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Gimme an X, Gimme an O,



RICHARD DICKMAN

What's that Spell? — Radio

HF ionospheric propagation may not happen quite the way you think it does.

Eric Nichols, KL7AJ

Let's see if you can answer this simple question. You hear a European DX station coming over the North Pole by skywave on 20 meters. What polarization is that signal when it arrives at your location: horizontal, vertical, whatever polarization the DX station is using or it's impossible to tell because the polarization gets scrambled by the ionosphere?

It will come as a surprise to even experienced amateurs that all of those answers are absolutely false. All ionospherically refracted signals are, in fact, elliptically polarized, the general case of circular polarization (CP). That's right — all of them. They may be clockwise elliptically polarized. They may be counterclockwise elliptically polarized. But they will be elliptically polarized. We can even go further than that. (See Note 1, "How Round is Round?")

Heresy

When I present this truth for the first time at Amateur Radio club meetings and other talks, I get the sort of reception as one who has just blasphemed a religion. This is somewhat understandable because, as with so many other situations, if a lie is repeated

often enough it begins to resemble the truth.

In this case, the most oft-repeated lie is that HF skywave signals are *randomly* polarized. As we will see, there is a remarkable consistency and predictability to skywave signals. If there's anything random, it's the average ham's methods of using them. By getting to the core of how HF propagation actually happens, we can actually learn and take advantage of this behavior, rather than merely chalking it up to general weirdness.

The fact of the matter is that this truth, the fact that all HF *skywaves* are elliptically polarized, has been known by ionospheric physicists, shortwave broadcasters and military communications experts for over 70 years. The only ones who seem to have missed the message entirely are radio amateurs.

Well, Perhaps Not Entirely

The March 1940 issue of *QST* has an outstanding, and completely accurate, description of this matter in an article entitled "The Ionosphere and Radio Transmission."² This article should be required reading for every ham who even thinks about operating HF. So this is not some newly discovered or oddball phenomenon. It is the normal way radio works. The real mystery is why this has had such scant mention in the annals of hamdom

in the intervening seven decades.

Before continuing my heresy any further, I want to make it absolutely clear that all these surprising assertions are easily confirmed by any radio amateur, with readily available hardware. In fact, I strongly recommend that you test these truths for yourself. Later in this article, we will describe exactly how to do this — actually using a couple of methods.

Mirror Images — Sort of

The ionosphere is a magnetized plasma, an ionized gas. This plasma is magnetized by the Earth's natural magnetic field. A magnetized plasma has a curious property called *birefringence*. This is defined as having two different refractive indices. The mathematics that describe this is known as the **Appleton-Hartree dispersion relation**, and it's a pretty hairy formula, well beyond "the scope of this course."

The end result, however, is fairly straightforward. If a linearly polarized electromagnetic wave is launched into a magnetized plasma, it splits into two separate counter rotating, circularly polarized waves. One of these is called the *O-mode* for *ordinary* wave, and the other twin is called the *X-mode* for *eXtraordinary* wave. (Nobody ever said physicists could spell.)

¹Notes appear on page 37.

A Switchable Sense HF Receiving Antenna

One possible objection to the use of circularly polarized (CP) antennas for HF is the fact that they use a bit more real estate than other antennas, at least for transmitting. However, one can take advantage of the CP properties of HF propagation by simply using CP antennas for *reception*. We'll describe a simple semi-compact CP turnstile (crossed inverted V) antenna for 15 MHz, so you can demonstrate X and O propagation using WWV as a test generator. Once you see how this works, you'll probably want to modify this antenna for your favorite ham band — or even several of them.

It's a simple matter to build an HF CP antenna with 30 to 35 dB of discrimination between clockwise and counterclockwise waves. There are two factors that determine how much discrimination you can get. First, you want to have an accurate 90° phase shift between your two crossed dipoles. Secondly, the arriving signal has to arrive on axis. For a CP turnstile antenna, the proper angle of arrival is perpendicular to the plane containing the two dipoles.

However, even if your turnstile is not oriented ideally, you can still get useful discrimination between modes, certainly enough to demonstrate that the X and O modes exist. In fact, a horizontal turnstile antenna at reasonable height is capable of separating X and O mode signals at most angles of arrival you're likely to encounter.

