An ACTS Mobile Receiver Simulation

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Abstract

The continuing demand for mobile communication and the growing congestion of currently assigned frequency bands has precipitated the development of K/Ka band mobile-satellite technology. The Jet Propulsions Lab (JPL), using the Advanced Communications Technology Satellite (ACTS), has conducted prototype testing of a K/Ka band mobile-satellite link. The JPL system uses a narrow beam antenna which tracks the satellite signal. As the JPL vehicle experienced changes in yaw, pitch, and roll, the antenna experienced a pointing error. A model to describe the power losses caused by pointing error is developed. This model shows a received power loss on the order of 2.0 dB.

1 Introduction

As mobile communications has become more popular, the congestion at currently assigned bands has increased. In an effort to relieve this congestion, the applicability of new frequencies to mobile communications has been explored. The Advanced Communications Technology Satellite (ACTS) was developed by NASA to support development of K/Ka band communications [1]. The ACTS Mobile Terminal (AMT) was developed by the Jet Propulsion Laboratory (JPL) as a test bed for proof-of-concept designs of K/Ka-band mobile satellite communication systems [2].

Pilot tone tests using the AMT were conducted to characterize the land mobile satellite channel at these frequencies. The system setup is illustrated in Figure 1 and a typical run is illustrated in Figure 2. The solid line in Figure 2 represents the one second average of the received pilot data while the dotted line identifies the maximum and minimum power levels received during each one second interval. Variations in the average power level are due to shadowing, multipath interference, thermal noise, and pointing error. The deep fades in the average signal power are due to shadowing while the short term variations indicated by the dotted lines are the result of thermal noise and multipath interference. The small changes in the average power (on the order of 2 dB) are due to pointing errors.

Usually, mobile satellite communications at L-band employ omni-directional antennas which do not require tracking systems and, as a result, incur no pointing errors. The antenna used in the AMT is a small antenna with a 1 dB beamwidth of approximately 6° in both azimuth and elevation. The antenna is mounted on a platform which tracks the satellite signal through 360° azimuth for a fixed elevation angle, 46° for Southern California. For a complete description, see [3]. Any pitch or roll imposed on the antenna platform through uneven or unlevel road surfaces induces a pointing error. This is the pointing error which causes the 1 to 2 dB variations in the average signal power observed in Figure 2.

This paper describes an analytical procedure for predicting the azimuth and elevation pointing errors caused by changes in vehicle pitch, roll, and heading. These pointing errors are then coupled with the antenna gain pattern to generate an estimate of the loss in received power due to these effects.

2 Pointing Error Calculation

The location of a ground station is usually specified by its latitude M_g, longitude 8_g, and altitude h_g defining its location in spherical Earth Centered Fixed (ECF) coordinates. A geostationary satellite orbits the earth in the equatorial plane at an altitude of 35,786 km [4] and is specified by its longitude at the equator, or subsatellite point 8_s.

The ground station location in Cartesian ECF coordinates is

$$\begin{align} x_g &= R_E \cos\phi_g \cos\lambda_g \tag{1}\\ y_g &= R_E \cos\phi_g \sin\lambda_g \tag{2}\\ z_g &= R_E \sin\phi_g, \tag{3} \end{align}$$

while the satellite location in Cartesian ECF coordinates is

$$\begin{align} x_s &= r\cos\lambda_s \tag{4}\\ y_s &= -r\sin\lambda_s \tag{5}\\ z_s &= 0 \tag{6} \end{align}$$

The satellite location in Cartesian topocentric (or south-east-up (SEU)) coordinates is

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\mathrm{SEU}} = \begin{bmatrix} \sin\phi_g\cos\lambda_g & \sin\phi_g\sin\lambda_g & -\cos\phi_g \\ -\sin\lambda_g & \cos\lambda_g & 0 \\ \cos\phi_g\cos\lambda_g & \cos\phi_g\sin\lambda_g & \sin\phi_g \end{bmatrix} \begin{bmatrix} x_s - x_g \\ y_s - y_g \\ z_s - z_g \end{bmatrix}. \tag{7}$$

Using the SEU coordinates the satellite location in spherical topocentric coordinates is

$$d = \sqrt{x_{\text{seu}}^2 + y_{\text{seu}}^2 + z_{\text{seu}}^2} \tag{8}$$

$$\tan AZ = \frac{y_{\text{seu}}}{x_{\text{seu}}} \tag{9}$$

$$\tan \theta = \frac{z_{\text{seu}}}{\sqrt{x_{\text{seu}}^2 + y_{\text{seu}}^2}} \tag{10}$$

where d is the slant range, AZ is the azimuth[1], and 2 is the elevation angle. The SEU coordinates are used to calculate the actual elevation angle and azimuth of the satellite with respect to the AMT.

