Statistical Assessment of Evaporation Duct Propagation

HERBERT V. HITNEY AND RALF VIETH

Abstract—**Over-the-horizon propagation from 0.6 to 18 GHz is presented in the form of accumulated frequency distributions of path loss, showing comparisons between theory and two measurement programs. The path-loss theory is based on waveguide solutions for a family of refractivity-versus-height profiles characterized by evaporation duct height in the range of 0 to 40 m. Annual frequency distributions of evaporation duct height have been prepared based on 15 years of marine surface meteorological observations and are combined with the waveguide path-loss-versus-duct-height results to give accumulated frequency distributions of path loss. These results are compared to long-term observations from experiments performed in the Aegean Sea and the North Sea. Excellent agreement of theory and observations is noted in most cases.**

I. Introduction

THE EVAPORATION duct has been recognized for many years as a propagation mechanism that can substantially increase beyond-horizon radio signals above diffraction levels for frequencies generally above 2 GHz [1], [2]. Recent advances in numerical waveguide propagation modeling techniques have shown good agreement with case-study observations, when a detailed refractivity-versus-altitude profile is available [3]. This paper will go beyond case studies to investigate statistical modeling of propagation in the evaporation duct resulting in frequency of occurrence of path loss based only on long-term meteorological measurements. Path loss is the ratio of transmitted to received power assuming loss-free isotropic antennas, which in free space is given by the formula

$$L = 32.44 + 20\log(F) + 20\log(R),$$

where L is path loss in dB, F is frequency in MHz, R is range in km, and log is base 10. The motivation for developing such a capability is to provide system design engineers with a method to compute statistical performance parameters, such as signal margins or maximum detection range, for various geographic areas. In this paper, results of such modeling will be compared to measured path loss statistics from two long-term measurement programs conducted in widely different geographic areas.

II. Models

The waveguide propagation model, known as MLAYER, used in this study was originally developed by Baumgartner and later modified by Pappert and is briefly described along with some case-study examples in [4]. The underlying theory of MLAYER is generally taken from Budden [5]. MLAYER can solve the modal equation for an arbitrary vertical multiple-linear-segment refractivity profile using a root-finding scheme that guarantees that all modes with an attenuation rate less than a given value are found. The model allows for either horizontal or vertical polarization. Surface roughness is taken into account through a modification to the surface reflection coefficient based on the variance of surface heights, which in turn is calculated from surface wind speed assuming a "fully developed" sea. For all the results shown in this paper, surface roughness was accounted for by setting the surface wind speed to 7 m/s, which corresponds to world average conditions. Horizontal homogeneity of refractive conditions is assumed by this model.

Over the ocean, the rapid decrease of moisture in the air in the first few meters creates a nearly permanent propagation mechanism known as the evaporation duct [4], [6]. Air immediately adjacent to the ocean is saturated with water vapor and the relative humidity is thus nearly 100%. A few meters above the surface, the relative humidity will decrease to an ambient value that depends on many meteorological processes. Let modified refractivity be defined by $M = N + (z/a)10^6$, where N is the radio refractivity, z is height above the ocean, and a is the earth radius. The modified refractivity versus altitude profile for an evaporation duct indicates a strong negative M gradient (i.e., a strong trapping gradient) at the surface which decreases in magnitude with increasing height. The height at which this M gradient equals zero is defined as the evaporation duct height, which has been shown to be a good measure of the strength of the evaporation duct [6]–[8]. The evaporation duct is a very different ducting mechanism than a surface-based duct from a trapping layer created by the vertical stratification of differing air masses [4]. The evaporation duct is most effective for frequencies above 1 GHz, while surface-based ducts can be effective for frequencies as low as 100 MHz.

Jeske [9] developed a method whereby the evaporation duct height could be determined from measurements of sea temperature, air temperature, relative humidity, and wind speed. Paulus [10] has developed a method for correcting Jeske's calculation for errors in the air-sea temperature difference that are frequently encountered in routine meteorological measurements. The Jeske-Paulus method has been used to compute evaporation duct height frequency distributions for 292 oceanic areas, defined by 10° latitude by 10° longitude Marsden Squares, using a 15-year subset of marine surface

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observations compiled by the United States National Climatic Data Center, Asheville, NC. This data base shows average duct heights vary from around 5 m in high-latitude areas to around 16 m in tropical areas, with the world average being 13 m. These duct height distributions are available from the IBM/PC-compatible Engineer's Refractive Effects Prediction System (EREPS) [11].

