# Interpreting Digital Ionograms

## Using modern digital ionosonde ionograms for understanding real-time propagation conditions

FIGURE 1: A modern portable Digisonde, with screen showing an ionogram.

**INTRODUCTION.** Ionograms show the heights of different layers in the ionosphere at different frequencies, measured using ionospheric sounding techniques. We are all more or less familiar with HF radar and, interestingly, ionospheric sounders use the same basic echo principles. The main differences between these two radars are range and type of object detected. Considering digital ionosondes (Digisondes), the information provided by sounders enables communicators to design radio systems, choosing frequencies and times of operation more effectively.

Sweep-frequency ionospheric sounding equipment was first developed more than 50 years ago. Originally the technology only utilised analogue techniques. In the early 1980s, the next logical step was taken in exploiting the inherent speed capabilities in digital processing techniques. Combining a general computer with a specialised RF processor, a Digisonde was created. It now had the capability of real-time data analysis and display by processing the numerical description of signal returns as they varied with range and frequency. **Figures** 1 and **2** show a modern portable Digisonde and aerial.

**IONOSPHERIC REGIONS AND LAYERS.** The ionosphere, a term first used by Sir Robert Watson-Watt, was defined as, "that part of the atmosphere in which free ions exist in sufficient quantities to affect the propagation of radio waves". The ionosphere is accepted as existing from approximately 31 miles (50km) to as high as several earth radii. There are three commonly known sections of the ionosphere called the D, E and F regions occurring at heights of 31 to 56 miles (50 to 90km), 56 to 87 miles (90 to 140km) and above 65 miles (120km), respectively. (The regions are not clearly defined and merge with one another). These regions can also be divided into smaller layers of ion distributions, with the E region occasionally showing E1, E2 and Es layers while the F region divides into F1, F1½ and F2 layers.

The F1 layer has a maximum between 160 and 180km, exists only in the presence of sunlight and has a maximum density at local noon. The F2 layer peaks between 200 and 600km, depending on factors such as time of day, season, phase of solar cycle, neutral winds, ion composition, etc. Due to the low densities of these altitudes, recombination (electron/s + ion = neutral) is very slow; the ionisation exists for many hours following sunset. The F1½ layer occurs sometimes after eclipse events, but rarely under normal conditions.

The F2 layer is the most important layer for radio communications, since it generally has the largest electron densities and, therefore, reflects the highest frequencies. It is found at the greatest height and, therefore, results in the largest possible 1-hop distance.

Some claims have been made for the existence of two other regions: C and G. The C region is thought to exist at the bottom edge of the D region, approximately 60km up, and is formed by cosmic rays and is therefore always present (since impinging cosmic rays are always present). The G region appears on ionograms as a little kink during a storm when the critical frequency of the F2 layer is greatly diminished. It's possibly not a distinct region but rather a phenomenon that occurs only at special times **[1]**.

**BASIC IONOSONDE THEORY.** The path of a radio wave is affected by any free charges in the medium through which it is travelling. The refractive index (the ratio of the phase velocity in free space to the phase velocity in the medium) is governed by the electron concentration and the magnetic field of the medium as well as the frequency and polarisation of the transmitted wave. These lead to some important properties for waves propagating in the ionosphere.

- The refractive index is proportional to the electron concentration.
- The refractive index is inversely proportional to the frequency of the transmitted wave.
- There are two possible ray paths depending on the sense of polarisation of the transmitted wave. This is a result of the magnetic field, which causes the ionosphere to be birefringent (or double refraction, is the decomposition of a radio wave into two rays when it passes through the ionospheric medium). The two rays are referred to as the ordinary and extraordinary components. To explain this, let's look at the special case of vertical propagation. For a vertically propagated signal, when the effects of the Earth's magnetic field are included, we set the refractive index result ($\mu$) to zero and solve the Appleton equation (not given here, although it is easily seen on the Internet). As there is a ± in the equation, there are two possible solutions – one for the ordinary ray and the other for the

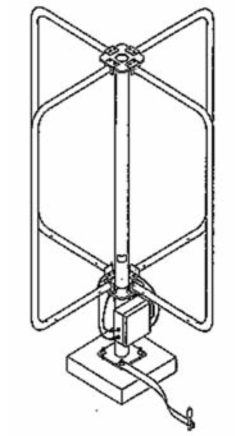


FIGURE 2: The aerial that accompanies the equipment in Figure 1.