A Little Geometry

It's a bit of a curiosity that a horizontal turnstile antenna (two horizontal crossed dipoles fed 90 electrical degrees apart) transmits and receives an *omnidirectional horizontally* polarized signal off the edges — that is, radially from the antenna. Looking straight down upon such an antenna, you will have an ideal circularly polarized antenna. This isn't too hard to visualize if you have some experience with NEC antenna modeling. For a simple dipole, of course, polarization is undefined off the ends. Also, any dipole has the greatest polarization sensitivity to signals arriving broadside, with progressively less polarization sensitivity for signals arriving off axis.

Such a turnstile antenna can be modified into the form of an inverted V with little sacrifice of performance; in

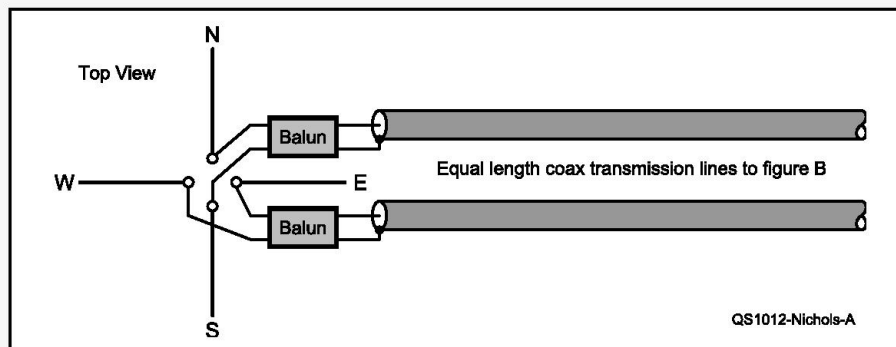


Figure A — Connection diagram of HF turnstile antenna.

fact it may have a little better overall sensitivity to low angle signals. At HIPAS observatory, we had a large array of such antennas, as well as a few portable ones for on the fly propagation studies. This configuration only needs one tall support, and it doesn't have to be a very tall one at that.

Free Ticks

Most hams know a little bit about WWV, but we seldom take advantage of all that the stations have to offer. See tf.nist.gov/timefreq/stations/www.html for more information on the opportunities. There's a bunch of great information there.

Since WWV's signal is so well defined, it's an ideal test generator for our X and O demonstrations. We all know about the frequency accuracy of WWV, but beyond that, the radiation characteristics are also rather precise. WWV transmits an ideal omnidirectional, vertically polarized signal with a very closely controlled effective radiated power (ERP).

At 15 MHz, the true ground wave of WWV attenuates rather rapidly. Unless you happen to live in their back yard, you won't need to unduly concern yourself with it. Also, as with any vertical antenna, there is a substantial *cone of silence* directly overhead, so you won't be led too far astray if you happen to be in the near vertical incidence skywave (NVIS) zone of the station.

The 1 s time ticks broadcast by WWV are of particular interest, as they give us reliable differential propagation information. Even with a linear polarized receiving antenna, you can see the two separate reflections of

the ticks with an oscilloscope bridged across your audio output. (With a little more sophisticated setup, using a dual trace scope and two CP antennas, one for each sense, you can accurately measure the difference in tick times for the X and O mode) In either case, the ticks give us a great time of flight marker for X and O demonstrations.

So Simple A Caveman Can Do It

The actual construction of a 15 MHz CP inverted V is so straightforward as to be trivial. You can adapt the basic design described to your available materials. The only thing you need to worry about is symmetry.

Using a 20 foot section of 4 inch diameter PVC plumbing as a center mast is quite convenient. The four half Vs act as guy wires. For 15 MHz, you want each half V to be about 5 meters long. The exact length is not too critical, but you want each of the two Vs to be identical (see Figure A). You want each the Vs to cross each other at 90°. You also want to drop them down from the mast at the same angle. 45° is a good choice, but not too critical. Just be sure they're all the same. Use enough rope or cord at the bottom end of the Vs to reach some ground stakes. Again, be sure the stakes are all the same distance from the base of the mast, so that the angles are all the same.

You want a good balun at the apex of each V. At HIPAS we used W2AU baluns, but anything is fine as long as they're the same model.

