Terrestrial Propagation at LWA Frequencies

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1 Introduction

LWA must contend with an interference environment which is severe in terms of numbers and strengths of interferers simultaneously present. The situation is also complex both because of the wide variety of types of interferers present, and also because of the complex and dynamic nature of the propagation between the source of interfering transmissions and receiving sites. Understanding the nature of this propagation is important both in understanding how to effectively manage or mitigate this interference, and in learning to predict the effect that new or anticipated sources of interference are likely to have on LWA.

In this memo, we briefly describe the nature of propagation channels in the LWA frequency range of interest, in this case taken to be 3 MHz to 108 MHz (including the entire FM broadcast band due to the potential for signals in this band to create linearity problems for LWA receivers). For the purposes of this memo "propagation channel" is defined as the transfer function between a transmitter and a receiver. The transfer function is typically defined in terms of an impulse response. The parameters which are used to characterize the impulse response of a propagation channel include path loss, delay spread, doppler spread, and coherence time.

The LWA frequency range of interest spans multiple "bands," as they are defined by common convention. The "high frequency" (HF) band is usually taken to be 3 MHz through 30 MHz, and the "very high frequency" (VHF) band is usually taken to be 30 MHz through 300 MHz. In many applications the term "VHF Low" is used to describe frequencies from 25 MHz to 50 MHz, which has significance primarily for regulatory as opposed to technical reasons. In this document, we use the term "HF" to refer to 3–30 MHz, and "VHF" to refer to 30–108 MHz. Significant differences exist in the nature HF and VHF propagation channels, so they are considered separately.

2 HF Propagation Channel (3–30 MHz)

At frequencies below 3 MHz ($\lambda > 100$ m), the Earth acts as a lossy dielectric and the dominant propagation mechanism is "ground wave" propagation in which the radiated wave is literally bound to the surface of the Earth [1]. Ground wave propagation generally has quite limited range as the lossy ground dissipates power as the wave propagates. As frequency increases, radiated waves are eventually able to decouple from the Earth, leading to the emergence of a "sky wave," which is essentially free-space propagation. The midpoint of this transition from ground wave propagation to sky wave propagation occurs around 10 MHz ($\lambda \sim 30$ m). Above that frequency, the Earth becomes sufficiently conductive that the ground wave mechanism is essentially "shorted out" and cannot efficiently propagate.

The efficacy of sky wave propagation is highly dependent on the ionosphere. The ionosphere is a layer of free electrons which exists above the Earth's atmosphere [2]. The presence of free electrons has a refractive and dispersive effect on propagating sky waves. The electron density is time-varying and inhomogeneous over spatial scales ranging from wavelengths to continental dimensions. In order for a sky wave to return to earth, the electron density must be sufficiently large for refraction to redirect the sky wave toward Earth. The effectiveness of the ionosphere in reflecting a sky wave decreases with increasing frequency, resulting in a "maximum useable frequency" (MUF) above which the ionosphere no longer efficiently reflects sky waves. The MUF varies with latitude, time of day, season, and phase within the 11-year solar cycle. Over a daily cycle, MUF varies roughly from a few MHz to tens of MHz.

A single reflection from the ionosphere is usually sufficient to allow propagation over continental distances or further. In the frequency range above a few MHz and below the MUF, both the ionosphere and the surface of the Earth are efficient reflectors, and thus the possibility of multiple reflections ("multiple hop") between the surface of the Earth and the ionosphere are possible. This allows HF band signals to sometimes propagate with very low loss over intercontinental distances.

Thus, spectral occupancy in the HF band, from the perspective of a receiver on the ground, appears to vary according to a daily cycle as transmission from more or fewer stations are able to propagate over the required distance.

