



## Signal strength variations at 2 GHz for three sea paths in the British Channel Islands: Observations and statistical analysis

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[1] Measurements of signal strength are reported for a study of UHF propagation on three transhorizon sea paths in the British Channel Islands. Enhancements of up to 30 dB from the mean occur for periods of hours or days, especially in the summer, and constitute about 5% of the overall data. The probability distribution of received power is tabulated for the three paths and various antenna heights, and is compared with predictions of signal strength using ITU-R Recommendation P.1546-2. The difference between median and upper decile in the data is much less than predicted, whereas the difference between upper decile and the upper percentile is much greater than predicted.

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### 1. Introduction

[2] The UHF spectrum is in quite intensive use for broadcast media and cellular communications, and the 2 GHz region is likely to become particularly stretched as the take-up and content of 3G wireless networks expand [Ofcom, 2006]. These applications use point to area networks, which are vulnerable to interference from other users, so it is important to have a robust and accurate means of estimating the range of a signal. This range of a UHF signal can be enhanced by a number of mechanisms [Crane, 1981; Bean and Dutton, 1968] which depend on prevailing meteorological conditions, and the complexity of the situation is greater in coastal areas where enhanced transhorizon propagation is particularly prevalent. The data presented here provide important information about the behaviour of the signal strength for the top few percent of the time, which can only be obtained from a long term study, and also gives insight into the diurnal and annual variations of the data, which might be used for adaptive power control to mitigate against interference.

[3] ITU-R Recommendation P1546-2 [ITU, 2005b] gives predictions for the propagation factor at frequencies of 100, 600 and 2000 MHz for paths over warm sea, cold sea or land (warm sea is exemplified by the Mediterranean and cold sea by the North Sea). Interpo-

lation is allowed for between the three frequencies and between terrain types for mixed paths. However, the curves for 2000 MHz are extrapolated from measurements at lower frequencies, and since data derived from experimental observations at the frequency of interest are preferable to extrapolated data, measurements at 2 GHz have recently been made over three over-sea paths in the British Channel Islands to help rectify this deficiency. A summary of these measurements is presented in this paper together with a statistical analysis of the received signal strength variations and a comparison with predictions made using current ITU-R Recommendations.

[4] The measurement campaign started on the 22nd August 2003 and continued until the end of September 2005 for Alderney, until the end of November 2005 for Guernsey and until the 15th August 2005 for Sark. The antenna heights were such that the ends of the links were beyond the optical horizon except for the shortest path, which was within the optical horizon for most of the time. The tidal range in the Channel Islands is large (up to 10 m in Guernsey on a spring tide), and consequently the obscuration due to the bulge of the earth varies significantly with tide height. Aside from this influence, propagation is strongly enhanced at all sites by effects related to changes in the refractive index profile of the lower troposphere (i.e. super-refraction and ducting). Signal enhancement occurs for periods of a few hours or days and approximately simultaneously for all receiving stations. Its magnitude increases for the more distant stations. The overall percentage time for which enhancement occurs depends on the exact definition of enhance-

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ment, as discussed below. However, it is of the order of 10% of the time on the longest path.

## 2. Experiment

### 2.1. Equipment

[5] The geographical layout of the transmitter and three receiver sites is illustrated in Figure 1, and the latitude/longitude of all stations is given in Table 1. A nominally 100W CW transmitter located on the Jersey coast radiated vertically polarised signals at 2.015 GHz to receiving stations located on Sark (distance 22 km), Guernsey (33.5 km) and Alderney (49.5 km). The transmitter had two antennas at 17.5 m above mean sea level (msl) and two at 14.5 m above msl. One pair (high and low) were pointed towards Alderney, while the other pair were directed halfway between Guernsey and Sark and were used for transmissions to both of these receiving stations.

[6] Each receiver site was provided with two antennas, at 14 and 10 metres above (msl) in Guernsey and at 13 and 10 m above msl in Alderney and in Sark. All antennas were shrouded Yagis (Jaybeam 7360) with a  $-3$  dB beamwidth of  $27^\circ$  and a gain of 17 dBi according to the manufacturer but measured to be 14.5 dBi. The measured value has been used in the calculations presented below.

[7] All receiving sites were provided with AOR 5000 + 3 general coverage receivers, together with a PC for control and data recording purposes. Accurate synchronisation between the transmitting and receiving equipment was achieved by means of PC-mounted GPS cards, which also provided accurate frequency references at each site.

### 2.2. Calibration

[8] Calibration was done by comparing the received signal to that produced by a known input from an accurate signal generator for a range of different signal strength values. This was done several times over the period of data collection, and the variation seen between the calibration curves produced was of the order of 1 dB.

[9] Measurements were made at the feeds to the transmit antennas to determine losses in the transmitter station. For each receiver station, cable losses were estimated from the manufacturer's data. Care was taken to ensure that the length of cable from each high antenna was equal to the length from the corresponding low antenna, so that the two signals at a particular receiving station are directly comparable. Connector losses can be discounted as they are also present during receiver calibration. In summary, the signal power at the receiver can be viewed as resulting from 100 W transmitted power reduced by system losses at both ends of the link,

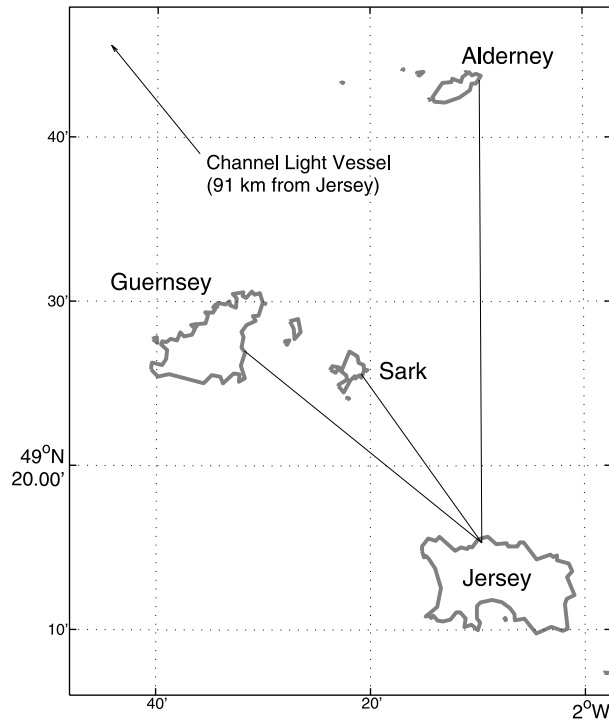
further reduced by the propagation losses. The system losses are estimated as 15.8 dB for Alderney and 11.1 dB for each of Guernsey and Sark. Calibrations of the receiver sensitivity were undertaken in December 2003, May 2004 and May 2005 for each of the three sites, very similar results being obtained on each occasion.

[10] Further adjustments were made to validate the relative signal strengths of the high antenna to those of the low antenna for each receiver station. To do this, the 99th, 90th, 50th, 10th and 1st percentiles of signal strength from each of the two antennas was plotted as a function of combined transmitter and receiver antenna height. Small amounts were added or subtracted from the whole data-set of each antenna in order to align the low antenna curves with those of the high antenna. It was found that for Sark, no correction was necessary, as the curves were already aligned. For Alderney, the 90th percentile curves of the low antenna were aligned with those of the high antenna, but the low antenna signal strength exceeded that of the high antenna for the median curves. As the median is more relevant to ITU Recommendation P1546-2, a correction was made to reduce the low antenna signal strength by 1 dB and increase the high antenna signal strength by 1 dB. For Guernsey, the upper antenna signal was increased by 2 dB and the lower reduced by 2 dB to achieve approximate collinearity for all the percentiles considered.

