Mobile Propagation Results Using the ACTS Mobile Terminal (AMT)

Deborah S. Pinck,[*] Michael Rice[†]

1 Introduction

The 1990's have proven themselves to be a decade of unprecedented growth in the field of wireless information services. Vehicular-based users traveling at high speeds through high population density areas are well served by the current and evolving land-based cellular network. However, for users in remote or inaccessible locations, or for applications that are broadcast over a wide geographic area, land mobile satellite systems are becoming an increasingly popular alternative. Land mobile satellite systems allow truly ubiquitous wireless communications to users almost anywhere at anytime.

Many operational terrestrial wireless systems operate at UHF (800 MHz), while most satellite systems operate at L- and S-bands (1-3 GHz). As the increasing demand for mobile communication capacity consumes the available bandwidth allocations at UHF, L-, and S-bands, K- and Ka-band frequencies offer potential relief.

However, the communication channel between a satellite and a land based mobile user presents a challenge. Multipath interference and shadowing cause severe variations in the received power making constant, reliable communications difficult and limiting system performance. The effects of shadowing are the most severe source of signal outages in a land mobile satellite system. The attenuation due to shadowing increases with frequency: L-band is worse than UHF, S-band is worse than L-band, etc. Since K-band frequencies are ten times those at L-band, a thorough and careful analysis of the fading effects is required to assess the viability of K-band mobile satellite systems.

NASA's Advanced Communications Technology Satellite (ACTS) provides an ideal spaced-based platform for analyzing the K/Ka-band mobile satellite channel. This paper reports on the results of the K-band mobile propagation analysis campaign using the ACTS Mobile Terminal (AMT) developed by the Jet Propulsion Laboratory (JPL). The objectives of the mobile propagation experiments were to measure and analyze the fading characteristics of the K-band channel. The analysis involved examining pilot tone tests in three environments: lightly shadowed suburban, moderately shadowed suburban and heavily shadowed suburban.

The system used to collect the data and a description of the environment are outlined in Section 2. Section 3 presents the measurement results as well as a comparison of K-band mobile propagation results with propagation results at lower frequencies.

[*]D. Pinck is with the Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 161-241, 4800 Oak Grove Drive, Pasadena, CA 91109.

[†]M. Rice is with the Department of Electrical & Computer Engineering, Brigham Young University, Provo, UT 84602.

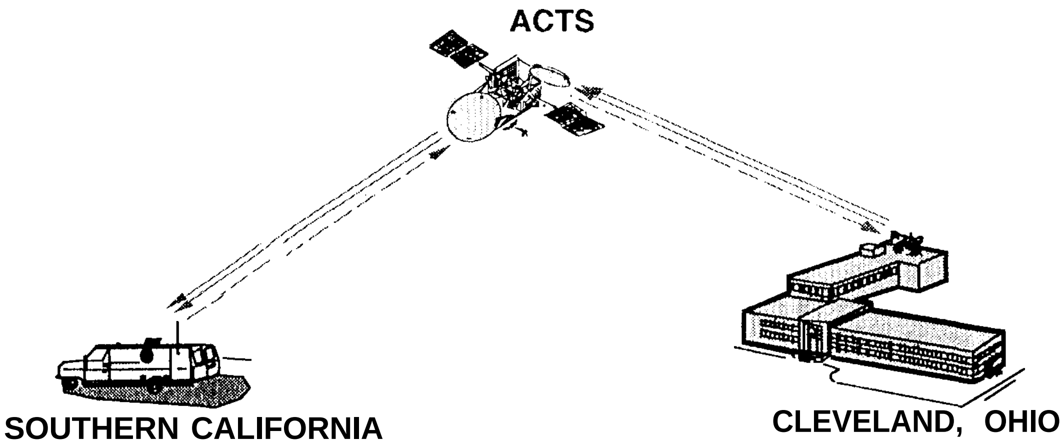

Figure 1: ACTS Mobile Terminal System Configuration

2 Experiment Description

2.1 System Description

NASA's ACTS satellite provides a stationary platform ideally suited to the measurement of mobile propagation effects at K/Ka-band (20/30 GHz). JPL has developed a proof-of-concept breadboard mobile terminal system to operate in conjunction with ACTS at K/Ka-band called the ACTS Mobile Terminal (AMT) []]. Field tests conducted during the first 7 months of 1994 using JPL's AMT provide channel characterization data for the K-band land- mobile satellite channel.

