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Propagation Analysis of Signal of Opportunity Measurements in Green Bank

Ryan S. McCullough, Todd R. Schumann, William Kozma Jr.,
Skyler Fennell, and Christopher R. Anderson

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Acronyms/Abbreviations

AC	alternating current	KETD	knife-edge terrain diffraction
AGL	above ground-level	KML	Keyhole Markup Language
BTL	basic transmission loss	LMR	Land Mobile Radio
CDF	cumulative distribution function	LNA	low noise amplifier
CSV	comma separated values	NPY	numpy
CW	continuous wave	NRAO	National Radio Astronomy Observatory
EIRP	equivalent isotropic radiated power	NRQZ	National Radio Quiet Zone
EMI	electromagnetic interference	NSF	National Science Foundation
EMS	Emergency Medical Service	NTIA	National Telecommunication and Information Administration
ERP	equivalent radiated power		
FFT	Fast Fourier Transform	PNG	Portable Network Graphics
FM	frequency modulated	RF	radio frequency
FSPL	free space path loss	RFI	radio frequency interference
GBO	Green Bank Observatory	RMSD	root mean squared difference
GPS	Global Positioning System		
IQ	in-phase and quadrature	SGRS	Sugar Grove Research Station
IQR	interquartile range	SMA	SubMiniature version A
ITM	Irregular Terrain Model	SMD	Spectrum Management Department
ITS	Institute for Telecommunication Sciences	STA	special transmit authority
ITU	International Telecommunication Union	UHF	ultra-high frequency
		USB	Universal Serial Bus
JSON	JavaScript Object Notation	VHF	very high frequency

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Propagation Analysis of Signal of Opportunity Measurements in Green Bank

Ryan S. McCullough, Todd R. Schumann, William Kozma Jr., Skyler Fennell, and Christopher R. Anderson¹

Abstract: Very high frequency propagation measurements were obtained from signal of opportunity transmissions collected during public safety communications field campaigns within the National Radio Quiet Zone surrounding Green Bank, West Virginia. Measured path loss was then compared with predictions from the Irregular Terrain Model in complex, forested terrain. The propagation measurements consisted of a series of week-long field measurements campaigns using fixed very high frequency transmitters operating at 169.5375 MHz and a vehicle-mounted calibrated receiver, collecting received power measurements over extensive drive routes. Received signal levels were converted to basic transmission loss and compared against Irregular Terrain Model median predictions and free-space path loss estimates. Across the measurement campaign, the Irregular Terrain Model was found to systematically under-predict measured path loss by a median of approximately 13 dB. The observed discrepancies are attributed primarily to foliage attenuation and terrain diffraction mechanisms beyond the double knife-edge model incorporated within the model. In a smaller subset of cases, the model over-predicted path loss, likely as a result of terrain-induced signal enhancement not captured by the model. These results provide empirical context for the use of the Irregular Terrain Model in heavily forested, mountainous environments and could inform future planning for public safety communications systems within the National Radio Quiet Zone.

Keywords: Basic Transmission Loss (BTL), foliage attenuation, Irregular Terrain Model (ITM), mobile propagation measurements, National Radio Quiet Zone (NRQZ), propagation model validation, signal of opportunity, spectral structure correlation power estimation, spectrum coordination, terrain diffraction, VHF propagation

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1. Introduction

1.1 Background

In 1958, the National Radio Quiet Zone (NRQZ) was established by the Federal Communications Commission and the Interdepartment Radio Advisory Committee to provide a geographically defined region in which sensitive instrumentation is protected from radio frequency interference (RFI). The Green Bank Observatory (GBO) and the Sugar Grove Research Station (SGRS) are two protected facilities that are located near the center of the West Virginia NRQZ. Within this region, the National Radio Astronomy Observatory (NRAO) Spectrum Management Department (SMD) manages the coordination process for all permanent fixed transmitters, evaluating proposed systems against predefined power density limits intended to protect these federally operated facilities.

Coordination within the NRQZ consists of a technical review of planned transmissions, after which applicants are either granted a concurrence letter or requested to modify system parameters, typically by reducing transmitted power in the direction of protected facilities. These power density limits vary significantly with transmitter location, frequency, antenna characteristics, and terrain. For transmitters located near federal facilities or on elevated terrain, the imposed limits can constrain system design and coverage. Recognizing the operational challenges this poses, particularly for public safety communications, NRAO SMD initiated discussions with affected public safety providers to explore viable options for ensuring adequate coverage of public safety transmissions while ensuring interference protection of federal systems.

Ideally, all transmitters within the NRQZ would operate fully within NRAO interference protection limits, ensuring maximal protection of scientific instruments at GBO. However, discussions with stakeholders and extensive independent modeling² demonstrated that, under current requirements, strict adherence to these limits would prevent adequate public safety coverage in some areas. As a result, NRAO SMD considered a limited set of operating frequencies at existing tower infrastructure, including: (1) very high frequency (VHF) low-band (30–108 MHz) (2) VHF high-band (150–174 MHz) (3) ultra-high frequency (UHF) Land Mobile Radio (LMR) (450–470 MHz), and (4) UHF Emergency Medical Service (EMS) (806–824 MHz).

After extensive research², the NRAO SMD determined that the VHF high-band (150–174 MHz) presented fewer interference concerns with existing and planned instruments than the other three band options. Accordingly, NRAO SMD recommended that exceptions to NRQZ protection limits may be considered on a site-by-site basis for public safety systems operating in the VHF high band.

² Sheldon Wasik of NRAO, email message to authors, November 6, 2025.

1.2 Study Scope and Approach

To support the use of VHF high-band for public safety communications within the NRQZ, a contract was created to conduct operational field measurements throughout Pocahontas and Pendleton counties inside the NRQZ in West Virginia under the authority of a special transmit authority (STA) granted for this purpose. Recognizing the rare opportunity to obtain propagation data in the complex terrain of the West Virginian NRQZ, the National Science Foundation (NSF) also coordinated with the National Telecommunications and Information Administration's Institute for Telecommunication Sciences (ITS) to perform a secondary propagation analysis using the operational transmissions as signals of opportunity. This study presents the field measurements from those signals of opportunity and compares the propagation characteristics with ITS-developed Irregular Terrain Model (ITM)[1] predictions. The terrain in these counties is characterized by steep ridges, deep valleys, elevated plateaus, and dense deciduous forest cover, providing a topographically complex environment for such comparisons.

The purpose of this study was neither to determine absolute service coverage or compliance with NRQZ protection criteria, nor to evaluate the overall performance of ITM; rather, it was to examine the direction and characteristic magnitude of systematic differences between ITM predictions and measured median basic transmission loss (BTL) – also referred to as path loss throughout this report – within this terrain. Quantifying these differences is essential to understanding how ITM-based evaluations should be interpreted in NRQZ spectrum coordination analyses. While this study focuses on ITM, NRQZ coordination analyses may also incorporate the SoftWright Rounded Obstacle Model, as defined in Section 7 of Tech Note 101 [2].

To accomplish this, ITS coordinated with the external team operating the transmitters to conduct supplemental spectral measurements of transmissions near 170 MHz during two separate week-long operational field campaigns within the NRQZ. The first week-long campaign used temporary trailer-based transmitters deployed at multiple locations within Pocahontas County. The objective was to emulate a rapid response scenario where public safety infrastructure would need to be installed on short notice. The second week-long campaign used transmit antennas installed on permanent tower facilities throughout Pendleton County, with different towers used each day to represent the fixed infrastructure employed by the public safety network.

Measurement results were collected using a vehicle-mounted receiver system designed to support repeatable, high-precision signal strength measurements, described in Section 2.1.3, during daily drive testing along predefined routes covering most of each county. The transmitted signal of opportunity was a continuous frequency modulated (FM) signal, described in Section 2.1.1. While suitable for operational communications testing, the waveform and transmitter configuration were not optimized for dedicated propagation sounding and consequently imposed limitations on the achievable propagation characterization. To accommodate these constraints and permit flexible post-processing, raw in-phase and quadrature (IQ) data were recorded throughout each measurement run. The receiver also continuously logged Global Positioning System (GPS) latitude and longitude positions.

The remainder of this paper is organized as follows. Section 2 describes the measurement campaign, receiver system, and methodology used to compare the measurements with the ITM predictions. Section 3 presents the measurement results and model comparisons. Section 4 discusses the principal observations and their implications. Section 5 summarizes the findings and identifies opportunities for improving studies like this in the future.

2. Methods

2.1 Experimental Configuration

2.1.1 Test Signal Definition

The test signal of opportunity transmitted during the study was an FM carrier modulated by a 1 kHz sinusoid represented by

$$s(t) = A_c \cos(2\pi f_c t + \beta \sin(2\pi f_m t)), \quad (1)$$

where A_c is the carrier amplitude, f_c is the carrier frequency, $f_m = 1 \text{ kHz}$ is the modulation frequency, and β is the FM modulation index, empirically estimated to be $\beta \approx 1.5$ based on the relative powers of the carrier and first two sidebands. An FM signal with this modulation produces multiple discrete sidebands at frequencies $f_c \pm k f_m$, where k is an integer with relative amplitudes governed by Bessel functions of the first kind. For $\beta \approx 1.5$, the transmitted signal will have approximately $k = 2$ significant sidebands based on an approximate bandwidth of 5 kHz given by Carson's rule:³

$$B \approx 2(\beta + 1)f_m. \quad (2)$$

2.1.2 Transmitter and Measurement Configuration

Propagation measurements were recorded throughout Pendleton County, West Virginia, using fixed-location transmitters. The transmitter location and radiated power varied daily, with each deployment corresponding to a unique site listed in Table 1. The transmitters consisted of an antenna mounted on a commercial tower and a power amplifier and signal generator housed in a control room at ground level. Heights of the transmitting antenna are given in Table 1 as above ground-level (AGL) heights, and separation distance ranges for each day are listed.

The public safety transmitter was deployed and operated externally, in coordination with the local county government. The transmitted signal of opportunity was a continuous FM signal modulated with a 1 kHz sinusoid, as described in Section 2.1.1, operating at 169.5375 MHz under an STA.

³ A significant sideband is defined here as a sideband that contributes 1% or more to the total signal power.

Table 1. Summary of August measurement campaign parameters. All measurements were performed in Pendleton County at 169.5375 MHz.

Date	Transmitter (Tx) Location	Tx Antenna Height AGL	Separation Distance	ERP
August 4, 2025	(38.646944, -79.541944)	42 m	0.997–38.885 km	87 W
August 5, 2025	(38.711142, -79.402000)	70 m	1.409–48.964 km	79 W
August 6, 2025	(38.637364, -79.291106)	78 m	3.222–52.517 km	77 W
August 7, 2025	(38.827305, -79.399274)	54 m	0.844–58.320 km	83 W
August 8, 2025	(38.849722, -79.269000)	29 m	2.297–67.875 km	90 W

2.1.3 Mobile Receiver System

Figure 1 illustrates the block diagram of the mobile measurement system. All receiver electronics were housed within a shielded enclosure and powered by batteries, allowing autonomous operation within the sensitive regions of the NRQZ.⁴ A vertically polarized 5/8-wavelength Motorola-style magnetic-mount antenna was used for the mobile receiver for its increased gain relative to a quarter-wave radiator and was tuned for operation at 169.5375 MHz. The antenna was mounted on the roof of the measurement vehicle, and an RG-58 coaxial cable connected the antenna mount to the shielded enclosure bulkhead. The antenna exhibits the typical omnidirectional azimuth response and low-elevation gain characteristic of a 5/8-wavelength vertical monopole.

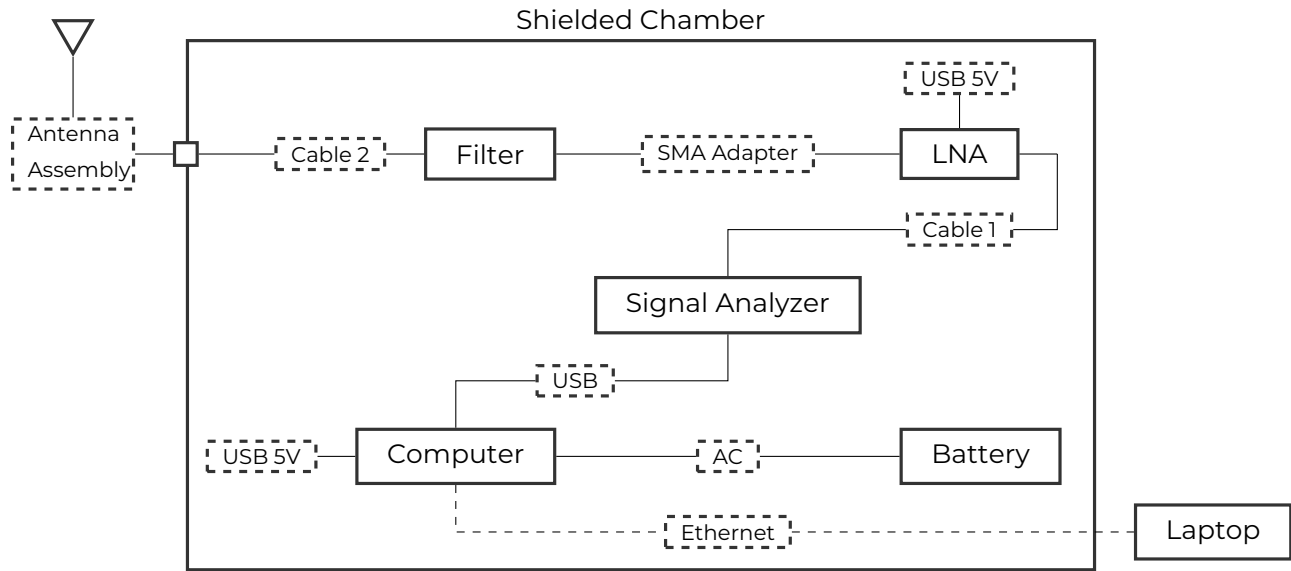


Figure 1. Diagram of the ITS mobile measurement system.

