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Wideband Channel Model for Aeronautical Telemetry

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A multipath channel model for wideband aeronautical telemetry links is presented. Channel sounding data were collected at Edwards AFB, CA, at both L-band and lower S-band. Frequency domain analysis techniques were used to evaluate candidate channel models. The channel model is composed of three propagation paths: a line-of-sight direct path and two specular reflections. The first specular reflection is characterized by a relative amplitude of 70% to 96% of the line-of-sight amplitude and a delay of 10–80 ns. This path is the result of “ground bounces” off the dry lake bed at Edwards and is a typical terrain feature at DoD test ranges located in the western United States. The amplitude and delay of this path are defined completely by the flight path geometry. The second path has a much lower amplitude and a longer delay. The gain of this path is well modeled as a zero-mean complex Gaussian random variable. The relative amplitude is approximately 2% to 8% of the line-of-sight amplitude. The mean excess delay is 155 ns with an rms delay spread of 74 ns.

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I. INTRODUCTION

Channel models are important for assessing the performance of modulation, equalization, and coding techniques on real channels. Channel models are usually categorized as either “narrowband” or “wideband.” Narrowband channel models are appropriate for situations where the signal bandwidth is much less than the coherence bandwidth of the multipath fading process [1, ch. 14]. In this case, the individual multipath reflections are not resolvable in the signal bandwidth. The resulting channel models are usually multiplicative fading models where a statistical description of the time-varying attenuation is the central focus of the model [2]. Examples of narrowband fading models include the Rayleigh fading channel commonly used for urban cellular channels [2], the Rice fading channel commonly used for modeling land-mobile satellite channels [3, 4], and a narrowband channel model for aeronautical telemetry [5].

Wideband channel models are used in those situations where the signal bandwidth is on the order of or larger than the coherence bandwidth of the multipath fading process. In this case, the individual multipath reflections are resolvable in the signal bandwidth. In this case the channel is modeled as a tapped delay line with time-varying coefficients to account for changes in the characteristics of the multipath. If the channel variations are slow enough, then over a short time interval, the channel can be modeled as a linear, time-invariant system whose complex baseband impulse response is composed of L propagation paths and is of the form

$$\tilde{h}(t) = \sum_{k=0}^{L-1} \tilde{\Gamma}_k \exp\{-j\omega_c \tilde{\tau}_k\} \delta(t - \tilde{\tau}_k) \quad (1)$$

where $\tilde{\Gamma}_k$ is the complex gain of the k th propagation path, $\tilde{\tau}_k$ is the propagation delay of the k th propagation path, and ω_c is the RF carrier frequency. We label path 0 the line-of-sight path and normalize the other path gains and delays to the line-of-sight path using

$$h(t) = \frac{\tilde{h}(t + \tilde{\tau}_0)}{\tilde{\Gamma}_0} \quad (2)$$

$$\begin{aligned} &= \delta(t) + \sum_{k=1}^{L-1} \frac{\tilde{\Gamma}_k}{\tilde{\Gamma}_0} \exp\{-j\omega_c(\tilde{\tau}_k - \tilde{\tau}_0)\} \delta(t - \tilde{\tau}_k + \tilde{\tau}_0) \\ &= \delta(t) + \sum_{k=1}^{L-1} \Gamma_k \exp\{-j\omega_c \tau_k\} \delta(t - \tau_k) \end{aligned} \quad (3)$$

where Γ_k and τ_k are defined implicitly in (3). A simple 2-ray model ($L = 2$) based on a single ground reflection has proven to be a useful propagation model for predicting large-scale signal strength for systems

that use tall towers and for line-of-sight microcell channels in urban environments [6]. Rummler's model [7] is a 3-ray ($L = 3$) model that is a good model for the 6 GHz terrestrial microwave line-of-sight channel. In the work presented here, we show that $L = 3$ yields an accurate model for the multipath observed in aeronautical telemetry applications. In addition, we provide models which accurately predict the values of the complex gains and delays for the two reflected propagation paths.