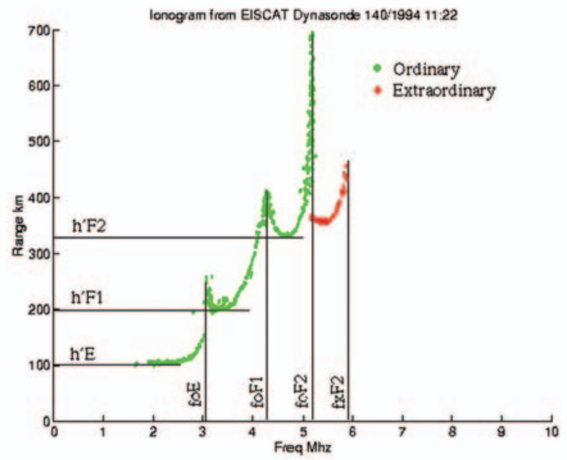
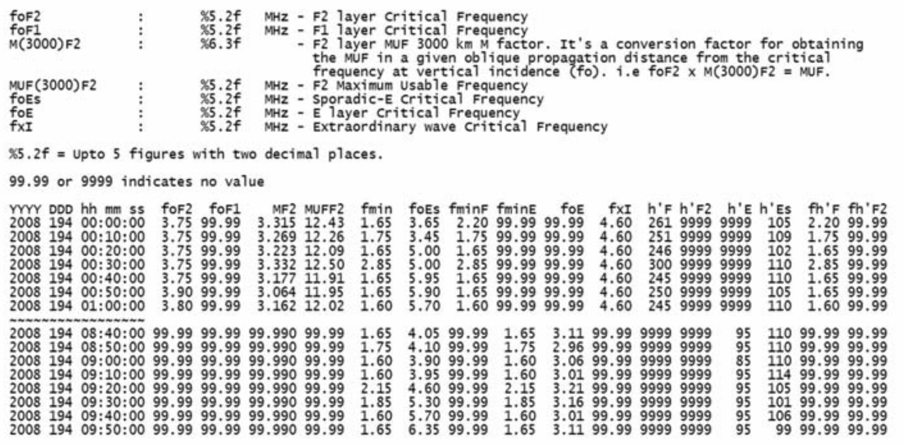


FIGURE 3: Typical ionogram from the Eiscat Dynasonde (Digisonde).



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foF2          :       %5.2f   MHz - F2 layer Critical Frequency
foF1          :       %5.2f   MHz - F1 layer Critical Frequency
M(3000)F2     :       %6.3f       - F2 layer MUF 3000 km M factor. It's a conversion factor for obtaining
                                    the MUF in a given oblique propagation distance from the critical
                                    frequency at vertical incidence (fo). i.e foF2 x M(3000)F2 = MUF.
MUF(3000)F2   :       %5.2f   MHz - F2 Maximum Usable Frequency
foEs          :       %5.2f   MHz - Sporadic-E Critical Frequency
foE           :       %5.2f   MHz - E layer Critical Frequency
fxI           :       %5.2f   MHz - Extraordinary wave Critical Frequency

%5.2f = Upto 5 figures with two decimal places.

