Modeling and Simulation for Realistic Propagation Environments of Communications Signals at SHF Band

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2005 Annual ITEA Technology Review Conference

Sponsored by the International Test and evaluation Association (ITEA)

July 12 -14, 2005

Georgia Tech Hotel and Conference Center,

800 Spring Street, NW

Atlanta, Georgia 30308

Abstract: In this article, most of widely accepted radio wave propagation models that have proven to be accurate in practice as well as numerically efficient at SHF band will be reviewed. Weather and terrain data along the signal's paths can be input in order to more accurately simulate the propagation environments under particular weather and terrain conditions. Radio signal degradation and communications impairment severity will be investigated through the realistic radio propagation channel simulator. Three types of simulation approaches in predicting signal's behaviors are classified as: deterministic, stochastic and attenuation map. The performance of the simulation can be evaluated under operating conditions for the test ranges of interest. Demonstration tests of a real-time propagation channel simulator will show the capabilities and limitations of the simulation tool and underlying models.

1. Introduction

When radio wave signals pass through the Earth's environment, because the ionosphere and atmosphere are random media, the signals are affected by perturbations in the refractive index of the medium. This results in received signals with degraded amplitudes and phases [1,2,3]. The relationship between each physical mechanism and wave parameter is shown in Figure 1. Complicated resultant phenomena include attenuation, fluctuation in signal amplitude, depolarization, and spectral broadening due to signal phase changes. As the signal frequency increases, the effects due to the troposphere become more significant. The degradation due to these propagation effects often cause unexpected communication disruption. Thus, accurately simulating these effects becomes increasingly necessary, even though it is a difficult task sometimes.

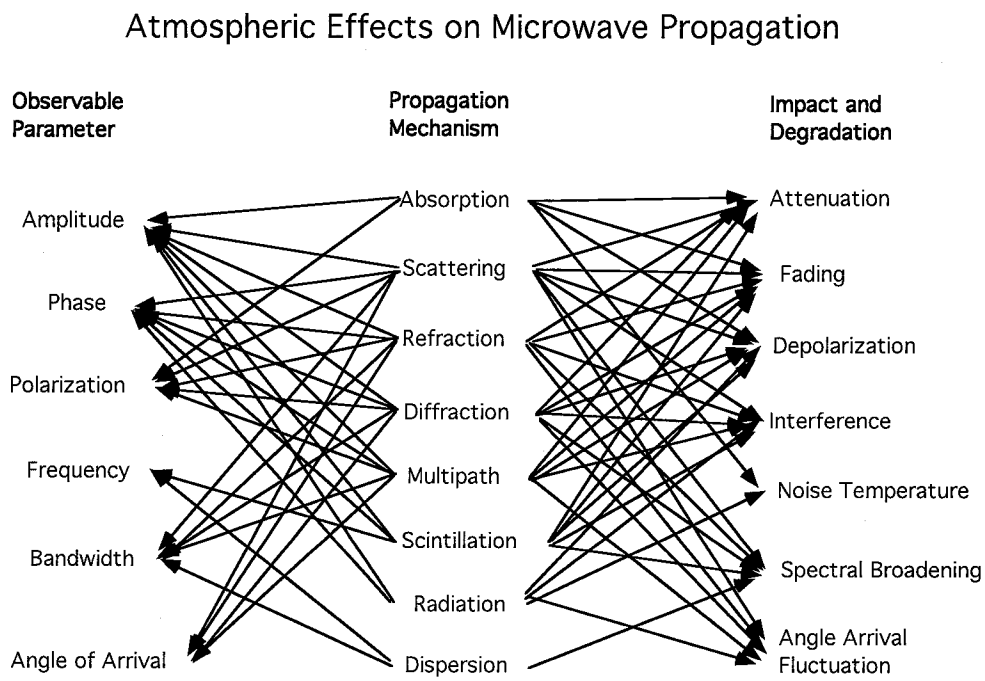

Figure 1. Relationships among radio wave parameters, physical mechanisms, and degradation phenomena.