II. CHANNEL SOUNDING EXPERIMENTS

A. Experimental Configuration

The experimental configuration for the channel sounding experiments is illustrated in Fig. 1. A length-127 PN sequence¹ was transmitted using a 10 Mbit/s binary phase-shift keyed (BPSK) transmitter with a 2 W linear power amplifier in a T-39 Sabreliner aircraft. The baseband NRZ PCM PN waveform was filtered by a 7th order elliptic low-pass filter with a 3 dB frequency of 10 MHz to limit the spectrum of the resulting RF modulated signal. The transmit antenna was a vertically polarized, hemispherically omni-directional antenna mounted under the aircraft fuselage. GPS data were recorded on board the aircraft for data correlation during postflight processing.

The receiving station used a parabolic reflector which tracked the airborne transmitter. This antenna was located at the main telemetry receiving complex (Building 5790) at Edwards AFB. The received signal was downconverted to a linear 70 MHz IF, filtered by an IF bandpass filter, and sampled at 100 Msamples/s using a high-speed sampling oscilloscope. In addition, the receiver AGC voltage was sampled at 50 ksamples/s and tagged with GPS-derived time stamps for calibration purposes during the postflight processing.

Two flight paths were used for the channel sounding measurements as illustrated in Fig. 2. The first is Cords Road, which is an approximately east-west flight corridor just north of the main telemetry receiving complex at Edwards AFB. The west end of the Cords Road run is located at 35°

Fig. 1. Block diagram of experimental configuration used for channel sounding experiments.

$5.22' N$, $117^{\circ} 59.98' W$ and the east end is located at $35^{\circ} 4.95' N$, $117^{\circ} 3.89' W$. The channel sounding flights conducted along the Cords Road corridor were at an altitude of 5,000 ft AMSL. The second is Black Mountain which is also an east-west flight corridor and is north of the Cords Road flight path. The west end of the Black Mountain run is located at $35^{\circ} 12.26' N$, $117^{\circ} 52.17' W$ and the east end is located at $35^{\circ} 11.46' N$, $116^{\circ} 53.90' W$. The channel sounding flights conducted along the Black Mountain corridor were at altitudes of 5,000 and 10,000 ft AMSL. The main telemetry receiving complex is at $34^{\circ} 53.62' N$, $118^{\circ} 0.68' W$ at an altitude of 2966 ft AMSL. The dry-lake bed that forms the reflecting surface is at an altitude of 2300 ft AMSL.

Two modes of operation were used to produce the data analyzed here. In the first mode, sampling was triggered by error events generated by the BPSK demodulator. During each trigger event, the digital oscilloscope recorded 10 consecutive data segments spaced $T_{\Delta\text{seg}}$ s apart with duration $T_{\text{seg}} = 100 \mu\text{s}$ (or 10,000 samples). In the second mode, sampling is performed continuously but interrupted by data transfer to a file when the sampling oscilloscope memory is full. The sampling process is performed in short bursts spaced $T_{\Delta\text{seg}} = 20 \text{ ms}$ apart with duration $T_{\text{seg}} = 50 \mu\text{s}$ (5,000 samples). With these numbers, oscilloscope memory allowed the sampling of 800 segments between data transfer events. In this way, snapshots of the channel impulse response were produced every $T_{\Delta\text{seg}}$ s. These details are summarized in Table I.

¹A PN sequence was chosen since it can be used to identify multipath reflections in the received signal using well-known cross correlation methods [8]. The cross correlation method identifies a multipath reflection only when its delay (relative to other propagation paths) is greater than twice the chip time. In this system, the minimum resolvable delay is 200 ns which is much greater than the delays produced by the system geometry. While there are multipath reflections that arrive with delays greater than the 200 ns resolution, the amplitudes are very small and are hard to extract from the cross correlation data. Some PN cross correlation results for the Edwards AFB data are presented in [9].

