simulation in the design and pre-test stages. Further, it can provide insight to the selection of modulation, equalization and coding for such channels.

INTRODUCTION

This paper is about the aeronautical telemetry with the emphasis of the two ray model and the dynamics of that model. The two ray model covers the most significant phase of an aeronautical telemetry test which would be the steady state phase where the aircraft is up above and cruising somewhere in the test range. This is the predominant channel for aeronautical telemetry which comes with a particularly challenging problem. The two ray results in a spectral null because of the destructive interference which causes significant phase distortion and loss of the signal somewhere in the band. Dr. Michael Rice's work shows the walking null [1].

By looking at the physics of the two ray channel, we can analyze the actual impulse response of the channel if we know the location, speed and position of the aircraft. Further, we can also predict the dynamics of the channel related to the motion of the aircraft. Therefore, we can show the overall variability or the limits of these dynamics over the range of the aircraft, the height of the aircraft, the antenna heights, the velocity and the direction of the aircraft. With any given flight scenario, if we have a transmitter and a receiver, an aircraft and a base station in any test range, by knowing these mentioned parameters, we can model the channel and its dynamics and their limits before the actual flight.

AERONAUTICAL TWO RAY CHANNEL MODEL

The two ray ground reflection model shows a line of sight and a ground reflection path between the test article and ground station which satisfies law of physics based on geometric optics [2]. For any given flight path scenario, the Doppler and phase shift of the flight path can be computed for each second of the flight duration using two ray ground reflection model. [4]

Figure 1 shows the aeronautical two ray channel model for Doppler and phase shift calculation for any flight path scenario.

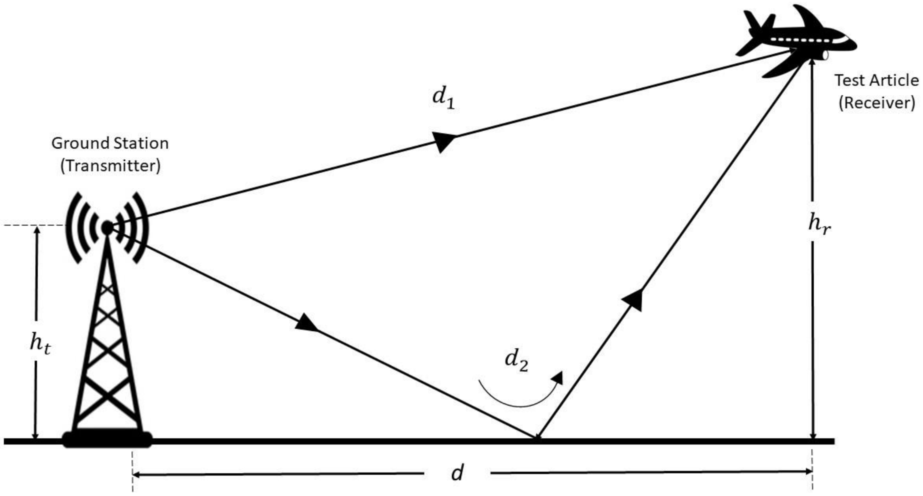

Figure 1: Aeronautical channel model for any flight path

Knowing the speed and position of the test article which are defined for the simple path created in flight path model, one can easily compute the distance and height of the test article from the ground station as a function of speed and climbing angle for each second,

$$d(t) = d(t-1) + \cos(\theta(t) * \nu(t)) \tag{1}$$

$$h(t) = h(t-1) + \sin(\theta(t) * \nu(t)) \tag{2}$$

Where, $\theta(t)$ = climbing angle of the test article at time t
$\nu(t)$ = speed of the test article at time t

Using the *method of images* from Rappaport [2], which is demonstrated in figure 2, the path difference Δ, between the line of sight and ground reflection can be expressed as,

$$\Delta = d'' - d' = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \tag{3}$$

