Table 2.2-2: Crane Rain Analysis - Rain Zone D3 (Memphis, TN)

Memphis, TN Rain Attenuation (dB)		Frequency			
		29 GHz	42 GHz	44.5 GHz	49.5 GHz
Elevation Angle	20.0°	42.60	69.06	73.40	81.43
	30.0°	31.90	51.34	54.51	60.33
	40.0°	25.59	41.12	43.65	48.29
	3.2 km LMDS Cell	13.4 dB	22.3 dB		

Earth Station Latitude = 35.0°
Height Above Sea Level = 0.06 km
Availability = 99.9%
Polarization Tilt Angle = 0°

Table 2.2-3: Crane Rain Analysis - Rain Zone E (Miami, FL)

Miami, FL Rain Attenuation (dB)		Frequency			
		29 GHz	42 GHz	44.5 GHz	49.5 GHz
Elevation Angle	20.0°	67.65	106.51	112.65	123.92
	30.0°	53.43	83.20	87.84	96.28
	40.0°	44.44	68.89	72.69	79.55
	2.0 km LMDS Cell	13.5 dB	21.5 dB		

Earth Station Latitude = 25.9°
Height Above Sea Level = 0.0 km
Availability = 99.9%
Polarization Tilt Angle = 0°

3.0 LMDS System Feasibility Above 40 GHz

The following information addresses the suitability of 40.5-42.5 GHz for future LMDS operation and examines the technical and financial feasibility for such operation. NASA has examined the propagation environment, frequency dependent equipment components, equipment availability and cost impact of providing LMDS services at 41 GHz vis-a-vis 28 GHz. The following shows that future LMDS service requirements can be accommodated in a cost effective and timely manner.

3.1 41 GHz Propagation Environment

Several factors must be considered when examining the propagation environment that would effect LMDS system operations at any frequency. These include attenuation due to rain, gaseous attenuation caused by oxygen molecules and water vapor in the air, foliage attenuation, and reflective and diffractive properties of buildings, etc. in the path of radio signals. Each of these are discussed below with comparison made between 28 GHz and 41 GHz.

3.1.1 Rain Effects

For comparative evaluation purposes, the characteristics of the CellularVision system as given during the LMDS/FSS 28 GHz NRMC will be used in the calculations that follow. For service in rain zone D2, a 4.8 km cell radius was proposed. A 13 dB rain margin is needed to achieve 99.9% availability. For the 4.8 km radius cell, 13 dB margin translates to 2.7 dB/km (13 dB/4.8 km = 2.7 dB/km). Using eq 1 from CCIR Report 721-2:

$$V_R = kR^{\alpha} \qquad (1)$$

Where:

V_R	Attenuation
R	Rain Rate (mm/hr)
k,α	Regression coefficients used in estimating specific attenuation

Horizontally polarized signals represent the worst case due to flattening of the rain droplets as they fall through the atmosphere. Regression coefficients, k and α, can then be interpolated using Table 6.3-3 (see attached) from the NASA Propagation Handbook.[6]

Freq.	k	α
28.5	0.1666	1.032
41.5	0.3765	0.9282

Using eq 1 with the regression coefficients shown in the table above for 28.5 GHz, we find that an attenuation of 2.7 km/hr corresponds to a rain rate of 14.5 mm/hr. Then from Table 6.3-1 (see attached) of the NASA Propagation Handbook, for rain zone D2, a point rain rate of 14.5 mm/hr corresponds to 99.9% availability.

At 41.5 GHz the rain margin can be increased by 3 dB, to 16 dB, due to a 3 dB increase in hub antenna gain over 28.5 GHz. (Appendix A demonstrates how LMDS hub antennas at 41 GHz can provide 3 dB gain over 28 GHz hub antennas and provide satisfactory coverage to the same size cell as 28 GHz LMDS hubs.) For the same 4.8 km cell radius, 16 dB rain margin corresponds to 3.33 dB/km available margin. Again using eq 1 and the regression coefficients for 41.5 GHz, 3.33 dB/km attenuation occurs for a rain rate of 10.5 mm/hr. Interpolating from Table 6.3-1, in rain zone D2, a rain rate of 10.5 mm/hr results in 99.84% availability.

It is therefore shown that in spite of increased attenuation due to rain when going from 28 GHz to 41 GHz, nearly identical availability can be achieved over the exact same size LMDS cell. Similar results can be shown when examining operation in other rain zones exhibiting higher point rain rates than rain zone D2.

Table 6.3-1 shows that for 99.9% availability in rain zone D3 (Memphis TN), the rain rate, R, is 22 mm/hr. Using R = 22 mm/hr in eq 1 and the regression coefficients in the table above, the attenuation is calculated to be 4.05 dB/km. A 13 dB rain margin at 28 GHz would result in a cell radius of 3.2 km (13/4.05) for 99.9% availability in rain zone D3. Assuming the same 3.2 km cell size at 41 GHz with an available rain margin of 16 dB as before, results in 5.0 dB/km attenuation. Again using eq 1 to now solve for R, at 41 GHz the corresponding rain rate is:

$$.3765(R)^{.9282} = 5 \text{ dB/km}; \quad R = 16.22 \text{ mm/hr}$$

Table 6.3-1 can then be used to calculate the resultant availability of 99.84%. It can be similarly shown that in rain zone E (Miami, FL), 99.9% availability corresponds to a rain rate of 35 mm/hr resulting in a 2.0 km cell radius for 13 dB margin at 28 GHz. For this same cell

[6] Propagation Effects Handbook for Satellite Systems Design, NASA Reference Publication 1082 (04) February, 1989.

