can consider this a useful assumption. At least it will be *daylight* along the entire path.

Now, it should be fairly easy to visualize that if we look at the wide "vertical fan" pattern of a typical HF transmitted signal, after every "bounce" the fan gets wider! The range of launch angles after every return to Earth becomes greater. In fact, many shortwave broadcast stations take advantage of this fact, launching at fairly high angles right out of the chute as it were, so that there are no "dead" zones along the path between the transmitter and the target destination. We radio amateurs however, are more interested in getting a strong signal at a final destination, and not too concerned with picking up an "audience" along the way. For cross-country amateur operation, it's usually an advantage to launch at the lowest angle possible so as to require the fewest number of skips. Of course the ionosphere dictates what elevation angles are available over a path — and the antenna's job is to put the most energy at that angle, whether it be high or low. As we will explore later, far few hams pay any attention to the vertical launch angle of their signals, under the common assumption that they can't do much about it anyway. As we will see later, there's a lot more under your control in this regard than commonly thought!

Your Friend the Ionogram

If you operate HF, it's never too early to learn about the *ionogram*, one of the most useful tools in radio propagation and analysis. An ionogram is a graph generated by an instrument called an *ionosonde*. The ionosonde is a high frequency radar; it sends short radio frequency pulses straight upward (normally) and receives the returning signal after reflection from the ionosphere. Each pulse is transmitted at an increasing frequency throughout some or all of the HF frequency range. The X-axis scale at the bottom is the frequency, and the Y-axis scale is the reflection height. There is a wealth of information that can be derived from an ionogram, and we will look at some of these in detail as we move along.

The ionogram shown in **Figure 6.6** is from the Boulder, Colorado, Digisonde, conveniently located somewhat between Palo Alto and Virginia Beach. A number of Digisondes are active around the world, and you can most likely find one relatively close to your location. You can often find one near the midpoint of where you are and where you want your signal to go, which is where it will be most useful, but this ideal state isn't necessary. You can learn a lot by looking at any ionogram.

Well, let's take a look at this particular ionogram in Figure 6.6. As you can see on the X-axis, we have a scale running from 1 to 17; this is the range of frequencies, in MHz, that the ionosonde scans. Some Digisondes are programmed to cut off at 8 or 9 MHz. It typically takes a minute or so for a complete scan to be performed. Depending on the particular site, a new ionogram is generated every 15 minutes or so.

Along the Y-axis, we have a scale running from 60 to 700; this is the reflection height in kilometers. The Y-axis is really a time of flight, and the reflection height (let's call it the "virtual height") assumes the wave travels at the speed of light. This can also be reprogrammed to show lower reflections, but 60 km at the bottom is a very typical configuration.

