# The Walnut Street Model of Ionospheric HF Radio Propagation

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May 1997

## *Abstract*

This paper describes the Walnut Street model of ionospheric propagation of HF radio signals. This model was developed for use in simulations of HF data link and network protocols, and includes temporal effects ranging from the multi-year sunspot cycle through Rayleigh fading on the order of seconds.

## Introduction

The ionospheric channel is well known for exhibiting temporal effects over a wide range of time scales [1], including multipath spreads on the order of milliseconds that produce intersymbol interference, various types of fading on the order of seconds to minutes, hourly diurnal variations, and so on up through the 11-year sunspot cycle. Despite these channel impairments, the value of beyond-line-of-sight wireless communications is such that technologies have been developed to deal with each of these challenges. These techniques are often evaluated via simulation in the earliest stages of development, so the HF radio research community found it useful to agree on a standard approach to simulating the ionospheric channel.

A group of these researchers, members of the HF Radio Technical Advisory Committee who advise the US Government on the development of standards for HF radio technology, met in a brew pub on Walnut Street in Boulder, Colorado to agree on a reasonable approach to simulating the HF channel over time scales of seconds to years. The result, described in this paper, was naturally named the "Walnut Street Model."

### HF Radio Channels

An HF skywave channel conveys signals beyond line of sight via refraction from the ionosphere (and possibly intermediate "bounces" off the earth) to one or more distant receivers. The refractive and absorptive characteristics of the ionospheric layers depend strongly on radio frequency, latitude, time of day, season, the solar weather, and so on. Signals reach the receiver via refraction from one or more ionospheric layers, each of which may be in motion. The received signal is often a composition of multiple signals having independent, time-varying path losses and phase shifts. Thus we may expect multipath interference, deep fades, and impulsive (non-Gaussian) noise, all superimposed on a slowly varying SNR trend. The remainder of this introduction summarizes characteristics of the HF channel, followed by a description of the Walnut Street model.

### Ionospheric Path Loss

It is useful to consider the effects of the ionospheric channel as a superposition of effects due to three categories of considerations:

- Path geometry relative to the sun, and other slowly varying factors (longest time scales)
- Fading effects due to ionospheric motion and similar phenomena (intermediate time scales)
- Multipath interference, which produces Rayleigh fading (shortest time scales)

The first category of effects has been captured in the models used in well-known ionospheric propagation prediction programs such as IONCAP (and its derivatives VOACAP and ICEPAC). The third category is usually represented using the Watterson model [2]. The intermediate category is not as well-known, however, so it is described in some detail below.

**Fading Categories**

Goodman [1] (p. 268) refers to CCIR Reports 266-6 and 304-2 in categorizing causes of fading:

| Category of Fading | Fade Periods | Discussion |
|---|---|---|
| Motion of small-scale inhomogenieties associated with micromultipath | < 1 s | ray interference. "flutter" fading: spread F: disturbed or auroral or tropical paths |
| Ionospheric motion in connection with multi-hop/multilayer multipath | 1 – 10 s | ray interference |
| Faraday effect, or rotation of the plane of polarization of the radio wave | 0.1 – 2 min | |
| Slow fading associated with lens type irregularities in the ionosphere | 10-60 min | ray interference |
| Temporal fluctuations in ionospheric absorption | 5 – 30 min | non-selective |
| Variation in ionospheric support at a specified frequency | irregular | non-selective |

Fading tends to be more rapid at the upper end of the HF spectrum since a given displacement of the ionosphere corresponds to more phase shift for shorter wavelengths.

**Fading Rates**

Goodman (p. 273) refers again to CCIR Reports 266-6 (slow nonselective fading) and 304-2 (fade rates). "Flutter fading, which is closely correlated with spread-F-induced scintillation in the equatorial zone, may range from 10/min to 180/min. The strongest class of fading is associated with sporadic E, and the equatorial variety may generate rates as high as 300/min. Normal E and F region fade rates may be as high as 10/min. Midlatitude fade rates are considerably smaller than those generally observed in the equatorial region. The rates become large once more for transauroral paths."

**Standard Deviation of SNR Variation**

Maslin [3] (p. 91) gives decile values D for day-to-day variability of noise from atmospheric (CCIR) and man-made sources, where D is related to the standard deviation of noise power as follows:

$$1.28\sigma_N = D$$

Atmospheric: 3 MHz D is about 8 dB during stable hours (all seasons)
D ranges from 10 to 17 dB (higher in summer)during transitional hours
0400-0800 and 1200-2000 (1600-2000 winter)

10 MHz D is about 5 dB in stable hours, 7 to 11 dB transitions

Man-made noise depends on the type of nearby human activity as well as the radio operating frequency. The standard deviations of man-made noise were reported as follows:

| Environment | <10 MHz | 10-20 MHz | >20 MHz |
|---|---|---|---|
| Business | 4 | 6 | 7 |
| Residential | 6 | 9 | 12 |
| Rural/Quiet rural | 10 | 7 | 4 |

Noise variability adds RMS, so the worst-case day-to-day noise variability is about 15 dB (quiet rural summer during the transition period at 3 MHz). How does this relate to mid-term SNR variation within a single hour?

Goodman [1] (p. 271) discusses the "fading range" (difference in dB between first and ninth deciles) of signal level as having lognormal statistics on hourly scale and Rayleigh for short intervals. "Often one can represent signal fading in terms of a (known) median component which is log-normal, and an (undetermined) instantaneous component which is thought to be Rayleigh distributed." The associated figure (4-55) shows standard deviations ranging from 0 to 20 dB.