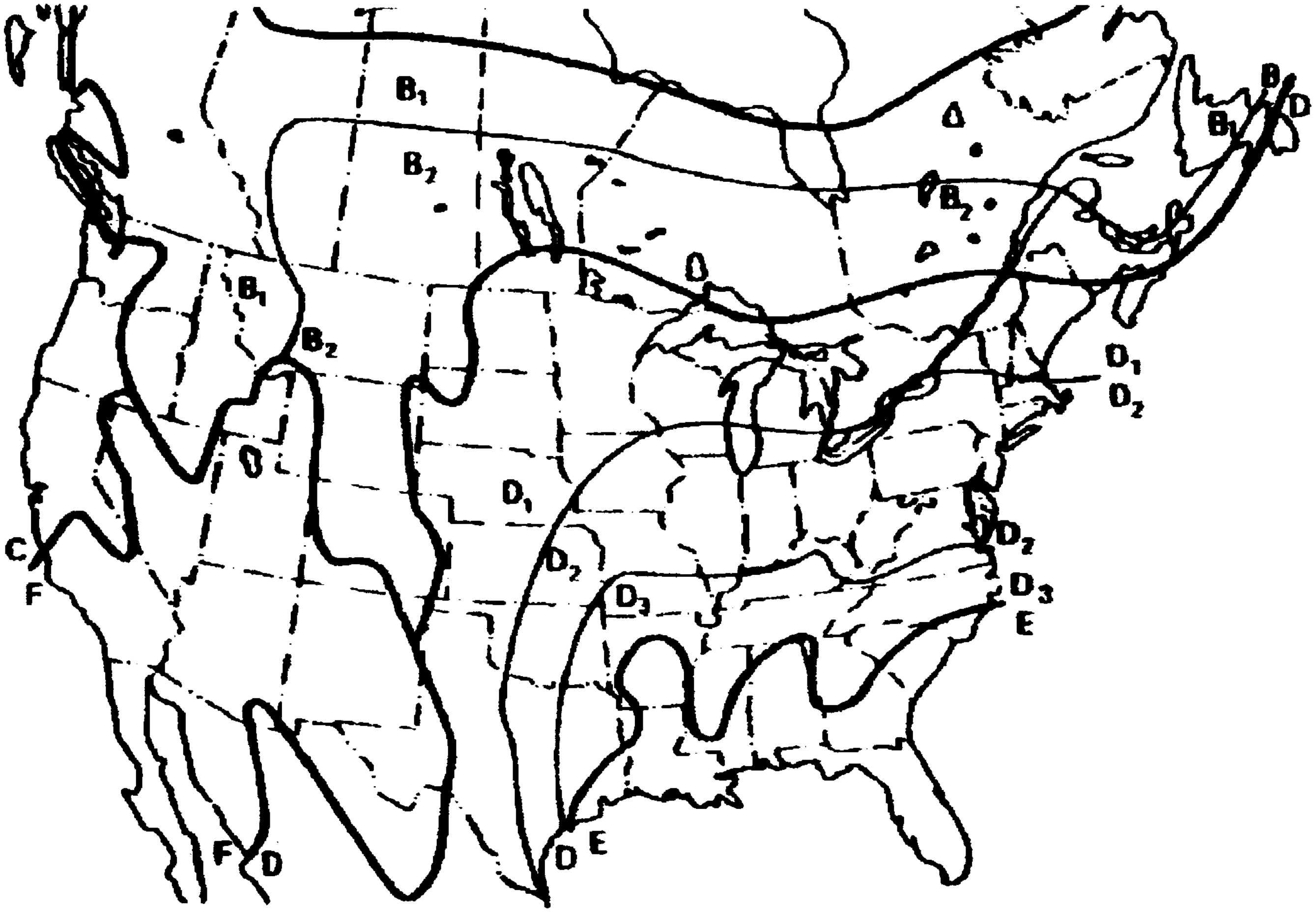

Figure 6.3-2. Rain Rate Climate Regions for the Continental U.S. and Southern Canada

Table 6.3-1. Point Rain Rate Distribution Values (mm/hr) Versus Percent of Year Rain Rate is Exceeded

Percent of Year	RAIN CLIMATE REGION												Minutes per Year	Hours per Year
	A	B_1	B	B_2	C	D_1	$D=D_2$	D_3	E	F	G	H		
0.001	28.5	45	57.5	70	78	90	108	126	165	66	185	253	5.26	0.09
0.002	21	34	44	54	62	72	89	106	144	51	157	220.5	10.5	0.18
0.005	13.5	22	28.5	35	41	50	64.5	80.5	118	34	120.5	178	26.3	0.44
0.01	10.0	15.5	19.5	23.5	28	35.5	49	63	98	23	94	147	52.6	0.88
0.02	7.0	11.0	13.5	16	18	24	35	48	78	15	72	119	105	1.75
0.05	4.0	6.4	8.0	9.5	11	14.5	22	32	52	8.3	47	86.5	263	4.38
0.1	2.5	4.2	5.2	6.1	7.2	9.8	14.5	22	35	5.2	32	64	526	8.77
0.2	1.5	2.8	3.4	4.0	4.8	6.4	9.5	14.5	21	3.1	21.8	43.5	1052	17.5
0.5	0.7	1.5	1.9	2.3	2.7	3.6	5.2	7.8	10.6	1.4	12.2	22.5	2630	43.8
1.0	0.4	1.0	1.3	1.5	1.8	2.2	3.0	4.7	6.0	0.7	8.0	12.0	5260	87.7
2.0	0.1	0.5	0.7	0.8	1.1	1.2	1.5	1.9	2.9	0.2	5.0	5.2	10520	175
5.0	0.0	0.2	0.3	0.3	0.5	0.0	0.0	0.0	0.5	0.0	1.8	1.2	26298	438

Table 6.3-3. Regression Coefficients for Estimating Specific Attenuation in Step 4 of Figure 6.3-6

Frequency (GHz)	k_H	k_V	α_H	α_V
1	0.0000387	0.0000352	0.912	0.880
2	0.000154	0.000138	0.963	0.923
4	0.000650	0.000591	1.12	1.07
6	0.00175	0.00155	1.31	1.27
8	0.00454	0.00395	1.33	1.31
10	0.0101	0.00887	1.28	1.26
12	0.0188	0.0168	1.22	1.20
15	0.0367	0.0347	1.15	1.13
20	0.0751	0.0691	1.10	1.07
25	0.124	0.113	1.06	1.03
30	0.187	0.167	1.02	1.00
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.442	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	0.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.13	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

* Values for k and α at other frequencies can be obtained by interpolation using a logarithmic scale for k and frequency and a linear scale for α

size at 41 GHz, the attenuation of 16/2 = 8 dB/km would result from a rain rate of 26.92 mm/hr leading to an availability of 99.86%.

These calculations along with the analysis given in Appendix A show that an LMDS system could be fielded at 41 GHz with exactly the same number of cells as would be required at 28 GHz with almost no reduction in system availability and no change in system technical characteristics. Properly designed 41 GHz hub antennas will result in 3 dB gain over 28 GHz designs with no adverse impact to coverage throughout the cell (see Appendix A). By also keeping the subscriber antenna aperture the same as at 28 GHz an additional 3 dB improvement results which when coupled with the hub antenna gain compensates for nearly all of the increase in rain attenuation occurring at 41 GHz (hence the slight reduction in availability).

3.1.2 Gaseous Attenuation

Differences in gaseous attenuation between 28 GHz and 41 GHz resulting from oxygen molecules and water vapor is negligible. The combined attenuation for a 4.8 km path and a water vapor density of 7.5 G/m^2 is 0.47 dB at 28 GHz and 0.72 dB at 41 GHz. This 0.25 dB difference is insignificant and more than offset by higher antenna gains at 41 GHz.

3.1.3 Foliage Attenuation

Foliage attenuation, whether at 28 GHz or 41 GHz will be a serious obstacle to LMDS on paths obstructed by trees. Measurements at 28 GHz by several investigators[7] have found signal attenuations in the range of 12-35 for a single tree in leaf. This would result in the LMDS signal margin of 13 dB being exceeded for as few as a single tree on the transmission path. Attenuation at 41 GHz through a 4 m wide tree has been calculated to be only 1 dB greater (14 dB vs. 13 dB) than at 28 GHz (less than a 10% change).

Foliage attenuation is therefore, no more of a impediment at 41 GHz than it would be at 28 GHz.

3.1.4 Reflection and Diffraction

At least one LMDS operator plans to use reflected signals to serve subscribers in areas blocked from line-of-sight. Analytic studies, supplemented by laboratory measurements, have been performed by NASA to determine the variation in reflection properties between the 28 and 41

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[7] Attenuation of Radio Signals by Foliage - LMDS/FSS 28 GHz NRMC/67.2.

GHz frequency bands. Appendix B provides the detailed results of these activities.

The analytical and experimental results both indicate that the reflection of incident signals by various building materials varies greatly based upon the type of material, the thickness of the material, and the angle of incidence, as well as frequency. However, the interaction of these parameters are such that cumulatively there is no significant difference in reflection properties between the two frequency bands that would result in measurably superior performance of an LMDS system at one band compared to the other.

3.1.5 Propagation Environment Summary

Upon analysis of the propagation environment at 41 GHz, including rain effects, gaseous attenuation, foliage attenuation and reflection/diffraction, only rain attenuation results in any appreciable difference compared to 28 GHz. It has been shown that the increased attenuation due to rain can be effectively compensated for with minimal impact on LMDS system characteristics while maintaining the identical cell sizes as proposed for 28 GHz operation in all rain zones.

3.2 41 GHz Equipment Parameters

Only a relatively small portion of the system elements that drive LMDS cost are frequency dependent. These are the RF portion of the hub transmitter (upconverter and power amplifier), the hub and subscriber antennas, the RF portion of the subscriber receiver (low noise block downconverter), and for LMDS systems employing two-way communications, the RF portions of the subscriber transmitter and hub receiver.

The remaining components which make up the majority of the LMDS system cost are the same, independent of frequency. These include for the hub, the transmitter modulators and IF's, encoders, power supplies, distribution equipment, site costs and equipment racks, cabling etc. At the subscriber, the demodulator and receiver IF, the decoder, user interface, power supply and case all would stay the same.

The following sections shall examine the feasibility, cost and availability of the various frequency dependent components.

3.2.1 RF Transmitters

At present there is a low rate production of 28 GHz helical TWTAs at a nominal 100 Watts rf power. These TWTAs are in the price range of $65K, about half the cost going to the TWT itself. The TWTs are presently about 10% efficient, rf efficiency being defined as the ratio of output rf power to the product of cathode current and voltage. The question arises as to whether these TWTs could be converted to operate at 41 GHz and retain their power production.

