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US WP-8D-14 (Rev 6)
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UNITED STATES OF AMERICA

IMPACT OF PROPAGATION IMPAIRMENTS ON THE DESIGN OF LEO MOBILE SATELLITE SYSTEMS PROVIDING PERSONAL COMMUNICATION SERVICES

1.0 INTRODUCTION

An optimally designed personal low-earth-orbit (LEO) mobile satellite communication system (MSS) delivers the best performance at the lowest cost. The successful design procedure has to consider time and frequency domain variations imposed upon the signal by propagation characteristics of the operating environment. Therefore, a thorough knowledge of propagation effects is required before they can be either mitigated or exploited in system design. This paper discusses findings of a series of propagation measurements performed from aircraft in simulation of LEO personal mobile satellite communication signal paths. The effect of propagation characteristics as well as the potential risks of not providing for adequate mitigation of anticipated propagation impairments is also discussed.

2.0 SYSTEM DESIGN CONSIDERATIONS

In designing a global digital non-geostationary satellite telecommunication system, a key parameter is system capacity. A second and equally significant parameter is system implementation cost. These key parameters are bounded by certain constraints that ultimately determine system viability. Some of these are RF bandwidth (a regulated allocation), launch vehicle throw weight capability vs. satellite weight (determines system deployment cost), personal communication terminal transmitter power (a regulated biological hazard limit), and communication channel impairments (determine service level and service quality).

As the boundaries of spectrum allocations are inflexible for the system designer, the key choices are satellite constellation design, communication signal format and transmitted signal power. Constellation design will determine earth coverage for subscriber service and influence other system choices. Transmitted power will determine communication quality, and is significant in its effect on satellite weight. The choice of signal format will strongly influence the efficiency of the allocated band usage, or in other words, capacity for individual communication channels. It also affects required transmitter power.

The choice of signal format can be characterized into several types, namely Narrow-band (e.g., FDMA), Wide-band (e.g., CDMA or TDMA) or combinations of these types. While each of the formats has its theoretical advantages, the realities of propagation impairments affect any of the choices in systems designed for efficient use of resources and allocations. Advantages that accrue theoretically may be unrealizable due to presence of certain impairments. The system design trade-off between transmitted signal power and communication quality is an example where communication channel impairments dominate. Robustness of the signal format therefore is of significant concern.

Terrestrial cellular conditions or solutions are not good models for satellite systems. In conventional cellular systems a subscriber's link usually operates at near 0 degrees elevation angle (elevation angle to the cell tower). Due to blockage by buildings or other structures, propagation therefore exhibits multipath dominance (Rayleigh statistics), as it lacks a dependable line of sight component. Terrestrial systems have options to overcome the attendant limitations by combination of shortened slant range and increased transmitter power. LEO satellite based systems for world-wide PCN service, on the other hand, will generally have a dependable line-of-sight (LOS) component (Rician or Log normal statistics) because elevation angle is not close to 0 degrees and because of LEO satellite relative motion. Exceptions to the general rule may be experienced in urban areas with high-rise structures. Here, blockage, hence absence of a LOS component, could be significant if its duration lasts for multiples of seconds.

Other system considerations affecting choice of signal format, include:

a) power control in both, up and down-link directions,
b) system capacity as affected by impairments and by power control requirement, and
c) acquisition and re-acquisition after link outage.

The satellite system design therefore is forced to look carefully at signal format. In this connection, at 1.6 GHz, the causes of channel fading effects such as tree shadowing, terrain multipath, or human body interference can be significant, i.e., introducing fades of 20 dB or greater.

3.0 PROPAGATION EFFECTS

With little data available for 1.6 GHz LEO propagation, a research program was established to obtain information on conditions that would affect direct line of sight communication. The characteristics of 2 potentially dominant effects were sought - fading and multipath from large structures (delay spread). Previous research [1] showed fading in the band 1610 - 1626.5 MHz to be flat (i.e., non frequency selective). Thus the propagation test signal for evaluation of fading could be a tone and receiver bandwidth < 5 KHz just to accommodate Doppler. Delay spread measurements, however, required a wide-band signal, (20 MHz PRN sequence) in order to permit good resolution (approximately 90 nsec.) of multipath signal returns over a long duration (approximately 20 μsec.). Analysis of data obtained from these tests confirmed that LEO-MSS communication links in this band experienced flat fading. Thus, both narrow and wide-band signal formats should anticipate fade effects uniformly across their operating spectrum in the 1.6 GHz band.

It was also confirmed (as in [1]) that fading in this band will have a burst characteristic, whether clear LOS or shadowed. This primarily is due to satellite motion, height of the PCN terminal above ground, shadowing by trees, user motion and user head or body interference. A system design, when specifying a signal structure and baseband structure, must carefully consider these fading characteristics.

3.1 Clear Line of Sight Fading

The clear line of sight propagation condition for communication can be easily misunderstood. A clear line of sight condition is one where neither natural nor man-made obstacles block the satellite signal.

An implicit but misleading assumption could be that clear line of sight to the satellite implies a very low level of impairment. In fact, a portable communication terminal using this path must contend with two impairment effects which may require additional margin. These two effects are ground reflection and interference by the body. The latter can also be described as head blockage or head interference when the personal communication terminal with integral antenna is used in telephone hand-set fashion.

