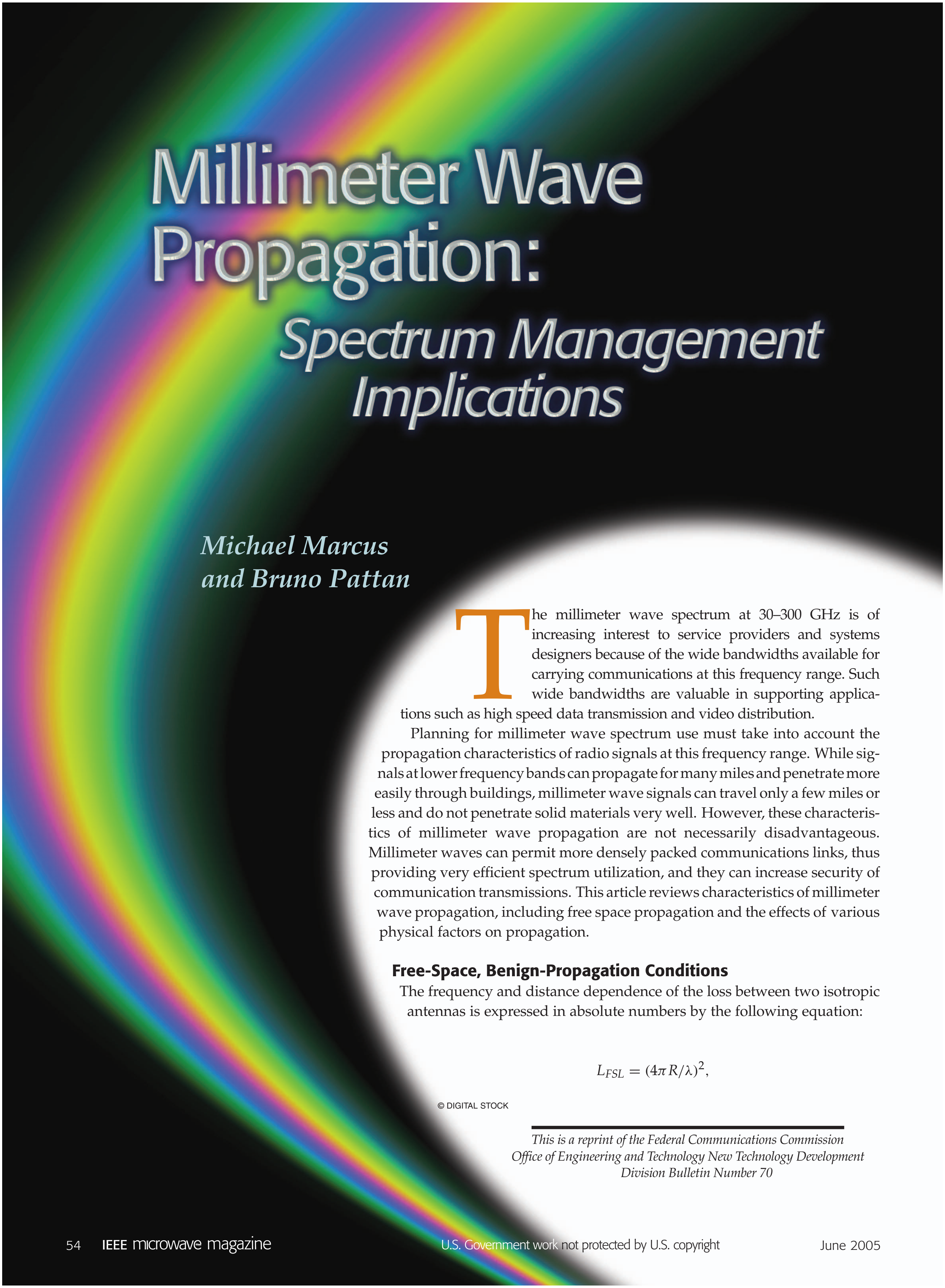

Millimeter Wave Propagation:

Spectrum Management Implications

Michael Marcus
and Bruno Pattan

The millimeter wave spectrum at 30–300 GHz is of increasing interest to service providers and systems designers because of the wide bandwidths available for carrying communications at this frequency range. Such wide bandwidths are valuable in supporting applications such as high speed data transmission and video distribution.

Planning for millimeter wave spectrum use must take into account the propagation characteristics of radio signals at this frequency range. While signals at lower frequency bands can propagate for many miles and penetrate more easily through buildings, millimeter wave signals can travel only a few miles or less and do not penetrate solid materials very well. However, these characteristics of millimeter wave propagation are not necessarily disadvantageous. Millimeter waves can permit more densely packed communications links, thus providing very efficient spectrum utilization, and they can increase security of communication transmissions. This article reviews characteristics of millimeter wave propagation, including free space propagation and the effects of various physical factors on propagation.

Free-Space, Benign-Propagation Conditions

The frequency and distance dependence of the loss between two isotropic antennas is expressed in absolute numbers by the following equation:

$$L_{FSL} = (4\pi R/\lambda)^2,$$

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This is a reprint of the Federal Communications Commission Office of Engineering and Technology New Technology Development Division Bulletin Number 70 where *FSL* is the free-space loss, *R* is the distance between transmit and receive antennas, and λ is the operating wavelength.

After converting to units of frequency and putting them in decibel form, the equation becomes:

$$L_{FSL\ \mathrm{dB}} = 92.4 + 20\log\ f + 20\log\ R,$$

where f is the frequency in gigahertz, R is the line-of-sight (LOS) range between antennas in kilometers.