As depicted in Figure 1, the system is comprised of a bent pipe propagation link connecting terminals at fixed and mobile sites. The forward channel originated at the fixed station with a 29.634 GHz pilot tone. This pilot tone was received by ACTS, mixed to the downlink frequency of 19.914 GHz, and transmitted on the Southern California spot beam. The for ward channel offered a composite C/N_0 of 55.63 dB-Hz and was the basis for the K-band results.

The AMT is equipped with a small (8″ x 3") high-gain reflector antenna [2] which tracks the satellite in azimuth for a fixed elevation angle (46" for these experiments). The antenna is mechanically steered and acquires and tracks the satellite over the entire 360° of azimuth with a pointing error less than 2°. Vehicle turn rates of up to 44" per second can be accommodated. the antenna has a G/T of -6 dB/K over a bane] width of 300 MHz. The 3 dB beam width is ±9° in elevation and ±6° in azimuth. 'J)hc antenna pointing systems enables the antenna to track the satellite for all practical vehicle maneuvers.

in support of AMT field experiments, data analysis software algorithms have been developed for processing the various data received at the fixed and mobile terminals. This processing is carried out both by the Data Acquisition System (DAS) as well as the AMT S1 'A RCStation Analysis Tool (A SAT). The DAS serves several purposes: (i) data reduction, (ii) "quick-look" data analysis and display, and (iii) data recording for post-test analysis by ASAT. The primary purpose of ASAT is in-depth analysis of data-events collected from both the fixed and mobile terminals.

The DAS, illustrate in Figure 2, measures inphase pilot voltage level and the non-coherent pilot power level. The inphase pilot voltage level was sampled at 4000 samples/second in a bandwidth

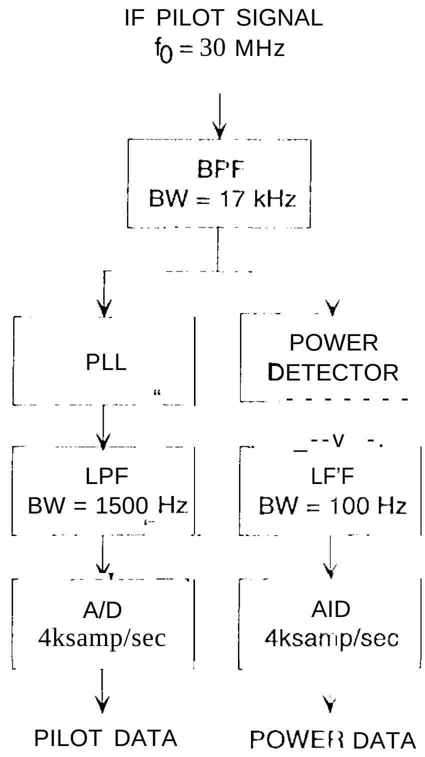

Figure 2: AMT Data Acquisition System Block Diagram

of 1.5 kHz and was used to analyze the channel characteristics presented in this paper. The data were stored on 5 Gbyte Exabyte tapes for off-line evaluation. The vehicle position, vehicle velocity, and time stamp were derived from an on-board GPS system and updated once each second. The DAS also provides real-time displays of various parameters to aid the experimenters in the field.

The ASAT is divided into two categories: (i) data extraction and (ii) data analysis and display. The data extraction routines allow data stored on the 5 Gbyte Exabyte tapes to be saved as files on the SPARCStation. These files can then be analyzed using any number of software packages including Matlab. Alternatively, the data could be interpreted by the ASAT analysis and display capabilities. These capabilities include the computation of various fading statistics (from pilot power and beacon data at the mobile terminal and fixed terminal, respectively) as well as the joint fade statistics (i. e., trajectories in the 2-D fade plane). The plots included in this paper were generated using the ASAT tool.

