Transhorizon Radiowave Propagation due to Evaporation Ducting

The Effect of Tropospheric Weather Conditions on VHF and UHF Radio Paths Over the Sea

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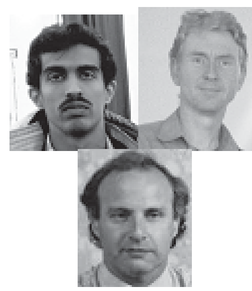
An evaporation duct is a weather phenomenon that occurs in the tropospheric region of the atmosphere over the open sea and other large water bodies. It has been observed that in addition to being interesting atmospheric occurrences from the meteorological perspective, evaporation ducts have far reaching implications on radio communications over the sea and in coastal regions (e.g. ship to ship and ship to shore communications). They are of particular importance at the extreme limits of propagation and allow radio waves to propagate beyond the horizon. Over the years, much research has been undertaken to explain the mechanism of radiowave propagation in evaporation ducts.



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SD Gunashekar is doing his PhD. His topic of research is the transhorizon propagation of UHF radio waves over the sea. (top left)

D R Siddle, Lecturer, is currently investigating the effect of tropospheric conditions on UHF transmissions, running an experimental program in the Britich Channel Islands. (top right)

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Background Theory

The lowest part of the earth's atmosphere is called the *troposphere*. Typically, the troposphere extends from the surface of the earth to an altitude of approximately 9 km at the poles and 17 km at the equator [1]. This upper boundary is referred to as the *tropopause* and is defined as the point at which the temperature in the atmosphere begins to increase with height. Within the troposphere, the temperature is found to decrease with altitude at a rate of approximately 7^{o} C per kilometre [1,2]. The earth's weather system is confined to the troposphere and the fluctuations in weather parameters like temperature, pressure and humidity cause the refractive index of the air in this layer to vary from one point to another. It is in this context that the troposphere assumes a vital role in the propagation of radiowaves at

VHF (30-300 MHz) and UHF (300-3000 MHz) frequencies. The meteorological conditions therefore influence the manner in which radiowave propagation occurs in the troposphere both on a spatial and temporal scale.

Refractive Index, Refractivity and Modified Refractivity

In general, the refractive index, n, of the troposphere decreases with altitude [2,3,4]. To simplify the mathematics involved variations in the horizontal are neglected and horizontal homogeneity of the refractive index of the troposphere is assumed in most discussions on this topic. A typical value for n at sea level is 1.000350. A few metres above sea level, this might decrease to a value such as 1.000300. For all practical purposes, at this scale, this change in the refractive index is negligibly small, with hardly any visible deviation. However, immediately above the surface of the sea, it is often this small (but rapid) change in the refractive index profile that facilitates the formation of meteorological phenomena called *evaporation ducts.*

A convenient way of expressing these unwieldy numbers is to use the concept of *refractivity* instead. Refractivity, N, is defined as follows [2,3]:

$$N = (n-1) \star 10^6 \tag{1}$$

So, for example, when $n = 1.000350$, $N = 350$.

A well-known approximation for refractivity N is given below [2, 3, 4]:

$$N = \frac{77.6}{T}\left(P + \frac{4810 \star e}{T}\right), \tag{2}$$

where P = total atmospheric pressure (in mb);
T = atmospheric temperature (in K);
e = water vapour pressure (in mb).