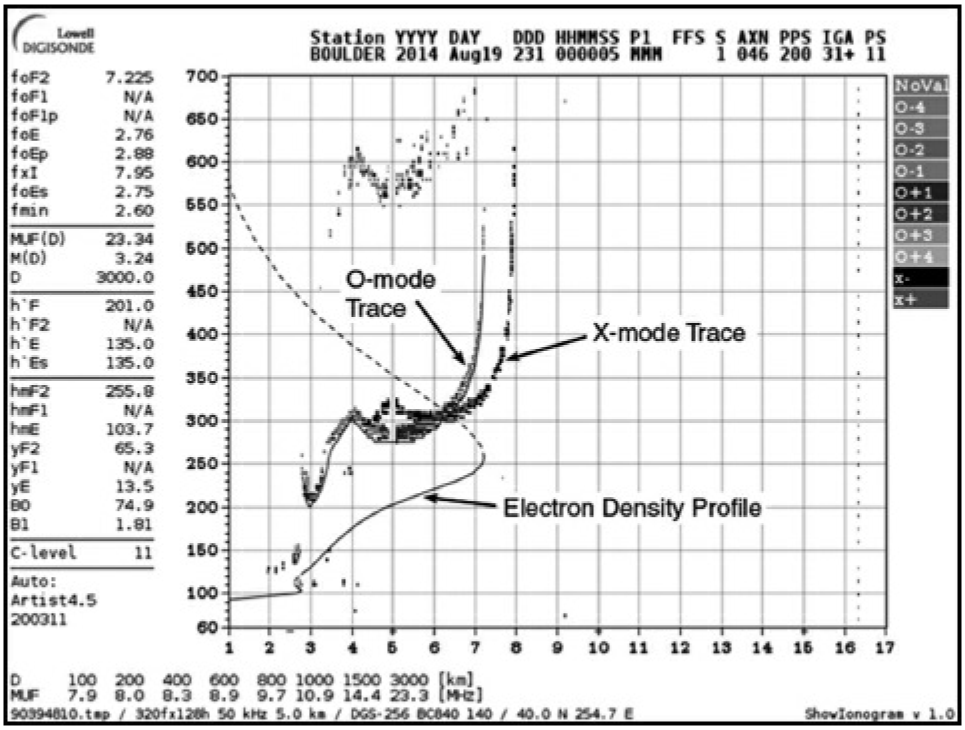

Figure 6.6 — A typical ionogram. See the text for a detailed discussion.

Now, let's look at the actual reflections, the plots we see on the graph. There are actually two traces of interest, the O-mode trace and the X-mode trace. Remember how we described the magnetized ionosphere as being *birefringent?* These two traces show this phenomenon clearly. The red and green traces are separated by means of two circularly polarized receiving antennas, one clockwise and one counterclockwise, while the transmitting antenna is *linearly* polarized.

Let's look at the O-mode trace first (the trace on the left here; it is in color on the actual ionogram). Look at the curve near 270 km in altitude, where the curve is fairly horizontal, between 4 and 6 MHz. (There appears to be a "cloud" up around 570 km. What's really happening is the 4 MHz energy is going up, coming back to Earth, going back up and then coming back down. Since we're really measuring time of flight, it shows up as twice the altitude since it's twice the time of flight.) We always want to look at just the first reflections, which give us the "real" information we're looking for. Now notice how the curve tends to increase with increasing frequency, and goes straight vertical at just over 7 MHz. This is called the *critical frequency*, and is the maximum frequency that will be reflected to Earth for a *vertical incident* signal. As we will learn, this is a worst case condition; the *maximum usable frequency* for lower angles is greater than the critical frequency, but related.

There is a column of "stats" to the left of the graph, of highly useful information, The first item is foF2, which is the critical frequency for the O-mode ray. In this case it's 7.225 MHz, which is what corresponds to the frequency at which the curve "goes vertical." This is the critical frequency of the F layer. There is also a critical E layer frequency (foE) on the ionogram at 2.76 MHz. The E layer is easily recognized because it looks so flat compared to F layer refraction. The E layer critical frequency is a *low* frequency limit, not a high one.

Now, direct your attention to the rows below the graph labeled, "D and MUF." D is distance per hop in kilometers, and MUF is maximum usable frequency. Notice that the MUF goes up proportionally to the D.

It shouldn't be too surprising that the distance per hop is a function of the vertical launch angle and the reflection height. Some simple line-of-sight geometry should make this pretty obvious. Now, we can do a little more trigonometry and determine the actual launch angle based upon reflection height and hop distance. But here's the interesting part that shows the reflection process is actually refraction. The maximum usable frequency is dependent on the angle of the wave penetrating the ionosphere, and in this case it ranges between 7.9 MHz (which is essentially the critical frequency for vertical incident waves), and 23.3 MHz for very low angle radiation. For horizontal rays, the skip distance is about 3000 km, which means you can cross the country with just a couple of hops at 23 MHz…pretty good conditions for 15 meters.

Returning to the left column, we can drop down to FxI, which is the X-mode critical frequency. It's a little more than 500 kHz above that of the O-mode ray, at 7.95 MHz, seen clearly on the O-mode trace as well. A few lines down, we have MUF of 23.34, which again, is the case for a horizontal launch. A few more lines down, we have hmF2, which is the height of the reflection at the "normal" region of the O-mode. The flatness of this region can vary considerably, but it's a good first order approximation of the reflection height.

Virtual Reality

One of the unnecessarily confusing figures you'll find in this business is the difference between "virtual" and "true" height. Because the ionosphere is a refractor, not a reflector, the speed of radio is not constant through its journey. As the radio wave penetrates the ionosphere, it gradually slows down, so it appears that the reflection point is a lot higher than it is. (Since time of flight is the only indicator we have on Earth for the reflection height, we have to take this into account). The "real" or "true" reflection height; that is, the point where the wave velocity slows to zero, reverses direction, and accelerates down toward the surface, is a bit lower, depending on many factors. When calculating skip distances, it's the virtual height that really matters, because it locates the "reflection" point in the ionosphere. We will address some of the other parameters later, especially with regard to E and sporadic E propagation.