In measuring fade data to characterize body or head interference effects it is difficult to separate the latter from ground reflection effects. However, it is adequate to quantify their combined effect, as in application both will be present simultaneously. Figure 1, showing cumulative statistics derived from the time domain fading process, depicts examples of these impairment conditions for various elevation angle ranges under clear line of sight conditions. Such impairment data was recorded on the ground during numerous data collection campaigns where the transmitter was located aboard an aircraft making simulated spacecraft fly-by's.

Clearly, a lower elevation angle geometry introduces more pronounced impairments. This was noted repeatedly during numerous observations. For arbitrary aspect angles of the source, the probability is relatively higher that the head will partially shadow either the antenna's direct line of sight or the ground multipath direction. This is true even where the antenna installation permits partial clearance above the head. For collection of data depicted in Figures 1 and 2 the antenna extension above the head was 2 inches. Figure 1 depicts two other elevation angle ranges, 13-27 degrees (intermediate) and 27-46 degrees (high). While the fade statistics in these elevation angle ranges do not differ significantly in the latter two ranges, there is a significant difference when comparing the data for low elevation angle, 8 degrees. This suggests that the influence of elevation angle in fading is most noticeable below a certain threshold, viz., 13 to 15 degrees.

Fading is a time domain process which affects both the amplitude and phase of the signal. Fading maximum rate of change, also referred to as fading bandwidth, is determined by the varying geometry between the two communication end points and also by object types which give rise to fades, e.g., trees, buildings, hills, etc. For example, where one end point is a LEO satellite and the other a stationary Personal Communication Network (PCN) terminal, the fade

bandwidth will be low and controlled by the relative motion of the satellite. Alternatively, where the two points are a mobile PCN terminal communicating with a LEO satellite, the fade bandwidth will be relatively high and controlled primarily by mobile terminal speed. Examination of a wide variety of data has shown that fade bandwidth varies between 20 Hz and 200 Hz. The higher values of fade bandwidth will affect receiver acquisition design and the design of systems with dependency on power control.

Referring to Figure 1, in the two higher elevation angle ranges, the fading effect is suppressed but is still not eliminated and it may be noted that the 90th percentile of fades (i.e., only 10% of the fades are expected to be higher), under clear line of sight conditions is 6.5 dB. At the low elevation angle, 8 degrees, the 90% fade level is 12 dB. System designs that do not recognize the need for margin to compensate for these conditions cannot be expected to deliver a high quality level of voice communication even in clear line of sight conditions.

3.2 Impairment Due to Shadowing by Trees

Reference is made to Figure 2, showing the effect for two different elevation angle ranges, 15-23 degrees and 25-85 degrees. The conditions are classified as "heavy shadowing" as the propagation line of sight was through heavily foliated trees with large canopies. A ground reflection or specular component is also present but is suppressed because its direction also implies tree penetration. Here, as indicated in the figure, the 90th percentile of fades is 13.5 dB and poses a significant challenge to satellite based PCN system design in the 1.6 GHz band. There is little difference in fade impairments between intermediate and high elevation angle ranges. This data characteristic was noted in the clear LOS data of figure 1 and also suggests that the shadowing effect, rather than elevation, dominates. For low elevation angle propagation in a tree shadowed scenario the 90th percentile of fades can be expected to exceed the above 13.5 dB value significantly.

3.3 Effects due to Multipath from Structures

Where tall structures are present, as in suburban or urban environments, two additional signal impairment effects are possible -

a) almost total blockage of the direct LOS signal component, and;

b) multipath (other than ground specular) from large structures e.g., buildings or water towers relative to the direct LOS signals.

In personal satellite communications, multipath, if present at a significant power level, is potentially serious if it is long delay multipath. The implication would be that fading may be frequency selective and that equalizers may be required in a receiver design. The effect is significantly different from that in terrestrial cellular or terrestrial trunk communication systems, where both have been designed to overcome this impairment by use of high transmitted power in relation to slant range. In satellite based systems, this solution is not viable due to high cost.

There is very little quantitative data on multipath for the geometry of satellite transmission paths. Therefore, a series of wide band measurements were conducted in downtown Chicago and the surrounding environment. Multipath information was derived from 20 MHz pseudo-random noise (PRN) sequence modulated transmissions from an aircraft at 11,500 ft. altitude. The ground receiver was synchronized to the PRN sequence and positioned at various representative distances from buildings. Again, flight paths were planned to simulate satellite passes and elevation angles.

A typical example of the results is depicted in Figure 3. This figure plots probability density contours for received multipath (MP) power relative to the direct signal power as a function of multipath delay. It is shown that Prob{MP Power > -27 dB | 2 μsec.} = 0.3%. Two μsec is used as a fiducial threshold for symbol rates near 200 Kbps. Longer delays could introduce inter-symbol interference. Shorter delays, if significant in relative power, would show a flat fading effect and thus could be compensated by link margin. Figure 3 shows that a higher threshold of -12 dB does not introduce delays exceeding 0.25 μsec.

Figure 4 depicts the delay effect in terms of percentile significance. For example, the curve labeled "1" represents 99% of the measured values, i.e., only 1% of the measured values exceed the limits depicted by the curve. Now, referring to the 0.2 percentile curve, it may be noted that delays of 2 μsec or longer are suppressed by 25 dB or more for 99.8% of measured values.

The multipath returns recorded in these measurements all have either a low power level or a very low probability level, or both, compared to that of the LOS component. Thus, structure induced multipath will not be deleterious in LOS communication. Furthermore, the conclusion may be drawn from these data that fading in the band will be flat (non frequency selective) and that receiver equalization should not be a requirement in systems with LOS communication links.As a consequence there seems to be no advantage among candidate signal modulation formats or bandwidths aimed at improving performance in the presence of long delay multipath impairments.