2.2 Overview of Campaign

Data were collected in a variety of locations in order to characterize environments typical of mobile satellite applications. In the absence of any standard definitions for the various environmental conditions typical of land mobile satellite channels, a set of general classifications specific to Southern California was adopted. All runs in this measurement campaign were conducted in Pasadena, California which presents a seasonally invariant suburban environment. The environments are divided

Table 1: Environmental Characteristics of AMT Propagation Runs

RUN	CAT.	DIRECTION		TERRAIN	OBSTRUCTIONS
020201	I	west	straight	hilly	none
070901	II	south, right lane	straight	flat	trees[1]
070903	III	north	curved	flat	trees[2] canopies cover road
070905	III	north, right lane	straight	flat	trees[1]
070906	III	South	curved	flat	trees[2] canopies cover road
070907	II	north, left lane	straight	flat	trees[1]
070912	III	south	curved	hilly	trees[3]: canopies cover road
070914	III	north	curved	hilly	trees[3]: canopies cover road
071016	III	north/south	curved	flat	trees[4]
071017	III	north/south	curved	flat	trees[4]
072405	II	east, left lane	straight	hilly	trees[5], utility poles
072406	II	west, left lane	straight	hilly	trees[5], utility poles
072407	II	east, right lane	straight	flat	trees[6], utility poles, buildings
072408	II	west, right lane	straight	flat	trees[7], utility poles
072409	II	south, right lane	straight	flat	trees[7]
072410	II	north, right lane	straight	flat	trees[1]
072411	II	south, left lane	straight	flat	trees[1]
072412	II	north, left lane	straight	flat	trees[1]

into three road categories based on the type of roadway:

Category I: a limited access multi-lane freeway

Category II: a broad suburban thoroughfare lined with trees and buildings. The tree canopies cause intermittent blockage and the buildings are either too far removed from the road side or not tall enough to cause significant blockage.

Category III: a small, two-lane roadway lined with trees and buildings. The tree canopies often cover the entire road way and buildings are close enough to contribute to the fading process.

This description is most appropriate in this case since the type and kind of obstructions are strongly dependent on the nature of the road. Table 1 shows a summary of the environmental features of the AMT runs.

[1] In order of concentration: Southern Magnolia, Fan & Date Palm, Coastal Live Oak, California Pepper

[2] In order of concentration: Coastal Live Oak, Southern Magnolias, Holly Oak.

[3] In order of concentration: Coastal Live Oak, Holly Oak, California Sycamore, Deadora Cedar, California Pepper

[4] In order of concentration: Oak, Pine, Sycamore, Magnolia, Cedar, Eucalyptus, Palm, California Pepper, Italian Cyprus.

[5] In order of concentration: Italian Cyprus, Palm, California Sycamore, Deadora Cedar

[6] In order of concentration: Ficus (aka Indian Laurel Fig), Date Palm.

[7] In order of concentration: Eucalyptus, Fan and Date Palm.

3 Measurement Results

3.1 Theoretical Considerations

The primary contributors to signal fluctuations in the lal)d-mobile satellite channel arc multipath interference and shadowing [3]. Multipath interference is the destructive interference caused by the reception of randomly phased reflections of the transmitted signal [4]. The transmitted satellite signal received by the mobile terminal consists of three major components:

1. The Line-Of-Sight (1,0S) Component which arrives at the receiver via a direct path.

2. The Specular Component which consists of a small number of reflections. Typically, the dominant reflect, ion is the ground reflection which arrives at the receiver at a negative elevation angle and can be neglected due to the attenuat ion effects of tile upward-looking receiver antenna [5].

3. The Diffuse Component which consists of a large number of weak reflections with random amplitudes and phases.

Shadowing is the complete or partial obstruction of the transmitted signal caused by the absorption and scattering of the incident direct signal by roadside trees or other obstacles in the path between the satellite and the vehicle [3]. Mobile satellite experiments at L-band [6, 7] show that the effects of shadowing dominate the statistics of the received signal.

The combination of multipath interference and shadowing manifests itself as relatively rapid variations about a local mean signal power (due to the multipath interference) superimposed on relatively slow variations in the received signal power (due to shadowing) [8].