⁴ The enclosure could be opened to allow an external laptop to interface with the internal control computer for configuration changes, including adjustment of measurement settings like the reference level—used for accommodating overload. Although the enclosure was designed with electromagnetic interference (EMI) in mind, the GBO and SGRS sensitive science equipment was not active at the time of the study, therefore EMI compliance was not required.

2.1.4 Calibration Procedure

The receiver was calibrated for each reference level setting used during the measurements using a noise diode and the Y-factor method [3]. The calibration was performed over a broad range of frequencies extending beyond the operational band, as shown in Figure 2, where the black dashed lines outline the frequencies studied. An approximately 1 dB reduction in measured gain at 170 MHz, above the operational frequencies was due to the larger equivalent noise bandwidth used at that frequency. This reduction and all other gains were quantified during calibration and incorporated into the frequency-dependent gain correction used to de-embed the measurement plane to the input of the preselector. The operational frequencies used narrower bandwidths and exhibited gain and noise figure values consistent with the remainder of the 150–170 MHz filter passband, indicating that they were not affected by the larger equivalent noise bandwidth or the filter roll-off.

Receiver overload was monitored throughout data collection. When consecutive measurements indicated overload, the receiver reference level was adjusted accordingly. Such adjustments were required infrequently, and measurements identified as overloaded were excluded from the quantitative analysis in Section 3.

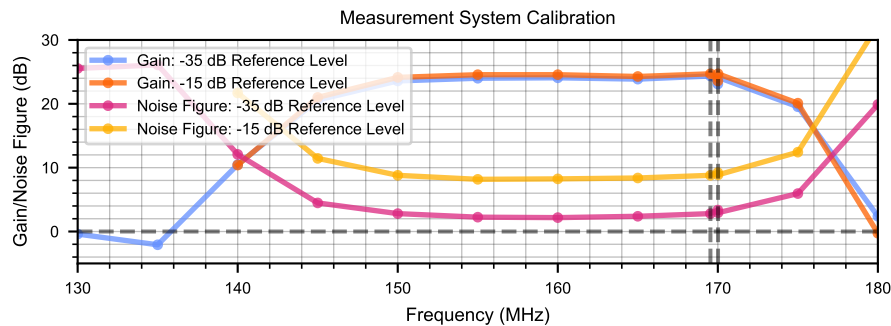


Figure 2. Receiver gain and noise figure calibration results of the full ITS mobile measurement system. The calibrated system noise floor ranged from approximately -102 dBm/10 MHz to -96 dBm/10 MHz across the receiver operating configurations. The black dashed lines outline the frequencies of this study.

2.2 Data Acquisition

2.2.1 Drive Routes

Drive routes were planned prior to measurement to provide broad spatial coverage of the county and to sample a range of terrain and separation distances. The routes were selected to traverse accessible roadways while capturing a broad range of propagation conditions. To provide locational context, Figure 3 highlights the counties studied, and Figure 4 and Figure 5 show aggregate drive route maps for the entire July and August campaigns.

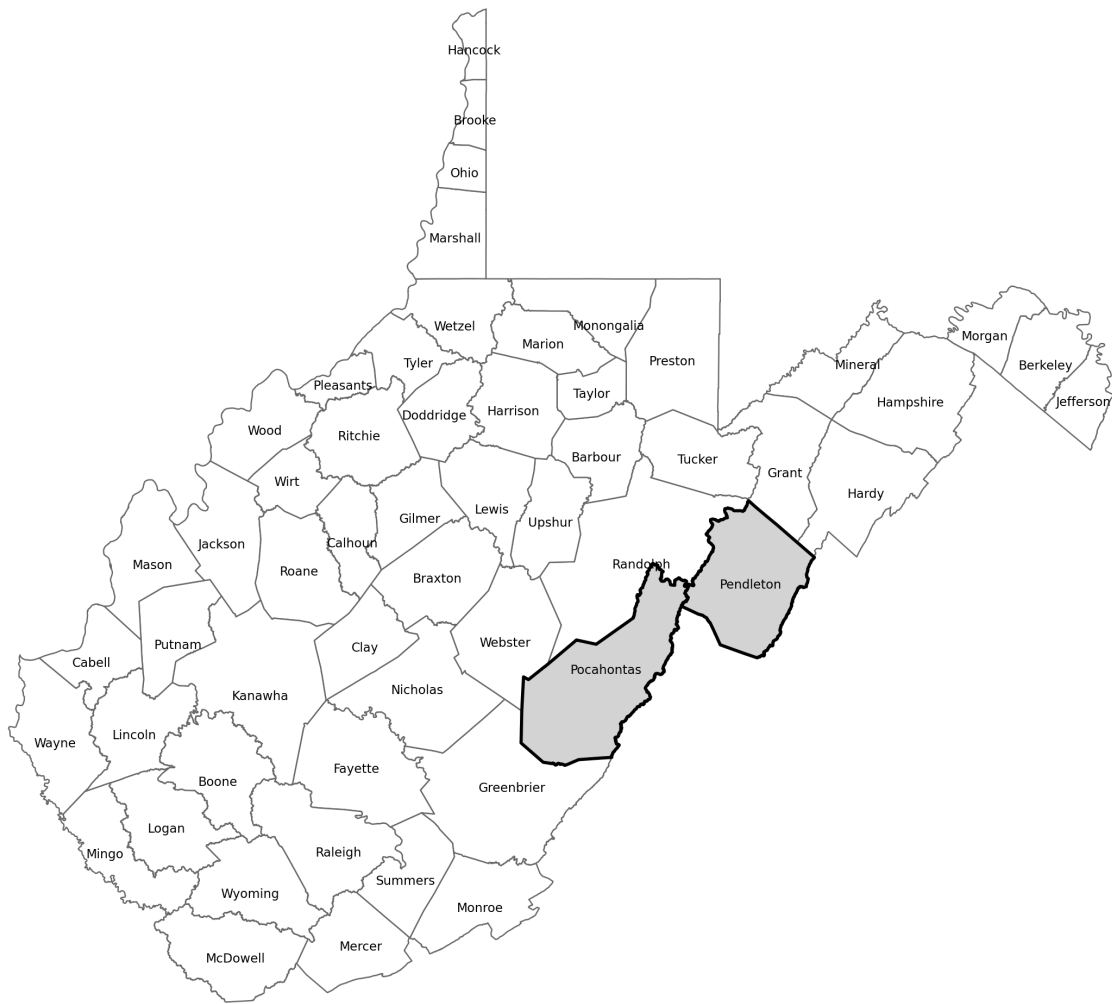


Figure 3. Map of West Virginia with Pendleton and Pocahontas counties shaded for locational context.

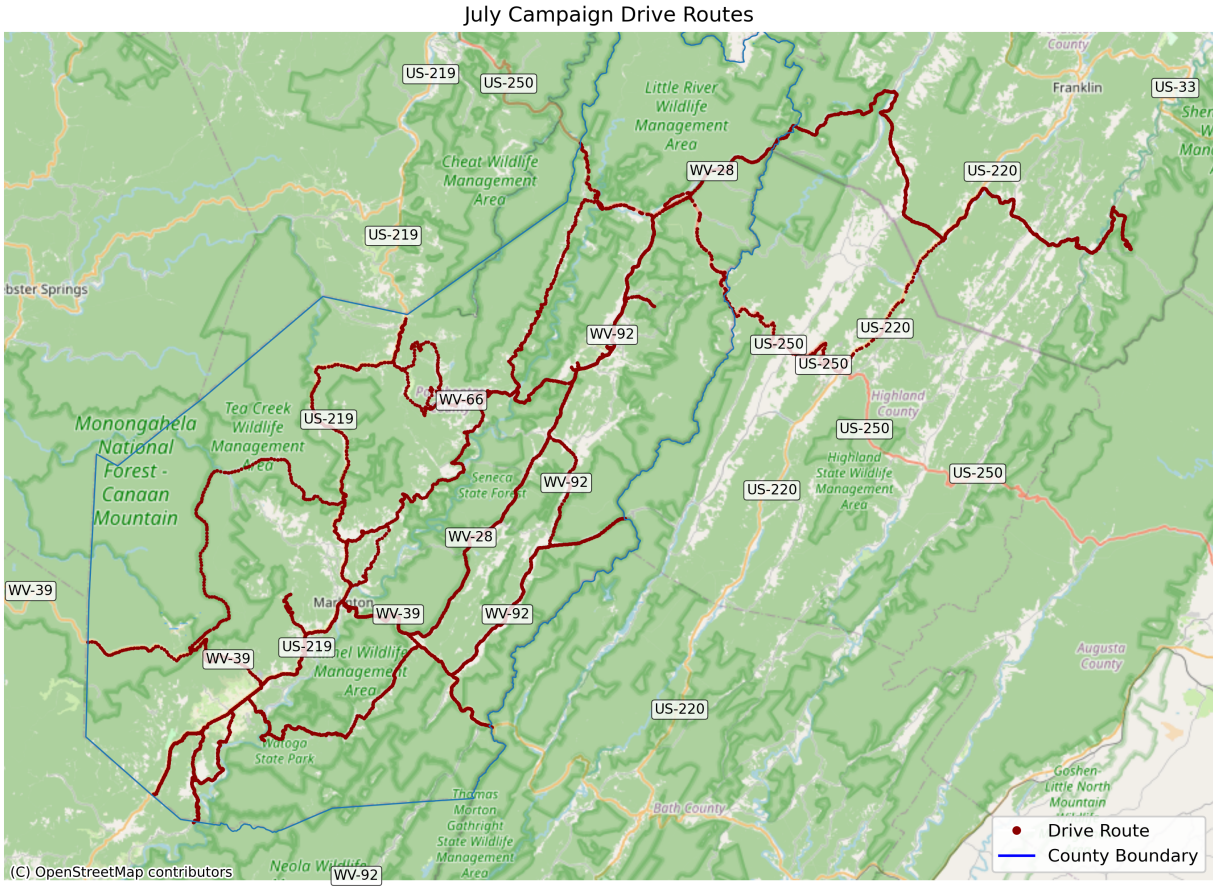


Figure 4. Pocahontas County, West Virginia, drive routes for the entire July measurement campaign.

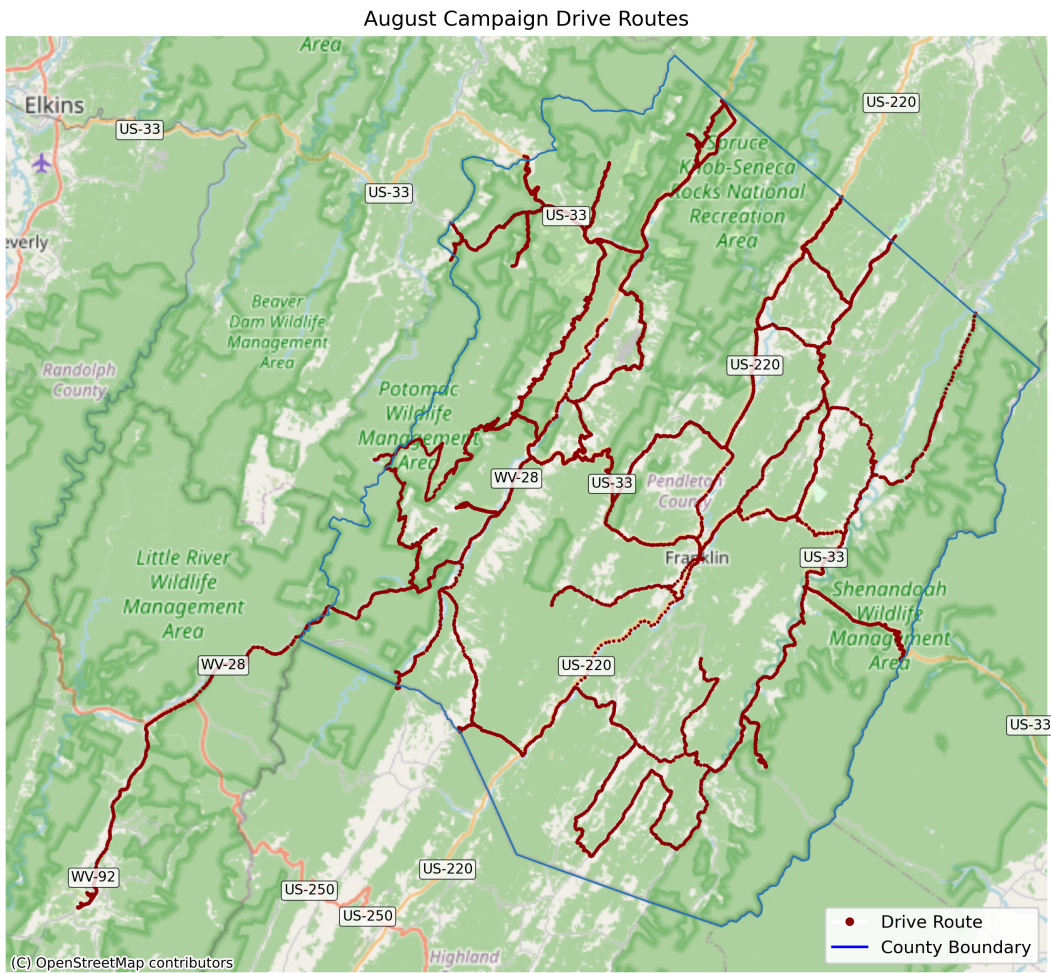


Figure 5. Pendleton County, West Virginia, drive routes for the entire August measurement campaign.