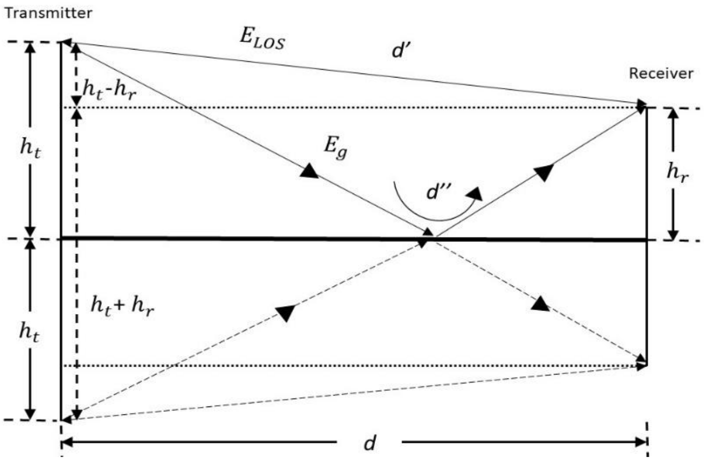

Figure 2: The 'method of images' to find the path difference between the line of sight and the ground station

Using equation (1), (2) and (3) we can now calculate the path difference, delta, Δ. Once the path difference is known, the phase difference $\theta_{\Delta}$and time delay τ_d, between the arrival of two component can be computed by the following relation,

$$\theta_{\Delta} = \frac{2\pi\Delta}{\lambda} = \frac{\Delta w_c}{c} \tag{4}$$

$$\tau_d = \frac{\Delta}{c} = \frac{\theta_{\Delta}}{2\pi f_c} \tag{5}$$

Using the two ray model, the phase difference in the two tones of the impulse response (figure 1) of a channel can be calculated. Then the phase difference from one between the direct path and the reflected path can also be modelled.

Modelling of the impulse response with delay and phase shift per tap is shown in figure 3 below.

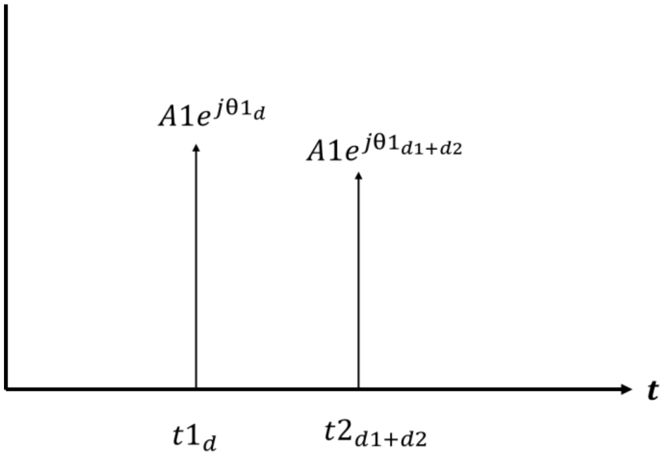

Figure 3: Channel Impulse Response

Figure 3 shows, at each time t, each path arrives after a delay Δt, which is a function of the distances for the direct path d and the reflected path $d1 + d2$, and each path arrives at an amplitude $A1$ and $A2$ at phases $\theta1$ and $\theta2$. We normalized these such that the direct path has an amplitude of 1 and a zero phase and the reflected path has an amplitude $A2$ and a phase $\theta2 - \theta1$. The calculation of the angle increment per tap was performed using equation (4).

The amplitude of first $A1$ is simply going to be the direct line of sight path loss, we could assume d^2 path loss model for aircraft well above the horizon. The second one will be same as the first one except there will be reflection bounce**.** The ITU Report [3] shows that, amplitude of $A2$ can be expressed as,

$$A2 \cong A1 * R_0 \tag{6}$$

Where, R_0 is the ground reflection coefficient. The coefficient R_0 is the function of angle of incident and also another coefficient C, which is related to the permittivity and conductivity equations [3].

R_0 is close to 1 for small glancing angles with a phase shift of 180 degrees, which covers most the range we are interested in. But sometimes it will be less than that, particularly when the angle of incident is small. For example, when the aircraft is reasonably far away from the ground station, relative to the height of the aircraft, the angles will be small and we will get our reflection coefficient close to 1. We modelled that at 0.95 but it could vary a little bit.

Now, we could model our dynamic channel and observe the dynamics of the channel as the flight changes.

MODELLING DYNAMICS OF CHANNEL

For modeling the dynamics of channel, the stationarity, i.e., the time variability of that channel is important for design of modulation, an equalizer, or coding. The channel might be characterized as short or time stationary depending on the flight conditions.

