Signal strength measurements at frequencies of around 300 MHz over two sea paths in the British Channel Islands

C. Y. D. Sim[1,2] and E. M. Warrington[1]

Received 1 November 2004; revised 6 February 2006; accepted 24 February 2006; published 14 June 2006.

[1] In order to gather information about the occurrence of ducting/superrefraction and signal-fading effects at frequencies around 300 MHz with antenna heights appropriate to intership communications, an experimental investigation has been undertaken with a transmitter and two receivers deployed in the British Channel Islands. Signal strength measurements made over a period of 17 months for a path from Jersey to Guernsey from April 2001 to September 2002 and 8 months of data for a path from Jersey to Alderney from November 2001 to September 2002 have been analyzed. Comparisons have been made between the received signal characteristics and several meteorological parameters such as sea state, weather conditions, and season, and the statistics of the occurrence of enhancements in signal strength due to superrefraction and ducting are presented.

Citation: Sim, C. Y. D., and E. M. Warrington (2006), Signal strength measurements at frequencies of around 300 MHz over two sea paths in the British Channel Islands, *Radio Sci.*, *41*, RS3005, doi:10.1029/2004RS003207.

1. Introduction

[2] It is well known that VHF and UHF signals can travel to distances well beyond the horizon under certain conditions. Several propagation mechanisms are responsible for this, in particular diffraction around the Earth's curvature, refraction within the atmosphere, and scattering within the troposphere. Depending on the vertical profile of the atmospheric refractive index, propagation may be enhanced through superrefraction and ducting (see *Craig* [2003] for an introduction to these topics).

[3] In order to gather information about the occurrence of superrefraction/ducting and signal-fading effects at frequencies around 300 MHz with antenna heights appropriate to intership communications, an experimental investigation has been undertaken with a transmitter and two receivers deployed in the British Channel Islands. Measurements were made over a period in excess of one year, and a summary of the more important aspects is presented here.

[1]Department of Engineering, University of Leicester, Leicester, UK.
[2]Now at Department of Computer and Communication Engineering, Chienkuo Technology University, Changhua City, Taiwan.

0048-6604/06/2004RS003207

2. Experimental Configuration

[4] During March 2001, a 25 W CW transmitter was installed on the north coast of Jersey. Two receiver sites were installed providing unobscured (by islands, etc) over-sea paths: the first (March 2001) in St Peter Port, Guernsey (33.3 km), and the second (November 2001) on the south coast of Alderney (48 km). A map indicating these sites is given as Figure 1. Log periodic antennas (nominal gain quoted by the manufacturers as 10–12 dBi) were employed at all sites, the heights of which above the sea level are indicated in Table 1. Measurements were made over the path to Guernsey for a period of approximately 17 months. While operation on Alderney began in November 2001 and continued until September 2002, reception at this site was not continuous (a several month gap due to storm damage occurred soon into the collection period, and since solar panels with limited capacity were employed because of the lack of available mains power, 24 hours/day operation was not possible). Nonetheless, useful measurements were made at this site for a period of around 8 months.

[5] In the data presentation, receiver power levels are quoted on a logarithmic scale on which 0 dBr corresponds to a power input to the receiver of −107 dBm. This value is a dB or so less than the signal power that causes the automatic gain control (AGC) to come into effect. Taking the transmitter power and antenna gains (for which there is some uncertainty) into account, 0 dBr corresponds to a path loss of approximately 168 dB.

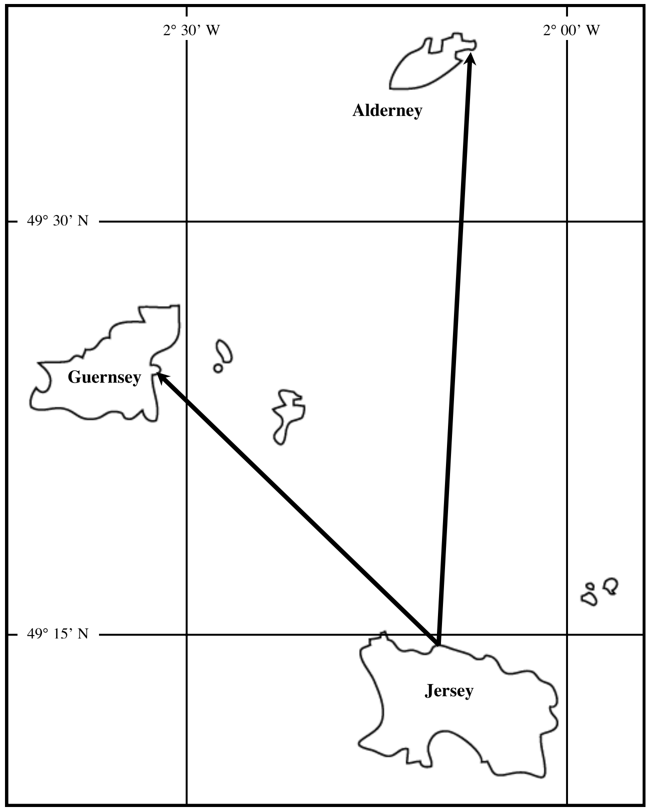

Figure 1. Map showing the position of the transmitter and receiver sites.

[6] During the course of the measurements, the transmitter alternated between two frequencies (248 and 341 MHz), remaining on each for 3 min. Within each 3 minute period, measurements were made of signal strength over 30 second intervals with vertical, horizontal and cross polarizations.

3. Tidal Conditions in the Channel Islands

[7] The tidal range in the Channel Islands is relatively large. During 2003 for example, the maximum predicted range in Guernsey was 9.9 m (high 10.1 m, low 0.2 m relative to chart datum), in Jersey 11.5 m (high 11.9 m, low 0.4 m relative to chart datum), and in Alderney 6.4 m (high 6.7 m, low 0.3 m relative to chart datum). High water in Jersey occurs approximately 5 min before Guernsey, and in Alderney approximately 40 min later than Guernsey.

[8] The precise sea height at different points along the paths is difficult to estimate because of the complexity of the tidal flows. Consequently, in the analysis presented in this paper, the predicted tidal height at Sark (located between the three sites) has been employed. Also, it should be noted that the actual day to day levels vary from those predicted because of the prevailing weather conditions. The sea level is raised in the direction toward which the wind is blowing and vice versa, and a low barometric pressure will raise the sea level by approximately 0.1 m for a reduction in pressure of 11.3 mbar from the mean value.

