Long-term statistics related to evaporation duct propagation of 2 GHz radio waves in the English Channel

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[1] This paper presents long-term statistics additional to those previously published pertaining to evaporation duct propagation of UHF radio waves in the British Channel Islands, with particular focus on a completely over-sea 50 km transhorizon path. The importance of the evaporation duct as an anomalous propagation mechanism in marine and coastal regions is highlighted. In particular, the influence of various atmospheric parameters on the performance of a popular operational evaporation duct model is examined. The strengths and weaknesses of this model are evaluated under specific atmospheric conditions. The relationship between the continually varying evaporation duct height and transmitter-receiver antenna geometries is analyzed, and a range of statistics related to the implications of this relationship on the received signal strength is presented. The various issues under investigation are of direct relevance in the planning of long-range, over-sea radio systems operating in the UHF band, and have implications for the radio regulatory work carried out by organizations such as the International Telecommunication Union.

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1. Introduction

[2] When considering over-sea propagation within the UHF band and above, the most common type of non-standard propagation mechanism that can result in radio waves traveling to beyond line-of-sight distances is the evaporation duct [Hitney *et al.*, 1985; Paulus, 1985; Hitney and Veith, 1990; Babin *et al.*, 1997; *Space and Naval Warfare Systems Command (SPAWAR)*, 2008]. An evaporation duct is a tropospheric phenomenon that primarily occurs immediately above the surface of the sea and other large bodies of water and exists because the amount of water vapor present in the air decreases rapidly with height in the first few meters above the surface of the water. By virtue of its nature of formation, an evaporation duct is a nearly permanent feature. The height of an evaporation duct is typically of the order of only a few meters (the world average evaporation duct height is reported to be approximately 13 m [SPAWAR, 2008]), however this can vary considerably with geographical location and changes in atmospheric parameters such as humidity, temperature and

wind speed [Hitney *et al.*, 1985; Paulus, 1985]. The evaporation duct height is often used as an indicator of its strength and its ability to trap radio waves [SPAWAR, 2008].

[3] When assessing over-sea propagation conditions at low altitudes, the refractivity profiles corresponding to the evaporation duct are of vital importance. Radio-wave propagation assessment packages such as AREPS [SPAWAR, 2008] require accurate vertical refractivity profiles in order to correctly predict communication and/or radar system performance. However, due to the highly variable nature of the troposphere immediately above the surface of the sea, it is not only very difficult but may be prohibitively expensive to directly measure the height of an evaporation duct (for example, the erection of 20 m masts in the open sea with meteorological sensors at multiple altitudes is impractical even if these instruments facilitate the recording of high-resolution measurements). Consequently, over the years, several models have been proposed to estimate evaporation duct heights using in situ surface meteorological measurements at a single altitude (e.g., meteorological buoys or lightships) as inputs [Jeske, 1973; Paulus, 1985; Babin *et al.*, 1997; Frederickson *et al.*, 2003, 2008]. Of these, the Paulus-Jeske (P-J) model [Paulus, 1985] is perhaps the most widely implemented technique and has been utilized to calculate the evaporation duct heights in this paper.

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Figure 1. Map depicting the transmitter and receiver locations in the British Channel Islands.

[4] The results and discussion presented in this paper highlight the fundamental impact that evaporation ducts have on over-sea propagation links and the work has important implications for the planning and operation of UHF radio systems operating in marine and coastal regions.

2. Experimental Arrangement

[5] Three completely over-sea 2 GHz radio paths were established in the British Channel Islands (see Figure 1): Jersey to Alderney (48.5 km), Jersey to Guernsey (33.5 km) and Jersey to Sark (21.0 km). Each site had two antennas: high antennas at 17.5 m (Jersey), 13.0 m (Alderney), 14.0 m (Guernsey) and 13.0 m (Sark) above mean sea level, and low antennas at 14.5 m (Jersey), 10.0 m (Alderney), 10.0 m (Guernsey) and 10.0 m (Sark) above mean sea level. Signal strength measurements were made alternately using the high and the low antennas. The transmitter radiated two vertically polarized signals in a minute (giving a total of 2880 signal strength readings per day per receiving antenna) and the system was synchronized such that transmissions were only from high antenna to high antenna and low antenna to low antenna. The Jersey-Alderney link is always beyond line of sight; the Jersey-Guernsey radio path is transhorizon for only certain

periods around low tide, while the Jersey-Sark link is predominantly a line-of-sight path. Sea level marine meteorological data were obtained on an hourly basis from the Channel Light Vessel (CLV) (49°54'N, 2°54'W) anchored in the English Channel to the northwest of all the radio paths (see Figure 1). Further details of the experimental setup are given by *Siddle et al.* [2007] and *Gunasekar et al.* [2007a].

