A Matlab-Based Virtual Propagation Tool: Surface Wave Mixed-path Calculator

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Abstract—A new Matlab-Based, user-friendly virtual propagation tool (VPT) that can be used for multi-mixed path surface wave path loss calculations has been designed. Any multi-mixed-path surface wave propagation scenario may be specified by the user together with all the necessary input parameters, and path loss vs. range plots may be produced. The effects of multi-mixed paths, electrical parameters of each propagation section, as well as the frequency can be observed and extra path losses can be predicted. The VPT can be used both for design and training purposes.

1. Introduction

In addition to decades of long-range marine communication systems in high frequency (HF) band surface wave high frequency radars (HFSWR) have become a great potential in this frequency region for integrated maritime surveillance systems (IMSS) both as primary and complementary sensors. Countries with wide-coastal regions such as USA, Canada, France, Germany, Italy, Brazil, Turkey, Sri Lanka, China, India, etc., have already deployed or completed the designs of such systems for their economic exclusive zones (EEZ) [1, 2]. One major problem in HF communication/radar systems is the prediction of surface wave propagation path loss. The propagation scenarios differ quite a lot from region to region. For example, engineers of the IMSS on the East Coast of Canada need to know maximum monitoring range for a given transmitter power. On the other hand, the problem of Turkey in the West Coast is to find out extra multi-mixed path propagation loss because of the existence of many different scaled islands in the region.

At HF frequencies, ground wave propagation is dominated by the surface wave. As long as the transmitter and receiver are close to surface direct and ground reflected waves cancel each other and only surface wave can propagate. The Earth's surface electrical parameters are important in reaching longer ranges. Sea surface is a good conductor, but ground is a poor conductor at these frequencies. A challenging problem is to predict surface wave path loss variations over mixed paths, such as sea-land or sea-land-sea transitions [3, 4]. A sharp decrease occurs in signal strength along sea-land transition and the signal recovers itself beyond the island, known as the Millington (recovery) effect [5].

We have introduced a few propagation packages for the calculation of surface wave propagation effects [6–10], where analytical ray and mode models (i. e., Norton and Wait formulations) are hybridized to extend their ranges of validity, accuracy, rate of convergence, etc., depending on such problem parameters as operational frequencies, source/observer locations and the physical propagation environment. The WAVEPROB packages uses analytical ray and mode methods in hybrid form that can handle propagation through standard atmosphere over smooth spherical Earth and can be best used from a few hundred kHz up to 40–50 MHz [7]. The ray shooting algorithm SNELL_GUI [8] shoots a number of rays through a propagation medium characterized by various piecewise linear vertical refractivity profiles, so the user may visualize various ducting and anti-ducting characteristics depending on the supplied parameters. The packages RAY_GUI and HYBRID_GUI [9] can be used to investigate ray/mode formulation inside a 2D non-penetrable parallel plate waveguide. The user may analyze individual ray/mode contributions and their collective effects as well as hybrid forms. Finally, the multi-purpose SSPE_GUI package completes the virtual set, which can be used directly in simulations of short- and long-range radiowave propagation over user-specified, non-smooth Earth's surface through non-homogeneous atmosphere [10].

In this study, we have developed and designed a new Matlab-Based, user-friendly virtual propagation tool (VPT) that can be used for multi-mixed path surface wave path loss calculations. The user may design a propagation scenario by just using the computer mouse, specify all other input parameters, and produce path loss vs. range plots. The effects of multi-mixed paths, electrical parameters of each propagation section, as well as the frequency can be observed and extra path losses can be predicted. The VPT can be used both for design and training purposes.

2. Analytical Formulation Based on Ray-mode Approach

The fundamental analytic models are based on ray and mode techniques and are mostly known as Norton [3] and Wait [4] formulations, respectively. The Norton formulation extracts a ray-optical asymptotic approximation from a wavenumber spectral integral representation. The Wait formulation restructures the spectral integral as a series of normal modes propagating along the earth's surface. They both assume a smooth spherical earth (and/or its earth-flattened approximate equivalent) with various smooth, penetrable ground characteristics, a radially homogeneous atmosphere above, and excitation by a vertical or a horizontal electric dipole on or above the earth's surface.