First we will look into the actual path difference, delta Δ, which is difference between d' and d'' from equation (3). To vary that over a variety of heights and distances so the aircraft will be some distance away and some height away and it hardly matters what the angle is relative to the ground station. We plot the path difference, delta Δ,over a variation of range of 1 to 100 km away from the ground station and 1 to 20 km in height.

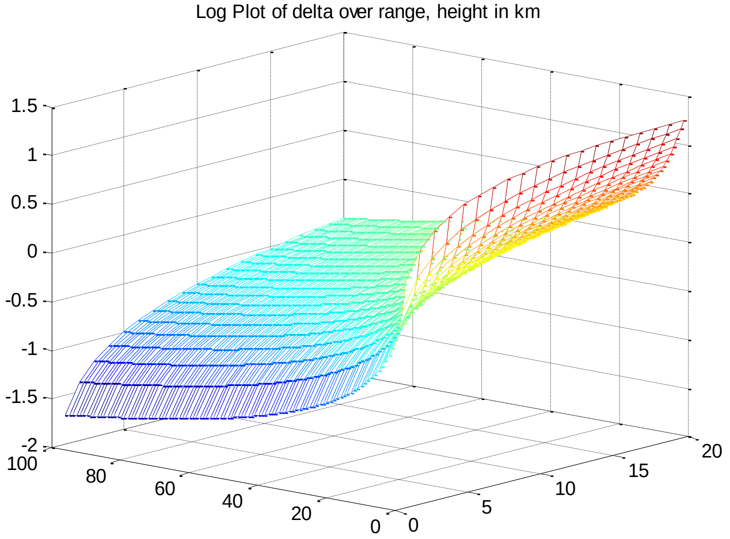

Figure 4: Log plot of path difference over range if distances and height

The three dimensional plot in figure 4 shows that range of delta Δ, varies by as little as 20 meters over this entire 100 km range and 20 km height. So the rate of change of path difference is only 20 meters over the whole range and it is continuous and the rate of change is actually relatively small relative to the heights and distances involved and it does not change very first.

Rate of change of delta vs height, Δ_h: By taking the derivative of delta Δ, with respect to the height of antenna, how delta Δ varies with the function of height can be shown. We can do the differentiation by parts. Change of rate of path difference delta Δ, with respect to height which is Δ_h, can be expressed as a function of distance d, height of the receiver antenna h_r and height of the transmitter h_t.

$$\Delta_h = \frac{\delta\Delta}{\delta h_t} = \frac{\delta d''}{\delta h_t} - \frac{\delta d'}{\delta h_t} \tag{7}$$

$$\Delta_h = \frac{\delta\Delta}{\delta h_t} = \frac{2(h_t + h_r)}{\sqrt{(h_t + h_r)^2 + d^2}} - \frac{2(h_t - h_r)}{\sqrt{(h_t - h_r)^2 + d^2}} \tag{8}$$

Figure 5 shows the 3D plot of rate of change of path difference vs height of antenna.