[6] In this paper, long-term statistics (for a 2 year period from August 2003 to August 2005) related to evaporation duct propagation are presented, with particular emphasis on the 48.5 km transhorizon Jersey-Alderney radio link.

3. Comparison of Marine Meteorological Data From Different Sources: Confirmation of the Assumption of Horizontal Homogeneity

[7] In order to ascertain that the utilization of meteorological data from the Channel Light Vessel is appropriate for the three radio links under consideration, data from two nearby lightships in the English Channel were compared to the weather data from the CLV. The Greenwich Lightship (50°24'N, 0°0'W) and the Sevenstones Lightship (50°6'N, 6°6'W), like the CLV, are maintained by Trinity House, UK (see Figure 2).

[8] Table 1 contains a list of the means and standard deviations of various weather parameters (air temperature, sea temperature, dew point temperature, pressure and wind speed) measured at the three lightships. Over the 2 years of the measurement campaign, there is excellent correlation between most of the important hourly meteorological parameters measured at the three lightships. The correlation coefficient values have been listed in Table 2. Additionally, scatterplots also confirm that the various weather parameters are well correlated between the CLV, the Greenwich Lightship and the Sevenstones Lightship. Therefore, in the absence of a closer source of marine meteorological data, horizontal homogeneity can be reasonably assumed and the bulk weather conditions in the British Channel Islands region can be approximated to those recorded at the Channel Light Vessel.

4. Observations and Analysis

[9] It has been reported previously by *Siddle et al.* [2007] and *Gunasekar et al.* [2007a] that there are possibly two distinct propagation mechanisms operating on the transhorizon over-sea radio link between Jersey and Alderney: evaporation ducting and diffraction for majority of the time (classified as periods of normal reception), and higher-altitude superrefractive/ducting structures for a small fraction of the time during which significant field strength enhancements occurred (classified as periods of

Figure 2. Map showing the relative locations of the Channel Light Vessel, the Greenwich Lightship, and the Sevenstones Lightship in the English Channel.

enhanced signal strength or ESS). Periods of ESS were identified when the received signal strengths exceeded a threshold calculated assuming free space loss along the path [Gunashekar *et al.*, 2007a]. For the Jersey-Alderney radio path, after taking into account cable and other system losses, this free space threshold was -69.0 dBm. Since this paper is primarily concerned with the effect of the evaporation duct, radio and meteorological data only related to periods of normal reception are mostly used in the analy-

sis. Furthermore, Gunashekar *et al.* [2007a] confirmed that the height of the evaporation duct strongly influenced signal strength on the Jersey-Alderney radio path, with higher ducts supporting higher signal strengths at most times. The evaporation duct was established as the principal propagation mechanism by modeling the propagation conditions in the English Channel. Specifically, the P-J evaporation duct refractivity profiles (obtained using meteorological data from the CLV) were utilized as inputs

Table 1. Comparison of the 2 Year (August 2003 to August 2005) Means and Standard Deviations of Meteorological Parameters Measured at Three Different Lightships in the English Channel: The Channel Light Vessel, the Greenwich Lightship, and the Sevenstones Lightship

Meteorological Parameter	Channel Light Vessel (49°54'N, 2°54'W)		Greenwich Lightship (50°24'N, 0°0'W)		Sevenstones Lightship (50°06'09"N, 6°06'W)	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Air temperature (°C)	11.8	3.5	11.8	4.0	12.3	3.3
Sea temperature (°C)	12.8	2.7	13.0	3.3	13.1	2.5
Dew point temperature (°C)	8.3	4.6	8.3	4.9	8.8	4.5
Pressure (mb)	1017.6	9.6	1017.1	10.0	1017.2	10.3
Wind speed (m/s)	7.8	4.1	8.4	4.6	8.8	4.6

