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Signal Attenuator through Foliage Estimator (SAFE) tool documentation

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INTRODUCTION

The Signal Attenuator through Foliage Estimator or SAFE tool is an open-source propagation model for Radio Frequency (RF) path loss predictions in foliage-dominant environments. Since many propagation tools currently available on the market fail to yield precise predictions in such environments, the tool aims at helping any Canadian individual, business, or academic access modern propagation models, targeting foliage-dominated areas. The source code is mostly based on ITU-R P.1812-6 (P.1812) and provides reasonable performance in terms of path loss prediction accuracy. To improve the prediction, SAFE is also supplemented with a physical foliage model, the Radiative Energy Transfer (RET) model.

The initial motivation for the work was to improve signal prediction accuracy primarily for Fixed Wireless Access (FWA) scenarios. However, the SAFE tool can equally be used for any cellular link in rural environments. Predictions with foliage along the signal path can be problematic generally as modeling foliage accurately is a very challenging task.

This document provides a comprehensive overview of the SAFE tool, its implementation, and the key components that make it a reliable propagation model in foliage-dominant environments. The document discuss how the tool uses above ground clutter data in the form of the High Resolution Digital Elevation Model (HRDEM) dataset and the P.1812 propagation model, as well as the RET model. The source code for the SAFE tool is freely available on GitHub at the URL: GitHub SAFE tool. A user's manual in form of a *read.me* can be found on the root of the GitHub repository.

HIGH-RESOLUTION DIGITAL ELEVATION MODEL

The High-Resolution Digital Elevation Model [1] is a height elevation dataset for Canada. HRDEM is a highly detailed map having a resolution of 1m (or 2m depending on location). HRDEM is derived from airborne Light Detection and Ranging (LIDAR) data from 2015 to the present day. As seen in Figure 1, it includes two components, namely, the Digital Terrain model (DTM) and the Digital Surface Model (DSM). The DTM represents the height above sea level of the land, including mountains, and roads, while the Digital Surface Model (DSM) represents the height above sea level of objects above the terrain, such as vegetation, buildings, and other types of clutter. The difference between DSM and DTM results in the height of clutter above the terrain.

Source: HRDEM product specification (NRCan)

Figure 1. Difference between Digital Terrain Model - DTM (Left) and Digital Surface Model - DSM (Right)

The source data for the HRDEM dataset is acquired through multiple projects with different partners (including municipal, provincial, and federal ministries). NRCan is responsible for creating, uniformizing, and making the dataset publicly available. New data are continuously being added to the dataset with yearly releases. The product currently covers 91 of the 100 largest Canadian cities. Figure 2 shows the coverage of the HRDEM dataset. While HRDEM is available only in Canada, other countries offer similar high-resolution elevation datasets (United States Geological Survey elevation data, United Kingdom's national LIDAR programme).