The Department of Defense is exploring the possibility of occupying the super high frequency (SHF) band in a range of 3–30 GHz to increase bandwidth. This frequency band includes the following sub-frequency bands designated by IEEE: S band (2 – 4 GHz), C band (4 – 8 GHz), X band (8 – 12 GHz), Ku (12 – 18 GHz), K band (18 – 27 GHz) and Ka band (27 – 40 GHz). In

these frequency bands the changes of link power margins need to be assessed as operating frequency increases. Another need is reliable identification of any new propagation anomalies that might arise at some frequencies in the range of investigation. Now the military also needs to enhance their capability to more accurately represent realistic radio signal propagation behavior. Effective and efficient models and algorithms should be selected and developed to simulate a real propagation environment.

Accompanying with increasing demands of high data volume transmission, communications industrials are moving into higher communication frequency bands. For example, in recent years, 3rd generation mobile (IMT-2000) [4,5] has moved from UHF band into S band. The high density fixed services (HDFS) [6] will use Ka band for the short distance links within the urban areas. In Los Angeles area, County Public Safety Department is going to use 4.9 GHz for their aeronautic mobile emergency communication [7], etc.

As the frequency increases, radio degradation effects become more significant due to atmospheric and weather changes. Dominantly responsible for additional losses to the free space loss become atmospheric absorption, clouds, fog, and precipitation, as well as scintillation/ multipath at low elevation angles [1,2,3,8]. A microwave propagation scenario through the atmospheric medium is shown in Figure 2. All of these losses due to the atmosphere at the studied frequency range cannot be neglected. The traditional Friis Equation applying for low frequency and free space conditions [9] needs to be modified to add an additional term, which includes all atmospheric attenuation and fading effects. In this paper, all radio wave propagation models developed will be reviewed. Various simulation approaches based on these models will be evaluated in predicting signal's variations in amplitude and phase.

2. Radio Wave Propagation Models

Through many years of studies various models of radio wave propagation in the SHF band have been developed under the International Telecommunication Union (ITU). NASA has also done pioneer works in studying the radio wave propagation effects in the SHF band [10]. In the 1960s, NASA's deep space radio communication systems transferred from L band to S band. A

transition from S- to X-band occurred subsequently in the 1970s. Now it is processing a new transition of moving to Ka-band spectrum region. Recent NASA's Advanced Communications Technology Satellite (ACTS) Mission had made very important contribution to Ka-band (around 30 GHz) study [11]. Through 6 years of measurements, ACTS mission has generated most complete Ka-band propagation models.