Table 2. List of the Correlation Coefficients Between Various Meteorological Parameters Measured at Three Different Lightships in the English Channel: The Channel Light Vessel, the Greenwich Lightship, and the Sevenstones Lightship (August 2003 to August 2005)

Meteorological Parameter	Correlation Coefficient Between Measurements at the Channel Light Vessel and the Greenwich Lightship	Correlation Coefficient Between Measurements at the Channel Light Vessel and the Sevenstones Lightship	Correlation Coefficient Between Measurements at the Greenwich Lightship and the Sevenstones Lightship
Air temperature	0.97	0.96	0.93
Sea temperature	0.99	0.91	0.92
Dew point temperature	0.94	0.93	0.87
Pressure	0.89	0.94	0.81
Wind speed	0.74	0.66	0.52

to the parabolic equation (PE) method [Dockery, 1988; Barrios, 1994; Levy, 2000], and the results indicated a very good agreement between the measured and predicted signal strengths during periods of normal reception.

4.1. Comparison of Evaporation Duct Statistics in the English Channel With Historical Data

[10] The United States National Climatic Data Centre (NCDC) has produced a comprehensive global database of surface meteorological measurements such as air temperature, sea temperature and wind speed [Hitney and Veith, 1990; SPAWAR, 2008]. A subset of this database, known as DUCT63, was analyzed by NCDC to produce a global evaporation duct climatology [Hitney and Veith, 1990; SPAWAR, 2008]. The smallest geographical region defined within this subset database which covers almost all ocean areas between 70°S and 80°N, is a 10° latitude by 10° longitude square referred to as a Marsden Square [Paulus, 1985; Hitney et al., 1985; Hitney and Veith, 1990; SPAWAR, 2008]. The British Channel Islands are contained within Marsden Square number 145 (40°N to 50°N and 0° to 10°W) (Figure 3). The Paulus-Jeske formulation has been used to determine evaporation duct heights within each Marsden Square [Paulus, 1985; Hitney and Veith, 1990].

[11] The occurrence distribution of the estimated P-J evaporation duct heights computed from the hourly CLV marine meteorological data (air and sea temperatures, wind speed, and relative humidity) for periods of normal reception at the Alderney high antenna is presented in Figure 4 (black data). The most commonly occurring duct heights lie in the range 4–10 m (approximately 50% of the data) with a maximum duct height of 23.7 m. The annual histogram of P-J evaporation duct heights for Marsden Square number 145 are also presented in Figure 4 (white data), exhibiting a very similar distribution to that of the CLV evaporation duct heights. In addition, for the purpose of comparison, hourly evaporation duct heights based on weather data from the Channel Light Vessel have been determined using a more recent bulk evaporation duct model called the Naval Postgraduate School (NPS) model

(further details about this model have been included in section 4.2.2). The histogram corresponding to the NPS evaporation duct heights has been presented as the gray data in Figure 4. Similar to the P-J duct height observations, the NPS duct heights very rarely exceed 20 m, with the most common duct heights lying in the 4–10 m range (approximately 53% of the time). However, over the 2 years, compared to the P-J model (mean duct height is equal to 8.3 m), the NPS model results in a mean evaporation duct height of 6.6 m.

Figure 3. Map showing Marsden Square number 145 (40°N to 50°N latitude and 0° to 10°W longitude) and the relative location of the British Channel Islands.

Figure 4. Occurrence frequency distributions of evaporation duct heights determined using (1) the Paulus-Jeske model (black data), (2) the Naval Postgraduate School model (gray data), and (3) historical data from Marsden Square number 145 (white data). The Paulus-Jeske and Naval Postgraduate School evaporation duct heights were calculated using 2 year (August 2003 to August 2005) weather data from the Channel Light Vessel during periods of normal reception at the Alderney high antenna.