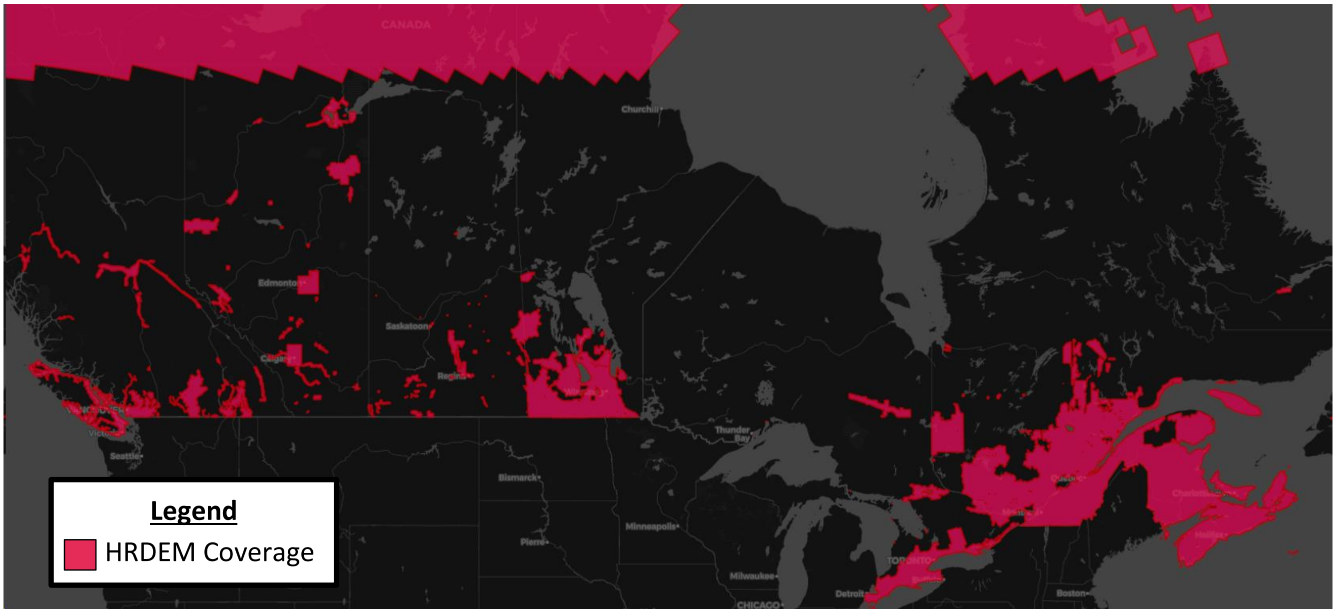

Figure 2. HRDEM coverage as of June 2022

The HRDEM dataset is split into smaller 10x10 km tiles, a tile being a subset section of the larger HRDEM dataset. Some tiles can be incomplete, as shown in Figure 3, meaning that no height information has been extracted in some parts of the tile for both DTM and DSM. A tile may have multiple providers who extracted the elevation in different years, with the date of extraction available in a separate metadata file.

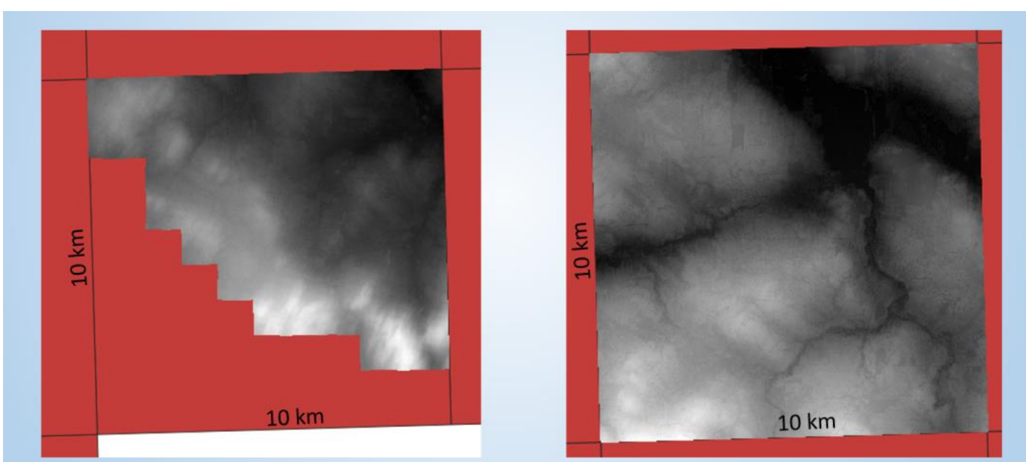

Figure 3. Example of an incomplete (left) vs. complete (right) HRDEM tile

Closer inspection of the information provided in a HRDEM tile reveals features such as streets, buildings, trees and other clutter. Figure 4 shows a side-by-side comparison of a satellite image and the corresponding HRDEM data. The HRDEM data contains elevation information that can be used to extract the path profile and better estimate the propagation of the signal.