2.2.2 Sampling and Recording

IQ data were recorded from the signal analyzer and initially processed and stored on the onboard control computer shown in Figure 1. Because the transmitted signal bandwidth was relatively narrow⁵, the maximum available decimation was applied, resulting in a sample rate of 218.75 kSps for a bandwidth of 156.25 kHz.

An IQ capture duration of 10 s was selected to mitigate the effects of small-scale fading associated with vehicle motion. Typical vehicle speeds during measurement ranged from 25–50 miles per hour (40–80 km/h). At 169.5375 MHz ($\lambda \approx 1.77$ m), these speeds correspond to traversal of approximately 60–125 wavelengths during each capture interval, thus providing substantial averaging of small-scale fading effects as shown in [4]. The maximum Doppler shift associated with these vehicle speeds is approximately 6–13 Hz, which is small relative to both the signal bandwidth and the frequency search region used during signal detection and power estimation described in Sections 2.3.1 and 2.3.2.

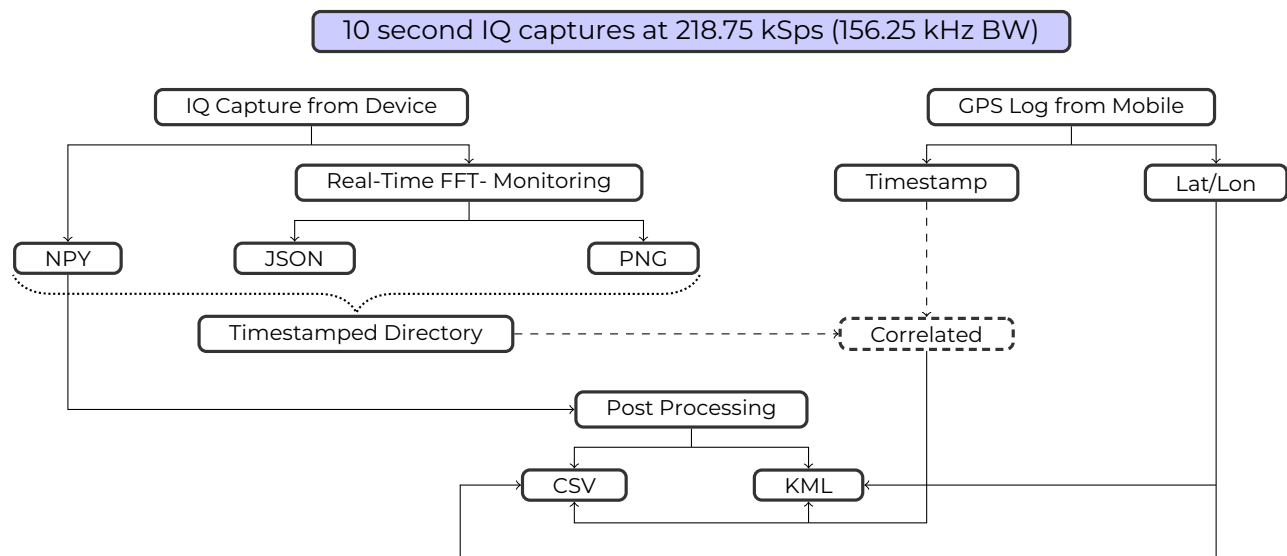


Figure 6. Data flow diagram of the ITS measurement system.

Accounting for processing and storage overhead, the 10 s IQ captures described in the previous paragraph became one measurement capture approximately every 10.5 s. The overall data collection and processing workflow is illustrated in Figure 6, with the post-processing described in Section 2.3. IQ data were stored in binary format and timestamped at the time of capture.

2.2.3 GPS Position Logging

GPS data were recorded independently and continuously throughout the drive routes at a rate of 1 Hz. Timestamp alignment between GPS logs and IQ capture files was used during post-processing to associate each received power measurement with the corresponding

⁵ Details on the test signal can be found in Section 2.1.1.

geographic coordinates. The more densely sampled GPS data enabled improved temporal alignment and finer spatial interpolation of each 10 s IQ capture. Because GPS data volume is minimal relative to IQ recordings, this higher sampling rate was readily supported without impacting system performance.

2.3 Signal Processing

The observed frequency offsets varied across the routes (approximately -100 Hz to $+160$ Hz), with capture-to-capture changes typically within ± 25 Hz over the 10.5 s cadence, as shown in Figure 7. This behavior, which is consistent with modest short-term frequency wander dominated by oscillator offsets rather than Doppler at the typical vehicle speeds mentioned in Section 2.2.2, motivated the use of a frequency-offset-tolerant spectral-structure correlator for signal detection and power estimation described in the subsequent sections. While acceptable for operational communications testing, these frequency variations are typically avoided in dedicated propagation measurement campaigns because they complicate received-power estimation and signal characterization.

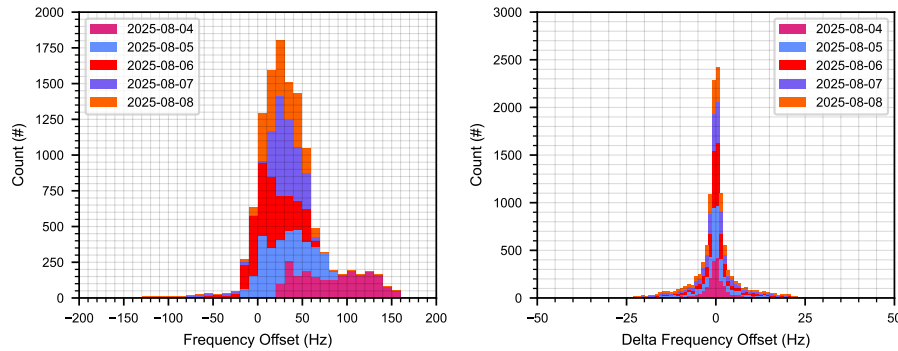


Figure 7. Histograms of the frequency shifts and differential frequency shifts for all captures in August with detected signal.

2.3.1 Signal Detection

The predictable multi-tone spectral structure was exploited to detect the signal and provide a power estimation using a form of structural correlation.⁶ A three-segment comb filter with 10 Hz wide segments was cross-correlated with the magnitude of the recorded signal Fast Fourier Transform (FFT). The FFT is based on the 218.75 kSps sample rate for 10 s, corresponding to a frequency resolution of 0.1 Hz. If the resultant cross correlation displayed five peaks greater than 1.25 dB above the surrounding noise with offsets of 1 kHz, the capture

⁶ Other processing techniques, such as using a matched filter, were hindered by such non-idealities in the capture as the local oscillator drift. Integration of the signal structure was deemed the most reliable processing technique for this dataset and resulted in signal being detected and estimated in nearly 99% of the captures for the dates in Table 1.

was said to contain signal with the frequency offset being the correlation shift of the center peak.

2.3.2 Power Estimation

In captures classified as containing signal, a second structural correlation was applied to the power-domain FFT using a five-segment comb filter with 40 Hz bandwidth per segment.⁷ The cross-correlation is evaluated over a ± 500 Hz frequency-offset search region. At each offset, the correlation value represents the integrated spectral power within the comb filter bandwidth at the expected tone locations. The peak value represents the integrated mean power where the mask best fits the signal structure and is denoted $p_{signal+noise}$.

A local noise estimate, $p_{noise-estimate}$, was obtained by evaluating the same filter at a nearby frequency offset, 500 Hz from the detected peak, thereby sampling the noise floor over an equivalent bandwidth (200 Hz). The signal power P_{signal} was then estimated as:

$$P_{signal} = P_{signal+noise} - P_{noise-estimate} \quad (3)$$

$$P_{signal} = 10\log(p_{signal}) \quad (4)$$

This approach concentrates integration over narrow spectral regions corresponding to the known signal structure, thereby reducing the effective noise bandwidth relative to broadband integration. A complete mathematical analysis of this method applied to the signal is forthcoming in a separate report dedicated to signal processing, but the results of the method are used in this study for propagation analysis.

2.3.3 Conversion to Basic Transmission Loss (BTL)

The extracted signal power levels were converted to BTL for comparison with ITM predictions. Consistent with the definition in International Telecommunication Union (ITU)-R Recommendation P.341 [5], BTL is defined as the difference between the equivalent isotropic radiated power (EIRP) of the transmitter and the received power referenced to an isotropic receiving antenna with a lossless connection. Accounting for the receiving antenna gain and cable losses, this translates to:

$$L_b[dB] = EIRP_t[dBm] + G_r[dBi] - L_{rc}[dB] - P_r[dBm], \quad (5)$$

where L_b is the BTL, G_r is the isotropic gain of the receiving antenna, L_{rc} is the cable loss from the receiving antenna to the signal analyzer, and P_r is the power measured.

The transmitting systems used during the measurement campaign were operated by a third-party contractor, and only the equivalent radiated power (ERP), referenced to a half-wave dipole, was provided for each site. Because detailed information regarding transmit antenna gain patterns and feeder losses was not available, the transmitter EIRP was derived from the reported ERP using the standard dipole-to-isotropic conversion factor of 2.15 dB (Equation 6).

$$EIRP[dBm] = ERP[dBm] + 2.15dB \quad (6)$$

⁷ The comb bandwidth was increased for power estimation to capture the spectral broadening associated with the non-ideal signal and the number of segments was increased to five to capture the second adjacent sidebands, consistent with the bandwidth called out in Section 2.1.1.

The received signal power estimates resulting from the post-processing described in Section 2.3 are calibrated to the input port of the shielded measurement chamber shown in Figure 1. Accordingly, these values represent the received power at the receiver input and do not include the external cable losses or receive antenna gain. The receive antenna gain, G_r , is approximated as 3 dBi, and the measured cable loss for the approximately four meter long RG-58 coaxial cable between the antenna and chamber bulkhead, L_{rc} , is 0.95 dB.

Substituting the receiver and transmitter factors for the corresponding variables in Equation 5 yields:

$$BTL[dB] = ERP[dBm] + 2.15dB + 3dBi - 0.95dB - P_r[dBm], \quad (7)$$

$$BTL[dB] = ERP[dBm] + 4.2dB - P_r[dBm], \quad (8)$$

where P_r is the calibrated received power estimate described in Section 2.3. This formulation produces BTL values directly comparable to ITM predictions, which are defined in terms of median BTL.

2.4 Propagation Modeling

2.4.1 ITM Point-to-Point Formulation

ITM, also known as the Longley-Rice model, was used in point-to-point mode to estimate median (50th percentile time, location, and situation) BTL between each transmitter location and the corresponding receiver middle positions⁸ along the drive routes. ITM is a largely deterministic, terrain-based propagation model that predicts long-term median path loss over irregular terrain. The predicted value represents the median after averaging over short-term fading and other transient propagation effects, and the model accounts for free-space loss, diffraction loss, and troposcatter as functions of distance, frequency, antenna heights, and terrain profile.

For each middle position described above, a terrain profile for the geodesic line between the notional receiver location and the corresponding transmitter location was generated using 1/3 arc-second (approximately 10 m resolution) elevation data from the U.S. Geological Survey 3D Elevation Program [6]. ITM was then executed in point-to-point mode using this terrain profile and the corresponding system parameters, as described in Section 2.4.2, to compute the predicted median BTL.

ITM internally determines the dominant propagation mechanism for each path segment, including line-of-sight, single-horizon diffraction, double-horizon diffraction, and troposcatter regimes. A detailed description of the model's propagation mode determination is provided in [1]. The reported propagation mode for each prediction was recorded and later used for categorical analysis of the differences between predicted and measured values.

⁸ The middle position here refers to the GPS position of the measurement vehicle at the 5 s point, marking the middle of the 10 s long measurement time.

2.4.2 Model Parameters and Settings

The model was configured to produce median predictions under standard atmospheric conditions consistent with the geographic region of interest. No additional clutter, vegetation, or building losses were applied within the ITM framework. As such, the predictions represent terrain-based median propagation loss without explicit foliage attenuation.

ITM was executed assuming vertical polarization, consistent with the antennas used in the measurements. Ground conductivity was set to 0.005 S/m and relative permittivity to 15, corresponding to standard "average ground" conditions. The minimum monthly mean surface refractivity reduced to sea level was set to 301 N-units, representing typical annual atmospheric conditions for a temperate continental climate.

2.5 Statistical Metrics

Model prediction difference was defined as the difference between the measured BTL and the ITM-predicted BTL for each measurement location:

$$d_i = L_{ITM,i} - L_{meas,i} \quad (9)$$

Under this convention, negative values indicate that the measured loss exceeded the ITM prediction (i.e., ITM under-predicted path loss), while positive values indicate over-prediction by ITM. All statistics were computed over the same set of measurement locations for each model comparison. As described in 2.3.1, a measurement was included in the statistical analysis only when the signal was detected. Signal detection required that the cross-correlation output exhibited five peaks at least 1.25 dB above the surrounding noise floor. Measurements that did not satisfy this criterion were excluded from the power estimation and subsequent comparison to model predictions. Consequently, the statistical analysis was performed only on uncensored measurements.

The distribution of differences is not assumed to be strictly Gaussian, and may exhibit skew and heavy tails due to clutter and other measurement effects. Therefore, multiple complementary metrics are used as described in the subsequent sections.