4.2. Evaporation Ducting and Radio-Meteorological Observations in the English Channel

4.2.1. Significance of Atmospheric Stability

[12] It is important to point out that the P-J method to estimate evaporation duct height is open ocean model [Paulus, 1985; Babin *et al.*, 1997]. It is expected to work well for conditions of atmospheric instability (air temperature < sea temperature; i.e., the air-sea temperature difference or ASTD < 0°C) and high wind speeds that are mostly prevalent in the open ocean (this point and related behavior are investigated further in section 4.2.2). However, stable atmospheres (air temperature > sea tempera-

ture; i.e., ASTD > 0°C) and low-wind conditions at low altitudes result in a reduction in convective mixing and mechanical mixing, two physical processes that the model intrinsically depends upon. Thus, a breakdown in the fundamental assumptions on which the model is based leads to an inaccurate estimation of the evaporation duct height. When the air temperature exceeds the sea temperature, the P-J model incorporates a temperature correction (on the assumption that an error has been made during measurement) that results in an underestimation of the evaporation duct height [Paulus, 1985]. This point was examined further by Gunashekar *et al.* [2007a] who noted

Figure 5. A 2 year plot (August 2003 to August 2005) of the (top) air-sea temperature difference at the Channel Light Vessel and the (bottom) corresponding high antenna signal strength measured at Alderney. (Black data, unstable atmospheric conditions; gray data, stable/neutral atmospheric conditions.)

that during periods of enhanced signal strength (which occurred primarily when stable atmospheric conditions were present), there was a departure from the normal trend of higher signal strengths corresponding to higher evaporation duct heights, which could be attributed to the underestimation of the evaporation duct height by the P-J model during periods of atmospheric stability.

[13] During periods of normal reception at both the high and low receiving antennas in Alderney, stable or neutral (ASTD is equal to 0°C) conditions are observed only approximately 34% of the time at the Channel Light Vessel. This effect is evident in Figure 5, which depicts a 2 year plot of the CLV air-sea temperature difference (Figure 5, top) and the corresponding high antenna signal strength measured at Alderney (Figure 5, bottom). The data corresponding to stable/neutral and unstable atmospheric conditions are depicted in gray and black, respectively. The overall mean ASTD for all periods of

normal reception is -1.1°C . However, the occurrence of enhanced signal strengths mostly corresponds to periods of atmospheric stability [Gunasekar *et al.*, 2007a, 2007b]. Specifically, during ESS periods at Alderney, the occurrence frequency of stable or neutral conditions at the CLV increases to about 77%, with the mean ASTD taking on a stable value (0.6°C). By and large, whenever the ASTD exceeds 0°C (i.e., the gray data in Figure 5), the signal strength is enhanced at the Alderney high antenna. Bar graph plots of the relative frequency distributions of the air-sea temperature difference at the Channel Light Vessel for ESS periods and for periods of normal reception at the Alderney receiver (high and low antennas) are shown in Figure 6. The marked changes in the signal strength occurrence statistics (relative to variations in atmospheric stability) during periods of ESS and normal reception are also observed at the Guernsey and Sark receivers.

Figure 6. Relative frequency distributions of the air-sea temperature difference at the Channel Light Vessel during periods of enhanced signal strength (gray data) and normal reception (black data) at the Alderney high and low antennas.

4.2.2. Radio-Meteorological Aspects of Using the P-J Evaporation Duct Model

[14] Over the 2 years of measurement, a wide range of atmospheric conditions was encountered in the Channel Islands. The mean air-sea temperature difference at the CLV was -1.0°C , while the mean relative humidity (RH) and wind speed (WS) at the CLV were approximately 80% and 7.8 m s^{-1} , respectively. Based on these values, a number of different atmospheric regimes were defined and a simple performance evaluation of the P-J evaporation duct model was conducted within these regimes. The evaluation was carried out within each regime by correlating the hourly averages of signal strength (during periods of normal reception at the Alderney high antenna) with the PE-predicted signal strengths (using the P-J evaporation duct refractivity profiles as input to the PE model).