The time-varying and inhomogeneous electron density of the ionosphere imparts both Doppler (frequency) spread and multipath (delay) spread onto the sky wave. The associated impulse response is well-described by a wide sense stationary uncorrelated scattering (WSSUS) model [3, 4]:

$$h(\tau; t) = \sum_{n=1}^{N} \alpha_n c_n(\tau; t) \delta(\tau - \tau_n) \tag{1}$$

where τ is the time parameter, and t is used simply to index the current state of the time-varying impulse response function. In this equation, N is the number of resolvable discrete paths (typically a small number or just 1), α_n is the attenuation associated with path n, τ_n is the differential delay associated with path n, $\delta(\tau)$ is the Dirac delta function, and $c_n(\tau; t)$ is a complex-valued quantity which describes both the unresolved portion of the delay spread as well as the doppler spread of path n. The received signal is then given by the convolution of $h(\tau; t)$ with the transmitted signal.

In general, $c_n(\tau; t)$ is quite complex; e.g., see [3, 4, 5]. However, HF ionospheric propagation channels can usually be treated as stationary over 10's of kHz and 10's of minutes. Exceptions are times around sunset and sunrise, and during periods of extreme ionospheric disturbance. Also, for the purposes of modeling propagation of narrow bandwidth communication signals, it is usually reasonable to simplify $c_n(\tau; t)$ to represent only Doppler shift, as the part of the delay spread modeled by this coefficient cannot be resolved over the limited bandwidth of most communications signals. The simplified model is then:

$$h(\tau; t) = \sum_{n=1}^{N} \alpha_n e^{j\omega_{d,n}\tau} \delta(\tau - \tau_n) \tag{2}$$

where $\omega_{d,n}$ is the Doppler shift associated with path n.

In terms of this model, the HF sky wave channel typically exhibits Doppler spreads less than 1 Hz, increasing to as much as 30 Hz during times of severe disturbance. Note that the Doppler spread can easily be as large as or larger than the expected frequency error associated with the transmitter: For example, 0.1 ppm frequency offset (representing a mediocre frequency standard at the transmitter) at 30 MHz is a 3 Hz error. Doppler can arise independently due to motion of the transmitter; e.g., transmission from ground vehicles, ships, or aircraft. Generally, only aircraft speeds are large enough to generate Doppler shifts sufficient to dominate over ionospheric Doppler or source frequency error.

Delay spreads for the HF sky wave channel are typically $\ll 1$ ms, increasing to as much as 7 ms during times of severe disturbance. The expected delay spread does not typically have much impact on received signals because the associated coherence bandwidth (the bandwidth over which the channel can be assumed to be approximately constant, and roughly equal to the reciprocal of the delay spread) is typically $\gg 1$ kHz, whereas most HF-band modulations occupy only a few kHz. However at extreme values associated with highly disturbed ionospheric conditions (e.g., 7 ms), the associated coherence bandwidth shrinks to just a few hundred Hz. Under these conditions, the channel can therefore become "frequency-selective" even from the perspective of typical HF communications bandwidths. Usually, however, the channel can be assumed to be "flat"; i.e., constant over the bandwidth of the signal.

3 VHF Propagation Channel (30–108 MHz)

The efficiency of the ionosphere as a reflector of radio waves falls off sharply with increasing frequency. Above 30 MHz, efficient ionospheric reflection is a relatively rare occurance. As a result, the propagation of signals at VHF tends to be limited by the curvature of the earth, with antenna height being a significant factor. A common expression for this "horizon" distance assuming that one antenna is located at ground level is

$$R = (4.12 \text{ km})\sqrt{\frac{h_a}{1 \text{ m}}} \tag{3}$$

where h_a is height of the other antenna above ground [14]. For example, a broadcast antenna mounted at a height of 100 m can cover a radius of about 41 km through line-of-sight (LOS) propagation, assuming no terrain blockage. If the LOS path within the circle defined by the radio horizon is blocked by terrain, then propagation is obviously impeded. In this case, a situation-specific propagation path loss prediction technique such as Longley-Rice (also known as the "Irregular Terrain Model" (ITM)) [6]–[9] is typically employed. (The Okumura-Hata method [10] is another popular technique but is not believed to be valid below 150 MHz.) Longley-Rice path loss predictions are nominally valid in the range 20 MHz to 20 GHz, but are known to be vulnerable to a number of problems of both a theoretic and practical nature (e.g., [11]). Various efforts to refine and standardize methodologies are considered in [12] (30–1000 MHz) and [13] (100 MHz–800 MHz). It should also be noted that terrain scattering can allow communications beyond the radio horizon, although typically with attenuation that is much greater than free space.

