

SURFACE WAVES: WHAT ARE THEY? WHY ARE THEY INTERESTING?

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ABSTRACT

Surface waves have been known about for many decades and quite in-depth research took place up until ~1960s . Since then, little work has been done in this area. It is unclear why, however today we have more powerful modelling methods which may enable us to understand their use better. It is known that high frequency (HF) surface waves follow the terrain and this has been utilised in some cases such as Raytheon's HF surface wave radar (HFSWR) for detecting ships over-the-horizon. It is thought with some more insight and knowledge of this phenomenon, surface waves could be extremely useful for both military and civil use, from communications to agriculture.

WHAT ARE SURFACE WAVES?

Over the many decades that surface waves have been researched, some confusion has built up over exactly what constitutes a surface wave. This was discussed by James Wait in an IEE Transaction in 1965¹ and was even a matter of discussion at the General Assembly of International Union of Radio Science (URSI) held in London in 1960. It was concluded that “there is no neat definition which would encompass all forms of wave which could glide or be guided along an interface”. However, the definitions which have been settled upon for this paper are as follows:

Surface Wave Region: The region of interest in which the surface wave propagates.

Surface Wave: A surface wave is one that propagates along an interface between two different media without radiation; such radiation being construed to mean energy converted from the surface wave field to some other form.

Space Wave: The space wave radiates and travels in the troposphere. It requires line-of-sight for communication; however it may undergo tropospheric refraction.

Ground Wave: The ground wave is the superposition of the surface wave and space wave components. It does not include the sky wave component.

Sky Wave: The sky wave is a radiating element which is reflected off the ionosphere. It generally is received over large distances and in non-line-of-sight communications but is highly dependent on ionospheric activity.

The definition of the surface wave is based on that in Barlow and Brown's 1962 book² and all of these definitions can be represented diagrammatically as shown in Figure 1.

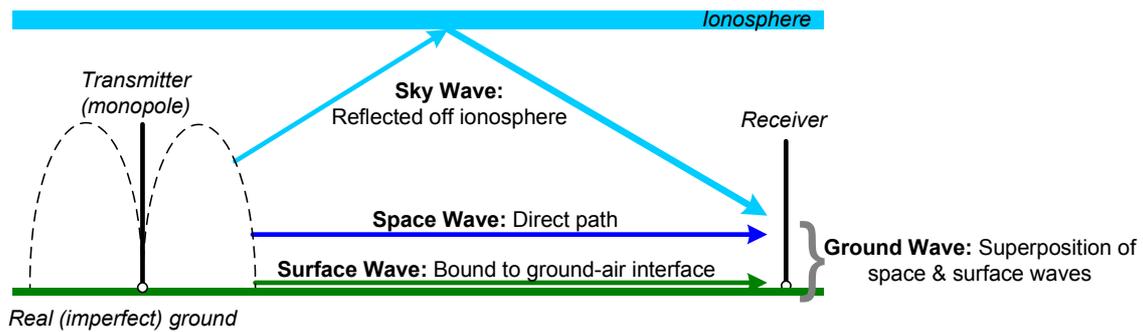


Figure 1 Diagrammatic definition of propagating wave components

There are many different types of surface wave and each can be defined by the guiding structure required. Two potential types of surface wave have been identified that may be useful for both civil and military applications, namely the Zenneck surface wave and the trapped surface wave.

Zenneck Surface Wave

The Zenneck surface wave is an inhomogeneous plane wave supported by a flat surface. It is a transverse magnetic (TM) mode and requires that the permittivities of the media either side of the interface are different but their permeabilities are the same³. It also requires an inductive reactance term in the surface impedance, Z_s for the medium it propagates along.

In order to excite a TM Zenneck surface wave, two conditions³ are required:

1. incidence close to the Brewster angle;
2. finite loss in one of the media.

Trapped Surface Wave

Trapped and quasi-trapped surface waves occur over (or in) a dielectric slab or dielectric coated conductors and can support both TE and TM surface waves. They can only exist when the ground is not homogeneous or is ideally stratified [pp. 99]⁴.