NASA's recent experience with the development of the highly successful 32.5 GHz Cassini tube indicates that a well-established helical TWT simulator, the modified Detweiler code, is a reliable design tool. We therefore applied this program to the conversion of the 28 GHz tube to a 42 GHz tube.

We obtained cathode current and voltage from the manufacturer and made reasonable estimates of the other tube parameters based on our 32 GHz experience. These parameters were then scaled to 42 GHz. We assumed an initial helix phase velocity equal to the velocity of the electrons in the beam (synchronous operation). Our design approach included the common practice of decreasing the helix pitch (distance between turns) at the end of the circuit to increase efficiency. Using a simple non-optimized linear pitch reduction, the code calculated 110 Watts output (9.2% rf efficiency).

We then examined the 28 GHz tube in a similar analysis and found that a linear tapering of helix pitch (phase velocity), as described above, could result in an approximate thirty Watt power increase to 130 Watts.

It should be noted that the above analyses are conservative and fit well with most manufacturers' fabrication schemes. More radical velocity tapering schemes, such as was used in the Cassini development, could result in even further efficiency (power) gains. Moreover, nothing in our design approach gave any indication of increased complexity or costs.

Our calculations verify information received from tube manufacturers who estimated that a non-optimized helical tube design, producing 120 W rf power at 28 GHz, could be used to produce 90 W rf power at 42 GHz. The vendors estimated that in low volume production, such a tube at 42 GHz would cost approximately 20-25% more than the 28 GHz equivalent tube. Substantial reductions in cost, of the order 50%, could be achieved if production were in volumes of several thousand. The proven efficiency enhancement techniques described above could be applied to increase the rf output power to at least 110 W with minimal cost impact.

It is important to stress that while some development time would be needed to achieve production of 41 GHz TWTA's (approximately 18-24 months), the current production volume for 28 GHz TWTA's is very low and would require time to develop new manufacturing techniques to achieve high volume production presumably needed for national LMDS deployment. These production techniques could be put in place during the development cycle for the 41 GHz TWTA so that high volume production would be possible upon completion of development. In this case, time to volume production of either 28 or 41 GHz TWTA's may not be substantially different.

For distributed amplifier hub designs, surveys of several manufacturers (TRW, Hughes, Alpha Industries, and Comsat) have revealed that 0.5 W SSPA's are currently available at 44 GHz with less than a 25% cost differential over 28 GHz SSPA's. SSPA's at 41 GHz would be readily achievable. Similarly, low power SSPA's for in the range needed for subscriber transmitters are readily achievable at 41 GHz for 10-20% cost differential over 28 GHz.

3.2.2 Antennas

Hub antennas at 41 GHz are easily achievable providing increased gain for similar size/design as at 28 GHz.

For subscriber antennas, reflector technology was preferred at both 28 and 41 GHz by the manufacturers surveyed. Planar array implementation is slightly less efficient at 41 GHz than at 28 GHz due to higher line losses in combining MMIC array patches.

3.2.3 RF Receivers

Receiver noise figures at or below the levels stated by LMDS proponents are readily achievable at 41 GHz with manufacturer estimated cost differentials of zero to 25% over 28 GHz low noise receivers. Suppliers indicated their eagerness to provide 41 GHz components.

3.2.4 Equipment Performance as it Affects Spectrum Efficiency

Spectrum efficiency is a function of antenna sidelobe and cross-polarization performance, both of which are directly related to antenna manufacturing tolerances. It is estimated that for the subscriber antennas proposed by LMDS proponents, antenna manufacturing tolerances need to be about 0.22-0.24 mm rms at 28 GHz and 0.15-0.17 mm rms at 41 GHz. Neither of these tolerance levels is expected to be a major technical challenge by antenna manufacturers once full production of the user transceivers is underway.

Historically, tolerances have been an issue with hardware that is manufactured in small quantities. Tolerance requirements was one factor in the relatively high cost of Ku-band equipment in the 1960's. With high volume production, such equipment now sells for 1/10 the cost of the 60's, in spite of significant inflation. There is no reason to expect any different result for 28 GHz or 41 GHz equipment.

Oscillator phase noise can degrade by as much as 3 dB at 41 GHz compared to a 28 GHz oscillator. For a well designed receiver system, however, oscillator phase noise can degrade by several tens of dB's without adversely impacting spectral efficiency. For a receiver system design that is only marginally functional, that is one with a bare bones oscillator exhibiting poor phase noise characteristics, it is conceivable that a 3 dB degradation in stability could result in adjacent channel interference. In such instances, it is conceivable that guard bands between LMDS video channels could require an additional cushion. A doubling of the guard band for the CellularVision FM video system would increase the total spectrum requirement by only 10% should their receiver system design so warrant.

3.2.5 41 GHz Equipment Parameters Summary

The preceeding sections have shown that 41 GHz LMDS implementation is technically achievable and can be deployed with the same cell density as a 28 GHz system. The cost impact is therefore limited to the relatively few frequency dependent components in the LMDS system. Surveys of manufacturers of these components have revealed that performance equivalent 41 GHz components can be made available at approximately a 20% cost differential over 28 GHz. Given that these frequency dependent components make up only a small portion of the total cost of the LMDS system, the overall cost impact to LMDS deployment at 41 GHz would be substantially less.

From a time availability standpoint, 41 GHz TWTA development is the pacing element and could be available in 18-24 months from initiation of development with nearly simultaneous large volume production. All other components could be available in production quantities within this time frame.

4.0 Conclusion

NASA has assessed the suitability of using frequency bands above 40 GHz for providing LMDS and/or commercial satellite communications services.

For LMDS it was found that there is an 8 dB penalty due to increased rain attenuation that must be accommodated in operating at 41 GHz versus 28 GHz. Due to the cellular nature of the LMDS systems, and the designed ability to vary cell sizes to compensate for differing rain zone areas in maintaining constant edge of cell service availability, the 8 dB penalty is the same for any rain zone. It was further shown that the 8 dB additional attenuation can be accommodated by taking advantage of increased antenna gain in the hub transmitter and subscriber antennas for the same aperture and accepting a small degradation in availability (99.84% at 41 GHz versus 99.9% at 28 GHz.)

LMDS frequency dependent components were found to comprise a small portion of the overall LMDS system. For these components, surveys of potential manufacturers indicate that 41 GHz components are easily achievable with the necessary performance characteristics at a cost which is approximately 20% greater than corresponding components at 28 GHz. The overall system cost differential would be substantially less. The longest lead time hardware component would be the hub transmitter TWTA with an 18-24 month development time line.

Overall it was found that an LMDS system could be fielded at 41 GHz, fully equivalent and having the same number of cells as at 28 GHz, with modest cost and schedule impact.

For commercial satellite communications, it was found that although military use of the 44 GHz band for uplink operations demonstrates the technical feasibility of using frequency bands above 40 GHz for satellite communications, the economic penalties would preclude such use for commercial applications at the present time. DoD willing accepts the high cost of achieving the strategic benefits of 44 GHz operation for reasons of national security. Commercial satellite communications systems must compete on a cost basis with terrestrial alternatives as well as foreign satellite competition and can not employ the same kind of hardware compensation used by the military in a manner which would provide competitive services.

APPENDIX A

LMDS Hub Antennas at 41 GHz Can Provide Satisfactory Coverage to the Same Size Cells as 28 GHz LMDS Hubs

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LMDS Hub Antennas at 41 GHz Can Provide Satisfactory Coverage to the Same Size Cells as 28 GHz LMDS Hubs

The types of hub-to-subscriber antennas proposed by LMDS proponents include sector horn and bi-conical horn antennas designed to provide nearly omni-directional coverage in the azimuthal plane and half power beamwidths (HPBW) ranging from about 6°-15° in the elevation plane. For the case of sector horn antennas in which the azimuth coverage of an individual horn is less than 360° (typically 60°-120°), the hub antenna would consist of an appropriate number of sector horns arranged in a circular configuration such that the composite pattern is omni-directional in azimuth.