[15] The atmospheric stability was divided into four regimes: $\text{ASTD} \leq -1^{\circ}\text{C}$ (strongly unstable), $-1^{\circ}\text{C} < \text{ASTD} \leq 0^{\circ}\text{C}$ (weakly unstable), $0^{\circ}\text{C} < \text{ASTD} \leq +1^{\circ}\text{C}$ (weakly stable) and $\text{ASTD} > +1^{\circ}\text{C}$ (strongly stable). Based on the hourly wind speed values, three regimes were defined: $0\text{ m s}^{-1} \leq \text{WS} < 5\text{ m s}^{-1}$ (weak winds), $5\text{ m s}^{-1} \leq \text{WS} < 10\text{ m s}^{-1}$ (moderate winds) and $\text{WS} \geq 10\text{ m s}^{-1}$ (strong winds). Finally, the data were also divided into three relative humidity regimes: $\text{RH} \leq 60\%$ (low RH), $60\% < \text{RH} \leq 80\%$ (moderate RH) and $\text{RH} > 80\%$ (high humidity).

[16] The correlation coefficients between the measured and PE-predicted signal strengths for the different atmospheric regimes and combinations of regimes are listed in Table 3 (for the high antenna Jersey-Alderney link). As expected, the P-J evaporation duct model performs well during periods of strong atmospheric instability ($\text{ASTD} \leq -1^{\circ}\text{C}$). Similarly, when strong winds ($\geq 10\text{ m s}^{-1}$) and low RH ($\leq 60\%$) conditions prevail in the lower atmosphere, the measured and PE-predicted signal strengths match up reasonably well. Overall, a strongly unstable atmosphere with high wind speeds yields the highest correlation coefficient (0.76) between the observed and PE-predicted signal strengths.

[17] When the atmosphere moves from being unstable to stable, the performance of the evaporation duct model degrades significantly. This degradation in performance is also evident during periods of low wind speeds or very high relative humidity. The reasons for this behavior have already been pointed out in section 4.2.1. Therefore, during stable atmospheric conditions with low to moderate wind speeds, the P-J-derived vertical refractivity profiles should be used with great care when trying to assess the performance of low-altitude UHF radio links over the sea.

[18] Despite being over 20 years old, the Paulus-Jeske evaporation duct model is an extensively adopted model. For instance, an evaporation duct climatology based on the P-J model is still currently employed by the U.S. Navy in

Table 3. List of the Correlation Coefficients Between the Measured Signal Strengths and the PE-Predicted Signal Strengths (Using the P-J Evaporation Duct Model Refractivity Profiles as Input) for Different Atmospheric Conditions in the English Channel^a

Atmospheric Condition Regimes	Correlation Coefficient Between PE-Predicted Signal Strength and Measured Signal Strength
All valid ducting data (i.e., radio data corresponding to periods of normal reception)	0.45
<i>Air-Sea Temperature Difference</i>	
ASTD $\leq -1^{\circ}\text{C}$ (strongly unstable)	0.74
$-1^{\circ}\text{C} < \text{ASTD} \leq 0^{\circ}\text{C}$ (weakly unstable)	0.42
$0^{\circ}\text{C} < \text{ASTD} \leq +1^{\circ}\text{C}$ (weakly stable)	0.32
ASTD $> +1^{\circ}\text{C}$ (strongly stable)	0.40
<i>Wind Speed</i>	
$0 \text{ m s}^{-1} \leq \text{WS} < 5 \text{ m s}^{-1}$ (weak winds)	0.22
$5 \text{ m s}^{-1} \leq \text{WS} < 10 \text{ m s}^{-1}$ (moderate winds)	0.40
$\text{WS} \geq 10 \text{ m s}^{-1}$ (strong winds)	0.72
<i>Relative Humidity</i>	
RH $\leq 60\%$ (low RH)	0.71
$60\% < \text{RH} \leq 80\%$ (moderate RH)	0.65
RH $> 80\%$ (high humidity)	0.30
<i>Combinations of Atmospheric Conditions</i>	
ASTD $\leq -1^{\circ}\text{C}$ and $\text{WS} \geq 10 \text{ m s}^{-1}$	0.76
ASTD $\leq -1^{\circ}\text{C}$ and RH $\leq 60\%$	0.72
$\text{WS} \geq 10 \text{ m s}^{-1}$ and RH $\leq 60\%$	0.57
ASTD $\leq -1^{\circ}\text{C}$, $\text{WS} \geq 10 \text{ m s}^{-1}$, RH $\leq 60\%$	0.57
ASTD $\leq -1^{\circ}\text{C}$, $\text{WS} \geq 10 \text{ m s}^{-1}$, RH $> 80\%$	0.65

^aASTD, air-sea temperature difference; WS, wind speed; RH, relative humidity.

their propagation assessment and operational planning efforts [Frederickson *et al.*, 2008]; the P-J technique to compute duct heights is also the default evaporation duct model in the AREPS propagation prediction tool [SPAWAR, 2008].