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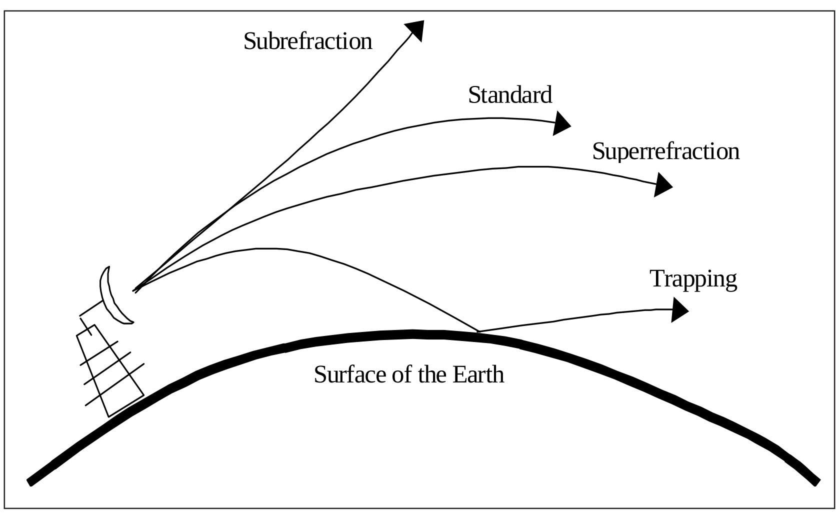
Evaporation duct, troposphere, radiowave propagation.

All three terms, P, T and e have been observed to fall with height in an exponential manner, resulting in a corresponding decrease in *N* with height [2,4]. A *standard* atmosphere, therefore is one in which the refractivity varies with altitude according to equation (1). Using Snell's law, a radio ray projected into the atmosphere will have to travel from a denser to rarer medium and will refract downwards towards the surface of the earth. The curvature of the ray, however, will still be less than the earth's curvature. The gradient of refractivity in this case generally varies from 0 to –79 N-units per kilometre [2]. When the refractivity gradient varies from –79 to –157 N-units per kilometre, a *superrefractive* condition is said to prevail in the troposphere and the ray will refract downwards at a rate greater than standard but less than the curvature of the earth [2]. A refractivity gradient that is even less than –157 N-units per kilometre will result in a ray that refracts towards the earth's surface with a curvature that exceeds the curvature of the earth [2]. This situation is referred to as *trapping* and is of particular importance in the context of evaporation ducts. Finally, if the refractivity gradient is greater than 0 N-units per kilometre, a *subrefractive* condition exists and a radio ray will now refract upwards, away from the surface of the earth [2]. Depending on the existing conditions in the troposphere, a radio wave will undergo any of the types of refraction: subrefraction, standard refraction, superrefraction or trapping. *Figure* 1 illustrates the four refractive conditions discussed above.

Figure 1. Diagram illustrating the four refractive conditions in the troposphere.



While dealing with radio propagation profiles, it is customary to replace curved radio rays with linear rays for the purpose of geometric simplicity. To account for drawing radio rays as straight lines, we must therefore increase the radius of the earth. The radius of this virtual sphere is known as the *effective earth radius* and it is approximately equal to four-thirds the true radius of the earth (i.e. roughly 8500 km) [2,3].

A more classical form of representing n is that of *modified* refractivity, M. In this case, the surface of the earth is represented by a flat plane and the radio rays are constituted by curves that are determined by Snell's law and the corresponding value of M at each point along the radio link. The following is the expression for M [1,5]:

$$M = N + \left(\frac{h}{a}\right) * 10^6 \tag{3}$$

$$= N + 0.157h, \tag{4}$$

where N = refractivity (in N-units),
h = height above sea level (in metres)
a = radius of the earth (in metres).

Theory of Evaporation Ducts

Formation of Evaporation Ducts

The air that is in immediate contact with the sea surface is saturated with water vapour (i.e. the relative humidity is 100%). As the height increases, the water vapour pressure in the atmosphere rapidly decreases until it reaches an ambient value at which it remains more or less static for a further increase in height. Therefore, for the first few metres above the surface of the sea, it is the water vapour pressure, e, in the expression for N that dominates. This rapid decrease in e causes a steep fall in N. This is reflected in the modified refractivity, M, which also correspondingly decreases. (The height term h, which increases, is more than offset by the rapidly decreasing N term). This behaviour can be clearly observed in the following graph of h vs.