Figure 1 shows the free-space loss, or attenuation, incurred for several values of frequency. For every octave change in range, the differential attenuation changes by 6 dB. For example, in going from a 2- to a 4-km range, the increase in loss is 6 dB. Note that, even for short distances, the free-space loss can be quite high. This suggests that, for applications in the millimeter-wave spectrum, only short-distance communications links will be supported.

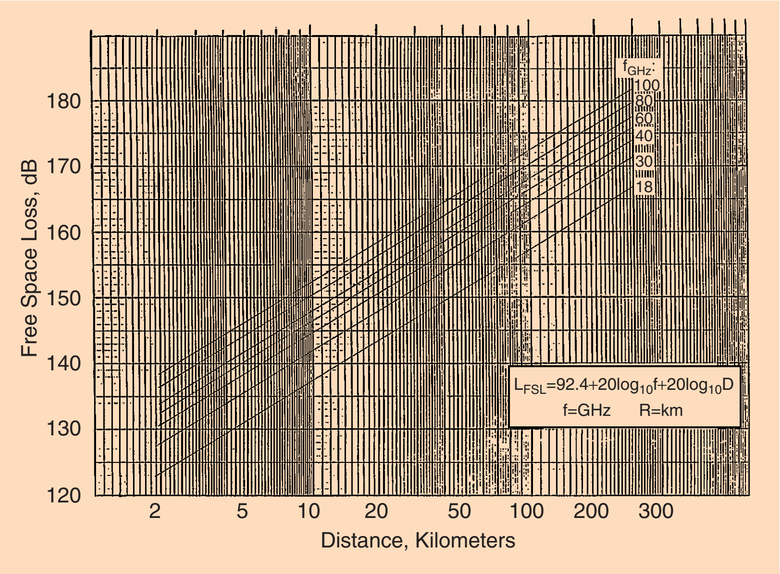


Figure 1. *Free-space loss between isotropic antennas.*

Millimeter-Wave Propagation Loss Factors

In microwave systems, transmission loss is accounted for principally by the free-space loss. However, in the millimeter-wave bands additional loss factors come into play, such as gaseous losses and rain in the transmission medium. Factors that affect millimeter wave propagation are given in Figure 2.

Atmospheric Gaseous Losses

Transmission losses occur when millimeter waves traveling through the atmosphere are absorbed by molecules of oxygen, water vapor, and other gaseous atmospheric constituents. These losses are greater at certain frequencies, coinciding with the mechanical resonant frequencies of the gas molecules. Figure 3 gives qualitative data on gaseous losses. It shows several peaks that occur due to absorption of the radio signal by water vapor (H_2O) and oxygen (O_2). At these frequencies, absorption results in high attenuation of the radio signal and, therefore, short propagation distance. For current technology, the important absorption peaks occur at 24 and 60 GHz. The spectral regions between the absorption peaks provide windows where propagation can more readily occur. The transmission windows are at about 35, 94, 140, and 220 GHz.

The H_2O and O_2 resonances have been studied extensively for purposes of predicting millimeter propagation characteristics. Figure 4 [3] shows an expanded plot of the atmospheric absorption versus frequency at altitudes of 4 km and sea level, for water content of 1 gm/m^3 and 7.5 gm/m^3, respectively (the former value represents relatively dry air while the latter value represents 75% humidity for a temperature of 10 °C).

An additional set of curves for *total* one-way attenuation through the atmosphere, including attenuation due to water vapor and oxygen, is given in Figure 5. This is shown for several angles from the vertical, or zenith. Clearly, the greater this angle Φ, the more atmosphere the signal goes through and, consequently, the more the signal is attenuated.

Figure 6 [1] shows the one-way attenuation through the atmosphere for *oxygen only*. The attenuation increases as the off-zenith angle Φ, increases, due to the longer distance atmospheric penetration. As one would expect, the loss is highest around the 60-GHz oxygen absorption peak for all elevation angles.

Figure 7 shows the gaseous attenuation for oxygen absorption and for water vapor absorption as a function of range, over and above the free-space loss given in Figure 1. The resonances for frequencies below 100 GHz occur at 24 GHz for water vapor and 60 GHz for oxygen.

Figure 8 depicts total attenuation, including free-space loss and gaseous attenuation, for three typical frequencies. There is no significant increase in attenuation due to gaseous absorption above the free-space loss given in Figure 1, except for the 60-GHz band. Above a distance of about 9 km, the composite loss (free-space loss plus absorption) increases significantly from free-space loss alone.

Figure 9 indicates the frequency reuse possibilities, based on atmospheric gaseous losses, for typical digital fixed service systems operating in the vicinity of