Fourier transform of the model (3) to obtain

$$H(\omega) = 1 + \sum_{k=1}^{L-1} \Gamma_k \exp\{-j(\omega\tau_k + \omega_c\tau_k)\}. \quad (6)$$

The continuous-time channel transfer function (6) is bandlimited by setting $H(\omega) = 0$ for $\omega T_s \notin W$. Using the relationship between bandlimited continuous-time systems and the equivalent discrete-time systems [12, ch. 7], the equivalent discrete-time channel transfer function is given by

$$H(e^{j\Omega}) = \begin{cases} 1 + \sum_{k=1}^{L-1} \Gamma_k \exp\left\{-j\left(\Omega \frac{\tau_k}{T_s} + \omega_c\tau_k\right)\right\} & \Omega \in W \\ 0 & \text{else} \end{cases}. \quad (7)$$

Equation (7) is a function of $2(L-1)$ parameters which we define as the set

$$\mathcal{S} = \{\Gamma_1, \tau_1, \Gamma_2, \tau_2, \dots, \Gamma_{L-1}, \tau_{L-1}\}. \quad (8)$$

The optimal parameter set $\mathcal{S}_{\text{opt}}$ is determined using a modified least squares criterion:

$$\mathcal{S}_{\text{opt}} = \underset{\mathcal{S}}{\text{argmin}} \left\{ \sum_{m \in \mathcal{M}} |10 \log_{10}(|H(e^{j\Omega_m}; \mathcal{S})|^2) - 10 \log_{10}(|\hat{H}(e^{j\Omega_m})|^2)|^2 \right\} \quad (9)$$

where the notation $H(e^{j\Omega_m}; \mathcal{S})$ has been used in place of $H(e^{j\Omega_m})$ to emphasize the fact that the model is a function of the parameters in the set $\mathcal{S}$. The decibel criterion was chosen to force the least-squares minimization algorithm to weight modeling errors corresponding to frequencies in multipath nulls equally with modeling errors corresponding to frequencies with unfaded signals. This was needed to emphasize the structure of the multipath nulls which depend on the delays thereby improving the estimates of the delays. Note that if the usual least-squares criterion were used, modeling errors in the nulls, where the amplitude is small, would not make a sufficient contribution to the total least squares error to produce accurate modeling results.

III. MODELING RESULTS

A. Number of Multipath Reflections

The number of multipath reflections L used in the model represents a trade-off between model accuracy and complexity. In general, the higher L is, the more accurate the channel model is, but the less useful it is since information about each multipath reflection is required. With this in mind, the first goal of our modeling process was to determine the

minimum number of paths required to represent the multipath interference with reasonable accuracy. A thorough examination of the data showed that $L = 3$ is a good value. The most extreme case is shown in Fig. 3 which plots the modeling results for a segment of data from Flight 10 along the Black Mountain flight path. The power spectra of the transmitted and received signals are illustrated in Fig. 3(a) and (b), respectively. The estimate of the channel transfer function $|\hat{H}(e^{j\Omega})|^2$ is shown by the solid line in Fig. 3(c) and (d). The dashed line in Fig. 3(c) is the best fit for the $L = 2$ channel model. We observe that the two-ray model does not possess enough degrees of freedom to represent the structure of the multipath distortion. Increasing L to 3 and following the modeling procedure produces the model shown by the dashed line in Fig. 3(d). The 3-ray model is needed to capture the “ripple” effect observed in the channel transfer function estimate.

All of the data runs measured at Edwards AFB are well modeled by a three-ray model. The channel consists of a line-of-sight propagation path and two multipath reflections. The first reflection has a large relative amplitude and short delay and is caused by a specular ground “bounce” or reflection. This conclusion is supported by using the location information recorded during the test flight to compute the system geometry. The second reflection is a much weaker reflection whose delay is an order magnitude larger. Given the differential path delays observed, we conclude that this reflection is caused by foothills and low mountains situated in between the airborne transmitter and the ground-based receiver. Since the terrain variations in this region appear random as the airborne transmitter progresses along its flight trajectory, the characteristics of this multipath reflection are better modeled as random variables.