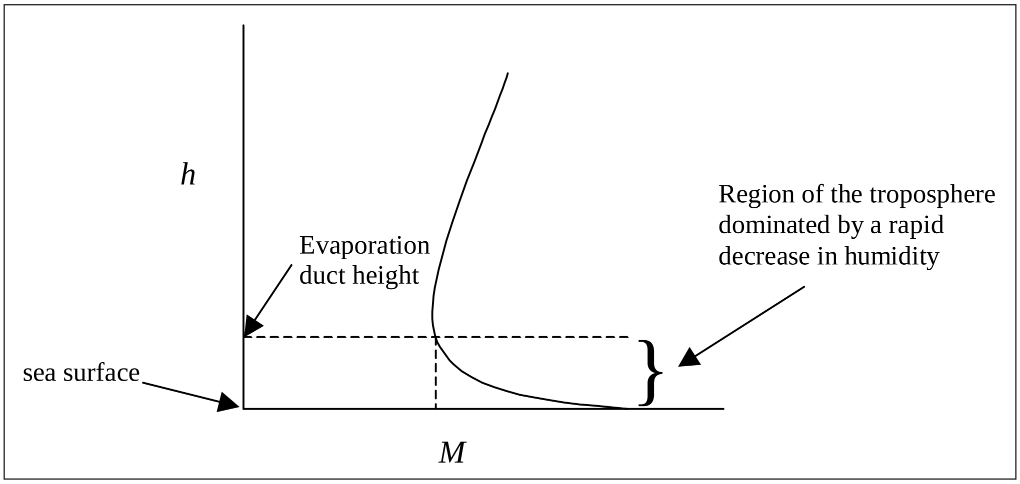


Figure 2. Modified refractivity profile of the troposphere above the surface of the sea indicating the presence of an evaporation duct.

M (*Figure* 2) as that portion of the curve with a strong negative M gradient. Therefore, despite the fact that the height h is increasing, it is the sharp fall in the water vapour pressure, e that contributes to the rapid decrease in M.

Once e has reached its ambient value at a given height, a further rise in altitude does not cause a substantial change in the humidity of the troposphere. Thus, as h increases further, N decreases more (since air pressure and temperature both decrease with height). But this decrease in N is very small over large height increments. Consequently, despite a decreasing N term, it is the h term that starts to dominate in the expression for M. Thus, M now gradually increases with height, and can be seen as the portion of the curve that has a positive M gradient.

The point at which the M gradient changes from negative to positive is referred to as the *evaporation duct height* (or *thickness*), and is a practical and realistic measure of the strength of the evaporation duct.

Evaporation Ducts and the Troposphere

By virtue of their nature of formation, evaporation ducts are nearly permanent features over the sea surface. Typically, the height of an evaporation duct is of the order of only a few metres; however, this can vary considerably with geographical location and changes in atmospheric parameters such as humidity, air pressure and temperature. In the lower regions of the troposphere where the earth's weather is confined, these parameters do, in fact, fluctuate significantly. The turbulent nature of the atmosphere contributes to its unpredictability and a variable atmosphere, in turn, is one of the major causes of unreliable wireless communications.

Depending on their location and the prevailing climate, evaporation duct heights may vary from a few metres to few tens of metres. The world average duct height has been reported to be 13m. Also, tropical climates are more favourable than temperate climates for the formation of evaporation ducts [6]. Additionally, it has been observed that calm sea conditions are more conducive for the creation of ducts. As a consequence of sporadic meteorological phenomena, evaporation duct heights undergo significant spatial and temporal variations.

Evaporation ducts are weather-related phenomena; their heights cannot easily be measured directly using instruments like refractometers and radiosondes. At best, the height of an evaporation duct can be deduced from the bulk meteorological parameters that are representative of the ongoing physical processes at the air-sea boundary. The dependence of evaporation ducts on the physical structure of the troposphere signifies that changing weather conditions can indeed result in alterations in radio wave propagation.

Evaporation Ducts and Radiowave Propagation

Over the years, much research has been undertaken to explain the mechanism of radiowave propagation in evaporation ducts. A key reason why evaporation ducts are so important for radio communications is because they are often associated with enhanced signal strengths at receivers.