Norton and Wait formulations parameterize the propagation process in terms of different phenomenological models, their ranges of validity, accuracy, rate of convergence, etc., depending on such problem parameters as operational frequencies, source/observer locations and the physical propagation environment, differ as well, with particular impact on computations. Using the ray-mode approaches separately or in hybrid form, one may deal with smooth-boundary problems [11], such as

- Surface wave path loss or field strength variation with respect to range (especially beyond the horizon and when both transmitter and receiver are on the surface).

- Range and/or height propagation variations in interference regions (i. e., when transmitter and receiver are above the surface and within the line-of-sight (LOS)).

- Surface wave path loss over multi-mixed propagation paths to account for, for example, land-sea or sea-land-sea (island) transitions.

It should be noted that ray-mode and their hybridized techniques cannot handle problems, such as propagation over rough surface terrain, and/or through surface and/or elevated ducts formed by inhomogeneous vertical as well as horizontal atmospheric conditions. Although height gain functions in mode theory [11] can be used to account for transmitter/receiver heights, it is difficult to deal with receiver heights in diffraction regions (beyond LOS) because of numerical problems in calculating higher order terms in the series representation of Airy functions.

3. Millington Effect and ITU Curve Fitting Method

Although perfectly reflecting boundary assumption provides in general sufficient approximation at VHF and above (i. e., frequencies higher than 100–200 MHz), the use of impedance boundary condition becomes essential at HF frequencies and below. This is especially required for the simulation of long-range marine communication and/or ocean surveillance systems using HF frequencies. A challenging problem is to predict surface wave path loss variations over mixed paths, such as sea-land or sea-land-sea (island) transitions. A sharp decrease occurs in signal strength along sea-land transition and the signal recovers itself after land-sea transition (beyond the island), known as the Millington (recovery) effect [5].

The path loss of a communication system between any pair of transmitter/receiver is defined as

$$L_p(d) = 10 \log \left(\frac{P_r}{P_t} \right) \tag{1}$$

For a $P_t = 1 \, \text{kW}$ transmitter (i. e., for a short electric dipole with a dipole moment of $M = 5\lambda/2\pi$), the received power at an arc distance d can be determined from the computed field strength E via

$$P_r(d) = \frac{E_r(d)^2}{Z_0} \times \frac{\lambda^2}{4\pi} \tag{2}$$

The path loss is then obtained from these two equations as

$$L_r(d) = 142.0 + 20 \log (f_{MHz}) + 20 \log (E_{\mu V/m}) \quad [dB] \tag{3}$$

where the units of the operating frequency and field strength are MHz and dBμV/m, respectively.

The Millington method uses a graphical interpolation approach to calculate the mixed path losses. Figure 1 shows a multi-mixed propagation medium including 5-paths. Let's consider a scenario for 2-paths with different surface parameters. The Millington method is based on an interpolation of a direct electric field E_D and an
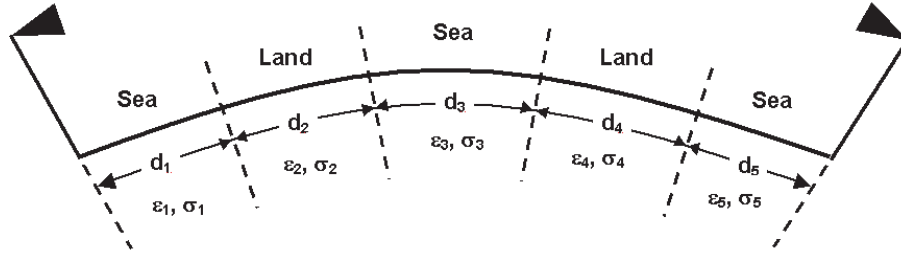
Figure 1: Multi-mixed-path surface wave propagation scenario for 5 paths.

inverse electric field E_I as:

$$E_D = E_1(d_1) + E_2(d_1 + d_2)E_2(d_1) \tag{4}$$
$$E_I = E_2(d_2) + E_1(d_1 + d_2)E_1(d_2) \tag{5}$$

Here, the field values $E_1(d_1)$, $E_2(d_2)$, $E_2(d_2)$, $E_1(d_1 + d_2)$, and $E_2(d_1 + d_2)$ are defined as follows:

$E_1(d_1)$:   Calculated field strength at a distance d_1 over homogeneous Med. I
$E_1(d_2)$:   Calculated field strength at a distance d_2 over homogeneous Med. I
$E_2(d_2)$:   Calculated field strength at a distance d_2 over homogeneous Med. II
$E_1(d_1 + d_2)$:   Calculated field strength at a distance $d_1 + d_2$ over homogeneous Med. I
                     (the whole path is assumed as Med. I)
$E_2(d_1 + d_2)$:   Calculated field strength at a distance $d_1 + d_2$ over homogeneous Med. II
                     (the whole path is assumed as Med. II)

Then the total electric field is calculated by taking the average as

$$E(d_1 + d_2) = 0.5(E_D + E_I). \tag{6}$$

The Millington method can be used for 3-paths in a similar way. If the path lengths are d_1, d_2 and d_3, respectively, the direct electric field E_D and the inverse electric field E_I are calculated via

$$E_D = E_1(d_1) + E_2(d_1 + d_2)E_2(d_1) + E_3(d_1 + d_2 + d_3)E_3(d_1 + d_2) \tag{7}$$
$$E_I = E_3(d_3) + E_2(d_3 + d_2)E_2(d_3) + E_1(d_3 + d_2 + d_1)E_1(d_3 + d_2) \tag{8}$$

and the total electric field is calculated again by taking the average as

$$E(d_1 + d_2 + d_3) = 0.5(E_D + E_I) \tag{9}$$

The extension to n-path formulas is straightforward.

4. Matlab-Based HF_PATH Package

The front panel of the HF_Path package is designed as shown in Figure 2, and is divided into three sub regions. The left part of the GUI is reserved for the user-supplied parameters. The user specified parameters are explained in Table 1. The operating frequency, range increment, transmitter height and receiver height are supplied first. Then the electrical parameters; the conductivity and the relative permittivity of the sea and land are to be specified next ($\mu = \mu_0$ everywhere and the atmosphere is homogeneous). The parameters of all sea paths (or land paths) are assumed same. Although it is doable, the package doesn't allow the user to specify N-path with N-different electrical surfaces. Finally the user specifies the number of paths along the range using a popup menu. Once the user determines the number of paths N, only N editable textboxes become visible to enable the user to specify the lengths of the paths. For example, in Figure 2 the number of paths is 6, so there are 6 visible textboxes. However in Figure 3, the number of paths is 3, so there are only 3 visible textboxes. It is also important to note that the first segment is always sea, and that a sea segment is always followed by a land segment and vice versa. The mid-part of the front panel is reserved for the figures. The upper figure

shows the geometry of the scenario and changes whenever the number of paths is changed by the user via the corresponding popup menu. The lower figure displays both the geometry and plots for Path Loss vs. Range or Field Strength vs Range variations. The sea and land segments are shown in blue and green, respectively, as shown in Figure 2. The lengths of the blue and green filled areas correspond to actual lengths specified by the user.
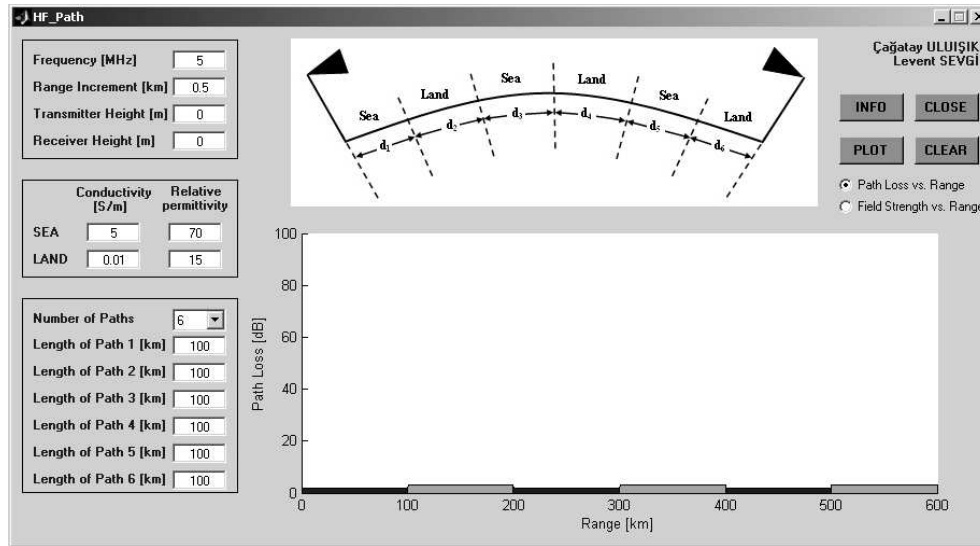

Figure 2: The front panel of HF_PATH package.