For thermally neutral conditions in which the air and sea temperature are equal, the modified refractivity M can be determined at any height z by the relationship

$$M(z) = M(0) + 0.125z - 0.125d \ln [(z + z_0)/z_0]$$

where d is evaporation duct height, ln is the natural logarithm, and z_0 is Jeske's roughness length of 1.5×10^{-4} m. This formula can be readily derived following the approach of Jeske [12]. It is assumed that over the ocean, conditions are near neutral and the above formula is, therefore, a good approximation for most conditions. Since MLAYER requires multiple linear vertical segments to define the refractivity profile versus height, the equation above was used to calculate M at 17 to 34 height levels, depending on the duct height. These height levels were chosen on a logarithmic basis to ensure more levels near the surface where the M-gradient is greatest. Selection of the final levels used in the profiles was done somewhat iteratively, by comparing results from MLAYER for one set of levels with results for the same duct height but defined with more levels. In other words, levels were added until the MLAYER results stabilized for each duct height.

For the cases presented in this paper, MLAYER was used to give path loss versus evaporation duct height using the profiles described above for duct heights in 2-m steps. These results were then weighted by the annual percent occurrence of evaporation duct height in each 2-m interval for the Marsden Square within which the experiment was performed to give accumulated frequency distributions of path loss, which are then compared to the measured distribution. For the case of zero duct height, the evaporation duct does not exist, and propagation effects are dominated by the normal diffraction process, which MLAYER can readily compute.

III. Aegean Sea Results

During 1972 a series of propagation measurements was made between the Greek islands of Naxos and Mykonos in the Aegean Sea [13]. The frequencies were 1.0, 3.0, 9.6, and 18.0 GHz. Transmitters were installed on Naxos at 4.8 m above mean sea level (msl) for all frequencies except 18.0 GHz, which was located at 4.5 m above msl. Receivers were located at Mykonos at three heights for each frequency, with the highest heights being 19.2 m above msl for 1.0, 3.0, and 9.6 GHz, and 17.8 m for 18.0 GHz. Only data from the highest receiver heights are used in this paper. The path was 35.2 km in length and entirely over water. The standard-atmosphere radio horizon for these geometries is about 27 km. Horizontal polarization was used at all frequencies. Received signal levels were measured during four two-to-three week periods in February, April, August, and November for all frequencies except 18.0 GHz, which was only recorded during August and

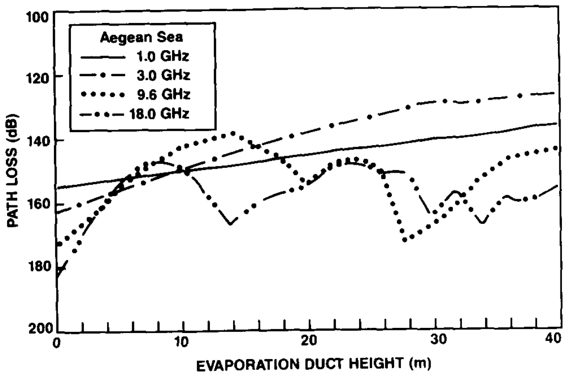

Fig. 1. Path-loss versus evaporation duct height for the Aegean Sea experiment.

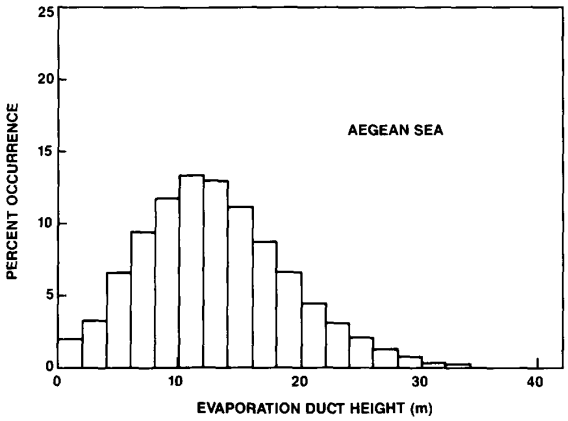

Fig. 2. Histogram of evaporation duct height occurrence in the Aegean Sea.

