VLBA ELECTRONICS MEMO NO. 1

A MICROWAVE TRANSMISSION LINK IN NEW MEXICO FOR THE NATIONAL RADIO ASTRONOMY OBSERVATORY

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The National Radio Astronomy Observatory would like to extend the baseline of its Very Large Array, located about 80 km west of Socorro, New Mexico, by adding a 25 m diameter antenna at a new site 60 to 100 km to the southeast. Other similar antennas at more distant locations are planned for a later date.

Two possible sites are being considered, one about 15 miles north of Truth or Consequences between Interstate 25 and Elephant Butte Lake, and the other about 15 miles north and slightly west of Winston on highway 59 near the junction of Catron, Socorro and Sierra counties. The North T or C site is better for communications and easier to maintain. The North Winston site is interesting to radio astronomers because its isolation and higher elevation may improve the reception of extra-terrestrial radiation, but the value of the expected improvement is difficult to quantify. An early hope that satisfactory communication might be obtained between North Winston and the VLA site by way of a passive reflector on Mt. Withington does not seem realizable because of high attenuation. An active repeater on South Baldy Mountain can serve either North Winston or North T or C, and the latter path (plain to mountain top) is expected to be more reliable.

The 27 antennas at the VLA site are in a Y formation, and each delivers four 50 MHz signals to the central location near the center of the Y. Each 50 MHz signal is transmitted by single sideband amplitude modulation on a suitable carrier through an oversized waveguide. Each 50 MHz signal is then digitized into 100 MBits per second before it is fed into the correlator. The end result is a magnitude and an angle, and this complex number is updated at a rate of about once per second. In some cases, the 100 MBit signal is subdivided into parallel streams of about 12 MBit each for recording on video tape.

The preferred method of operation of the new and distant site is to transmit its four 50 MHz signals back to the VLA correlator in real time. Neither waveguide nor single sideband, amplitude modulated, radio transmission is feasible for the distances involved. Inasmuch as the information is to be digitized before going into the correlator, it is almost necessary to digitize at the distant site and to transmit to the VLA by digital microwave facilities.

The 100 MBit rate is only slightly higher than the commercially available 90 MBit microwave equipment now operating in 30 MHz channels at carrier frequencies above 6 GHz.* This equipment meets and exceeds the requirement of at least 2.6 bit per hertz imposed by the FCC to prevent inefficient use of the spectrum. Improved equipment with bit rates of 135 or 140 MBits per second in 30 or 40 MHz channels can be expected in the near future because of the intense competition between North American and Japanese manufacturers.

An antenna array depends on a known and constant phase relationship between the individual elements that make up the array. A timing error between two elements distorts the received information in the same way as a bump on the surface of the more familiar parabolic reflector. The allowable error is usually limited to either 1/8 or 1/16 of a wavelength, which at 25 GHz is about 1 mm. This allowable error is sometimes stated as 1° in phase per GHz, or as a timing error of about 3×10^{-12} seconds.The diurnal variations in transmission time on a 100 km path, uncorrected for changes in atmospheric refraction, may be as much as 10^{-8} seconds, which means 250 cycles at 25 GHz. Short term variations, assuming full correction for atmospheric refraction, may be as high as $100/3 \times 10^{5}$ divided by 3×10^{6} (the uncertainty in the present knowledge of the velocity of light in a vacuum), which amounts to about 10^{-10} seconds or 2.5 cycles at 25 GHz. The average value of this fundamental limitation may be lower because of random rather than direct addition, An atomic clock and a phase locked loop are needed to correct for the variations. The rate of change of phase is not expected to exceed about 2° to 5° per second for , say, 98% of the time; but momentary peak rates of up to about one radian per second can occur during multipath fading on the radio path.

A similar tight requirement on the phase of the carrier frequency is not needed in communication services, but a similar limit does apply to the information band and to the radio channel width. For example, in a digital system a timing error of 1/16 of the pulse length can be tolerated without adding appreciably to the bit error rate, and in voice transmission an echo delay of 1/16 of the syllable length is acceptable, while somewhat longer delays require corrective measures.

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* The usual application of the 90 MBit equipment is for 1344 voice circuits of 4 kHz at 8 levels, that is, $4000 \times 2 \times 8 \times 1344$ + signalling information = 90 MBits. The NRAO information is in a different format, namely. $5 \times 10^{7} \times 2 \times 1 \times 1 = 100$ MBit, but when information is in digital form, "a bit is a bit is a bit".