4. Some Theoretical Considerations

[9] It is not the purpose of this paper to develop or to extensively reproduce the theory of VHF/UHF propagation over the sea, rather to present measurements of signal strength variations, and to interpret these measure-

Table 1. Antenna Heights at the Three Sites Relative to the Mean Sea Level and to Chart Datum[a]

Site	Height Above Mean Sea Level, m	Height Above Chart Datum, m
Jersey (tx)	18.5	24.7
Guernsey (rx)	16.3	21.6
Alderney (rx)	14.5	18.4

[a]Here tx means transmitter and rx means receiver.

Table 2. Fresnel Zone Radii at the Path Midpoints

	248 MHz, m	341 MHz, m
Jersey–Guernsey	100.4	85.6
Jersey–Alderney	120.5	102.9

ments in terms of current theory. Consequently, the reader is referred to the original sources for full details.

4.1. Surface Waves

[10] In analyzing this propagation mechanism near to the Earth's surface, ground waves are often separated into three components: direct, reflected and surface waves. *Bullington* [1977] notes that the surface wave component is the major component of ground waves for frequencies of a few MHz, but of secondary importance at VHF and can be ignored at frequencies higher than 300 MHz. *Bullington* [1977] further suggests that the surface wave can be ignored for antenna heights, over seawater, greater than 3 m at 248 MHz and greater than 2 m at 341 MHz, both heights being significantly less than those employed in this investigation.

4.2. Path Obscuration by the Earth's Curvature

[11] For a signal to be received without significant diffraction losses, adequate clearance between the direct path and any obstacles (including the ground) is essential. The curvature of the Earth results in a bulge along the paths, reaching a maximum of 21.4 and 45.2 m respectively at the midpoints of the paths to Guernsey and Alderney. Atmospheric refractive index effects will normally result in a decrease in the effective Earth curvature, reducing the bulge height (for example, the $k = 4/3$ rule of thumb would reduce the bulge heights to 16.1 and 34.0 m respectively). The necessary clearance between the direct path and an obstacle is usually expressed in terms of the Fresnel zone. A commonly employed criterion is that 0.6 of the first Fresnel zone should be unobstructed [*Bacon*, 2003]. The radii of the first Fresnel zones at the midpoints of our paths are given in Table 2, and since these values are well in excess of the antenna heights employed, significant diffraction losses are to be expected.

4.3. Diffraction Loss With a Smooth Spherical Earth

[12] The diffraction path loss may be considered as the sum of the free-space loss which exists in the absence of obstacles and the diffraction loss introduced by the obstacles [*Roda*, 1988]. Formulae for signal attenuation losses due to diffraction over a smooth, spherical Earth are given in ITU-R P.526-7 (these are consistent with those given by *Roda* [1988]) for the condition where the receiver lies within the shadow zone beyond the transmitter's horizon. Assuming a 4/3 k factor, the amplitude versus tide height variations for both receiving sites determined from these equations predict a change of signal amplitude of around −1.2 dB per meter increase in sea height, with a slightly higher value (−1.4 dB/m) for vertically polarized signals at the higher frequency.

4.4. Tropospheric Scattering for VHF/UHF Signal Propagation

[13] At sufficiently large distances beyond the horizon, diffraction losses increase and tropospheric scatter (troposcatter) propagation becomes the dominant propagating mechanism [*Griffths*, 1987]. This mode of propagation arises because of the variations in refractive index associated with irregularities in the meteorological parameters, such as humidity, temperature and pressure, at heights of several thousand meters. Electromagnetic radio waves are scattered by these irregularities resulting in usable propagation over the frequency range 100 MHz to 10 GHz.

4.5. Overall Predictions With the Receiver in the Shadow Zone

[14] By applying the equations for free space, diffraction and scattering losses associated with troposcatter, the overall path attenuation due to these mechanisms can be estimated. Figure 2 shows the total path losses for vertical polarization at the lower operating frequency (248 MHz), at distances up to 100 km with antenna heights of 18.5 m (transmitter) and 14.5 m (receiver) above the Earth's surface, together with curves for these antenna heights ±5 m (note that in these calculations the effective Earth radius was assumed to be 8500 km (4/3R rule)). These heights correspond to the heights of the antennas at Jersey and Alderney at midtide, together with curves at approximately the tidal extremes. Curves for the higher frequency and for horizontal polarization differ only in detail (the figures for both paths, frequencies and polarizations are given in Table 3). The range at which troposcatter is estimated to become the dominant mechanism appears on the plot as a kink in the curve at around 47 km for high-tidal conditions, increasing to 72 km at low tide. This transition from diffracted to troposcattered energy at these antenna heights and ranges is of particular significance for the 48 km path to Alderney.

4.6. Superrefraction and Ducting

[15] The situation described above depends upon the atmospheric refractive index conditions being such that the receiver lies in the shadow beyond the radio horizon, and also a constant lapse rate assumed to be that of an average atmosphere (−40 N/km, where N is the refractivity defined as $(n - 1).10^6$ and n is the refractive index). With increasingly negative lapse rates, the trajectory of the signal leaving the transmitter will have an

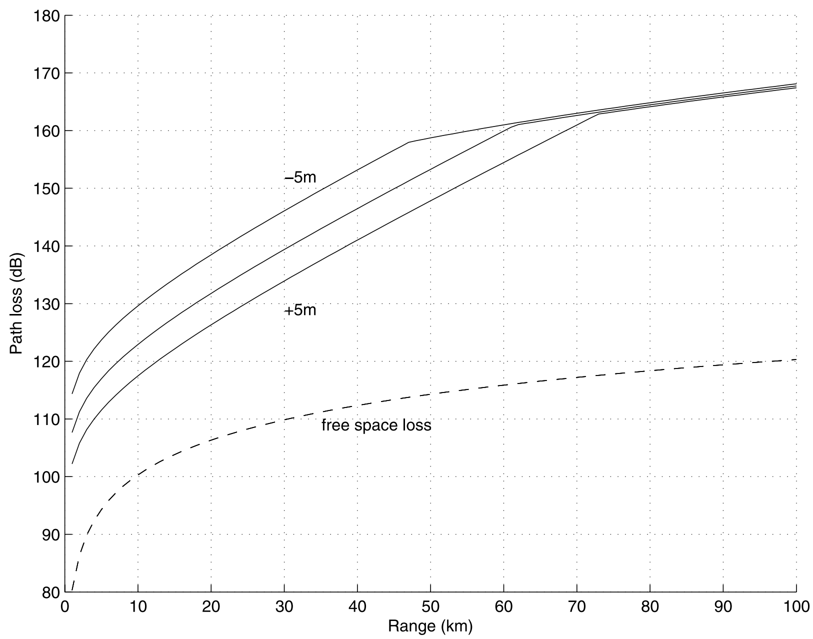

Figure 2. Path attenuation at 248 MHz (free space, diffraction, and scattering) versus distances for antenna heights of 18.5 and 14.5 m (corresponding to Jersey and Alderney at midtide), together with curves for these heights ±5 m. Vertical polarization is used.

increasing tendency to bend toward the Earth, until with a lapse rate of −157 N/km or less ducting to long ranges will occur.