[11] In addition to these changes, the Guernsey signal was found to be attenuated by a further 10 dB by the walls of the lighthouse on which the antennas were mounted. This near field attenuation of the walls was clearly demonstrated over a period of several hours during a period of non-enhanced signal strength (which provides a very predictable signal). The antennas were moved away from the wall and the signal strengths when plotted, were parallel to the expected signal strengths for each antenna, but 10 dB higher. The expected signal strengths were based on the previous two tidal cycles. No other variation was seen during this test, and none were likely, from a theoretical viewpoint, so it is assumed that this 10 dB offset is a static one, which can simply be deducted from the Guernsey signals. After the test, the original mounting positions were maintained due to the weather protection they provided, and a 10 dB offset was added to the Guernsey high and low antenna signals.

### 2.3. Operation

[12] The system was scheduled to alternate between the Jersey-Sark/Guernsey and Jersey-Alderney paths, and between the high and low elevation antennas (measurements were only made between high elevation antennas and between low elevation antennas). In each minute, each receiving station recorded the signal power during two 1-second intervals on each of its antennas, giving 2880 data points per day per antenna. In the data



**Figure 1.** Map depicting transmitter and receiver locations in the Channel Islands. The path lengths are 49 km for Jersey to Alderney, 33 km for Jersey to Guernsey and 21 km for Jersey to Sark.

represented here, each 1-second transmission is represented by a single value, which is converted to absolute power at the receiver input via calibration tables.

### 3. Environmental Data

#### 3.1. Tidal

[13] The effective heights of the antennas above sea level at any time depends on the tide height and are estimated using tide prediction tables for Jersey, Guernsey and Alderney. The Guernsey tables are also used for

**Table 1.** Positions of Transmitting and Receiving Stations

|          | Longitude | Latitude | High Antenna<br>Alt., m above<br>m.s.l. | Low Antenna<br>Alt., m above<br>m.s.l. |
|----------|-----------|----------|---|--|
| Alderney | 2°10'W    | 49°43'N  | 13                                      | 10                                     |
| Guernsey | 2°31'W    | 49°27'N  | 14                                      | 10                                     |
| Sark     | 2°21'W    | 49°26'N  | 13                                      | 10                                     |
| Jersey   | 2°10'W    | 49°16'N  | 17.5                                    | 14.5                                   |

**Table 2.** Positions of Weather Stations

|                      | Longitude | Latitude | Altitude, m |
|----------------------|-----------|----------|-------------|
| Alderney             | 2°12'W    | 49°43'N  | 71          |
| Guernsey             | 2°36'W    | 49°26'N  | 102         |
| Jersey               | 2°12'W    | 49°13'N  | 84          |
| Channel Light Vessel | 2°54'W    | 49°54'N  | 5           |

Sark as no annual tide tables are published for this island. By comparison with the daily tidal data provided by the BBC Weather Centre, the maximum discrepancy in sea level between Sark and Guernsey is 40 cm, but for most of the time, the difference will be much less than this. The range of the tide and the time of the extrema vary amongst the islands. About an hour's difference in timing between Alderney and Jersey is the maximum temporal difference seen, and ignoring this could at worst, give about 2.5 metres error in antenna height.

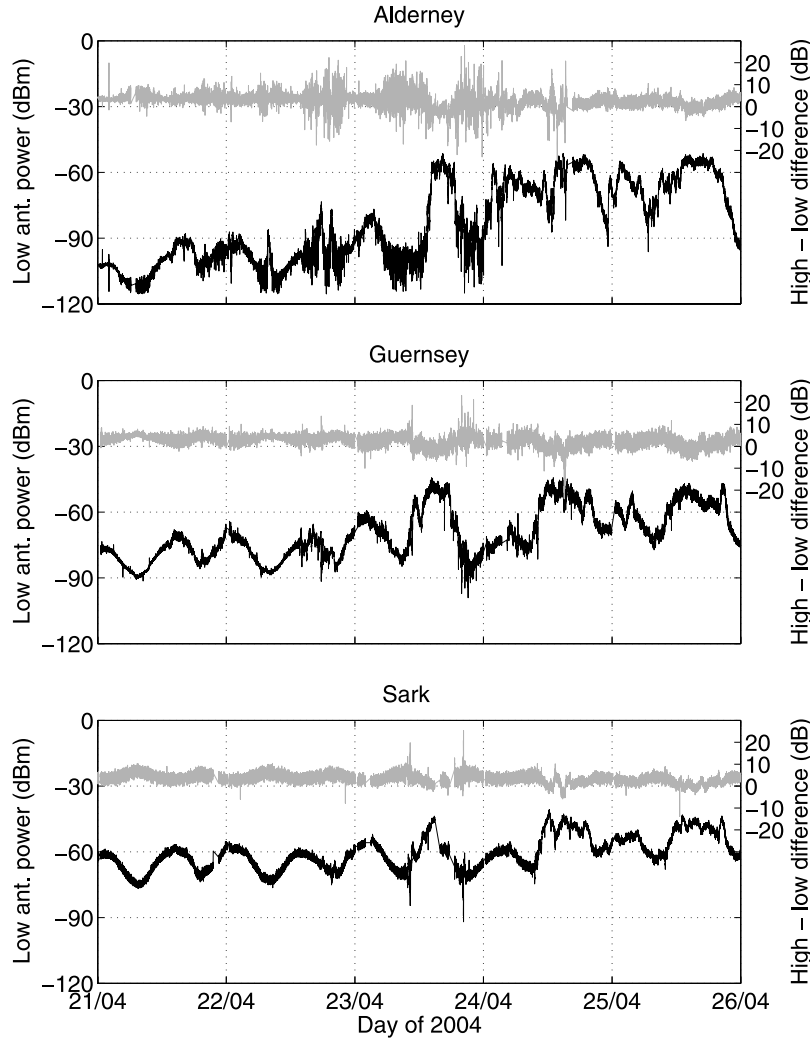
[14] The sea surface height will also be affected by up to half a metre either way from this value by air pressure changes with a consequent effect on the received signal power. Similarly, wave height and meteorological conditions alter the signal power.

#### 3.2. Meteorological

[15] In order to interpret the changing signal levels in terms ducting or other refractive phenomenon, meteorological data were collected from a number of sites for the duration of the experiment. These were obtained from meteorological stations at Alderney, Guernsey and Jersey airports, which are at heights of 89, 102 and 84 m above mean sea level respectively. Each receiver is within 10 km of the nearest airport. Meteorological data were also collected from the Channel Light Vessel, situated about 70 km northwest of the mid-point of the Jersey-Alderney path. The nominal height for this station is five metres above sea level. The positions of the meteorological stations are given in Table 2.

### 4. Example Measurements

[16] Figure 2 shows the signal power at each receiver for a period of five days in April 2004. The low antenna signal strengths are plotted in black, while the difference between high antenna signal strengths and low antenna signal strengths is in grey. A 12-hourly oscillation is apparent on the first few days. This is approximately consistent with diffraction over the changing height of the earth's bulge as the tide rises and falls. The observed change in signal strength is 1.1 to 1.4 dB per metre change in tide height, whereas ITU Recommendation P.526 estimates 1.6 dB/m. The tidal variation becomes less clear with increasing range from Sark to Alderney,



**Figure 2.** Examples of data from the three receiving sites for five days in April 2004. The low antenna signals are shown in black (left hand scale) and the difference (high antenna signal minus low antenna signal) is shown in grey (right hand scale).

as loss becomes more dependent on meteorological factors and less dependent on antenna height.

[17] After midday on the 23rd April, several periods of dramatically reduced propagation loss are seen fairly simultaneously for each of the receivers. The reduction in loss is up to about 15 dB on the shortest path to Sark and about 30 dB on the longest path to Alderney. During the enhanced period, the propagation loss is much less dependent on range and on tide height than it is for normal propagation (which depends on diffraction). Furthermore, during the period of enhancement, deep ( $\sim 20$  dB) fading is seen on a scale of around an hour, whereas the non-enhanced signal is rather more constant.