Other factors contributing to variations in the received signal power include thermal noise, Faraday rotation, and ionospheric scintillation [9]. The contribution of' these factors relative to the fading caused by shadowing and multipath interference is so small that these effects may be ignored on a well designed satellite link.

The best way to characterize a fading channel is by looking at the fade depth statistics. Fade depth determines how often the fades arc worse then a particular fading threshold. The results are described in the following sections as well as a comparison of fade depth for K-band with fade depth at lower frequencies.

3.2 Description of Measured Data

Time series for two representative runs are illustrated in Figures 3 and 4. In these plots, the received pilot power is normalized to the power of unshadowed line-of-sight power level. These plots show characteristics typical of land mobile satellite communication systems: shallow fades due to multipath interference and deep fades duc to shadowing superimposed on slow variations in tile mean signal power due to changes in the shadowing profile of the local environment.

3.2.1 Fade Depth Statistics

In computing the fade depth statistics, or cumulative fade distribution, an average clear-line-of-sight pilot data leve1 is first determined. When a fade is encountered, the pilot level during the fade is compared to the previously computed clear-line-of-sight level to determine the *fade level* for that

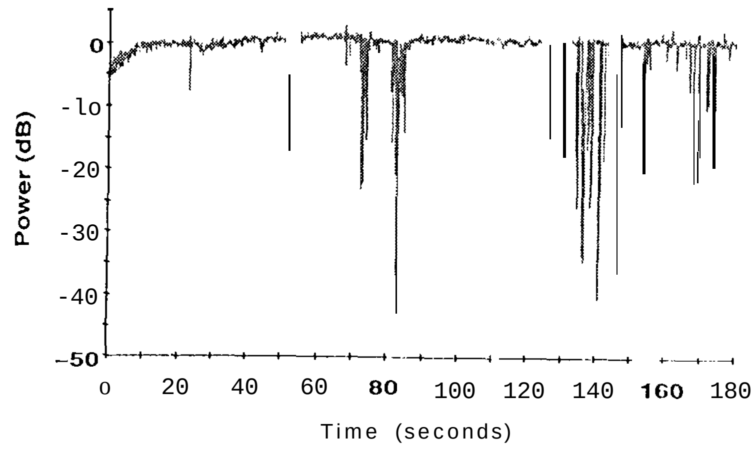

Figure 3: Received Pilot Power vs. Time for Run 072406”

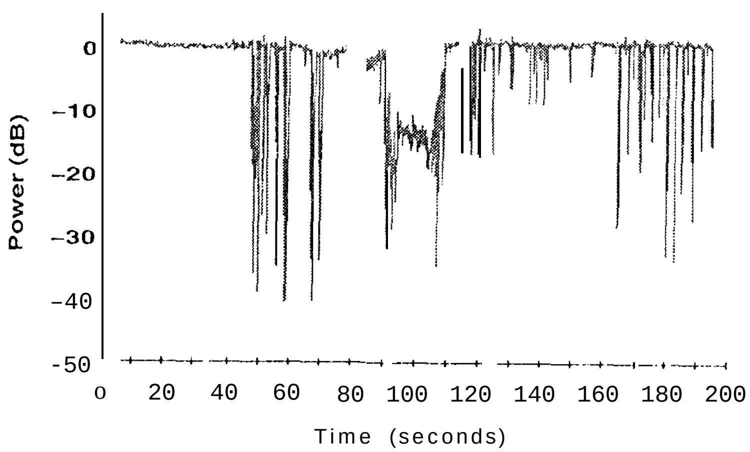

Figure 4: Received Pilot Power vs. Time for Run 072412

Table 2: Summary of Fade Exceedance Levels

RUN	CAT.	1% FADE LEVEL (dB)	5% FADE LEVEL (dB)	10% FADE LEVEL (dB)
022201	I	[illegible]	0.2	0.1
070901	III	8.0	1.0	1.0
070903	III	>> 30.0	>> 30.0	29.0
070905	II	>> 30.0	> 30.0	27.0
070906	III	> 30.0	17.5	6.0
070907	II	27.5	16.0	7.5
070912	III	>> 30.0	> 30.0	27.0
070914	III	>> 30.0	>> 30.0	> 30.0
071016	II	> 25.0	2.0	1.5
071017	II	22.2	2.0	1.5
072405	II	> 30.0	21.0	11.0
072406	II	23.0	7.0	1.5
072407	II	>> 30.0	>> 30.0	> 30.0
072408	II	21.0	8.0	1.0
072409	II	9.5	1.5	1.0
072410	II	>> 30.0	> 30.0	26.5
072411	II	10.0	2.0	1.5
072412	II	30.0	16.0	9.0

particular time. The cumulative fade distribution is then computed by dividing the range interval of the fade levels into bins and generating a histogram of' the percentage of fades for each fading level.