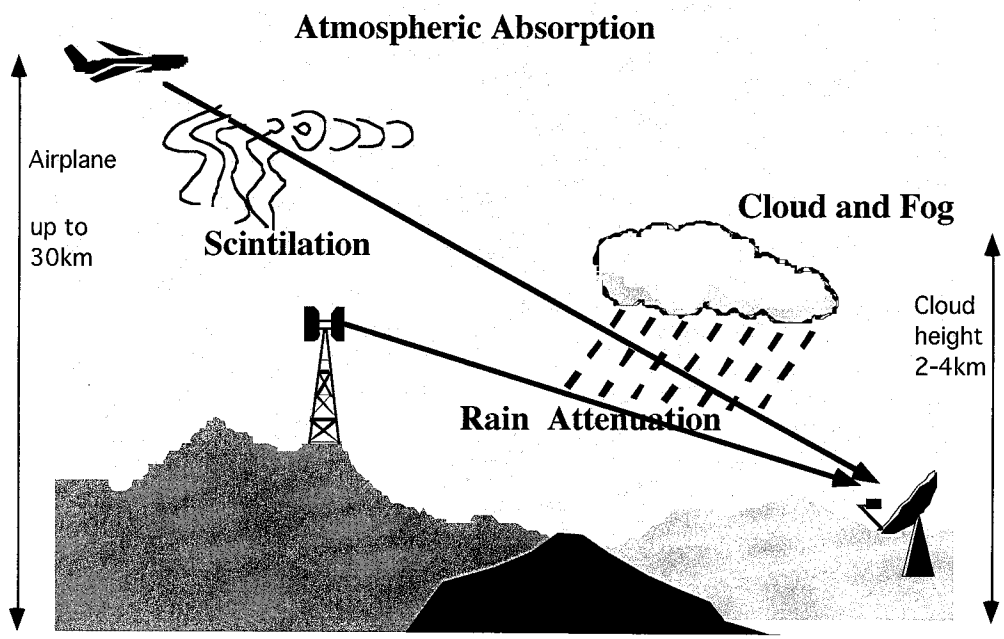

Figure 2. Microwave atmospheric propagation environment. Typical radio paths linking aircraft to the ground and ground to ground are shown. There are mainly four types of attenuations at SHF band: Atmospheric gaseous attenuation from O_2 and condensed H_2O, rain attenuation, cloud and fog absorption and atmospheric scintillation.

Propagation models developed in last several tens of years cover the entire SHF band. Table 1 lists some major models that describe almost all propagation effects depicted in Figure 1. Among these models, most of them calculate signal amplitude changes due to destructive or constructive combination of wave components for communications link margin analysis, while a few evaluate the changes of phase and polarization.

Experimental and study results show that above 3 GHz, most ionospheric effects are negligible, while the tropospheric effects become more important on signal propagation. Except the free space loss, for a line of sight (LOS) path, other significant effects include: atmospheric gaseous absorption [12]; hydrometeor attenuations from rain, fog, ice, snow and cloud [1,2,3,8];

multipath due to ground reflection and atmospheric refraction, scintillation due to atmospheric turbulence [13,14]; Earth surface defocusing; etc. Rain droplets especially can absorb, scatter, and radiate radio signals, making them a dominant factor in microwave attenuation [8]. Tropospheric scintillation at low elevation angles can cause rapid fluctuation of signals in amplitude and phase, affecting high-resolution data transmission [13].

For a trans-horizon path, the situation becomes even more complicated [15]. Besides the fact that radio signals propagate by terrain diffraction over the spherical Earth, mountaintops and urban skyscrapers [16], there are several anomalous modes that can propagate beyond the horizon over several hundreds of kilometers as shown in Figure 3. They are, respectively, tropospheric scattering, surface and elevated ducting, and rain scattering. At very small percentage of time, their propagation losses can be significantly small.

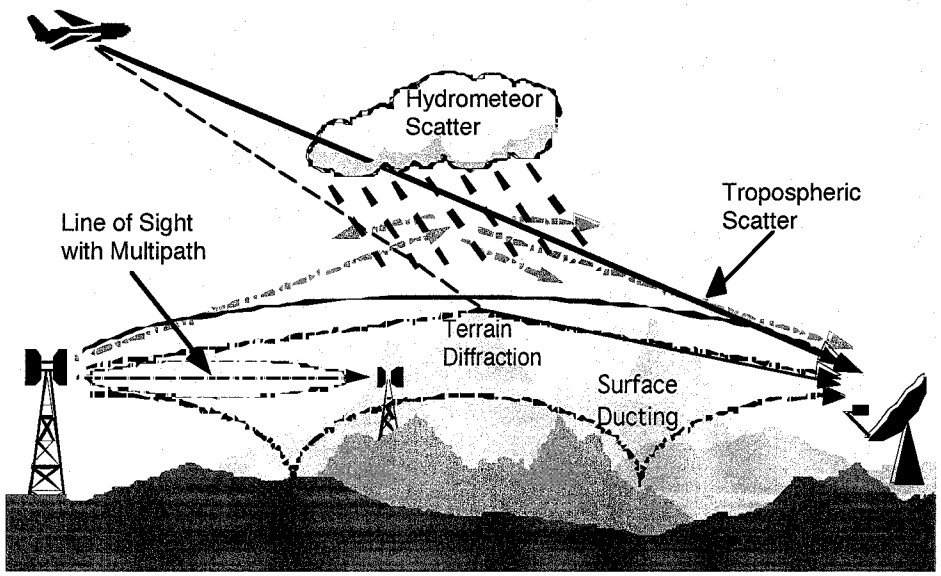

Figure 3. Four types of propagation mechanisms can propagate transhorizontally: Terrain diffraction, tropospheric scattering, ducting, and rain scattering.