[19] Several other evaporation duct models have been proposed over the years in order to address the deficiencies in the P-J model. Notable among these is the evaporation duct model (model “A”) proposed by Babin *et al.* [1997]. According to the authors, the physical theory upon which their model is based not only allows the height of the evaporation duct to be determined during periods of low wind speed, but also computes the duct heights more accurately than the P-J model. Furthermore, since the model carries out a sensitivity analysis of the input parameters, an estimate of the standard deviation is output along with the evaporation duct height. A drawback of model “A” (and indeed other evaporation duct models), however, is that it makes an implicit assumption of horizontal homogeneity in the marine boundary layer, which may not always be applicable, particularly with respect to radio communication applications in coastal regions.

[20] More recently, a novel evaporation duct model, known as the NPS model, has been developed and tested by the Naval Postgraduate School (California, USA) [Frederickson *et al.*, 2003, 2008]. This model has also

been included in the AREPS propagation prediction tool along with the P-J model [SPAWAR, 2008]. Results from various over-sea propagation experiments have demonstrated that in unstable atmospheric conditions, the NPS model produces highly accurate evaporation duct refractivity profiles that are superior to that of the P-J model [Frederickson *et al.*, 2008]. However, even though the NPS model appears to perform reasonably well during some stable situations, users of the model need to be cautious when employing the model to assess propagation conditions in strongly stable atmospheric conditions with low wind speeds (P. Frederickson, personal communication, 2007). The NPS evaporation duct model, along with up-to-date and more comprehensive meteorological data sets and climate analysis tools, is being presented as a promising technique to modernise the global evaporation duct climatology, which will have an overall impact on the performance of over-sea radio systems [Frederickson *et al.*, 2008].

4.3. Implications of the Estimated P-J Evaporation Duct Height and Antenna Geometries on Signal Strength Behavior

[21] This section examines the effect that the relationship between the estimated evaporation duct height and the

Figure 7. Example signal strength measurements at the (top) Alderney high and low antennas in December 2003 and the (bottom) corresponding Paulus-Jeske evaporation duct heights, and high antenna transmitter and receiver heights.

antenna heights at the transmitter and receiver, has on the signal strength received at Alderney.

[22] The variation in the heights above sea level of the upper antenna at the Jersey transmitter and the Alderney receiver over a period of 1 month of normal reception in December 2003 is shown in Figure 7 (bottom). The antenna heights exhibit a distinctive sinusoidal variation due to the diurnal oscillation in the tide in the English Channel. The corresponding P-J evaporation duct heights

have also been indicated. Throughout this period, the transmitter is almost always located above the estimated evaporation duct height. Comparison with the Alderney signal strength plot in Figure 7 (top) shows that it is not necessary for either the transmitting or the receiving antenna to be located within the evaporation duct for signals to be received at Alderney. However, a closer observation of the signal strength pattern indicates that higher signal strengths are received as the evaporation duct

Figure 8. Cumulative frequency distribution curves for different duct height-transmitter-receiver antenna geometries for signals received at the (top) Alderney high antenna and the (bottom) Alderney low antenna from August 2003 to August 2005.

begins to include either or both the transmitting and receiving antennas within it.

[23] To explain, Figure 8 illustrates cumulative frequency distribution curves for the following duct height-transmitter-receiver antenna geometries for signal strength data at the Alderney high (Figure 8, top) and low (Figure 8, bottom) antennas from August 2003 to August 2005: (1) Both transmitting and receiving antennas are located within the evaporation duct. (2) Both transmitting and receiving antennas are located outside the evaporation

duct. (3) The receiving antenna is within the duct but the transmitting antenna is outside the evaporation duct.

[24] Since the heights of the transmitting antennas are greater than that of the receiving antennas, there are no cases where the transmitting antenna is within the duct but the receiving antenna is outside the duct.