2.5.1 Mean Signed Difference

The mean signed difference was computed as:

$$\bar{d} = \frac{1}{n} \sum_{i=1}^n d_i \quad (10)$$

and quantifies systematic over- or under-prediction.

2.5.2 Root Mean Squared Difference (RMSD)

The sample-based root mean squared difference (RMSD) is computed as:

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n d_i^2} \quad (11)$$

and captures both systematic and random difference components and is more sensitive to large deviations and heavy tails. The variable n in both Equation 10 and Equation 11 is the number of samples.

2.5.3 Absolute Difference

Absolute difference is just the magnitude of the difference $|d_i|$, and two different percentiles are considered. The median absolute difference characterizes typical model deviation. The 90th percentile absolute difference provides an indication of upper-bound behavior.

2.5.4 Cumulative Distribution Function (CDF) and Box Plot Representation

Empirical cumulative distribution functions (CDFs) and box plots were constructed directly from the ordered mean signed difference samples. The box plots shown follow the standard statistical definitions described below. The box spans the 25th to 75th percentiles. The whiskers extend to the most extreme values within 1.5 times the interquartile range (IQR), where the IQR is the difference between the 75th and 25th percentile values. Because the whisker limits are based on this numerical range rather than fixed percentiles, the proportion of data outside the whiskers depends on the distribution.

3. Results

3.1 Determination of the Quantitative Analysis Dataset

The measurement methods described in Section 2 were applied during both the July and August measurement campaigns; however, observed uncertainties in transmitter configuration and transmitted power could not be sufficiently resolved during the July campaign to support a rigorous quantitative comparison with ITM predictions. Consequently, only data from the August campaign were used in the formal quantitative propagation analysis presented in this paper. The July campaign nevertheless provided valuable operational measurement data, and its measurement results and preliminary ITM predictions are included in Appendix A for completeness.

3.2 Measured BTL and Spatial Distribution

Table 1 summarizes the transmitter and drive route parameters for each day of the measurement campaign, including transmitter location, transmitter antenna height above ground level, transmitter ERP, and the range of transmitter to receiver separation. All transmissions in August were done in Pendleton County with a center frequency of 169.5375 MHz. The top plots of Figures 8–12 show the transmitter locations and the corresponding measured BTL values along the drive routes for each day, providing spatial context for the subsequent propagation analysis. The bottom plots of Figures 8–12 illustrate the ITM deviation from the measurement BTL values on the same day and drive route as the top plots. These results are shown for comparison and will be discussed in the following sections.

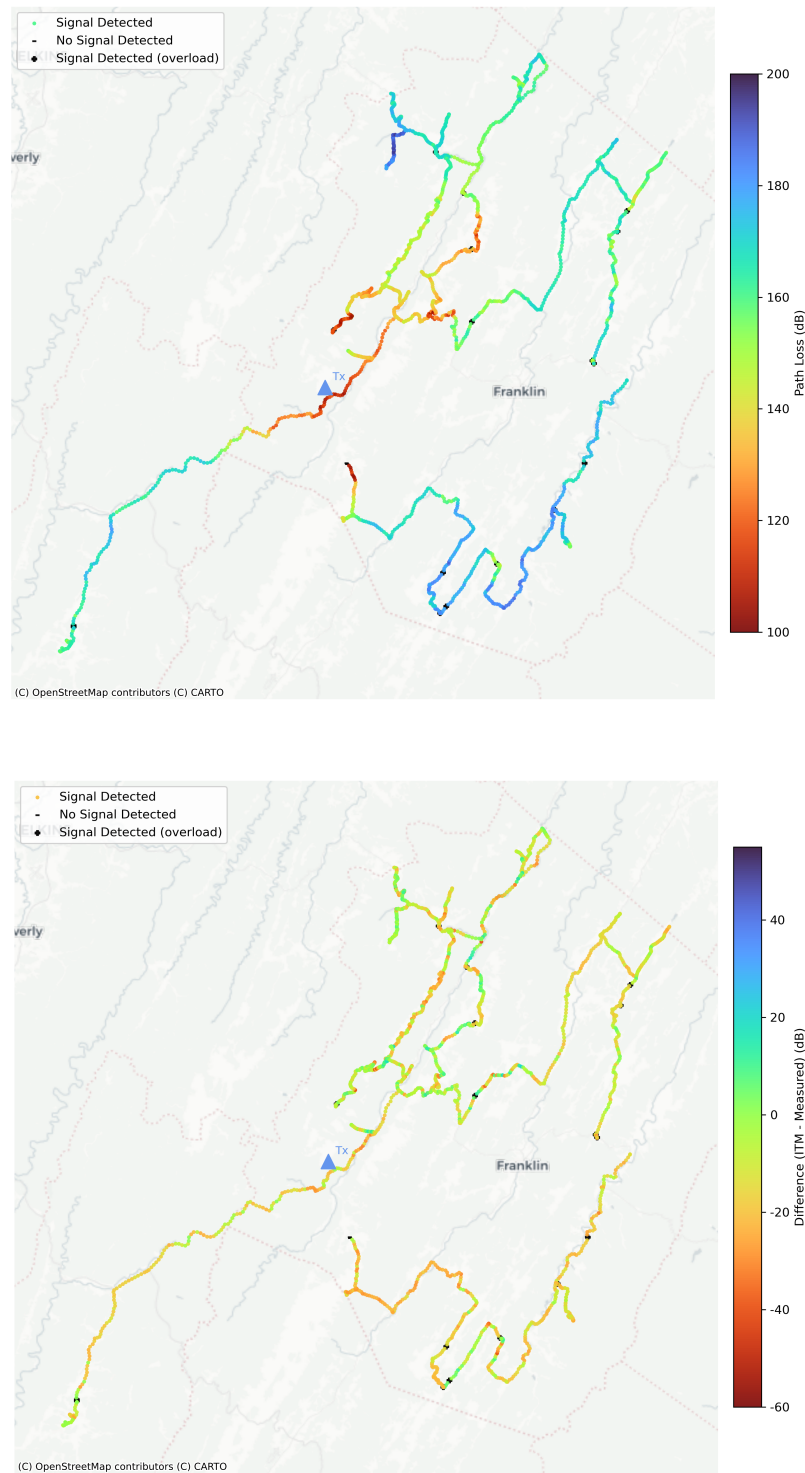


Figure 8. Top: basic transmission loss (path loss). Bottom: ITM prediction signed difference (ITM - Measured) for Pendleton County, West Virginia, measurements taken on August 4, 2025.

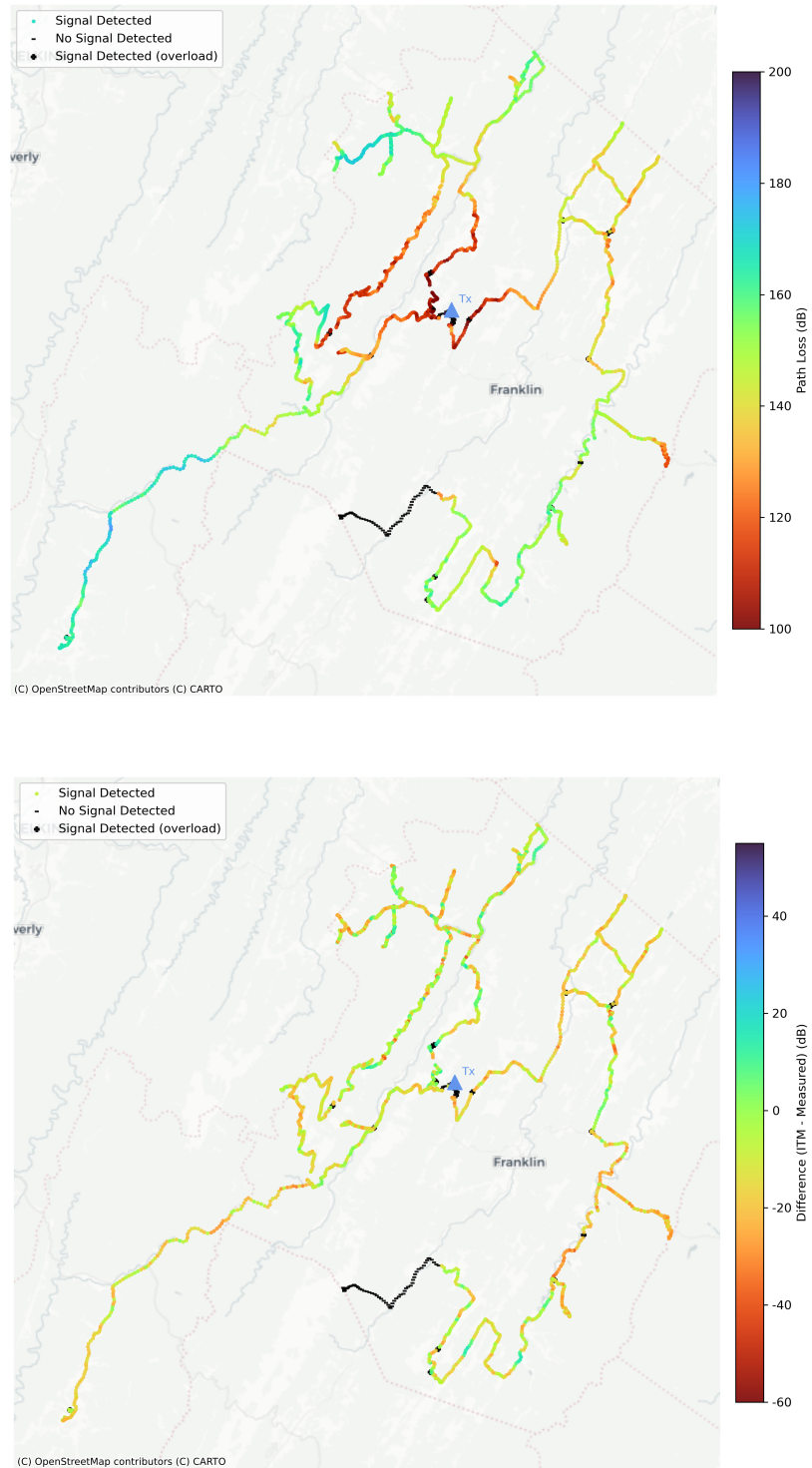


Figure 9. Top: basic transmission loss (path loss). Bottom: ITM prediction signed difference (ITM - Measured) for Pendleton County, West Virginia, measurements taken on August 5, 2025.

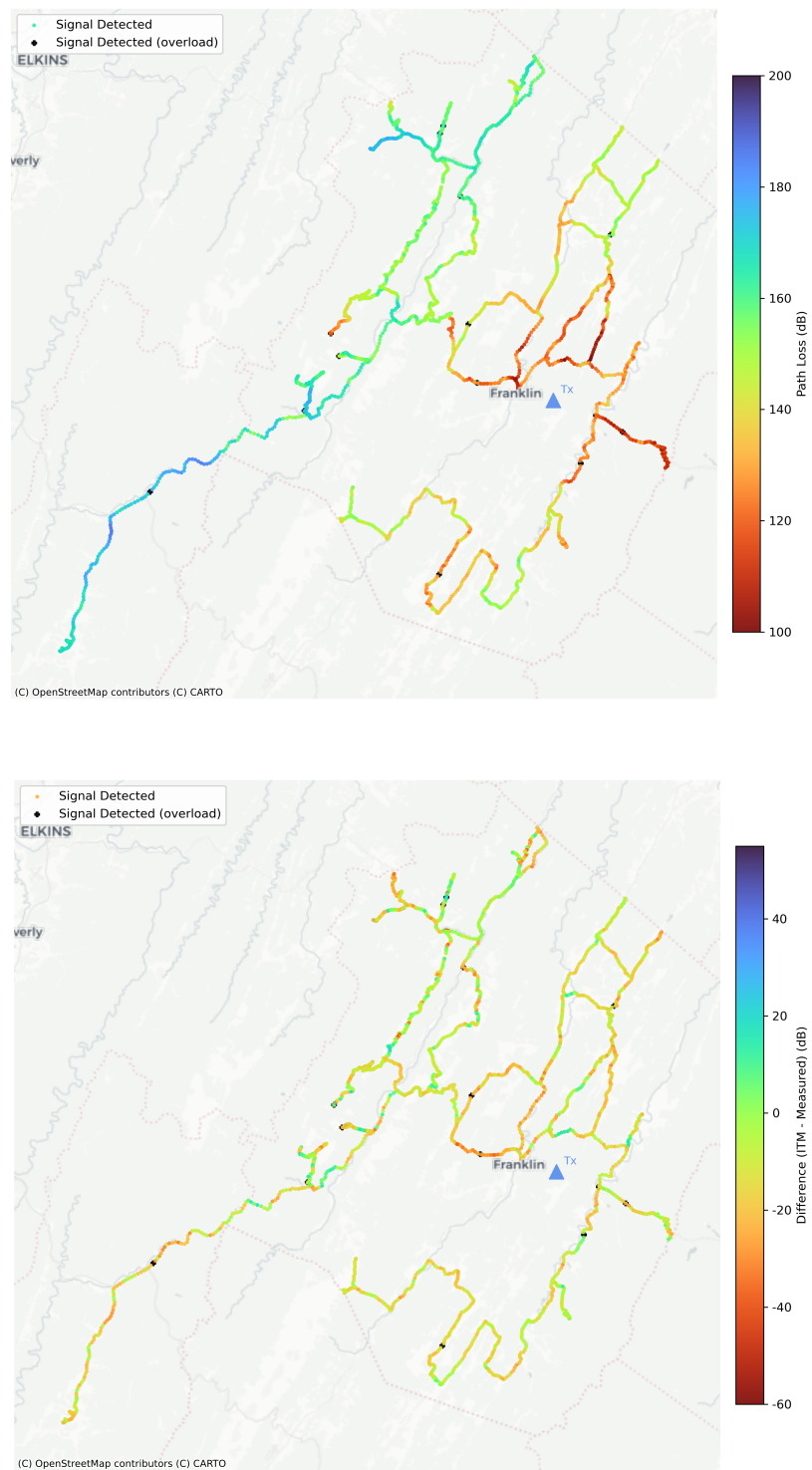


Figure 10. Top: basic transmission loss (path loss). Bottom: ITM prediction signed difference (ITM - Measured) for Pendleton County, West Virginia, measurements taken on August 6, 2025.