This change of signal strength and fading character is typical of periods of enhancement throughout the data.

## 5. Received Power Distribution

[18] Tables 3–8 present the cumulative frequency distributions of received signal power for the six links described above (three paths, each with two antenna heights). The data in these tables is presented as a function of transmitter antenna height and receiver antenna height separately, each rounded to the nearest metre. The five sections of each table give the value that the received power expected exceeded for 99, 90, 50, 10 and 1 percent of the time over a year.

**Table 3.** Jersey High to Alderney High Measurements<sup>a</sup>

|    | 12                              | 13     | 14     | 15     | 16     | 17     | 18     | 19     | 20     | 21     | 22     | 23     |
|----|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|    | <i>Exceeded 99% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 10 | -107.1                          | -109.9 | -106.7 | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 11 | -106.4                          | -109.5 | -108.7 | -107.9 | -107.1 | -      | -      | -      | -      | -      | -      | -      |
| 12 | -                               | -110.6 | -107.9 | -106.7 | -107.1 | -105.4 | -105.7 | -      | -      | -      | -      | -      |
| 13 | -                               | -      | -      | -106.7 | -105.8 | -106.1 | -105.2 | -105.2 | -105.5 | -      | -      | -      |
| 14 | -                               | -      | -      | -      | -      | -106.7 | -105.7 | -104.9 | -104.8 | -103.6 | -      | -      |
| 15 | -                               | -      | -      | -      | -      | -      | -      | -104.0 | -104.7 | -104.2 | -104.8 | -      |
| 16 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -102.4 | -102.6 | -103.9 |
|    | <i>Exceeded 90% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 10 | -103.0                          | -102.8 | -101.3 | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 11 | -102.7                          | -101.9 | -101.3 | -100.3 | -99.7  | -      | -      | -      | -      | -      | -      | -      |
| 12 | -                               | -97.7  | -100.1 | -99.6  | -99.6  | -98.5  | -97.8  | -      | -      | -      | -      | -      |
| 13 | -                               | -      | -      | -98.2  | -98.0  | -97.6  | -97.2  | -96.3  | -94.5  | -      | -      | -      |
| 14 | -                               | -      | -      | -      | -      | -96.6  | -96.3  | -95.7  | -95.1  | -94.7  | -      | -      |
| 15 | -                               | -      | -      | -      | -      | -      | -      | -94.8  | -94.8  | -94.2  | -93.9  | -      |
| 16 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -91.9  | -92.6  | -92.9  |
|    | <i>Exceeded 50% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 10 | -95.4                           | -95.7  | -93.6  | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 11 | -94.7                           | -94.6  | -93.2  | -92.6  | -92.6  | -      | -      | -      | -      | -      | -      | -      |
| 12 | -                               | -93.6  | -92.6  | -91.9  | -91.2  | -90.5  | -90.5  | -      | -      | -      | -      | -      |
| 13 | -                               | -      | -      | -91.5  | -90.0  | -89.1  | -89.7  | -88.9  | -88.0  | -      | -      | -      |
| 14 | -                               | -      | -      | -      | -      | -89.4  | -88.3  | -87.9  | -87.8  | -87.2  | -      | -      |
| 15 | -                               | -      | -      | -      | -      | -      | -      | -87.8  | -87.2  | -86.5  | -86.6  | -      |
| 16 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -86.6  | -86.4  | -86.1  |
|    | <i>Exceeded 10% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 10 | -87.6                           | -86.4  | -80.1  | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 11 | -87.6                           | -83.0  | -78.0  | -79.3  | -81.4  | -      | -      | -      | -      | -      | -      | -      |
| 12 | -                               | -89.1  | -76.7  | -75.7  | -76.3  | -76.6  | -79.3  | -      | -      | -      | -      | -      |
| 13 | -                               | -      | -      | -77.0  | -72.7  | -69.4  | -73.4  | -74.4  | -71.6  | -      | -      | -      |
| 14 | -                               | -      | -      | -      | -      | -76.7  | -73.5  | -69.3  | -72.6  | -76.3  | -      | -      |
| 15 | -                               | -      | -      | -      | -      | -      | -      | -77.0  | -74.6  | -74.0  | -77.1  | -      |
| 16 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -78.0  | -77.6  | -80.2  |
|    | <i>Exceeded 1% of the Time</i>  |        |        |        |        |        |        |        |        |        |        |        |
| 10 | -60.7                           | -52.6  | -52.1  | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 11 | -80.7                           | -51.5  | -51.1  | -53.2  | -52.1  | -      | -      | -      | -      | -      | -      | -      |
| 12 | -                               | -79.8  | -50.4  | -52.1  | -52.0  | -50.9  | -53.2  | -      | -      | -      | -      | -      |
| 13 | -                               | -      | -      | -49.7  | -50.9  | -49.9  | -51.1  | -50.7  | -49.7  | -      | -      | -      |
| 14 | -                               | -      | -      | -      | -      | -49.8  | -50.4  | -50.4  | -50.4  | -52.2  | -      | -      |
| 15 | -                               | -      | -      | -      | -      | -      | -      | -51.6  | -50.4  | -51.1  | -51.6  | -      |
| 16 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -49.2  | -53.6  | -59.8  |

<sup>a</sup>All values in dBm.

[19] The total number of data recorded for each combination of antenna heights is given in Tables 9–14. Due to various outages, the number of data from each season varies considerably, so rather than using simple percentiles, an algorithm was devised which gives equal importance to each season. To do this, the data are all put together in order of signal strength and each datum is given a weighting according to the season in which it was measured. Data from summer will tend to have a higher weighting than those from winter, to make up for

fewer recorded data in the summer. Then defining the  $x$ th percentile to be  $S$  dBm means that all signal strength values less than  $S$  dBm contribute  $x\%$  of the total weight of all data. This algorithm was used to determine the values in Tables 3–8.

[20] Figure 3 presents cumulative frequency distributions of the received signal strengths at the receiver for each antenna. These curves show the fraction of the total time (y-axis) for which the received signal has exceeded a specified power (x-axis). Unlike in the tables, the effect of the tide is not explicit here, rather the variation in