In comparing operation of LMDS at 28 GHz with that at 41 GHz, certain LMDS proponents have claimed that the 41 GHz hub antenna must have an equivalent azimuth/elevation coverage and sidelobe pattern (i.e. same radiation intensity pattern) as the 28 GHz hub in order to ensure coverage of subscribers both close to and distant from the hub transmitter site. Under this assumption, the 41 GHz antenna will therefore require different dimensions from the 28 GHz design and the directivity of the two antennas will be exactly equal since antennas having the same power pattern have the same directivity regardless of frequency. Furthermore, by considering the fact that rain losses and free space losses are higher at 41 GHz, one can arrive at the mistaken conclusion that - all other things being equal - the 41 GHz hub cannot provide the same quality of service (as measured by the received CNR at the subscriber) in the same size cell as the 28 GHz hub and therefore smaller cell sizes are required at 41 GHz (along with more cells and more hub transmitters to provide service to the same overall coverage area). **However, this conclusion is based in part on the *false* assumption that the 41 GHz hub antenna must have the same radiation intensity pattern - and therefore same directivity - as the 28 GHz antenna.** This need not be true, however. What is important is that whatever gain and sidelobe characteristics the 41 GHz antenna may have, they are sufficient to provide the required CNR performance for all subscribers within the cell (taking into account the higher rain fades). (Note also that at 41 GHz, the sky-oriented sidelobe suppression of the 28 GHz design would not necessarily be required.) With proper design, a 41 GHz hub antenna with higher gain can provide the same quality of service to the same size cell as a 28 GHz hub.

To illustrate, a sector horn antenna was designed using the design equations in [1] which has a directivity of 17.4 dBi, gain of 15.2 dBi (assuming a 60% antenna efficiency), HPBW in the elevation plane of 6.4°, and HPBW in azimuth of about 68°. Six such sector horns arranged in a circle would form a composite beam which is omni-directional in azimuth. The dimensions of the horn and a plot of its relative gain pattern in the elevation plane is shown in Figure 1. Since the wavelength at 41 GHz is 0.73 cm, the absolute dimensions of the horn would be about 22 cm axial length with an aperture of about 6.6 cm x 0.66 cm (note that the aperture width is very narrow in order to give the large beamwidth in azimuth). The gain of 15.2 dBi is about 3 dB higher than the 12 dBi gain of the 28 GHz design. Using the 15.2 dBi sectoral horn antenna, an analysis was conducted to determine the impact of the pattern on the CNR performance at various distances from the cell center. For computation purposes, the following parameters were chosen

- cell size is 3-mile (4.8 km) radius (*same size as 28 GHz system*)

- the hub antenna is assumed to be approximately 100 feet (30.48 meters) above ground level on top of a building or tower

- the main beam of the hub antenna is assumed to be tilted downward 1° below the horizontal (assuming a 4.8 km radius cell, this results in the boresight axis intersecting at a point 1750 meters from the cell center)

- a specific rain attenuation of α = 3.33 dB/km is assumed at 41.5 GHz which gives 99.84% availability in rain zone D2 (this compares with a specific rain attenuation of 2.7 dB/km at 28 GHz for 99.9% availability)

- the *subscriber* antenna gain G_R is also assumed to be 3 dB higher at 41 GHz than at 28 GHz giving a receive gain of 35 dBi

The remaining performance parameters were taken from the CellularVision link budget contained in the document, "LMDS is not Viable in the Frequency Bands above 40 GHz". These are listed below:

- P_T = 20 dBW (100 W) peak = hub transmitter power
- L_{bo} = 7 dB = TWT backoff for linearity
- L_{sh} = 17 dB = power reduction due to power sharing among 50 channels (i.e. a single TWT is used for all 50 20-MHz channels)
- L_{line} = 1 dB = transmit line loss
- N_t = -125.4 dBW = receiver thermal noise level in 18.6 MHz channel bandwidth assuming 6 dB receiver LNA noise figure
- Required CNR of 16 dB

The equation for the received CNR (per channel) at a given subscriber location is then given by.

$$CNR = P_T - L_{bo} - L_{ch} - L_{line} + G_T(\theta) - L_{fs} - L_{rain} + G_R - N_t$$ (all quantities expressed in dBs)

where in addition to the parameters defined above,

$G_T(\theta)$ is the gain of the hub antenna in the direction of the subscriber and θ is the off-axis angle of the subscriber from the main beam axis of the hub antenna (main beam of hub is assumed to be tilted 1° below the horizontal)

L_{fs} is the free-space loss $= \lambda^2/(4*\pi*Z)^2$ where λ is the wavelength (in meters) and Z is the range (expressed in meters)

L_{rain} is the rain loss $= Z*\alpha$ where Z is the range (in km) between subscriber and hub antenna and α is the specific rain attenuation

Using this equation, the received CNR as a function of distance from the cell center was computed. The results of the analysis are shown in the figures below. Figure 2(a) shows the received CNR vs distance from the cell center taking into account the sidelobe pattern of the hub sector horn antenna, the variation in free-space loss, and the variation in rain loss as one moves away from the center. It can be seen that the CNR requirement of 16 dB is met all the way out to the edge of the cell. The CNR at the very edge of the cell is 16.15 dB.

Figure 2(b) shows the associated hub antenna gain. The peak gain occurs at a distance of about 1750 meters, but beyond that point the gain is very nearly flat all the way out to the edge of the cell. This is because the off-axis angle of those points remains close to zero as shown in Figure 2(c). Subscribers close in to the center experience little gain from the hub antenna, but their CNR is still well above 40 dB since their range losses and rain losses are very small compared to those farther out as shown in Figure 2(d).

Hence, by proper design and placement of the hub antenna, the required CNR performance can be met or exceeded throughout the entire LMDS cell when operating at 41 GHz and there is no need to go to a smaller cell size. (Blockage due to buildings, trees, etc. will of course prevent reception at every point just as it will at 28 GHz.)

[1] Antenna Theory Analysis and Design, Constantine A. Balanis, Chapter 12.

Figure 1 Plot of Sectoral Horn Antenna Pattern in the Elevation Plane

The dimensions of the horn are:

ρ_1 = axial length of horn = 30λ

b_1 = length along aperture = 9λ

a = width of aperture = 0.9λ

Ψ = flare angle = 17°

(at 41 Ghz, λ = 0.73 cm)

The gain and beamwidth characteristics of the horn are

θ_{EL} = HPBW in the elevation plane = 6.4°

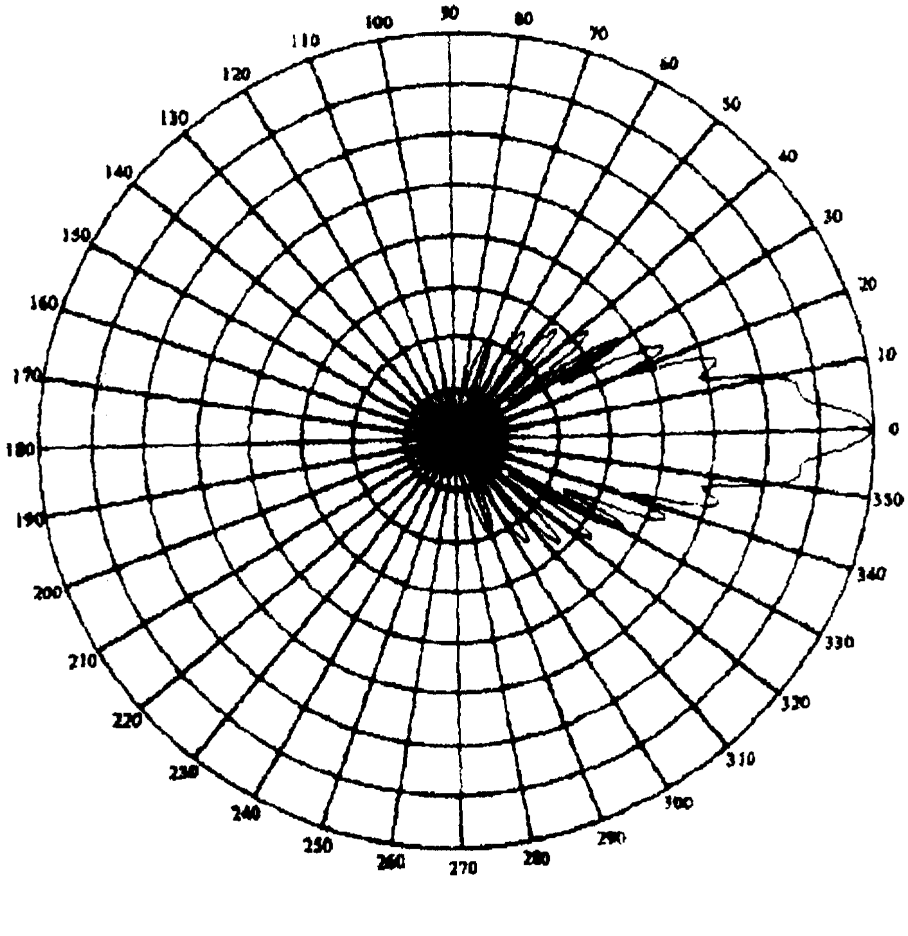
θ_{AZ} = HPBW in the azimuth plane = 68°

D = Directivity = 17.4 dBi

G = Gain = 15.2 dBi (60% efficiency)

Since the azimuth HPBW is about 60°, six sector horns are sufficient to give nearly omnidirectional coverage in azimuth.