November. All recorded data were averaged over a 5-min period, with samples taken every 15 min, 24 hours per day. The received signal levels were then converted to path loss taking proper account of periodic calibration measurements, radiated power, receiver sensitivity, antenna gains, and system losses.

Fig. 1 shows the path loss versus evaporation duct height derived from MLAYER for each of the four frequency/geometry combinations described above. At 1.0 and 3.0 GHz, the path loss is seen to monotonically decrease across the entire range of duct heights. At 9.6 and 18.0 GHz, the path loss is seen to decrease initially with increasing duct height, and then alternately increase and decrease with increasing duct height. This later behavior is due to multiple waveguide-mode interference, not seen at the lower frequencies because only one waveguide mode is supported by the duct. Fig. 2 shows the annual evaporation duct height distribution from EREPS for the area in which the measurements were made. Note the most common duct heights are between 10 and 12 m, with duct heights greater than 30 m being quite rare. The results from Figs. 1 and 2 were combined to give accumulated frequency distributions of path loss for each frequency. Figs. 3–6 show these results compared to the measured distributions for the lowest to highest frequency, respectively. Modeled distribu-

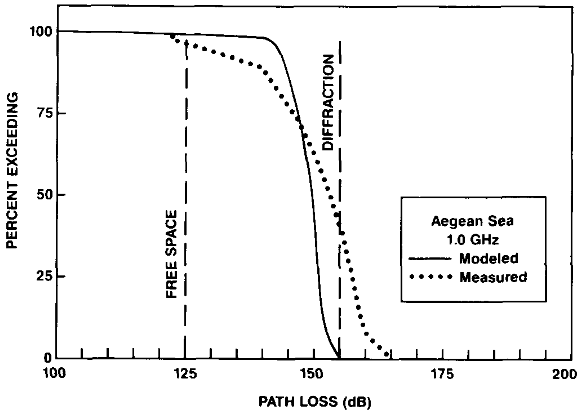

Fig. 3. Path-loss distribution for the Aegean Sea experiment at 1.0 GHz.

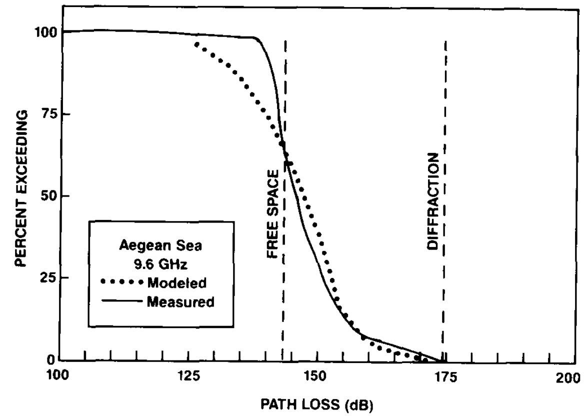

Fig. 5. Path-loss distribution for the Aegean Sea experiment at 9.6 GHz.

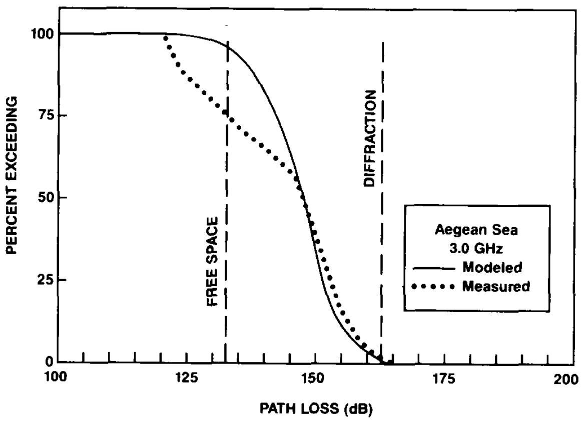

Fig. 4. Path-loss distribution for the Aegean Sea experiment at 3.0 GHz.