**Table 4.** Jersey Low to Alderney Low Measurements

|    | 9                               | 10     | 11     | 12     | 13     | 14     | 15     | 16     | 17     | 18     | 19     | 20     |
|----|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|    | <i>Exceeded 99% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 7  | -113.0                          | -113.3 | -112.2 | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 8  | -112.8                          | -113.0 | -112.6 | -111.8 | -111.3 | -      | -      | -      | -      | -      | -      | -      |
| 9  | -                               | -113.9 | -112.2 | -111.2 | -111.5 | -109.8 | -109.2 | -      | -      | -      | -      | -      |
| 10 | -                               | -      | -      | -111.0 | -110.1 | -110.1 | -108.9 | -108.8 | -108.6 | -      | -      | -      |
| 11 | -                               | -      | -      | -      | -      | -110.1 | -109.5 | -108.6 | -108.0 | -107.0 | -      | -      |
| 12 | -                               | -      | -      | -      | -      | -      | -      | -107.5 | -108.2 | -106.2 | -107.9 | -      |
| 13 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -105.4 | -105.0 | -108.0 |
|    | <i>Exceeded 90% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 7  | -107.5                          | -107.7 | -105.2 | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 8  | -107.2                          | -106.7 | -106.0 | -105.2 | -104.7 | -      | -      | -      | -      | -      | -      | -      |
| 9  | -                               | -101.2 | -104.6 | -104.3 | -104.2 | -103.1 | -102.5 | -      | -      | -      | -      | -      |
| 10 | -                               | -      | -      | -102.5 | -102.2 | -101.7 | -101.4 | -100.5 | -99.3  | -      | -      | -      |
| 11 | -                               | -      | -      | -      | -      | -100.5 | -100.2 | -99.6  | -99.2  | -98.6  | -      | -      |
| 12 | -                               | -      | -      | -      | -      | -      | -      | -98.5  | -98.3  | -97.8  | -97.5  | -      |
| 13 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -95.3  | -95.9  | -96.7  |
|    | <i>Exceeded 50% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 7  | -99.9                           | -100.7 | -98.0  | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 8  | -99.8                           | -99.3  | -97.4  | -97.1  | -96.9  | -      | -      | -      | -      | -      | -      | -      |
| 9  | -                               | -98.3  | -96.7  | -96.3  | -95.3  | -94.6  | -94.6  | -      | -      | -      | -      | -      |
| 10 | -                               | -      | -      | -95.3  | -94.2  | -93.0  | -93.5  | -92.8  | -91.3  | -      | -      | -      |
| 11 | -                               | -      | -      | -      | -      | -93.2  | -92.1  | -91.7  | -91.7  | -91.0  | -      | -      |
| 12 | -                               | -      | -      | -      | -      | -      | -      | -91.3  | -90.7  | -90.0  | -90.3  | -      |
| 13 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -90.0  | -89.8  | -89.0  |
|    | <i>Exceeded 10% of the Time</i> |        |        |        |        |        |        |        |        |        |        |        |
| 7  | -93.0                           | -90.7  | -85.0  | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 8  | -92.7                           | -85.7  | -81.2  | -82.7  | -84.9  | -      | -      | -      | -      | -      | -      | -      |
| 9  | -                               | -93.9  | -78.2  | -77.5  | -78.2  | -77.8  | -82.2  | -      | -      | -      | -      | -      |
| 10 | -                               | -      | -      | -77.4  | -74.4  | -70.8  | -75.1  | -76.4  | -74.4  | -      | -      | -      |
| 11 | -                               | -      | -      | -      | -      | -78.2  | -75.1  | -70.8  | -74.6  | -78.7  | -      | -      |
| 12 | -                               | -      | -      | -      | -      | -      | -      | -78.6  | -76.8  | -76.1  | -79.4  | -      |
| 13 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -79.1  | -80.5  | -83.6  |
|    | <i>Exceeded 1% of the Time</i>  |        |        |        |        |        |        |        |        |        |        |        |
| 7  | -64.2                           | -55.1  | -54.6  | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| 8  | -86.6                           | -53.5  | -52.9  | -54.1  | -53.5  | -      | -      | -      | -      | -      | -      | -      |
| 9  | -                               | -90.0  | -51.8  | -52.7  | -52.9  | -51.8  | -54.6  | -      | -      | -      | -      | -      |
| 10 | -                               | -      | -      | -49.6  | -51.3  | -49.6  | -51.3  | -51.8  | -50.7  | -      | -      | -      |
| 11 | -                               | -      | -      | -      | -      | -50.2  | -51.3  | -50.7  | -50.7  | -53.7  | -      | -      |
| 12 | -                               | -      | -      | -      | -      | -      | -      | -52.4  | -50.7  | -52.4  | -52.4  | -      |
| 13 | -                               | -      | -      | -      | -      | -      | -      | -      | -      | -48.6  | -54.1  | -60.9  |

signal strength represented on the x-axis is due to all mechanisms, tidal and atmospheric in order to bring all the data in the tables onto a single curve for each receiver antenna. The values represented here use the same algorithm as the data in the tables to give equal weighting to each season. The overall signal strength variation increases with range, being smallest for Sark and largest for Alderney, as expected. For Sark, the top and bottom tails of each curve are similar in size, and this approximate symmetry about the median is consistent with the tide being the main influence on signal strength at Sark. However, for Alderney the tail at high signal strength is

much more prominent than the lower tail indicating the signal strength at Alderney is also influenced by ducting and refraction.

[21] Figure 3 shows that the maximum signal strength for each of the paths is around  $-40$  or  $-45$  dBm. This is much higher than even the signal strengths predicted using only free-space loss, which are  $-69.0$  dBm,  $-61.1$  dBm and  $-57.0$  dBm for Alderney, Guernsey and Sark respectively. One explanation of this is that the energy is trapped in a layer some tens of metres wide. Instead of spreading out in two dimensions, as described by the Friis formula, the wavefronts are constrained to

Table 5. Jersey High to Guernsey High Measurements

|    | 12                              | 13    | 14    | 15    | 16    | 17    | 18    | 19    | 20    | 21    | 22    | 23    |
|----|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|    | <i>Exceeded 99% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -82.4                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -84.7                           | -85.9 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -85.2 | -84.3 | -82.8 | -     | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -83.0 | -83.5 | -82.2 | -     | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -80.6 | -81.2 | -80.6 | -     | -     | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -80.6 | -80.3 | -73.0 | -     | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -79.3 | -78.6 | -72.6 | -     | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -77.8 | -78.3 | -79.2 | -     | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -75.6 | -76.7 | -74.4 | -     |
| 18 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -75.9 | -89.0 |
|    | <i>Exceeded 90% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -82.1                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -81.7                           | -81.3 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -80.6 | -79.4 | -78.2 | -     | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -78.9 | -78.0 | -77.4 | -     | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -78.3 | -76.7 | -75.7 | -     | -     | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -75.3 | -74.6 | -71.4 | -     | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -74.0 | -73.3 | -71.8 | -     | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -72.7 | -72.4 | -71.2 | -     | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -71.0 | -71.1 | -70.6 | -     |
| 18 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -70.3 | -70.2 |
|    | <i>Exceeded 50% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -77.4                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -76.0                           | -75.6 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -74.9 | -73.8 | -73.0 | -     | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -73.3 | -72.4 | -71.6 | -     | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -71.6 | -71.1 | -70.3 | -     | -     | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -69.7 | -69.1 | -69.1 | -     | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -68.5 | -67.8 | -67.2 | -     | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -67.2 | -66.7 | -66.5 | -     | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -66.3 | -65.7 | -65.1 | -     |
| 18 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -65.1 | -65.1 |
|    | <i>Exceeded 10% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -70.3                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -70.7                           | -69.4 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -68.0 | -66.2 | -65.7 | -     | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -66.0 | -64.8 | -63.9 | -     | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -65.7 | -63.3 | -62.5 | -     | -     | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -62.3 | -61.5 | -62.9 | -     | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -61.5 | -60.1 | -59.6 | -     | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -60.1 | -60.0 | -60.0 | -     | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -61.0 | -59.1 | -59.1 | -     |
| 18 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -60.0 | -60.6 |
|    | <i>Exceeded 1% of the Time</i>  |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -66.7                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -62.9                           | -54.5 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -52.1 | -51.6 | -48.4 | -     | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -48.3 | -48.4 | -45.9 | -     | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -55.4 | -47.8 | -47.9 | -     | -     | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -47.9 | -47.5 | -48.4 | -     | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -48.3 | -47.0 | -46.6 | -     | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -47.0 | -46.5 | -43.2 | -     | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -47.4 | -47.4 | -47.9 | -     |
| 18 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -48.9 | -58.1 |

