# On sporadic E VHF propagation and solving a mystery about maximum usable frequencies – Part 1

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The classical model of Es propagation can support maximum usable frequencies above 144 MHz, but only rarely. How, then, to explain the frequent reports, worldwide, of VHF propagation with high maximum usable frequencies (MUFs)? This paper demonstrates, for the first time, that this propagation likely occurs by means of *petit chordal hop* in a disturbed Es layer, and outlines another possible high-MUF mode – *layer trapping*.

An outline version of this article was posted on the VK Logger's *Propagation & Solar Cycle News* forum on 17 March, 2011. Without the facility of the VK Logger, the research behind it would have been much more difficult and lengthy, if not impossible. For that, we have Adam Maurer VK4CP to thank. He is the developer and maintainer of the VK Logger (www.vklogger.com).

## Introduction

There has been much comment, discussion and speculation over decades on the whys and wherefores of sporadic E (Es) propagation at VHF. Given that it is an ionospheric mode, just how Es supports propagation at frequencies into the mid-VHF range and higher has puzzled amateurs and scientists alike and led to some interesting speculation on occasions.

Sporadic E contacts between amateurs on the 50 MHz band have been commonplace for many decades. With the proliferation of amateurs operating on 144 MHz in countries the world over, reporting of contacts via sporadic E has burgeoned over the last 20 years. It is almost 50 years since I first experienced Es DX on 6 m and 2 m, 40 years since I first researched ionospheric sporadic E and VHF propagation.

Sporadic E has been denoted as Es in the scientific and technical literature for more than 70 years. Writing it with an apostrophe – E's – is unnecessary. When speaking of sporadic E, the term is pronounced "ee ess", NOT "eez". End of soap box session.

In my early career, during the 1970s, I worked in a senior technical position at the Australian IPS Radio and Space Services (IPS) for some seven years. I learned a lot about the ionosphere and ionospheric radio propagation. I learned to interpret and scale ionograms (read off the parameters). I worked in transequatorial VHF propagation research and ionosonde technology, among other things, and pursued my interest in sporadic E in my own time, with the encouragement of colleagues at IPS. I have trawled through and scaled many thousands of ionograms, recorded on 35 mm and 16 mm film in that era. When I rekindled my interest in sporadic E in recent years, all this experience came in handy.

Es propagation on 50 MHz (and 70 MHz in Europe) is generally considered to be via conventional ionospheric propagation mechanics. The simple geometry you learned about when studying for your licence exam. But many amateurs are sceptical of or do not believe this could hold up at 144 MHz (or even 100 MHz in the FM broadcast band). Or if it did, such events would be extremely rare. But reports of widespread 144 MHz Es DX over decades are now so numerous as to confound that [1], while the observations of Pocock and Dyer on the 88-108 MHz FM broadcast band are legion [2]. So what is happening?

With the advent of the VK Logger for reporting VHF propagation, and the availability of IPS ionograms online [3], I have been able to scrutinise VHF propagation paths where the mid-points are located within 'view' of an ionosonde as this enables direct modelling of the propagation geometry and its relation to ionospheric conditions. The results have been both 'as expected' and delightfully surprising!

Mid-latitude sporadic E consists of thin, dense layers of ionisation formed by wind shears in the E-region that compress long-lived metallic ions into horizontal clouds or 'patches' from less than one km to about five km thick, appearing at heights ranging generally between 90 and 130 km altitude. Patches may be only 100 m across, with clouds up to 1000s of km in extent [4, 5, 6].

Many amateurs confuse the E-region (often called the E-layer, but it is not really a layer, being 40 km thick) and sporadic E, as if the latter is an "extension" of the E-region. It is not. It is more akin to a thin, horizontal sheet of gelatin floating within a column of water. That is, a sporadic E layer is a "stranger", or "foreigner", appearing in the E-region. The ions within a sporadic E layer are long-lived metallic ions, principally iron ($Fe^+$) and magnesium ($Mg^+$), while the ions in the E-region are generally oxygen ($O^+$), nitrogen ($N^+$) and nitric oxides ($NO_X$), which dissipate at night. The electron density (electrons/$cm^3$) in sporadic E generally exceeds that in the E-region by many times, and the peak Es electron density can exceed that in the F-region by many orders of magnitude.

I have found that VHF propagation by sporadic E occurs by at least two principal modes:

(a) conventional ionospheric reflection ("classical") by a thin, 'plane' Es layer, and
(b) by successive reflections via the crests of ripples or other structures in an Es layer that subsequently returns the raypath to Earth – which I call *'petit chordal hop'*.