Table 1: User-specified parameters of the HF_Path package.

Parameter	Explanation	Default Value
Frequency	Operating Frequency	5 MHz
Range Increment	The difference between each observation point	0.5 km
Transmitter Height	Height of the Transmitter in [m]	0 m
Receiver Height	Height of the Transmitter in [m]	0 m
Conductivity of Sea	Conductivity of each sea segment in [S/m]	5 S/m
Conductivity of Land	Conductivity of each segment land in [S/m]	0.01 S/m
Relative Permittivity of Sea	Relative permittivity of each sea segment	70
Relative Permittivity of Land	Relative permittivity of each land segment	15
Number of Paths	Number of sea and land segments between the transmitter and the receiver (min :1 ; max: 6)	3
Length of Path 1	Length of the first segment (sea) in [km]	100 km
Length of Path 2	Length of the second segment (land) in [km]	100 km
Length of Path 3	Length of the first segment (sea) in [km]	100 km
:	:	:
:	:	:

The control push buttons are located at the upper right part of the panel. Pressing the "*Info*" button opens the MATLAB Help window that includes explanations on how to use the package. Typing "help HF_Path" at the MATLAB command line also displays the same explanations. The "*Close*" button terminates the program. The "*Clear*" button clears the graph. Once the "*Plot*" button is pressed, the user-specified parameters are written line by line to an input file named "*HFMIX.INP*", then the program HFMIX.EXE is executed and the outputs are both displayed in the figure and written to files "*LMIX.DAT*" and "*EMIX.DAT*". Both files consist of 2-columns of data in text format. The first column belongs to the range values in km and the second column of *LMIX/EMIX* corresponds to Path Losses/Field Strengths in dB. The check boxes below the Plot button are used to select whether to plot the Path Loss vs. Range or Field Strength vs. Range. Operational parameters

may be changed by the user and multi-plots may be displayed by pressing the plot button more than once (as long as the propagation scenario, i.e., the segment lengths, is kept same). The user may clear previous plots by using the "Clear button" before the "Plot button".
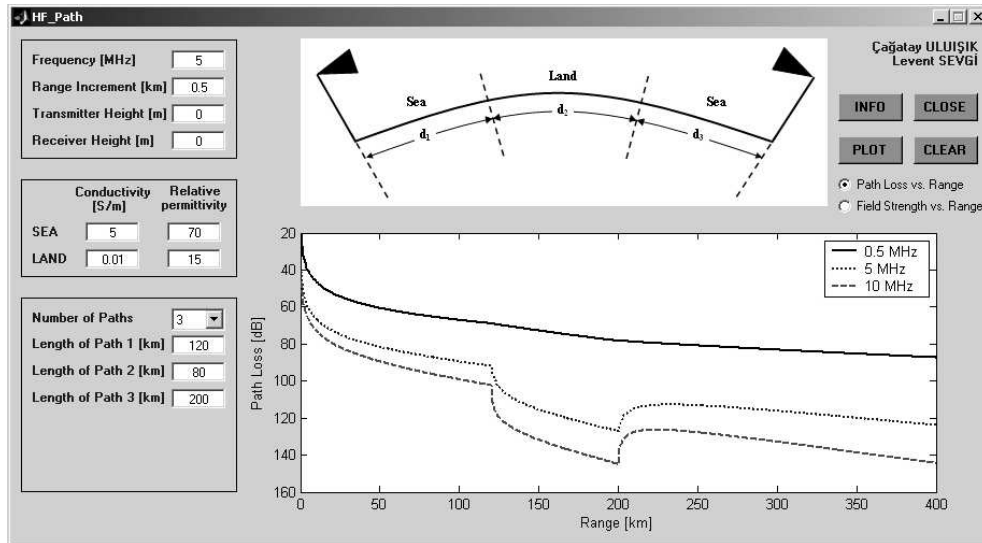