**Table 6.** Jersey Low to Guernsey Low Measurements

|    | 9                               | 10    | 11    | 12    | 13    | 14    | 15    | 16    | 17    | 18    | 19    | 20    |
|----|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|    | <i>Exceeded 99% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 5  | -90.4                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 6  | -92.1                           | -90.8 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -89.8 | -88.7 | -87.1 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -87.8 | -87.1 | -86.3 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -86.0 | -85.5 | -84.4 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -84.2 | -83.8 | -77.1 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -83.3 | -82.3 | -76.0 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -81.6 | -82.0 | -82.8 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -79.2 | -80.0 | -81.2 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -79.8 | -75.7 |
|    | <i>Exceeded 90% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 5  | -88.1                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 6  | -87.5                           | -87.1 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -86.1 | -84.6 | -83.3 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -83.5 | -82.8 | -82.0 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -82.1 | -81.2 | -80.6 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -80.0 | -79.2 | -74.7 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -78.6 | -77.9 | -74.7 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -76.8 | -76.6 | -75.7 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -75.3 | -75.3 | -74.5 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -74.2 | -73.4 |
|    | <i>Exceeded 50% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 5  | -82.2                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 6  | -82.4                           | -81.5 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -80.5 | -79.2 | -78.0 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -78.6 | -77.5 | -76.6 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -76.9 | -75.9 | -74.9 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -74.4 | -73.7 | -72.0 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -73.0 | -72.0 | -69.9 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -71.3 | -70.6 | -70.0 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -69.5 | -69.4 | -68.4 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -69.1 | -69.2 |
|    | <i>Exceeded 10% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 5  | -77.6                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 6  | -77.1                           | -76.3 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -74.6 | -72.0 | -71.6 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -71.7 | -70.5 | -69.0 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -70.6 | -68.4 | -67.6 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -67.1 | -65.9 | -67.0 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -65.7 | -64.6 | -64.0 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -64.5 | -63.8 | -62.9 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -64.2 | -62.9 | -62.7 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -62.9 | -63.3 |
|    | <i>Exceeded 1% of the Time</i>  |       |       |       |       |       |       |       |       |       |       |       |
| 5  | -75.8                           | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 6  | -67.4                           | -57.8 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -54.2 | -54.6 | -48.6 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -51.7 | -49.5 | -44.4 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -62.0 | -48.6 | -48.7 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -47.7 | -47.7 | -44.8 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -48.6 | -46.9 | -44.4 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -46.8 | -45.8 | -45.3 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -45.3 | -46.3 | -48.2 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -48.7 | -59.8 |



**Table 7.** Jersey High to Sark High Measurement

|    | 12                              | 13    | 14    | 15    | 16    | 17    | 18    | 19    | 20    | 21    | 22    | 23    |
|----|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|    | <i>Exceeded 99% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -69.9                           | -77.7 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -72.9 | -72.9 | -67.4 | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -     | -73.3 | -71.1 | -68.0 | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -     | -66.1 | -68.4 | -66.2 | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -66.6 | -65.7 | -60.3 | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -65.2 | -64.7 | -58.5 | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -     | -64.7 | -65.7 | -64.3 | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -     | -60.1 | -64.7 | -64.3 | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -64.7 | -65.2 |
|    | <i>Exceeded 90% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -66.5                           | -66.1 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -65.7 | -64.7 | -63.3 | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -     | -63.4 | -62.9 | -62.0 | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -     | -62.0 | -61.6 | -60.5 | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -60.3 | -59.4 | -56.8 | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -59.1 | -58.3 | -56.8 | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -     | -57.7 | -57.3 | -56.6 | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -     | -56.8 | -56.8 | -56.8 | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -56.3 | -54.7 |
|    | <i>Exceeded 50% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -62.1                           | -61.6 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -60.8 | -59.9 | -59.0 | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -     | -59.3 | -58.5 | -58.1 | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -     | -58.3 | -57.3 | -56.7 | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -56.3 | -55.5 | -53.6 | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -55.2 | -54.7 | -53.2 | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -     | -54.2 | -53.6 | -53.2 | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -     | -53.0 | -52.7 | -52.3 | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -52.1 | -52.1 |
|    | <i>Exceeded 10% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -58.8                           | -58.1 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -57.3 | -55.8 | -55.4 | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -     | -55.1 | -54.9 | -54.3 | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -     | -55.1 | -53.6 | -53.2 | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -52.9 | -52.3 | -52.6 | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -51.9 | -51.4 | -51.6 | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -     | -51.1 | -50.5 | -50.1 | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -     | -50.5 | -50.1 | -49.7 | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -49.7 | -49.5 |
|    | <i>Exceeded 1% of the Time</i>  |       |       |       |       |       |       |       |       |       |       |       |
| 9  | -54.3                           | -48.7 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -49.1 | -46.1 | -46.5 | -     | -     | -     | -     | -     | -     | -     | -     |
| 11 | -                               | -     | -43.2 | -43.7 | -44.3 | -     | -     | -     | -     | -     | -     | -     |
| 12 | -                               | -     | -     | -49.1 | -44.2 | -42.5 | -     | -     | -     | -     | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -43.7 | -43.9 | -43.3 | -     | -     | -     | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -43.8 | -42.9 | -40.9 | -     | -     | -     |
| 15 | -                               | -     | -     | -     | -     | -     | -     | -42.5 | -42.5 | -42.7 | -     | -     |
| 16 | -                               | -     | -     | -     | -     | -     | -     | -     | -43.3 | -43.8 | -43.3 | -     |
| 17 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -43.4 | -47.9 |

**Table 8.** Jersey Low to Sark Low Measurements

|    | 9                               | 10    | 11    | 12    | 13    | 14    | 15    | 16    | 17    | 18    | 19    | 20    |
|----|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|    | <i>Exceeded 99% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 6  | -76.7                           | -83.7 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -78.9 | -78.9 | -72.7 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -78.5 | -76.4 | -72.9 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -70.7 | -72.9 | -71.1 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -70.7 | -69.3 | -63.7 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -68.9 | -68.4 | -62.1 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -68.0 | -68.9 | -66.6 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -63.4 | -68.0 | -67.0 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -67.0 | -67.0 |
|    | <i>Exceeded 90% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 6  | -72.9                           | -72.2 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -71.3 | -70.1 | -68.1 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -68.5 | -68.0 | -66.6 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -66.6 | -66.1 | -64.7 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -64.2 | -63.3 | -60.7 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -62.8 | -62.0 | -59.4 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -61.0 | -60.5 | -59.6 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -59.6 | -59.6 | -59.6 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -59.1 | -56.8 |
|    | <i>Exceeded 50% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 6  | -68.3                           | -67.4 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -66.2 | -65.1 | -63.8 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -63.9 | -63.0 | -62.3 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -62.5 | -61.3 | -60.3 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -59.8 | -58.9 | -56.7 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -58.5 | -57.6 | -56.3 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -57.1 | -56.4 | -55.8 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -55.7 | -55.2 | -54.7 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -54.3 | -54.1 |
|    | <i>Exceeded 10% of the Time</i> |       |       |       |       |       |       |       |       |       |       |       |
| 6  | -64.2                           | -63.4 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -62.1 | -60.3 | -59.4 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -59.4 | -58.8 | -58.0 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -59.3 | -57.1 | -56.4 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -56.3 | -55.4 | -55.5 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -54.9 | -54.1 | -54.7 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -53.6 | -53.0 | -52.7 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -53.0 | -52.1 | -51.9 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -51.7 | -51.4 |
|    | <i>Exceeded 1% of the Time</i>  |       |       |       |       |       |       |       |       |       |       |       |
| 6  | -58.1                           | -51.5 | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 7  | -                               | -52.6 | -48.3 | -48.4 | -     | -     | -     | -     | -     | -     | -     | -     |
| 8  | -                               | -     | -44.3 | -44.8 | -45.7 | -     | -     | -     | -     | -     | -     | -     |
| 9  | -                               | -     | -     | -45.2 | -45.2 | -42.4 | -     | -     | -     | -     | -     | -     |
| 10 | -                               | -     | -     | -     | -     | -44.3 | -43.9 | -42.4 | -     | -     | -     | -     |
| 11 | -                               | -     | -     | -     | -     | -     | -44.7 | -42.2 | -39.9 | -     | -     | -     |
| 12 | -                               | -     | -     | -     | -     | -     | -     | -41.6 | -41.9 | -43.7 | -     | -     |
| 13 | -                               | -     | -     | -     | -     | -     | -     | -     | -43.3 | -43.4 | -43.8 | -     |
| 14 | -                               | -     | -     | -     | -     | -     | -     | -     | -     | -     | -43.4 | -49.7 |