Changes in the vehicle heading, pitch, and roll alter the orientation of the vehicle-mounted antenna. To track these changes, a coordinate system which follows the movements of the vehicle is required. For this purpose, a vehicular topocentric coordinate system is derived. A Cartesian vehicle-centered system (VEH) is defined where the positive X-axis points in the direction of the vehicle heading, the positive Y-axis points to port, and the positive Z-axis points "up". The VEH system can be derived from the SEU system by a series of coordinate transformations. First a transformation is needed to convert SEU to a north-east-down (NED) system (this is done for compatibility with transformations found in [5]). Following the convention found in [5], the yaw ψ, pitch Θ, and roll Φ, defined in terms of the NED coordinate system, are

Yaw A rotation of the $X-Y$ plane about the Z-axis by ψ degrees, measured positive to the right.
This is the definition of heading.

Pitch A rotation of the $X-Z$ plane about the Y-axis by Θ degrees, measured positive with the nose up.

Roll A rotation of the $Y-Z$ plane about the X-axis by Φ degrees, measured positive with the left-side up .

The VEH system is therefore related to the SEU system by [5]

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[1] Since AZ is measured east of north and the topocentric coordinate system is south-east-up, the satellite location in spherical coordinates uses 180+AZ when λ_g is west of λ_s and 180-AZ when λ_g is east of λ_s in the northern hemisphere

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{VEH}} = B \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{SEU}} \tag{11}$$

where

$$B = \begin{bmatrix} \cos\Theta\cos\Psi & \cos\Theta\sin\Psi & -\sin\Theta \\ \cos\Phi\sin\Psi - \sin\Phi\sin\Theta\cos\Psi & -\cos\Phi\cos\Psi - \sin\Phi\sin\Theta\sin\Psi & -\sin\Phi\cos\Theta \\ -\sin\Phi\sin\Psi - \cos\Phi\sin\Theta\cos\Psi & \sin\Phi\cos\Psi - \cos\Phi\sin\Theta\sin\Psi & -\cos\Phi\cos\Theta \end{bmatrix}. \tag{12}$$

Equation (11) gives the coordinates of the satellite location in terms of the vehicle-centered Cartesian coordinates which incorporate pitch, roll, and heading. The actual azimuth and elevation angle between the vehicle and the satellite are given by

$$\tan(AZ_V + \Psi) = \frac{y_V}{x_V} \tag{13}$$

$$\tan(\theta_V) = \frac{z_V}{\sqrt{x_V^2 + y_V^2}}. \tag{14}$$

The azimuth and elevation angle pointing errors are given by

$$\Delta AZ = AZ - AZ_V \tag{15}$$

$$\Delta\theta = \theta - \theta_V \tag{16}$$

where AZ and *2* are given by Equations (9) and (10), respectively.

A horizontally-polarized spot beam supported by ACTS was used to test the AMT antenna. The tilt of the antenna (caused by the pitch, roll, and heading of the vehicle) resulted in polarization mismatches between the antenna and the incoming ACTS signal. For any given vehicle heading, an upper bound for the tilt of the antenna is the angle formed by the roof of the van and the horizontal. This will be referred to as the maximum polarization error.

The SEU coordinates of three points p_1, p_2, and p_3, which define the SEU X-Y plane are individually transformed into VEH coordinates using Equation (11). The vehicular coordinates of p_1, p_2, and p_3 are then used to define a plane and its normal, $\vec{n}$ [6]:

$$\vec{a} = \vec{p_2} - \vec{p_1} \tag{17}$$

$$\vec{b} = \vec{p_3} - \vec{p_1} \tag{18}$$

$$\vec{n} = \vec{a} \times \vec{b} \tag{19}$$

The maximum polarization error N_p is the angle between $\vec{n}$ and the normal to the vehicular X-Y plane $\vec{h} = [0, 0,1]$. N_p is given by [6]:

$$\cos(\phi_p) = \frac{\vec{h} \cdot \vec{n}}{\| \vec{h} \| \| \vec{n} \|}. \tag{20}$$