Whereas the ionosphere is usually not a factor in VHF propagation, terrain features such as mountain ranges are sufficiently large compared to a wavelength to become efficient reflectors. Since terrain features are utterly stationary, the associated multipath channels tend also to be highly stationary and free of doppler. However, VHF frequencies are commonly used for mobile communications (where, in contrast to HF frequencies, compact resonant-mode antennas are possible). Thus, considerable doppler is often observed due to motion of the transmitter. For example, the maximum Doppler shift expected from a vehicle moving at 100 mph at 50 MHz is about 25 Hz. Source frequency errors are usually negligible unless the transmitter is fixed.

If significant multipath scattering exists at the transmitter's location (regardless of whether it resolvable in time or not), then an interference pattern (commonly known as "Rayleigh fading") is created which is spatially periodic with a period of $\sim \lambda/2$ [14]. The associated coherence time can be taken to be roughly 1/10 of this time. So for the example of a vehicle moving at 100 mph and transmitting at 50 MHz the coherence time is lower bounded at $\sim$ 20 ms.

Delay spread in the VHF channel depends on the difference in propagation time between the most direct path and paths which are specularly-reflected from terrain features. To have significant strength, the longer path must typically lie entirely within the radio horizon, which then places an upper bound on the maximum possible delay spread. For example, consider the $h_a = 100$ m example above, where the other end of the link is located at the radio horizon. A rough guess at the path length associated with the longest detectable multipath is $\sqrt{2}R$. The delay spread is then determined by the associated differential propagation delay $(\sqrt{2}R - R)/c \approx 57~\mu$s. In practice, maximum delay spreads of only about 1/10 of this; i.e., $\sim 5~\mu$s, are encountered in practice (e.g., [16]). Given that multipath at VHF and above appears under normal circumstances to be determined primarily by reflection from terrain features, it could be anticipated that the delay spread is frequency independent. This is consistent with the findings of experimental studies [14, 15]. The associated coherence bandwidth at is lower-bounded to $\sim 1/(5~\mu\text{s}) = 200$ kHz and thus VHF-band communications, which have bandwidths of 200 kHz or less, typically do not experience frequency-selective fading.

Occasionally, ionospheric conditions become disturbed in a way that allows HF-type ionospheric propagation to prevail even at VHF frequencies. For example, "Sporadic E" (E_s) conditions can occur in which the ionosphere temporarily becomes an efficient reflector over a region of the Earth for minutes to hours at a time [2]. When this happens, a portion of the VHF band behaves very similarly to HF below MUF. The MUF for E_s conditions is often as high as 70 MHz, and occasionally much higher, but only very rarely extending into the FM broadcast band. Because E_s conditions

	HF	VHF
Frequency Range (for this memo)	3–30 MHz	30–108 MHz
Primary Mechanism	Sky wave refraction	LOS & terrain scattering
Typical Range	Regional to intercontinental (see "caveats")	$\sim$ to radio horizon (see "caveats")
Doppler	$<$ 1 Hz typ. up to 30 Hz	$<$ 50 Hz due to TX motion
Source Freq. Error	Can be comparable to Doppler	Mobile transmitter: Negligible Fixed transmitter: Possibly important
Delay Spread	$\ll$ 1 ms typical up to 7 ms	$<$ 5 ms typical
Coherence Bandwidth	$\gg$ 1 kHz typical Due to ionosphere	$>$ 200 kHz typical Due to terrain reflection
Coherence Time	$\sim$ 10 min typical Due to ionosphere	$\geq$ 10 ms; much longer for broadcast Due to transmitter motion
Caveats	Disturbed ionosphere, Multiple hop possible	Sporadic E, Meteor scatter

Table 1: Summary of HF- and VHF-band propagation.

are localized, multiple reflections are typically not possible. E_s is most common over North America in daylight hours from April through July, and events range in length from a few minutes to a few hours.