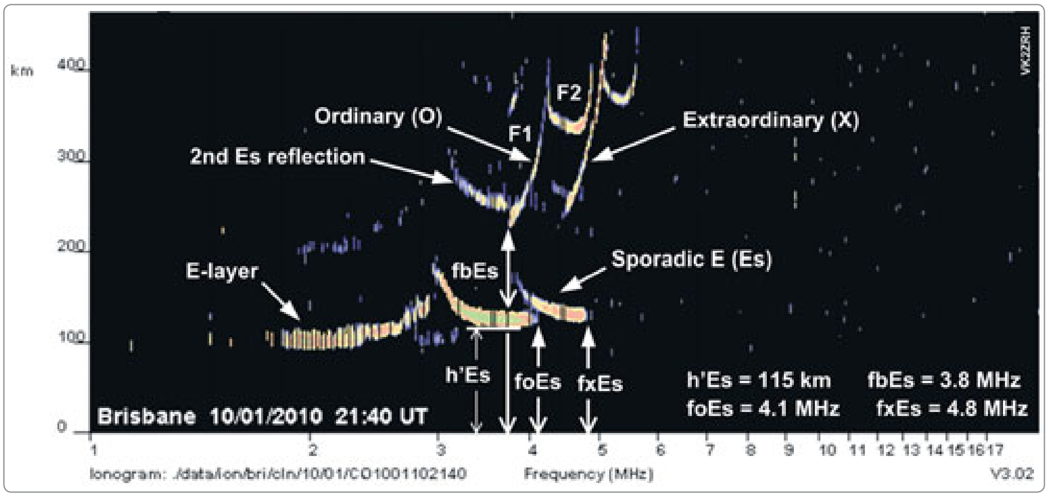


*Figure 1: Vertical incidence ionogram with various key features marked. The ordinary (O) and extraordinary (X) ray reflections are clearly seen, O to the left, X to the right. The ordinary ray penetration frequency of the Es layer, foEs, is a measure of the peak electron density. The Es layer is 'blanketing' the F1 layer below 3.8 MHz (denoted as fbEs).*

In each case, I can demonstrate that the well-established propagation geometry and ionospheric science can be applied to analyse and model the propagation and the maximum usable frequency for a path. Mode (b), petit chordal hop, nearly doubles the MUF for a path, yielding MUFs to at least 230 MHz with intense Es. However, there may be a third propagation mode, that I have dubbed *'layer trapping'*, and capable of supporting even higher MUFs, which I will discuss later.

Before going into the details of the models for these propagation modes, it is first necessary to understand something about sporadic E as seen on vertical incidence (VI) ionograms.

## Es on ionograms

VI ionograms are produced by swept frequency, pulsed RF HF radars with antennas pointed straight up. The echoes returned from the various regions of the ionosphere are displayed on a graph of height versus frequency. Figure 1 is a fairly typical summer morning ionogram for Brisbane, showing the E, F1 and F2 layers and sporadic E [3]. I have marked the various features. The ordinary (O) and extraordinary (X) reflections are clearly seen, O to the left, X to the right. The 'split' reflections result from the effect of the Earth's magnetic field on RF propagation in the ionosphere. The E, F1 and F2 echoes curve upwards to a cusp as frequency increases due to group retardation of the signal near the peak electron density. The Es traces do not curve up as the layer is very thin and the ionosonde resolution is insufficient to resolve it. Note the multiple reflections. After the first return, the others are from repeated ground-ionosphere-ground echoes.

The ordinary ray penetration frequency, or foEs, is important because it is a measure of the layer's peak electron density. The Es virtual height, or h'Es, plays a key role in determining the propagation path distances and, in conjunction with foEs, the MUF of the path.
The extraordinary ray penetration frequency, fxEs, is 0.7 MHz higher than foEs. The difference (called the 'split') is half the gyrofrequency (fH), the natural 'spin rate' of electrons in the ionosphere, which is 1.4 MHz at Brisbane [7]. Hence, fxEs – foEs = 0.7 MHz.

## The ionosonde 'view'

IPS ionosonde antennas are upward pointing crossed-deltas (many ionospheric stations use these antennas). They have a half-power beamwidth of about $90^{\circ}$ through the mid-HF range, narrowing to about $60^{\circ}$ above 10 MHz.