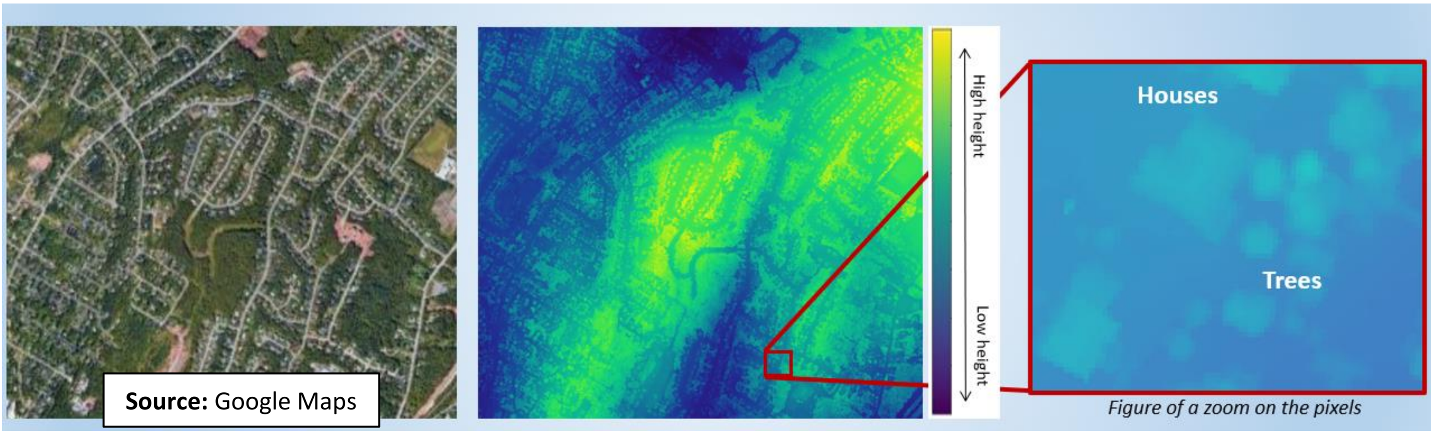

Figure 4. A satellite image of a suburban area in Saint John, New Brunswick (left) and the corresponding HRDEM data (middle)

In cases where it may not be possible to obtain HRDEM tiles at all, the SAFE tool makes use of the Canadian Digital Elevation Model (CDEM) [2] dataset as a fallback option. The CDEM dataset is a lower-resolution terrain elevation dataset, on the order of 30m. Although CDEM is not as detailed as the HRDEM dataset, it can still provide useful information about the terrain in a given area. However, it should be noted that CDEM is not used as a source of surface information, as this dataset does not include information about clutter. The SAFE tool is designed to make use of both HRDEM and CDEM datasets so as to create accurate 2D elevation profiles even in situations where detailed information may not be readily available.

ITU-R P.1812-6

International Telecommunication Union - Radiocommunication Sector (ITU-R) Recommendation P.1812-6 [3] is a propagation prediction model suitable for terrestrial point-to-point services in the frequency range 30 to 6000 MHz. The model is appropriate for radiocommunication links having path lengths ranging from 0.25 km up to 3000 km, with both Transmitter (Tx) and Receiver (Rx) situated within about 3 km above ground. The time percentage p and location percentage p_L are both set at 50%. Unlike other general-purpose propagation models such as the Longley-Rice model [4], P.1812 makes use of the clutter information above ground (i.e., buildings and foliage). In SAFE, P.1812 is used with both terrain elevation and clutter data derived from HRDEM.In this model, path profiles between a transmitter and a receiver are described using three sets of data of equal size. For each profile point, inputs include (1) the distance from the transmitter, (2) the terrain height above sea level and (3) the representative clutter height (see Table 1). SAFE uses equally-spaced profile points with a fixed resolution of 30 m. Figure 5 shows the three sets of input data based on path-specific data. For each profile point, clutter is detected based on the difference in height between DSM and DTM data. For all paths, the first and last element of the representative clutter height vector must be 0 so as to prevent the P.1812 model from overestimating diffraction loss at the endpoints. Table 1 presents the different clutter types of P.1812 and the representative clutter heights for each class.

Table 1. Default representative clutter heights for each clutter type (P.1812)

Clutter Type	Representative Clutter Height (m)
Water/Open (O)	0
Suburban (S)	10
Urban/trees/forest (U/T)	15
Dense urban (D)	20