B. Properties of First Multipath Reflection

The first ray is well modeling as a single “ground bounce” off a flat, smooth earth. The typical flight geometry, illustrated in Fig. 4 reveals why this is so. The flat reflecting surface between the airborne transmitter and ground-based receiver represents the dry lake beds typical of test ranges located in the deserts of the western United States. For a receive antenna with beamwidth θ_a set at elevation angle θ_e , a specular reflection with grazing angle θ_g will only cause multipath interference when the specular reflection arrives within the mainlobe of receive antenna gain pattern; that is when

$$\theta_e + \theta_g < \frac{\theta_a}{2}. \quad (10)$$

For aeronautical telemetry applications, antenna beamwidths range from approximately 6° for the 8 ft L-band antenna to about 3° for the 15 ft L-band antenna at Edwards AFB. Given this scenario,

Fig. 3. Data processing example from Flight 10. (a) Power spectral density of transmitted signal. (b) Power spectral density of received signal. (c) Estimate of channel transfer function (solid line) and best 2-ray model fit (dashed line). (d) Estimate of channel transfer function (solid line) and best 3-ray model fit (dashed line).

Fig. 4. Geometry of aeronautical telemetry channel.

multipath interference is most likely to occur when the elevation angle θ_e is small and the environmental geometry supports a multipath reflection with a very small grazing angle.

The physical properties of the specular reflection are well understood in electromagnetic theory [13]. Given the propagation geometry illustrated in Fig. 4, the reflection coefficient is well modeled as E-field reflection at an interface between free space and a semi-infinite dielectric. For vertical and horizontal polarizations, the reflection coefficients are

$$\Gamma_V = \frac{-\cos\theta_i + \sqrt{\frac{\epsilon_0}{\epsilon_1}} \sqrt{1 - \frac{\epsilon_0}{\epsilon_1} \sin^2\theta_i}}{\cos\theta_i + \sqrt{\frac{\epsilon_0}{\epsilon_1}} \sqrt{1 - \frac{\epsilon_0}{\epsilon_1} \sin^2\theta_i}} \quad (11)$$

$$\Gamma_H = \frac{\cos\theta_i - \sqrt{\frac{\epsilon_1}{\epsilon_0}} \sqrt{1 - \frac{\epsilon_0}{\epsilon_1} \sin^2\theta_i}}{\cos\theta_i + \sqrt{\frac{\epsilon_1}{\epsilon_0}} \sqrt{1 - \frac{\epsilon_0}{\epsilon_1} \sin^2\theta_i}}, \quad (12)$$

respectively, where $\epsilon_0 = 8.85 \times 10^{-12}$ F/m is the permittivity of free space and ϵ_1 is the permittivity of the reflecting media. For dry earth, $\epsilon_1 = 3\epsilon_0 + 3 \times 10^{-4}/j\omega_c$ [13]. As the grazing angle θ_g gets small, the incidence angle θ_i approaches 90° so that $\Gamma_V \rightarrow +1$ and $\Gamma_H \rightarrow -1$. Expressions for the delay τ_1 and grazing angle θ_g assuming a flat smooth earth are given by (19) and (20), respectively, in the Appendix.