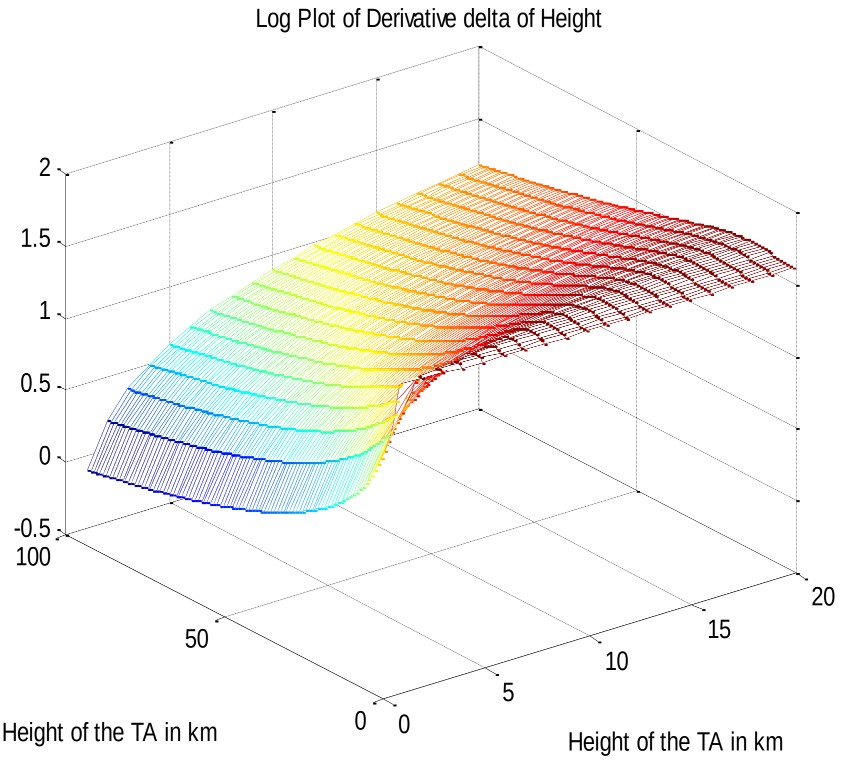

Figure 5: Rate of change of delta vs height

Figure 5 shows relatively slow varying contour, and it is a continuous contour, there is no discontinuity. The only anomaly is when the aircraft is extremely close to the ground station and height is relatively small compared to the tower. If you have an aircraft which is close the ground station you will see that it will change very rapidly and that is a boundary condition.

Rate of change of delta vs distance, Δ_d: We can also look at the behavior of delta Δ, as a function of distance d, which is the distance of the aircraft along the plane of the earth from the ground station by taking the derivative with respect to d. This can also be done by parts and can be expressed as,

$$\Delta_d = \frac{\delta\Delta}{\delta d} = \frac{\delta d''}{\delta d} - \frac{\delta d'}{\delta d} \tag{9}$$

$$\Delta_d = \frac{\delta\Delta}{\delta d} = \frac{2d}{\sqrt{(h_t + h_r)^2 + d^2}} - \frac{2d}{\sqrt{(h_t - h_r)^2 + d^2}} \tag{10}$$

Figure 6 shows the 3D plot of rate of change of path difference vs distance.