Elevation Pattern of E-plane Sector Horn



(Note: the radial direction represents relative gain (dB down from peak) with the radial grid lines at 5 dB increments)

Figure 2(a). CNR (dB) vs Distance from Center of Cell (meters) (1° mainbeam tilt angle)

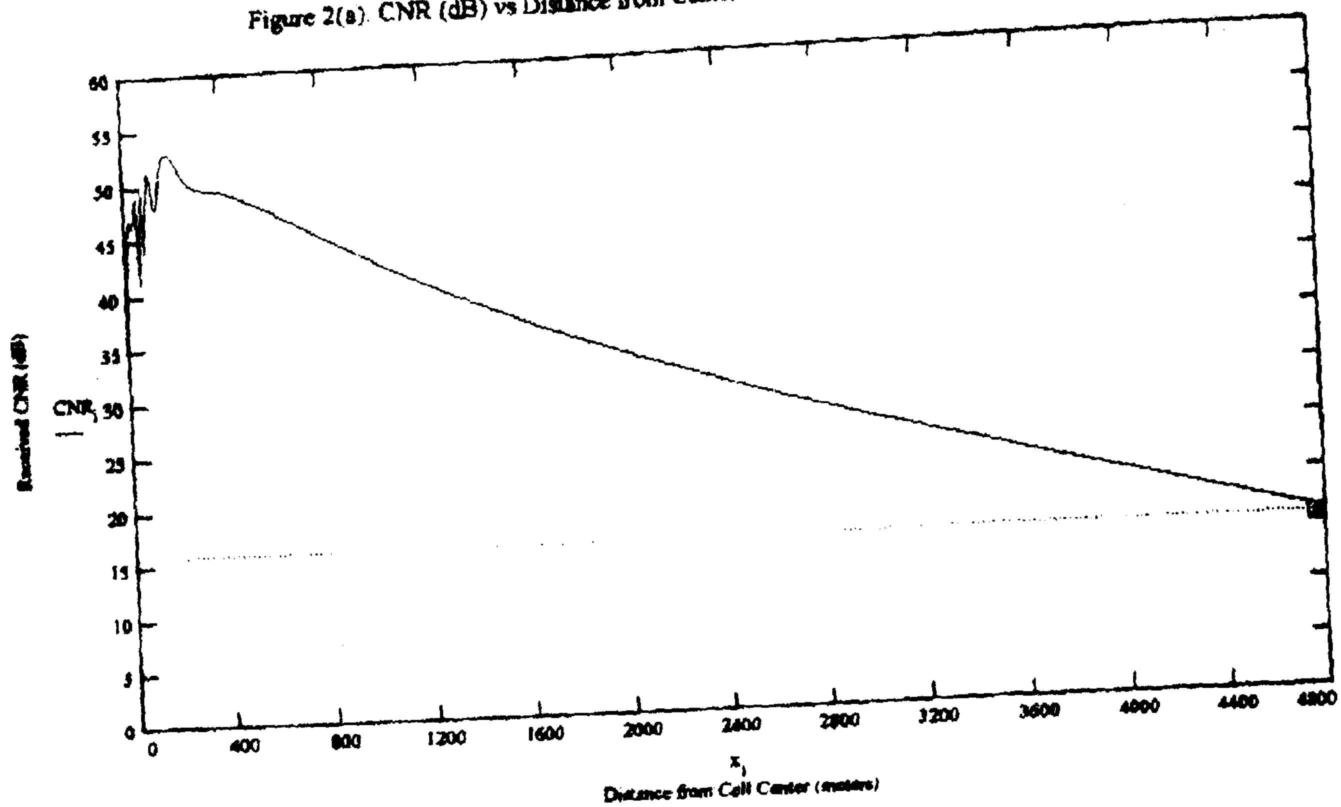


Figure 2(b) Transmit Hub Antenna Gain of Sectoral Horn Antenna vs Distance from Cell Center (1° tilt)

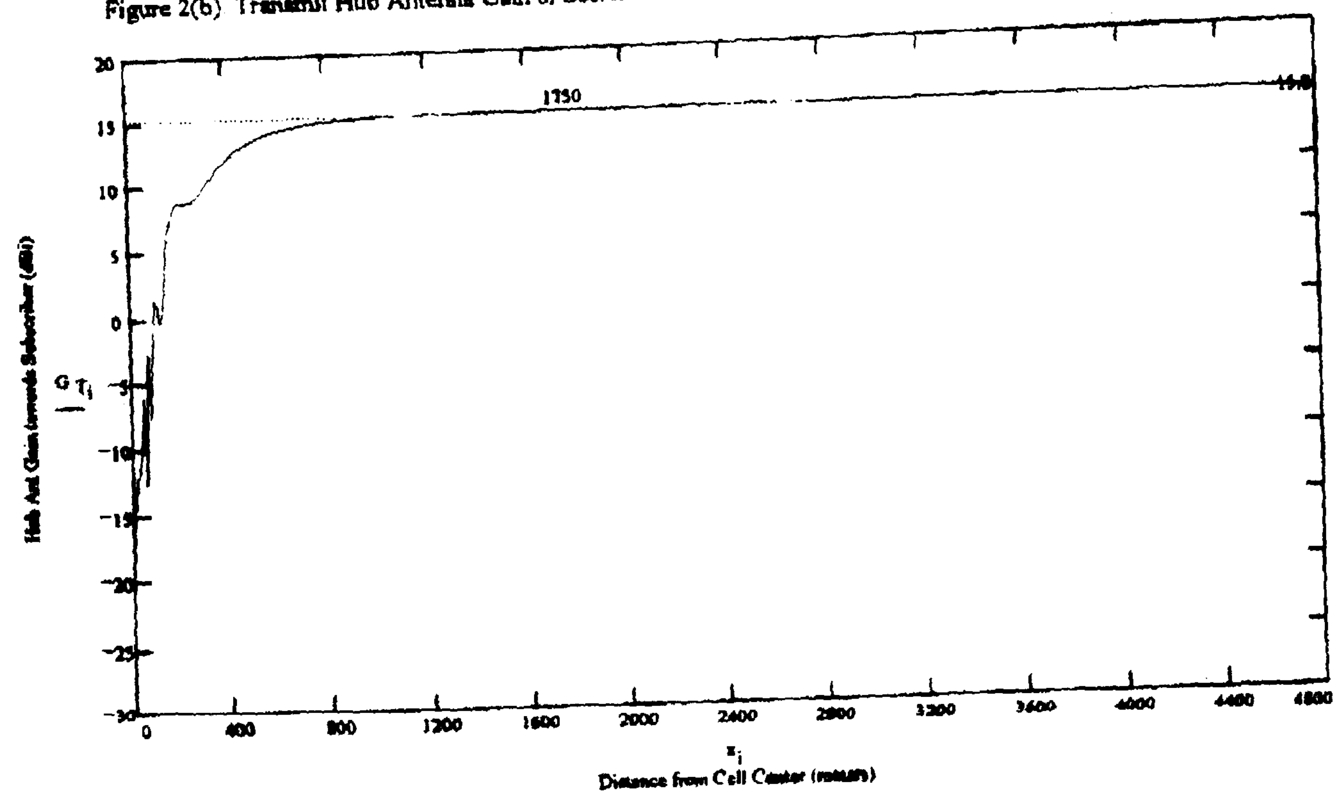


Figure 2(c). Off-axis Angle of Subscriber from Hub Antenna Mainbeam Axis vs Subscriber Distance from Cell Center