Saving Phase

Once you've built your symmetrical

crossed V antenna, only one thing is critical, the 90° phasing network. You can build a 90° coax stub at the feed point of the antenna, but you'll have a lot more versatile (and verifiable) antenna, if you run two identical runs of coax into your shack. If you do the phase shifting in the shack, it's a lot easier to change frequencies, which you will eventually want to do. It also makes it easier to gain access for various test instruments.

You will want to cut a quarter wave chunk of coax (at 15 MHz) for your phasing section. Be sure to compensate for the velocity factor of your coax. When in doubt, you can short one end, couple the opposite end to a grid dip oscillator with a small loop, and see that your grid dip oscillator (GDO) or antenna analyzer dips at exactly 15 MHz. Once you have the phasing section cut, simply add it in series to one of your transmission lines, and then feed both lines into a coaxial T. The output of your T goes to your receiver. To switch between X and O modes, insert the series section into the opposite transmission line. Eventually, you will want to build some sort of switch for this (see Figure B),

or use a couple of coaxial relays. (PIN diode switches work great for this as well, and allow you to do very rapid X and O switching for some interesting experiments.)

Although it isn't critical for demonstration purposes, in ionospheric research it's standard practice to orient the antenna with magnetic North. You might want to clearly label your EW and NS transmission lines inside your shack, if you decide to align your antenna. More importantly than magnetic orientation, however, is your relative EW and NS phasing, if you want to positively identify your X and O modes. Your north and east legs should be attached to the center conductor of your transmission line, while the south and west legs should be connected to the shield. If you're using a voltage balun, the north and east terminals of your balun should correspond. If you delay the NS by 90° with respect to EW, using this polarity, the result will be clockwise CP (O mode in the northern hemisphere).

By the way, this is reversed if you transmit through the array. Just to keep things simple, we'll only deal with this as a receiving array.

The Proof

In all likelihood, your O mode signal will be a little stronger, all things being equal. Since WWV transmits an omnidirectional signal, you probably won't be able to discriminate azimuth skewing too well. However at low takeoff angles, there will be a large difference in distance between the X and O modes. If you have access to a local digisonde (see ulcar.uml.edu/slist.htm) you can make an educated guess as to whether the X or O mode is landing at your location. The closer you live to WWV, the more likely you will be to receive the O mode, assuming you're near the maximum useable frequency (MUF). If WWV is a long distance from you, you're more likely to be receiving the X mode, at least on the first hop.

The best way to get the feel for how things are at your location is as follows: Tune in WWV with just the NS antenna connected. Note the signal strength. Switch to the EW antenna. If everything is working reasonably well, the signal strength should be nearly identical.

Now connect both antennas. Your signal will either increase by 3 dB or drop precipitously. If it increases by 3 dB, you know your polarization sense is matched to the mode of the incoming wave. If it goes way down, you're on the wrong polarization — at least for that mode.

Jim Parkinson, W9JEF, is one of my handful of "CP Envoys" in the lower 48, where conditions are likely to be a lot more typical than they are up here in the subarctic. Jim reports that upon first firing up his antenna, he was astonished at the difference in signal strength between the X and O modes — on just about any signal. This is a very typical response on one's first encounter with HF CP antennas. The shocker isn't so much that it's a great antenna by most standards, but that there is such a huge difference in sensitivity between modes — something alien and jolting, to even seasoned old timers — and impossible to experience on any linearly polarized antenna. As much as a 3 S-unit difference is easily achieved on even a haphazardly assembled CP antenna.

Don't take our word for it. Build it and see. For those who want to go into this one step deeper, an advanced I and Q polarimeter receiver is described in the QST-in-Depth Web site (www.arrrl.org/qst-in-depth).