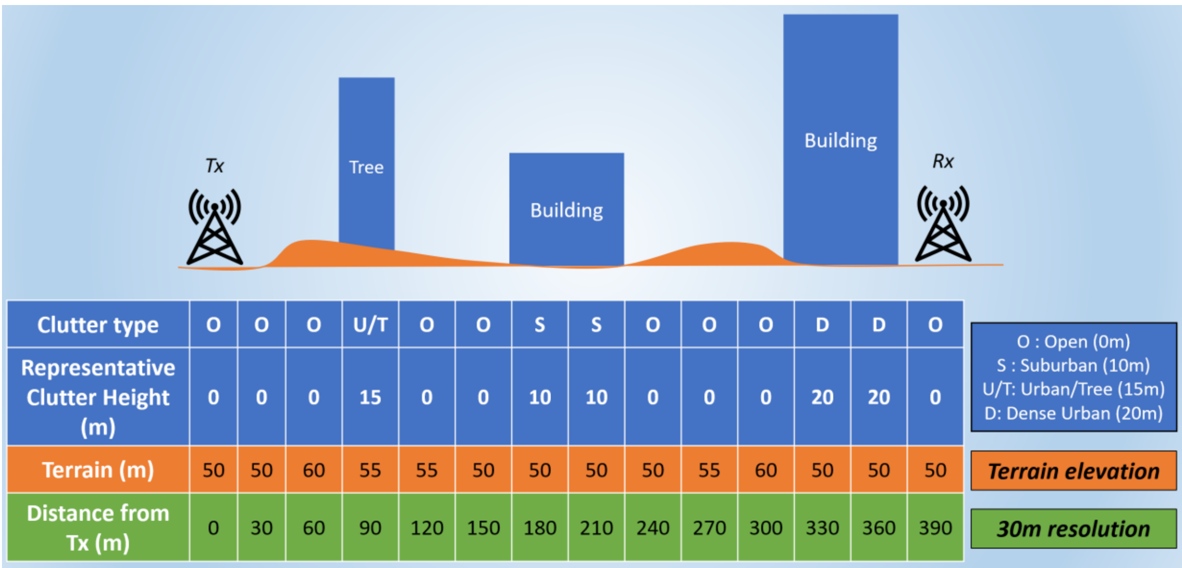

Figure 5. Input parameters for P.1812 in a built-up area with trees

RET MODEL

In order to estimate the attenuation through a given expanse of foliage, SAFE determines whether the direct path between the Tx and Rx is obstructed by clutter. The loss through foliage depends on the tree species, the total foliage depth, the incidence angle, the beamwidth of the receiving antenna in the Rx and the frequency of operation. SAFE currently assumes that all clutter is foliage, and uses a default a given tree species and Rx beamwidth to determine the attenuation due to foliage in decibels (dB).

SAFE relies on a model based on the theory of Radiative Energy Transfer [5][6]; this RET model yields reasonably accurate predictions of loss through in the microwave and millimeter wave bands. The grazing incidence version of the RET model was adopted by the ITU-R (see Rec. ITU-R P.833 [7]).

The loss measured through foliage versus distance at various angles of incidence Θ as shown in Figure 6, shows a steep initial attenuation rate (dB/m) curve over the first few meters of propagation through foliage and a lower attenuation rate at larger distances. Note that this angle Θ is measured with respect to local horizontal and refers to the angle at which the signal encounters the top of the foliage. A grazing incidence (Θ = 0) means that the signal enters the foliage parallel to the ground. For foliage depths around 25 m, the RET model predicts a loss in excess of 30 dB for grazing incidence of 30°. The predicted loss is even larger at 60° (blue curve). The magnitude of this loss suggests that the signal may reach the receiver via other paths (e.g., over or around trees) that offer lower losses. Clearly, the "through" signal component is likely not the dominant one for large expanses of foliage such as those found in rural areas. Moreover, since these forests are typically much wider than they are tall and that ground reflections are likely negligible, the top diffracted path probably is dominant over the side-diffracted ones.