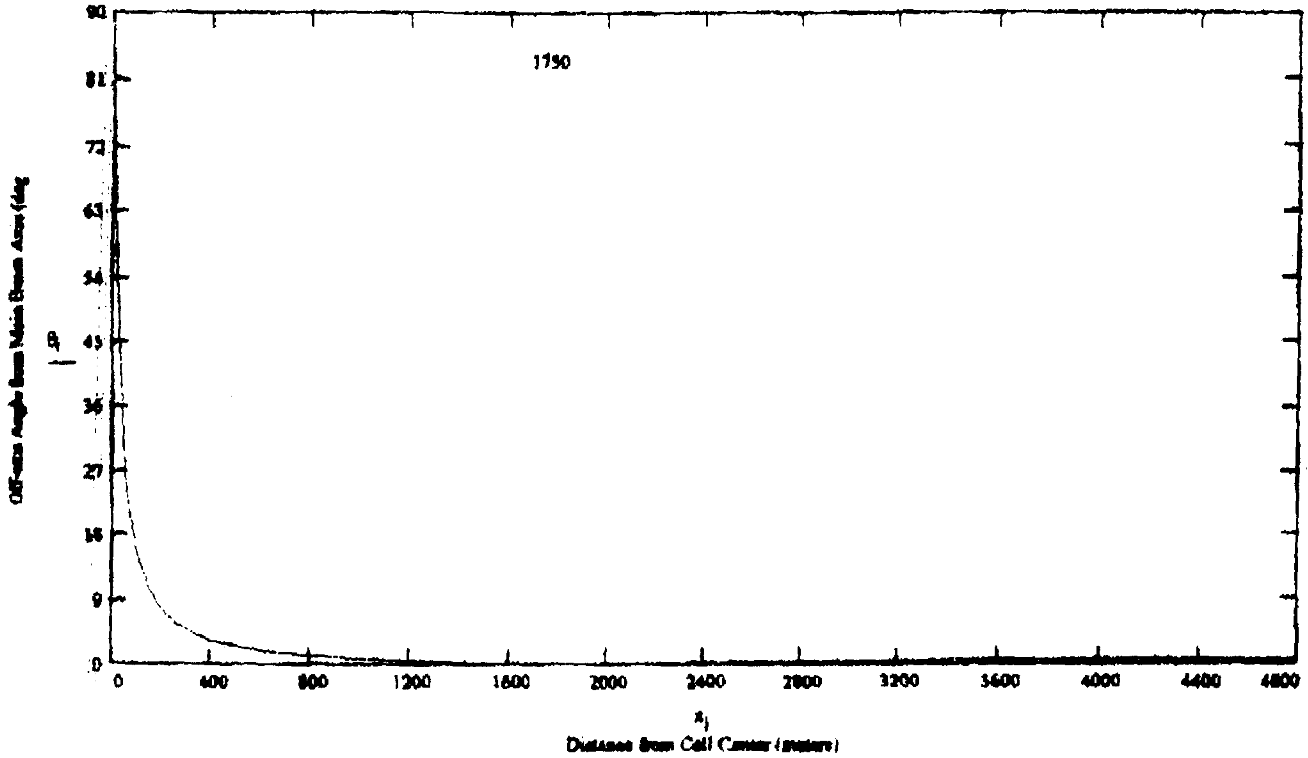
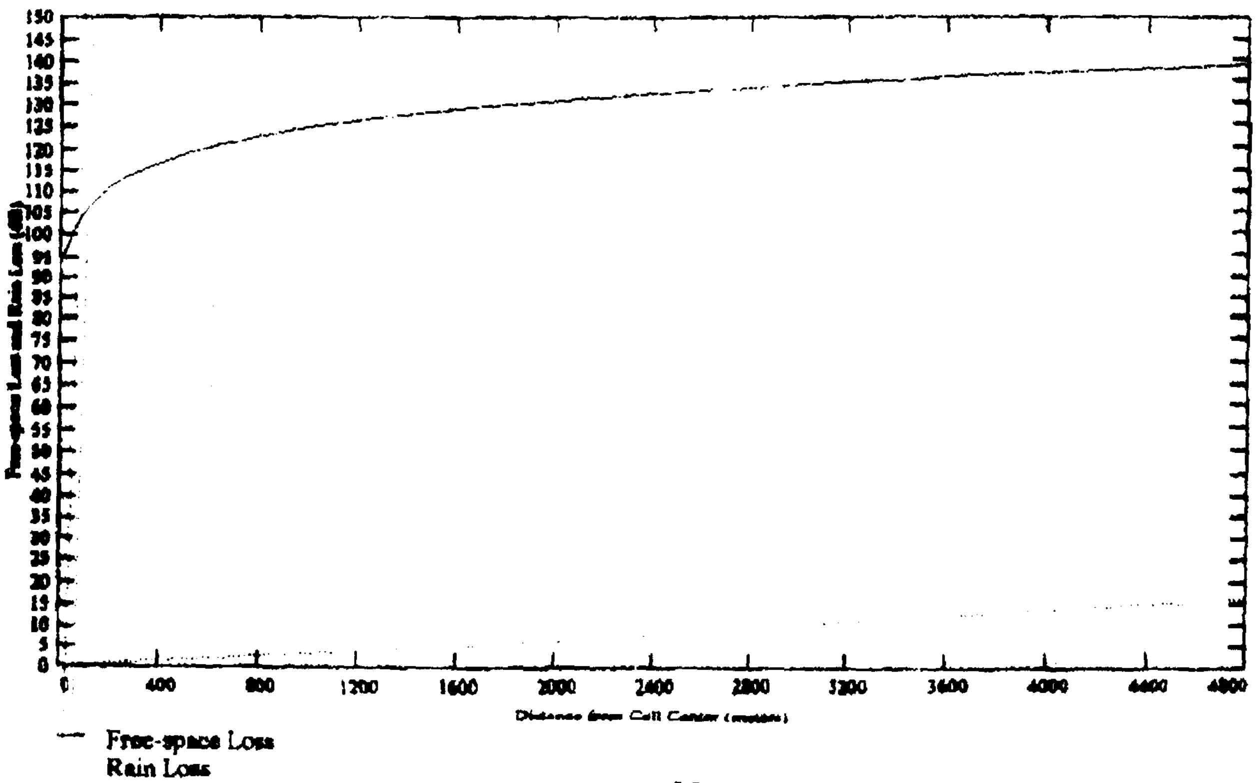


Figure 2(d) Free-Space Loss and Rain Loss vs Distance from Cell Center



APPENDIX B

Reflection Properties at 28 and 41 Ghz

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LMDS - Reflection Properties at 28 and 41 GHz

Analytical studies, supplemented by laboratory measurements, have been performed at NASA Lewis to determine the variation in reflection properties between the 28 and 41 GHz frequency bands.

The analytical and experimental results both indicate that the reflection of incident signals by various building materials varies greatly based upon the type of material, the thickness of the material, and the angle of incidence, as well as frequency. However, the interaction of these parameters are such that cumulatively there is no significant difference in reflection properties between the two frequency bands that would result in a measurably superior performance of an LMDS system at one band compared to the other.

The results of the analysis and measurements are summarized by the following tables and plots.

CALCULATED RESULTS

Figures 2 through 5 are plots of the calculated reflection coefficients for glass and plywood of several thicknesses.

Figure 2 plots the reflection coefficient for 0.125 inch thick glass at 28.5 and 41.5 GHz. Below 45°, the reflection coefficient is higher at 28.5 GHz, while above 45° the reflection coefficient is higher at 41.5 GHz.

Figure 3 plots the reflection coefficient for 0.625 inch thick plywood at 28.5 and 41.5 GHz. The reflection coefficient is higher at 28.5 GHz for reflection angles of between 20° and 48°, and above 56°. At all other reflection angles, the reflection coefficient is higher at 41.5 GHz.