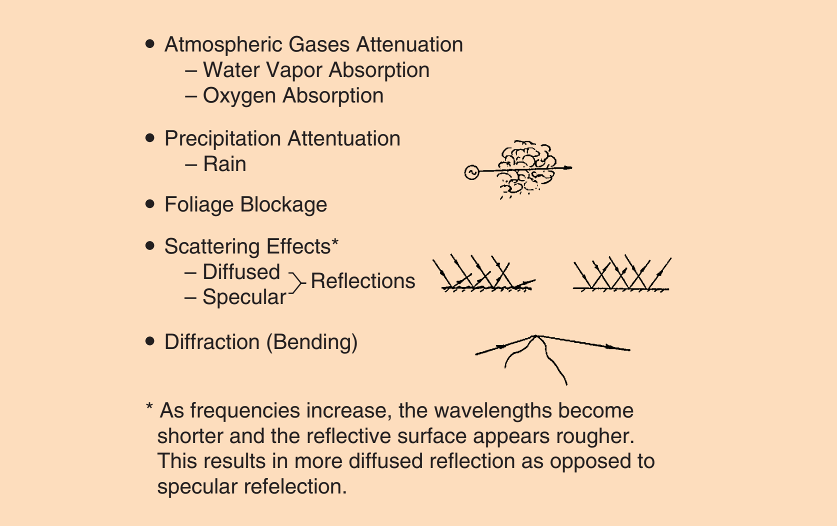


Figure 2. *Propagation effects influencing millimeter-wave propagations.*

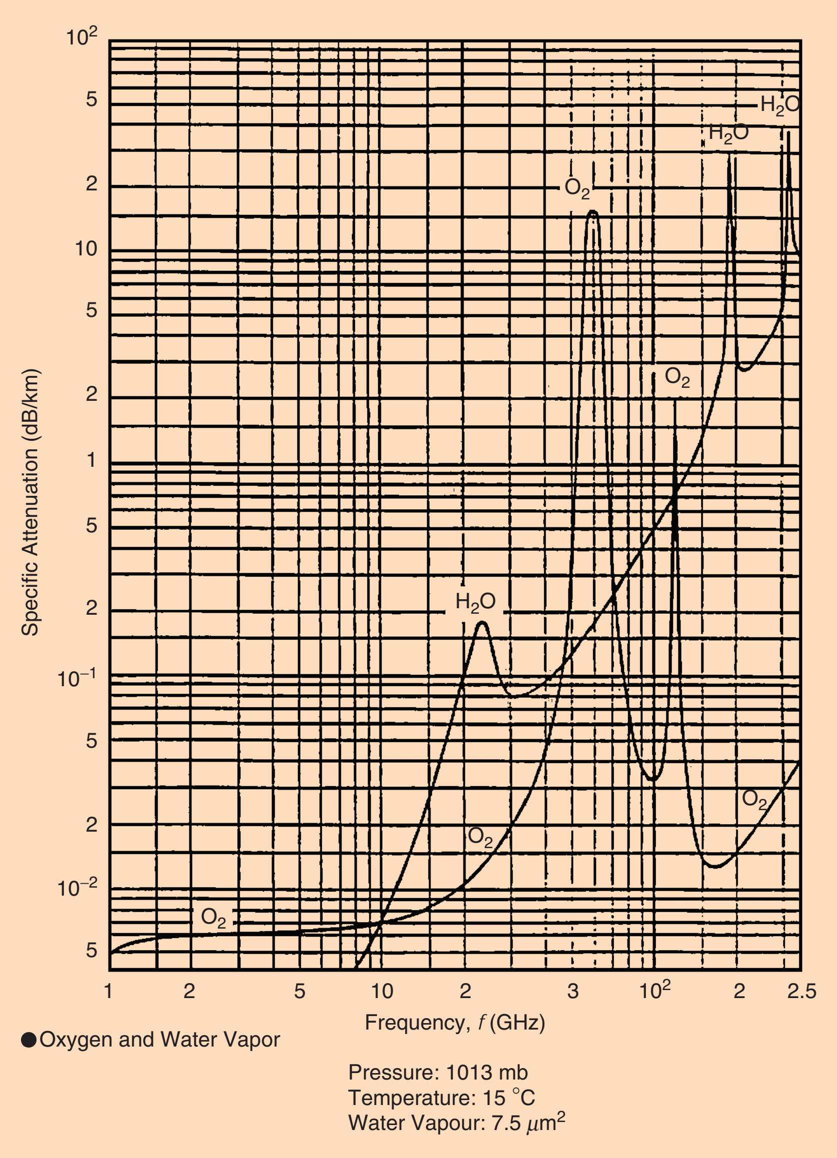


Figure 3. *Specific attenuation due to atmospheric gases.*

60 GHz. Note that at the 60-GHz oxygen absorption peak, the working range for a typical fixed-service communications link is very short, on the order of 2 km, and that another link could be employed on the same frequency if it were separated from the first link by about 4 km.

By contrast, at 55 GHz, the working range for a typical fixed service link is about 5 km, but a second link would have to be located about 18-km away to avoid interference. Other factors must be considered in determining actual frequency reuse such as antenna directivity and intervening obstacle path loss.

Rain Losses

Millimeter-wave propagation is also affected by rain. Raindrops are roughly the same size as the radio wavelengths and, therefore, cause scattering of the radio signal. Figure 10 [1], [2] shows the attenuation per kilometer as a function of rain rate. The rain rate in any location in the continental United States can be determined by referring to a map of rain rate climate regions and a chart of associated rainfall statistics, which are shown in Figure 11(a) and (b), respectively. For example, from Figure 11(b), for 0.1% of the year (99.9% availability) the rain rate is about 14.5 mm/hr for the sub-region D_2 (Washington region) shown in Figure 11(a).

An increase in the rain factor reduces the communications signal availability. A measure of this availability and the corresponding communications outage is shown in Figure 12. For example,for an availability of 99.99%, the outage is 8.8 hr/year or 1.44 min on a 24-hr basis.