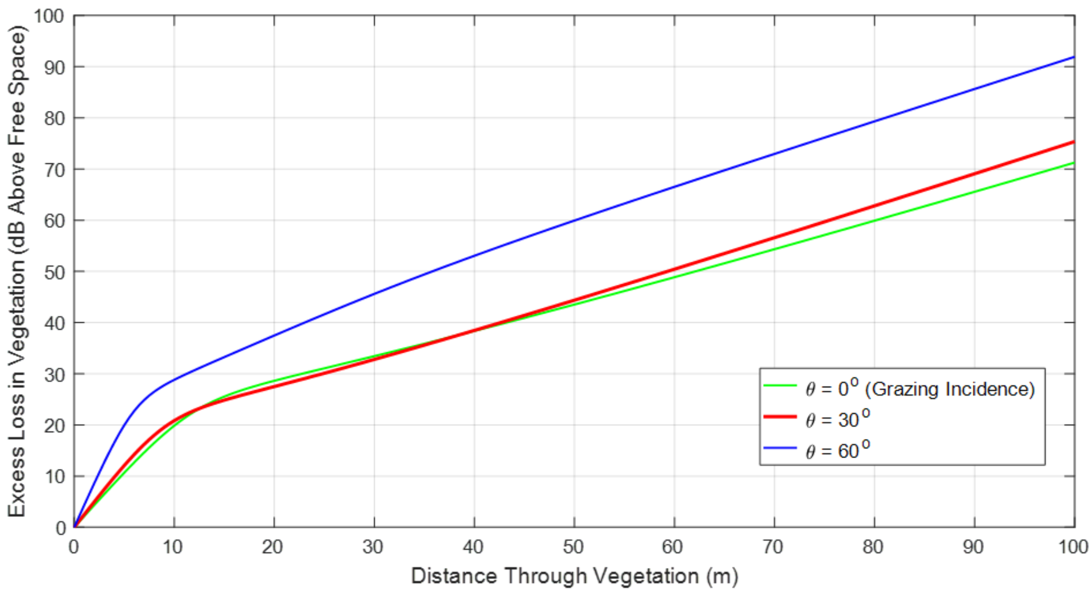

Figure 6. Predicted loss through American Plane Trees in leaf at 3.5 GHz based on the RET model

SAFE TOOL ARCHITECTURE

The architecture of the SAFE tool is heavily reliant on the HRDEM dataset, which serves as its primary input. The SAFE tool generates a 2D elevation profile from the HRDEM dataset between the transmitter and receiver, which is then fed into two models: the P.1812 path loss model and the RET model. These models computes two propagation loss values, which are then used to generate the SAFE path loss prediction. In addition, the tool provides important metrics such as total foliage depth and terrain blockage, which can assist in practical applications. Figure 7 shows the functional architecture of the SAFE tool and how HRDEM is used between the different components

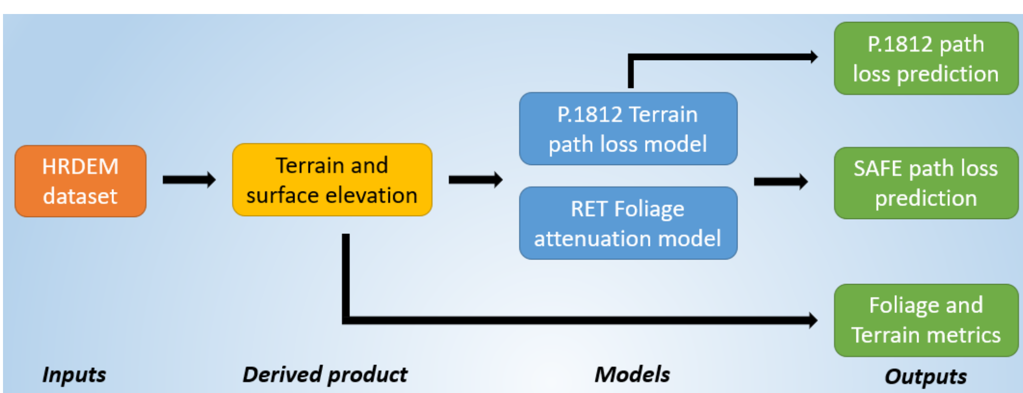

Figure 7. SAFE tool architecture

Figure 8 shows a typical 2D radio path profile between the transmitter and receiver. The tool automatically downloads the necessary HRDEM tiles, which are then ordered by date, with the most recent tiles first. In the event that some information is missing for a particular tile, the SAFE tool will make use of an older tile to fill in any gaps. It should be noted that the download and path profile creation steps are the bottleneck of the propagation model prediction process.