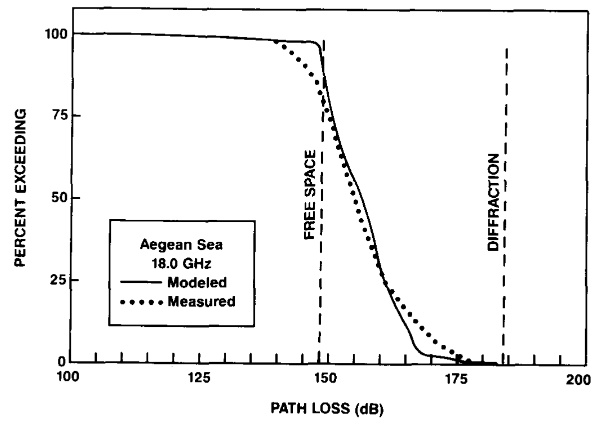

Fig. 6. Path-loss distribution for the Aegean Sea experiment at 18.0 GHz.

tions are shown by a solid curve and the observations are shown by a dotted curve. Reference lines are included in these figures showing the free-space and diffraction-field path-loss values for each frequency. The diffraction field was calculated based on a standard 4/3 effective-earth-radius atmosphere.

Fig. 3 shows that both the modeled and measured path-loss values were reasonably close to the diffraction level most of the time at 1.0 GHz. Fig. 4 shows a substantial decrease in path loss compared to diffraction much of the time at 3.0 GHz, with the median path loss being 15 dB less than diffraction. The modeled and measured distributions are in excellent agreement at the higher path-loss values, but differ up to 12 dB at the lower path loss levels. It is speculated that effects from surface-based ducts created by elevated trapping layers are responsible for this discrepancy, which have not been accounted for in the modeling. Fig. 5 shows the results for 9.6 GHz. Both the modeled and measured curves are in good agreement over most of the range with median values showing some 26 to 28 dB reductions compared to diffraction. At this frequency, the median values are actually much closer to the free-space value than to the diffraction value. As with the 3.0 GHz case, there is a discrepancy between modeled and measured results at the lower path loss values. Fig. 6 shows the results for 18.0 GHz, which follow the same general form as the 9.6 GHz results. Overall, the modeled and measured distributions are considered quite good for all frequencies, and in particular for frequencies above 1.0 GHz.

IV. North Sea Results

The measurements referred to in this section were performed in 1961 by Jeske [9]. He used a one-way propagation path between Weddewarden (near Bremerhaven at the north coast of Germany) and the island of Helgoland (German Bight) for field strength measurements at 0.6, 2.3, and 6.8 GHz. The distance between the transmitters and receivers was 77.2 km. The transmitter antennas on the coast were located at 35, 28, and 29 m, and the receiver antennas were placed on the island at heights of 32, 31, and 33 m, respectively. The optical horizon for this geometry was about 40 km and the radio horizon for a standard atmosphere was about 46 km.

Jeske's field strength measurements were obtained from continuously plotted receiver input voltages. Hourly median, as well as the maximum and minimum, field strength values were taken from these plots. The path loss was calculated for duct height increments of two meters from 0 to 24 using the

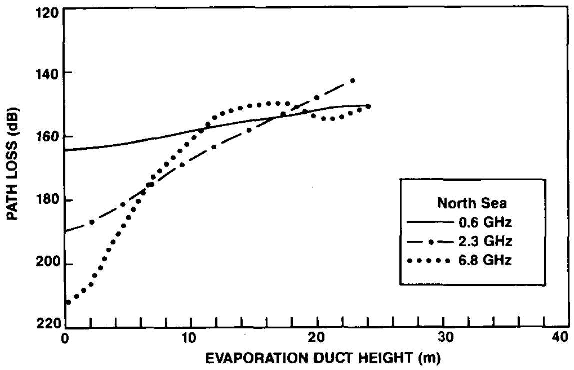

Fig. 7. Path-loss versus evaporation duct height for the North Sea experiment.