These models generally divided into two categories in predicting signal's variations: deterministic and stochastic ones. Some wave factors, such as propagation losses, are deterministic and can be computed as a function of the locations of the transmitter and receiver; while most types of signal impairments are stochastic in nature. These will be modeled based on long-term statistical distributions most suitable for the test ranges. Using these statistical models

one can only estimate the fading range at certain percentages of the time, instead of instantaneous phase and amplitude values. Most models listed in Table 1 belong to the latter one.

Table 1. Major Radio Wave Propagation Models and Applicable Ranges

Radio Propagation Models	Applied Phenomena and Parameters	Applied Frequency Ranges	Corresponding ITU Recommendations
Gaseous Attenuation Model	Oxygen and water vapor absorption	> 1.0 GHz	ITU-R P.676, 836 [12,17]
Scintillation and Multipath Model for Troposphere	Scintillation and multipath fading	> 1.0 GHz	ITU-R P.618 [18]
Attenuation Frequency Scaling Model	Rain attenuation	7 – 50 GHz	ITU-R P.618 [18]
Cumulative Distribution of Fade Duration Model	Fading duration	> 400 MHz	[1,10]
Diffusely Scattering Wave Model	Satellite to mobile with Doppler shift	> 100 MHz	[1,10]
Empirical Roadside Shadowing Model	Canopy shadow for land mobile	> 100 MHz	[1,10]
Maritime Link: Fading Due to Sea Reflection	Rough sea surface for marine mobile	0.8 – 8.0 GHz	ITU-R P.680 [10]
Altshuler Fog Model	Fog attenuation	5 – 100 GHz	ITU-R P.840 [19]
ITU Cloud Model	Cloud attenuation	5 – 100 GHz	ITU-R P.840 [19]
Radio Noise Model	Galactic and atmospheric noise	100 MHz – 100 GHz	ITU-R P.372 [1,10]
ITU Rain Model	Rain attenuation, rain rate distribution	1 – 400 GHz	ITU-R P.618, 837, and 838 [18,20,21]
Global Rain Model	Rain climate zones	1 – 400 GHz	[1,2]
Wet Antenna Surface Model	Wet factor	~ 20 GHz	[1,11]
Ice and Rain Depolarization Model	Co-polar attenuation (CPA) and XPD	4 – 35 GHz	ITU-R P.618, 530 [18,22]
Site Diversity Model	Site separation during rain	10 – 30 GHz	ITU-R P. 618 [18]
Line of Sight with Multipath Model	Space to Earth or Earth to Earth	> 2.0 GHz	ITU-R P. 530, and 619 [22,23]
Terrain Diffraction Model	Knife-edge and rounded surface	30 MHz – 10 GHz	ITU-R P.526, and 530 [16,22]
Transhorizon Propagation Model	Anomalous models: Ducting and scattering	> 0.7 GHz	ITU-R P.452 [15]

From Table 1, we can observe that the ITU recommendations are available for most well developed models. However, for some new experimental models (such as wet antenna, and sand

effects), ITU has not adapted these models yet. For example, very little is known about the effects of sand and dust storms on radio signals. Available data show that sand attenuation effects for frequencies below 5 GHz can almost be neglected.

When ITU Recommendations (models) are available, these models should be used for simulating prediction, because all ITU models are well developed and validated through a great deal of experimental data and are recognized by the worldwide communications community. When an ITU model is not available for a certain phenomenon, we should employ those non-ITU models listed in the table for the study, which generally have not been extensively examined yet. Applicable ranges of these models are listed in the table and their limitation can be found in the references in detail.