[25] With respect to the high antenna link (during periods of normal reception), when both the transmitting and receiving antennas are located outside the evaporation duct, almost all (>99%) the signals exceed -110 dBm with

Table 4. List of the Number of Occurrences (and the Occurrence Frequencies Shown in Parentheses) of the Various Evaporation Duct Height Transmitter-Receiver Antenna Geometries (Listed in the Text) for the Jersey-Alderney Path, and the Mean Received Signal Strengths Corresponding to Each Case

	Alderney Receiver	
	High Antenna	Low Antenna
(1) Both the transmitting and receiving antennas are within the evaporation duct.		
Number of cases	469 (4.2%)	958 (9.8%)
Mean signal strength	-86.4 dBm	-91.7 dBm
(2) Both the transmitting and receiving antennas are outside the evaporation duct.		
Number of cases	9,390 (84.6%)	6,756 (68.8%)
Mean signal strength	-90.8 dBm	-94.8 dBm
(3) The receiving antenna is within the duct, but the transmitting antenna is outside the duct.		
Number of cases	1,240 (11.2%)	2,098 (21.4%)
Mean signal strength	-86.3 dBm	-92.6 dBm
Total		
Number of cases	11,099	9,812
Mean signal strength	-90.1 dBm	-94.0 dBm

approximately 44% of the signals exceeding -90 dBm. When either or both the transmitting and receiving antennas are located within the duct, the percentage of signals exceeding -90 dBm increases to about 75%. Similarly, for the low antenna link for which the mean signal strength is lower than that of the high antenna link [see *Siddle et al.*, 2007; *Gunasekar et al.*, 2007a], approximately 24% of the received signals exceed -90 dBm when both the transmitting and receiving antennas are outside the duct. However, this figure increases to approximately 36% when the receiving antenna is submerged within the evaporation duct and the transmitting antenna is outside the duct. About 44% of the received signals exceed -90 dBm when both the low transmitting and receiving antennas are contained within the evaporation duct.

[26] Table 4 contains a list of the number of occurrences (and the occurrence frequencies shown in parentheses) of the three cases listed above at Alderney. The mean signal strengths corresponding to each situation have also been listed. The statistics contained in Table 4 also indicate that the probability of receiving higher signal levels is increased if both the transmitting and receiving antennas are located within the duct. For instance, with respect to the Jersey-Alderney high antenna link, there are 9390 out of a total of 11099 cases (84.6%) that correspond to scenario 2 when both the transmitting and receiving antennas are

Figure 9. Plot of signal strength difference between the high and low antennas at Alderney and the corresponding Paulus-Jeske evaporation duct heights, for all cases when both the transmitting and receiving antennas are located within the evaporation duct.

Figure 10. Plot of signal strength difference between the high and low antennas at Alderney and the corresponding Paulus-Jeske evaporation duct heights, for all cases when only the receiving antenna is located within the evaporation duct.

located outside the evaporation duct (having a mean signal strength of approximately -90.8 dBm). However, when scenario 1 is considered (i.e., when both the transmitting and receiving antennas are submerged within the evaporation duct), despite comprising only 4.2% of all the data, the mean signal strength increases by almost 4.4 dB to -86.4 dBm. Furthermore, this corresponding occurrence frequency for the low antenna link increases by more than twofold to 9.8%.

[27] Since the mean transmitting and receiving antenna heights (above mean sea level) are higher than the mean duct height encountered (8.3 m), the majority of cases (84.6% for the Alderney upper antenna link and 68.8% for the Alderney lower antenna link) correspond to the situation when both the transmitting and receiving antennas are higher than the corresponding duct height (i.e., scenario 2). This statistic confirms that it is not essential for the transmitting and receiving antennas to be located within the evaporation duct on a transhorizon radio path. However, as can be seen from Figure 8, the relative occurrence frequency of a given signal strength is lower when compared to scenario 1, in which both antennas are within the duct. This decrease is more appreciable for the upper antenna link.