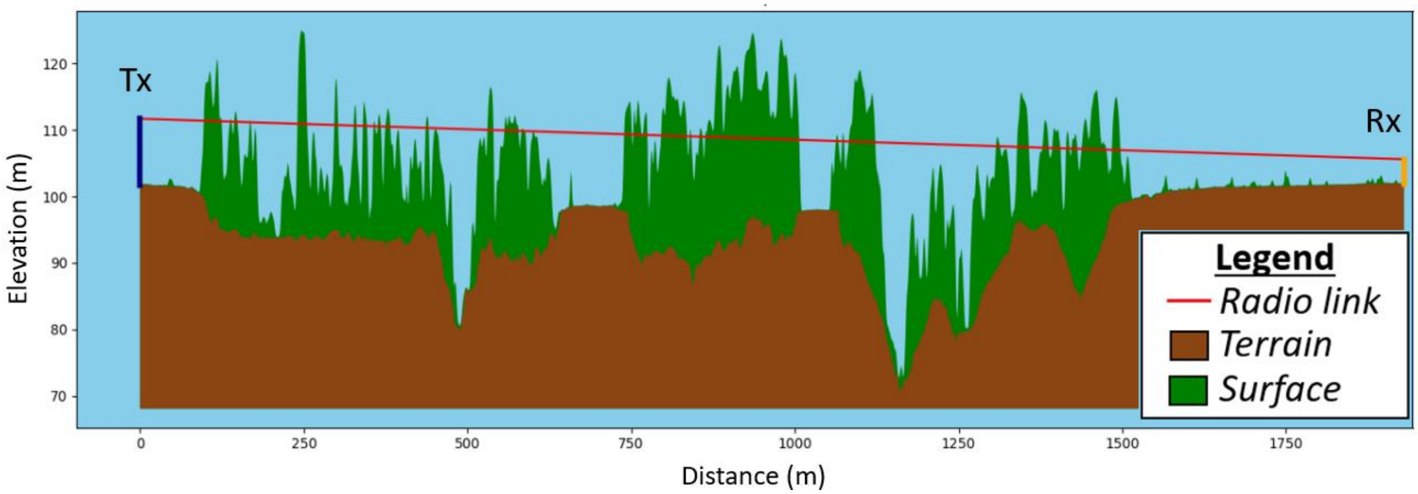

Figure 8: 2D path profile for an actual FWA link extracted from HRDEM data

METRICS AND PATH LOSS OUTPUT

In rural areas, where foliage represents the bulk of the clutter, one of the main metrics is the total foliage depth This metric represents the combined thickness of foliage that block the signal (the radio link in Figure 8). At each point along the link, it is determined if the tree height is intersecting with the path between the Tx and the Rx. Similarly, the terrain blockage metric describes the amount of terrain (horizontal distance) that obstructs the main ray. It is a useful metric for links across mountainous terrain.

Table 2 presents the list of metrics of the SAFE tool that can be used for further analysis. *Total Foliage Depth* has been Additionally, a plot similar to Figure 8, detailing the 2D elevation profile of both the surface and the terrain, is created. It is worth noting that metrics provided by the SAFE tool, such as *Total Foliage Depth*, *Average Tree Height* and attenuation calculated using the RET model (*Loss RET*), are a direct derivative of the high resolution of the HRDEM data.

Table 2 of the lists of metrics of the SAFE tool

Metric Name	Description
Index	Unique identifier for a specific simulation run. Used for tracking of the simulation results.
HRDEM available	Boolean value describing whether or not the HRDEM dataset was available during the simulation run. When the value is False, the CDEM dataset is used.
Link Distance	Geodesic distance between the Tx and Rx in meters.
Loss RET	The output of the RET Model in dB. The RET model calculates the loss through foliage

	along the signal path.
Average Tree Height	The mean height of the clutter (surface) that intersects with the signal path in meters.
Total Foliage Depth	The horizontal distance of the clutter that intersects with the signal path.
Terrain Blockage	The horizontal distance of the terrain that intersects with the signal path.
p1812 path loss no clutter	Predicted path loss (P.1812) using only the terrain from HRDEM. It is the path loss prediction if there was no clutter or other obstructions along the signal path.
p1812 path loss	Predicted path loss (P.1812) using the derived terrain and surface from HRDEM. The represented clutter is all set to tree/forest.
SAFE path loss	Predicted path loss (P.1812) without clutter augmented by the loss predicted by the RET model.