As illustrated in Figure 2, when Es is present, the antenna system "illuminates" an area with a radius equal to the height of the Es layer (also referred to as "whole sky" illumination) and the receiver will respond to returns from within the entire area covered. If h'Es is 100 km, the view radius is 100 km. At the narrower beamwidth, the radius of the circle illuminated is about 58% of that for the wider beamwidth. Nevertheless, the ionosonde receiver responds to echoes across the whole area, particularly when the Es has ripples or other structures within it.

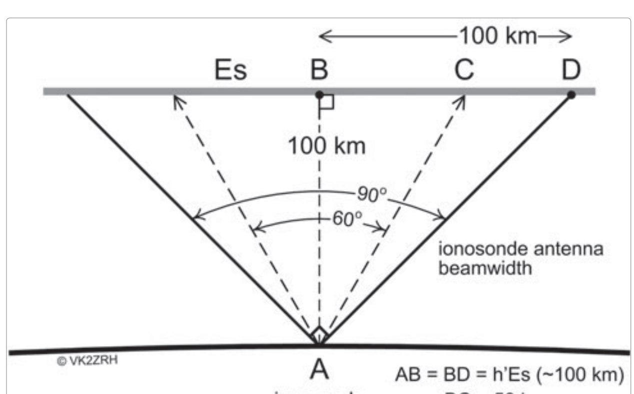


*Figure 2: Vertical elevation, showing geometry of the ionosonde 'view' of a sporadic E layer (not to scale). As shown, if h'Es is 100 km, the antenna system illuminates a circle of 100 km radius (BD). If h'Es is 115 km, then the view radius is 115 km.*

## Ionograms of particular interest

Figure 3 is an ionogram showing Es typical of a flat (or 'plane'), thin, dense layer over Brisbane. Note the multiple reflections. No F-layer echoes can be seen, so the Es is said to be fully blanketing. The virtual height of the first return is 110 km, and it ceases at the 'top' penetration frequency, denoted as ftEs, which is 9.6 MHz. To determine foEs from an ionogram like this, ftEs is generally assumed to be fxEs, and foEs is found by subtracting half the gyrofrequency. So in this instance, ftEs – 0.7 MHz = foEs= 8.9 MHz.

Figure 4 is another ionogram, this time showing "spread" Es. The spreading of the Es traces likely arises from crinkles, ripples or other structures in the Es layer, which reflect the transmitter pulses from varying ranges at oblique angles, as well as from directly overhead, perhaps at different heights. Group retardation also contributes to the spreading. Note that the Es trace extends off-scale at 20 MHz and only partially blankets the F-layer. Spread Es is a common phenomenon.