An evaporation duct can be regarded as a natural waveguide that steers the radio signal from the transmitter to a receiver that may be situated well beyond the radio horizon [1, 4, 5]. The drop in

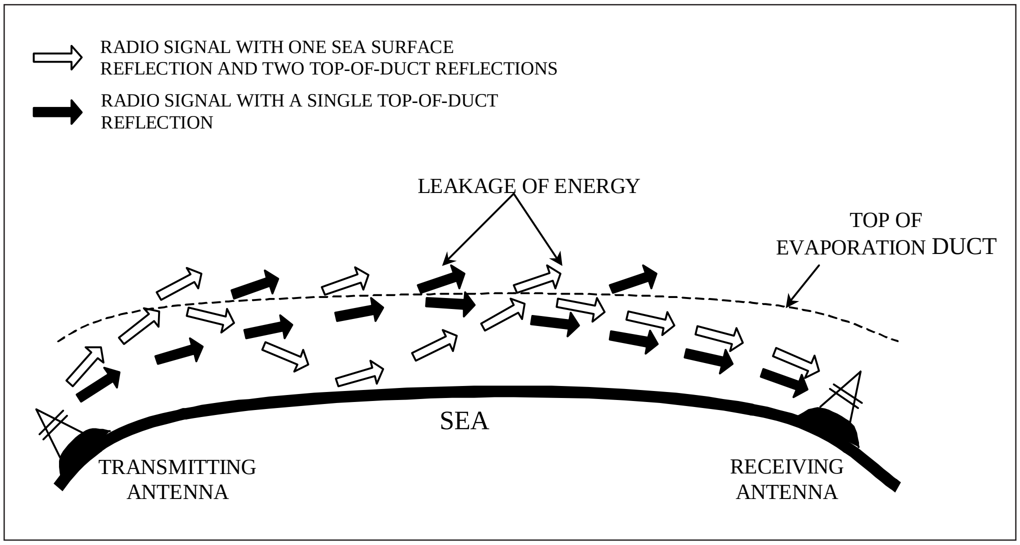


Figure 3. Diagram illustrating evaporation duct propagation.

the refractive index of the atmosphere within the first few metres above the surface of the sea causes incident radio waves to be refracted towards the earth more than normal so that their radius of curvature becomes less than or equal to that of the earth's surface. The sudden change in the atmosphere's refractivity at the top of the duct causes the radio waves to refract back into the duct, and when it comes in contact with the surface of the sea, it gets reflected upwards again. The waves then propagate long ranges by means of successive reflections (refractions) from the top of the duct and the surface of the earth (*Figure* 3).

It is worth mentioning here that since the top of an evaporation duct is not 'solid' (as in the case of an actual waveguide), there will be a small but finite amount of energy leakage into the free space immediately above the duct (*Figure* 3). However, despite this escape of energy, radio waves are still capable of travelling great distances through the duct, with relatively small attenuation and path loss.

It must be remembered that this is a very simplistic and one-dimensional means of illustrating radiowave propagation in evaporation ducts, one that is based on the assumption that the atmosphere's refractive index is horizontally homogeneous.

As mentioned previously, this ducting effect often results in radio signals reaching places that are beyond the radio horizon with improved signal strengths. This naturally has far reaching implications on practical radio propagation patterns. For this reason, evaporation ducts and their impact on radio wave propagation have been studied extensively over the years. Numerous statistical models have been proposed to describe evaporation ducts and compute the duct heights under different atmospheric conditions [5].