The difference between reflection coefficients for the above cases is plotted in Figure 4.

Figure 5 plots the reflection coefficient as a function of frequency for three different thicknesses of glass and plywood. The plots indicate considerable variability as a function of frequency, material, and material thickness.

MEASURED RESULTS

Figure 1 shows the laboratory test setup for a set of reflection measurements performed on four material: metal (aluminum sheet), concrete brick, wood(composite of 0.5 inch plywood and 1 inch by 2 inch cross pieces), and mirror (0.125 inch silvered glass)). The reflection coefficient was measured for incident angles of 10°, 30°, 45°, and 60°.

The test results are summarized in Tables I and II. In table I, the measured reflection coefficients are given, where the reflection coefficient is calculated for the brick, wood, and mirror by comparison to the results for metal. The metal, approximating a perfect conductor, is used as a system calibration. The results are given for frequencies of 28.5 and 39.0 GHz (due to instrumentation limitations, results at 41.5 GHz could not be obtained.)

In table II, the difference between the measured results obtained at 28.5 and 39.0 GHz is listed. A positive number indicates a higher reflection coefficient at 28.5 GHz, while a negative number indicates a higher refection coefficient at 39.0 GHz. The results indicate the variation in reflection properties between the two frequencies resulting from different materials and reflection angles. Of the 12 cases presented, the reflection coefficient is higher at 28.5 GHz in 6 instances. The average for the 12 cases is -0.68 dB, or a slightly higher average reflection at 39.0 GHz.

Limitations in laboratory instrumentation and available materials for testing, as well as for time to complete the measurements make a direct comparison between the measured and calculated results difficult.

Figures 6 through 14 give a comparison of the uncorrected measured results, plotted as a function of frequency, with the calculated results. Please note differences in the horizontal (frequency) scale between the measured and calculated data. Figures 6 - 8 show measured data for mirror and wood and calculated data for glass and plywood, at an incident angle of 10°. Figures 9 - 11 show measured data for mirror and wood and calculated data for glass and plywood, at an incident angle of 30°. Figures 12 - 14 show measured data for mirror and wood and calculated data for glass and plywood, at an incident angle of 60°. Taking into account the difference in conditions between measured and calculated cases, the plots in figures 6 - 14 show general agreement between the measured and calculated results in terms of the variation of reflection coefficient with frequency.

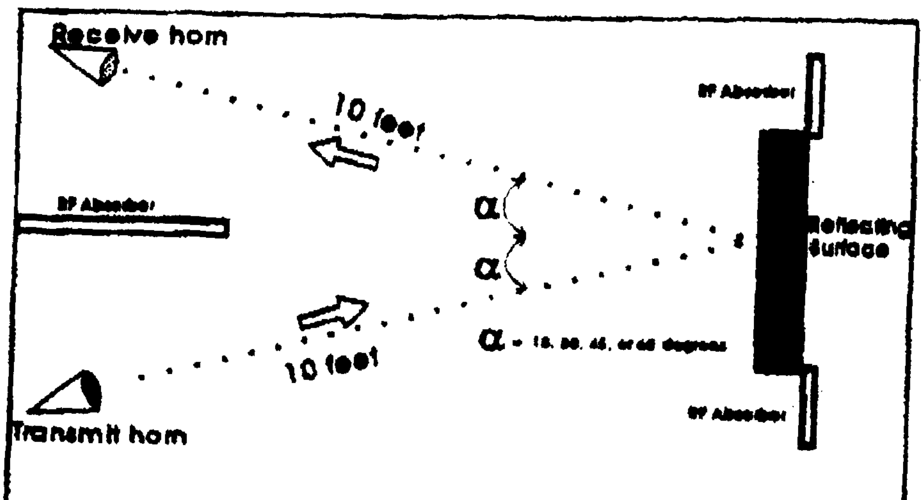


Figure 1 - Laboratory Test Configuration

TABLE I

Measured Reflection Coefficient at 28.5 and 39.0 GHz
for Several Building Materials

REFLECTION ANGLE	REFLECTION COEFFICIENT (DB) BRICK		REFLECTION COEFFICIENT (DB) WOOD		REFLECTION COEFFICIENT (DB) MIRROR	
	28.5 GHz	39.0 GHz	28.5 GHz	39.0 GHz	28.5 GHz	39.0 GHz
10°	-11.5	-15.8	-16.5	-11.1	-3.1	-0.8
30°	-10.3	-7.7	-12.8	-12.2	-0.5	-2.3
45°	-13.6	-5.2	-15.1	-17.3	-3.2	-2.7
60°	-4.3	-4.4	-13.1	-14.5	-0.7	-2.8

TABLE II

Difference between received reflected power
at 28.5 GHz and 39.0 GHz

INCIDENT ANGLE	REFLECTED POWER DELTA (dB) BRICK	REFLECTED POWER DELTA (dB) WOOD	REFLECTED POWER DELTA (dB) MIRROR
10 Degrees	4.3	-5.4	-2.5
30 Degrees	-2.6	-0.6	1.8
45 Degrees	-8.4	2.2	-0.5
60 Degrees	0.1	1.4	2.1

The delta shown in the chart is derived by subtracting the calibrated received power at 39.0 GHz from the calibrated received power at 28.5 GHz. A positive value indicates a higher received power at 28.5 GHz; a negative value indicates a higher received power at 39 GHz.

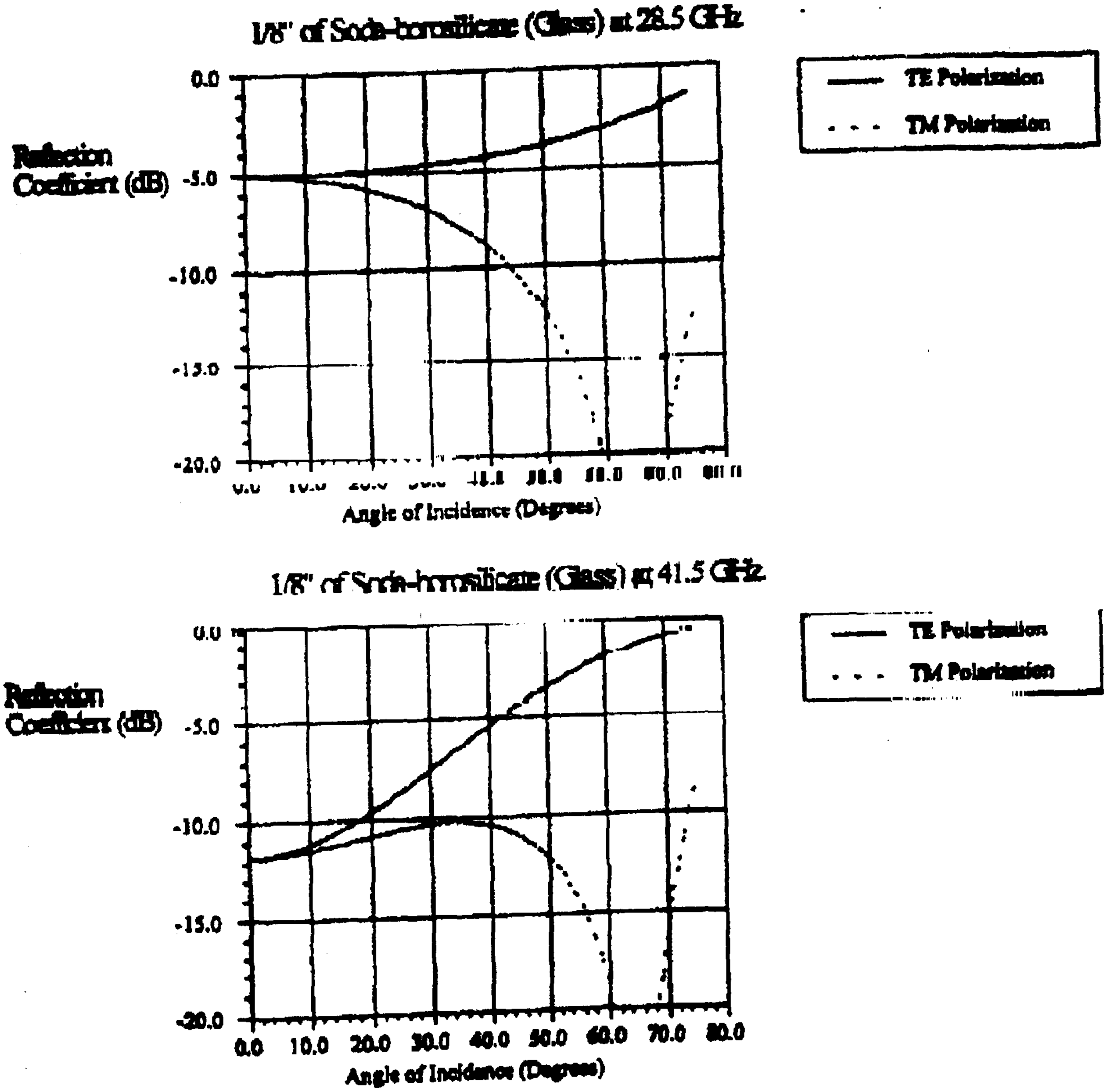


Figure 2. Theoretical Reflection Coefficient of a Type of Glass.