The loss in signal power received due to polarization mismatch is then upper bounded by [7]:

$$L_{p,\mathbf{max}} = \cos^2(\phi_p). \tag{21}$$

The angle γ between the azimuth direction and the axis of the vehicle tilt may be computed from the elevation angle 2_V and azimuth AZ_V. First, the pointing vector of the antenna $\vec{d}$ is calculated as follows:

$$\begin{aligned} d_x &= \cos\theta_V \cos AZ_V && (22) \\ d_y &= -\cos\theta_V \sin AZ_V && (23) \\ d_z &= \sin\theta_V, && (24) \\ \vec{d} &= [d_x, d_y, d_z] && (25) \end{aligned}$$

A vector $\vec{t}$ in the direction of the axis of tilt of the van is found as the cross product of the normals
$\vec{n}$ and $\vec{h}$:

$$\vec{t} = \vec{n} \times \vec{h}. \tag{26}$$

Therefore, γ is the angle between the vectors $\vec{t}$ and $\vec{d}$:

$$\cos(\gamma) = \frac{\vec{t} \cdot \vec{d}}{\| \vec{t} \| \| \vec{d} \|}. \tag{27}$$

We take the reflection of the maximum loss $L_{p,max}$ in the direction the antenna is pointing in order to find the actual loss in received signal power due to polarization mismatch:

$$L_p = L_{p,\mathbf{max}} \cos(\gamma) = \cos^2(\phi_p)\cos(\gamma). \tag{28}$$

Using the conditions of the AMT test, the maximum polarization loss in received signal power $L_{p,max}$ is 0.042 dB. This was found from Equation (21), using a fairly steep road tilt consisting of a 4° roll and a 4° pitch. For the data shown in Figure 2, the maximum calculated polarization loss L_p is 0.026 dB. When the polarization losses are compared to the losses due to pointing error (on the order of 1 dB), these levels are considered negligible.

3 Results and Concluding Remarks

A series of Matlab scripts were written to model the effects of changes in vehicle heading, pitch, and roll on the signal power received by the AMT. From the azimuth and elevation angle errors calculated using Equations (15) and (16), the loss in signal power due to each was computed using logarithmic interpolation of the antenna gain pattern data.

Measurements of the pitch, roll, and heading of the vehicle carrying the antenna system were taken at 0.1-mile intervals along the route circling the Rose Bowl in Pasadena, California. These pitch, roll, and heading data were used by the Matlab scripts to produce plots of the received signal power as a function of time as illustrated in Figures 3 and 4. For the purposes of comparison, the actual pilot power measured during the test run is included in these plots. For both runs, the maximum vehicle pitch angle was 3.3 degrees, while maximum roll angle was 4.5 degrees which resulted in maximum elevation angle and azimuth errors of 3.9° and 3.3°, respectively.

These results show that changes in vehicle heading, pitch, and roll can predictably account for an overall loss of 1.5 dB in the signal power received by a vehicle-mounted antenna. Differences between the measured data and the simulated data points are due to shadowing and multipath interference which are not modeled by the pointing error calculations developed in this paper. The losses generated by the simulation account for most of the long term average power variations observed in the measured data. Polarization mismatches were found to be fairly insignificant in the overall loss.

References

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[6] E. Swokowski. Calculus. PWS - Kent, Boston, fifth edition edition, 1991.

[7] M. Jensen, 1995. Department of Electrical & Comptuter Engineering, Brigham Young University , private communication.