**Table 9.** Jersey High to Alderney High: Number of Occurrences

|    | 12                             | 13    | 14    | 15     | 16     | 17    | 18    | 19     | 20     | 21     | 22    | 23   |
|----|--------------------------------|-------|-------|--------|--------|-------|-------|--------|--------|--------|-------|------|
|    | <i>Number of Data in Slice</i> |       |       |        |        |       |       |        |        |        |       |      |
| 10 | 10465                          | 22054 | 1201  | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 11 | 2027                           | 59270 | 92434 | 58295  | 7001   | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 12 | 0                              | 215   | 39001 | 107005 | 126219 | 79684 | 8997  | 0      | 0      | 0      | 0     | 0    |
| 13 | 0                              | 0     | 0     | 9280   | 64826  | 74923 | 94661 | 76173  | 1765   | 0      | 0     | 0    |
| 14 | 0                              | 0     | 0     | 0      | 0      | 16118 | 65641 | 111719 | 133389 | 30770  | 0     | 0    |
| 15 | 0                              | 0     | 0     | 0      | 0      | 0     | 0     | 13208  | 47849  | 103456 | 48146 | 0    |
| 16 | 0                              | 0     | 0     | 0      | 0      | 0     | 0     | 0      | 0      | 4242   | 29868 | 8485 |

one dimension, which would increase the signal strength by  $10 \log_{10}(d)$  for a path length  $d$ , giving a 13–17 dB increase for these paths. This constraint within a layer would also account for the fading seen in the enhanced data, as some rays reflect off the top of the duct or the sea to reach the receiver. Another possibility is that the rays are focussed by the laminar structure of the lower troposphere.

## 6. Comparison With Current ITU-R Predictions

[22] The procedure in Recommendation ITU-R P526-8 [ITU, 2005a] was used to model the received signal strengths. This recommendation aims to predict path losses due to diffraction over the earth’s curvature using only the antenna heights and range, taking no account of ducting or refraction by the atmosphere (*i.e.* earth radius enhancement factor,  $k = 1$ ). As such, this represents a method of comparison between the stations of only the more predictable part of the signal strength. For each of the six receiver antennas, the mean height of transmitter and receiver antennas above sea level was used to obtain a predicted signal strength, which is shown in row 3 of Table 15.

[23] For comparison with the predicted values, a mean ‘cold-weather’ signal strength was calculated from the

observations. A threshold signal strength was chosen for each of the six receiver antennas, to separate ‘cold-weather’ values from the enhanced signal strength caused by strong refraction effects. All the observations which lay below this threshold were averaged to make the mean ‘cold-weather’ signal strength given in row 2 of Table 15. The thresholds are given in the first row of the table, and the differences (observation minus prediction) are given in the final row. In effect this ‘cold weather mean’ never differed from the general mean by more than 3 dB. The differences between theory and observation are notably large, suggesting that some refractive effect is at work all the time. Furthermore, the discrepancy increases with range from between Sark and Alderney, so the observed dependence on range is less than that predicted by diffraction.

[24] The measured data have also been compared with predictions made using ITU-R Recommendation P1546-2. This recommendation is based upon empirical data and gives estimates of the signal strength exceeded 1%, 10% and 50% of the time only as a function of transmitter and receiver antenna heights.

[25] The differences between observed and predicted received power levels were calculated for each possible combination of heights of each pair of antennas. The differences were then weighted by the number of data available at that pair of heights, as given in Tables 9–14, and a weighted mean was derived for

**Table 10.** Jersey Low to Alderney Low: Number of Occurrences

|    | 9                              | 10    | 11    | 12    | 13     | 14    | 15    | 16    | 17     | 18    | 19    | 20   |
|----|--------------------------------|-------|-------|-------|--------|-------|-------|-------|--------|-------|-------|------|
|    | <i>Number of Data in Slice</i> |       |       |       |        |       |       |       |        |       |       |      |
| 7  | 8523                           | 18286 | 1059  | 0     | 0      | 0     | 0     | 0     | 0      | 0     | 0     | 0    |
| 8  | 1537                           | 49685 | 81010 | 51324 | 6300   | 0     | 0     | 0     | 0      | 0     | 0     | 0    |
| 9  | 0                              | 117   | 33949 | 96242 | 111145 | 70833 | 8297  | 0     | 0      | 0     | 0     | 0    |
| 10 | 0                              | 0     | 0     | 7918  | 57532  | 64744 | 81803 | 68462 | 1548   | 0     | 0     | 0    |
| 11 | 0                              | 0     | 0     | 0     | 0      | 14088 | 58091 | 98079 | 119716 | 27752 | 0     | 0    |
| 12 | 0                              | 0     | 0     | 0     | 0      | 0     | 0     | 11416 | 42111  | 91132 | 41072 | 0    |
| 13 | 0                              | 0     | 0     | 0     | 0      | 0     | 0     | 0     | 0      | 3412  | 24651 | 7601 |

**Table 11.** Jersey High to Guernsey High: Number of Occurrences

|    | 12                             | 13    | 14     | 15     | 16     | 17    | 18    | 19     | 20     | 21     | 22    | 23   |
|----|--------------------------------|-------|--------|--------|--------|-------|-------|--------|--------|--------|-------|------|
|    | <i>Number of Data in Slice</i> |       |        |        |        |       |       |        |        |        |       |      |
| 9  | 1016                           | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 10 | 11745                          | 49030 | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 11 | 0                              | 28821 | 119855 | 4479   | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 12 | 0                              | 0     | 10390  | 164251 | 38790  | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 13 | 0                              | 0     | 0      | 1074   | 142135 | 65428 | 0     | 0      | 0      | 0      | 0     | 0    |
| 14 | 0                              | 0     | 0      | 0      | 0      | 87886 | 92661 | 574    | 0      | 0      | 0     | 0    |
| 15 | 0                              | 0     | 0      | 0      | 0      | 0     | 62422 | 150880 | 925    | 0      | 0     | 0    |
| 16 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 34200  | 167697 | 8285   | 0     | 0    |
| 17 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 3839   | 120901 | 20739 | 0    |
| 18 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 51293 | 7908 |

each of the six receiver antennas. The results are shown in Table 16.

[26] The observed median signal strengths exceed predictions by 10–15 dB for all paths and there is a trend of greater excess for a longer path and a lower antenna, indicating that the loss due to diffraction over the earth’s bulge is being partially circumvented. This suggests that ducting may be more important a mechanism of propagation for this frequency than was apparent from P1546-2. The other notable trend is that signal strengths exceed predictions by broadly similar amounts for the median and 1% levels, but by much less at the 10% level. This suggests that, compared to the prediction, much less everyday (*i.e.* tidal) variation is seen on these three paths, but enhanced propagation (*i.e.* a couple of days per month in the summer where the path loss reduces by 20 dB) is more prevalent.

## 7. Seasonal and Diurnal Variations

[27] Although an attempt has been made to make the percentiles of signal strength representative of a whole

year, the occurrence of enhanced signal is very dependent on the occurrence of warm weather in any year. Although it is useful to resolve the significance of air temperature, sea temperature and other meteorological factors on the occurrence of enhanced signal strength, this analysis is reported in the paper accompanying this [Gunashekar *et al.*, 2007]. Here, the analysis is kept to statistics of the regular annual and diurnal variations, so that the data are potentially useful to predict enhancement without recourse to any model or assumption.