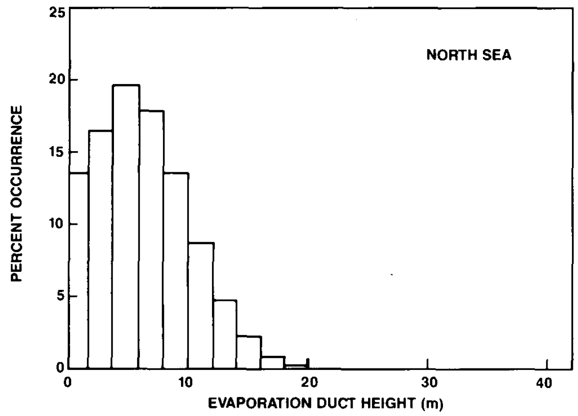

Fig. 8. Histogram of evaporation duct height occurrence in the North Sea.

MLAYER model and is presented in Fig. 7. These results were combined with the annual duct height distribution from EREPS for the North Sea area, shown in Fig. 8, to achieve the path loss distributions. Note by comparing Figs. 2 and 8, that evaporation duct heights are typically less in the North Sea than in the Aegean. To compare these models with the field strength measurements in 1961, Jeske's data were converted to path loss.

Figs. 9–11 show the percentage of time the path loss exceeds the abscissa value for each frequency. Comparisons of the measured data and the modeled results are presented in the same format as the Aegean results.

As in the Aegean results, the path loss reduction relative to the diffraction level (i.e., signal-level improvement over diffraction) increases with increasing frequency. Here the signal improvement of the one way path at the 50% level is measured to be 6 dB for 0.6 GHz, 12 dB for 2.3 GHz and 33 dB for 6.8 GHz above the diffraction path loss. The model gives 3, 13, and 34 dB, respectively. For the 0.6 GHz case, the difference between the measured and the modeled results is 3 dB. The differences for 2.3 GHz and 6.8 GHz are each 1 dB at the 50% level. As with the Aegean results, the overall comparisons between the measured and modeled results for the North-Sea experiment are considered to be quite good.

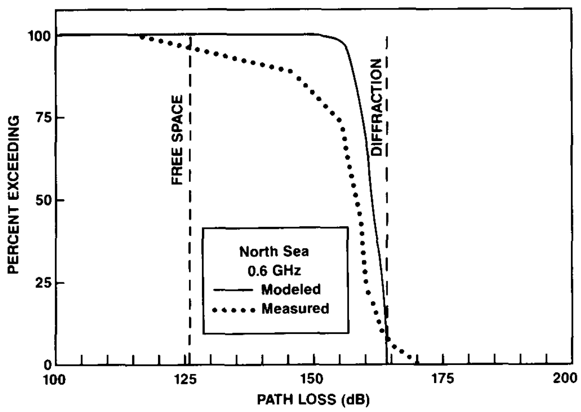

Fig. 9. Path-loss distribution for the North Sea experiment at 0.6 GHz.

V. Discussion

The frequent occurrence of very low path-loss values in the measured data is believed to be due to either surface-based ducts or super-refractive effects. The models used here only account for evaporation duct effects. Surface-based ducts and super-refractive effects were not modeled. Surface-based ducts occur in the Aegean area about 11% of the time

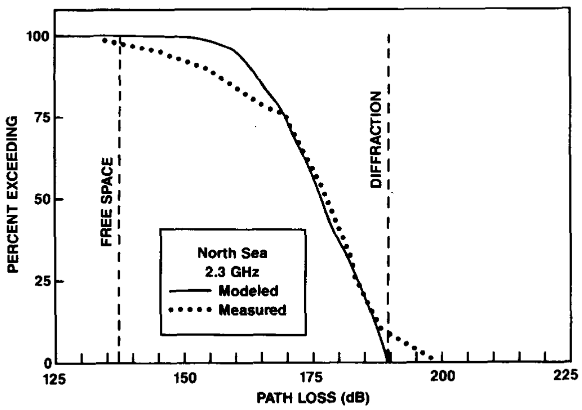

Fig. 10. Path-loss distribution for the North Sea experiment at 2.3 GHz.