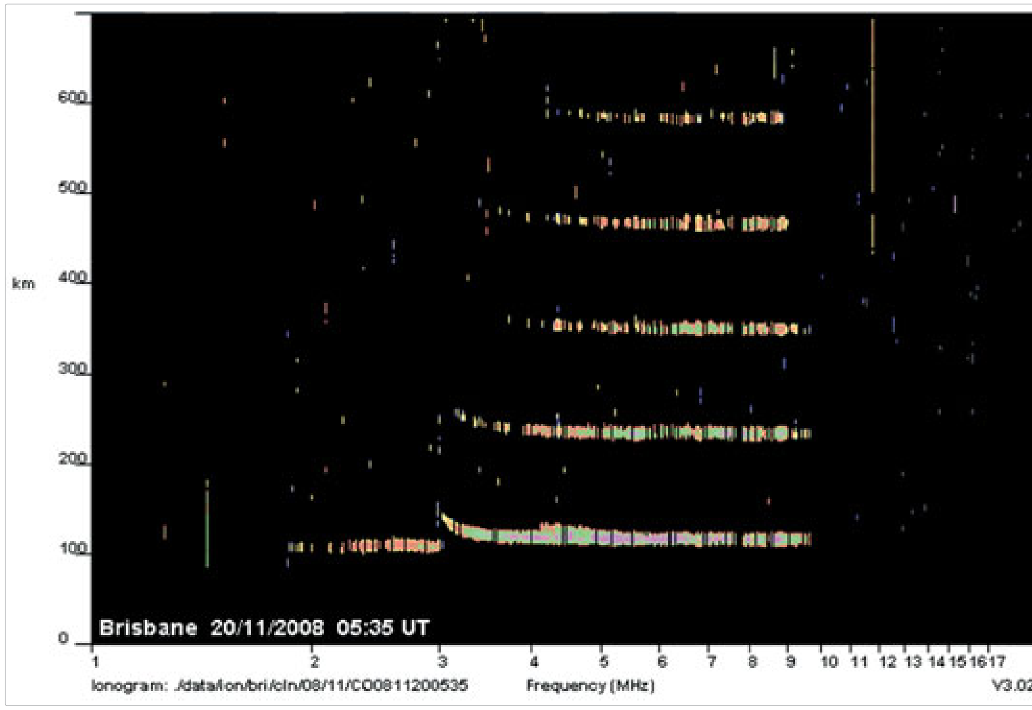


*Figure 3: Ionogram showing a dense, totally reflecting plane Es layer at 110 km, having a high value for ftEs of 9.6 MHz. Hence, foEs here is 8.9 MHz.*

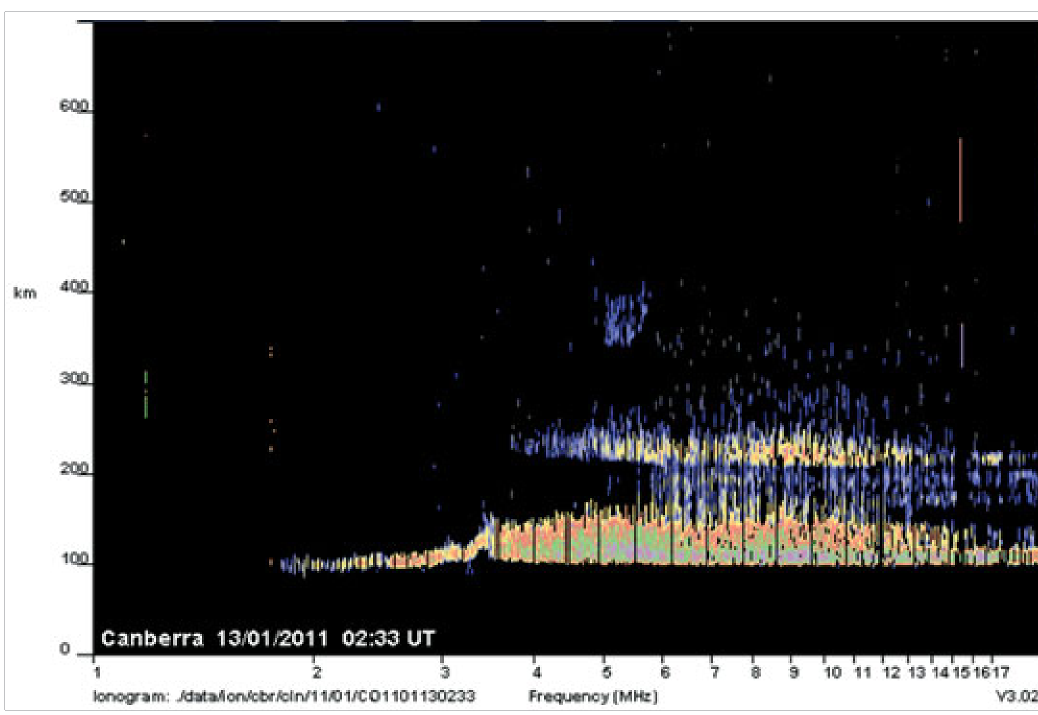


*Figure 4: An example of "spread Es". The first F-layer echo is mid-image; fbEs is 5 MHz. Lowest virtual height, h'Es, is 99 km. The top frequency is above 20 MHz, so peak electron density is very high.*

## VHF propagation via a thin, 'plane' Es layer

The geometry of a propagation path via plane Es is illustrated in Figure 5. A plane Es layer lies parallel to the Earth's surface, not tilted across its extent or having ripples or other structures in it (no lumpy bits!).

The raypath of a signal from a transmitter at A, at an angle (e) above ground, travels towards the Es layer, is refracted towards the ground at P and received at B. The common convention refers to this as reflection. Here, (*i*) is the angle between the incident raypath and the vertical line through P, while (*r*) is