A trapped mode occurs when the angle of incidence from the dielectric medium to the air-dielectric interface is greater than the critical angle θ_c , defined by,

$$\sin \theta_c = \frac{1}{\sqrt{\epsilon}} \quad (1)$$

When the angle of incidence is at or greater than the critical angle total internal reflection will occur, with the field outside the dielectric decaying exponentially away from the interface [pp. 712-714]⁵.

WHY ARE SURFACE WAVES INTERESTING?

Surface waves have many interesting properties that could be of benefit to various applications. These include increased range due to the surface wave's bound nature and signal covertness. Additionally, by understanding the effect of the surface impedance one can gain greater insight into how these properties can be of use.

Increased Range

Potential Capability: Increased range for same power consumption, reduced power consumption for same range.

Surface waves are already utilised in some applications indirectly. For example, marine communication and terrestrial radio broadcast can both be received over-the-horizon. This is partly due to the sky wave but also due to the surface wave. If one could instead transmit all the power into the surface wave, it is expected that much greater ranges could be achieved.

Zenneck's 1915 book [pp. 249]⁶ states the range could be extended from $\frac{1}{r^2}$ to $\frac{1}{r}$ for a signal of the same power utilising surface waves. This relationship can be derived from Maxwell's equations, but does not necessarily take into account conductive losses in the medium. An example of this is Raytheon's HF Surface Wave Radar (HFSWR). Due to this increased range, it claims to be "one of the lowest operating costs per unit coverage area of all other radar types"⁷.

Covert Signal

Potential Capability: Covert communications, covert sensors

In addition to the increased range, surface waves are, by definition, non-radiating and therefore could be considered for covert systems. This assumes that a pure surface wave can be launched or that the space wave can be attenuated away rapidly close to the transmitter. Various design considerations may be able to achieve the latter methodology as some texts state that it is impossible to launch a pure surface wave. However, for real applications, simply ensuring that the majority of the power is transmitted into the surface wave should be sufficient.

The main problem that may be encountered is that when the signal travels over certain topologies it may be re-radiated (considered a loss mechanism) and some energy transferred back to the space wave. It is however, expected that the energy re-radiated will be small in each incidence that occurs.

Terrain Following

Potential Capability: Non-line-of-sight communication, over-the-horizon communication

Terrain following is the ability for the signal, or in this case an electromagnetic wave, to follow the topology of the Earth.

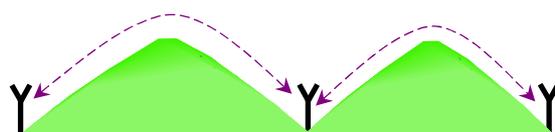


Figure 2 Antennas without line-of-sight communication

Due to the surface wave being bound to the interface, it should follow the terrain. By utilising a surface wave based system, one could ensure more signal power is transmitted to the desired location, following the terrain and not omni-directionally radiated when the space wave is diffracted. This results in the capability of non-line-of-sight communication. This could be useful over short distances due to local topology or over longer ranges, such as over-the-horizon communication (e.g. HFSWR).

The main limitation of terrain following will be the 'sharpness' of angle around which a surface wave can still remain bound to the interface. It is expected that some loss through radiation will occur when passing over different topologies and this loss will increase with its 'sharpness'. However, it is expected that this should not cause excessive loss as most natural topologies are relatively gradual or small compared to the wavelength at HF.

Two situations were modelled in HFSS, both of which had a smooth, shallow gradient of 108.5 degrees measured clockwise from the z-axis. In the first model (a) an imperfect ground plane with $Z_s=10+j50$ ohms was used. The second simulation (b) used a PEC ground plane and no surface wave should be present.