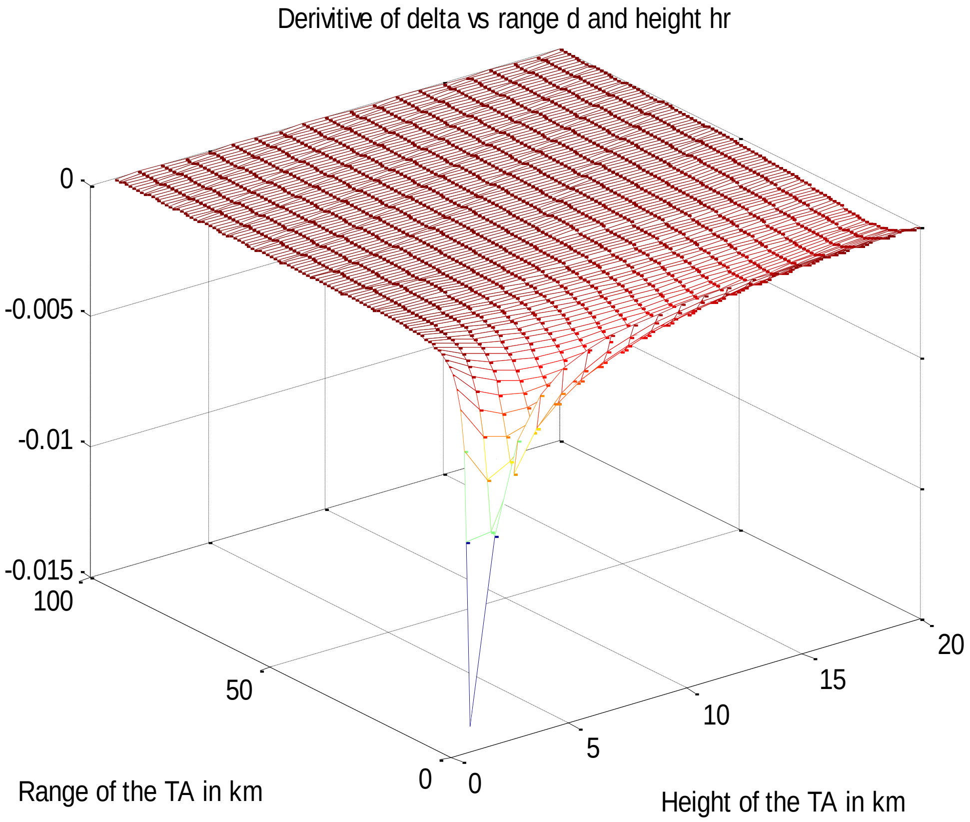

Figure 6: Rate of change of delta vs distance

Figure 6 shows the rate of change of delta Δ, is quite small except near ground station. Once the aircraft is 1 or 2 kilometer away from the ground station the system behaves very predictably and very slowly.

Rate of change of delta vs time, Δ_t: Another important aspect is to show the rate of change of delta Δ, as a function of time. We can compute Δ_t as a product of Δ_d and $\frac{\delta d}{\delta t}$,

$$\Delta_t = \frac{\delta\Delta}{\delta t} = \left(\frac{\delta\Delta}{\delta d}\right) \cdot \left(\frac{\delta d}{\delta t}\right) \tag{11}$$

But, $\frac{\delta d}{\delta t}$ is the velocity of the aircraft.

$$\Delta_t = \frac{\delta \Delta}{\delta t} = (velocity).\left(\frac{2d}{\sqrt{(h_t + h_r)^2 + d^2}} - \frac{2d}{\sqrt{(h_t - h_r)^2 + d^2}}\right) \tag{12}$$

And finally, we can then compute the change in radian frequency versus time,

$$\frac{\delta \theta}{\delta t} = \left(\frac{\delta \Delta}{\delta t}\right).\left(\frac{2\pi}{\lambda}\right) \tag{13}$$

$$\lambda = \frac{c}{f} \tag{14}$$

Now, we plot the angular rate of change vs time.