4.0 IMPACT ON SYSTEM DESIGN

Section 3 describes the pertinent propagation effects and shows that fading will be important. A well designed LEO satellite, PCN system must include provisions to mitigate communication channel fading before quality voice service can be offered. As introduced in Section 2, two of the key design choices are: signal format and transmitter power. The latter determines how much link margin will be available to offset deep fading and its adequacy is of paramount importance if voice quality is to be maintained even under nominally simple conditions of clear line of sight communication.

Fading is a time domain process with bandwidths up to 200 Hz [1] as a result of which channel quality can change many times during the course of an average spoken sentence, i.e., 5 to 10 seconds. With digital speech communication (the only practical method for introducing error protection), voice is segmented into vocoded frames. Research has shown [3] that a given frame error rate is more readily tolerated than the same rate of channel bit errors. That is, burst errors in a vocoded channel cause less voice quality degradation than an equal but uniformly distributed rate of errors. Since the statistics of either shadowed or clear line of sight channels principally are burst fades, the communication quality of a system design would be enhanced if it exploits this property. Methods available to accomplish such exploitation include vocoder (with associated error protection) design and choice of signal format.

4.1 Performance in a Vocoded Narrow-band Channel

Using the propagation data as described in section 3, the performance capability of narrow-band, TDMA burst communication was evaluated. The burst format implemented time compression by a factor of 11 in forming 8 msec transmission packets to communicate each 90 msec of vocoded data. It is believed that such time compression may help to improve communication quality in channels with burst fading. Results of the evaluation are illustrated in Figure 5 which summarizes link margin requirements for acceptable quality of vocoded voice communication. Impairments in this graph are characterized by the 90 percentile dB fade level, a level taken from graphs such as those in Figures 1 and 2. The impairments include either tree shadowed or clear line of sight conditions. Figure 5 depicts a form of signaling robustness. That is, in an environment where 90% of the fades are below a specific level and in a link with a defined BER, the vocoder-required margin for quality voice communication is significantly less than the maximum fade depth. For example, 8 dB of link margin will accommodate a link where 90% of the fades are less than 10 dB. Acceptable quality of vocoded voice communication has been determined, using simulation techniques, as equal to at least 90% of the vocoder's ideal-channel quality score (e.g., MOS value).

The link margin values in Figure 5 are dB values in excess of that Eb/No which would be required to maintain a given BER for QPSK signaling in a static Gaussian channel. This was determined by application of channel fade measurements to a vocoded voice link with selective, rate 2/3 coding. The vocoder used in this determination was VSELP 4800. A well designed vocoder/error protection scheme will permit quality communication in a 1% BER channel. In Figure 5 the 1% BER line is the least mean square error, linear fit of the data values. It is possible, by theoretical means, to project required performance capability for higher percent BER conditions and these are also depicted in the figure. Specifically, referring to a standard BER curve [2] for QPSK signaling, the increase from 1% to 5% BER is equivalent to a decrease of signal power by 3 dB. Therefore, to maintain constant voice quality at a given fade level the link margin must increase in proportion to the BER increase. This condition applies also to non-Gaussian faded channels. In general, communication channel induced fade levels exceeding the 1% to 3% BER conditions introduce a requirement for additional

vocoder data protection. The most efficient way this can be achieved is by excess link margin.

4.2 Link Margin

LEO satellite based PCN systems may have to contend with low elevation angle scenarios. Figure 1 shows an expected low elevation angle fade profile (8 degrees elevation) for clear line of sight. The value not exceeded by 90% of the fades is 12 dB. Now, referring to Figure 5, a 12 dB value in a link with a static BER of 1% requires at least 10 dB of link margin in order to provide quality voice communication even under this seemingly favorable, clear line-of-sight condition.

Even in the higher elevation angle range of 13-27 degrees and clear line-of-sight, the 90 percentile fade depth is 6.5 dB. This still suggests a channel with significant impairment and, as Figure 5 implies, there will be a need for at least 4.5 dB of link margin in a channel with static BER of 1%.

In more difficult scenarios where heavy tree shadowing is encountered (see Figure 2) the 90 percentile fade value increases to 13.5 dB for elevation angles between 15 and 85 degrees. In referring this value to the chart in Figure 5, it may be concluded that at least 12 dB of link margin will be required for quality voice communication where the channel design is based on a static 1% BER.

4.3 Deep Fades

The consequence of a deep, protracted fade, e.g., 1 sec or longer, is a re-acquisition of the communications signal as soon as possible after the fade. This requirement is fundamental irrespective of which communication format is being utilized. A temporary signal loss due to a deep fade could result from either severe shadowing or signal blockage and the signal format should be designed to minimize the effect. Initial acquisition or re-acquisition in a digital channel generally requires the transmission of a preamble and/or frame synchronization code. These two components are usually included in TDMA formats as integral elements of each frame (or packet) and similar provisions would have to be integrated into other signal schemes. In a channel-dedicated scheme an individual subscriber would be assigned to occupy a channel continuously for the duration of his communication. In these schemes measures such as the use of

stable clocks to allow signals to flywheel through outages of short duration and periodic re-transmission of carrier and clock recovery sequences to allow rapid re-acquisition in the case of fades of longer duration could be employed.