Atmospheric Refraction

The refractive index of the earth's atmosphere, denoted by n, depends on pressure, temperature and water vapor content, and can be represented by $n = 1+N \times 10^{-6}$. At sea level, N is about 300 and can have diurnal variations of $\pm$ 10 or more. The resulting variations in transmission time (phase) are slow compared with the information rate, can usually be neglected in communication services but can not be neglected within an array of antennas. The value of N decreases with elevation, and the rate of decrease, dn/dh, bends the ray away from the commonly assumed, straight line, "line of sight" path. The deviation from a straight line at a distance D_1 from one end of a radio path, whose total length is D_1+D_2 is given by

$$-2 D_o^2 \, dn/dh = \frac{2 D_o^2 (1-1/k)}{a} \qquad (1)$$

where $D_o = D_1D_2/(D_1+D_2)$
a = radius of the earth
$1/k = 1 + a \, dn/dh$

The fiction of straight line propagation can be maintained for computational purposes by assuming an effective earth radius of ka. An average value of k = 4/3 is usually assumed for radio frequencies below the 22 GHz absorption line, and land surveyors usually use the equivalent of k = 5/4 or k =6/5 for optical transmission. The earth radius factor can, in theory, take on any value, but the practical range seems to be $2/3 < k < \infty$. The lower limit of k = 2/3 ($dn/dh = 7.8 \times 10^{-8}$ per meter) causes unfavorable bending and produces radio "blackouts" and optical mirages. When $k = \infty$, ($dn/dh = -1/a = -7.8 \times 10^{-8}$ per meter), the ray bends around the curvature of the earth as if it were straight line propagation over a flat earth; still larger negative gradients cause ducting.

The adverse refraction represented by k = 2/3 may occur only a few times per year, but when it does happen the blackout can persist for several hours until broken up by wind or temperature changes. It is associated with either ground fog or, more likely in New Mexico, a negative temperature gradient of the order of -1^{o}C per 10 meter increase in elevation.

For example, in the middle of the 70 km path between North Winston andSouth Baldy the radio "ray" is 96 meters above a geometrically straight line when $k = \infty$, 24 meters at k = 4/3, 16 meters at k = 6/5 and is 48 meters below the straight line for k = 2/3 and 96 meters below for k = 1/2. Consequently, the required clearance needs an allowance of 48 meters to prevent blockage during the infrequent times when k < 2/3.

Path Clearance

Almost all of the energy in an electromagnetic wave is contained in the first Fresnel Zone, whose central axis is the geometrical ray. A good line-of-sight microwave path needs adequate clearance over all intervening obstacles so that the full first Fresnel Zone (or at least 0.6 of it) is on or above the horizon even under the adverse bending represented by k=2/3. The first Fresnel Zone has a circular cross-section with a radius of $\sqrt{\lambda D_o}$ at wavelength λ. In the above example of a 70 km path($D_o \cong$ 17.5 km), the radius of the first Fresnel Zone is 23 meters for a 10 GHz radio wave. The total required clearance is 48+23 = 71 meters relative to true earth (k = 1). The resulting angle at a distance of 35 km is about 7 minutes of arc.

Observations with a transit at North Winston in the middle of a clear day indicated an angle of 7 arc minutes for optical transmission. On the assumption that average refractive conditions (k = 6/5) existed, the corrected optical measurement is about 7 - 1.6 = 5.4 arc minutes, somewhat lower than the desired 7 arc minutes. Of course, the probable error is high, and the indicated precision may be misleading. The conclusion is that the North Winston to South Baldy path is marginal; it probably will perform satisfactorily for 95% and perhaps for 99% of the time, but it is a risk. A more accurate determination of the probable outage time may require continuous measurements for up to a year.

Angle of Arrival and Antenna Size

The preceding information on atmospheric refraction indicates that the angle of arrival (or departure) relative to true earth conditions (k = 1) is

$$\theta = \frac{(D_1 + D_2)(1 - 1/k)}{2a} = -\frac{(D_1 + D_2)\, dn/dh}{2} \qquad (2)$$

For the range $2/3 < k < \infty$ on a 70 km path, the angle of arrival varies from + 19 arc minutes to -9 minutes relative to k = 1, or about $\pm$ 0.25° around the average value of k = 4/3. The minimum 3 dB beamwidth of an antenna (or passive reflector) should, therefore, be at least $\pm\frac{1}{4}^\circ$ and proportionately larger for paths longer than 70 km; this calculation leaves no margin for misalignment, either initially or during periods of heavy wind or ice loading.