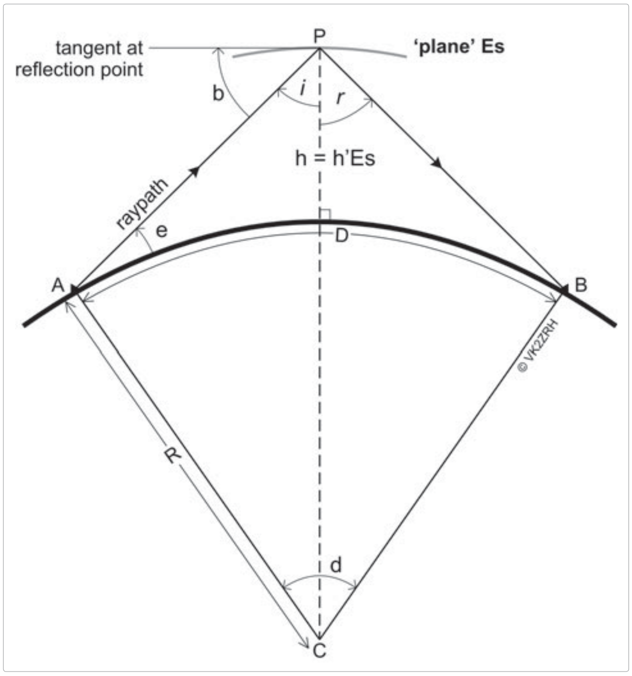


*Figure 5: Geometry of propagation via plane Es (exaggerated scale). R is the radius of the Earth. D is the distance over the Earth's surface between A and B. The line from C to P is at right angles to the Earth's surface and has a length of R + h. Angle (b) = 90 – (i).*

the angle between the vertical and the emerging raypath. Angle (e) is the raypath elevation angle, while angle (b) is that between the incident raypath and a tangent to the reflection point at P, which is a horizontal line. These angles are important in determining the MUF for a path.

In *Ionospheric Radio* [8], author Davies sets out the relationships for propagation in a thin layer in a series of very useful equations.

$$f_{OP} = foEs.sec(i) \qquad (1.0)$$

where $f_{OP}$ is the usable operating frequency, and
foEs the measured ordinary ray vertical incidence penetration frequency at P
sec(*i*) is the secant of the angle of incidence

This is the well-known "secant law" relationship, from which the "classical MUF" can be evaluated. The secant of an angle varies from 1.0 at $0^O$ to infinity at $90^O$. So you can see immediately that the larger the incident angle, the greater the usable operating frequency for a given value of foEs. There is a maximum value for (*i*), which is reached when the raypath elevation angle is tangent to the Earth, ie. angle (e) = $0^O$. Triangle CAP is now a right angle triangle. Hence, sin(*i*) = CA/CP. The length of CA is R, while CP is R+h, so we can find the maximum of angle (*i*) as follows:

$$(i)_{MAX} = \arcsin\left[\frac{R}{(R+h)}\right] \qquad (1.1)$$

The term 'arcsin' means the angle (in degrees) for this numeric value of sine.

When (e) is $0^O$, this sets the maximum (theoretical) one-hop range or path distance, expressed as:

$$D_{MAX} = \sqrt{8Rh} \qquad (1.2)$$

This situation also sets the maximum possible usable frequency, expressed as:

$$f_{MAX} = foEs\sqrt{\left(1 + \frac{R}{(2h)}\right)} \qquad (1.3)$$

These three equations cover the "limiting case", where (e) = $0^O$. Equation 1.3 gives us the MUF for the limiting case. Clearly, the height of the Es layer (h'Es = h) is important to all these relationships, so all the critical parameters of Es propagation are determined by foEs and h'Es. For a given value of foEs, the maximum path distance and $f_{MAX}$ vary directly with the Es layer height, as shown in Table 1. The mean radius of the Earth used in the calculations is 6371 km [9].

| foEs | h'Es (km) | $D_{MAX}$ | Angle (i) | $f_{MAX}$ |
|---|---|---|---|---|
| 9 MHz | 90 | 2141.8 | 80.43 | 54.2 |
| | 100 | 2257.6 | 79.91 | 51.5 |
| | 110 | 2367.8 | 79.43 | 49.2 |
| | 120 | 2473.1 | 78.97 | 47.2 |
| | 130 | 2574.1 | 78.52 | 45.4 |

*Table 1: Es propagation parameters for the limiting case, where angle (e) = $0^O$. Indicative values of $f_{MAX}$ are derived for foEs of 9 MHz. Note how $D_{MAX}$ and $f_{MAX}$ vary with h'Es.*

Achieving a raypath elevation of $0^O$ is generally impractical, but many Es propagation paths occur at remarkably low angles, often in the range 1-$3^O$. VHF antenna radiation patterns in the vertical plane may show low responses at such angles compared to the peak gain elevation angle, but the response is not zero. Remember that aircraft enhanced propagation on long paths (eg. 500+ km) occurs at angles below $1^O$, for example.