3. Simulation of Communications Environments

While it is relatively easy to compute free-space losses and gaseous absorption at the carrier frequency in a real-time system sampling at 10 MHz to 100 MHz, it is almost impossible to accurately model the multipath environments, terrain, weather conditions, and other trans-horizon anomalies specific to the transmitter and receiver location at the SHF band sample rate, even with the most advanced computers today to simulate any instantaneous changes of signal's amplitude and phase. However, we can use much simplified propagation models to simulate a radio propagation channel by tracing signal's ray paths (mostly along the great circle).

3.1. Propagation Channel Simulator: Figure 4 shows how this radio propagation channel we have modeled works. Combining propagation models with weather and terrain data, we can more realistically simulate changes in phase and amplitude of the received signals. The input parameters to the model include locations of the transmitter and receiver, carrier frequency, signal bandwidth, trajectory and velocity of the test vehicle, terrain type (which affects the reflection coefficient of the Earth surface), location, weather condition (which is usually dependent on location, season, elevation, percent of time, etc.), and receiver antenna diameter. There are more than ten radio climatic or radio meteorological parameters, such as refractive index and its gradients [24,25], water vapor content [17], rainfall rate [20,21], columnar cloud water content [19], radio climatic zone, and surface reflection coefficient, etc. As the transmit

samples are given to the propagation models, the received signals (which include amplitude attenuations and any phase rotation due to the environment, as well as any Doppler shift in the signal) are produced at the output of the model. The models will be checked to ensure they generate the desired distributions as well as to make sure the output statistics of the overall propagation model closely matches the empirical data.

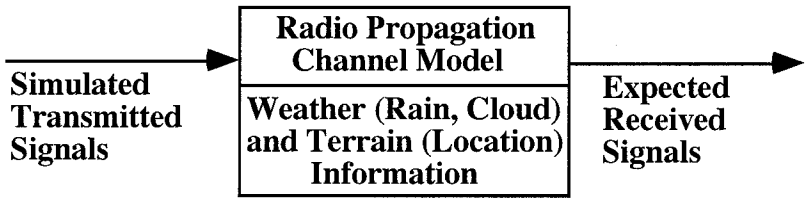

Figure 4. A radio propagation channel simulator that simulates the radio signal degradation effects due to channel fluctuations. Radio meteorological parameters from weather and terrain data are incorporated with propagation models to produce expected signal degradation effects.

The simulation codes will incorporate both deterministic and stochastic parameters of the models. The multipath environments are modeled using either Rician distributions (or Rice-Nakagami) for links with line-of-sight plus scattering, or Rayleigh distributions for diffuse scatter components. For terrain diffraction and ducting, we usually use a distribution of percentage of time for evaluation because both modes are related to atmospheric gradients. We will use a Monte Carlo simulation to generate the random variables with the appropriate distributions to model each of the stochastic propagation effects. These random variable simulations are especially good for application to cases such as fading duration due to rain, amplitude variances due to scintillations, anomalous mode propagation losses, etc. For each time of run, we may generate different results because of random properties of the atmospheric medium. However, as long as we have run enough times, it will be found that the solutions follow the probability density distribution in the models very well. The models will assume a unit-gain omni-directional antenna at the transmitter and a directional parabolic dish at the receiver, and the model will include nominal antennal gains at the receiver for a given antenna diameter.

Some efforts need to be made for integrating propagation models into the propagation channel simulator. This requires proper interfacing at both the input and output of the propagation model

as well as parameters needed by propagation models to accurately replicate the propagation environment probabilistically.

3.2. Simulation Approaches: Generally there are three types of approaches to simulate real communication signal impairments corresponding to features of models: Deterministic solution, stochastic solution, and terrain attenuation maps. The first (deterministic) type of solution is to generate an exact solution in the signal's phase and amplitude for relatively simple propagation paths (either free space or lower frequency signals). For example, using the Faraday rotation model and Oxygen absorption model, changes in phase and amplitude of signals can be quite accurately determined when the condition of the paths is known. When exact rainfall rate and droplet size distribution at a certain region is provided, we can also accurately calculate the signal power attenuation. However, only very few cases can be simulated in this way.