[28] The evaporation duct is higher than the Alderney receiving antenna but lower than the transmitting antenna

on 1240 (11.2%) and 2098 (21.4%) occasions for the upper and lower links, respectively (scenario 3). With one antenna within the duct and the other outside the duct, the probability of receiving higher signals is in between scenarios 1 and 2, at least throughout most periods. This behavior is more pronounced for the lower antenna link (Figure 8). Finally, at higher signal strengths (approaching the free space level and beyond), the evaporation duct becomes less influential, thus supporting the conclusion that during periods of abnormally high signal strength, additional propagation mechanisms such as higher-altitude ducting/superrefractive structures, have a more significant effect [Siddle *et al.*, 2007; Gunashekar *et al.*, 2007a, 2007b].

[29] Further evidence of the trapping capability of higher evaporation ducts on transhorizon paths can be obtained from Figures 9–11. Figure 9 is a plot of the signal strength difference between the high and low antennas at Alderney versus the calculated P-J evaporation duct heights, for all cases when both the transmitting and receiving antennas (for the Jersey-Alderney high antenna link) are within the evaporation duct. Figure 10 is the same plot for all cases when the receiving antenna is within the duct but the transmitting antenna is outside the bounds of the evaporation duct. All the cases when both the trans-

Figure 11. Plot of signal strength difference between the high and low antennas at Alderney and the corresponding Paulus-Jeske evaporation duct heights, for all cases when both the transmitting and receiving antennas are located outside the evaporation duct.

mitting and receiving antennas are located outside the evaporation duct have been plotted in Figure 11.

[30] With particular reference to Figures 9 and 10, at all times, the upper antenna receives a higher signal strength than the low antenna; however, as the height of the evaporation duct increases, the difference between the high and low antenna signal strength decreases. This implies that as the lower antenna becomes more submerged within the duct, it tends to become a better receptor of radio signals, although it never outperforms the upper antenna (since there are no signal strength reversals observed). When both the transmitting and receiving antenna are outside the evaporation duct (Figure 11), the inverse relationship between duct height and signal strength difference is statistically insignificant. Under these circumstances, the signal strength difference remains relatively constant as the duct height increases.

5. Concluding Remarks

[31] The observations and results reported in this paper underlines the significance of the evaporation duct as an anomalous propagation mechanism in marine and coastal regions. The various issues under investigation in this long-term study are of direct relevance in the planning of

over-sea communication links operating in the UHF band, and have implications for the radio regulatory work carried out by organizations such as the International Telecommunication Union and Ofcom (UK).

[32] The height of the evaporation duct is a key parameter that must be taken into account when planning communication systems operating over the sea. The observations and results undoubtedly suggest that the evaporation duct is the dominant propagation mechanism on transhorizon over-sea paths in the English Channel. The dependence of the evaporation duct height on various meteorological parameters, in particular, the prevailing atmospheric stability, has been examined. A simple performance analysis of a popular evaporation duct model was conducted for several atmospheric regimes by comparing measured and modeled signal strength data. In particular, for 2 years of data corresponding to periods of normal reception, a strongly unstable atmosphere ($ASTD \leq -1^\circ\text{C}$) with wind speeds exceeding 10 m s^{-1} resulted in the highest correlation coefficient (0.76) between the observed and predicted signal strengths. Analysis of the evaporation duct height and antenna geometries with respect to the signal strength measurements confirms that it is not necessary for the antennas to be located within the duct, though the probability of receiving a higher signal increases if

either or both the transmitting and receiving antennas are completely submerged within the duct (or when the height of the duct becomes significant). For example, when both the transmitting and receiving antennas (on the Jersey-Alderney high antenna link) are located above the evaporation duct, the received signals exceed -90 dBm approximately 44% of the time, however, when either or both the transmitting and receiving antennas are located within the duct, the proportion of signals exceeding -90 dBm increases to 75%. Furthermore, when considering two receiving antennas at different altitudes, as the low antenna becomes more submerged within the evaporation duct, it tends to become a better receptor of signals, though it never outperforms the high antenna.

[33] Currently, a new experimental campaign is being conducted with concurrent VHF and UHF transmissions over two links in the English Channel of varying path lengths (approximately 50 km and 150 km, respectively) in order to investigate the effects of both frequency and path length. Finally, the impact of utilizing the evidently superior NPS evaporation duct model instead of the standard P-J model for propagation loss predictions will be examined in detail (by using existing as well as future radio-meteorological data).

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