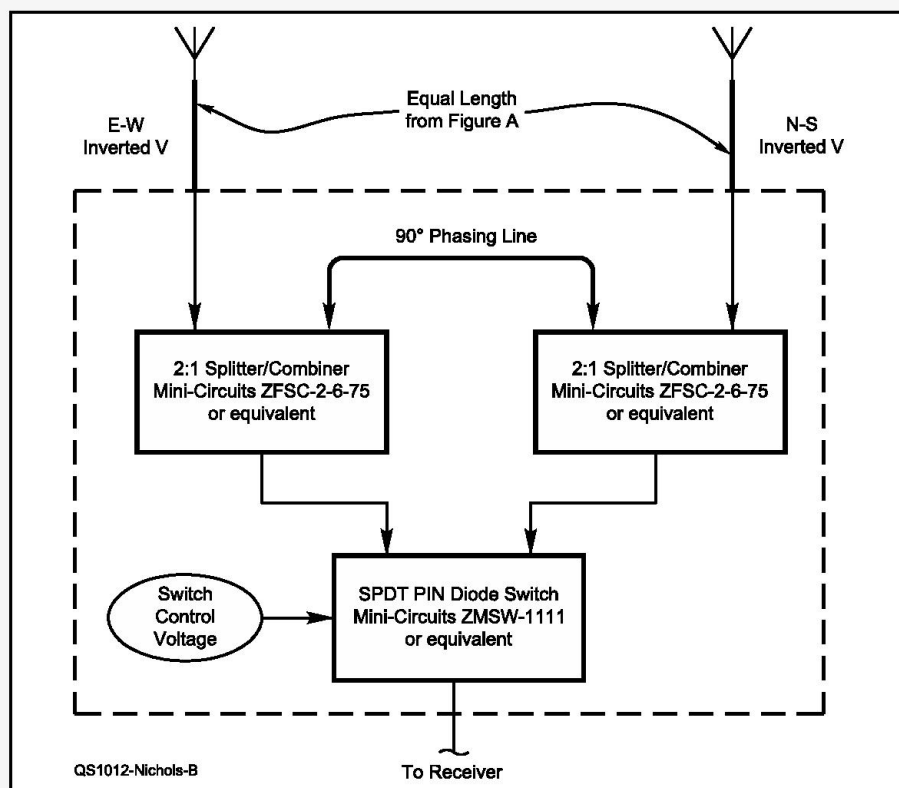


Figure B — Simple X-O switch for 15 MHz.

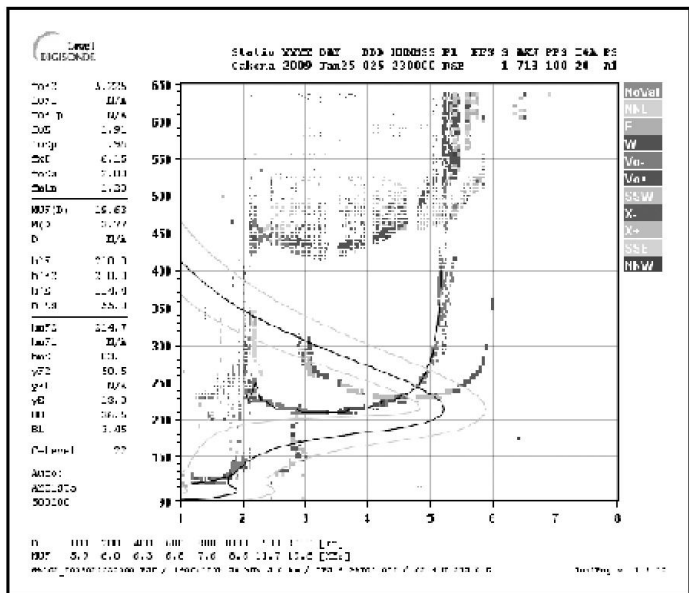


Figure 1 — Real time ionogram showing the reflection height of vertically transmitted signals as a function of frequency. See the text for an interpretation of the significance of the data.

The O-mode wave is aligned with the actual electron orientation in the plasma. It travels a little faster and with a little less loss than the X-mode wave. Conversely, the X-mode wave tends to operate a bit against the grain of the natural plasma. The different velocity factors of these two waves due to there being two different but simultaneous refractive indices, has a couple manifestations of interest to radio amateurs. The first is that the X-mode signal travels higher into the ionosphere before being refracted. This difference in *time of flight* is easily visible on any of the numerous real time ionograms available from the worldwide ionosonde network.

Taking a Look

Figure 1 is a typical ionogram taken from the HAARP Digisonde in Gakona, Alaska.³ There are a lot of features here, but let's look at just a few of the crucial ones. The X axis is the sounding frequency. In this case the sounder is swept from 1 to 8 MHz. (This range can be tweaked by the operator to accommodate prevailing conditions). The Y axis is the reflection height in kilometers; this particular instrument is accurate between 90 and 650 km, about the upper extremity of the F2 layer. The traces in red are the O-mode (clockwise CP) returns and the green traces are the X-mode (CCW CP) returns. Notice there are two clear sets of returns for both modes — this is due to double hops, a good sign of low absorption. In fact, you can see just a trace of a third O-mode reflection right at the top of this sample.