The second approach (Monte Carlo) models the multipath environments, terrain, weather conditions, and other trans-horizon anomalies in a probabilistic/stochastic matters. It can only predict the signal's amplitude, phase, and loss under certain probabilities of occurrences. These comprise most of the propagation cases, which model all wave parameters according to statistical distributions for the specific test site and the weather condition. For each case, you can start to run a random number generator and the result from the run will fall into the range of statistical distributions that are governed by models. At the most time, the probability means the percentage of time of weather, because the long time weather changes are correlated with the atmospheric variations very well.

The third method (terrain attenuation maps) requires pre-calculations of propagation losses and carrier shifts for a particular base location. The data is then stored in memory and retrieved as a function of the transmitter location and altitude. Figure 5 shows an example of propagation losses to a particular receiver site under certain link availability. The attenuation map over the terrain is calculated using the computer software of Trans-Horizon Interference Propagation Loss (THIPL) which was recently developed at JPL based on the most sophisticated ITU P.452 models for 1% of time exceeded at 30 GHz. High spatial resolution of terrain data which include detailed mountain, valley, canyon, and urban topographic information are very important in

generating high resolution loss map. When an aircraft 100 meters above the ground moves from points A to B, we can see that the attenuations of its communications link with the base station (O) will experience variation from being inside shadow, getting out of shadow, and entering shadow again. The signal attenuation between the base station and a mobile user at certain elevations can be found from the map instantaneously. The only drawbacks of this approach, obviously, are the huge amount of information that needs to be stored in advance and that the propagation models are receiver-site dependent.