[28] Diurnal and seasonal variations were previously reported using a definition of enhancement related to the mean value of signal strength at each receive antenna [Siddle and Warrington, 2005]. However, in order to compare the likelihood of enhanced propagation between the different paths, a more objective definition of an enhanced signal is used here, which is equally valid for Alderney with its relatively small tidal range and large enhancements and for Sark with its larger tidal range and lesser enhancements. To achieve this, all the non-enhanced signals for a particular receiver antenna (using thresholds given in Table 15) were plotted against the combined height of transmitter and receiver antennas. A

**Table 12.** Jersey Low to Guernsey Low: Number of Occurrences

|    | 9                              | 10    | 11     | 12     | 13     | 14    | 15    | 16     | 17     | 18     | 19    | 20   |
|----|--------------------------------|-------|--------|--------|--------|-------|-------|--------|--------|--------|-------|------|
|    | <i>Number of Data in Slice</i> |       |        |        |        |       |       |        |        |        |       |      |
| 5  | 1016                           | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 6  | 11580                          | 48449 | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 7  | 0                              | 28564 | 119032 | 4448   | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 8  | 0                              | 0     | 10352  | 163017 | 38503  | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 9  | 0                              | 0     | 0      | 1077   | 141338 | 65030 | 0     | 0      | 0      | 0      | 0     | 0    |
| 10 | 0                              | 0     | 0      | 0      | 0      | 87488 | 92258 | 575    | 0      | 0      | 0     | 0    |
| 11 | 0                              | 0     | 0      | 0      | 0      | 0     | 62089 | 150383 | 926    | 0      | 0     | 0    |
| 12 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 34108  | 167074 | 8260   | 0     | 0    |
| 13 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 3831   | 120353 | 20643 | 0    |
| 14 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 50948 | 7891 |

**Table 13.** Jersey High to Sark High: Number of Occurrences

|    | 12                             | 13    | 14     | 15     | 16     | 17    | 18    | 19     | 20     | 21     | 22    | 23   |
|----|--------------------------------|-------|--------|--------|--------|-------|-------|--------|--------|--------|-------|------|
|    | <i>Number of Data in Slice</i> |       |        |        |        |       |       |        |        |        |       |      |
| 9  | 11531                          | 49739 | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 10 | 0                              | 31092 | 124967 | 4734   | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 11 | 0                              | 0     | 11052  | 171841 | 41187  | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 12 | 0                              | 0     | 0      | 1075   | 151592 | 70403 | 0     | 0      | 0      | 0      | 0     | 0    |
| 13 | 0                              | 0     | 0      | 0      | 0      | 94375 | 99281 | 583    | 0      | 0      | 0     | 0    |
| 14 | 0                              | 0     | 0      | 0      | 0      | 0     | 65323 | 159416 | 929    | 0      | 0     | 0    |
| 15 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 36772  | 176732 | 8697   | 0     | 0    |
| 16 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 4001   | 124662 | 21053 | 0    |
| 17 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 51735 | 7107 |

best-fit line was found for each dataset, so that an estimate could be made of the expected signal strength for any given time. Enhancement was deemed to have occurred when the actual signal strength exceeded this estimate by a given value, called the clearance.

[29] Figure 4 shows the percentage of time for which each of the signals is enhanced by a clearance of 10 dB as a function of the time of day of each measurement. This plot uses all the data, so winter and summer days are combined here. The diurnal variation is very similar, with each path showing a minimum around 0700 UT and a maximum around 1700 UT. This fits well with the diurnal temperature variation, although the mechanism causing the enhancement may be directly linked to air temperature at a particular height, or may be an indirect effect, such as the land breeze/sea breeze diurnal oscillation. Variation is seen in the magnitude of the enhancement probability with path. The peak probability at Alderney high antenna reaches 22%, while Guernsey and Sark reach only 10% and 5% respectively. The minimum amount of enhancement at Alderney is 10%, while that at the other sites drops almost to zero. Another feature is that the low antennas at each site have a slightly higher occurrence of enhancement than the high

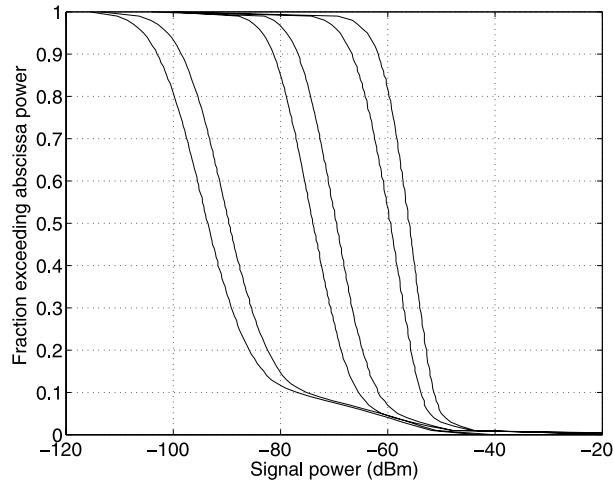
antennas. This is because the non-enhanced value of the signal strength is slightly lower for the lower antennas, while the occurrence of enhancement seems to typically affect both antennas at a particular site equally, being independent of height. Since the enhancement is defined against a base level of non-enhanced signals, the effective size of the enhancement is therefore slightly larger for the lower antennas.

[30] Figure 5 shows the variation of the same quantity over the year, using all the data and a 10 dB clearance. Again, the three paths are qualitatively similar, with the magnitude of the effect an increasing function of path length, and the maximal percentages are similar. However, in the winter, the occurrence of enhancement practically vanishes for all the paths. Again, low antenna values exceed high antenna values slightly. Enhanced signals generally occur between March and September, which again corresponds with the thermal cycle.

[31] These results generally agree with those obtained when enhancement is more simply defined as 10 dB above the mean of the signal strength at a particular antenna. However, for smaller clearances, the tidal variation will dominate, introducing noise into the diurnal and annual variations seen here. Using the method used

**Table 14.** Jersey Low to Sark Low: Number of Occurrences

|    | 9                              | 10    | 11     | 12     | 13     | 14    | 15    | 16     | 17     | 18     | 19    | 20   |
|----|--------------------------------|-------|--------|--------|--------|-------|-------|--------|--------|--------|-------|------|
|    | <i>Number of Data in Slice</i> |       |        |        |        |       |       |        |        |        |       |      |
| 6  | 11527                          | 49723 | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 7  | 0                              | 31093 | 124911 | 4730   | 0      | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 8  | 0                              | 0     | 11046  | 171314 | 41149  | 0     | 0     | 0      | 0      | 0      | 0     | 0    |
| 9  | 0                              | 0     | 0      | 1074   | 151425 | 70379 | 0     | 0      | 0      | 0      | 0     | 0    |
| 10 | 0                              | 0     | 0      | 0      | 0      | 94358 | 99249 | 583    | 0      | 0      | 0     | 0    |
| 11 | 0                              | 0     | 0      | 0      | 0      | 0     | 65319 | 159387 | 932    | 0      | 0     | 0    |
| 12 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 36745  | 176572 | 8684   | 0     | 0    |
| 13 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 3996   | 124620 | 21049 | 0    |
| 14 | 0                              | 0     | 0      | 0      | 0      | 0     | 0     | 0      | 0      | 0      | 51723 | 7100 |



**Figure 3.** The cumulative frequency distributions of high and low antenna signal strengths for all three receiving stations. (From left to right, the curves represent Alderney low antenna, Alderney high antenna, Guernsey low antenna, Guernsey high antenna, Sark low antenna and Sark high antenna.)

in Figures 4 and 5, it is possible to go to lower clearances. Interestingly, as 0 dB clearance is approached, the peak and trough seen in the diurnal trend remains, while the seasonal trend is lost with a clearance of 2 dB.