[16] As the lapse rate becomes increasingly negative, the signal travels further above the surface of the Earth (this may be considered as an increase in the effective Earth radius) and, consequently, the path obscuration decreases. Ray tracing (assuming that geometrical optics apply) indicates that for antennas located 15 m above the sea, superrefraction leads to the raypaths to Guernsey and Alderney being just above the Earth's bulge at lapse rates of approximately −50 and −110 N/km respectively, with the clearances increasing more or less linearly to 28 and 20 m respectively at a lapse rate of −200 N/km. Note however that even for rays that just clear the Earth's bulge, the diffraction losses may still be significant (in excess of 10 dB) and the raypath would have to clear the Earth by a significant portion of a Fresnel zone for this to become minimal.

4.7. Rough Sea Effects

[17] The presence of waves on the sea surface will increase the mean blockage, the effect being to raise the bulge of the Earth between the terminals by an amount on the order of the significant wave height.

[18] Theoretical considerations given by *Matthew* [1965] indicate that the sea surface can be considered as a smooth reflector if the variations of the surface are such as to cause variations in the path length of less than an eighth of a wavelength. The sea may therefore be considered as smooth if the wave height satisfies the condition $H\psi < 3.6\lambda$ where ψ is the angle of incidence (degrees), H is the sea wave height (m) and λ is the radio wavelength (m).

5. Jersey–Guernsey Observations

[19] During the majority of winter days and during cool summer days, the received signal amplitude displayed a simple relationship to the tide height. This is

Table 3. Predicted Path Losses for Both Paths With Antennas at the Mean Tide Height and for Antenna Heights ±5 m Relative to This Value at Both Frequencies and for Both Horizontal (H) and Vertical (V) Polarization[a]

	−5 m	Mean Tide	+5 m
Guernsey, 248 MHz, H	144.0	138.0	133.5
Guernsey, 248 MHz, V	146.8	140.4	135.2
Guernsey, 341 MHz, H	144.8	138.7	134.1
Guernsey, 341 MHz, V	146.7	139.1	134.1
Alderney, 248 MHz, H	155.9	149.5	144.7
Alderney, 248 MHz, V	158.2	151.9	146.5
Alderney, 341 MHz, H	157.7	151.1	146.3
Alderney, 341 MHz, V	159.8	151.8	146.3

[a]Values are given in dB.

illustrated in Figure 3 for a day in which the tidal range at Sark was around 9 m and wave heights between approximately 1.2 and 2 m were measured at the Channel Light Vessel. Air pressure, temperature and relative humidity are key parameters in the calculation of the refractive index, and these parameters measured at Jersey and at the Channel Light Vessel are also shown in Figure 3, together with other meteorological parameters. Ideally, radiosonde measurements of the various meteorological parameters would have been made along the paths, but the authors were unable to do this during these experiments, hence the reliance on measurements at Guernsey, Jersey and the Channel Light Vessel. Figure 4 depicts the variation of signal amplitude with the tide height. A decrease in signal level with increasing tide height is evident, the relationship being approximately 1.1 dB reduction in signal strength per meter increase in tide height. This value is in good agreement with that predicted from the diffraction equations given in ITU-R P.526-7 [*International Telecommunication Union* (*ITU*), 2001] and by *Roda* [1988]. This consistency between the measurements and the theoretical values suggest that the dominant propagation mechanism for this path during calm weather conditions on winter and cool summer days is smooth Earth diffraction.

[20] Although rough sea states or high wind speeds were observed on a number of occasions, there were only three occasions during spring 2001 on different days during which the propagation appeared to be influenced by rough sea conditions. These amount to less than 0.1% of the total time.

[21] One day for which the sea state appeared to affect the signal amplitude was 7 April 2001. For this day, the wave height varied between 2 and 4 m and the wind speed measured at the Channel Light Vessel varied between 6 and 18 m/s. On one of the tides the vertically polarized signals were reduced in amplitude by between 3 and 6 dB (see Figure 5 which exhibits two traces, the upper associated with "normal" behavior, and the lower corresponding to the decreased amplitude associated with the rough sea state). No effect on the average signal level was apparent on the horizontally polarized signals. The reasons for the amplitude reduction on the vertically polarized signals, but not on the horizontally polarized signal, is not apparent. In addition, fading of up to 15 dB within a 30 second period was observed on the horizontally polarized signal close to high tide compared with fading of around 3 dB on the vertically polarized signal.

[22] Very significant increases in signal strength occurred on warm summer days (at such times the refractive index decreases with height more rapidly than normal resulting in superrefraction or ducting). An example of measurements made on one such day together with meteorological data is presented in Figure 6, and the corresponding signal amplitude variation versus tide height is presented in Figure 7. An increase in signal strength in excess of 15 dB relative to the cool weather days is apparent. It is interesting to note that the occurrence of enhanced signal strengths is reasonably well correlated with the difference in temperature between that of the air measured at Jersey airport and that of the sea exceeding 4°C (see Figures 8 and 9). With such a relationship with the air/sea temperature difference being apparent, it is unsurprising that the occurrence of such events was strongly dependent upon time of year with hardly any occurring during the winter time and with the peak occurrences during the summer. It is also interesting to note the significant difference between 2001 and 2002.

[23] The enhanced signal strengths observed during warm days possibly arise because of the presence of a surface-based duct. However, with the meteorological measurements available to us, the existence of a surface-based duct cannot be verified; to do this would require a vertical profile of pressure, temperature, and humidity measurements. However, the statistics shown in Figures 8 and 9 at least provide a clue as to the possible existence of a surface-based duct (this requires not only a temperature inversion to occur but a sharp gradient in relative humidity; these parameters are coupled to produce a surface-based duct).