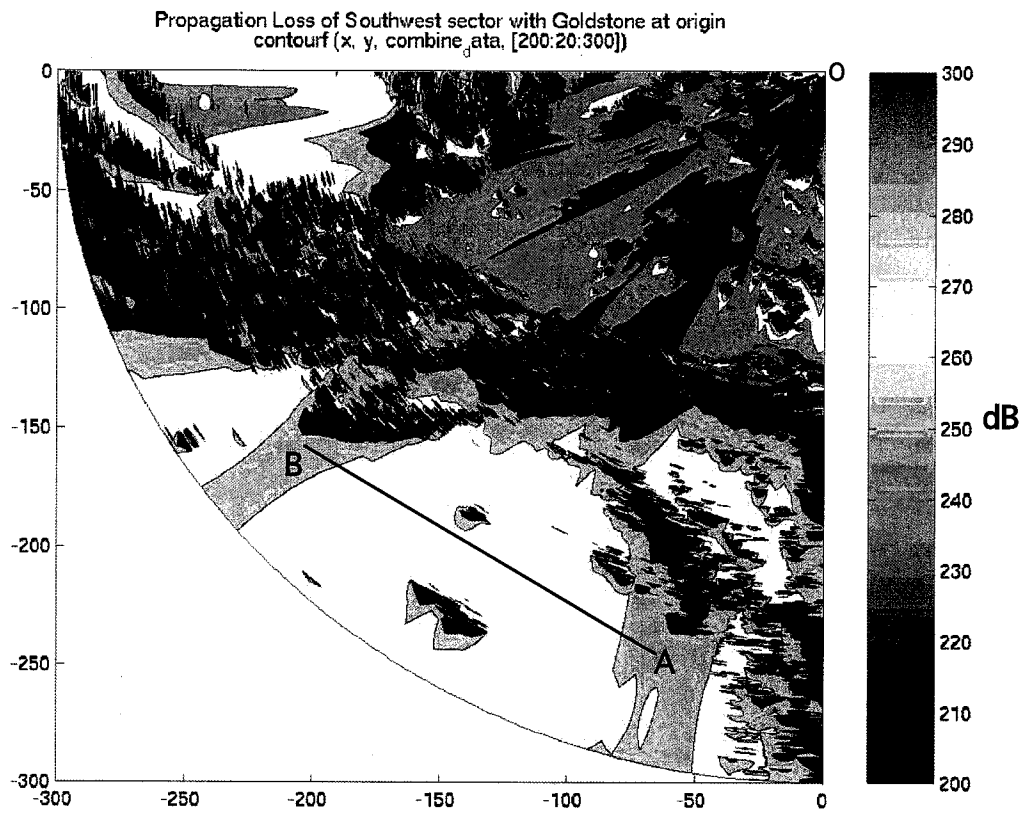

Figure 5. A contour map showing transhorizon propagation losses (dB) in an area of southwest sector with a 300 km radial distance relative to a central station (right upper corner, O). The map shows the minimum losses for all propagation models over terrain at 1.0% of time exceeded for 30 GHz. Communication link shadows (with higher attenuations) clearly show in the downstream sides of mountains. A straight line from points A to B shows a possible aircraft route (100 m above the surface) and communication signal attenuation with the station over the terrain.

Figure 6 is an example of how the signal attenuations change with a terrain profile for three propagation modes: Terrain diffraction, tropospheric scattering, and ducting. In the shadow sides of the mountaintops, there are always larger attenuations than their forward sides. After passing a large mountain locate around 150 km away from the transmitter, the signal losses for the ducting mode significantly increase and bypass the other two modes. This shows that tall mountains can greatly block the propagation of surface and elevated ducting modes.

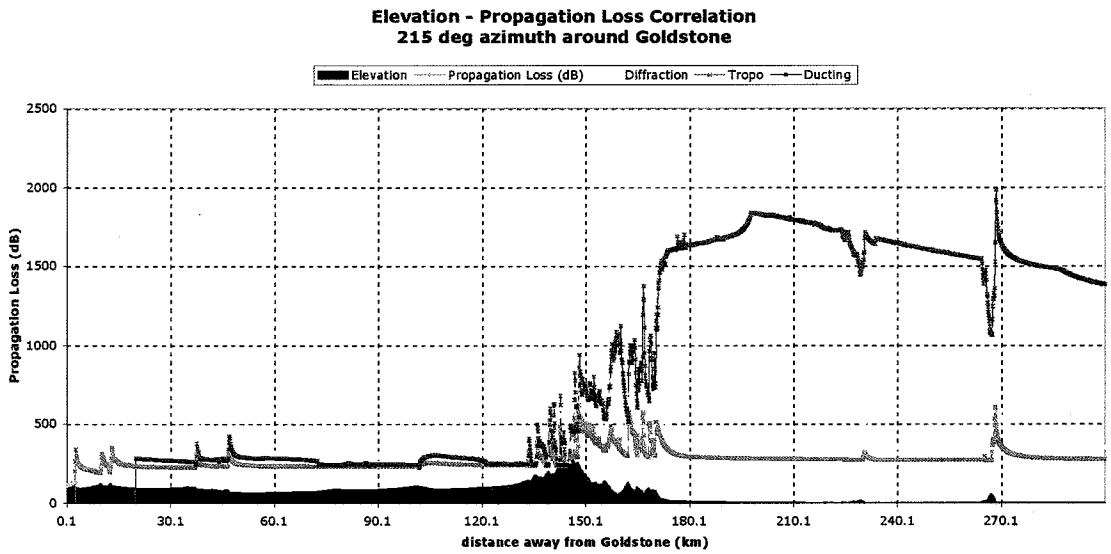

Figure 6. Chart showing correlation between a terrain profile (dark green) and losses from three propagation models: Terrain diffraction, tropospheric scattering, and ducting (the legend shown in the top). It shows that losses sharply increase in the shadow side of hilltops and that tropospheric scattering has the smallest loss over this hilly terrain profile.

Recently, a commercial software called "Visualyse" has become widely accepted in the ITU community and used by a wide range of professionals, in simulating radio wave propagation environments. This software package is a flexible and powerful modeling tool to perform all types of work in simulating both satellite and terrestrial networks and interactions between them.