The presence of evaporation ducts might not always indicate enhanced signal strengths. For instance, if there is an unwanted distant transmitter also located within the duct, then there is always the possibility of the system under consideration being susceptible to signal interference and interception. This, of course, is dependent on the location of the radio paths being investigated. Another scenario that might arise is the interference between the various propagation modes that exist within the evaporation duct itself. Depending on the separation of the transmitter and receiver and the prevailing atmospheric conditions, there could be destructive interference between the direct and reflected rays, the latter of which is comprised of the various multiple hop (one-hop, two-hop, and so on) propagation modes (*Figure* 3). Additionally, signal degradation may also occur if there is destructive interference between various modes that arrive at the receiver after refraction from different heights in the troposphere. All these situations could possibly cause key problems in the domain of cellular mobile communication systems in littoral regions. Thus, in addition to aiding radiowave propagation, evaporation ducts could also be principal limiting factors in beyond line of sight over-the-sea UHF propagation.

Marine Boundary Layer Processes

It is a well-established fact that the occurrence of evaporation ducts over the open sea is highly dependent on the various physical processes and interactions that exist at the *air-sea boundary layer* [1,5]. It has been proposed that the difference in temperature between the sea and the air in immediate contact with the sea is a significant contributing factor in the formation of evaporation ducts. This temperature difference is referred to as the *air-sea temperature difference* (ASTD). When this quantity is positive, that is, when the air temperature is higher than the sea temperature, we have a *stable atmospheric condition*. This is because colder air (in direct contact with the cold ocean) remains beneath the warmer rising air, thus preventing convection currents from arising. On the other hand, when the air temperature is somewhat less than the sea temperature, an *unstable condition* is said to prevail. Such a situation tends to occur when the warmer air (in immediate contact with the warm ocean) begins to rise above the cold sinking air, thereby resulting in a convective motion. Meteorological observations reveal that in the open ocean, unstable conditions are more likely to exist.

Practical Results: Enhanced Signal Propagation in the British Channel Islands due to Ducting

This section contains graphical outputs and statistical results using experimental data to clearly verify the theory and conclusions that have been presented. The various results have been obtained from a research experiment being conducted in the British Channel Islands by the Radio Systems Research Group, Department of Engineering, University of Leicester, UK. Specifically, a number of scatter plots have been produced that try to explain the correlation between enhanced signal strength occurrences and specific meteorological conditions in the English Channel along a 50 kilometre transhorizon UHF radio link (Jersey to Alderney).

In general, the sea temperature is a few degrees above the air temperature, reflecting the prevalent unstable atmospheric conditions in the open sea. However, there are periods when the air temperature exceeds the sea temperature (*Figure* 4a). Enhanced signal strengths were observed during most of these periods (*Figure* 4b). The plots reveal that for enhanced propagation to occur, the following conditions must both be satisfied:

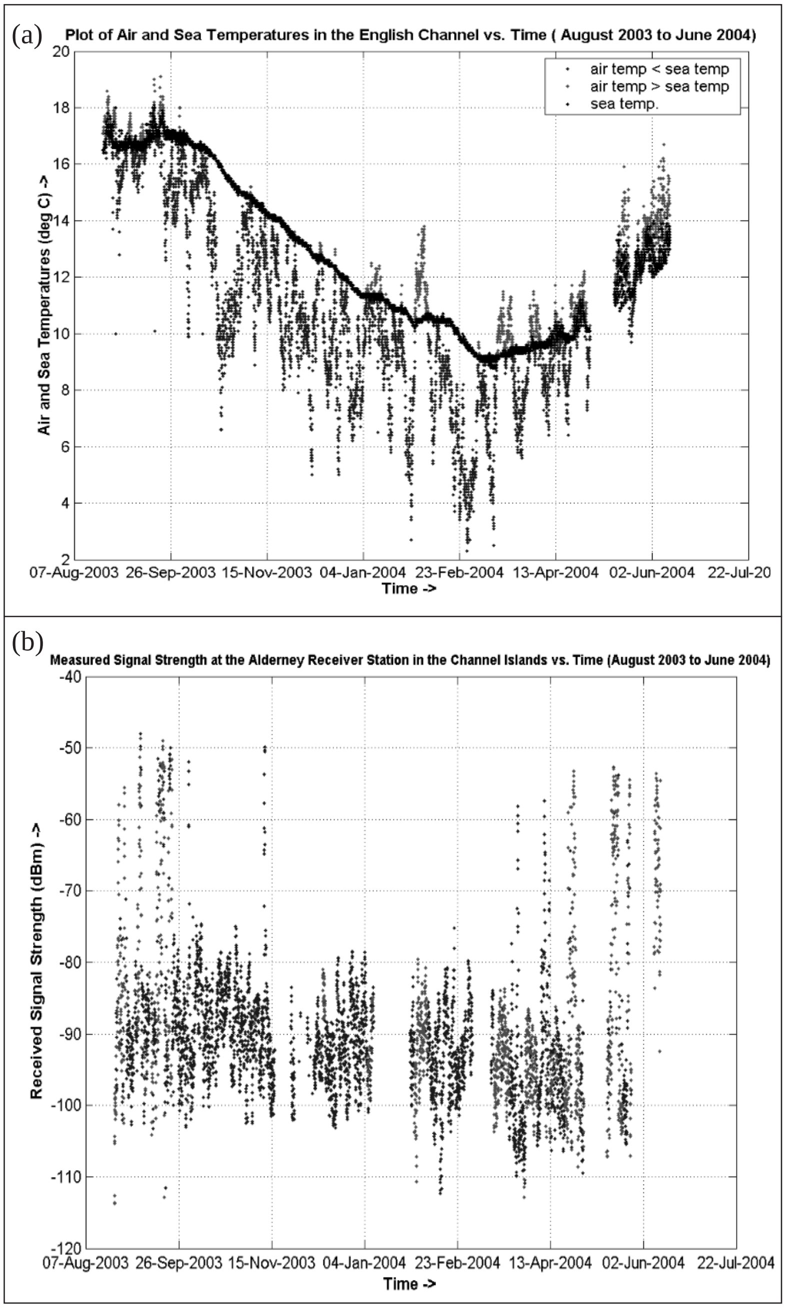


Figure 4. (a) The variation in the air and sea temperatures in the English Channel with time (from August 2003 to June 2004) (blue data = times when $T_{air} < T_{sea}$; red data = times when $T_{air} > T_{sea}$). (b) The signal strength measured at the Alderney receiving station antenna in the Channel Islands as a function of time (blue data=times when $T_{air} < T_{sea}$; red data = times when $T_{air} > T_{sea}$.)