99.99 or 9999 indicates no value

YYYY DDD hh mm ss  foF2  foF1    MF2 MUFF2  fmin  foEs fminF fminE   foE   fxI  h'F h'F2  h'E h'Es  fh'F fh'F2
2008 194 00:00:00  3.75 99.99  3.315 12.43  1.65  3.65  2.20 99.99 99.99  4.60  261 9999 9999  105  2.20 99.99
2008 194 00:10:00  3.75 99.99  3.269 12.26  1.75  3.45  1.75 99.99 99.99  4.60  251 9999 9999  109  1.75 99.99
2008 194 00:20:00  3.75 99.99  3.223 12.09  1.65  5.00  1.65 99.99 99.99  4.60  246 9999 9999  102  1.65 99.99
2008 194 00:30:00  3.75 99.99  3.332 12.50  2.85  5.00  2.85 99.99 99.99  4.60  300 9999 9999  110  2.85 99.99
2008 194 00:40:00  3.75 99.99  3.177 11.91  1.65  5.95  1.65 99.99 99.99  4.60  245 9999 9999  110  1.65 99.99
2008 194 00:50:00  3.90 99.99  3.064 11.95  1.65  5.90  1.65 99.99 99.99  4.60  250 9999 9999  105  1.65 99.99
2008 194 01:00:00  3.80 99.99  3.162 12.02  1.60  5.70  1.60 99.99 99.99  4.60  245 9999 9999  110  1.60 99.99
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2008 194 08:40:00 99.99 99.99 99.990 99.99  1.65  4.05 99.99  1.65  3.11 99.99 9999 9999   95  110 99.99 99.99
2008 194 08:50:00 99.99 99.99 99.990 99.99  1.75  4.10 99.99  1.75  2.96 99.99 9999 9999   95  110 99.99 99.99
2008 194 09:00:00 99.99 99.99 99.990 99.99  1.60  3.90 99.99  1.60  3.06 99.99 9999 9999   85  110 99.99 99.99
2008 194 09:10:00 99.99 99.99 99.990 99.99  1.60  3.95 99.99  1.60  3.01 99.99 9999 9999   95  114 99.99 99.99
2008 194 09:20:00 99.99 99.99 99.990 99.99  2.15  4.60 99.99  2.15  3.21 99.99 9999 9999   95  105 99.99 99.99
2008 194 09:30:00 99.99 99.99 99.990 99.99  1.85  5.30 99.99  1.85  3.16 99.99 9999 9999   95  101 99.99 99.99
2008 194 09:40:00 99.99 99.99 99.990 99.99  1.60  5.70 99.99  1.60  3.01 99.99 9999 9999   95  106 99.99 99.99
2008 194 09:50:00 99.99 99.99 99.990 99.99  1.65  6.35 99.99  1.65  3.11 99.99 9999 9999   95   99 99.99 99.99
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FIGURE 4: Data table output from the Chilton Digisonde, the important abbreviations are explained.

extraordinary ray. For the positive-sign case, the outcome is X=1. This is the result that is associated with reflection of the ordinary ray. Now if we solve the equation for the negative sign, we get one of two additional solutions: X=1 – Y or it can also give X=1 + Y, where Y refers to the influence of the Earth's magnetic field on the signal. Each of these signals travel completely independent paths through the ionosphere. It is as though the ionosphere splits the single radio transmission into two simultaneously transmitted, but independent, transmissions. Each wave component can be endowed with a different mixture of power levels (that together total the power of the signal before it enters the ionosphere and is split), which is dependent upon some complicated relationship between the ordinary and extraordinary ray at the base of the ionosphere. On the higher frequencies, the ordinary and extraordinary rays often follow very similar paths.

The ionisation in the atmosphere is in the form of several horizontal layers and so the electron concentration and, therefore, the refractive index of the ionosphere vary with height. By broadcasting a range of frequencies and measuring the time it takes for each frequency to be reflected, it is possible to estimate the concentration and height of each layer of ionisation.

An ionosonde broadcasts a sweep of frequencies, usually in the range of 0.1 to 30MHz. As the frequency increases, each wave is refracted less by the ionisation in the layer and so each penetrates further before it is reflected. As a wave approaches the reflection point, its group velocity (of a standing wave, is the velocity of propagation of the envelope, provided that the envelope moves without significant change of shape) approaches zero and this increases the time-of-flight of the signal. Eventually, a frequency is reached that enables the wave to penetrate the layer without being reflected. For ordinary mode waves, this occurs when the transmitted frequency just exceeds the peak plasma frequency of the layer. In the case of the extraordinary wave, the magnetic field has an additional effect and reflection occurs at a frequency that is higher than the ordinary wave by half the electron gyro-frequency. (Earth's magnetic field passes through the ionosphere and exerts a force on ionospheric electrons that is proportional to their instantaneous velocities and to the component of the magnetic field at right angles to their directions of motion. The force direction is at right angles to the component of the magnetic field producing the deflecting force and also to electron motion directions caused by radio waves. The effect at high radio frequencies is to cause each electron to vibrate in an elliptical path and at low radio frequencies to vibrate in a loop. A crossover between elliptical and loop electron paths occurs at approximately 1400kHz where each electron moves in a spiral path. That special frequency is called the gyro-frequency.)

The frequency at which a wave just penetrates a layer of ionisation is known as the critical frequency of that layer. The critical frequency is related to the electron density by the simple relation

F_c = 8.98*√(Ne)
for the ordinary mode, and
F_c = 8.98*√(Ne) + 0.5*Be/m
for the extraordinary mode.

Here *F_c* is the critical frequency in Hz, *Ne* is the electron concentration per metre cubed, *B* is the magnetic field strength, e is the charge on an electron and *m* is the mass of an electron.