5.0 SUMMARY

This paper has described the results of special tests to quantify propagation impairments in LEO-MSS signal paths at L-band. The paper also shows how the nature of these impairments can be accommodated in the design of LEO-MSS/PCN systems. Key findings regarding propagation effects in these LEO satellite paths are:

a) The temporally dynamic nature of received signal levels which is due to satellite motion, PCN subscriber terminal usage, and physical environment.

b) The presence of significant and time-varying fading under clear line-of-sight conditions between LEO satellite and PCN terminal. This fading is caused by ground specular reflection in the subscriber's vicinity and interference or shadowing introduced by the subscriber's head and body.

c) The existence of significant fades in propagation paths that are shadowed by trees.

d) The fact that non frequency selective (flat) fading was observed and that its affect must be overcome with link margin if quality communication is to be sustained.

e) The fact that urban or suburban structure induced multipath reflections with long delay are low in power relative to the LOS component and are statistically infrequent in occurrence.

The characteristics of these LEO propagation impairments are different than those encountered in terrestrial PCN system service. Moreover, where they are somewhat similar, some system solutions used in terrestrial mobile communications, such as increased transmitter power or decreased slant range, are not appropriate for cost-effective LEO satellite system implementation. It has also been shown in this paper that channel and modulation characteristics can

be important factors in LEO-MSS/PCN system design to overcome propagation impairments in a cost-effective manner.

The paper has also shown that link margin of at least 12 dB is necessary for quality communication under a broad array of possible propagation conditions with a direct line of sight to the LEO spacecraft. It has shown furthermore that a narrow-band FDMA/TDMA signal format can overcome the observed propagation impairments of LEO channels in the 1.6 GHz band.

References:

[1] Goldhirsh, J. and W. J. Vogel, "Propagation Effects for Land Mobile Satellite Systems: Overview of Experimental and Modeling Results," NASA Reference Publication 1274, February 1992

[2] Spilker, J. J., "Digital Communication by Satellite," Prentice-Hall, Inc. 1977, (page 324)

[3] This finding is based on VSELP vocoder research and development for vocoders in real operating environments. The vocoded bits are error protected with rate 2/3 equivalent codes.

Figure 1
Fading for Different Elevation Angles
Clear Line of Sight with Head Blockage

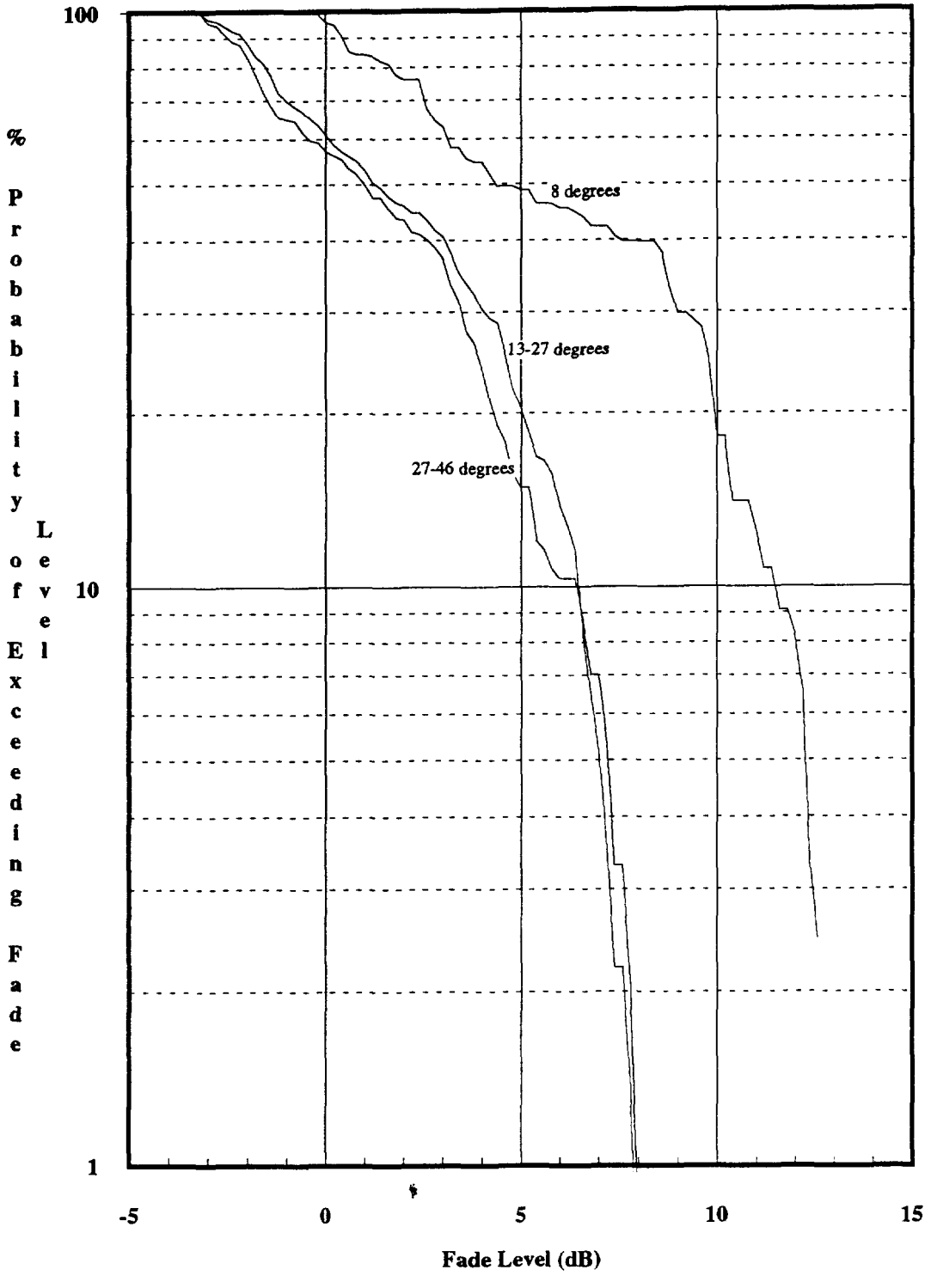


Figure 2
Fading for Different Elevation Angles
Heavy Shadowing With Head Blockage