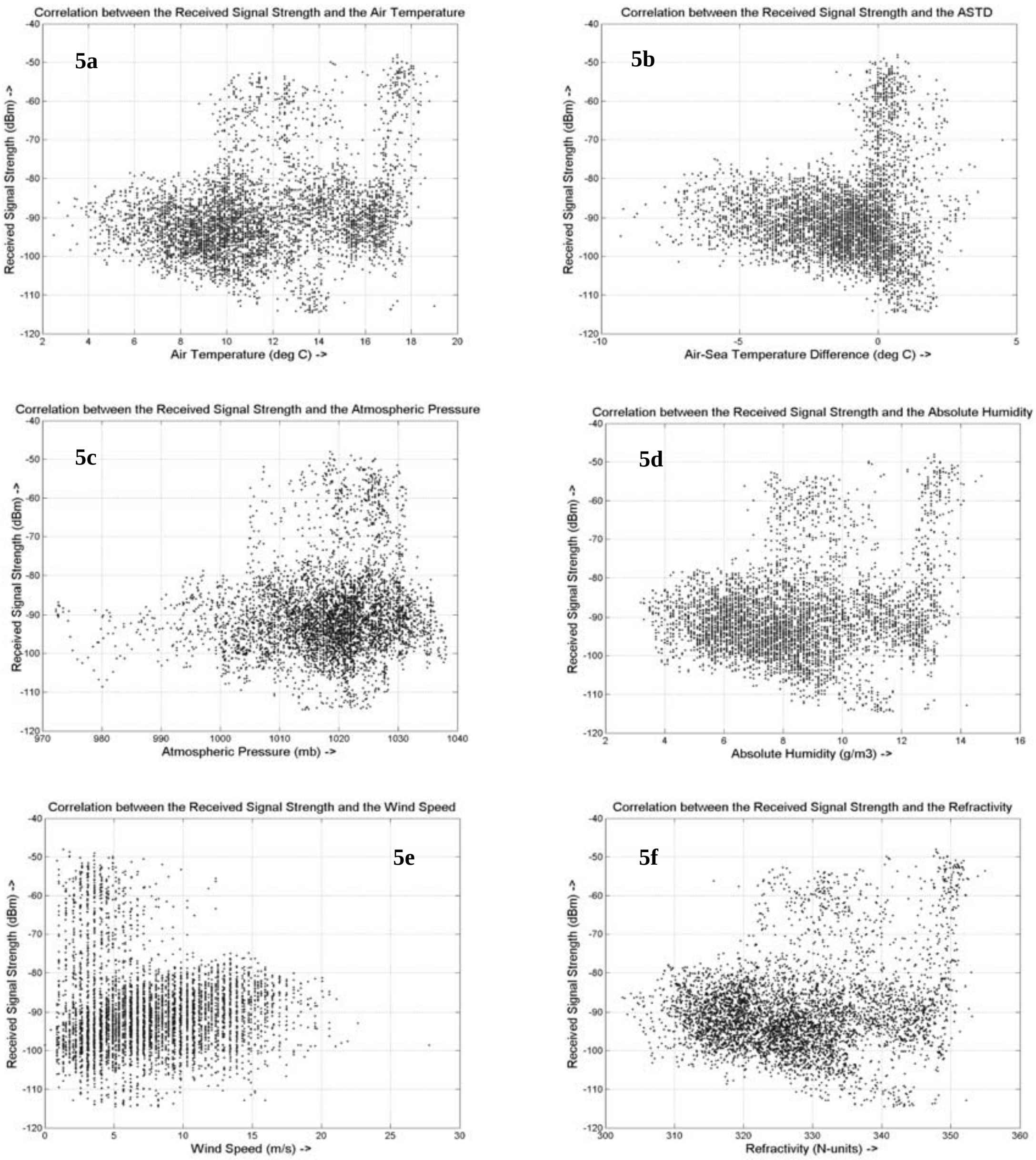


Figure 5. Graphs illustrating the correlation between the measured signal strength at the Alderney receiving station antenna in the Channel Islands and the various marine meteorological parameters time (from August 2003 to June 2004)

- $T_{air} > T_{sea}$
- $T_{sea} > 12$ °C (approximately)

In particular, when enhanced signal strengths occur, the following meteorological conditions were prevalent:

- an increase in the air (>16°C) and sea (>12°C) temperatures (e.g. during summer months) (*Figure* 5a)
- a positive air-sea temperature difference (ASTD) that is associated with a thermally stable atmosphere (*Figure* 5b)
- the existence of high-pressure centres over the region (i.e. anti-cyclonic weather) (*Figure* 5c)
- an enhancement in the absolute humidity of the air immediately above the sea surface (> 9 g/m^3) (*Figure* 5d)
- the presence of low velocity (<6m/s) winds (i.e. calm sea conditions) (*Figure* 5e)
- an increase in the refractivity of the lower troposphere (> 340 N-units) (*Figure* 5f)
- wind blowing from continental Europe to the sea.

Conclusion

A detailed description of evaporation ducts and their relevance to radiowave propagation over the sea has been presented. The constantly changing weather conditions over the sea mean that marine and coastal environments, in particular, are prone to these unusual tropospheric phenomena that facilitate radio waves to have higher signal strengths and to travel longer distances than expected. Therefore, the influence of evaporation ducts on over-sea radiowave propagation needs to be thoroughly investigated. Research in this area will have implications for maritime communication systems used in coastal cellular telephone networks, commercial shipping, naval radar operations and sea-rescue.

Suggested Reading

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