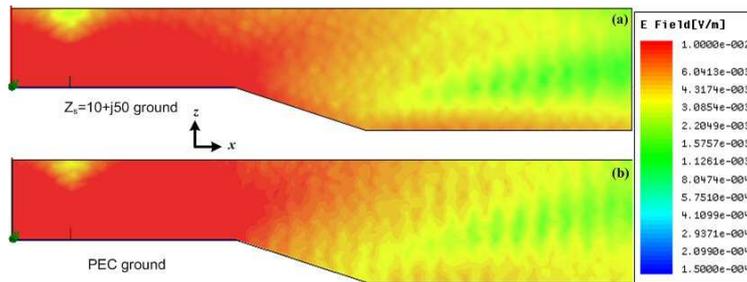


Figure 3 Terrain following showing total magnitude of electric field over (a) imperfect ground plane; (b) PEC ground plane

Figure 3 shows the magnitude of the total electric field and in both cases the wave front appears to follow the terrain; however there is more field present along the surface in Figure 3a, which has an imperfect ground plane. This could be due to the bound nature of the surface wave. To conclusively prove this, additional investigation needs to be completed. Nonetheless, these simulations are highly indicative that a surface wave is present and that terrain following is occurring.

Surface Impedance

The properties and thus surface impedance of the ground over which a surface wave is to propagate has a large impact on not only the ratio of surface wave to space wave launched, but also how much loss the wave is affected by and the possible range of the signal.

The surface impedance also defines how tightly bound the surface wave is to the interface and how quickly the space wave will attenuate away from the boundary.

The surface impedance is defined in terms of the surface resistance, R_s and reactance, X_s ,

$$R_s = \sqrt{\frac{\omega\mu_1 \left(\sqrt{\omega^2 \epsilon_1^2 + \sigma_1^2} + \omega\epsilon_1 \right)}{2(\omega^2 \epsilon_1^2 + \sigma_1^2)}} \quad (2)$$

$$X_s = \sqrt{\frac{\omega\mu_1 \left(\sqrt{\omega^2 \epsilon_1^2 + \sigma_1^2} - \omega\epsilon_1 \right)}{2(\omega^2 \epsilon_1^2 + \sigma_1^2)}} \quad (3)$$

where, ϵ_1 , σ_1 and μ_1 are the properties of the medium through which the surface wave will propagate and ω is the angular frequency.

Theory predicts that the higher the surface reactance, the faster the decay of the space wave away from the interface, whilst the more tightly bound the surface wave becomes. Therefore, a ground with a high reactance should exhibit better terrain following abilities.

A high reactance also results in a decreased surface wave spread outside of the surface increasing the energy within the surface wave region. This can be further enhanced by the fact that a high resistance increases the tilt of the wave. However, increasing the resistance also increases the attenuation of the surface wave. This implies that there is a trade-off with regards to the optimum surface impedance for production and propagation of a surface wave whilst minimising the space wave. It can be seen that a high reactance is desirable, however

depending on the application the desired resistance may vary. For short range applications, a high resistance may be preferable as more energy is directed into the surface wave region and the attenuation occurs with distance. Over larger distances a low resistance would be preferred to reduce this attenuation.

Skin Depth

Metallic ground planes are frequently used to optimise the propagation and launch of space waves, however this is not the best method for surface waves. As conductivity increases, the magnitude of the surface wave electric field decreases. Bound surface waves cannot exist in or over a perfect conductor (PEC) due to it having zero skin depth.

A surface wave requires an interface between two media as it exists partially in both. Therefore if the electric field is unable to penetrate into one of the media, a surface wave cannot propagate. This could therefore imply that the skin depth is proportional to the magnitude of surface wave produced and indirectly proportional to the magnitude of space wave produced with an exponential dependence. It is from this concept that the definition of the 'surface wave region' was derived.

Wave Tilt

The electric field, magnetic field and direction of propagation should all be perpendicular to each other under ideal circumstances; however, when there is a surface wave present there is a forward tilt in the electric field. The magnitude of this tilt depends on both the conductivity and permittivity of the medium over which the wave is propagating. This tilt can be calculated from the surface impedance equation [pp. 654]⁸,

$$\frac{Z_s}{\eta_o} = \frac{E_H}{E_V} = \frac{1}{\eta_o} \sqrt{\frac{\omega\mu}{\sqrt{\sigma^2 + \omega^2\epsilon^2}}} \angle \frac{1}{2} \tan^{-1}\left(\frac{\sigma}{\omega\epsilon}\right) \quad (4)$$