Angle of arrival measurements are frequently summarized as $\pm 0.5^{o}$ in the vertical plane and $\pm 0.1^{o}$ in the horizontal plane, but are vague about variation with path length. Small differences between theory and experiment may be due to any one of several factors, including

a. A criterion based on a $\pm$ 3/4 dB decrease in signal rather than 3 dB, as used above,
b. An allowance for structural stability,
c. Search for maximum off beam "ray", even though other "rays" of comparable magnitude might be closer to the antenna axis.

It is concluded that the vertical beamwidth of an antenna (or passive reflector) should be at least $\pm 0.25^{o}$, and preferably no wider than about $\pm 0.5^{o}$. These limits on beamwidths correspond to an antenna whose vertical dimension is between 100 and 50 wavelengths respectively. The gain of an antenna whose diameter is 50 wavelengths is theoretically 45 dB, but is limited to 42 or 43 dB when non-uniform illumination of the reflector and other inefficiencies are taken into account. The physical size is about 2 m diameter at 8 GHz and 85 cm diameter at 18 GHz. An antenna whose diameter is 100 wavelengths is twice as large and provides 6 dB more gain because of its narrower beamwidth.

Transmission Loss Calculations

On line-of-sight paths with adequate clearance, the ratio of power at the receiving antenna terminals to the power radiated by the transmitting antenna is given by

$$10 \log \frac{P_{rec}}{P_{tr}} = 10 \log \frac{1}{1+\frac{(\lambda D)^2}{A_1 A_2}}$$

$$\approx 10 \log \frac{A_1 A_2}{(\lambda D)^2} = 10 \log G_1 G_2 \frac{\lambda^2}{(4\pi D)^2} , \quad (3)$$

where A_1 and A_2 are the effective cross-sectional areas of the transmitting and receiving antennas measured in the same units as the wavelength λ and the path length D.

The antenna gain $G = \frac{4\pi A}{\lambda^2} = \frac{\pi}{B_v B_h}$; ideally, A is the geometrical area of the antenna "window", which produces a conical far field radiation pattern with total angle $2B_v$ in the vertical plane and $2B_h$ radians in the horizontal plane. The idealized assumption of a uniform field with sharp edges is not practical, so it is customary to account for the rounded edges by assuming that the effective area A_{eff} is only 50% (3 dB) or 67% (2 dB) of the true geometrical area. For example, when the path length D is 100 km., λ =1.67 cm.(18 GHz) and $A_{eff}=(50\lambda)^2$ (10 log G = 45 dB), the free space transmission loss is 67.5 dB.

When a passive reflector with projected area of A_R is used in the far field of both terminals, the total transmission loss is given by

$$10 \log \frac{P_{rec}}{P_{tr}} = 10 \log \frac{A_1 A_R}{(\lambda D_1)^2} \times \frac{A_R A_2}{(\lambda D_2)^2}$$

$$= 10 \log \frac{A_1 A_2}{\lambda^2 (D_1+D_2)^2} \times \frac{A_R^2 (D_1+D_2)^2}{(\lambda D_1 D_2)^2}$$

The first form of the above equality shows that the overall loss with a passive reflector is that of two free space paths in tandem.* The second form also has two factors, neither of which can exceed unity; the first factor is the loss to be expected if the reflector were not needed, and the second factor is the additional loss introduced by the passive reflector. The quantity $\lambda D_1 D_2/(D_1+D_2)$ is the size of the first Fresnel Zone at the reflector location, so the added loss is determined by the portion of the first Fresnel Zone that is intercepted by the reflector.

Rain Attenuation

Rain attenuation can be neglected if sufficient radio frequency assignments can be obtained below 8 or 9 GHz. Should it become necessary to use frequencies near 18 GHz, rain outages can be expected on the order of 500 minutes per year (0.1% of the time) in New Mexico, and 5 to 10 times more often in West Virginia. The NRAO 17 GHz path in W. Va. seems to be longest one now in use, and measurements of the probability of occurence vs. attenuation would add considerably to the present knowledge.