[24] Of particular interest from the systems planning viewpoint are the occurrence statistics, in particular the occurrence and duration of the periods of enhanced signal strength and the magnitude of the signal strength increases and when they occur. The magnitude of the increases was determined relative to the observations on a "normal" day (i.e., one for which an approximately linear variation in amplitude (measured in dB) relative to tidal height was observed). This statistical information is given in Table 4, each month considered separately.

6. Jersey–Alderney Observations

[25] The receiving system in Alderney was established during November 2001. The system was powered by solar panels, and unfortunately the supply capacity was insufficient for 24 hours per day operation, particularly during the winter months. Data collection was also disrupted a number of times because of occasional equipment failures and wind damage to the antennas. The downtimes for the Alderney receiver make the production of fully developed statistics difficult. Nevertheless, data received for all seasons were analyzed and the signal behavior during the measurement periods can be segregated into several categories.

[26] During periods of cold weather, a variation in signal amplitude with tide height similar to that shown in Figure 4 for signals received in Guernsey was apparent. The relationship was a little less linear for this path,

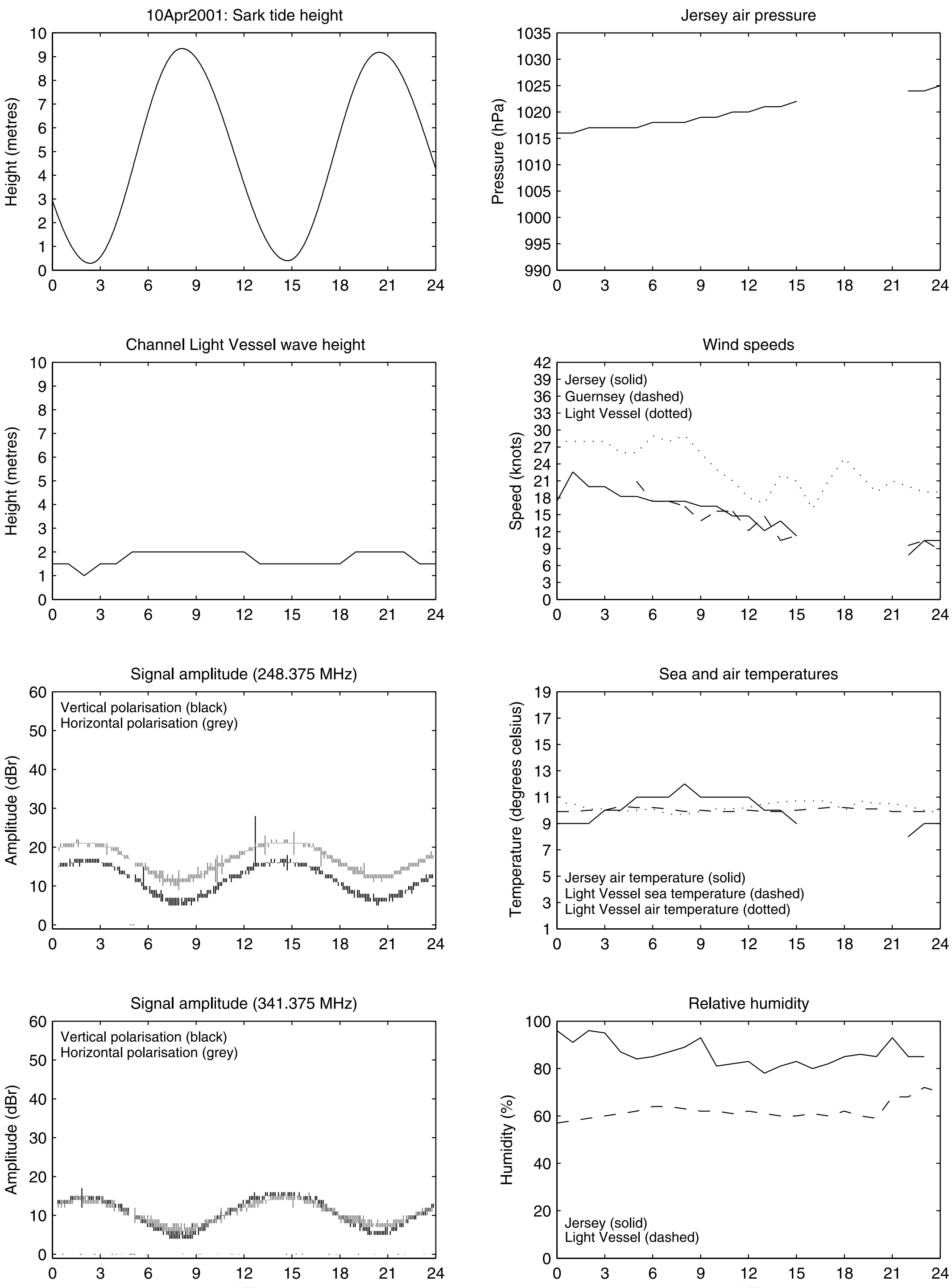

Figure 3. Signal strengths measured at Guernsey (minimum and maximum recorded values plotted) for both frequencies with horizontal and vertical polarization, together with a range of meteorological parameters as a function of time, on a calm spring day (10 April 2001). Note that the meteorological data collected from both Jersey and Guernsey sites are occasionally disrupted for periods of a few hours, hence the missing data on several curves.