For path geometries other than the limiting case, that is, generally 'usual' circumstances, a little trigonometry provides the following equations for determining (*i*) and D:

$$(i) = \arcsin\left[\frac{R}{(R+h)}\sin(90+e)\right] \qquad (2.1)$$

$$D = \frac{2R}{57.3}\left[(90-e)-i\right] \qquad (2.2)$$

The MUF is determined by the secant law:

$$MUF = foEs.sec(i) \qquad (2.3)$$

Knowing foEs and h'Es at a path mid-point, and thus being able to derive angle (*i*), sec(*i*) is referred to as the "M factor" (multiplier), for obvious reasons. To make life easier in determining the MUF, it is more convenient to deal with the more familiar sine and cosine trigonometric functions, which are 'standard' functions on scientific calculators and in printed tables of sin, cos and tan values. The secant of an angle is the inverse of its cosine, so 2.3 can be rewritten as:

$$MUF = \frac{foEs}{\cos(i)} \qquad (2.4)$$

As angle (b) is the complement of (*i*) [that is, 90 – (*i*)] and sine is the complement of cosine, 2.4 can be rewritten as:

$$MUF = \frac{foEs}{\sin(b)} \qquad (2.5)$$

Thus, the M factor can be evaluated from either 1/cos(*i*) or 1/sin(b).

$$\text{M factor} = \frac{1}{\cos(i)} = \frac{1}{\sin(b)} \qquad (2.6)$$

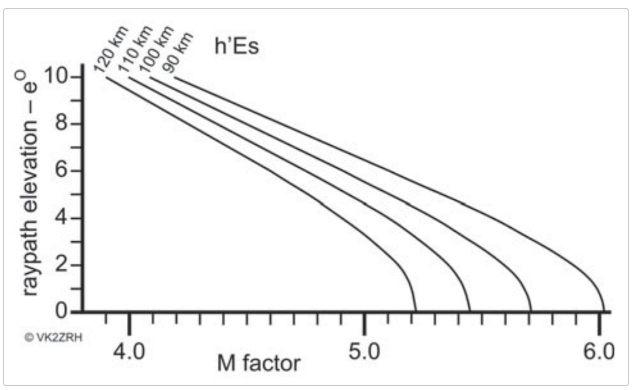


*Figure 6: How the M factor varies with the raypath elevation angle and height of a plane Es layer.*

The relationship between the raypath elevation angle (e) and the M factor is non-linear, with a different curve for different Es layer heights, as illustrated in Figure 6. Es layers at the lower heights yield a higher M factor and thus higher MUFs. A lower raypath elevation angle, with longer paths, rapidly improves the M factor, but angles below 2° experience a flattening of the M factor increase in all cases.

Table 2 illustrates the MUFs achievable for a variety of ionospheric and path parameters. The range of h'Es values here are commonly observed on ionograms (e.g. Figures 3 and 4) and the path lengths are generally typical, at least in the Australasian-South Pacific region. A column listing foEs values for a 98 MHz MUF, in the middle of the FM broadcast band is included as this band is widely used as a propagation indicator. For Es propagation at 144.5 MHz, note that foEs needs to be above 24 MHz for elevation angles up to 4° or 6°. I have personally observed such values of foEs on ionograms when 'sondes swept 1-30 MHz (1950s-70s era). Indeed, I have seen ionograms with *off-scale* Es (at 30 MHz) from that era. However, while memorable, they were not common. Instances of off-scale Es (at 20 MHz) on present era ionograms are readily found among the online displays of the IPS network stations [3].

Figure 7 sums up the case for the geometry of VHF propagation via plane Es. As Es is very thin compared to its altitude, the trigonometry is much simpler than that employed for F-layer propagation and parallels optical reflection from a mirror.