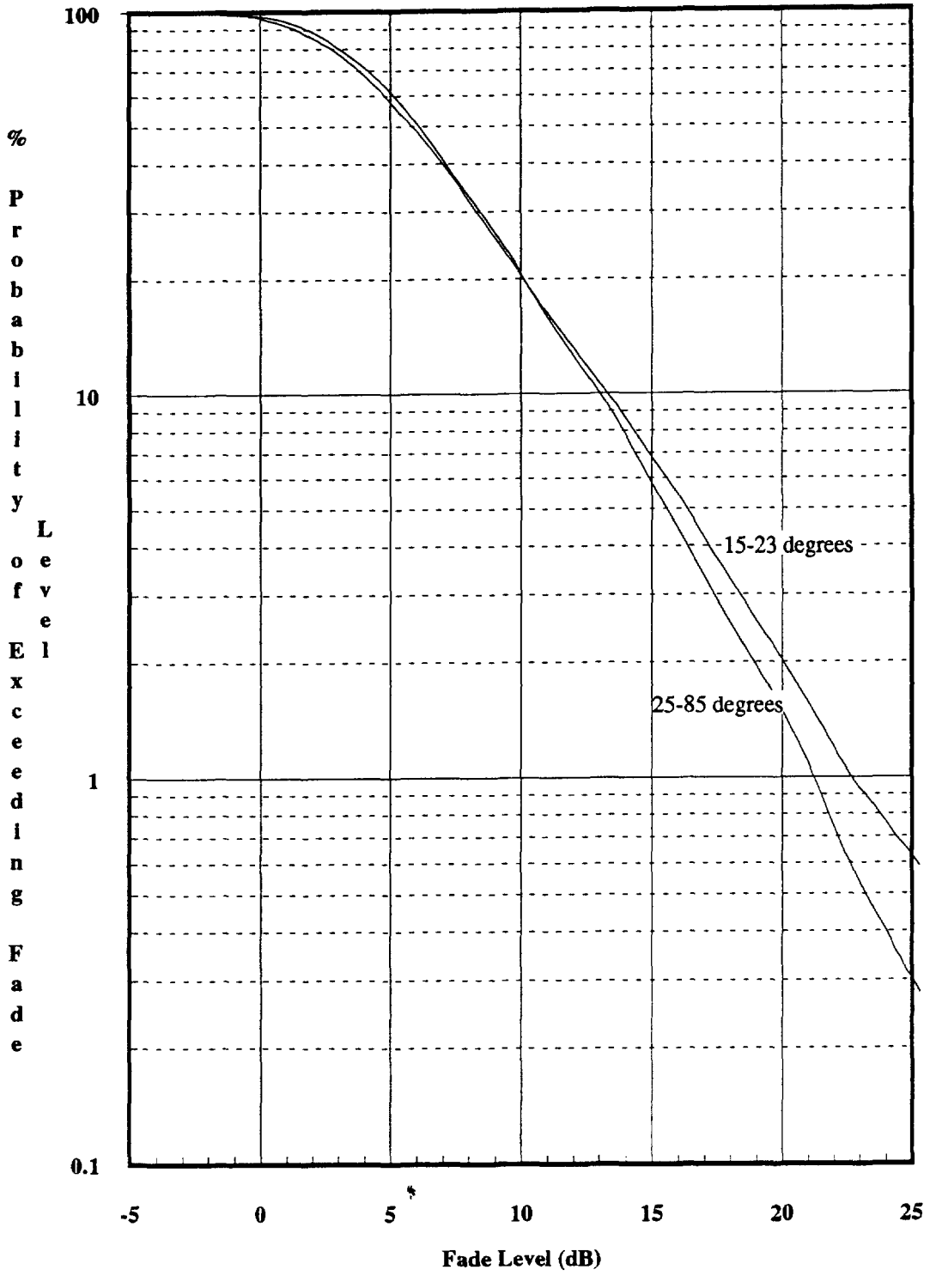


Figure 3
PROB{ Delay Relative Power > Threshold | Delay }
Chicago Data, 5-8 September 1991