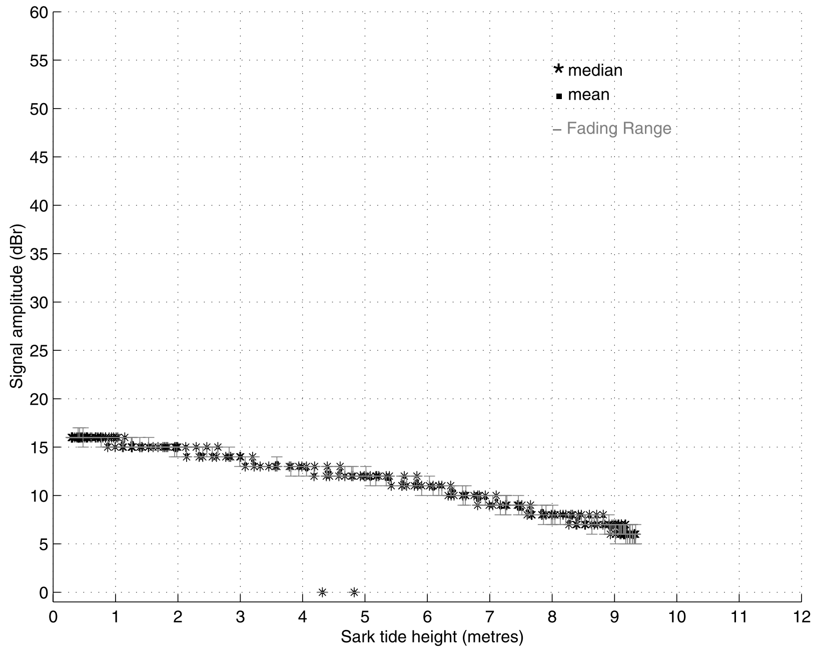

Figure 4. Variation in signal amplitude (dBr) with tide height measured at Sark (approximately midpath) on 10 April 2001 for the 248 MHz vertically polarized signal received on Guernsey. The sea state is calm.

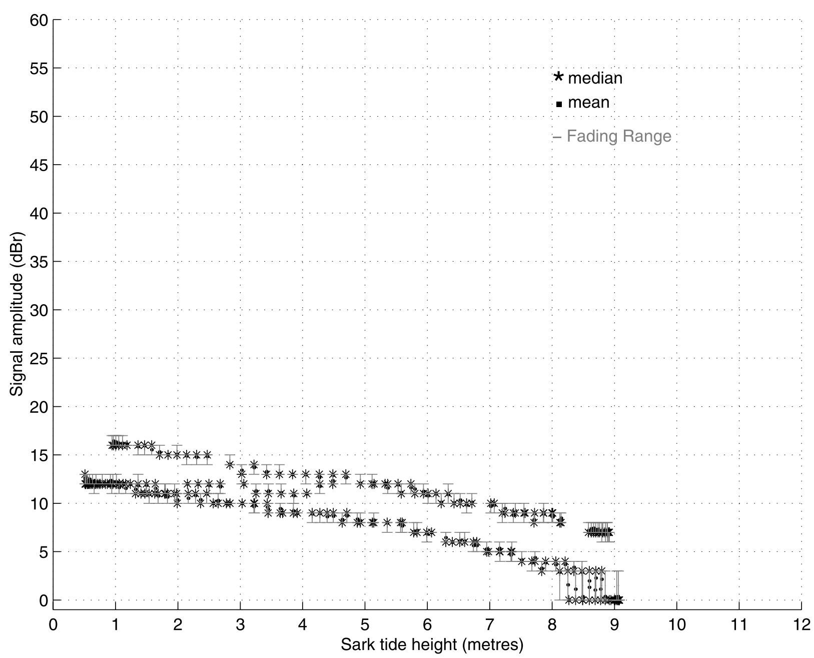

Figure 5. As in Figure 4 except for 7 April 2001 with a rough data sea state.

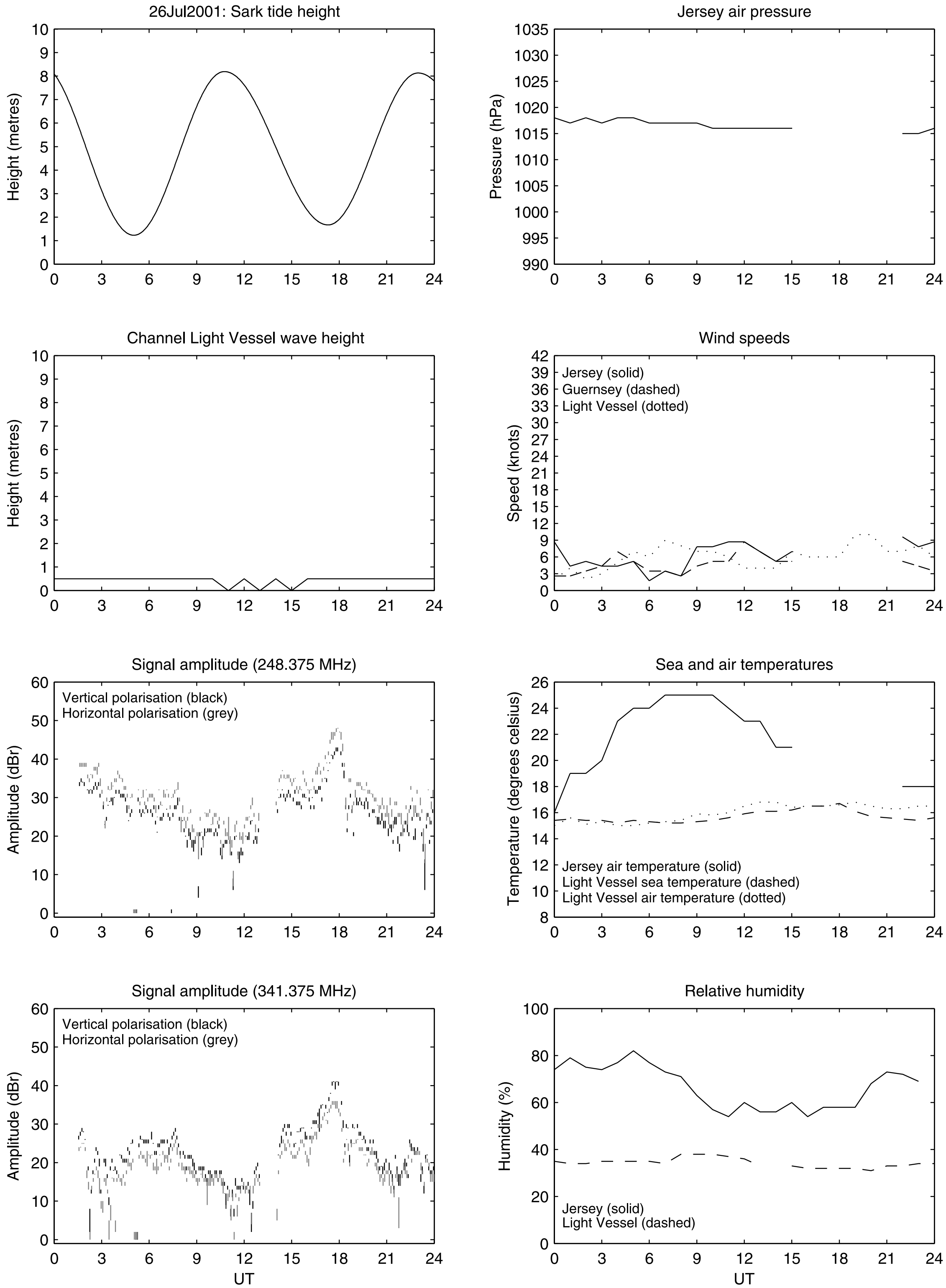

Figure 6. Signal strength variation on a hot day (26 July 2001) with respect to high Jersey airport temperature.