Electrons

Last but not least, we have the *electron density profile.* This is the black squiggly line that starts at about 95 km in altitude and runs up to around 575 km. What this line shows is the relative number of free electrons versus altitude. The horizontal scale is not shown, but it is generally measured in electrons per cubic centimeter or some such. Note that it's not the actual numbers that are important but the relative density. Notice there is a well-defined peak at 250 km. This is where you have the greatest number of free electrons. The peak of the F2 layer electron density is at the F2 layer critical frequency — from that it's easy to calculate the number of electrons. This is called the *critical height*, and it's also the height above which ground based sounding is impossible.

Now, see the dashed part of the line above the peak of the electron density profile. It's interesting to know that we can get no reflections above this altitude. The reason the upper part of the line is dashed, is that the electron density cannot be directly measured above this point, so it must be extrapolated. Fortunately, it is well known that the electron distribution follows a parabolic curve above that point.

Notice also the tiny little bump in density at around 100 km. This is E or sporadic E. (Note that the following text is about sporadic E, not the normal E layer.) These electrons are generally caused by either ablation (burning up) of micrometeors entering the atmosphere, or local lightning strikes. It is likely also that wind shear effects may cause these electrons to appear. What makes these electrons very different from "normal" ionospheric electrons is that in this region we do have almost nothing but electrons, without nearby associated ions. Because we don't have the stabilizing effect of ions in this area, the electron clouds are, almost by necessity, short lived, or "sporadic." Another feature of sporadic E (which will be shown in a different ionogram) is that there is no discernible frequency dependence…the reflection curve is remarkably flat. This speaks strongly of true reflection instead of refraction. We go abruptly from a region of no free electrons to nothing but free electrons when sporadic E is in play. There is still a great deal to be learned about sporadic E, and it is a wide open field for experimentation.

Layer by Layer

We've described how the presence of ions guides the ionosphere into fairly well-defined layers, which serve to make the whole region suitable for radio propagation. Let's talk a bit more about these layers and their unique characteristics. There's really something for everybody "up there" whether you operate "from dc to daylight" or never venture out of the confines of your 2 meter handheld.

Ionospheric layers are sorted by letters of the alphabet, beginning with the D layer. Perhaps you're wondering why there's no A, B, or C layers. Well, actually there are, but those are not actually ionospheric layers, but the troposphere, the stratosphere, and the mesosphere, respectively. Those particular spheres are not part of the ionosphere because they are not ionized, curiously enough. This is not strictly true, however. A lightning bolt creates very high levels of ionization, right down to the ground, but these are confined to very small regions and nothing resembling a worldwide *sphere*. And this is not to imply that there aren't some very interesting things happening near ground level. But for the most part, we begin our radio adventure at the D layer, which lies at an altitude between about 60 and 90 kilometers.

An Absorbing Subject

Most of what happens at the D layer is actually counterproductive to radio propagation. It is called the *absorption* layer, because when it is active, during daylight hours, lower frequency HF signals and medium wave signals are greatly attenuated. It is D layer absorption that is responsible for AM broadcasting to be strictly ground wave during the day. Such radio signals would be refracted from the upper ionosphere, except for the fact that they never get past the D layer in the first place. D layer absorption is actually strongly in effect up through the 80 meter band, with somewhat lesser effect on 40 meters. For this reason, the "low bands" are essentially nighttime bands, most effective when the D layer has dissipated.

The actual *process* of D layer absorption is rather complex and counterintuitive in comparison with the more "beneficial" layers. One could understandably conclude that if a little ionization is good for radio propagation, a lot of ionization is better. And indeed, it takes a lot more energy to cause ionization to occur at the low altitude of the D layer. Well, there can be too much of a good thing. D layer absorption is caused by frequent *collisions* between electrons, where they don't have the degree of freedom that they do at higher altitudes. There are a lot of complex *resonance* phenomena happening too, which contributes to the losses at low frequencies. Higher frequencies radio signals tend to slip by the resonances, unperturbed to a large degree.