As an example, the magnitude, phase, and delay of the first multipath reflection predicted by this assumption is plotted in Fig. 5 for a 16 s segment of data from the Cords Road run. Also included in the plot are the modeling results. We observe close agreement between the predicted values and modeling values for τ_1 and $|\Gamma_1|$. The gap in the modeling results (from about 9 to 14 s) is due to the inability of the analysis procedure to model the multipath when the spectral null is phased so that it does not occur within the band occupied by the transmitted signal. Variations in the modeling for $|\Gamma_1|$ result from the fact that the Earth is not exactly smooth. This roughness causes

Fig. 5. Comparison of predicted multipath parameters (dotted lines) with measured values (solid lines) at timestamp 18:10:05 during Flight 18 at Edwards AFB. Top: delay. Middle: phase. Bottom: magnitude.

some diffuse scattering that reduces the power in the reflection as seen by the receive antenna.

For an airborne transmitter following the Cords Road flight path at an altitude of 5,000 ft, the simple geometric model predicts $|\Gamma_1|$ ranges from 0.81 to 0.95 (west to east) and τ_1 ranges from 55 to 13 ns (west to east). Likewise for the Black Mountain flight path at 5,000 ft, $|\Gamma_1|$ ranges from 0.89 to 0.96 (west to east) and τ_1 ranges from 31 to 11 ns (west to east). At 10,000 ft $|\Gamma_1|$ ranges from 0.74 to 0.90 (west to east) and τ_1 ranges from 87 to 32 ns (west to east). Model parameters obtained from the data processing at various points along these flight paths for Γ_1 and τ_1 agreed very well with these values.

The dynamic behavior of the first reflection is due to changes in the reflection geometry as the airborne transmitter proceeds along its flight trajectory. The location of the spectral null is determined by the overall phase of the multipath reflection which is

$$\theta_{\text{total}} = \angle \Gamma_1 - \omega_c \tau_1. \quad (13)$$

As the airborne transmitter moves through space, $\angle \Gamma_1$ and τ_1 change. The rate of change of these values is determined by the time derivatives of the differential delay τ_1 and grazing angle θ_g . Expressions for these values are given by (21) and (22) in the Appendix where it is observed that θ_g is negligibly small for the geometries of interest (i.e. θ_g is well approximated

by a constant). For the geometries of interest, $\dot{\tau}$ is also small. But since ω_c is large, the product is large enough to observe. As a result, θ_{total} is proportional to $\dot{\tau}$ and the null appears to “sweep” through the spectral band occupied by the modulated signal. This phenomenon is illustrated in Fig. 6. Note that the null progresses through the signal bandwidth as small changes in the differential delay impose significant changes in θ_{total} . A plot of $\dot{\tau}_1$ calculated using (21) for the three channel sounding flight paths is shown in Fig. 7. The product $\omega_c \dot{\tau}_1$ has units rads/s and indicates the rate at which the null sweeps across the spectrum.³

C. Properties of Second Multipath Reflection

The second reflection is a result of bounces off the foothills and mountains along the flight path for both Cords Road and Black Mountain. Since these terrain features are much more uneven and unpredictable, the resulting multipath properties appear random in nature. As a consequence, a statistical characterization is adopted.

A histogram of the complex amplitude Γ_2 for both the Cords Road and Black Mountain runs are

³Since the nulls occur every $1/\tau_1$ Hz, the time required for $\omega_c \dot{\tau}_1$ to change by 2π is the time required for the null to sweep through $1/\tau_1$ Hz on a spectrum analyzer.

Fig. 6. Sequence of channel transfer functions for Flight 18. Each slice in plot is a plot of channel transfer function based on best fit model parameters.

Fig. 7. Plot of $\dot{\tau}_1$ for three channel sounding flight paths.

shown in Figs. 8 and 9, respectively. In each figure, the solid line is a plot of the Gaussian probability density function (pdf) defined by the sample mean and variance. The amplitudes are well approximated by a complex valued Gaussian random variable where the real and imaginary components each have zero-mean and variance 1.6×10^{-3} . Consequently, $|\Gamma_2|$ is Rayleigh distributed and $\angle \Gamma_2$ is uniformly distributed.