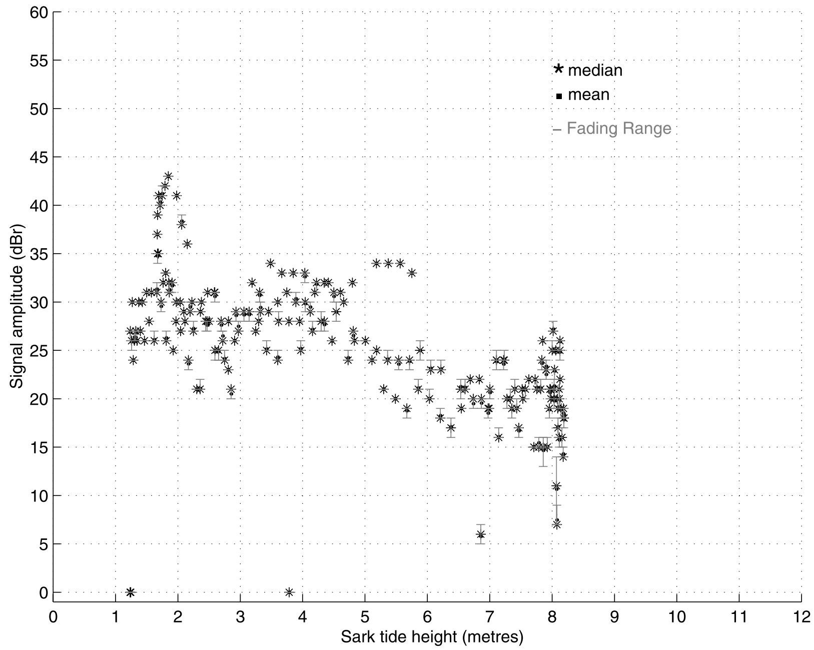

Figure 7. As in Figure 4 except the data were collected on a warm day (26 July 2001).

possibly because of the uncertainty of the tide height over the path (see comments in Section 3).

[27] Of particular note for this path is the frequent presence of marked fading with timescales of the order of seconds. An example of this is given in Figure 10, in which the received amplitude at Alderney is presented for a 30 s interval (approximately 25 AGC samples per second). No such fading was evident on the shorter path to Guernsey at this time.

[28] A possible mechanism for this is interference between the signal energy diffracted around the Earth's surface and energy scattered from within the troposphere. Figure 2 illustrates the path loss calculated from the formulae given in ITU Recommendation P.526-7 [*ITU*, 2001] and elsewhere [*Matthew*, 1965; *Roda*, 1988] for antenna heights corresponding to midtide and midtide ±5 m. The "kink" in the curves at 47 km (for high tide) and 72 km (for low tide) occur since at these ranges the

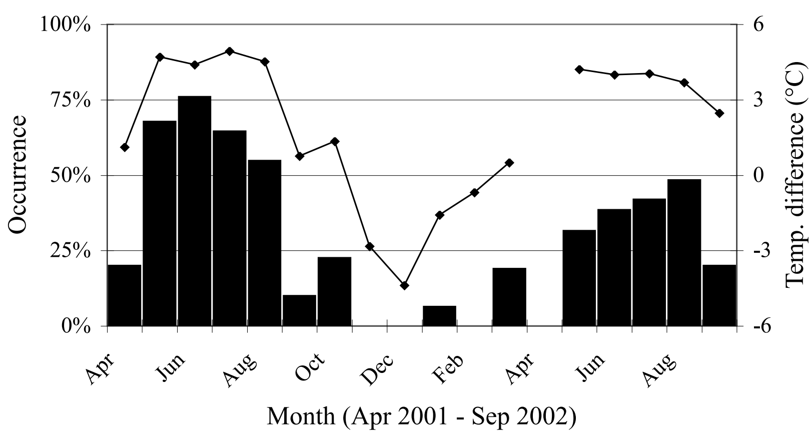

Figure 8. Monthly statistics of the percentage occurrence of enhanced signal strength (histogram plot) with respect to average temperature differences (Jersey airport–Channel Light Vessel sea temperature) from April 2001 to September 2002 for the Jersey to Guernsey path.