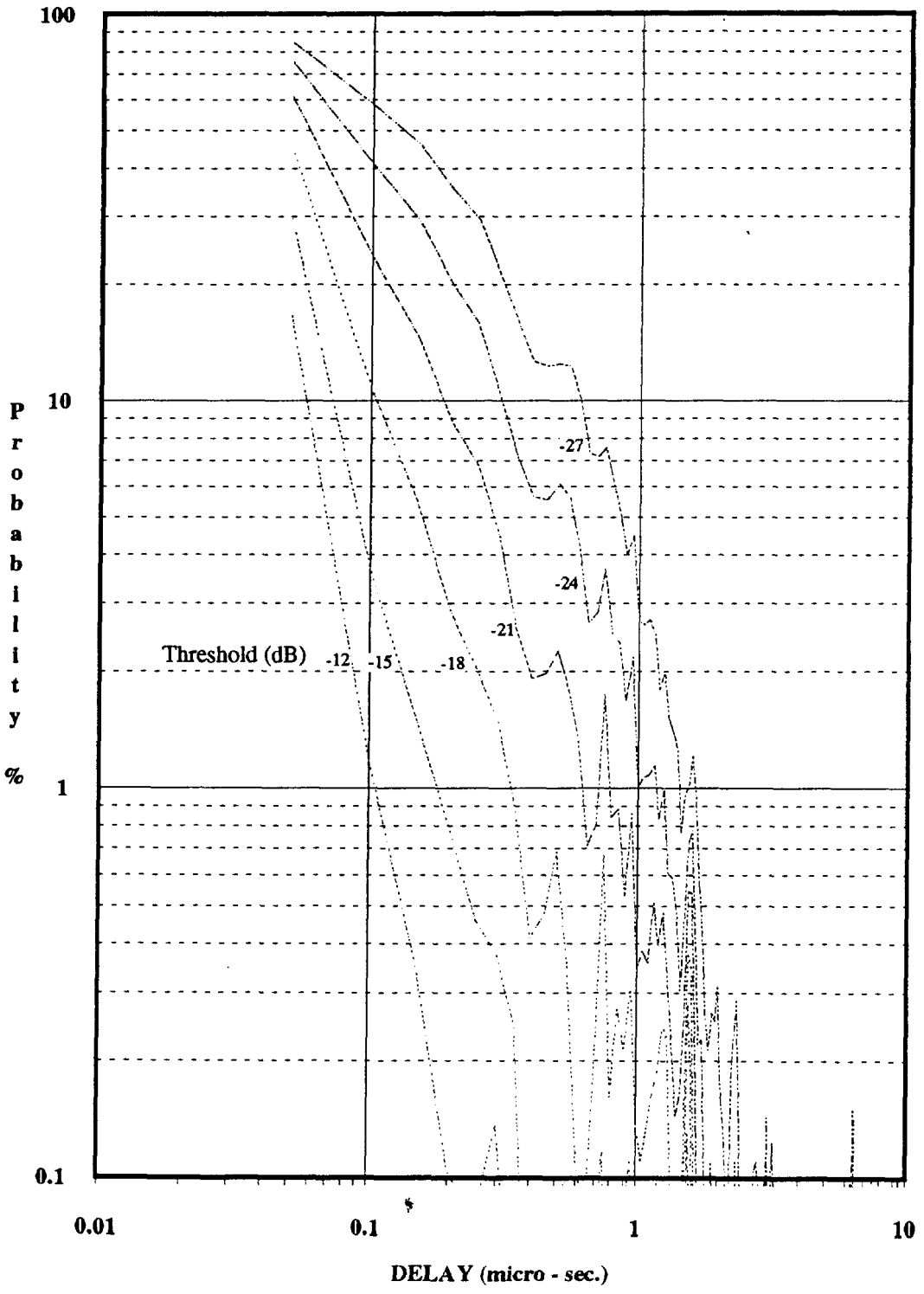


Figure 4
DELAY SPREAD PROBABILITY CONTOURS
Chicago Data, 5-8 September 1991

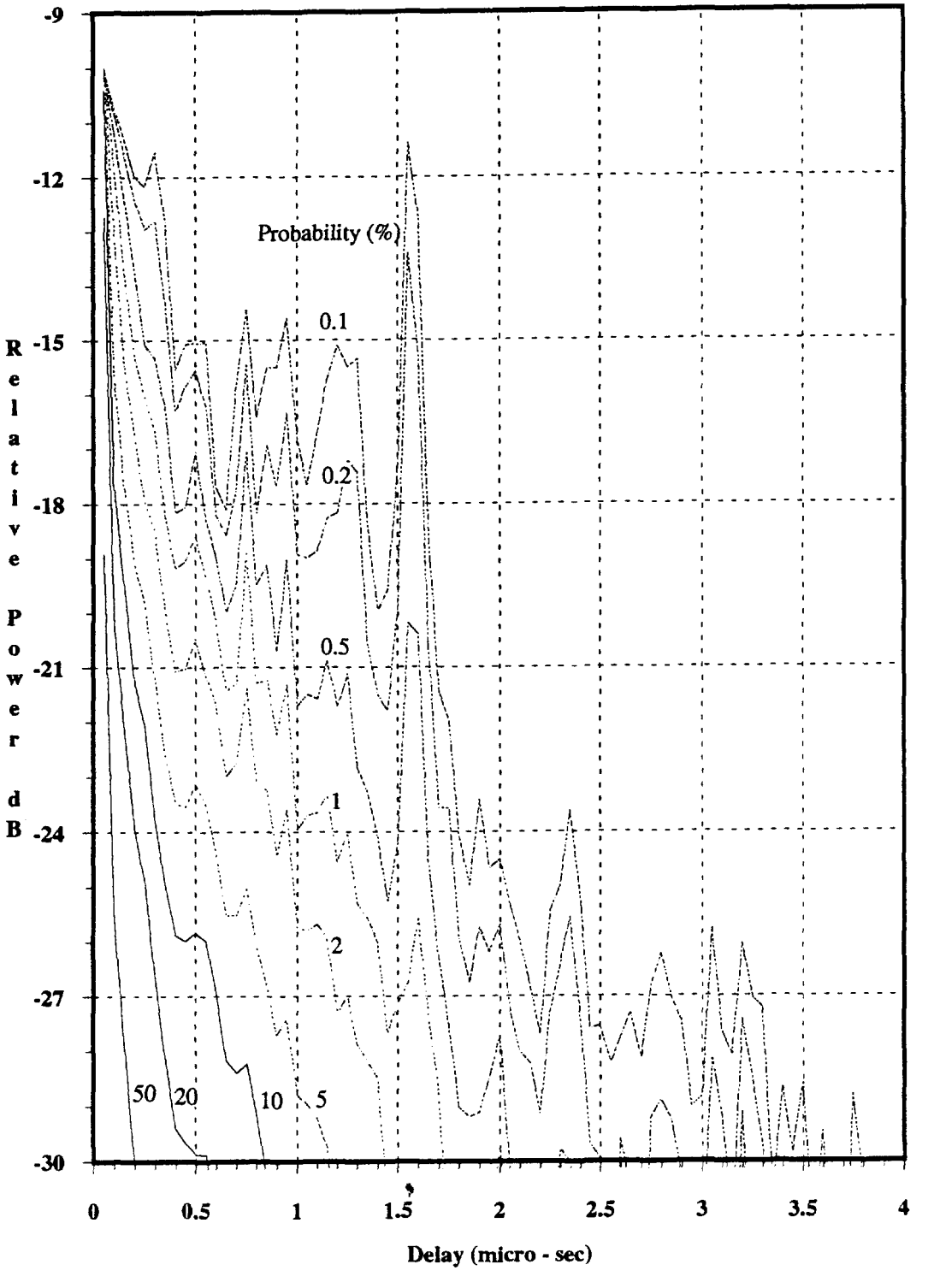
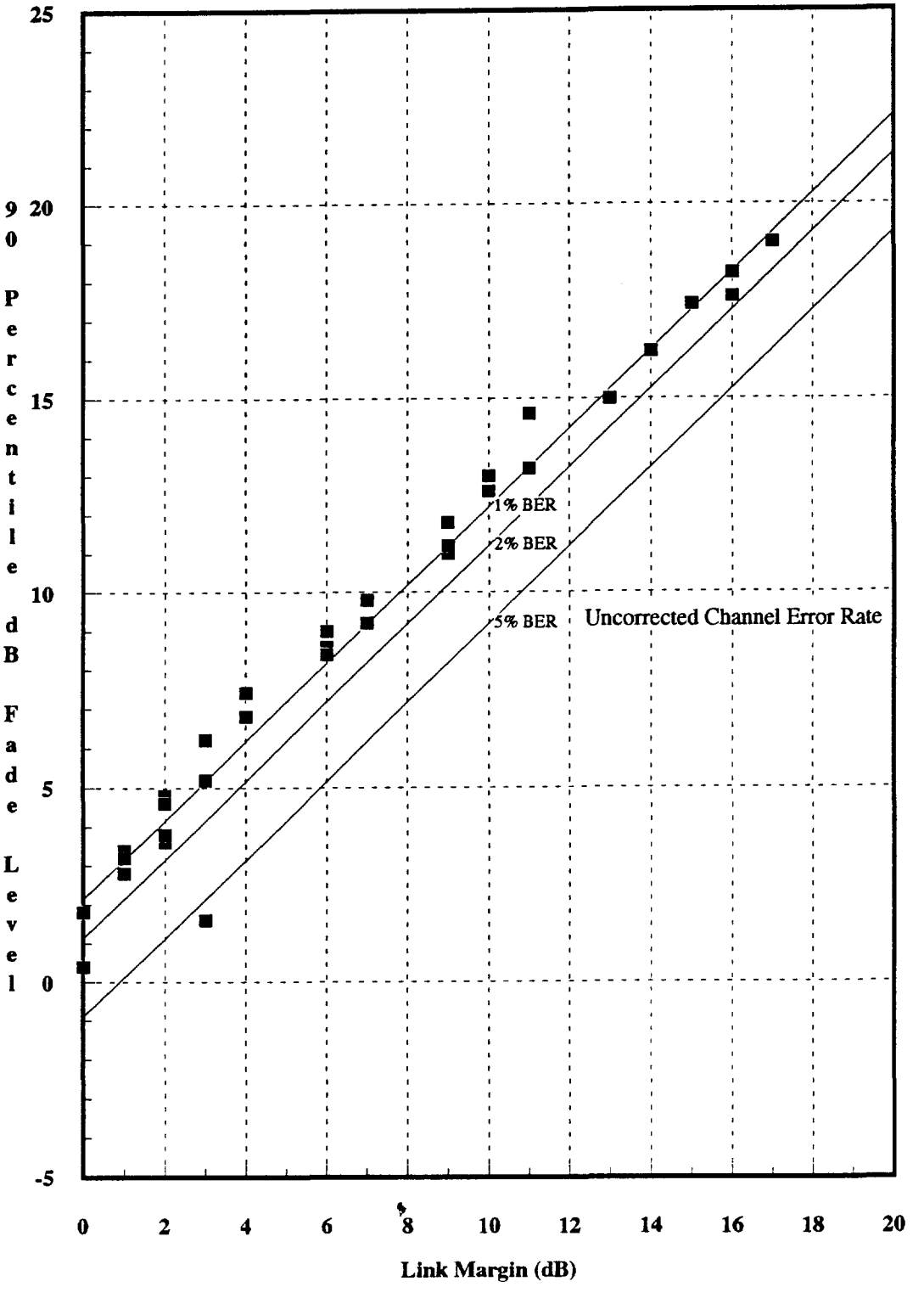


Figure 5
Link Margin Required for Acceptable Voice Quality



APPENDIX 2

JANSKY/BARMAT TELECOMMUNICATIONS, INC.
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December 11, 1992

To: Jim Vorhies
Tom Sullivan
Ming Louie
Ron Lepkowski
Harry Ng

From: Mel Barmat

Subject: USA 8D-36 (Rev. 2)

The subject of methodology to evaluate the potential for interference of space-to-Earth transmissions in the 1613.8 to 1626.5 MHz band is probably desirable as an information paper in the CCIR forum. It is obviously inappropriate to propose a sharing criteria for a secondary service. However, the subject includes complex technical and regulatory issues and must not be addressed in a piecemeal and incomplete manner, lest those not in the middle of the activities in the field be misled.