The absorption per km. of path caused by a given rate of rainfall as a function of frequency has been calculated using a reasonable (but nevertheless assumed) distribution of raindrop dimensions. The total rainfall per year or day, and sometimes by hour, is also reasonably well known for many different locations. The principal uncertainties concern the distribution on a second by second basis at the same time at all points along the path, and whether the rain gauge data taken near the ground is a good measure of the number, size and velocity of the drops as they fall through the elevated radio path.

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* In a beamwidth limited system, the variations in the angle of arrival limit the maximum useful size of the passive reflector in the same way as for antennas.

Irregular Atmospheric Refraction

Thus far, atmospheric refraction has been assumed to be either independent of height or with a uniform gradient. The second order effects (d^2n/dh^2) cause amplitude and phase distortion that increases rapidly as the path length is increased beyond about 3×10^5 wavelengths. The distortion appears as multiple paths (echoes) with interference-type selective fading. The fading is reasonably flat over a few megahertz, but is frequency sensitive to a troublesome degree when larger bandwidths are used.

Two or more separate paths that differ in travel time by one half cycle or more can interfere destructively. The sum of two waves with random amplitude and phase (or of many waves of equal amplitude but random phase) is given by the Rayleigh Distribution, e^{-R^2}, where R is the ratio of the momentary amplitude to its rms value. A 10 dB fade is likely for about 10% of the time, 20 dB fade for 1%, 30 dB fade for 0.1% of the time, etc. The probability of a deep fade reaching the receiver can be reduced by the use of frequency or space diversity.

A large amount of data has been collected over several decades on the magnitude of multipath fading , how it varies with path length, frequency and weather conditions and on the improvement to be obtained by the use of diversity. The most recent summary of this material, published by the CCIR, relies heavily on work published by Barnett and by Vigants at Bell Labs. A typical example of the predictions based on these methods is shown in the attached Figure 1, for a 50 km path at 8 GHz. Essentially the same results are expected for a 50 km path at 18 GHz when the assumed 8 meter separation at 8 GHZ for the space diversity antennas is scaled to 8/18x8=3.5 meters for 18 GHz transmission.

Outage probabilities per link of 10^{-5}, or even less than 10^{-6}, are needed for commercial telephone service because many links may be connected in tandem, but less severe requirements may be acceptable in some NRAO applications. Normal operations at the VLA may not be seriously inconvenienced by 1% or 2% unavailable time on the microwave link. Consequently, it seems desirable to plan for the use of space diversity but not to install it until operating experience demonstrates that the improved reliability on the radio link will be worth its cost. It is unlikely that the NRAO can use frequency diversity because of the associated need to double the already large requirements for frequency assignments. In any event, a fading margin of at least 25 dB is necessary and more than 30 dB is desirable.

The probability of outage vs. depth of fade shown on Figure 1 is the result of low signal to noise ratio. A communication system can also fail because of excessive amplitude or phase distortion. A timing error of an appreciable part of the pulse length or the lack of a flat amplitude response across the channel can increase the bit error rate significantly, even in the absence of fading. The right hand scale on Figure 1 shows, for example, that a 6 dB slope across the radio channel is expected to cause a bit error rate of almost 10^{-3}.

The need for dynamic equalization increases as either the information bandwidth or the reliability objective is increased. A few manufacturers are leading the field in providing adaptive equalization, while others provide no equalization except flat gain control. The latter group explain that they meet CCIR and CCITT Recommendations, that the CCIR is still studying the equalization question and that they will add equalization when an official recommendation is made; this attitude leaves them 5 to 10 years behind the state of the art.

The foregoing discussion of the magnitude of fading needs to be supplemented by information on the rates of change of both amplitude and phase. Quantitative data on the rates of change are more difficult to obtain than on the probability of a given depth of fade, but the equipment designer needs at least a "ball park" figure. An estimate is given on Figure 2 for 4 GHz transmission on a 50 km path.* For example, a 20 dB fade is expected about 1% of the time, and for a 20 dB fade of median duration the phase is expected to change at a rate of about 0.03 radian (2°) per second. One percent of the 20 dB fades will be sufficiently fast that the phase will change as fast as 0.6 radians per second. Deeper fades will occur less often but with more rapid rates of change. The rates of change are expected to increase as the square root of the frequency, so the above numerical examples should be doubled for operation in the 16 to 18 GHz band.