All transmitted frequencies above this critical frequency will penetrate the layer without being reflected. Their group velocity will, however, be slowed by any ionisation and this will add to the time-of-flight. If such a wave encounters another layer, whose plasma frequency is higher than the frequency of the wave, it will be reflected and the return signal will be further delayed as it travels back through the underlying ionisation. The apparent, or *virtual* height indicated by this time delay will therefore be greater than the true height. The difference between true-height and virtual height is governed by the amount of ionisation that the wave has passed through. Recreating the true-height profile of electron concentration from ionogram data is an important use of ionosonde data. Such a procedure is known as true height analysis [2].

**THE IONOGRAM.** Figure 3 shows a conventional ionogram from the Eiscat Digisonde. An ionogram is a graph of time-of-flight against transmitted frequency. Each ionospheric layer shows up as an approximately smooth curve, separated from each other by an asymptote at the critical frequency of that layer. The upwardly curving sections at the beginning of each layer are due to the transmitted wave being slowed by, but not reflected from, underlying ionisation that has a plasma frequency close to, but not equalling the transmitted frequency. The critical frequency of each layer is scaled from the asymptote and the virtual height of each layer is scaled from the lowest point on each curve.

An ionogram can be much more complicated than just two layers. There can also be such phenomenon as;

- The F1 layer.
- Sporadic-E, Es. This layer is a patchy, very dense layer sometimes exceeding 16MHz ($3.1x10^{11}/m^3$). Despite their intensity, these layers do not extend over a large height range, and so do not exhibit an asymptote at the critical frequency, as the transition is too sudden. They appear on an ionogram as a narrow horizontal line at around 100km. An intense Es layer can prevent any echoes from reaching the upper layers. This is known as blanketing.
- Multiple hops. The return signal can skip from the Earth to the ionosphere and back again, sometimes several times before it is attenuated. These multiple echoes appear on an ionogram as multiples of the original virtual height.
- D-region Absorption. This is caused by ionisation in the D-region that absorbs the transmitted wave before it can return to the ground. This absorption is characterised by no echoes being received from the low frequency end of an ionogram.
- Lacuna. When turbulence occurs (as the result of large electric fields for example), the stratified nature of the ionosphere gives way to a more complex structure. Under such conditions, the reflected signal may not reach the receivers and so the height range at which the turbulence occurs is lost on the ionosonde trace. Such gaps are termed *Lacuna* and their position on an ionogram gives some indication as to the height at which the turbulence is occurring.

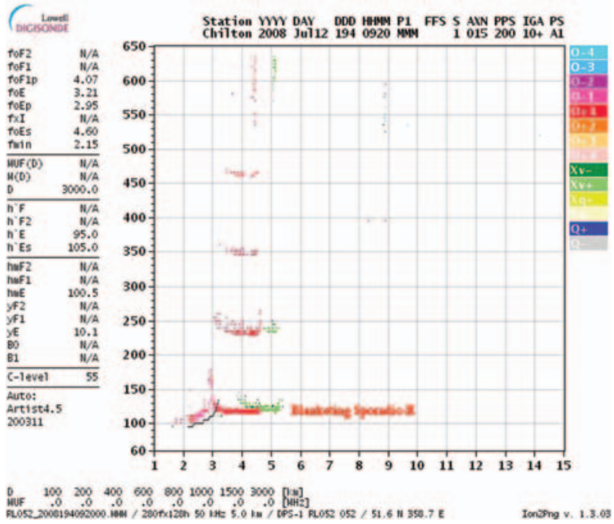

FIGURE 5: An ionogram from the Chilton Digisonde showing blanketing Sporadic-E. The abbreviations are the same for the Fig.4. X-axis = MHz whilst the Y-axis = height in km.

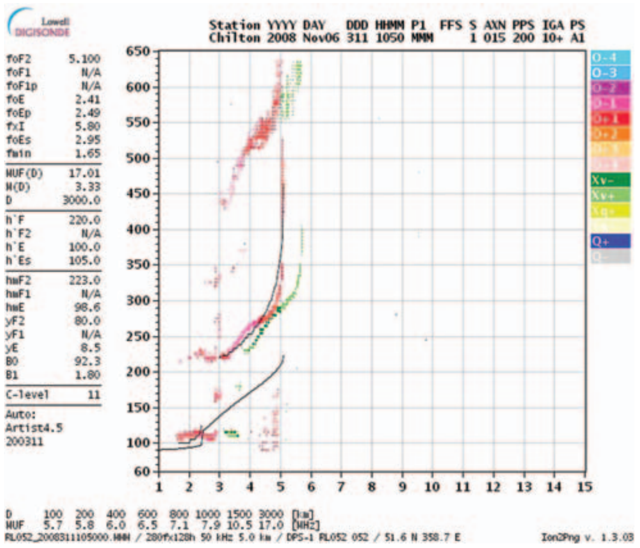

FIGURE 6: Another Chilton ionogram, this is more normal but does show a two-hop reflection, which contains some spreading.