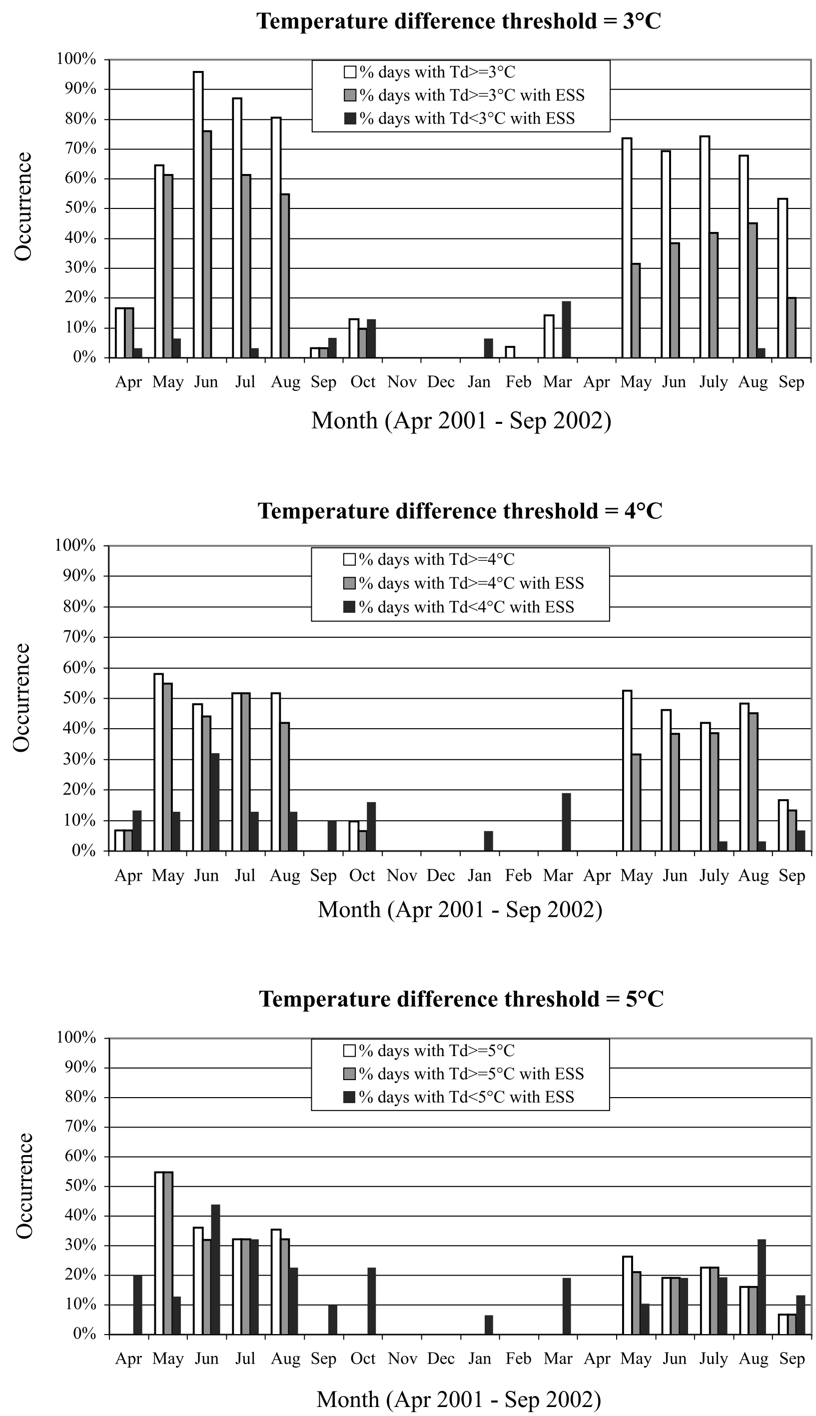

Figure 9. Monthly distribution of enhanced signal strength occurrence with respect to temperature difference threshold.

Table 4. Statistics of the Occurrence of Enhanced Signal Strength Events at Guernsey Due to Either Superrefraction or Ducting

	Occurrence, Percentage of Time	Median Duration,[a] hours	Upper Quartile, hours	Max Duration, hours	Median Increase, dB	Upper Decile, dB	Max Increase, dB
April 2001	9	(10)	0	12	2	5	2
May	61	21	22	23	4	10	24
June	50	14	23	24	3	12	33
July	61	21	22	23	4	11	23
August	43	22	23	24	4	8	18
September	6	(13)		15	4	10	16
October	13	(13)		24	3	7	15
November							
December							
January 2002	5	(19)		22	3	5	8
February							
March	5	(9)		23	2	3	6
April							
May	19	(14)		24	4	8	13
June	29	18	24	24	2	6	14
July	30	17	24	24	3	7	20
August	37	18	24	24	4	10	21
September	16	(19)		24	3	5	10

[a]Parentheses indicate mean values.

strength of the troposcatter signal is expected to exceed that of the diffracted components. The observed values shown in Figure 10 may be compared with the predicted values in Figure 2. The suggested mechanism seems plausible since (approximately) 13 dBr on the signal amplitude scale corresponds to a path loss of 155 dB.

[29] It is interesting to note the seasonal variation of this effect. In winter, short-term fading of up to around

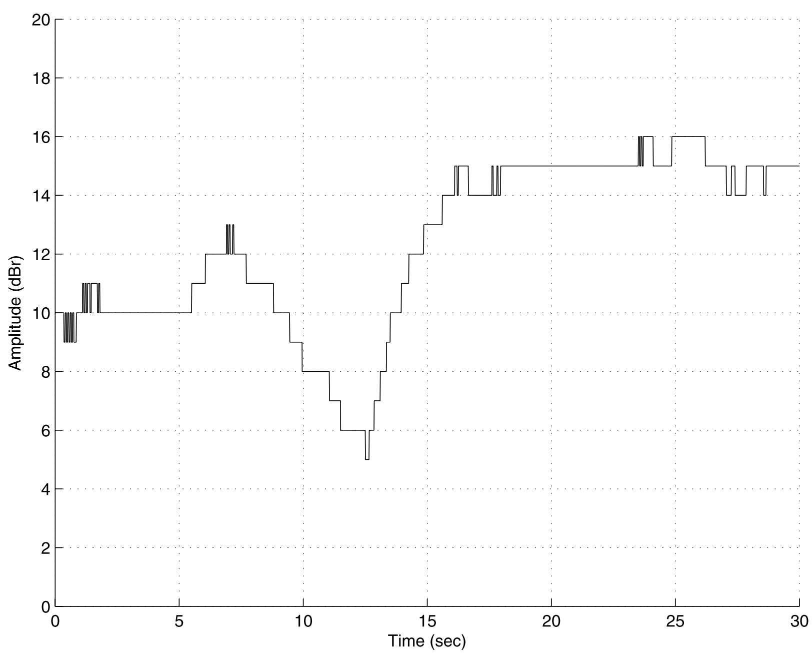

Figure 10. Short-term fading comparison for the 248 MHz vertically polarized signals received on Alderney on 17 November 2001.

Table 5. Fading Period and Range for an Autumn and a Cool Summer Day, Jersey–Alderney Path[a]

	17 Nov 2001 (Autumn)				12 June 2002 (Cool Summer)			
	248 MHz Horz.	248 MHz Vert.	341 MHz Horz.	341 MHz Vert.	248 MHz Horz.	248 MHz Vert.	341 MHz Horz.	341 MHz Vert.
Maximum fading range, dB	11	12	8.5	10	6	7.5	7.5	7.5
Maximum fading period, s	20	21.5	22	16	17	16.8	18	17.5
Average fading period, s	6.6	9.2	8.4	6.2	7.1	7.3	7.5	7.6

[a]Horz. means horizontal polarization and Vert. means vertical polarization.