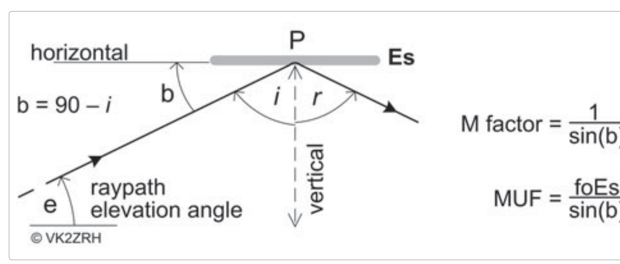


*Figure 7: Close up of the geometry for propagation via plane Es.*

| h'Es | (e) | (*i*) | D (km) | M factor | MUF for foEs of | | foEs for MUF[3] (MHz) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 9 MHz | 20 MHz | 50.5 | 98.0 | 144.5 |
| 90 km | 1 | 80.37 | 1919.1 | 5.98 | 53.82 | 119.6 | 8.5 | 16.4 | 24.2 |
| | 2 | 80.22 | 1730.1 | 5.89 | 53.01 | 117.8 | 8.6 | 16.7 | 24.6 |
| | 4 | 79.63 | 1416.5 | 5.56 | 50.04 | 111.1 | 9.1 | 17.7 | 26.0 |
| | 6 | 78.72 | 1174.1 | 5.11 | 45.99 | 102.2 | 9.9 | 19.2 | 28.3 |
| | 8 | 77.55 | 989.6 | 4.64 | 41.76 | 92.8 | 10.9 | 21.2 | >30 |
| 100 km | 1 | 79.87 | 2030.3 | 5.69 | 51.21 | 113.8 | 8.9 | 17.3 | 25.4 |
| | 2 | 79.72 | 1841.3 | 5.6 | 50.4 | 112 | 9.1 | 17.5 | 25.8 |
| | 4 | 79.16 | 1521 | 5.32 | 47.88 | 106.4 | 9.5 | 18.5 | 27.2 |
| | 6 | 78.28 | 1271.9 | 4.92 | 44.28 | 98.4 | 10.3 | 20.0 | 29.4 |
| | 8 | 77.15 | 1078.5 | 4.5 | 40.5 | 90 | 11.3 | 21.8 | >30 |
| 110 km | 1 | 79.38 | 2139.2 | 5.42 | 48.78 | 108.4 | 9.4 | 18.1 | 26.7 |
| | 2 | 79.24 | 1948 | 5.36 | 48.24 | 107.20 | 9.5 | 18.3 | 27.0 |
| | 4 | 78.71 | 1621.1 | 5.11 | 45.99 | 102.2 | 9.9 | 19.2 | 28.3 |
| | 6 | 77.86 | 1365.4 | 4.76 | 42.84 | 95.2 | 10.7 | 20.6 | >30 |
| | 8 | 76.77 | 1163 | 4.37 | 39.33 | 87.4 | 11.6 | 22.5 | >30 |

*Table 2: MUFs achievable via plane Es for common path geometry parameters and two indicative values of foEs, plus foEs values required for propagation on 6 m, the FM BC band and 2 m. Note how relatively small changes in h'Es and path elevation angle (e) affects the MUF.*

## A case study of plane Es VHF propagation

Figure 8 shows a path between VK4 and VK7 where the path mid-point passes within the view of the Canberra ionosonde at Es heights. The mid-point, and likely point of reflection, is marked PoR. Scott VK4CZ frequently spots this 50.057 MHz beacon on the VK Logger with RST reports ranging from 419 through 599. Figure 9 is the ionogram nearest to the time of one such spot – 2304 UTC on 2/01/2009. Here, ftEs is 10.2 MHz. As fH is 1.6 MHz at Canberra [7], foEs would be 10.2 – 0.8 = 9.4 MHz. As the path length is known, the elevation angle (e) is calculated to be 2.6°, and angle (*i*) to be 79.98°. Hence, angle (b) is 10.02°. Thus, MUF = 9.4/sin(b) = 9.4/0.17399 = 54.026 MHz. We can be confident that it was Es within the Canberra 'sonde's view that supported the propagation on this occasion as the VK7RAE signal raypath to the north of the PoR passes below the Es layer at the latitude of the Sydney 'sonde by at least 15 km. A raypath from VK7RAE slightly lower than 2.6° would be reflected from the Es layer in the Sydney 'sonde's view, but make landfall some 100 km north of VK4CZ (in the sea!).

End Part 1.

This article will be concluded in an upcoming issue.