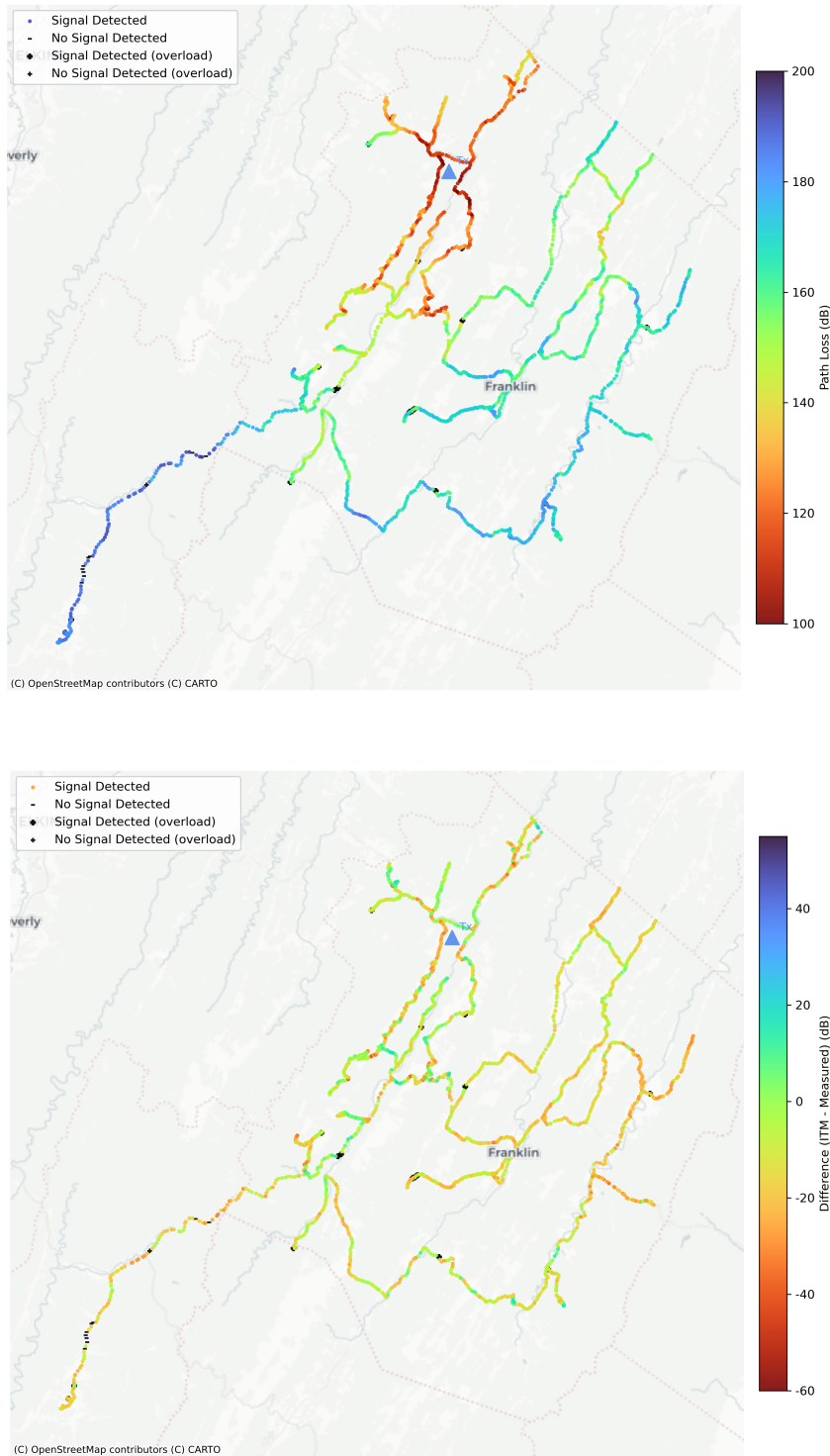


Figure 11. Top: basic transmission loss (path loss). Bottom: ITM prediction signed difference (ITM - Measured) for Pendleton County, West Virginia, measurements taken on August 7, 2025.

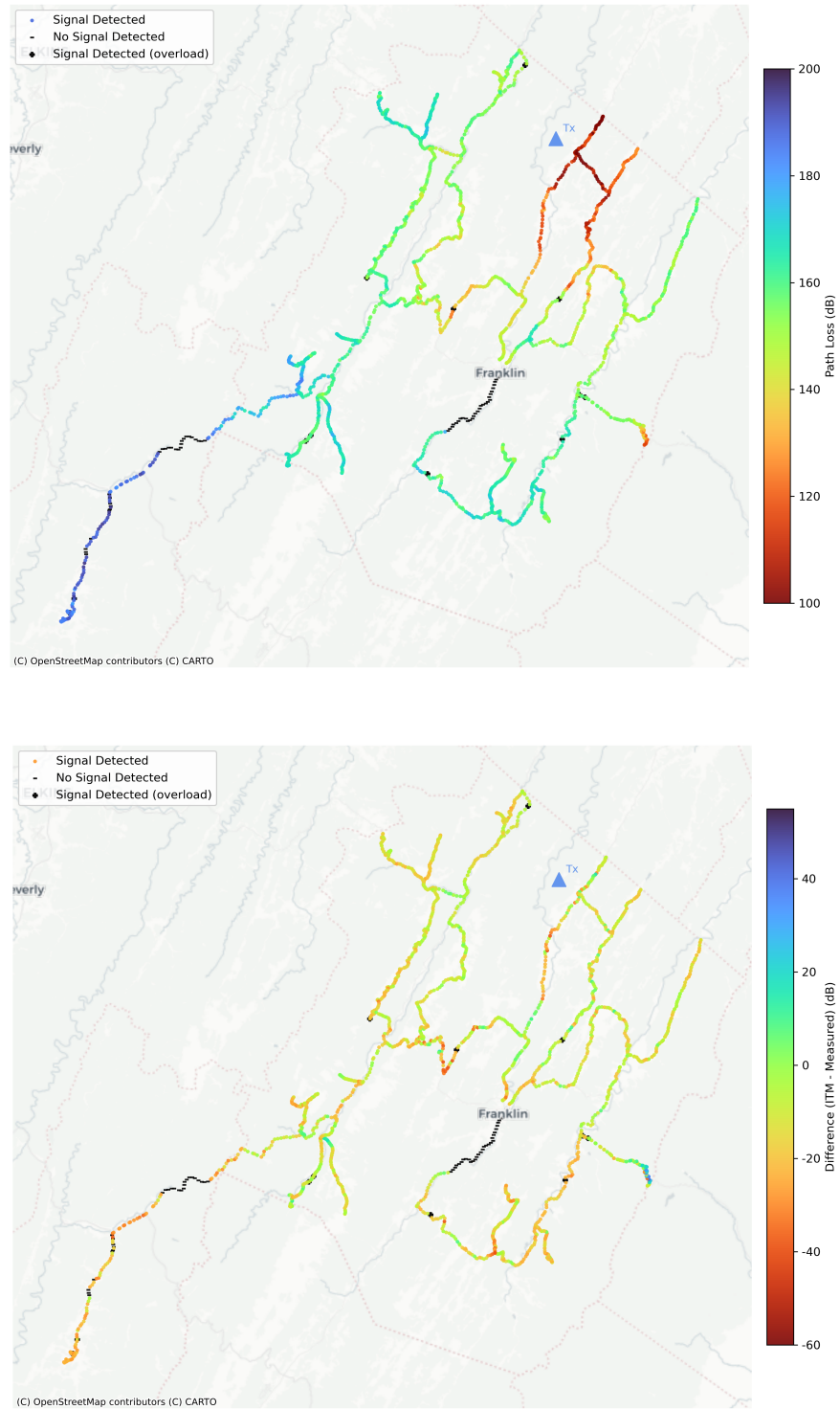


Figure 12. Top: basic transmission loss (path loss). Bottom: ITM prediction signed difference (ITM - Measured) for Pendleton County, West Virginia, measurements taken on August 8, 2025.

3.3 BTL as a Function of Distance

Figure 13 presents a scatterplot of the measured BTL values obtained during the August measurement campaign. For reference, the corresponding ITM-predicted BTL and free space path loss (FSPL) are also shown. FSPL comparisons are included solely as a reference baseline and not as a candidate propagation model.

Fewer than 10 measurement points were located at transmitter–receiver separations below 1 km, which is near the lower limit of the recommended applicability range of the ITM. These points were retained because they represent a negligible fraction of the overall dataset and do not materially affect the reported statistics.

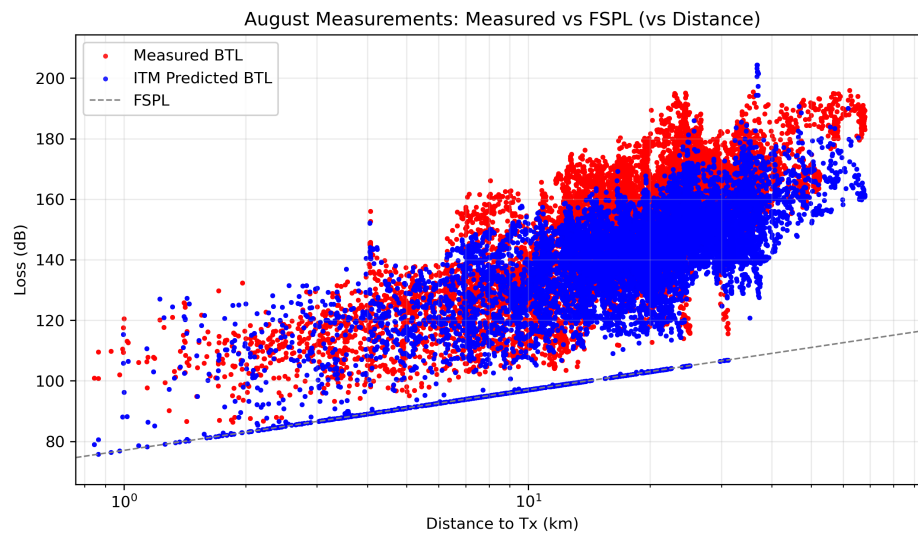


Figure 13. The Pendleton County, West Virginia, measured and predicted losses as a function of distance for the August measurement campaign.

3.4 Overall Difference Statistics

The left plot of Figure 14 presents the histogram of the prediction differences between ITM and measured BTL values while the right plot of Figure 14 presents the CDF of the prediction differences between ITM and measured BTL values.

Table 2 summarizes these results quantitatively using the mean signed difference, median absolute difference, 90th percentile absolute differences, and RMSD between the measured BTL values and those predicted by both ITM and FSPL propagation models for the full measurement campaign, as described in Section 2.5.

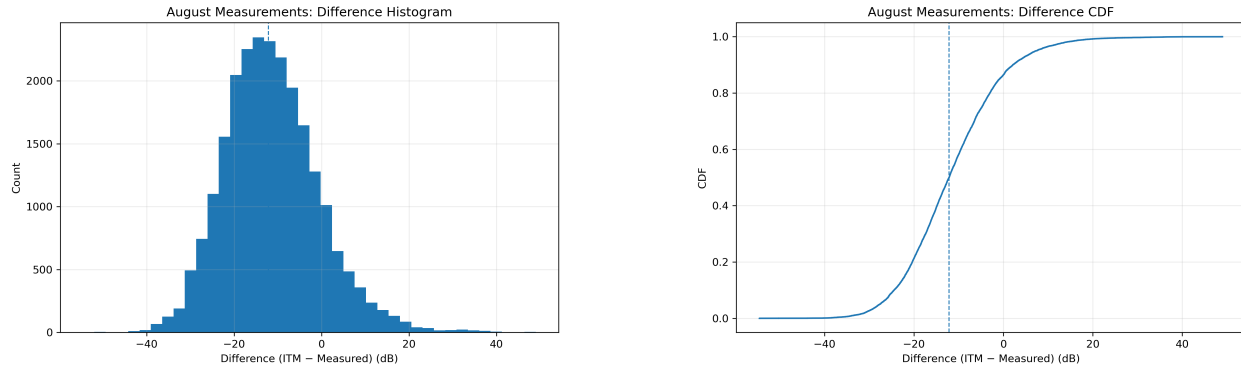


Figure 14. The statistical characterization of ITM prediction signed differences over the entire Pendleton County, West Virginia, August measurement campaign. The figure on the left is the histogram of prediction signed differences illustrating the overall difference distribution. The figure on the right is the corresponding CDF used to assess median and high-percentile difference behavior.

Table 2. Comparison of measured BTL against ITM and FSPL predictions for all detected locations within Pendleton County, West Virginia, during the August measurement campaign (N=11,821 samples).