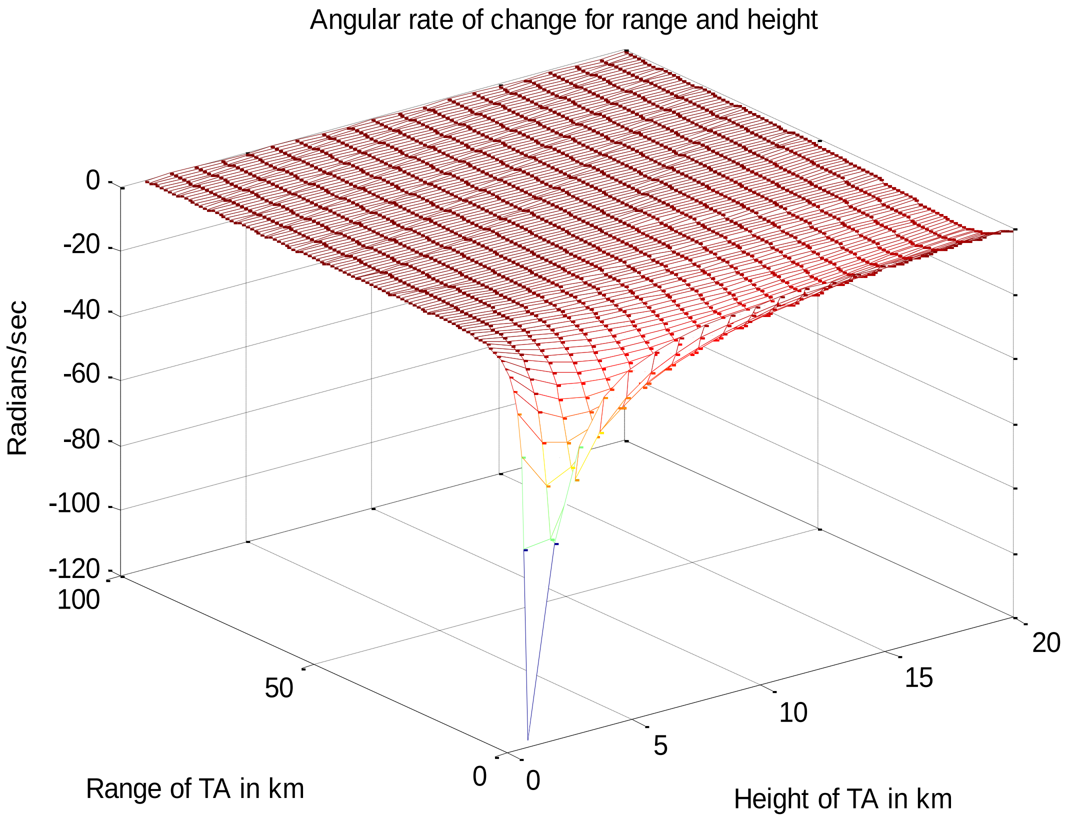

Figure 7: Rate of angular change of delta vs time

Figure 7 shows the phase variation in radians per second as a function of the height of the aircraft and the distance from the test article with a Mach 1 speed. The number of radians per second is small, very little change of phase angle over that space. And likewise this contour is continuous except near the edge and close to the ground station.

We have now expressions of radial angle change of that path relative to time as a function of height of the aircraft, the height of the ground station, the distance from the ground station and the speed of the aircraft. Now we have expression for all the variability.

ANALYSIS

We can now predict the actual impulse response of the channel as a function of the physical location of the aircraft. We can also predict the dynamics over time. As we vary the behavior of the channel, the frequency response shown in figure 8, shows a null that varies in time. This is the walking null we have seen in Dr. Rice's measured channels [1]. But the rate of change is quite small. And therefore, we can predict that the system changes on a continuous pace and change of this is relatively slow compared to overall dynamics of the channel. Even when the aircraft is operating at a high speed of Mach 1.

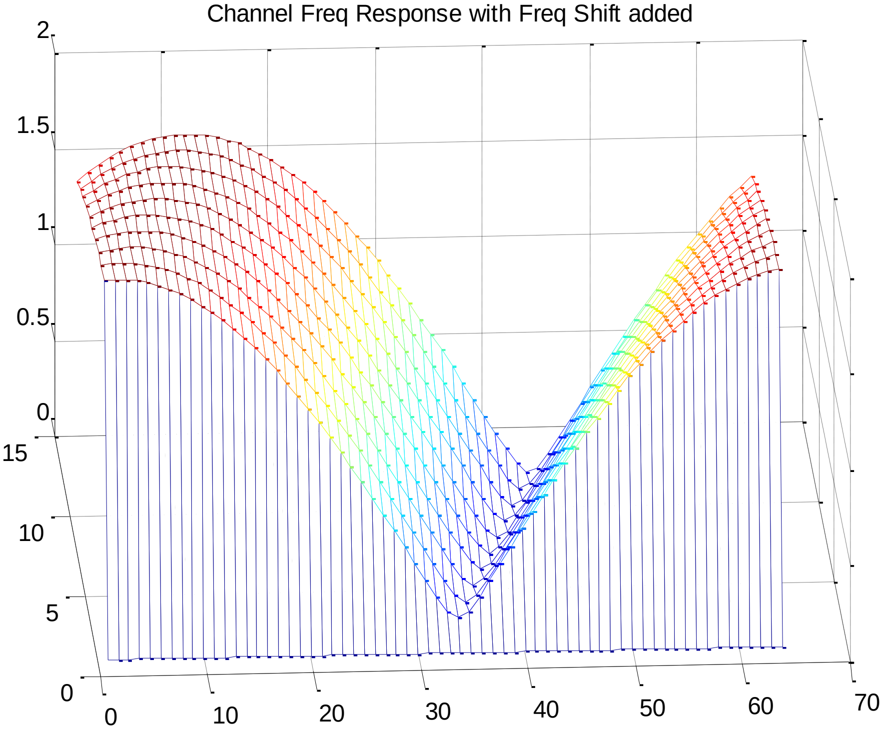

Figure 8: Frequency response of the channel with added

Now the question is how to optimally communicate over this channel. If using a serial tone modem, for example offset SOQPSK, it suffers not just in amplitude with a null in the middle of the channel but a significant phase distortion in the region of the null, which is a significant challenge for the recovering the signal.

Figure 9 shows that there are really three sections to this channel. There are two sections which are quite a good channel. And then there is a section in the middle where the channel is poor and perhaps unusable. The serial tone modem tries to equalize the spectrum. And then when it inverses the spectrum, it inverses the null and emphasize the null portion of the spectrum. This means taking the noisiest part of the spectrum and amplifying it which degrades the overall performance of the system.