[32] Figure 6 shows the percentage of enhanced signal strengths for each of the receivers as an overall value (i.e. averaged over the day and the year) as a function of the clearance. Each of the curves is similar in shape, having a steep part for smaller values of clearance and a flatter part at larger values. Furthermore, the break point between these parts occurs at a different value of clearance for each path. From Figure 6, an approximate overall percentage of enhancement can be given for a broad range of definitions of enhancement. Thus, the Alderney signal can be said to be enhanced for about

**Table 15.** Mean “Cold-Weather” Observations of Signal Strength and Corresponding Predictions Using ITU-R P526<sup>a</sup>

|                              | Alderney |        | Guernsey |       | Sark  |       |
|------------------------------|----------|--------|----------|-------|-------|-------|
|                              | High     | Low    | High     | Low   | High  | Low   |
| Threshold                    | -74.0    | -78.0  | -57.0    | -58.0 | -47.0 | -50.0 |
| Observation                  | -90.4    | -94.6  | -70.0    | -74.3 | -56.5 | -60.2 |
| Prediction                   | -115.1   | -119.9 | -86.1    | -91.6 | -67.1 | -71.9 |
| Observation -Prediction (dB) | 24.7     | 25.3   | 16.1     | 17.1  | 10.6  | 11.7  |

<sup>a</sup>Values in dBm except for the last row.

**Table 16.** Weighted Means of the Measurements Minus Values Predicted Using ITU-R P.1546-2<sup>a</sup>

| Exceedence | Alderney |       | Guernsey |       | Sark  |       |
|------------|----------|-------|----------|-------|-------|-------|
|            | High     | Low   | High     | Low   | High  | Low   |
| 50%        | +14.5    | +14.6 | +12.1    | +12.5 | +10.5 | +11.0 |
| 10%        | -3.0     | -1.5  | -2.5     | -3.1  | +2.2  | +2.1  |
| 1%         | +12.5    | +14.5 | +6.8     | +9.9  | +8.4  | +10.7 |

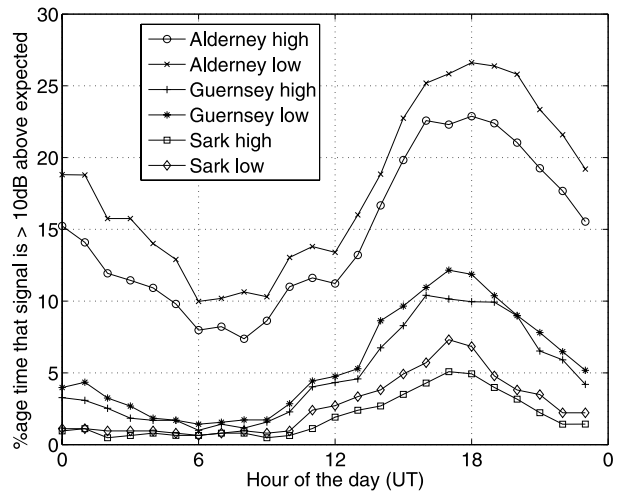
<sup>a</sup>All values in dB.

10% of the time if enhancement is defined as an increase of 15–25 dB on the tidal best-fit estimate.

### 8. Concluding Remarks

[33] Signal strength data have been presented from 2 GHz transhorizon links showing diurnal and seasonal variations and a dependence on path length and transmitter height and two different propagation regimes have been identified. Normal propagation is seen at most times, and gives a signal strength which depends strongly on the tide height, decreasing by 1.6 dB per metre increase in tide height and yet the mean signal strength is 10–25 dB above the signal strength predicted using ITU Recommendation P.526-9 (which has been configured to ignore ducting and refraction). Since the evaporation duct is an almost permanent feature of the maritime atmosphere, it is assumed that this propagation mechanism is some mixture of low-level ducting and diffraction.

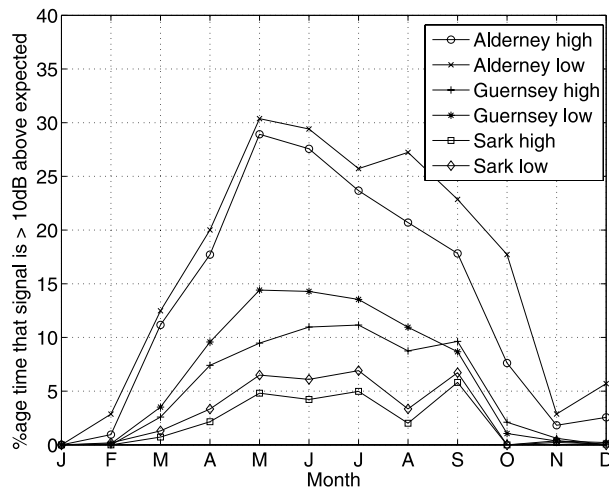
[34] The dramatic changes in signal strength between normal and enhanced levels occur simultaneously on all



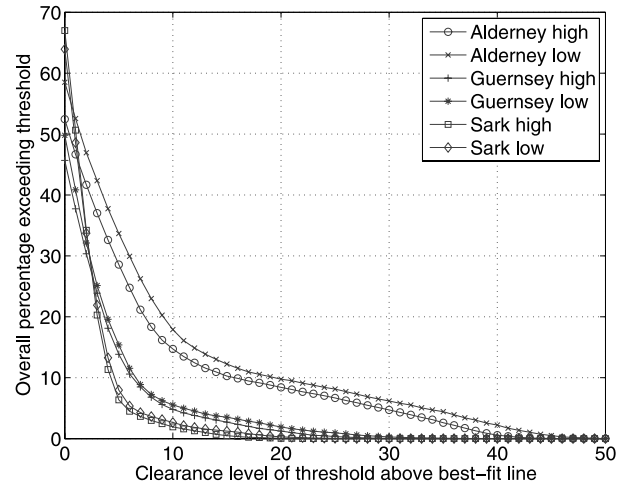
**Figure 4.** The percentage of time for which signal strength exceeds the expected value by 10 dB as a function of the time of day.

three paths investigated. The enhanced state is typified by signal strengths at or exceeding free-space values, very little dependence on range and antenna height and fading on a scale of about an hour. If an enhanced signal is defined as one exceeding its normal observed level by 10 dB, then the Alderney signal was enhanced about 17% of the time, while those received in Guernsey and Sark were enhanced 5% and 2% of the time respectively. Enhancement is markedly more prevalent in the spring and summer and has a diurnal dependence that peaks around 1700 UT. Its ultimate cause is therefore believed to be a rise in temperature.

[35] Various percentiles have been derived from the data using an algorithm that compensated for the relative scarcity of summertime data. When compared to predictions using ITU Recommendation P.1546-2, the observed median values and the values exceeded 1% of the time are typically higher by up to 15 dB, whereas for the values exceeded 10% of the time, reasonable agreement is seen. This indicates that the frequency of occurrence of enhanced signal strengths is underestimated by ITU-R P.1546-2, but also that the variation attributed to normal tide-dependent propagation is overestimated by the recommendation. This trend seems to become more pronounced as the path length is increased from Sark to Alderney. The reason for these discrepancies is not currently understood, but these results suggest that ITU-R P.154-2 underestimates considerably the amount of interference possible from distant systems using the upper end of the UHF band. The reasons for the behaviour of the data are investigated in the paper accompanying this [Gunashekar *et al.*, 2007].



**Figure 5.** The percentage of time for which signal strength exceeds the expected value by 10 dB as a function of the month.



**Figure 6.** The overall percentage of time for which enhanced signals are seen as a function of the value of clearance used in defining enhancement.

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