While the currently proposed paper (USA 8D/36 Rev. 2) is a useful first draft to bring forward comments, it is very far from the stage where is should go forward to the international community with the imperatur of U.S. industry and the U.S. government. Below are a few reasons I believe the current paper is not ready for national and international release.

1. The paper has undergone major changes in content and direction in each of two versions in only a few days, making adequate review unlikely. In colloquial words, this paper has been a "moving target" and would probably continue to be.

2. The paper establishes a rigid and invalid criterion, that is, the secondary downlink source of interference must produce less harm than the primary uplink transmitters of the same network. I know of no basis in the Radio Regulations or in logic for such a criterion. If there is any such requirement in Radio Regulations, it should be cited. In terms of logic, one need only consider the case where the aggregate uplink e.i.r.p. of a network absorbs 1% of the interference tolerance of a satellite receiver. If the secondary downlink were to cause <u>two times</u> the interference of the uplink, the effect of transmissions in both directions would absorb 3% of the

interference tolerance of the satellite receiver. Thus, the result would almost surely be acceptable.

3. Critical definitions for equations are incomplete and inexact, e.g.,

a) Eup is defined as the "e.i.r.p. (dBW) per transmitting earth station ...". However, in a mobile environment, the power controlled uplink e.i.r.p. will vary among the stations in the network, depending on location in the satellite beam, foliage shadowing, etc. Moreover, for those stations operating with higher instantaneous e.i.r.p. because of foliage shadowing in the line-of-sight to the desired satellite, it can not be known whether the line-of-sight path to the interfered-with satellite will be shadowed or not. Therefor the definition must indicate an "average e.i.r.p." should be used. Moreover, the paper should discuss how the averaging should be accomplished.

b) Nuser is defined as the "number of uplink transmissions ... in the geographic area covered by the interfered with space station antenna beam". There are two problems with this definition. First, since the uplink transmissions may be discontinuous because of voice activation and/or a TDMA system, the definition needs to be modified by the word "simultaneous". Second, defining the area of concern to that "covered by the ... beam" is by far too vague. The area should be defined by a specific contour of the beam or beams and more importantly, the calculation should include a factor to consider the distribution of uplink transmitters in relationship to the antenna gain pattern of the satellite.

c. The proposed methodology assumes the antenna of the user terminal has omnidirectional gain - without stating so.

4. The paper does not recognize that the Glonass system has many downlinks in a portion of this band. The interference level of Glonass signals should be addressed in this paper.

The above criticisms of the 8D/36 (Rev. 2) paper are not meant to be all inclusive, they come from only the first two pages of text. Undoubtedly, there are problems throughout the paper. The point I am trying to make is that this is a complex issue and should be dealt with in a thorough, professional manner, representative of the standing of the U.S. in this forum. This paper should not go forward until it is thoroughly reviewed and all technical aspects are deemed valid and complete.

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DEC 15 '92 09:12AM NTIA/OSM/SPAP

UNITED STATES DEPARTMENT OF COMMERCE
National Telecommunications and
Information Administration
Washington, D.C. 20230

December 14, 1992

Warren Richards
Chairman, U.S. CCIR
National Committee
Department of State
Washington D.C. 20520

Dear Warren:

CCIR Working Party 8D will be meeting in Tokyo during January 1993. U.S. Ad Hoc 8D has been preparing contributions for this meeting. All but one of these papers have now been circulated to the National Committee. A final paper has been proposed addressing the issue of interference from a low orbit MSS system operating the "reverse direction" in the "Big LEO" band at 1610-1626.5 MHz. WARC-92 made a downlink allocation in this band on a secondary basis. Motorola is proposing to make use of this allocation in its system.

Motorola has objected to the paper because of its technical deficiencies as well as their view that it is inappropriate for CCIR to set criteria for secondary sharing cases. It was agreed at our last meeting of U.S. WP 8D, that notwithstanding the objections of Motorola to having such a paper, that the questions raised are of a policy nature that need to be resolved by the National Committee. The paper has been redrafted to remove some of the more controversial aspects since the 8D meeting.

My view is that the paper should not be submitted at this time because of the number of substantial technical issues which have not been resolved; the fact that this paper is already the subject of debate in the FCC "Big LEO" rulemaking; that we have little of consequence to say on this subject at this time; and that the paper raises questions that we are not prepared to address at the Tokyo meeting. Essentially we would have a contribution that cannot be advanced at this meeting and the paper will expose domestic disputes in an international forum. I believe that this paper will not be helpful to U.S. objectives at the Tokyo meeting.

Sincerely,

Jim Vorhies
Convener, U.S. 8D

Attachments
U.S. CCIR 8D/36 Rev 3
Memorandum from Leslie Taylor
Memorandum from Don Jansky