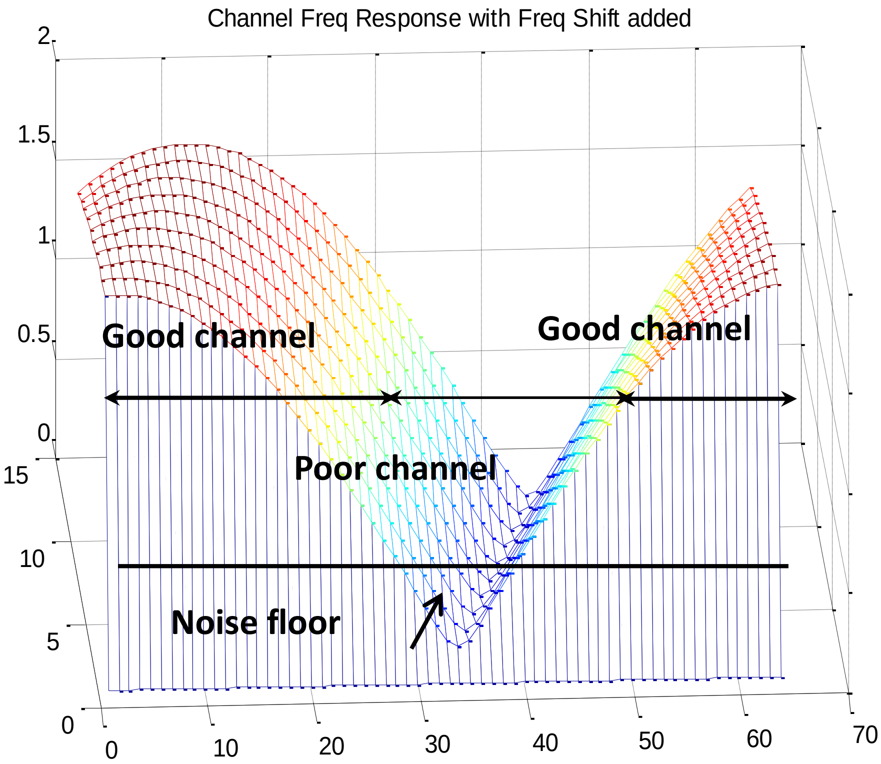

Figure 9: Three Section of the channel

We would prefer to not transmit any signal over the poor channel or to transmit with lower QAM value over the poor channel of the spectrum and transmit signal with higher QAM value over the good portion of the spectrum. Such an approach is possible using a parallel tone modem such as with an Adaptive Orthogonal Frequency Division Modulation (AOFDM) which was designed with such channels in mind. Future work will see if this can be applied in practice.

CONCLUSION

We have developed an analytical model for the two ray aeronautical channel. We have been able to characterize the features of the channel and their dynamics over a wide range of conditions with results that are similar to what has been seen with a live testing. Using this two ray aeronautical channel model we determined the dynamics for a given flight path scenario of a system called Link Dependent Adaptive Radio (LDAR) and has analyzed the effect of channel dynamics on LDAR [5]. Also, we have been able to characterize the behavior walking null in the spectrum which is a serious degradation to the channel, particularly for serial tone modems. Finally, that we see that this channel is uniquely suited to an AOFDM modulation structure which would be our future work.

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REFERENCES

[1] BYU Telemetry Laboratory: Wideband Channel Modelling, Animation: Flight 18, Time stamp: 15:18:18, captured on 07/20/2017.
[2] T. Rappaport, Wireless Communications, Principles and Practices, 2nd Edition, Prentice Hall PTR, Upper Saddle River, New Jersey 07458
[3] ITU Report 1008-1 1986-90
[4] Ibrahim Fofanah, Wannaw Assegu, Farzad Moazzami, Richard A Dean, Arlene Cole-Rhodes, "Delay Spread Characterization of the Aeronautical Channel", ITC 2015, Las Vegas, NV.
[5] Tasmeer Alam, Dr. Farzad Moazzami, Dr. Richard Dean, "Link Dependent Adaptive Radio Performance on Dynamic Channel," ITC 2018, Glendale, AZ.