Yet another phenomenon which can cause VHF to take on HF-like ionospheric propagation behavior is *meteor scatter* [17]. Meteors entering the Earth's atmosphere leave a trail of ionization which can be sufficiently dense to become an efficient reflector of sky waves at frequencies throughout the VHF band. These ionization trails are very localized and typically last only for seconds; on the other hand there is a steady stream of meteors falling to earth throughout the day. From the perspective of the receiver, propagation via meteor scatter is perceived as only an intermittent "ping" during which a transmitter which would not normally be detectable is briefly observed. Meteor scatter is sufficient to allow communications at VHF frequencies over continental distances.

4 Summary

Findings of this memo are summarized in Table 1.

References

[1] W. Stutzman and G. Thiele, *Antenna Theory & Design*, 2nd Ed., Wiley, 1998.

[2] K. Davies, *Ionospheric Radio*, Peter Peregrinus Ltd, London, 1990.

[3] C.C. Watterson, J.R. Juroshek, and W.D. Bensema, “Experimental confirmation of an HF channel model,” *IEEE Trans. Comm. Tech.*, vol. COM-18, no. 6, December 1970, pp. 792803.

[4] L.E. Vogler and J.A. Hoffmeyer, “A model for wideband HF propagation channels,” *Radio Science*, Vol. 28, No. 6, 1993, pp. 1131–42.

[5] L.E. Vogler and J.A. Hoffmeyer, “Correction to ‘A model for wideband HF propagation channels’,” *Radio Science*, Vol. 29, No. 1, 1994, pp. 153–4.

[6] U.S. Department of Commerce NTIA/Institute for Telecommunication Sciences, “Irregular Terrain Model (ITM) (Longley-Rice),” [on-line] http://flattop.its.bldrdoc.gov/itm.html.

[7] A. G. Longley and P. L. Rice, “Prediction of Tropospheric radio transmission over irregular terrain, A Computer method”, ESSA Tech. Rep. ERL 79-ITS 67, U.S. Government Printing Office, Washington, DC, July 1968. Out of print; see [6].

[8] G. A. Hufford, A. G. Longley, and W. A. Kissick, “A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode,” NTIA Rep. 82-100, Apr. 1982. Out of print; see [6].

[9] Office of Engineering and Technology (OET), “LongleyRice Methodology for Evaluating TV Coverage and Interference, Federal Communications Commission Bulletin No. 69, July 2, 1997.

[10] M. Hata, “Empirical Formula for Propagation Loss in Land Mobile Radio Services,” *IEEE Trans. Vehicular Technology*, Vol. VT-29, 1980, pp. 317–25.

[11] O. Bendov, “On the validity of the LongleyRice (50,90/10) propagation model for HDTV coverage and interference analysis,” *Proc. NAB Broadcast Engineering Conf.*, Las Vegas, NV, 1999.

[12] International Telecommunications Union (ITU), “VHF and UHF Propagation Curves for the Frequency Range from 30 MHz to 1000 MHz,” Rec. ITU-R P.370-7, 1995.

[13] C. Prez-Vega & J.M. Zamanillo, “Path-loss model for broadcasting applications and outdoor communication systems in the VHF and UHF Bands,” *IEEE Trans. Broadcasting*, Vol. 48, No. 2, Jun 2002, pp. 91–6.

[14] W.C.Y. Lee, *Mobile Communications Engineering*, McGraw-Hill, 1982.

[15] J.J. Egli, “Radio Propagation Above 40 Mc over Irregular Terrain,” *Proc. IRE*, Oct 1957, pp. 1383–1391.

[16] G. Hufford, “A characterization of the multipath in the HDTV channel,” *IEEE Trans. Broadcasting*, Vol. 38, No. 4, December 1992, pp. 252– 5.

[17] D.L. Schilling, *Meteor Burst Communications: Theory and Practice*, Wiley, 1993.