On the average, microwave fading varies as 10 log $[(\text{distance})^3 \times (\text{frequency})]$. For a given path length and frequency, a path between plain and mountain top (such as North T or C to South Baldy) is usually better than average, and a path between two mountain tops (such as Sandia Crest to South Baldy) is usually worse than average.

Interference from local thunderstorms is noticeable at 50 MHz (TV Channel 2), but is 20 dB weaker at 500 MHz and 40 dB weaker at 5 GHz. Transmission paths parallel to a weather front are affected more severely than one perpendicular to the front.

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* K Bullington, "Phase and Amplitude Variations in Multipath Fading of Microwave Signals", Bell System Technical Journal, vol 50, no. 6, pp 2039-2053, July-August 1971.

Characteristics of a Typical Digital Microwave System

The net loss on a 100 km line of sight path with 45 dB antennas (70λ diameter) and one watt of radiated power is 60 dB at 8 GHz and 67 dB at 18 GHz. A typical value for the power required at the receiver for satisfactory reception is -95±3 dBw. The difference of about 32± 6 dB is available for fading and for small miscellaneous losses in cables and filters. A few extra dB can be obtained by the use of the maximum available transmitter power and by low noise receivers, but extreme measures are usually not worth the extra cost and decrease in reliability. Breaking up a 100 km path by means of a passive reflector in the middle increases the loss by 48 dB at 8 GHz and by 55 dB at 18 GHz. There is no practical way to make up this large extra loss, except by large reductions in both bandwidth and fading margin.

The specifications for a representative 90 MBit microwave system are shown on Figure 3. This equipment (non-Western Electric although it refers to AT&T information) is designed for the 6 GHz common carrier band, but similar equipment is available in the 7 to 8.5 GHz band and can be made available at higher frequencies. Typical transmission loss calculations are as follows:

	8 GHz	18 GHz
Free space loss on 100 km path in dB	-150	-157
Antenna gain---45 dB at each end	+ 90	+ 90
Line and filter losses-3 dB at each end	- 6	- 6
Net loss in dB	- 66	- 73
Power of 8 watts at 8 GHz and 4 at 18 GHz	+ 9 dBw	+ 6 dBw
Free space signal at receiver input	- 57	- 67
Receiver threshold in dBw	- 95±3	- 95±3
Fading margin in dB	38±3	28±3

Conclusions

The conclusions can, perhaps, be expressed best by the following recommendations:

1. An active repeater on South Baldy Mountain is needed for transmission to the VLA site from either the North T or C or North Winston locations.
2. The North T or C site is better for communications and is easier to maintain, at least during poor weather conditions.
3. Transmission of the four 50 MHz signals should be by digital microwave facilities. Single sideband amplitude modulation on either radio or waveguide does not seem feasible.

4. Commercially available digital microwave equipment with "state of the art" dynamic equalization can be adapted for use with the NRAO signals. The many man-years of development represented by the commercial equipment should be utilized so that NRAO personnel can concentrate their effort on their special needs and on problems not yet solved by others.

5. Four 30 MHz or 40 MHz radio channels are needed in each section. Assignments in the 7 GHz to 8.5 GHz band are preferred, but higher frequencies can be used, with the difficulty incresing with frequency. A total of 8 adjacent channels are requested for the two sections from North T or C (or Winston) to South Baldy and then on to the VLA. Alternate channels should be used in one section and the intermediate channels used in the second link. In the event that 8 such channels are not available, four alternately spaced channels can probably be made to work by the use of opposite polarization in the two links and high performance antennas (low sidelobes) at the repeater site on South Baldy. Both polarizations should not be used in the same section because most of the expected polarization discrimination can be lost during multipath fading.

6. Transmission of the timing signals will require a separate, narrow band radio channel. It should travel the same paths as the wideband signals. A different route, such as by way of a passive reflector on Mt. Withington, would not "see" the same phase variations.

7. The vertical dimensions of the antennas should be between 50 and 100 wavelengths.

8. A fading margin of at least 25 dB and preferably more than 30 dB should be provided.

9. Space diversity should be included in the planning but not installed, if, as now believed, an outage time of 1% or 2% can be tolerated on the microwave facility. This assumption is a reasonable one if microwave fading and poor "seeing" conditions for radio astronomy tend to occur at the same time. Should experience demonstrate that improved reliability is needed for efficient operation, the addition of space diversity is the first step.

10. If there is any appreciable chance that reliability approaching telephone company requirements will be needed in the future, it should be built initially. Improvements in reliability are expensive, and doubly so, on an "add on" basis.