Although P.1812 considers several different clutter types (see Table 1 and Figure 5 again), *p1812 path loss* currently handles only the tree/forest type with a representative clutter height of 15 meters. However, the model can be modified to incorporate multiple clutter types in the future, increasing the range of its capabilities. In order to accurately detect and incorporate the presence of clutter along a signal path, the model relies on the HRDEM dataset. The detection threshold for clutter (i.e., the difference between surface and terrain data, DSM - DTM) is currently set to 1 meter.

The SAFE tool combines path loss predictions from the P.1812 model (without clutter) with the foliage loss predicted by the RET model. This foliage model can sometimes predict very large losses as seen in Figure 6, which can limit its usefulness. To address this, a limit of 30 dB has been imposed on the RET model attenuation loss. This limit will be removed when a suitable top diffraction model will be integrated into SAFE. The path loss is currently given by :

$$SAFE\ path\ loss\ = P.1812\ no\ clutter + MIN(30\ dB, RET\ \text{Model})$$

Equation 1. SAFE tool path loss equation

RESULTS

In order to assess the performance of the SAFE tool, tests were conducted on multiple links in rural areas of Canada. Results show that the SAFE tool outperforms P.1812, as demonstrated in Table 3, which shows the root-mean-square error (RMSE) between the measured path loss values and the model's predictions. Additionally, Figure 9 shows a histogram of the prediction errors, revealing that P.1812 with no clutter underestimates the path loss, as expected from a model neglecting foliage. The histogram of SAFE's error seems to fit a zero-mean Gaussian distribution, neither under-predicting nor over-predicting compared to measurements. The data (many thousands of measurements) were collected in rural areas of Canada.

Table 3 of the RMSE of various propagation models

Model	RMSE (dB)
SAFE	13.2

P.1812 (Urban/Trees Classification)	16.6
P.1812 (no clutter)	25.7

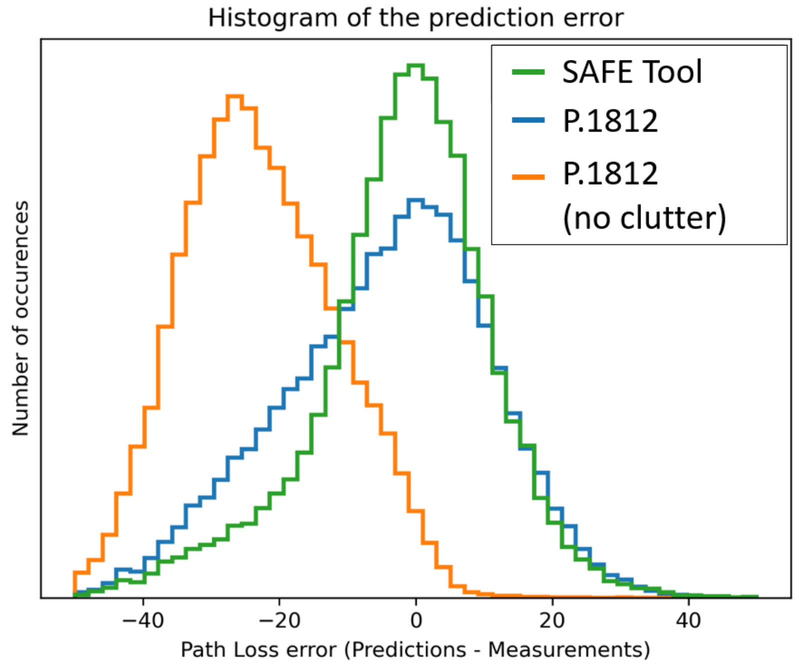

Figure 9: Histogram of the prediction error for various propagation models

CONCLUSION

The SAFE tool is an open-source propagation model that provides an improved prediction of path loss in foliage-dominant environments. The integration of a top diffraction model in addition of the RET model and P.1812 model will improve the accuracy of the SAFE tool. Furthermore, employing the HRDEM dataset ensures accurate modeling of both foliage and terrain by providing the necessary data on elevation and surface characteristics. The current version of the tool provides various metrics, including foliage loss, terrain blockage, and path loss. Future work on the tool includes the integration of various tree species into the RET model, reliance on datasets of land usage to differentiate between foliage and terrain, and the addition of further metrics.

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