The delay τ_2 is statistically characterized using the power delay profile [6]. The power delay profiles for Cords Road, Black Mountain, and the two combined are shown in Figs. 10, 11, and 12, respectively. The

mean excess delay τ_e and the delay spread σ_τ are summarized as follows.

	Flight 18 Cords Road (5,000 ft)	Flight 18 Black Mountain (5,000 ft)	Flight 18 All Data (5,000 ft)
τ_e	155 ns	154 ns	155 ns
σ_τ	77 ns	61 ns	74 ns

The dynamic behavior of the second reflection is characterized using the autocorrelation function

Fig. 8. Cords Road data set from Flight 18 at Edwards AFB. Histograms of real (top graph) and imaginary (bottom graph) parts of Γ_2 compared with Gaussian pdf formed from mean and variance of each data set.

$$R_{\Gamma_2}(\Delta t) = E\{\Gamma_2(t)\Gamma_2^*(t - \Delta t)\} \quad (14)$$

$$\approx \frac{1}{N} \sum_{n=0}^{N-1} \Gamma_2(n)\Gamma_2^*(n - \Delta t) \quad (15)$$

where the notation $\Gamma_2(n)$ means the model parameter Γ_2 obtained from the data corresponding to the n th segment. A plot of this function for a 16 s interval from the Cords Road run at 5000 ft is shown in Fig. 13. This plot, typical of all data runs at Edwards AFB, shows that the sequence of Γ_2 is uncorrelated. As such, Γ_2 changes rapidly with position (and time).

IV. CONCLUSIONS

Channel sounding data collected at Edwards AFB, CA was used to characterize the multipath propagation observed on the aeronautical telemetry channel. A channel model based on an analysis of this data was developed and presented. The channel model consists of three propagation paths: a line-of-sight propagation path and two specular reflections. The first specular reflection is well modeled as a single ground bounce

from a flat, smooth earth. The amplitude and delay are determined from the flight profile. For the flight paths used for channel sounding experiments, the amplitude of this path ranged from 70% to 96% of the line-of-sight path and the delay was 10–80 ns relative to the line-of-sight path. The dynamic behavior of this reflection was also analyzed. It was shown that small changes in the position of the airborne transmitter cause the spectral null associated with this multipath reflection to sweep through the spectral band occupied by the modulated signal.

The second reflection is a much lower amplitude propagation path that is caused by irregular terrain (foothills and mountains) along the propagation path. Since the irregular terrain varies in an unpredictable way, the amplitudes and delays appear to vary in a random way. The amplitude is well modeled by complex valued, zero-mean Gaussian random variable. The resulting amplitude is on the order 2% to 8% of the line-of-sight amplitude. The sequence of complex amplitudes is uncorrelated which indicates rapid variations in time and space. The mean excess delay is 155 ns with an rms delay spread of 74 ns.

Fig. 9. Black Mountain data set from Flight 18 at Edwards AFB. Histograms of real (top graph) and imaginary (bottom graph) parts of Γ_2 compared with Gaussian pdf formed from mean and variance of each data set.

Fig. 10. Power delay profile for second multipath reflection. Data shown here was collected at Edwards AFB along Cords Road flight path during Flight 18.

Fig. 11. Power delay profile for second multipath reflection. Data shown here was collected at Edwards AFB along Black Mountain flight path during Flight 18.

Fig. 12. Power delay profile for second multipath reflection for combined data from Figs. 10 and 11.

The dominant feature of the multipath interference is the spectral null generated by the first multipath reflection. The time variations of this reflection depend on the flight path of the airborne transmitter and are slow enough to be tracked by an adaptive equalizer. The second multipath causes a small amplitude “ripple” in the channel transfer function that varies quickly with time. The changes in this ripple are probably too rapid to be tracked by an adaptive equalizer. Fortunately, this characteristic is not the dominant multipath distortion on this channel.