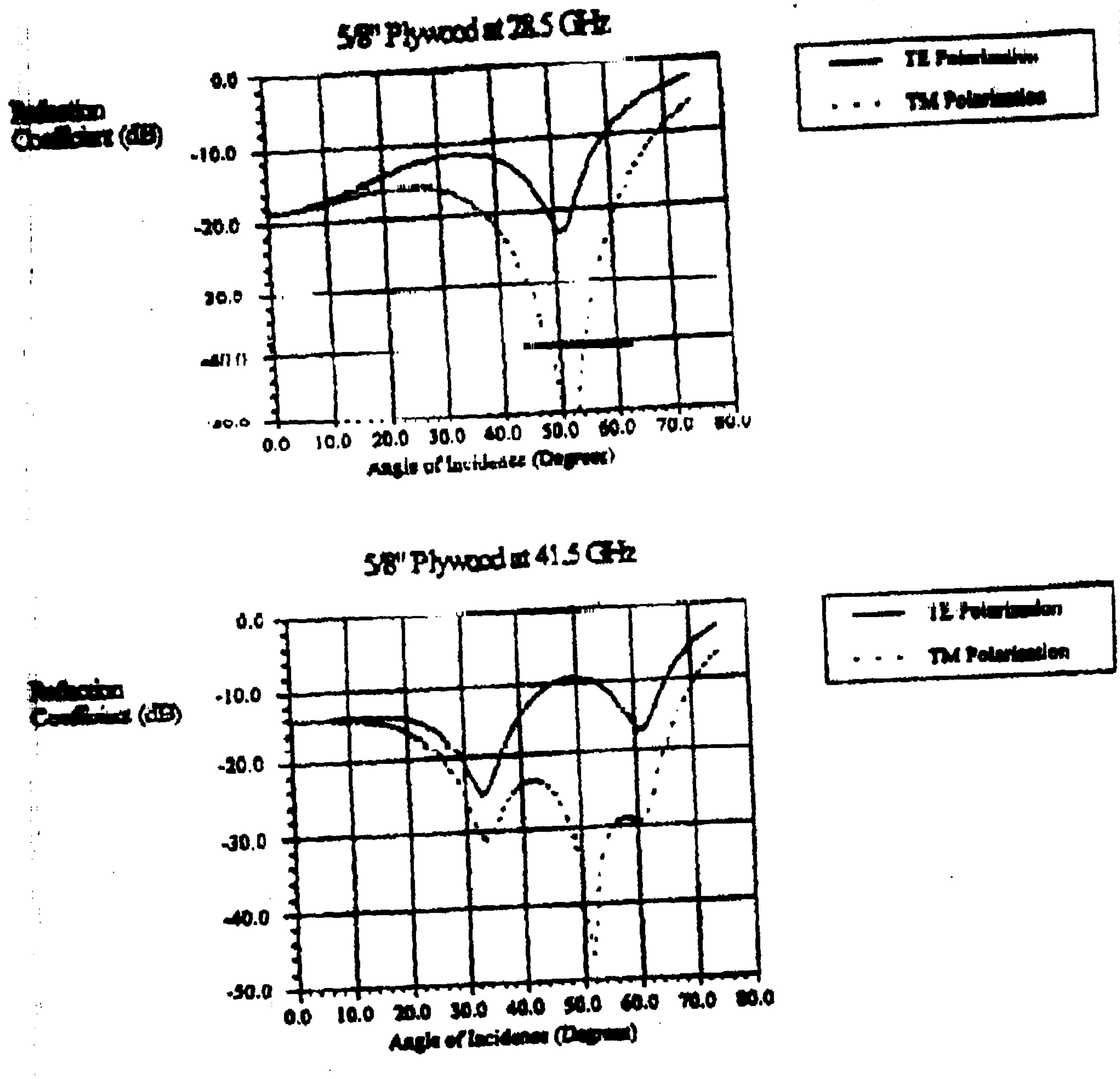
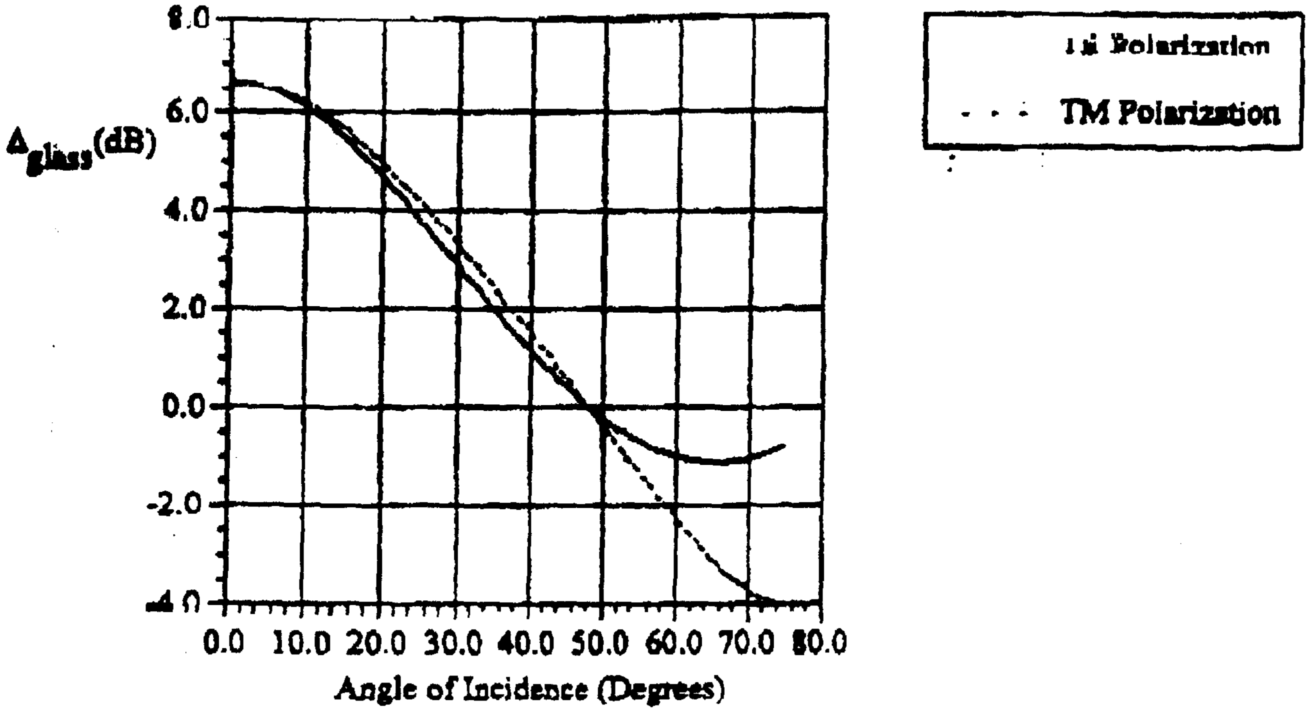


Figure 3. Theoretical Reflection Coefficient of Plywood.

1/8" of Soda-borosilicate (Glass)



5/8" Plywood