Foliage Losses

Foliage losses at millimeter-wave frequencies are significant. In fact, foliage loss may be a limiting propagation impairment in some cases. An empirical relationship

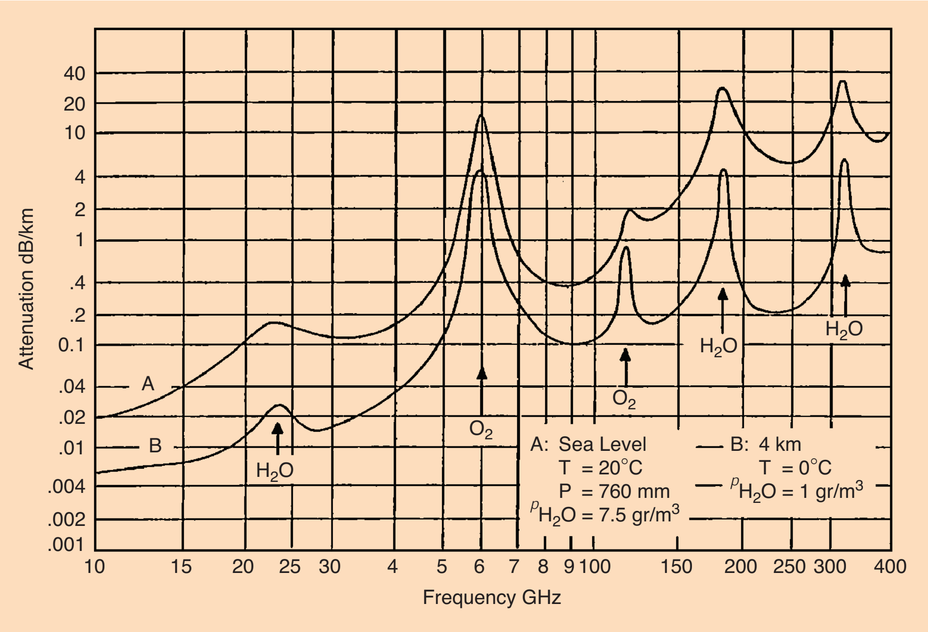


Figure 4. *Average atmospheric absorption of millimeter waves.*

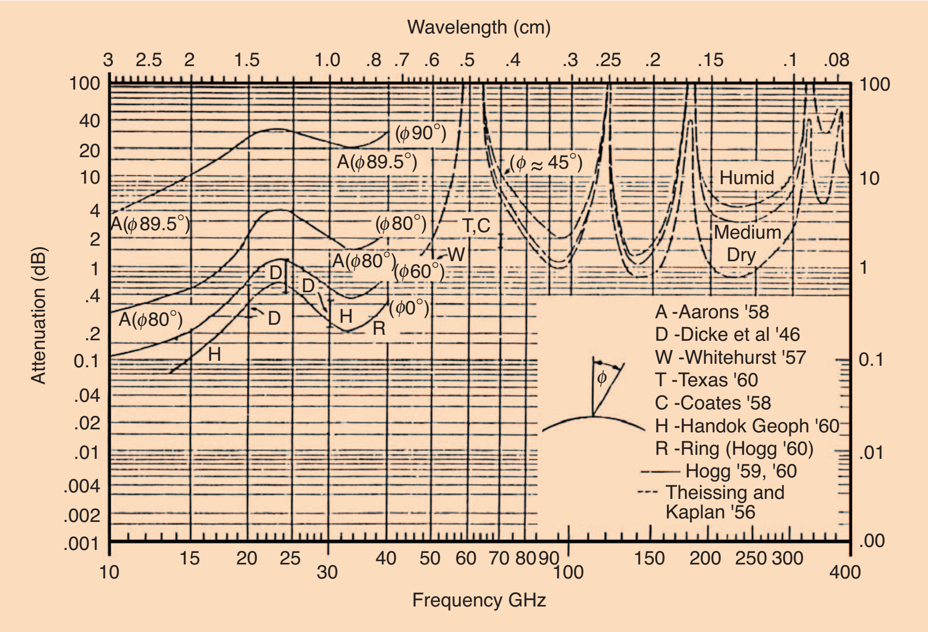


Figure 5. *Total attenuation for one-way transmission through the atmospere.*

has been developed (CCIR Rpt 236-2), which can predict the loss. For the case where the foliage depth is less than 400 m, the loss is given by

$$L = 0.2\, f^{0.3}\, R^{0.6}\ \text{dB},$$

where f is the frequency in megahertz, and R is the depth of foliage transversed in meters and applies for $R < 400$ m.

This relationship is applicable for frequencies in the range 200–95,000 MHz. For example, the foliage loss at 40 GHz for a penetration of 10 m (which is about equivalent to a large tree or two in tandem) is about 19 dB. This is clearly not a negligible value.

Scattering/ Diffraction

If there is no LOS path between the transmitter and the receiver, the signal may still reach the receiver via reflections from objects in proximity to the receiver or via diffraction or bending. The short wavelengths of millimeter-wave signals result in low diffraction. Like light waves, the signals are subject more to shadowing and reflection. (Shadowing makes it easier to shield against unwanted signals in communications systems.)