APPENDIX A. GEOMETRIC APPROXIMATIONS USED FOR FLAT EARTH MODEL

The geometry of the flight path assuming a flat-smooth earth is illustrated in Fig. 14. In Fig. 14(a), the transmitter location $\mathbf{T}' = [x'_T, y'_T, z'_T]^T$, the receiver location $\mathbf{R}' = [x'_R, y'_R, z'_R]^T$, and the specular point $\mathbf{S}' = [x'_S, y'_S, z'_S]^T$ are plotted on a south-east-up coordinate system [14] (x', y', z') centered at sea level at the latitude and longitude of the receiver. For our simple model of a flat, level reflecting surface, the

Fig. 13. Autocorrelation function for Γ_2 for 16 s interval from the Cords Road run at 5000 ft.

points T' , R' , and S' reside in a plane as shown. As such, the three points may be plotted in a new coordinate system (x, y, z) which is produced from (x', y', z') by a clockwise rotation about the z' axis as illustrated in Fig. 14(b). The angle of rotation is $\phi = \tan^{-1}\{x_T/y_T\}$. In the new (x, y, z) coordinate system, the transmitter location T is related to its coordinates in the old (x', y', z') coordinate system by $T = P_\phi T'$ where P_ϕ is the rotation matrix given by

$$P_\phi = \begin{bmatrix} \cos \phi & -\sin \phi & 0 \\ \sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (16)$$

Similarly, $R = P_\phi R'$ and $S = P_\phi S'$.

Using simple geometric operations in the new coordinate system, the differential path length Δ and the grazing angle θ_g are given by

$$\Delta = \sqrt{(z_T + z_R - 2z_S)^2 + y_T^2} - \sqrt{y_T^2 + (z_T - z_R)^2} \quad (17)$$

$$\theta_g = \tan^{-1} \left\{ \frac{z_T + z_R - 2z_S}{y_T} \right\}. \quad (18)$$

For most of the cases of practical interest, $y_T \gg z_T, z_R, z_S$ so that (17) and (18) are well approximated by truncated Taylor series. Using the Taylor series approximations and the relationship $\tau = \Delta/c$ we

Fig. 14. Geometric details of multipath reflection. (a) Geometry of multipath reflection in south-east-up Cartesian coordinate system (x', y', z') located at sea-level at latitude and longitude of receiver. (b) Geometry of same multipath reflection in rotated Cartesian coordinate system (x, y, z) .

obtain

$$\tau \approx \frac{2(z_T - z_S)(z_R - z_S)}{cy_T} \quad (19)$$

$$\theta_g \approx \frac{z_T + z_R - 2z_S}{y_T}. \quad (20)$$

For dynamic channel behavior, the time derivatives of the spatial coordinates are computed. If the transmitter velocity vector is $\mathbf{v}_T' = [\dot{x}_T', \dot{y}_T', \dot{z}_T']^T$, then $\mathbf{v}_T = [\dot{x}_T, \dot{y}_T, \dot{z}_T]^T$ is given by $\mathbf{v}_T = P_\phi \mathbf{v}_T'$. The corresponding changes in τ and θ_g are

$$\dot{\tau} = -\frac{2(z_T - z_S)(z_R - z_S)}{cy_T^2} \dot{y}_T + \frac{2(z_R - z_S)}{cy_T} \dot{z}_T \quad (21)$$

$$\dot{\theta}_g = -\frac{z_T + z_R - 2z_S}{y_T^2} \dot{y}_T + \frac{1}{y_T} \dot{z}_T. \quad (22)$$

Again, for the cases of practical interest, $y_T \gg z_T, z_R, z_S$ so that $\dot{\theta}_g \approx 0$. Hence the changes in the reflections coefficients given by (11) and (12) are negligible. Changes in τ will also be small. But even small changes in τ will cause significant changes in the overall phase of the multipath reflection since the shift since the phase shift is $\omega_c \tau$ and the carrier frequencies are in the L-band (1500 MHz) and lower S-band (2200 MHz).

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