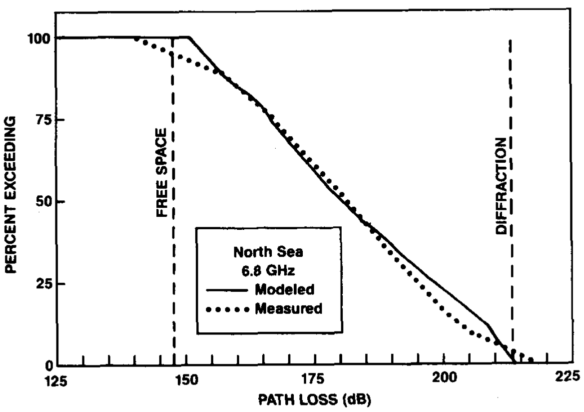

Fig. 11. Path-loss distribution for the North Sea experiment at 6.8 GHz.

annually, and in the North Sea area about 1.7% of the time. Note that the difference between the measured and the calculated curves for the lower path-loss values is less for the North Sea results than for the Aegean results, perhaps due to the lesser occurrence of surface-based ducts. As radio frequency increases for both experiments, the difference between the modeled and the measured curves for low path-loss values generally decreases, because lower frequencies are less sensitive to evaporation duct effects than higher frequencies. At lower frequencies, surface-based ducts, superrefractive effects, or other phenomena not modeled by MLAYER seem to be more important propagation mechanisms than the evaporation duct, and are thus responsible for both the lower path loss values and the greater overall disagreement of measured and calculated results.

There is also a difference between the measured and calculated curves at high path-loss values. The measured path loss exceeds the standard atmosphere diffraction level when mechanisms such as rain or subrefractive conditions occur. The duct heights in the EREPS data base are set to 0 for subrefractive conditions, which implies standard atmosphere conditions. Therefore the calculated values can't exceed the diffraction level. Jeske made meterological measurements during his experiment from a ship stationed approximately at midpath, that show subrefractive conditions occurring about 3% of the time. Had this effect been included in the models, it is thought that the high-path-loss comparisons would be better.

Despite the differences at the lower and upper ends of the curves, modeled and measured data are in very good agreement, particularly for those frequencies above 2 GHz. For the Aegean, the distributions are very close from near 0 to 50% at 3.0 GHz, and from near 0 to 75% at 9.6 and 18.0 GHz. For the North Sea good agreement is seen between the 10 and 75% time levels at 2.3 GHz, and from 5 to 90% in the 6.8 GHz case. Especially in this last case, where the evaporation duct is the dominant effect, the match of modeled and measured curves is remarkably good.

The generally good comparisons of measurements to theory may at first appear surprising, considering the rather crude treatment given to surface roughness. Since wind speed is an important factor in determining both surface roughness and evaporation duct height, it may seem inconsistent to use the world average wind speed for the roughness, but the complete distribution for the duct height. Other investigations not reported on here using MLAYER show very small effects from surface roughness over most reasonable wind speeds at the frequencies studied in this paper. Thus it is concluded that roughness is a minor consideration compared to the evaporation duct, and the modeling results would probably have been nearly the same had a smooth surface been assumed.

A perfect match of the curves should not be expected because of the variation between the 15-year evaporation duct data base used and the actual duct height distribution in 1972 or 1961 in the area of the experiments. However, a favorable comparison has been made of the duct height distribution from Jeske's meteorological measurements and the long-term distribution shown by Fig. 8.

Most noteworthy of this study is the substantial reduction of path loss, or increase in signal, that is both modeled and observed on over-the-horizon paths, particularly at the higher frequencies. Many system engineers use standard diffraction theory to estimate required margins or to otherwise specify their systems. As we have shown, at 7–18 GHz, the median levels may actually be closer to free space than to diffraction, for a net gain of 20–30 dB or more. At frequencies as low as 2 GHz, there is also a substantial increase. For the radar application, this effect could clearly give median detection ranges far in excess of those predicted on the basis of diffraction alone.

VI. Conclusion

From this study, it is concluded that the evaporation duct is the dominant over-the-horizon propagation mechanism at frequencies above 2 GHz. The comparison of measured and modeled path loss distributions shows very good agreement at frequencies where the evaporation duct effect is dominant, in particular at median levels. Some discrepancies are noted at the upper and lower path loss values, which are thought to be a result of propagation effects not modeled, such as surface-based ducts from elevated layers or subrefractive effects. Finally, it is noted that signal improvements relative to diffraction theory can be substantial, in particular at the higher frequencies.

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