Figure 3: Path loss vs. range for a 3-section-path propagation scenario at 0.5 MHz, 5 MHz and 10 MHz.
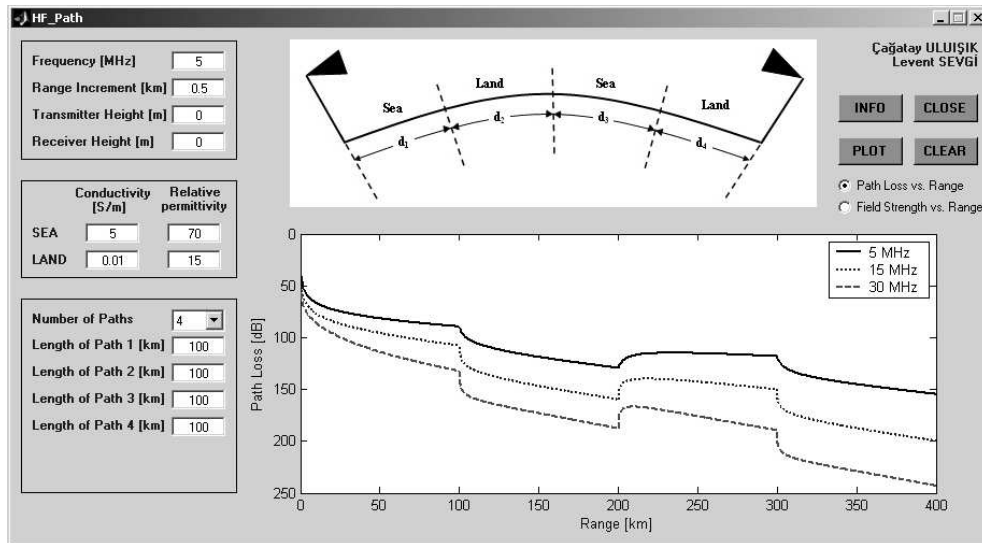

Figure 4: Path loss vs. range for a 4-section-path propagation scenario at 5 MHz, 15 MHz, and 30 MHz.

5. Matlab-Based HF_PATH Package

To show the power and beauty of the HF_PATH package some examples and typical results are presented in this section. The first case belongs to a propagation scenario consisting 3-paths and is displayed in Figure 3. The lengths of the segments are: $d_1(\text{sea}) = 120\,\text{km}$, $d_2(\text{land}) = 80\,\text{km}$, $d_3(\text{sea}) = 200\,\text{km}$, which makes the total range from the transmitter to the receiver 400 km. The conductivity of sea/land are specified as 5/0.01 S/m. The relative permittivities are 70/15. The height of the transmitter and the receiver are both chosen as 0 m. The calculations are performed for three different operating frequencies; 0.5 MHz, 5 MHz, and 15 MHz. All three Path Loss vs. Range graphs corresponding to these frequency values are displayed in the figure with different

colors. The Millington effect is observed at MHz frequencies and above as shown in the figure. The sharp decrease on the sea-land transition region, and signal recovery beyond the land-sea transition are also visible in the figure. It should be noted that, the higher the frequency the higher the path loss at the same distance.

The next example consists of a 4-segment propagation path and results are shown in Figure 4. In this example the segment lengths are same and are equal to 100 km. The range variations of path losses at three different operating frequencies are plotted in the figure.

The third example is shown in Figure 5 for a 5-segment-path. The example corresponds to a propagation scenario with 2 islands with lengths of 32 km and 58 km at radial distances 98 km and 274 km from the source. The Path Loss vs. Range graphs correspond to frequency values of 5 MHz, 15 MHz and 30 MHz.