D layer absorption phenomena can be particularly strong in polar regions where the Earth's magnetic field lines converge. *Cyclotron* resonances are prominent in these regions, as electrons oscillate about the magnetic field lines. The program *Proplab Pro 3* is one of the few ionospheric programs available that addresses cyclotron resonances. See Chapter 15, Software and Such.

E is for Excellent

Once you manage to make it past the D layer, radio becomes a lot of fun. The next level of interest is the E layer. For many hams, E is synonymous with sporadic E; in fact, you hardly ever hear about non-sporadic E in typical Amateur Radio discussion. The fact of the matter is that E is a region and *sporadic E* is a *phenomenon*. Sporadic E happens in the E region, but there is a lot of other stuff happening there too!

The E layer lies between about 90 and 120 kilometers in altitude. It's a rather thin region, though it might be hard to fathom 30 mile slice of sky as being thin! In terms of the entire ionosphere, it is a mere onion skin, however.

The E layer consists mainly of ionized molecular oxygen, (O_2), ionized primarily by soft (longer wave) ultraviolet. Most curiously, "normal" E is sort of a backward absorption layer; at low angles of incidence, it absorbs signals *above* about 10 MHz and refracts those below 10 MHz quite effectively. However, because the layer is so thin, it's quite easy to "miss" low angle E-layer refraction. In addition, because it is thin, one is unlikely to observe *dispersive* effects. Above the absorption frequency, the reflections from this layer are relatively independent of frequency.

While "normal" E propagation subsides quickly after sunset, *sporadic E,* on the other hand, can occur at any time of day or night. This is because the ionization process is not due to a steady bath of UV, but rather by very intense *localized* events. While the jury is still out on this, there are three most likely causes of this intense ionization: ablation of meteorites (micrometeors), lightning storms, and wind shear. All these phenomena can generate vast concentrations of free electrons. Wind shear is the most intuitive, because it is most analogous to the buildup of static electricity by the rubbing of dissimilar objects. Once you have blobs of electrons available, you have highly reflective mirrors. Sporadic E reflections are notable because of their highly *specular* or mirror-like reflections. Using HF radar, sporadic E reflections look like solid metallic objects, with well-defined boundaries. These blobs of electrons are effective reflectors of any radio signals whose wavelength is significantly less than their dimensions, up to the upper VHF range, where absorption becomes an issue again.

The F Region

Above the E layer we have the F region, which actually consists of two layers, ranging from about 200 km to 600 km in altitude. It is by far the "biggest" region of the ionosphere, by volume, and as such has the widest variation of propagation within its domain. It is in the F region where we observe wide radio frequency *dispersion*, the frequency dependent propagation of HF signals. Because the F region is so thick, HF radio signals spend a lot of time there in transit.

During the daytime, in seasons of high solar activity, the F region can separate into two distinct layers, the lower F1 layer and the higher F2 layer. The F2 layer remains considerably thicker, however, and for the most part, the F2 will play the predominant role in worldwide HF communications. One can spend a long "career" in Amateur Radio without actually noticing F1 activity. When it exists, however, the F2 layer is clearly visible on an ionogram, and can be responsible for very strong "short skip" signals.

Figure 6.7 shows an ionogram with foF1 (the F1 layer critical frequency) reported at 4.43 MHz. In this image, foF1 corresponds to an inflection point in the electron density profile — it's not another peak like the F2 layer (foF2 at 10.6 MHz).

As the Sun goes down, the F region "retreats" from the bottom up. The upper extreme pretty much stays fixed, while the region gets thinner. The F1 layer, naturally, goes away first, and the band "goes long" as the reflection height increases in the F2 layer. What's truly amazing is just how *fast* this retreat can be. Using Doppler ionosonde methods, the reflection height can be seen to move upward at more than 700 meters per second, right after local sundown! This can continue for a half hour or so until the reflection height settles in at its nighttime altitude.