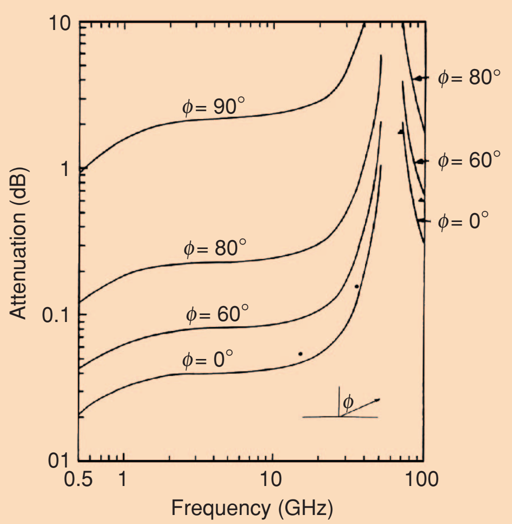


Figure 6. *One-way attenuation through the atmosphere for oxygen only.*

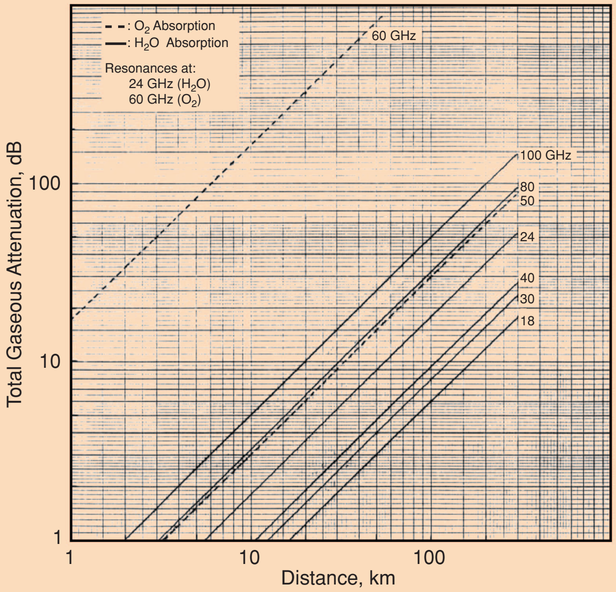


Figure 7. *Gaseous attenuation over and above the free-space loss.*

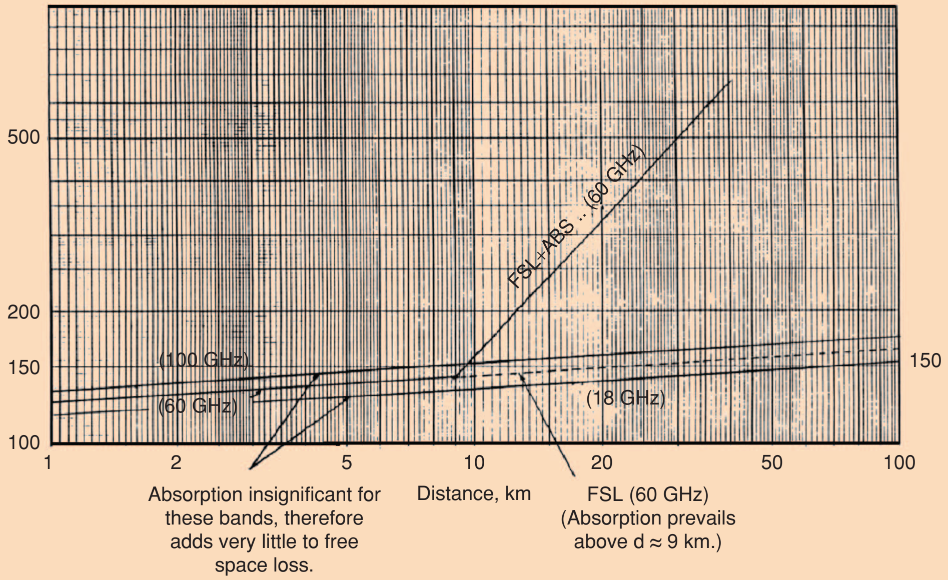


Figure 8. *Combination free-space loss plus absorption.*

Frequency-Band Designations

Q	33–50 GHz
U	40–60 GHz
V	50–75 GHz
E	60–90 GHz
W	75–110 GHz
F	90–170 GHz
D	110–170 GHz
G	140–220 GHz

Normally, for non-LOS paths, the greatest contribution at the receiver is reflected power.

Reflections and the associated amount of signal diffusion are strongly dependent on the reflectivity of the reflecting material. Shorter wavelengths (higher frequencies) cause the reflecting material to appear relatively "rougher," which results in greater diffusion of the signal and less specular (i.e., direct) reflection. Diffusion provides less power at the receiver than specular reflected power.

Sky Noise (Brightness Temperature) in Millimeter Bands

Anything that absorbs electromagnetic energy is also a radiator. Constituents of the atmosphere that cause attenuation, such as water vapor, oxygen, and rain, radiate signals that are noiselike. When these signals impinge on a receiver antenna, they degrade system performance.

An earth-station antenna aimed at a satellite at a high-elevation angle will pick up sky noise emanating from atmospheric constituents (and other sources). This is referred to as the sky-noise temperature or brightness temperature. For low-elevation angles, the dominant noise will be mostly from terrain and will be picked up by the antenna sidelobes.

Figures 13 and 14 [5] show the sky-noise temperature as a function of frequency. The sky noise peaks at the millimeter-wave, gaseous-molecule resonance bands, and this phenomenon also affects the suitability of the millimeter-wave spectrum region for communications applications.