11. The phase locked loop needs to be capable of following changes in phase of a few degrees per second and an occasional peak rate of up to one radian per second.

12. Long term measurements should be made on the NRAO 17 GHz path in West Virginia, especially if it appears that frequency assignments below 9 GHz will not be available in New Mexico.

Kenneth Bullington
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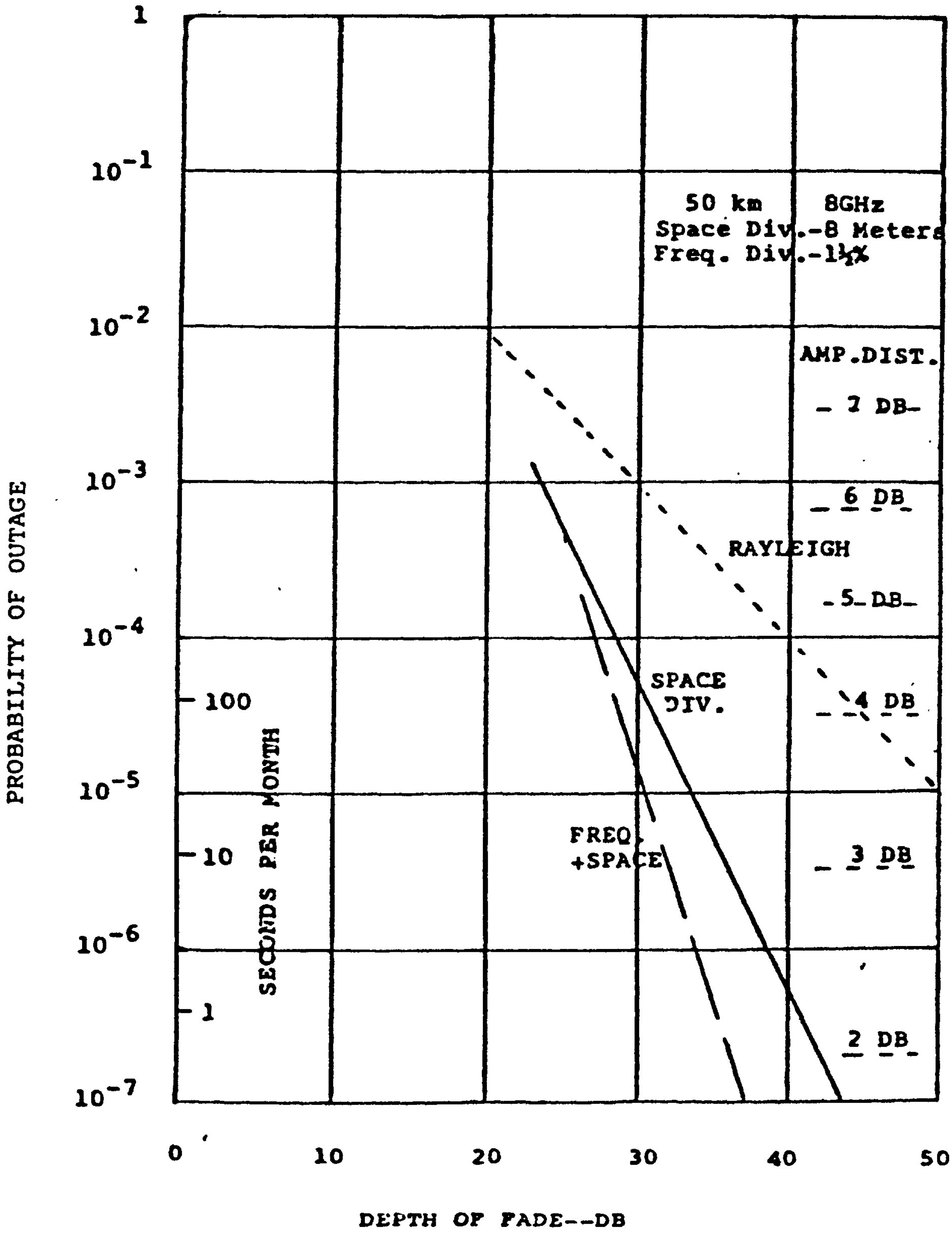
PROBABILITY OF MICROWAVE FADING