**Statistical Characterization of Fading**

Furman and McRae [4] noted that between the short-term Watterson model effects and the long-term variation described by prediction programs lies an intermediate-term regime characterized by lognormal SNR fluctuations of several dB with time constants on the order of seconds. Their measurements of intermediate-term SNR variations on a north-south link between Melbourne, FL and Rochester, NY exhibited lognormal variation with a standard deviation of around 4 dB and a time constant of about 10 seconds.

# Simulation Model

The Walnut Street approach for simulation of HF communications in skywave channels comprises three components:

- The shortest-term channel effects (as in the Watterson model) are included in the *modem* model via measurements of the specific modem of interest using a Watterson-model channel simulator.
- Hourly- and longer-term effects are introduced using prediction programs (e.g., ICEPAC), often using precomputed tables to remove these computations from the running time of simulations.
- Intermediate-term effects are modeled as a lognormal random process. Until additional measurements become available, the Furman/McRae characteristics (4 dB standard deviation and 10 s time constant) are used.

The modem model is given instantaneous SNR values produced by the superposition of the longer- and intermediate-term effects. During a simulation, hourly SNR values are obtained from a prediction program. The prediction program will supply a mean SNR and upper and lower deciles, reflecting the distribution of SNR expected for that hour, at a specific frequency, in a specific month, and for a specific sunspot number.

To generate a single SNR value for the top of each hour, we generate a uniformly distributed random quantile which, together with a normal distribution fitted to the predicted mean and deciles for that hour, determines the SNR value. In an attempt to use these statistics in a realistic manner, we assume for each simulation run that each hourly SNR value falls at the same quantile in its hourly distribution. That is, if the SNR for 1700 falls at the 70$^{th}$ percentile of the hourly distribution for hour 17, then the SNR for 1800 will be the 70$^{th}$ percentile of the hourly distribution for hour 18. This "pick your ionosphere" procedure ensures that an especially high SNR in one hour is not followed by as especially low SNR (for that hour) in the next hour. Subsequent simulations draw new random quantiles and therefore model "different ionospheres."

During each hour, the slowly varying (longer-term) component of SNR is found by interpolating between the adjacent hourly values. The lognormal variation is generated as a separate random process, and is added to the slower component, as shown in Figure 1.

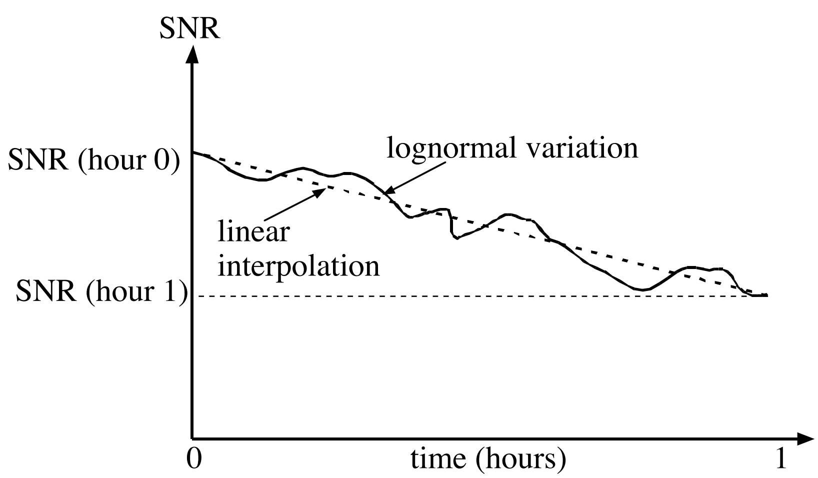


Figure 1: Superposition of Long- and Intermediate-Term SNR Variation

### Validation

A simulator (NetSim-SC) that was developed to support the systems engineering of high-power HF radio networks was independently validated by the US Defense Information Systems Agency (DISA) Joint Interoperability Test Command (JITC) [5]. The Walnut Street channel model was validated using measurements from radios aboard Air Force One to various ground stations during an extended trip abroad by the U.S. President. The measurements consisted of Link Quality Assessment (LQA) scores recorded by the radios aboard Air Force One; corresponding scores were generated by simulated radios that were measuring Walnut Street channels. The results agreed to within acceptable bounds:

> "Output data produced by NetSim-SC correlates closely with observed 'real world' data. The average LQA deviation was +/-7.42 LQA points and the frequency selection was +/-1.93 MHz. These values are within the criteria of +/-10 LQA points and +/-2 MHz."

## Conclusion

The Walnut Street Model for HF communications via skywave channels integrates research results from three temporal regimes into a straightforward model of fading and other SNR processes. This model has been independently validated, and is currently in use in HF network simulation programs.

## References

1. J. Goodman, *HF Communications Science and Technology*, Van Nostrand Reinhold, New York, NY, 1992.
2. C.C. Watterson, J.R. Juposher and W.B. Bensema, "Experimental Verification of an Ionospheric Model," ESSA Technical Report, ERL 112-ITS, 1969. The Watterson model is also described in ITU-R recommendation F.1487.
3. N. Maslin, *HF Communications — A Systems Approach*, Plenum Press, London, 1987.
4. W. Furman and D. McRae, "Evaluation and Optimization of Data Link Protocols for HF Data Communication Systems," *Proceedings of 1993 IEEE Military Communications Conference*, Boston, MA, October 1993, pp. 67-72.
5. R.K. Bullock, "SCOPE Command High Frequency (HF) Network Simulation Model (NetSim-SC) Verification and Validation Report," Joint Interoperability Test Command, Ft. Huachuca, AZ, January 1997.