The noise entering a receiver from the antenna is commonly referred to as the antenna noise temperature and includes components of sky

Glossary of Terms

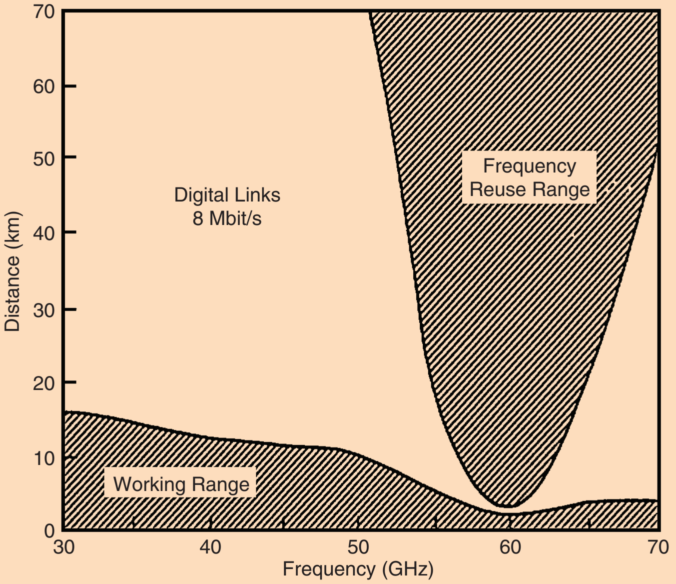
Diffraction: Change in direction (bending) of propagating energy around an object cause by interference between the radiated energy and induced current in the object. There is no line of sight between the transmitter and receiver.

Free-Space Loss: The amount of attenuation of RF energy on an unobstructed path between isotropic antennas. Basically, dilution of energy as the RF propagates away from a source.

Isotropic Antenna: An antenna that radiates in all directions (about a point) with a gain of unity (not a realizable antenna, but a useful concept in antenna theory).

Refraction: Change in direction of propagating radio energy caused by a change in the refractive index or density of a medium.

Resonant Energy: Frequencies in the band where attenuation peaks. In contrast to windows, where the attenuation bottoms out and is lower.



Note: The potential working range is the average maximum distance over which a typical fixed link can operate. The range is influenced by the attenuation of the radio waves in the intervening space, being shorter in cases of high attenuation. Where two links employ the same frequency (i.e., frequency reuse), if they are separated by a distance greater than the frequency reuse range, it will be certain that mutual interference will be below an acceptable level. The frequency reuse range is, thus, always larger than the working range. If the two links are separated by less than the reuse distance, detailed calculatios are necessary to determine whether other factors, e.g., the directionality of the antennas, will provide sufficient protection from mutual interference.

Figure 9. *The potential working and frequency reusage range of millimetric fixed links.*

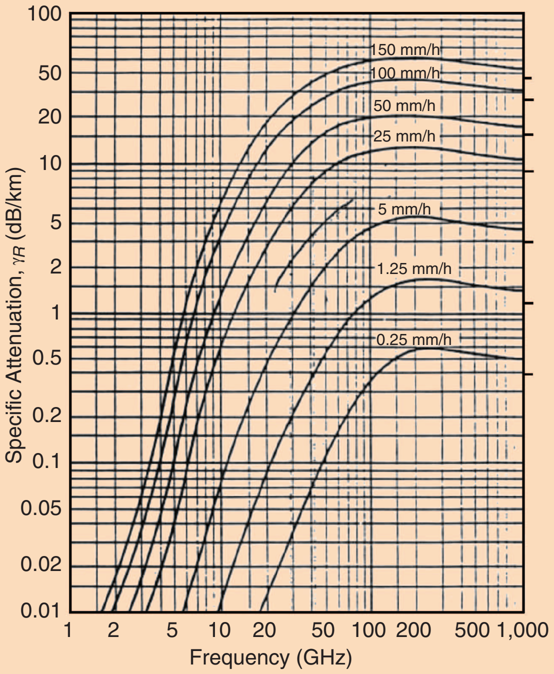


Figure 10. *Specific attenuation due to rain.*

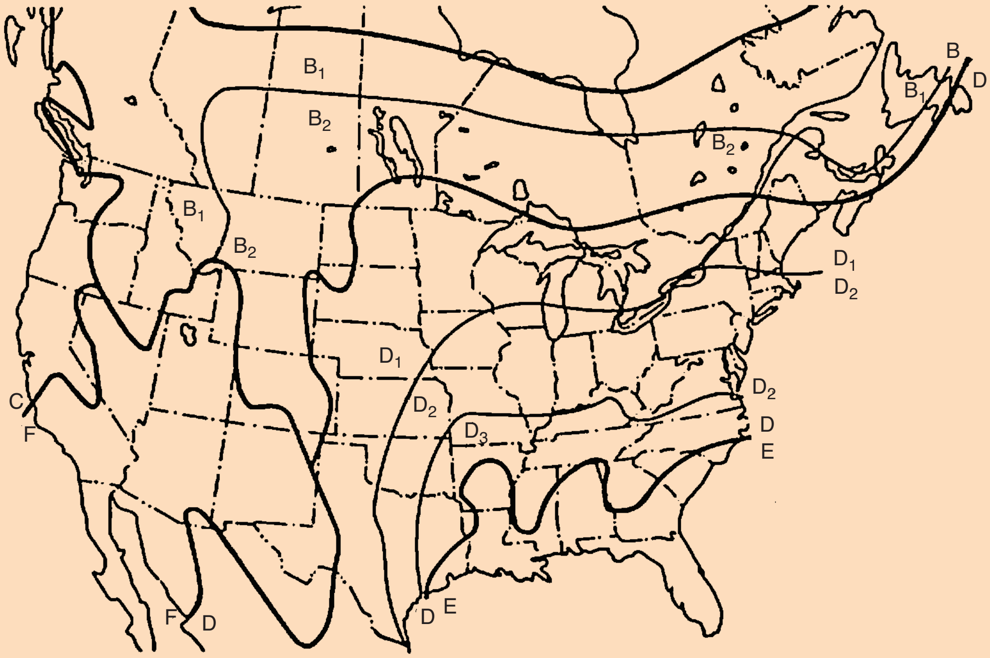
noise. The antenna-noise temperature adds to the receiver noise temperature to form the system noise temperature:

$$T_s = T_{\mathrm{ANT}} + T_{\mathrm{RCVR}}.$$

(To be strictly correct, the system-noise temperature stems from several sources, which are depicted in Figure 15.)

Millimeter-Wave Application

Communication systems operating at millimeter wave



(a)

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
							↑							

(b)

Figure 11. *Rain rates in the United States and Canada.*

frequencies can take advantage of the propagation effects described in the preceding sections. For example [7]:

- Propagation ideally suits short range (<20 km) communications.
- Limited range permits a high degree of frequency reuse.
- In the absorption resonance bands, relatively secure communications can be performed.

On the other hand, propagation effects impose restrictions:

- high attenuation in a rain environment
- limited communications range, typically <20 km
- poor foliage penetration.

		Time per	
Availability %	Outage/Year	Month (Avg)	Day (Avg)
50	4380 hr	360 hr	12 hr
70	2628 hr	216 hr	7.2 hr
80	1752 hr	144 hr	4.8 hr
90	876 hr	72 hr	2.4 hr
95	438 hr	36 hr	1.2 hr
98	175 hr	14 hr	29 min
99	88 hr	7 hr	14.4 min
99.5	43.8 hr	3.6 min	7.2 min
99.9	8.8 hr	43 hr	1.44 min
99.99*	53 min	4.3 min	8.5 s
99.999	5.3 min	26 s	0.86 s
99.9999	32 s	2.6 s	0.086 s

*e.g., one year has 8,760 hr, or 8,760 × 60 min.

For link availability of 99.99%:

unavailability is 1–0.9999 = 0.0001 (outage), outage(%) = 1–availability

or 0.0001 × 8,760 × 60 = 52.56 min.

does not necessarily imply that there is a complete loss of signal, but signal may be present at reduced quality.

Figure 12. *Relationship between system availability and outage time.*#

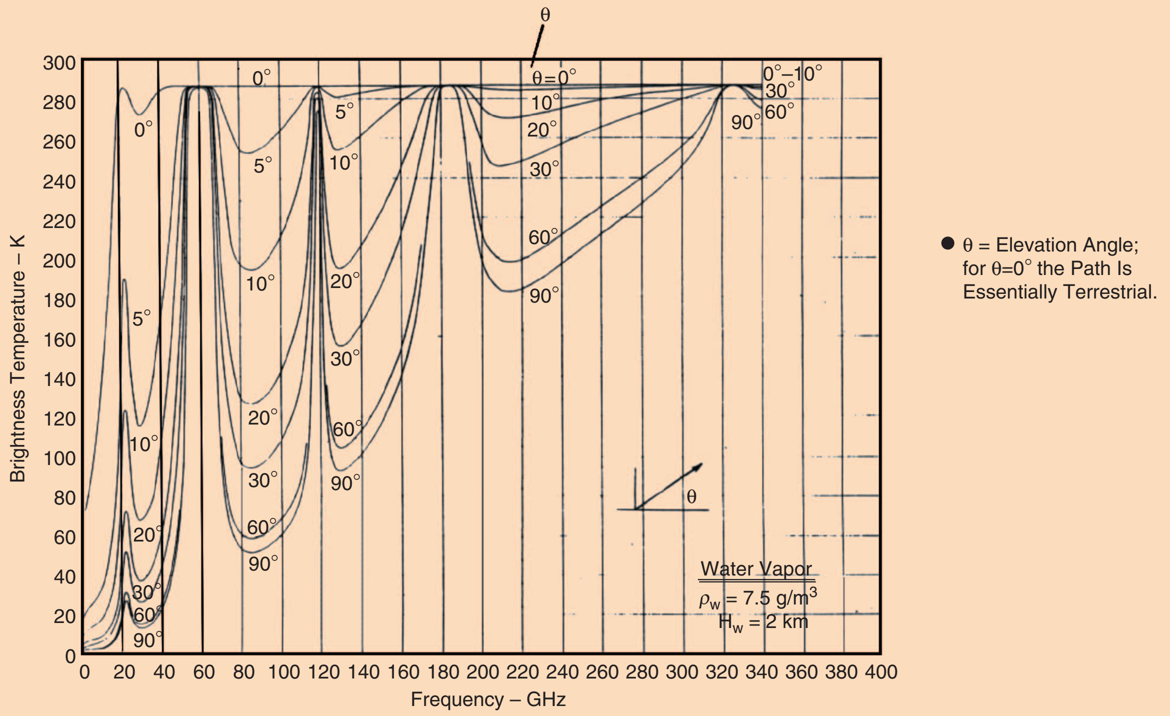


Figure 13. *Brightness temperature (clear air) for a water vapor concentration of 7.5 g/m^3, for frequency ranges 1–350 GHz.*