The last example is another 3-section-path propagation scenario as shown in Figure 6. The plots correspond to different types of lands with conductivity values of $\sigma_{LAND} = 0.001 \, \text{S/m}, 0.1 \, \text{S/m}, 1 \, \text{S/m}$.
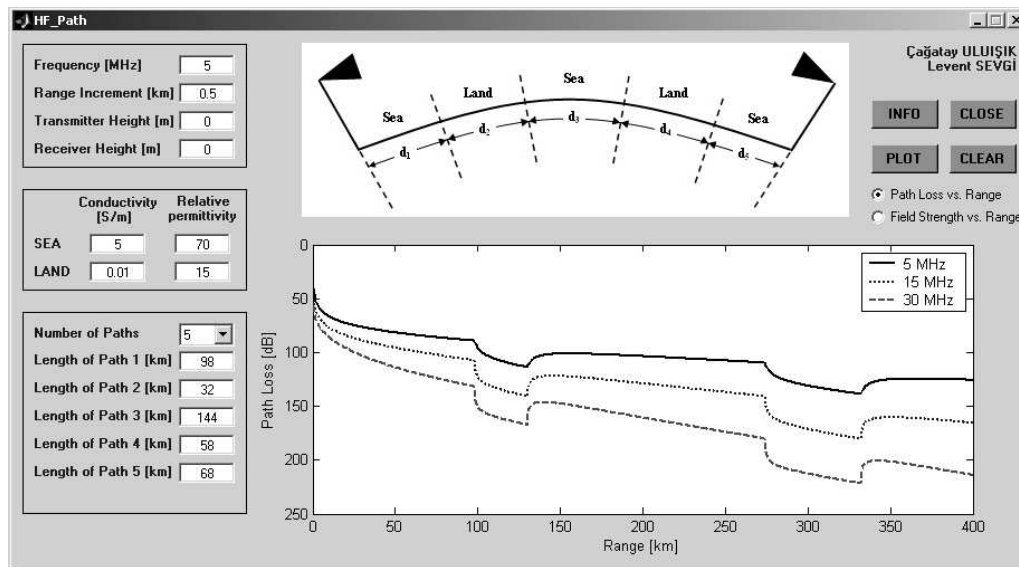

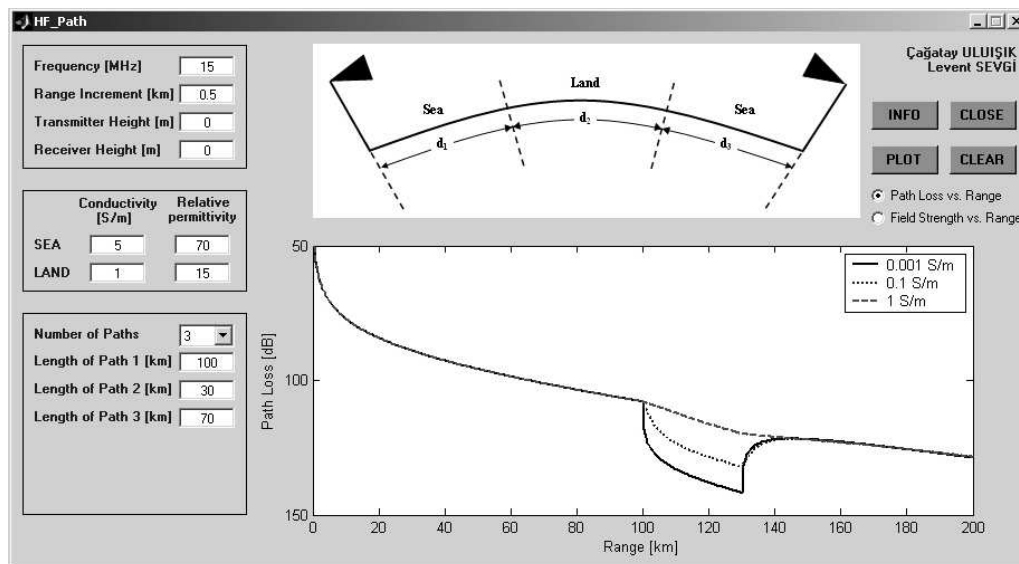Figure 5: Path loss vs. range for a 5-section-path propagation scenario at 5 MHz, 15 MHz, and 30 MHz.

Figure 6: Path loss vs. range for a 3-section-path propagation scenario at $\sigma_{LAND} = 0.001, 0.1, 1 \, \text{S/m}$.

6. Conclusions

The new Matlab-Based, user-friendly HF_PATH virtual propagation tool can be used for multi-mixed path surface wave path loss calculations. Any multi-mixed-path surface wave propagation scenario may be specified by the user together. The electrical parameters of the propagation segments and the operating frequency are also user-specified parameters. The effects of multi-mixed paths, electrical parameters of each propagation section, and the frequency on to the range variation of path loss can be simulated easily. The HF_PATH can be used for both design and training purposes.

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