The cumulative fade distributions for several representative runs are shown in Figure! 5. These histograms show the percentage of time the fade is above (or below) a particular fade level. For example, for run 070901, 1% of the time the fade level is worse then 8 dB below the reference level (in other words, 99% of the time, the fades are better then 8dB below the reference level). For another example, run 070912, we see that 10% of the time the fade exceeds 8 dB below the reference level. The 1%, 5%, and 10% fade exceedance levels are typically used to describe the shape of the histogram and are tabulated for all runs of the AMT campaign in Table 2.

All curves have a distinct characteristic: a "knee" at 2 to 3 dB signifying a transition region between fading due to multipath interference and fading due to shadowing. The curve is steep for the first few dB which is typical of Ricean fading. Below the transition region, the curve exhibits a more gradual roll-off characteristic of an exponential dependency. These plots show clearly the time share nature of the fading processes at K-band. This characteristic shape has also been observed at L-band [1 O, 11, 7], at S- and Ku-bands [11], and at K-band [12].

The results of the sole category I run were expected. The absence of obstructions combined with the rejection of any off-axis reflections by the narrow-beam antenna produced a signal with no appreciable multipath interference.

The results of the category II runs are mixed. For the north-south runs where the lane tree geometry provided a relatively clear path to tile satellite, the results are promising: 1% fade levels