- Spread-F. With an ionosonde, echoes are received from any portion of the ionosphere where the electron density gradient is perpendicular to the transmitted wave. This most often happens overhead, but occasionally conditions exist such that echoes from other regions of the sky return to the ionosonde. If the electron concentration in these regions differs from the ionosphere overhead, two traces are observed. For a given angle from the zenith, the horizontal separation is greatest in the F-region, and so differences in ionospheric conditions are most likely to be observed in the F-region. If the geometry is right for echoes to be received from a whole range of locations and the ionospheric conditions vary over that range (such as when a trough is overhead) multiple traces will appear on an ionogram, and the F trace is said to be 'spread'. With a digital ionosonde, such as the Digisonde, these traces can be resolved by considering the horizontal position of each echo.

**IONOSONDE DATA.** Thus far we have only considered ionograms, however, Digisondes also provide a table of data (sometimes this is all that is available), which lists numerically the Digisonde information. A portion of such a table is shown in **Figure 4**, the important abbreviations at this point are annotated. From this table it is easily recognised that following the '~' line, very few values were being recorded. Usually the reason for this is fairly simple, ie Sporadic-E, as shown in **Figure 5**. These tables can be utilised to produce daily graphs of foF2 (critical frequency) or any of the other parameters.

When available, ionograms provide an easier way to assimilate ionospheric conditions. **Figure 6** shows a typical November ionogram at this time of the sunspot cycle. There is a considerable amount of information contained within these ionograms, some of which should now be self explanatory, but some will not. We can disregard what looks like a coloured legend on the extreme upper right. Not necessary for our discussions as the meanings seem to change, depending upon who is producing the ionogram.

All the parameters pointed out in Figure 4 are easily seen here, as well as where the determination originates. The X-axis shows frequency in megahertz and the Y-axis shows ionospheric height in km. A multiple hop can been seen in this figure between about 430 and 630km with some spreading also evident. Modern Digisondes also include the black line depicting the ionosphere's shape, making the ionospheric density easier to visualise. Two lines at the bottom of the ionogram labelled [km] and [MHz], show the MUF at the distances given. For example, near-vertical incidence skywave on 5MHz is available at least as close to the transmitters as 100km. The MUF at 3000km is 17.0MHz, etc.

**IONOGRAM AVAILABLILITY.** Chilton ionograms are available at **[2]**. It is necessary to register, but that takes very little time. Another useful source is DIAS **[3]**, again it is necessary to register. Lowell University, a leading light in Digisonde technology, has its own website at **[4]** where a map is shown of around 77 sites worldwide that use this technology. Sometimes clicking on the stars brings up a recent ionogram from that site, however, my experience is that the links seldom work; when they do those sites should be bookmarked. This list is not exhaustive and does not include for example the USAF's ionosonde databank **[5]** or the Australian Digisondes.

**IONOGRAM USAGE.** Various uses of these graphs have previously been alluded to. However to sum up, their practical usage includes, for NVIS – visualising whether 3.5, 5, 7 or 10.1MHz are suitable for inter-G working, the latter frequency will only be available for NVIS during the height of the sunspot cycle. As was discussed in the March 2007 issue of *RadCom* by G0IJZ, it can be visualised when the extraordinary ray may be attributed to NVIS communication. The MUF at 3,000km can give a good indication that DX may be available at or about that frequency, the higher the MUF the easier it will be to work DX. Blanketing Sporadic-E depicted in Figure 5 gives the opportunity to those seeking it the chance to work this mode, the situation where this blanks out the higher layers is what to look for, for example, during May, June and July 2008 at least some hours in the majority of days saw blanketing Sporadic-E. These are just some of the practical uses, it should not be discounted that just being able to see what is actually happening can be enlightening.

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## REFERENCES

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[5] USAF, www.swpc.noaa.gov/ftpdir/lists/iono_day/.