10 dB was apparent superimposed on the usual pattern in which the signal strength varies steadily with changing tide height (around 1.2 dB per meter). During calm spring days in May 2002 when the temperature had begun to rise, the short-term fading of a few dB is predominant during periods of high water. Table 5 indicates the fading range and period for two example days, and Table 6 the percentage of the time for which this type of fading occurred.

[30] During warm weather, a high correlation was apparent between the occurrence of enhanced signal strengths (assumed to be due to superrefraction or ducting) at Guernsey and Alderney. During August 2002, for example, 129 hours were observed where both receiving sites exhibited enhanced signal strengths, and 121 hours when neither site exhibited this effect. In contrast, there were only 11 and 5 hours when increased signal strengths were exhibited only at Guernsey and Alderney respectively. Similar agreement was evident at other times of the year, details of which are provided in Table 7 for the period May–September 2002.

7. Summary and Concluding Remarks

[31] Data collected over a period of 17 months over the Jersey to Guernsey path from April 2001 until September 2002 and 8 months of data for the Jersey to Alderney path from November 2001 until September 2002 have been analyzed. Comparisons have been made between the received signal characteristics and several meteorological parameters such as sea state, weather conditions, season, etc.

[32] During times of calm sea state in winter, an approximately linear relationship between the signal amplitude (measured in dB) and the tide height was observed. The signal amplitude decreases by approximately 1.1 dB for every meter increase in the sea level. Little short-term fading was observed in Guernsey, however for the longer path to Alderney a fading range of around 10 dB was often observed. Statistically, this high level of fading varies dramatically from around 80% of the time to 31% during the autumn/winter period from November 2001 until January 2002. The average fading period was around 7 s, with a maximum fading period of approximately 22 s and a depth of 12 dB during the autumn period.

[33] During rough seas for the Jersey to Guernsey path, on a few occasions (less than 0.1% of the time) it was observed that the amplitude of the vertically polarized signal was reduced by between 3 and 6 dB. The horizontally polarized signal was not affected. Although other rough sea days occurred, this phenomenon did not often recur and was never observed in the Jersey to Alderney measurements. Its cause is therefore uncertain.

[34] During cool summer days for the Jersey to Guernsey path, similar signal behavior occurred to that observed during calm sea winter days (i.e., an

Table 6. Percentage of the Time That Fast Fading Was Observed at Alderney

Month	Percentage of the Time
November 2001	80
December 2001	47
January 2002	31
May 2002	41
June 2002	48
July 2002	35
August 2002	40
September 2002	66

Table 7. Number of Hours That Enhanced Signal Strengths Were Observed During May–September 2002 at Both Receiving Sites[a]

	Alderney and Guernsey	Guernsey Only	Alderney Only	None
May 2002	48	3	0	119
June	31	1	6	86
July	107	11	8	119
August	129	11	5	121
September	39	11	8	203

[a]Times when the Alderney receiver was not operational have been omitted.

approximately linear 1.1 dB reduction in signal amplitude per meter increase in tide height). Similar average signal strength variations were also observed over the Jersey to Alderney path. In the latter case, however, short-term (several seconds) fading was observed mainly during high tides (transmitting and receiving antennas at minimum height above sea level) during spring and summer. For a cool summer day, the average short-term fading period was around 7 s with a maximum of 18 s, and a depth 7.5 dB.

[35] During a hot summer day for the Jersey to Guernsey path, because of an increase in air temperature with respect to the sea temperature and the consequent change in the atmospheric refractive index profile, the signal amplitude was increased by up to a maximum of 21 dB. Statistically, the median increase in signal amplitude is around 3 dB, with upper and lower decile values of 10 and 1 dB respectively. Although there is little short-term fading, longer-term fades in excess of 20 dB were observed within periods of a few hours. The periods of enhanced signal strength were observed to last for periods of a few hours to 9 days continuously. In contrast, during ''nonsummer'' periods, periods of enhanced signal strength lasted from a few hours up to a day with signal amplitude increases of up to around 5 dB. Enhanced signal strengths appeared around 45 to 60% of the time during summer 2001 and around 20 to 35% of the time during summer 2002. This difference resulted from the fact that the summer of 2002 was cooler than that of the preceding year. In winter, the occurrence of enhanced signal strength was for less than 10% of the total time.

[36] During a hot summer day for Jersey-Alderney when enhanced signal strengths occurred throughout the day, the increase in signal amplitude and the fading characteristics are similar to the Jersey-Guernsey path. Although there is much similarity (e.g., period of occurrence) between Jersey-Guernsey and Jersey-Alderney, the differences in signal amplitude increase on the same day for both receiving sites could be up to 10 dB.

[37] **Acknowledgments.** The authors are grateful to QinetiQ (formerly DERA) (Portsdown West) for their financial support of this work. The authors are also grateful to Jon Kay-Mouat (Alderney), St. Peter Port Harbour Authority (Guernsey) and Ronez Quarry (Jersey) without whose help, cooperation, and agreement it would have been impossible for the measurements to have been made.

References

Bacon, D. (2003), Introduction to diffraction, in *Propagation of Radiowaves*, 2nd ed., edited by L. W. Barclay, pp. 129–144, Inst. of Electr. Eng., London.

Bullington, K. (1977), Radio propagation for vehicular communications, *IEEE Trans. Veh. Technol.*, *26*(4), 295–308.

Craig, K. H. (2003), Clear air characteristics of the troposphere, in *Propagation of Radiowaves*, 2nd ed., edited by L. W. Barclay, pp. 103–128, Inst. of Electr. Eng., London.

Griffths, J. (1987), *Radio Wave Propagation and Antennas: An Introduction*, Prentice-Hall, Upper Saddle River, N. J.

International Telecommunication Union (ITU) (2001), ITU-R Recommendation P.526-7, Propagation by diffraction, P Series, Geneva, Switzerland.

Matthew, P. A. (1965), *Radio Wave Propagation at VHF and Above*, CRC Press, Boca Raton, Fla.

Roda, G. (1988), *Troposcatter Radio Links*, Artech House, Norwood, Mass.

C. Y. D. Sim, Department of Computer and Communication Engineering, Chienkuo Technology University, Changhua City, 500, Taiwan.

E. M. Warrington, Department of Engineering, University of Leicester, Leicester LE1 7RH, UK. (emw@le.ac.uk)