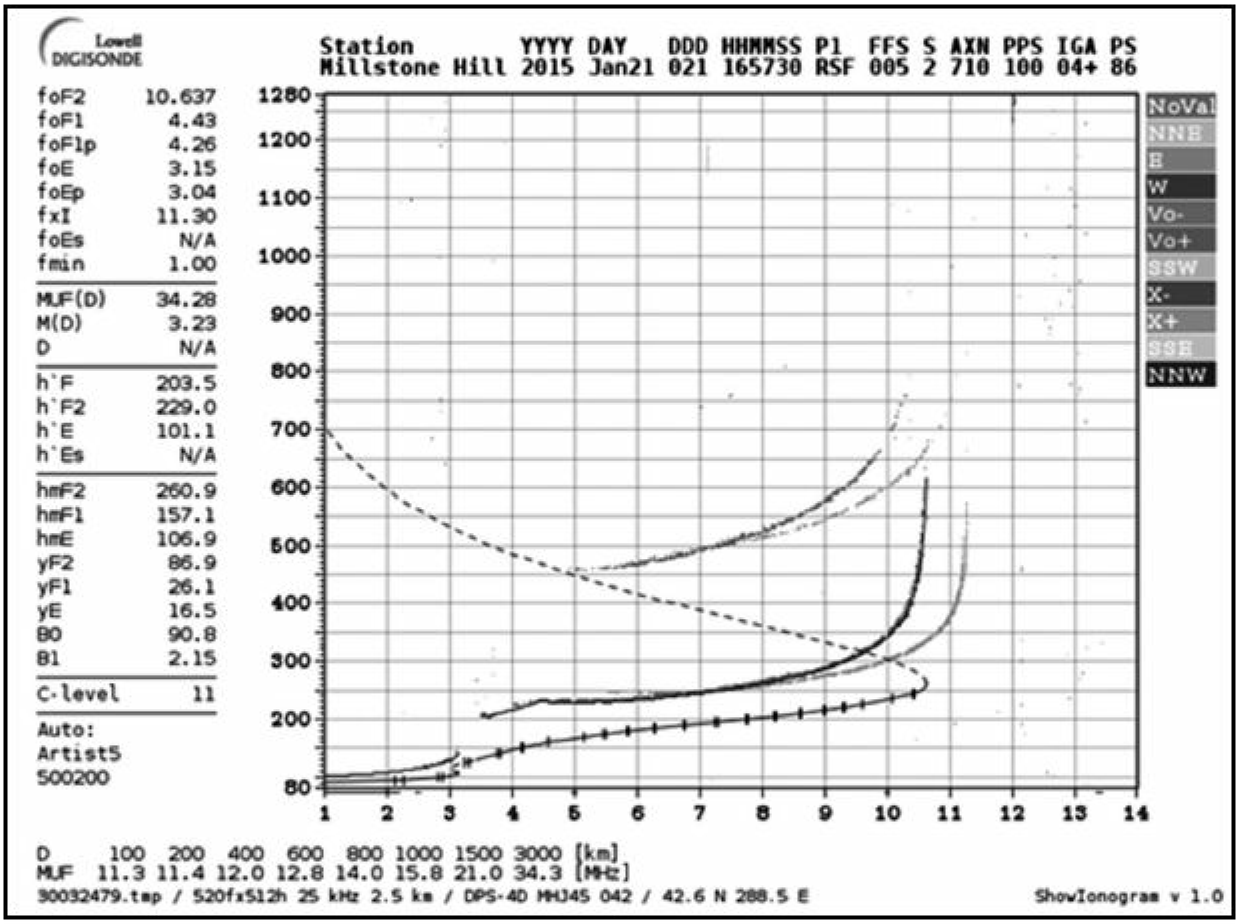

Figure 6.7 — This ionogram shows foF1 at 4.4 MHz (the small inflection in the electron density profile) as well as the obvious F2 layer peak at 10.6 MHz. [courtesy Carl Luetzelschwab, K9LA]

Now it shouldn't take a rocket scientist to conclude that if the F layer retreats on the dark side of the Earth and advances on the daylight side, the entire ionosphere cannot be truly spherical! And, in addition, it has to have a pretty big tilt somewhere along the line. The net result of this is that if you launch an HF signal from the daylight side of the Earth across into the nighttime side, (or vice versa), the vertical angle of arrival will be much different than the vertical launch angle! Again, some simple geometry prevails.

This factor is not often noticed by hams, since, as we indicated earlier, very few are aware of or equipped to systematically deal with different vertical angles of arrival. As we delve into this more, however, we will find that, for the average HF operation, the control of antenna elevation may be every bit as important, or even more so, than azimuth control!

This chapter has been a fairly general overview of *expected* HF behavior, and for the most part will be confirmed by most experienced radio amateurs. In the next chapter, we will look at some of the more exotic behavior of the ionosphere, and methods of exploring and exploiting the same.