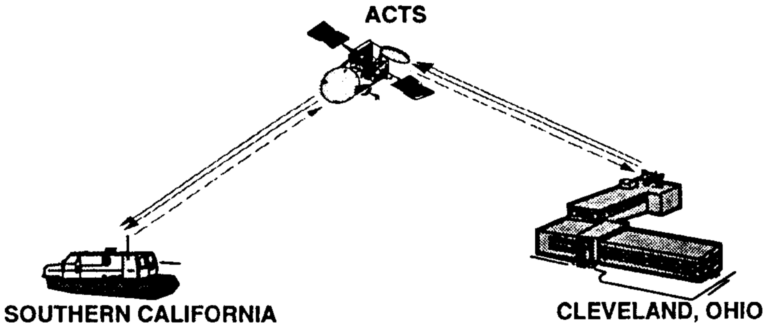

Figure 1: ACTS Mobile Link Diagram

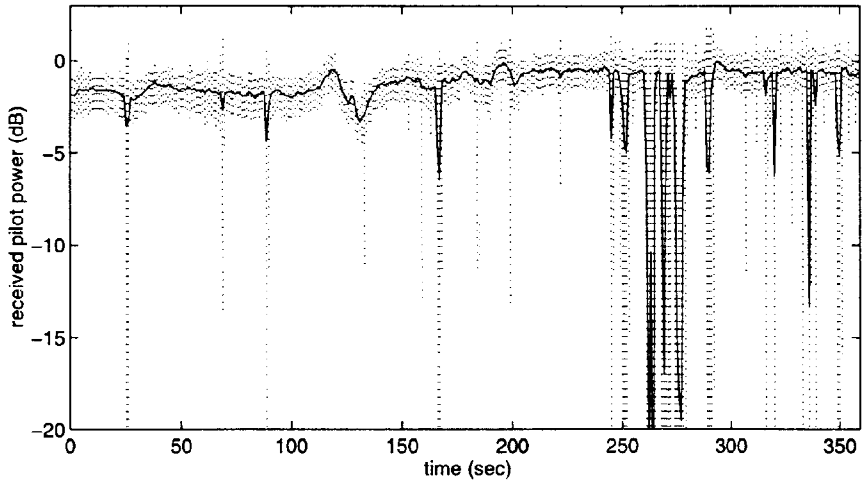

Figure 2: AMT received signal Power for a typical run in Pasadena, California. The solid line represents the received power averaged over one second.

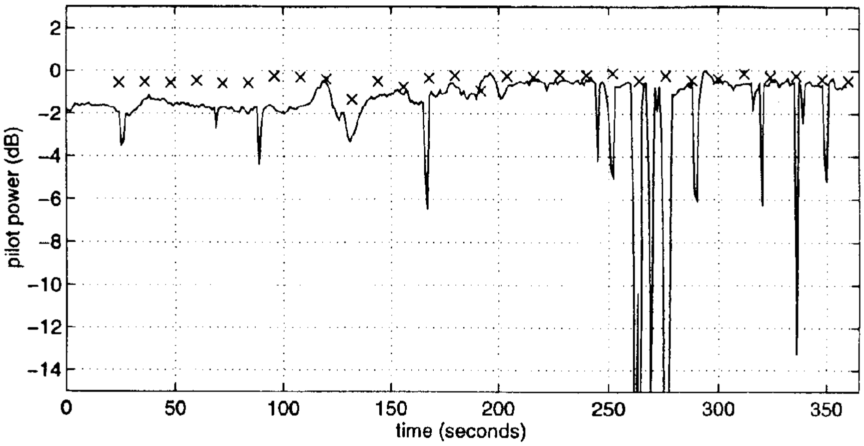

Figure 3: Pilot power (dB) vs. Time (s) for the Clockwise Rose Bowl Route (X = simulation, solid line = measured data).

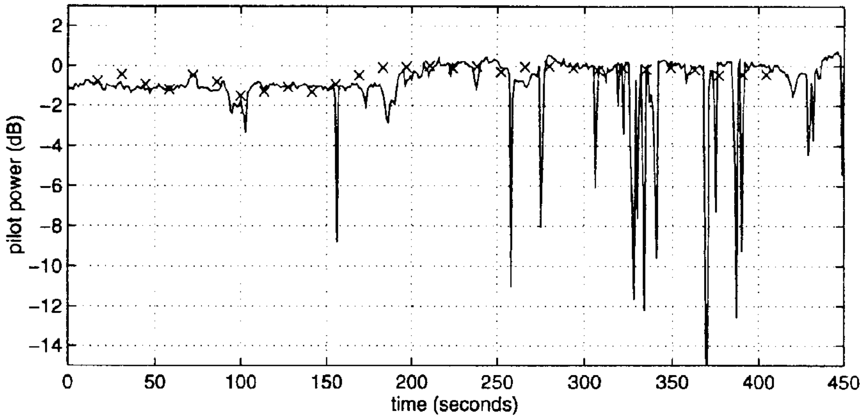

Figure 4: Pilot power (dB) vs. Time (s) for the Counter-clockwise Rose Bowl Route (X = simulation, solid line = measured data).