Model	Mean Signed Difference (dB)	Absolute Difference Percentile		RMSD (dB)
		50th	90th	
ITM	-11.42	12.80	24.73	15.74
FSPL	-47.99	48.92	68.29	50.62

3.5 Difference by ITM Propagation Mode

ITM also provides a classification of the dominant propagation mode used to compute each predicted path loss value. The modes available to ITM and applicable to this propagation study include line-of-sight, diffraction single horizon, and diffraction double horizon. The top plot of Figure 15 compares the ITM-predicted BTL values against the measured BTL values, grouped by propagation mode predicted for the measured paths. The bottom plot of Figure 15 presents corresponding box plots that illustrate the distribution of prediction signed differences within each propagation category as well as the overall performance for comparison.

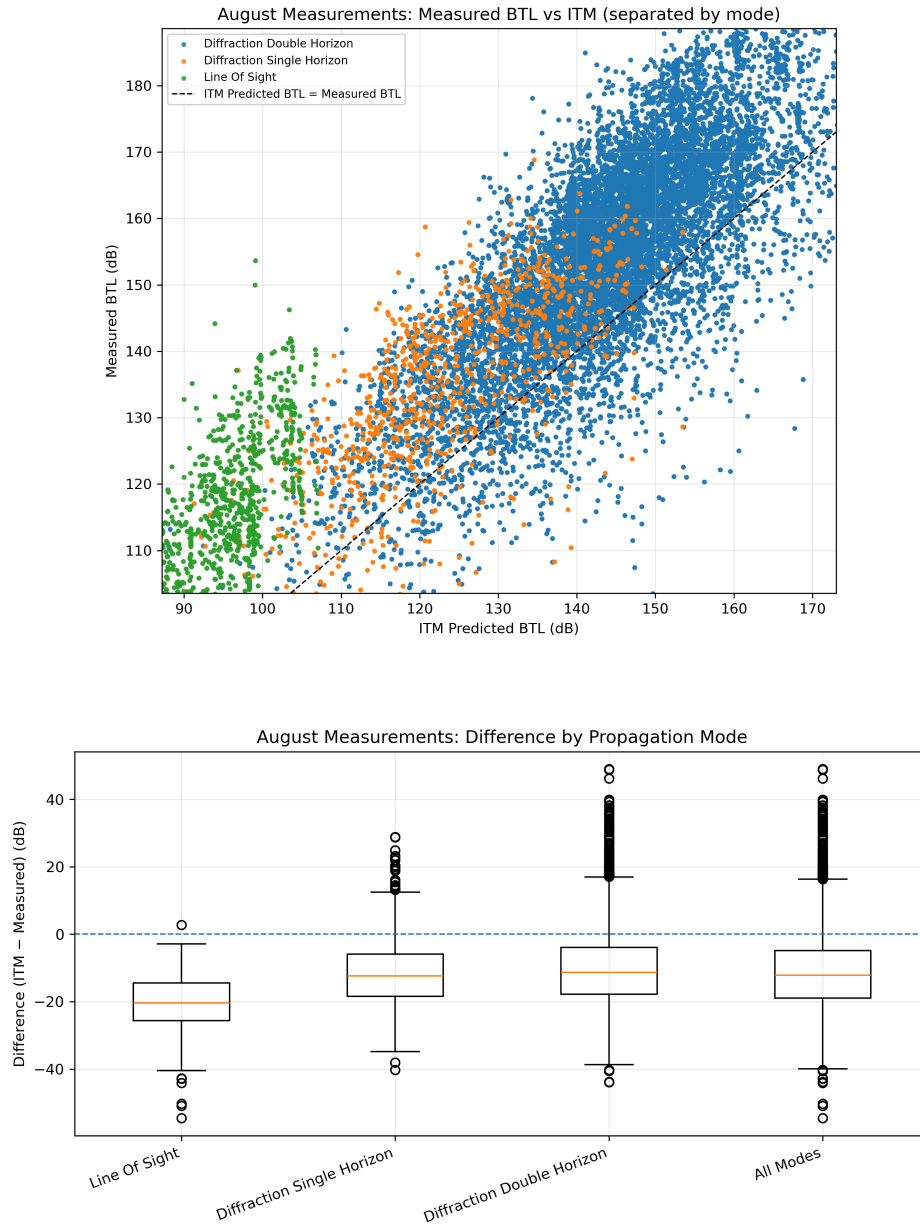


Figure 15. Plots of the measured and ITM predicted path losses by ITM designated propagation modes (Double Horizon Diffraction, Single Horizon Diffraction, and Line of Sight) within Pendleton County, West Virginia, throughout the August measurement campaign. The top figure shows a scatterplot comparing the measured BTL with the ITM predicted BTL with the modes separated by color. The bottom figure shows a box plot providing visual statistics for each propagation mode.

4. Discussion

4.1 Key Observations

The mean signed difference values shown in the left and right plots of Figure 14, and explicitly listed in Table 2, indicate that ITM generally under-predicts the measured BTL. The top and bottom plots of Figure 15 show that paths classified by ITM as line-of-sight exhibit the largest systematic under-prediction of loss relative to the measured BTLs. However, line-of-sight instances account for only approximately 9.3% of the propagation paths in the dataset. As a result, the larger systematic under-prediction observed for these paths has a limited influence on the aggregate results. The bottom plot of Figure 15 also shows a notable number of outliers above the upper whisker, as defined in Section 2.5.4, indicating instances where ITM over-predicts path loss relative to the measurements.

4.2 Sources of Model and Measurement Discrepancy

The overall under-prediction and the presence of outliers are consistent with known limitations of terrain-based propagation modeling and with the complex topography of the hills of West Virginia. The following sections examine these effects in detail. Sections 4.2.1 and 4.2.2 discuss limitations inherent to the ITM framework in the context of the observed results, including terrain modeling constraints and the absence of clutter representation. Section 4.2.3 then considers measurement related uncertainties, followed by an assessment of transmitter parameter uncertainty. Because this analysis was conducted using transmissions from an operational study rather than a dedicated propagation measurement campaign, uncertainties associated with the transmitted signal represent a significant source of unexplained variance. As a result, further efforts to quantitatively isolate and attribute the remaining sources of discrepancy were determined to be of limited value within the scope of this study. The following sections therefore identify and discuss the likely contributors to the observed differences while noting investigative approaches that would typically be pursued in a more tightly controlled propagation measurement campaign.

4.2.1 Terrain Modeling Limitations in ITM

First, ITM is restricted to computing diffraction using only two knife-edge terrain diffraction (KETD) points along a propagation path. This number of KETD is likely inadequate in this hilly terrain especially when the first Fresnel zone is up to 173 m in radius at the operating frequency of 169.5375 MHz and a distance of 67.9 km. If further investigation were warranted, propagation paths exhibiting large discrepancies between measured and predicted loss could be examined to determine whether the terrain profile contains additional diffraction features beyond those represented by the two-obstacle approximation used by ITM. For

paths where additional diffraction features are identified, a model permitting a greater number of diffraction obstacles, such as Vogler's model [7], could be evaluated and compared with ITM predictions to assess whether the two-obstacle limitation is a significant contributor to the observed discrepancy.

Also, while small-scale fading is largely mitigated by the 10 s integration interval used in this study[4], constructive interference and signal enhancement can persist due to site-specific terrain interactions that are stable over the measurement interval. Given the complex terrain geometry and the large Fresnel zones associated with VHF propagation, multiple reflected and diffracted propagation components—including interactions with extended and out-of-plane terrain features—may arise; these effects are not represented in ITM and can produce localized signal enhancement. This interpretation is consistent with the smaller number of over-prediction outliers observed for paths classified as line-of-sight.

Finally, rounded-edge diffraction effects are not included in ITM's BTL calculations and can therefore lead to over-prediction of measured loss for individual paths. Potential rounded-edge diffraction effects were not directly identifiable from the aggregate measurement statistics. If further investigation were warranted, locations with large measurement-prediction discrepancies could be screened using terrain profiles to determine whether the dominant obstruction was better represented as a rounded terrain feature than as a knife edge. Candidate paths could then be evaluated using a rounded-obstacle diffraction formulation, such as the methods in ITU-R P.526 [8], and compared with the corresponding knife-edge result. The expected difference between knife-edge and rounded-edge diffraction is path-specific rather than a fixed correction at VHF, depending on the obstruction radius, path geometry, clearance, and frequency.

4.2.2 Vegetation and Clutter Effects

ITM also does not account for vegetation or other clutter losses. The dense deciduous foliage present throughout the measurement area, and which intersects a significant portion of the first Fresnel zone of many propagation paths, is therefore expected to contribute additional attenuation that is not captured by the model, leading to systematic under-prediction of path loss.

Although ITM is a terrain-based model that does not explicitly account for vegetation or terminal clutter, it is possible to pair ITM with an external clutter/foilage attenuation model when such effects are material (e.g., ITU-R P.2108 [9] for clutter and ITU-R P.833 [10] for vegetation). Measurement-based work has shown that incorporating clutter terms can reduce the signed difference in some environments (e.g., [11]). While the application of a full vegetation attenuation model is beyond the scope of this report, it is illustrative to consider bounds on the expected foliage loss. ITU Recommendation P.833-10 defines the maximum attenuation experienced by a terminal embedded within a specific vegetation type and depth. Under-canopy VHF woodland measurement summarized in ITU-R P.833-10 report a maximum excess attenuation, also referred to as the saturation loss, on the order of 9–10 dB at 100 MHz. Although the higher operating frequency of 169.5375 MHz used in this study is expected to introduce some additional attenuation, based on the recommendation, a saturation loss on the order of 10 dB is within the expected range described by the ITU recommendation.

Using the parameterization and formulation in P.833-10, the corresponding distance at which the attenuation exceeds 99% of the saturation value for the operating frequency is on the order of 1 km. Given that the median propagation distance in the August campaign was 19.2 km and considering the heavily forested terrain of West Virginia, the majority of measured paths are long relative to the foliage saturation distance, making near-saturation terminal vegetation losses physically reasonable for a substantial fraction of the measurements. This magnitude of excess loss is therefore consistent with a significant portion of the observed discrepancy between ITM predictions and measured BTL values. It is noted that P.833-10 characterizes terminal-embedded vegetation loss over a continuous path of clutter rather than in hilly terrain where the propagation path would enter and exit foliage clutter; however, the saturation distance provides a useful scale for assessing whether vegetation-related excess loss is likely to be significant for the present measurements.

If further investigations were warranted, path-specific clutter characterization could be incorporated using LIDAR-derived or land-cover datasets to estimate the distance each propagation path traverses through vegetation. These estimates could then be combined with the established P.833-10 foliage attenuation model to assess the extent to which vegetation contributes to the observed measurement-prediction discrepancies.

The overall under-prediction is expected given the effects of unmodeled foliage attenuation that are not captured by ITM's point-to-point formulation when applied to temporally averaged mobile measurements.

4.2.3 Measurement Uncertainties

Although ITM accounts for terrain interactions, including partial Fresnel-zone obstruction, its propagation mode classification and associated loss mechanisms are determined solely from the terrain profile corresponding to a single point-to-point path that uses a knife-edge diffraction formulation. In contrast, each 10 s measurement interval represents a spatially extended path over which the receiver traverses varying terrain and obstruction conditions. Within this interval, the received signal may transition gradually between diffraction-dominated and line-of-sight conditions as the vehicle moves through varying terrain. Furthermore, much of the terrain within the NRQZ is composed of broad, gently rounded ridgelines rather than sharp, distinct peaks, deviating substantially from the knife-edge geometry assumed in ITM. The measured power therefore reflects a composite of these propagation mechanisms, whereas ITM predicts loss based only on the propagation profile at the midpoint of the measurement window.

These effects are illustrated in Figure 16, which shows consecutive 10 s capture measurement locations for which the measured BTL exceeds the ITM prediction by 36.33 dB. In this example, ITM correctly classifies the first location as diffraction-limited and the subsequent location as line-of-sight based on the respective terrain profiles. However, the intervening terrain consists of rolling ridgelines such that, over the duration of the 10 s integration, the received signal experiences contributions from both propagation regimes. As a result, diffraction-related losses present in the measured data are not fully represented in the ITM prediction for measurements classified as line-of-sight, leading to a systematic under-prediction of loss in this category. It is noted that the observed behavior does not indicate an error in the ITM formulation, but rather reflects the limitations of applying a static,

point-to-point propagation model to time-averaged mobile measurements in highly variable terrain.

If further investigation were warranted, these effects could be mitigated through both measurement and analysis refinements. First, the integration time could be adjusted as a function of vehicle speed to minimize the distance traveled during each integration while maintaining the minimum averaging distance of 60 wavelengths required to suppress fast fading. This would reduce the likelihood that a single integration spans substantial terrain changes not represented by the midpoint propagation path. Additionally, each integration interval could be subdivided and the corresponding propagation paths examined to identify transitions between propagation modes occurring within a single averaged measurement.

4.2.4 Transmitter Parameter Uncertainty

It is also important to note that several aspects of the measurement campaign introduce additional uncertainty that may contribute to discrepancies between measured and predicted path loss. The transmitter system, including antenna configuration and output power, was operated by an external contractor rather than by personnel directly involved in the analysis. The contractor reported a fixed ERP for each measurement day; however, potential variations in antenna gain or transmitter output power were not independently verified and could not be accounted for during post-processing. In addition, the use of a continuous FM modulated by a 1 kHz signal provided advantages for evaluating demodulation robustness and public safety communication relevance, but is less conventional for pure propagation studies and necessitated more complex signal extraction and power estimation procedures.