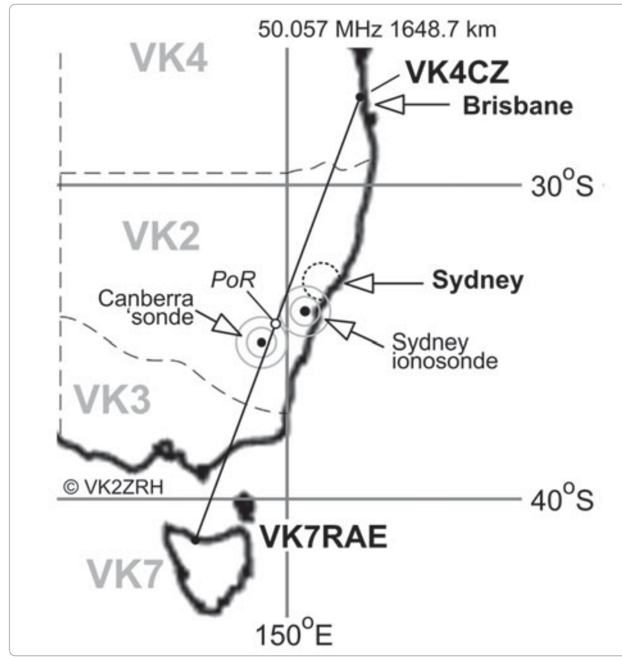


*Figure 8: The path between the VK7RAE 50.057 MHz beacon at Devonport and VK4CZ on the north side of Brisbane. The circles around the two ionosonde locations show each ionosonde's view at Es heights; they don't quite overlap.*

### References


[1] Kraft, J. DL8HCZ/CT1HZE 2008, "Midlatitude Sporadic E on VHF in Correlation to the 22-year Magnetic Cycle of the Sun", DUBUS Technik 8.

[2] Pocock, E. and Dyer, P.J. 1992, "Eleven Years of Sporadic E", QST, March, pp23-28.

[3] *www.ips.gov.au/HF_Systems/1/3*

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[8] Davies, K. 1990, "Ionospheric Radio (IEE Electromagnetic Waves Series, Vol. 31)", P. Peregrinus, London, ISBN 10 086341186X; chapter 6, Oblique propagation.

[9] *http://en.wikipedia.org/wiki/Radius_of_earth*

[10] *www.vklogger.com/beacon.php*


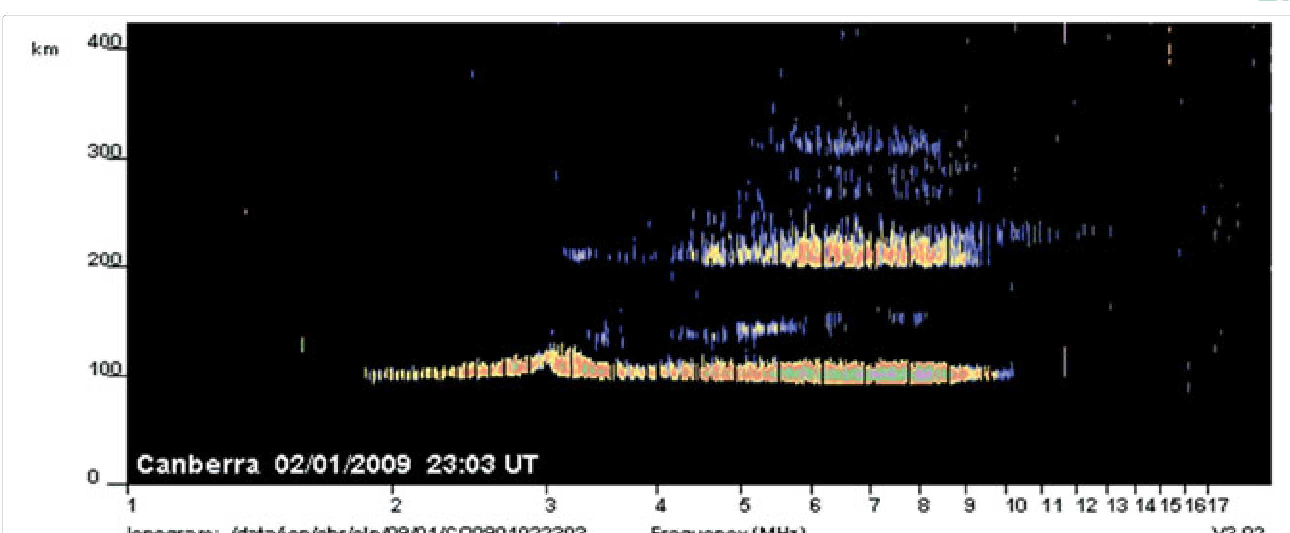


*Figure 9: Ionogram for the VK7RAE (beacon) spot by VK4CZ on 2304 UTC 2/01/2009. The beacon runs 20 W to crossed dipoles [10]. RST was 549. h'Es is 92 km. ftEs is 10.2 MHz. An echo from another Es cloud at a large oblique angle (44°!) is evident. Path length is 1648.7 km.*