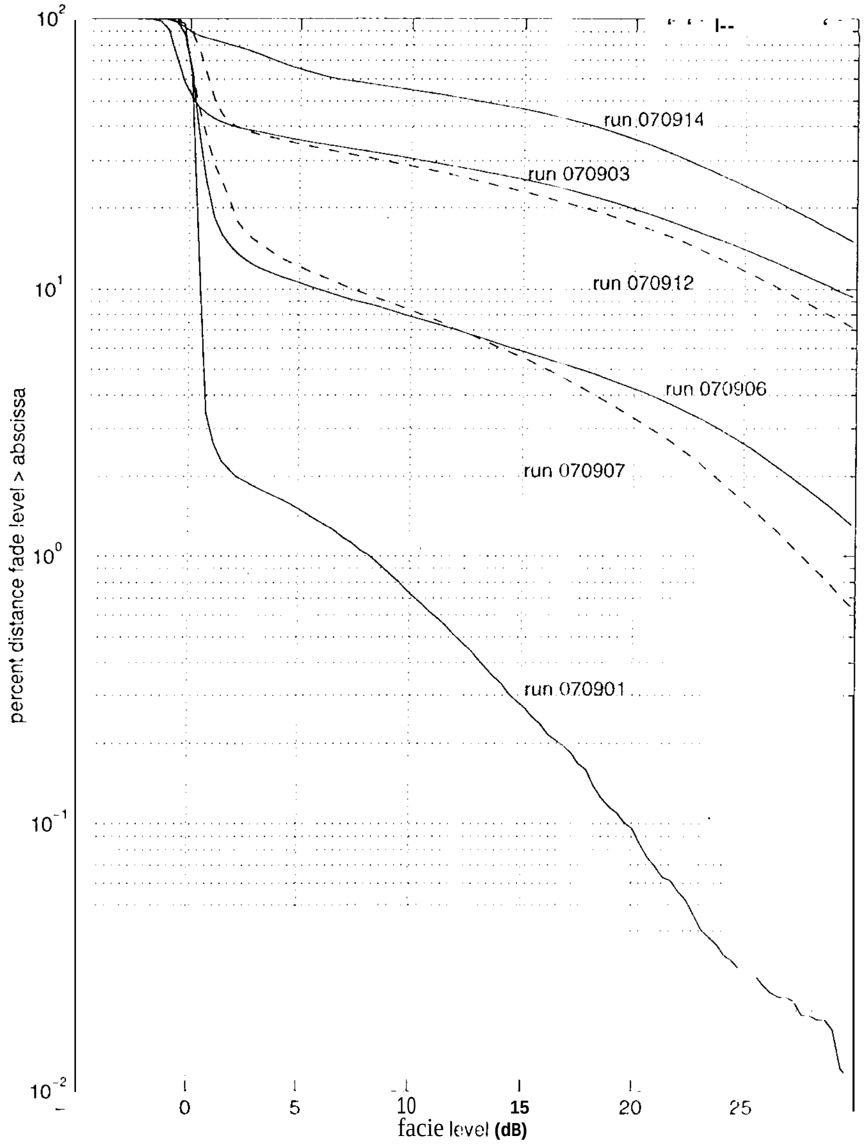

Figure 5: Cumula ive Fade Depth Distribution for Representat ve 1{1111s

range from 8 to 10 dB while the 10% fade levels arc all about 1 dB. The 01 her north-south runs were conducted on lanes too close to the trees for an unobstructed path to the satellite to be continuously available. These runs display severe fading with 1 % fade levels 27 dB or greater and lo% fade levels varying from 7.5 to 30 dB. For example, runs 072409 072.412 were all conducted in different lanes of Orange Grove Blvd. The western most lane (run 07240{) the south bound, right lane) provides the best view to the satellite resulting in the lowest fade exceedance levels of the four runs. The fade exceedance levels become progressively worse as the run lane moves west, culminating in run 072410 (northbound, right lane). The difference in 10% fade exceedance levels between the "best" and "worst" lanes here is 25.5 dB. Thus wc can see that the channel characteristics arc extremely sensitive to lane Changes.

All the cast-west runs (runs 072405- 072408) show deep fades at the 1 % level but very moderate fades at the 5% and 1 O% levels. This characteristic is to be expected since the azimuth to the satellite is 1500 (SSE) so that routes with a roughly north-south direction may find unobstructed "seams" between the foliage lining the road. Thus the east- west runs are as good as the best north-south runs 90% to 95% of the time but arc much worse 10/0 of the t ime since the line-of-sight, path is always skirt ing the tops of the trees. Runs 071016 and 071017 were particularly interesting in that the routes had isolated locations where the trees produced severe shadowing but were relatively clear in all other areas. This characteristic is reflected in the low 5% and 10% fade exceedance levels (~ 2 dB) together with very high 1% fade exceedance levels (~ 25 dB).

With one exception, all category 111 runs showed deep fades well in excess of 30 dB at the 1% level and ranging from 27 to 30 dB at the 10% level. The lone exception was Run 070906 where the orientation between that particular lane and the t rccs lining t he road allowed an unobstructed view of the satellite for most of the run the same characteristic observed in the category II runs. The inability of the K-band signal to penetrate the foliage, together with the reject ion of off-axis reflections by the narrow-beam antenna severely, limit the received satellite signal.

3.2.2 Comparisons Between K-band and Lower Bands

The 1%, 5%, and 10% fade exceedance levels arc helpful in facilitating comparisons with other measurement campaigns in different locations and at different frequencies. As point ed out in [1 1], the absence of standard definitions for various environment al categories makes the reporting of the results and comparison of the results with other measurement campaigns problematic even when the environments for different experiments arc classified in the same general categories. However, some general conclusions may be drawn from the data. Tables 3 to 6 summarize the most similar conditions from other land-mobile experiments reported.

The L-band experiments reported in [7] show that for constant environment, tile fade exceedance levels increase as the antenna beam pattern narrows while the experiments reported in [11] show that for constant environment, the fade exceedance levels increase as frequency increases. 'J'bus, as expected, the fade exceedance levels for the narrow-beam, K-band AMT experiments show deeper 1 % percent fade exceedance levels than the corresponding L-band experiments. While the 1 % fade exceedance levels for the AMT experiments are greater, most of the 1 0%, levels arc lower. This shows that the time-share Characteristic of the fading process is much more pronounced for the AMT experiments. The increased effect is due to the combination of the narrow beam antenna and the severe shadowing caused by foliage at K-band.