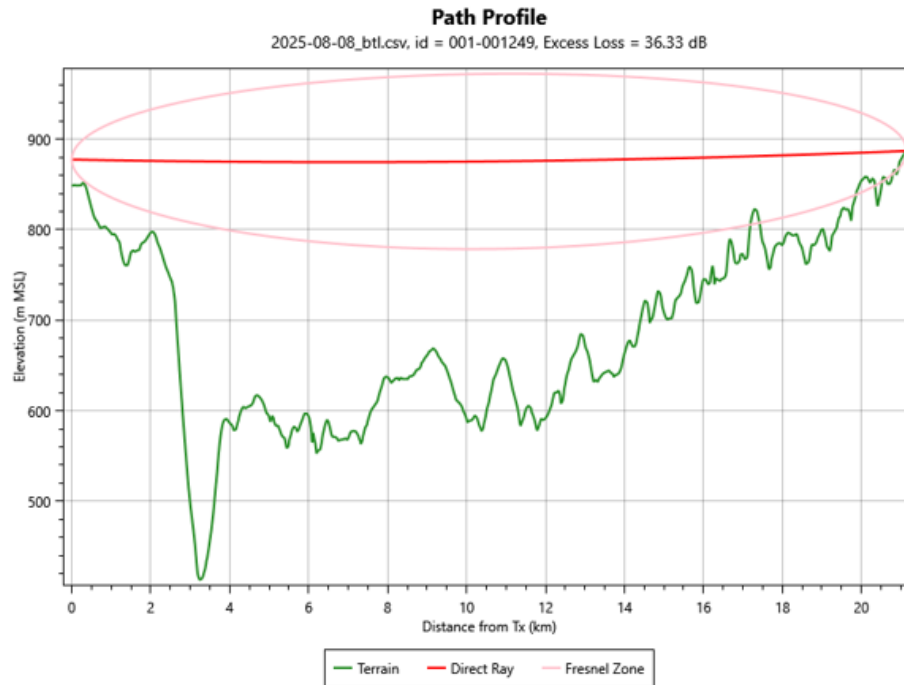
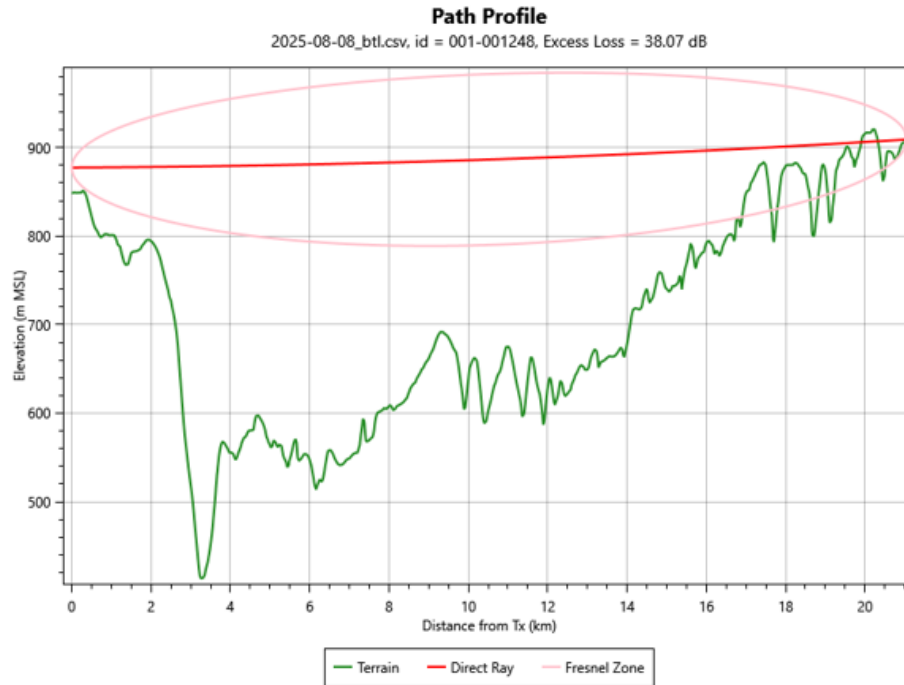


Figure 16. Sequential terrain profiles corresponding to consecutive 10 s measurement intervals, illustrating a transition between diffraction-limited and line-of-sight propagation classifications in the ITM model. Although each profile is accurately classified on a point-to-point basis, the measured BTL reflects time-averaged propagation over rolling terrain not fully captured by a single path profile.

5. Observations and Future Work

5.1 Observations

Overall, the results of this study suggest that ITM exhibits a systematic bias toward under-predicting the path loss experienced in the densely forested hilly terrain of West Virginia. Across the full measurement campaign, the median under-prediction relative to measured BTL was approximately 12.8 dB. Several physical mechanisms likely contribute to this bias, including the presence of more than two effective KETD points, attenuation due to dense foliage, and the cumulative effects of variable terrain-induced diffraction experienced over the spatial extent of each 10 s measurement interval—these are not fully captured by ITM’s point-to-point prediction framework. These effects are not explicitly accounted for in ITM and are therefore expected to result in systematic underestimation of loss.

Vegetation attenuation appears to be a dominant contributor to this discrepancy. ITU recommendation P.833-10 predicts that foliage-induced excess loss for under-canopy VHF propagation can approach saturation values on the order of 9–10 dB. Given the dense deciduous foliage present along the measured propagation paths and the operating frequency of 169.5375 MHz, foliage loss alone plausibly accounts for a substantial fraction of the observed ITM under-prediction. These results suggest that, in similar terrain and frequency regimes, ITM median loss predictions may represent lower-bound estimates of path loss unless additional mechanisms such as foliage attenuation and multi-edge diffraction are explicitly incorporated.

Although under-prediction dominates the difference between measurement and model predictions, ITM was also observed to over-predict path loss in a small subset of measurements, particularly for paths where ITM identified diffraction as the dominant propagation mode. These cases are likely attributable to localized and persistent constructive interference mechanisms, including terrain-induced reflections and diffraction from extended or rounded ridgelines, which can enhance received signal strength over extended spatial and temporal scales. Such effects are inherently site-specific, are not represented in ITM, and may persist over the 10 s integration intervals used in this study. Depending on the relative phase relationships of the contributing paths, these same mechanisms can produce either constructive or destructive interference, contributing to increased scatter about the median prediction.

ITM predictions in this terrain exhibit a mean signed difference of -11.42 dB, indicating systematic under-prediction of transmission loss relative to measured values. This mean difference and the associated dispersion, reflected by 90th percentile absolute differences of 24.73 dB, are consistent with the combined effects of vegetation attenuation, terrain diffraction, and site-specific propagation mechanisms discussed in Section 3. Together, these characteristics define the direction and characteristic magnitude of model deviation in this environment and provide context for interpreting ITM-based coordination analyses within the West Virginia NRQZ, without implying deterministic service or interference outcomes.

5.2 Recommendations for Future Study

Future measurement campaigns of this type could benefit from several methodological refinements[12]. For propagation-focused studies, the use of continuous wave (CW) test tones is preferred, as their simplicity enables more direct and accurate power estimation. Continuous monitoring of transmitted radio frequency (RF) power using an in-line power meter would further reduce uncertainty associated with transmitter variability. Finally, direct characterization of both transmit and receive antenna gain patterns and radiation efficiencies would substantially improve the overall uncertainty budget and strengthen the quantitative comparison between measured path loss and propagation model predictions.

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Appendix A. Supplementary Measurement Results (July Campaign)

This appendix presents the measurement results from the July week-long campaign. As noted in Section 1.2, transmitter ERP values provided for this campaign were inconsistent (see Table A-1) and other transmitter-configuration uncertainties were identified during independent review. Due to these unresolved uncertainties in radiated power and system setup, these measurements were not included in the primary ITM-based statistical analysis in Section 3. The results are nevertheless presented here for transparency and completeness, and use the same figures and metrics as the main body. For guidance on interpreting these plots, refer to the explanations in Section 2.5.

All figures and tables in this appendix use the same formats and definitions as those presented in Section 3. No additional analysis was performed beyond that described in that section.

Table A-1. Summary of July measurement campaign parameters. All measurements were performed in Pocahontas County at 170.0125 MHz.

Date	Transmitter (Tx) Location	Tx Antenna Height AGL	Separation Distance	ERP
July 21, 2025	(38.232689, -80.147719)	3 m	0.311–74.437 km	~100 W
July 22, 2025	(38.268766, -80.239881)	3 m	1.767–78.255 km	~100 W
July 23, 2025	(38.323389, -80.149569)	3 m	11.823–79.335 km	~100 W
July 24, 2025	(38.412808, -79.997064)	3 m	7.100–63.892 km	~100 W
July 25, 2025	(38.505292, -79.740600)	3 m	1.869–46.097 km	~100 W

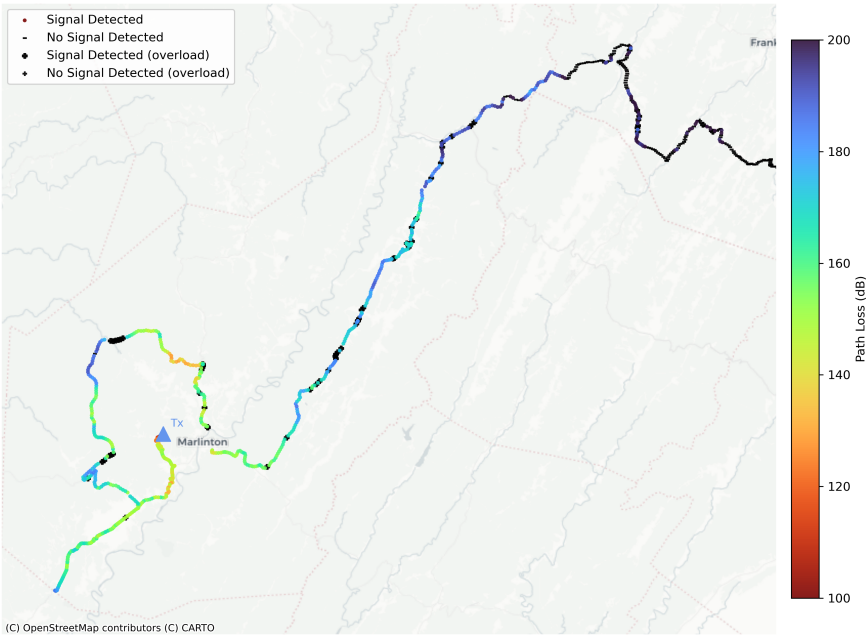


Figure A-1. Pocahontas County, West Virginia, drive routes and basic transmission loss (path loss) for measurements taken on July 21, 2025

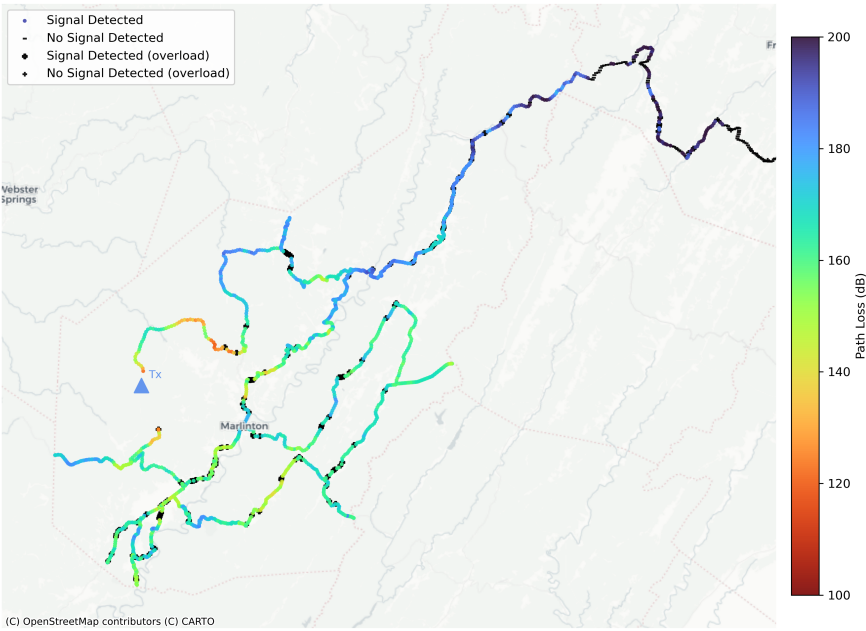


Figure A-2. Pocahontas County, West Virginia, drive routes and basic transmission loss (path loss) for measurements taken on July 22, 2025

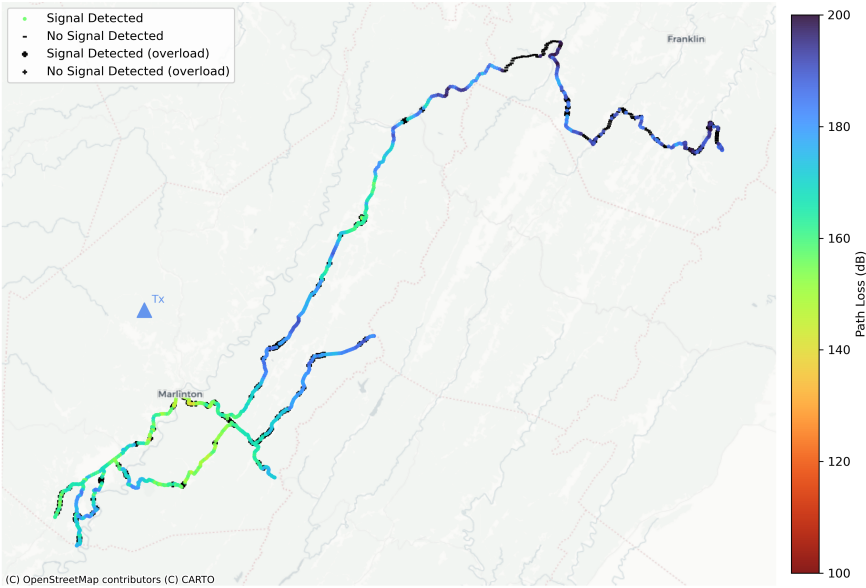


Figure A-3. Pocahontas County, West Virginia, drive routes and basic transmission loss (path loss) for measurements taken on July 23, 2025