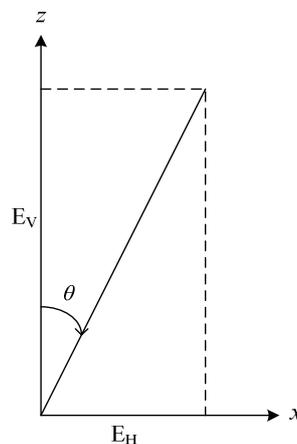


Figure 4 Diagram to show angle described in Equation 4

The arctangent of the magnitude part of Equation 4 represents the angle by which the E_H field component leads the E_V field component, as shown in Figure 4 and the wave tilt represented by θ . This implies that there will be a small but finite value of horizontal E component, which is given by the first part of Equation 4. Figure 5 shows by how much the horizontal component leads the vertical component over grounds with different properties.

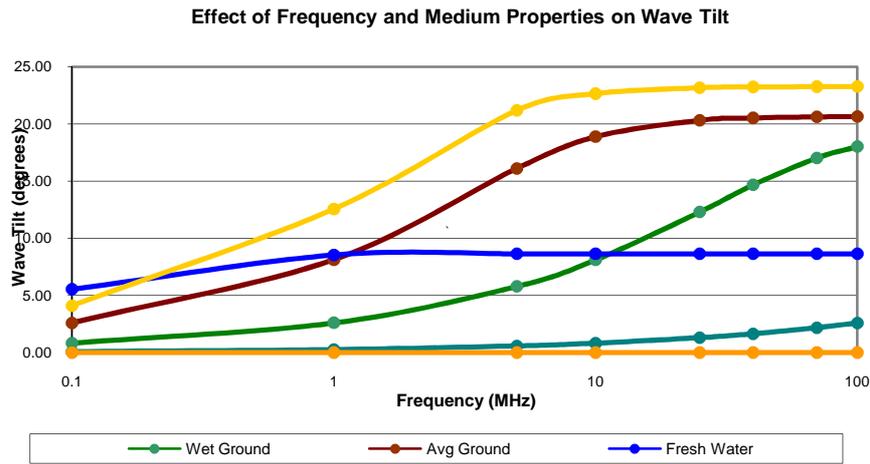


Figure 5 Effect of frequency on wave tilt for different ground properties

This result could be used to help identify the surface wave in both simulations and measurements. If it is known how much the electric field vector will tilt, and that the electric field is not perpendicular to the direction of travel, the vertical component of the Poynting vector should be non-zero. It also indicates that the surface wave is highly dependent on its frequency and the properties of the ground over which it propagates. Another implication of the wave tilt is that the resulting radiation will have elliptical polarisation, not linear (vertical) polarisation as given by the phasor part of Equation 4.

POTENTIAL APPLICATIONS

The following table summarises many of the potential applications of surface waves and why surface waves would benefit this application.

Potential Capability	Surface Wave Characteristics Assisting with Capability
Short range communications (e.g. between sensor nodes)	Signal covertness Terrain following over local topology (e.g. small craters/holes)
Long range communications / marine communications (e.g. over-the-horizon communications)	Increased range Terrain following
Buried object detection	Ground would be main region of propagation Potential increased range compared to space wave
Covert communications	Signal covertness
Surface wave radar (e.g. over-the-horizon radar)	Terrain following Increased range
Communication and sensing through pipes, tunnels, etc.	Terrain following Increased range
Ground water detection (e.g. agriculture)	Wave tilt depends on the ground properties

Table 1 Potential applications of a surface wave based technology

From the above table, one can see that a surface wave technology has diverse applications, from land-based to marine, military to civil. Each of these potential applications will have

different requirements and will therefore require the research to focus on a different area, e.g. for ground water detection in agriculture, loss through radiation will not be a major problem as covertness is not a concern, whereas with a covert military link, this could pose serious problems.

CHALLENGES

Perhaps the biggest challenge in this research is trying to isolate out the surface wave from the space wave. These two components are very tightly coupled and to date no rigorous methodology has been found. Two potential methodologies are discussed below, both of which have been attempted and show reasonable results.