The AMT results are quite similar to the K-band results reported in [12] which arc summarized

Table 3: Fade Exceedance Results from [7] for L-band with 51° Elevation Angle and Two Receive Antenna Gain Patterns: omni-azimuth/55° °-elevation for Runs 322,343.359 and 45°-azimuth/45°-elevation for Runs 406,409.

	CAT.	1% FADE LEVEL (dB)	5 '70 FADE LEVEL (dB)	10 % FADE LEVEL (dB)
Run 322	II	10.0	3.0	1.0
Run 343	III	> 15.0	> 15.0	14.0
Run 359	II	10.2	5.5	2.5
Run 406	11	16.5	10.5	7.5
Run 409	II	24.2	15.0	12.0

Table 4: Fade Exceedance Results from [10] for L-band with 43° Elevation Angle and Hemispherical Receive Antenna Gain Pattern.

	CAT.	1% FADE LEVEL (dB)	5 % FADE LEVEL (dB)	10 % FADE LEVEL (dB)
City	III	27.5	23.0	21.0
Highway	I	3.5	2.0	1.5

Table 5: Fade Exceedance Results from [1 1] for L-, S-, and Ku- bands with 60° Elevation Angle and 640-azimuth/640-elevation for L- and S-band Receive Antennas; 80°- azimuth/80°-elevation for Ku-band Receive Antenna.

	CAT.	1 % FADE LEVEL (dB)	5 % FADE LEVEL (dB)	1070 FADE LEVEL (dB)
L-band	11"	16.5	8.0	5.0
S-band	11	18.5	9.0	6.0
Ku-band	11	27.5	19.5	13.0

Table 6: Fade Exceedance Results from [12] for K-band with 55° Elevation Angle in 'Texas and 55° Elevation Angle in Maryland; 27° Beamwidth Receive Antenna.

	CAT.	1% FADE LEVEL (dB)	5 % FADE LEVEL (dB)	10 % FADE LEVEL (dB)
Bastrop, TX	111	28.0	20.0	15:0
Austin, 1X	III	32.0	24.0	21.0
Austin, TX	II	15.0	9.0	7.0
Rt.108, MD	111	24.0	15.0	11.0
RT.295, MD	11	14.0	2.5	2.0

in Table 6. The small differences are primarily due to the different environments. Compared to the experiments conducted in Texas, the AMT experiments were performed using a receive antenna with a narrower beam-width at a lower elevation angle. This combination produced slightly deeper fade exceedance levels for what appear to be roughly similar environments.

4 Summary

The results of the ACTS Mobile Terminal Propagation campaign indicate that the 1 % facie exceedance levels at K-band are much higher than those at 1,-band while the 10% fade exceedance levels at K-band are lower. This behavior shows that the mobile K-band channel is more likely to be extremely "good" or extremely "bad" than somewhere in between. The characteristics of the cumulative fade distribution are strongly dependent on environment even which lane the vehicle is in. The extremes seem to be much more severe at K-band than what has been reported at L-band. This is due to the increased sensitivity of the AMT K-band system to the time share nature of' the multipath and shadowing contributions to the fading process.

The results indicate that K-band pilot tones experience significant multipath and fading effects. It Inay be possible to design link margins to provide reliable service for the lightly shadowed suburban environment at K-band. However, for areas with moderate and heavy shadowing, the link margin required to realize reliable communications with 99% availability is excessive (26 dB for moderate shadowing, and greater then 30 dB for heavy shadowing). An alternate approach would be to use shadowing/fading countermeasures (e.g., interleaved error control coding and antenna diversity). Such mitigation techniques, necessary for reliable K-band mobile communication within a suburban (ill\'il'C)lllllClll~, are currently being considered within the NASA program.

Acknowledgments

The research described in this paper was completed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors are grateful to Mr. Jim Mosa, Forestry Inspection Foreman for the City of Pasadena, and Mr. Steve Jessup, C.G.C.S. Brookside Golf Course, for their assistance in identifying foliage along the experiment routes.

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