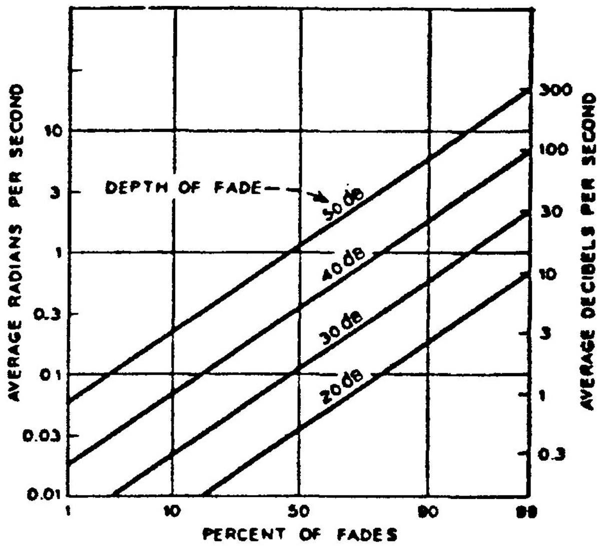


Fig. 2—Rates of change in amplitude and phase during fading at 4 GHz on a 30-mile path.

From "Phase and Amplitude Variations in Multipath Fading of Microwave Signals", Bell System Technical Journal, vol 50, July-August 1971, pp 2039-2053.

Figure 2

SPECIFICATIONS

FCC Data

Frequency Range .... 5.925 to 6.425 GHz
Emission Designator 30,000F9Y
Modulation .... 8 PSK
Data Rate .... 90.258 Mb/s
Data Efficiency .... 3.01 b/s per Hz
Transmit Frequency Stability 0.0005%
Maximum Transmitter Power*
  Frequency Diversity .... 10 watts
  Hot-Standby .... 20 watts

Environmental

Temperature Range
  Guaranteed Performance .... +10° to +40°C
  Operable .... -20° to +50°C
  (NOTE: Operable means system gain may degrade by 3 dB.)
Humidity .... Up to 95% at 50°C
Altitude .... 4572 r ' ft)

Receiver

Receiver Noise Figure** .... 8 dB
IF Frequency .... 70 MHz
Maximum Normal Receive Carrier Level
(with no degradation) .... -8 dBm
Receiver Threshold**

BER	Guaranteed Over 10° to 40°C	Guaranteed at 25°C	Typical
10^{-6}	-62 dBm	-65 dBm	-67 dBm
10^{-3}	-65 dBm	-69 dBm	-70 dBm

Effective Fade Margin at 10⁻³ BER
(with adjacent channel interference) .... 37 dB

Transmitter

Power Output**
  Frequency Diversity .... +36 dBm
  Hot-Standby .... +39 dBm

	Guaranteed Over 10° to 40°C	Guaranteed at 25°C	Typical
System Gain (BER = 10^{-6})	98 dB	101 dB	103 dB
System Gain (BER = 10^{-3})	101 dB	105 dB	106 dB

(NOTE: For hot-standby, space-diversity operation, add 3 dB to system gain figures.)

Operation With Adjacent Analog Radio Channel

Noise Contribution to Analog Channel
With 1200- or 1800-Channel Capacity
(for details contact engineer) ... <4 dBrnC0

DS3 Interface

DS3 Interface .... In accordance with AT&T Compatability Bulletin No. 119

Equipment Alarms

SYSTEM

BER > 10^{-3}	Input Converter
BER > 10^{-7}	Output Converter
Loss of Synchronization	Loss of Clock
Data Switch	Switch Off Normal

RECEIVE

LO Power	Power Supply
LO Lock Limit	Receive Carrier Level
LO Off Frequency	Loss of Frame
AGC Off Normal	

TRANSMIT

LO Lock Limit	Encoder Activity
LO Off Frequency	Power Supply
Modulator Activity	Transmit Level
Loss of Frame	Power Output
Loss of Clock	

Current Requirements (Typical)

Terminal Rack (2 TR Units)
  -24 V .... 24 A
  -48 V .... 12 A

Repeater Rack (2 TR Units)
  -24 V .... 18.5 A
  -48 V .... 9.3 A

Repeater Rack With Drops (2 TR Units)
  -24 V .... 24 A
  -48 V .... 12 A

*This is for FCC information only; not to be used as guaranteed power output. See transmitter specifications for guaranteed power output.

**Measured at antenna port of branching circulator.

Figure 3