The software Visualyse is a simulation product that can model radio communication systems of almost any type and size, terrestrial or satellite, from 100 MHz to 100 GHz. The software includes four modules: Terrain, traffic, IDWM, and Monte Carlo, for more specific needs. The software has strong function on animating and visualizing the complicated space-to-ground links. The ITU and regional regulators (such as the FCC) are using the software in designing, launching, and operating the system to meet the constraints imposed by spectrum sharing. Figure

7 is an example of using Visualyse to simulate the communication links between two aircrafts and a ground station around the east coast.

Figure 7. An animation showing the communication links between two aircrafts and a ground station around east coastal region. The aircrafts have rotating scanning beams.

3.3. Performance Evaluation: The performance of the simulations needs to be evaluated in operational conditions with collected propagation data. This will be done in two steps. The first step requires collecting sufficient statistics to ensure the propagation model after being integrated with the propagation channel simulator still produces the desired outputs. The second step requires the evaluation of the overall end-to-end system performance and comparison of this against actual data.

A more realistic simulation for propagation channels at high frequencies (> 3.0 GHz) needs a good weather model as an input. We can use reproduced weather data for testing simulation. However, it should be pointed out that, for a real time prediction of radio signal degradation in the future, we need to use accurate real time weather data covering the entire signal path. There is a close relationship between weather conditions and signal attenuation. For example, rainfall rate and rain height will determine the severity of signal fading. Refractive index profiles, which are determined by atmospheric pressure and temperature profiles, will govern the ray path and multipath scenarios.

It is important to properly define the demonstration tests and analyses using available visualized tools. The demonstration will help us in understanding the real world communication environments and radio signal characteristics for the paths. In one demonstration scenario, we can collect precise location of the test vehicle, the data transmitted and the received signal at the receiver. Then the locations and the transmit signals can be input into the simulator. Although it is difficult to match the simulated received signal with the collected data unless the transmit signal can be correlated exactly to the location of the test vehicle (or aircraft) at every sample of the simulation. We can, however, use the simulator with the propagation models to monitor the overall link performance. The aircraft should fly in paths that would produce propagation effects such as multipath, diffraction, etc. This will demonstrate the capability of the software module to model these difficult propagation factors.

4. Summary

The military aeronautical telemetry (AT) operations are upgrading their operating frequency from below 3 GHz to the super high frequency (SHF) band in a range of 3–30 GHz. Communications industrials are also moving into higher frequency bands in order to gain broader bandwidth. Microwave signals in the SHF band are expected to have severer impairments due to effects of atmosphere and terrain. Through many years of studies, especially led by NASA and International Telecommunication Union (ITU), several propagation models in the SHF band have been successfully developed. These models describe phenomena of atmospheric absorption, and scintillation, refraction, diffraction, multi-path, ducting and rain attenuation and scattering, etc. for both the line of sight and trans-horizon paths. In this article, radio wave propagation models in the frequency band of interest have been reviewed with their features, applications and limitations. Based on these models and the algorithms, various simulation tools have been developed to simulate signal changes in amplitude and phase by inputting weather and terrain data.

There are generally three types of simulation approaches in representing realistic radio signal propagation environments: deterministic, stochastic and attenuation map. For a few cases with the short line of sight, exact solutions in phase and amplitude of signals can be made. However,

for most cases, only stochastic solutions under certain percentage of time can be produced that are governed by the probability distribution function based on a long-term statistical result, because of random properties of Earth's atmosphere. For these cases, a random number generator (Mont Carlo variables) can be used to simulate the wave characteristics. In order to reduce the time in computing most complicated terrain effects, a powerful tool in generating the trans-horizon interference propagation losse (THIPL) maps including all anomalous propagation modes have been developed recently at JPL. Based on these loss maps, the communication link availability for any mobile users at various elevations around a central station can be estimated. It is also noted that a commercial software, Visualyse, has recently become widely accepted in the ITU community, in simulating radio wave propagation environments under various types of communication links over ground and space. The performance of simulation can be further evaluated through the comparison study with field experimental measurements.

Acknowledgements: Authors would like to thank for the support from Advanced Range Telemetry (ARTM) staffs, especially Mr. Saul Ortigoza, at Edwards Air Force Base, California. The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA (JPL Task Plan Number 81-6775).

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