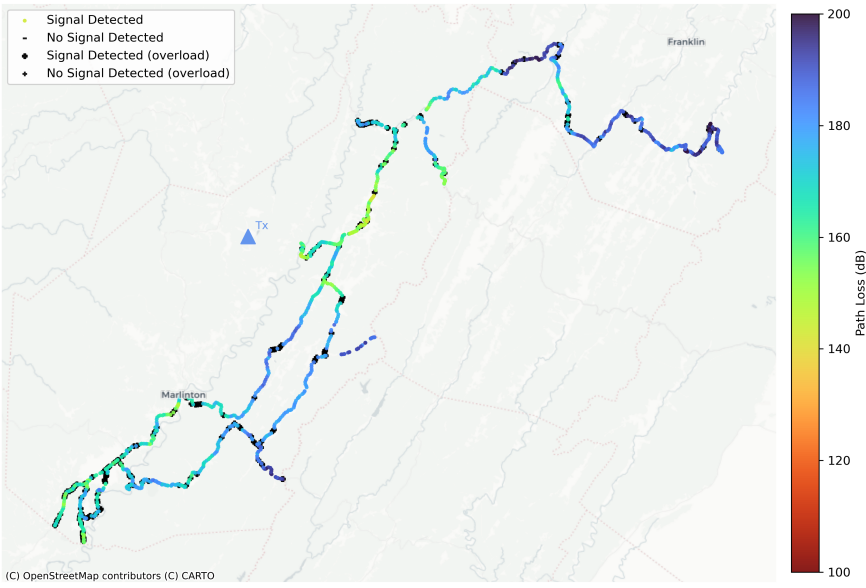


Figure A-4. Pocahontas County, West Virginia, drive routes and basic transmission loss (path loss) for measurements taken on July 24, 2025

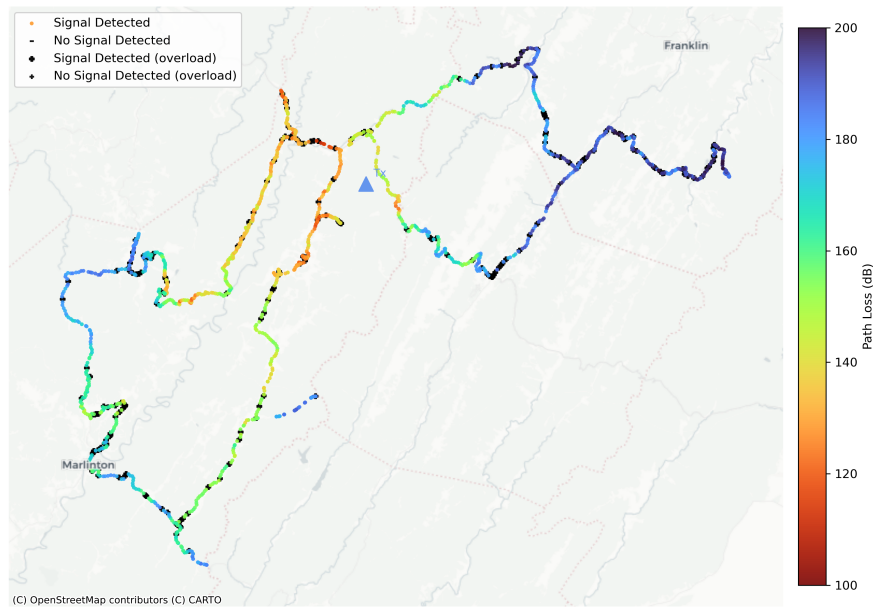


Figure A-5. Pocahontas County, West Virginia, drive routes and basic transmission loss (path loss) for measurements taken on July 25, 2025

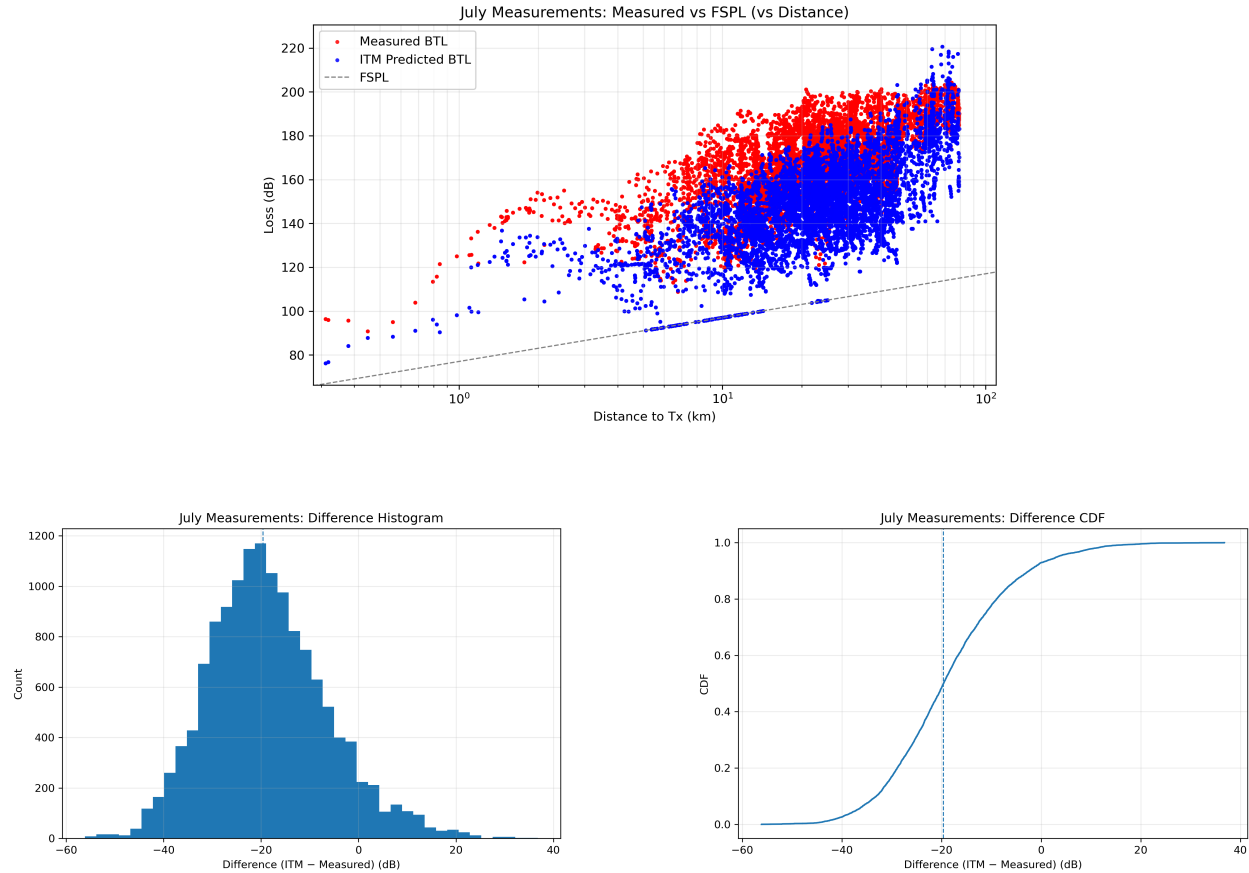


Figure A-6. The top plot shows the measured and predicted losses as a function of distance within Pocahontas County, West Virginia. The bottom left plot and bottom right plot are the statistical characterization of ITM prediction signed differences over the entire July measurement campaign. The bottom left plot is the histogram of prediction signed differences illustrating the overall difference distribution. The bottom right plot is the corresponding CDF used to assess median and high-percentile difference behavior.

Table A-2. Comparison of measured BTL against ITM and FSPL predictions for all detected locations within Pocahontas County, West Virginia, during the July measurement campaign (N=6,905 samples).

Model	Mean Signed Difference (dB)	Absolute Difference Percentile		RMSD (dB)
		50th	90th	
ITM	-11.42	12.80	24.73	15.74
FSPL	-47.99	48.92	68.29	50.62

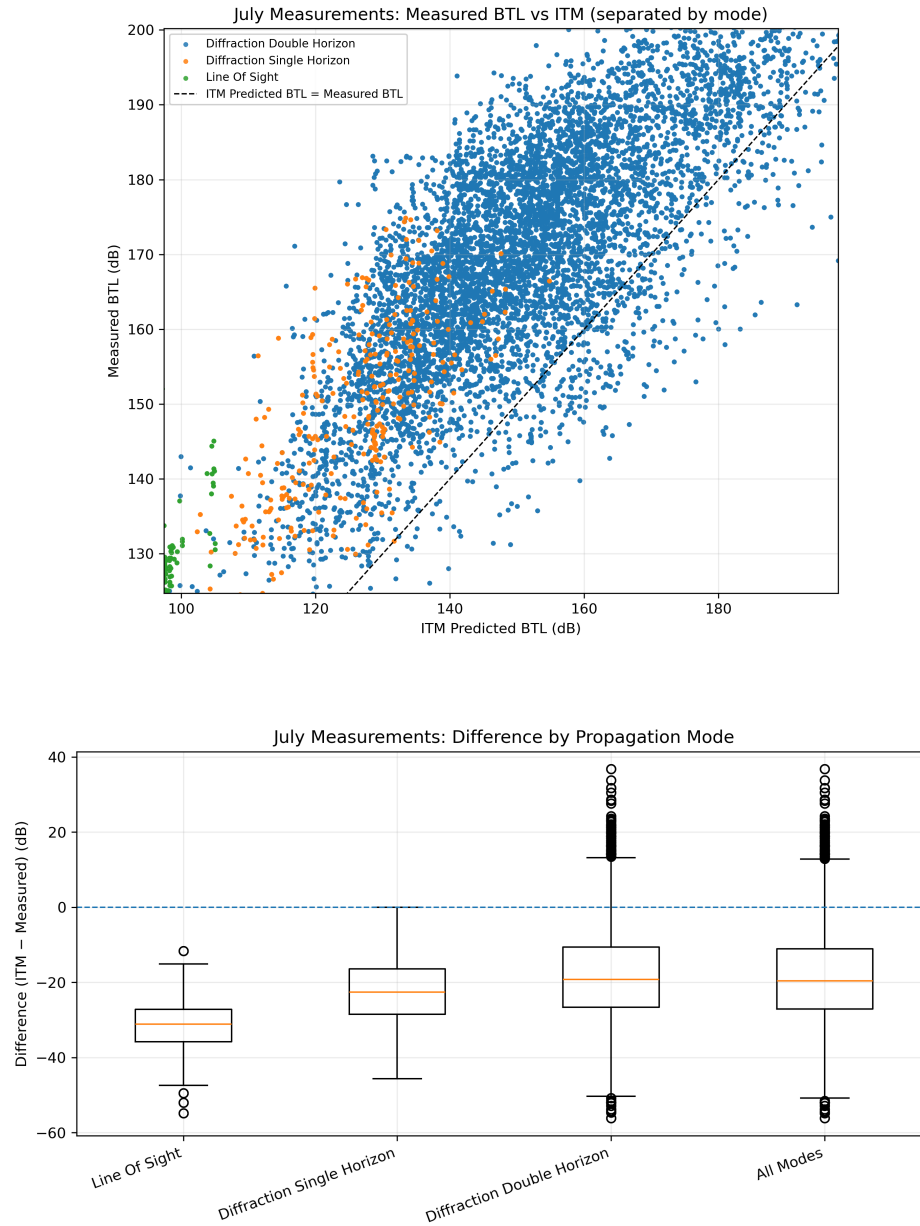


Figure A-7. Plots of the July measured and ITM predicted path losses by ITM designated propagation modes (Double Horizon Diffraction, Single Horizon Diffraction, and Line of Sight) within Pocahontas County, West Virginia. The top plot of the figure shows a scatterplot comparing the measured BTL with the ITM predicted BTL with the modes separated by color. The bottom plot of the figure shows a box plot providing visual statistics for each propagation mode.

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14. ABSTRACT Very high frequency propagation measurements were obtained from signal of opportunity transmissions collected during public safety communications field campaigns within the National Radio Quiet Zone surrounding Green Bank, West Virginia. Measured path loss was then compared with predictions from the Irregular Terrain Model in complex, forested terrain. The propagation measurements consisted of a series of week-long field measurements campaigns using fixed very high frequency transmitters operating at 169.5375 MHz and a vehicle-mounted calibrated receiver, collecting received power measurements over extensive drive routes. Received signal levels were converted to basic transmission loss and compared against Irregular Terrain Model median predictions and free-space path loss estimates. Across the measurement campaign, the Irregular Terrain Model was found to systematically under-predict measured path loss by a median of approximately 13 dB. The observed discrepancies are attributed primarily to foliage attenuation and terrain diffraction mechanisms beyond the double knife-edge model incorporated within the model. In a smaller subset of cases, the model over-predicted path loss, likely as a result of terrain-induced signal enhancement not captured by the model. These results provide empirical context for the use of the Irregular Terrain Model in heavily forested, mountainous environments and could inform future planning for public safety communications systems within the National Radio Quiet Zone.					
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