NEC Methodology

This methodology uses various assumptions as to the regions where the space wave and surface wave are dominant and then uses this knowledge to interpret results from NEC. It was not detailed in the final report⁹ submitted to the DTC office in January 2008; however, it is contained within the conference paper presented at the DTC Annual Conference in June 2008¹⁰ and the Y1 Interim Report¹¹. This method is detailed in this section for completeness.

Using the knowledge that there should be no field present perpendicular to the direction of propagation one expects that there is no electric field in the E_r direction, which in this case is the direction of propagation. If there was a component of electric field in the direction of propagation, the wave would be in violation of its boundary conditions. Due to this fact, in the NEC simulations, the radial component of the electric field, E_r is taken to represent a TM surface wave (

Figure 6).

At $z=0$ m, E_r will be travelling in the direction of the wave parallel to the ground and therefore is considered to be the surface wave component. At 0 m height, E_r is equivalent to E_x in the near electric field (x -direction).

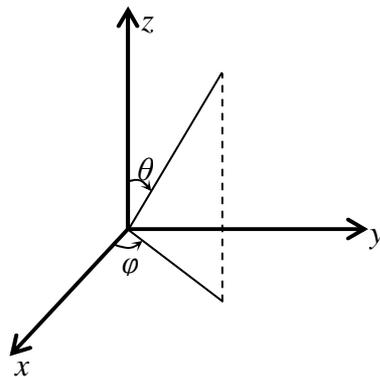


Figure 6 Diagram to show relationship between θ , ϕ and r in the far field [pp. 2]¹²

Figure 7 shows the field strength, E_r with respect to height at 1 km for a 75 m, 1 MHz quarter-wave monopole antenna with 1 V applied over a real (Sommerfeld) ground with properties $\epsilon_r=15$, $\sigma=0.05$ S/m.

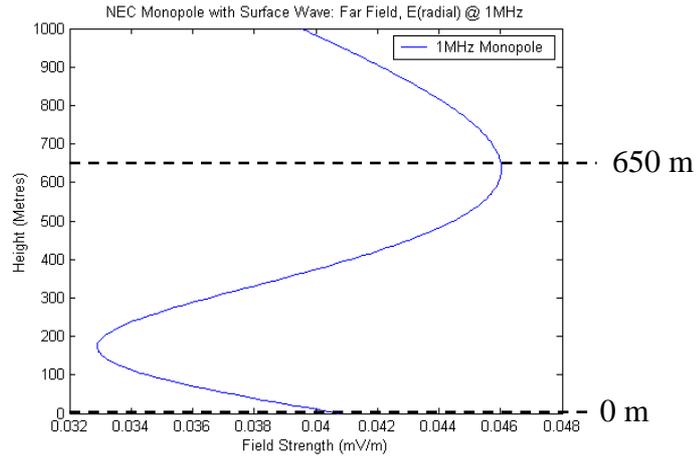


Figure 7 E_r for a 1 MHz Monopole simulated in NEC4

When one examines the NEC output graph, one sees that there is electric field present in the direction of propagation and one can therefore use this to assist with calculations of the expected surface wave magnitude at various heights above the interface. The second thing to notice in Figure 7 is that there is a maximum of field present at ~650 m. This peak is seen consistently at various distances from the transmitter and is also visible at other frequencies. It is therefore assumed that this peak must be due to a different propagation mode and this is taken to be where the space wave dominates as at larger z , the space wave component will have some E_r component due to the transmitter not being a point source, however further research will be required to conclusively prove this.

A height of 650 m was chosen to best represent when the space wave dominates; however, some surface wave will still be present even at this height, but in comparison to the space wave, its contribution is expected to be negligible.