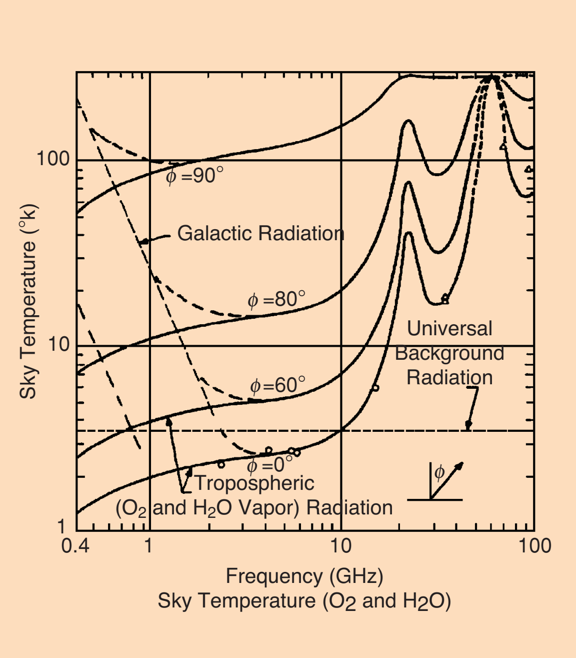


Figure 14. *Sky temperature versus frequency for various antenna beam pointing the angles zenith.*

System designers can take advantage of the propagation properties manifested at millimeter-wave frequencies to develop radio-service applications. The windows in the spectrum are particularly applicable for systems requiring all weather/night operation, such as vehicular radar systems, or for short-range, point-to-point systems such as local-area networks. The absorption bands (e.g., 60 GHz) would be applicable for high data-rate systems where secure communications with low probability of intercept is desirable, for services with a potentially high density of transmitters operating in proximity, or for applications where unlicensed operations are desirable.

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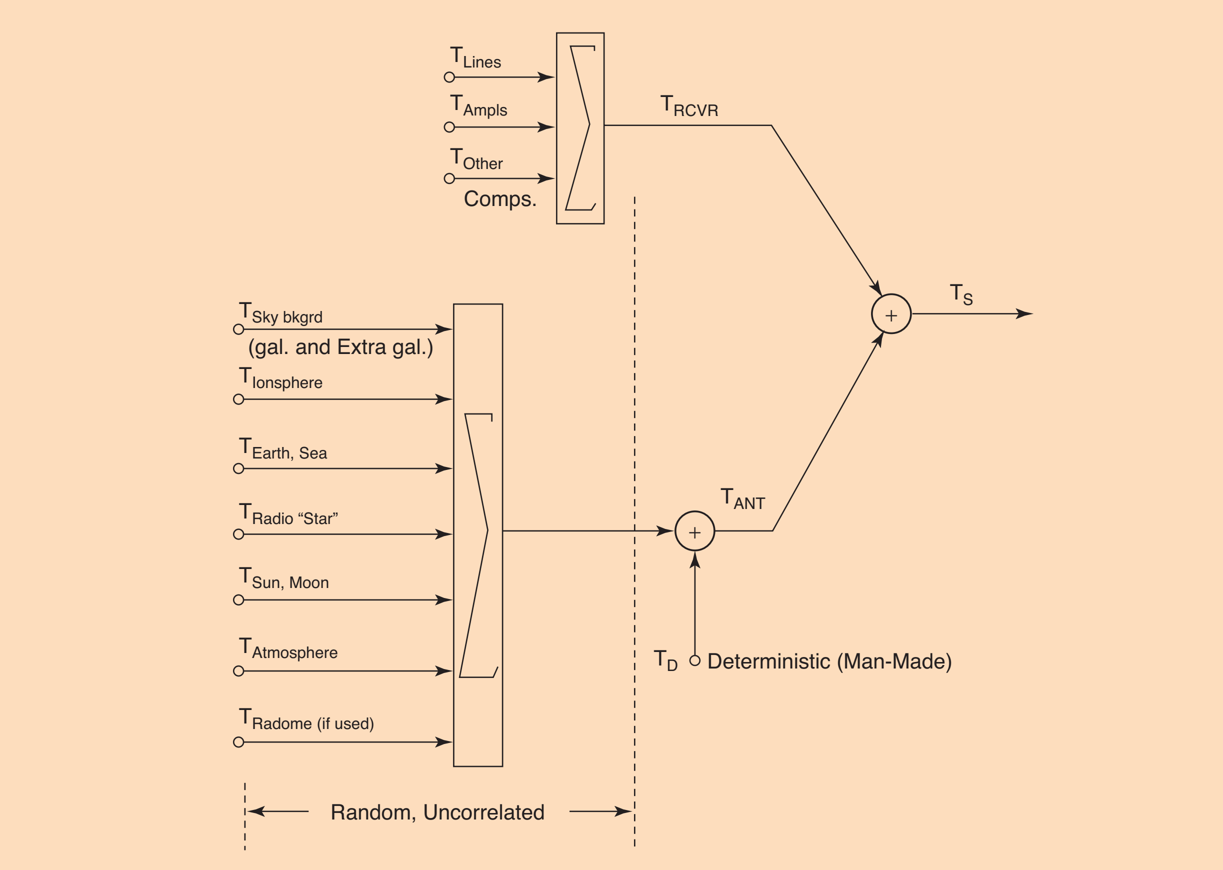

Figure 15. *A model depicting contributors to the system-noise temperature.*