This assumption is based on Barlow & Brown's book [pp. 5]² which states that the decay of the Zenneck surface wave with height is exponential. When the mathematics are examined one finds that the electric field of the surface wave, $E_{r,surface}$, is the tangential component of the surface wave,

$$E_{r,surface} = D \exp(-\gamma z) \exp(j\omega t) \quad (5)$$

where, γ is the propagation coefficient and z is the height. D can be considered to be a constant if,

- $E_{r,surface}$ is measured at a constant distance from the antenna (i.e. $r=1$ km);
- The wave is propagating through a homogeneous isotropic medium (i.e. γ is constant for all locations)

Therefore as D does not depend on height,

- only the magnitude of $E_{r,surface}$ is considered;
- only the real part of γ is taken (i.e. attenuation coefficient, α);
- the sinusoidal time variation can be suppressed (i.e. $t=0$),

Using the above assumptions and setting $z=0$ m gives,

$$E_{r,surface} = D \quad (6)$$

Using the value obtained in NEC4 for a real ground ($\epsilon_r=15$ and $\sigma=0.05$ S/m) at $z=0$ m and $x=1$ km,

$$|\mathbf{D}| \sim 4 \times 10^{-5} \quad (7)$$

The attenuation coefficient can be calculated from the Equations in the Equations in Griffiths [pp. 38, eq. 2.10]¹³.

Therefore, if we substitute $z=650$ m and $\gamma=\alpha=0.188$ into (5),

$$|E_{r,surface}| \sim 10^{-58} \text{ V / m} \quad (8)$$

This implies that the magnitude of the surface wave does not contribute to the peak seen at $z=650$ m (Figure 7).

Field Subtraction Methodology¹⁴

It is known that the surface wave is non-radiating. In theory, the radiation pattern produced by the simulation software should only take into account the space wave and not the surface wave. If one subtracts the magnitude of the radiation field pattern from the full field pattern, the resultant field should be only the non-radiating component, i.e. the surface wave. This technique can be applied to the field patterns in both HFSS and NEC.

As an alternative, one can use the knowledge that over a PEC ground, no surface wave will propagate, however if a real ground is used with finite conductivity a surface wave is present. A field subtraction technique was therefore used, whereby the field results from a PEC ground were subtracted from those above a real ground.

Both of these techniques have been trialled with varying degrees of success in HFSS, and more promising results in NEC.

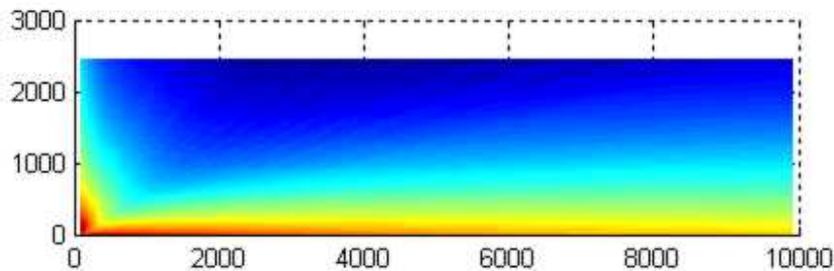


Figure 8 Subtraction of radiation pattern from total electric field in NEC for wet ground

Figure 8 shows the results when the radiation pattern is subtracted from the total electric field in NEC2 over a ‘wet ground’ simulated ground. This, in theory, should only leave the surface wave component, and one can see that it decays with distance as expected.

SUMMARY

From the research performed so far, it appears that surface waves could be of great benefit to a broad range of applications, from agriculture to defence, communications to radar. All in all, a surface wave system could be of great benefit if realised.

However there are still some challenges to overcome before it will be possible to utilise surface waves with the main one being isolating it. Some good progress has been made, however the analysis done to date is qualitative and ideally this should be rigorous before concluding the research. Using HFSS as a simulator as oppose to NEC has not been as easy

as first hope with several limitations in the software identified early, namely it can be resource hungry requiring a relatively powerful computer (64-bit processor, 16GB RAM) and up to an hour simulation time per model. NEC however has already proved it is very limited and has displayed incorrect results making the software use hard to justify. Nonetheless, it is felt that it is possible to still make progress with the tools at hand when driven correctly.

Looking forward, it is hoped that some breakthroughs will occur during the next phase of research, helping towards our goal of having a potential design by the end of 2011.

ACKNOWLEDGEMENT

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