The first hop is what we're interested in, of course, which is what all the numbers on the left table are derived from. Let's just look at what's happening below 300 km, the primary reflection. For now, we can also ignore what's below 2 MHz. In this case we see a

significant F1 layer as well. Most frequently it's the F2 layer where the magic happens.

Another prominent feature is the black line with a bell shaped curve. This is the electron density profile. This shows us the relative number of free electrons versus height. Note that there is no units scale for this trace. In this case we see that we have the maximum electron density at around 215 km. But notice what else coincides with the maximum electron density, the critical height. This is the height at which the O-mode trace turns vertical. The frequency at which this occurs is the O-mode critical frequency, which in this case is 5.225 MHz, the first listing on the column at the left.

Since the curve doesn't make a sharp right angle bend at the critical frequency, there's a lot more number-crunching here than meets the eye. In fact, the electron density profile is derived from the shape of the O-mode trace near the critical height and frequency, not measured directly. The gray lines flanking the black line are error probability boundaries, so there's a lot of room for slop in achieving the electron density profile. The critical frequency and height are right there — what you see is what you get.

What's it all Mean?

Notice the X-mode critical frequency (at which the green trace turns vertical). It's about 1 MHz higher than the O-mode, critical frequency, around 6 MHz. This means that you can use X-mode propagation around 1 MHz higher than for O-mode, all things being equal. But also notice that the average reflection height of the X-mode is a bit higher as well (the horizontal part of the curve). This means for a given frequency, the X-mode will have a longer skip distance.

Most ionosondes are *vertical incidence*

instruments, meaning they shoot a signal straight up, and look for a signal coming straight down. Of course, this is of limited application for most radio amateurs. As the launch angle becomes lower, however, it shouldn't take a great deal of imagination to see what happens. The X-mode and O-mode signals will return to Earth at different distances, the distance differential being progressively greater at lower launch angles. But this is only part of the story, and, actually of lesser importance for most amateur operation.

What you don't see in the ionosonde data is the profound difference in lateral (azimuth) angle of the two different waves. In fact, near the magnetic poles (such as in Fairbanks, Alaska) the azimuth difference between the X and O signals can diverge by as much as 90°. It also explains why great circle paths up here are essentially meaningless.

Now, though this extreme case of X/O azimuth skewing is confined to the magnetic polar regions, the effect is present to some degree everywhere. The one exception would be the case of communication between two stations both lying precisely on the magnetic equator, not too likely.

For a given mode, for example, O-mode going both directions, the direction of skew is the same relative to wave propagation. In other words a wave going North would be skewed to the right (West), while a south-bound signal will also be skewed to the right, (East). Might this conceivably result in non-reciprocal propagation? You betcha. In fact, this is the primary cause of the *one way skip* we experience in Alaska.⁴

What It Isn't

Without exception, when I introduce this X and O business to people, someone will pipe up: “Oh, that’s just Faraday rotation.”

No it isn't. Faraday rotation will twist the *plane* of a radio signal, but at any point in space, the Faraday rotated signal is still linearly polarized. X and O modes are circularly polarized. This is easily tested by means of circularly polarized antennas. A simple crossed dipole with a 90° phasing line between the elements is all you need to do this experiment. You will see a 3 dB increase in signal strength of any given mode skywave signal over a simple dipole, or nearly complete cancellation of the signal if you are using circular polarization of the opposite sense. Most hams are positively astonished when they actually demonstrate this to themselves.

Out of the Lab and into the Shack

I've found that, once I'm able to convince hams that X and O modes actually exist, it's a relatively simple task to explain the "so what." The implications of these two very distinct and separate signals being generated by every long distance HF transmission become

fairly self evident. We can reuse frequencies by careful use of CP antennas. We get an automatic bonus of 3 dB just by using CP receiving antennas. We can even more accurately predict DX propagation by making an educated guess as to which mode we're working with — and concentrate our efforts on just that mode. Probably most importantly of all, many of the mysteries of propagation we normally just chalked up to weirdness are suddenly, and nearly as mysteriously, gone. Things begin to make sense. There is new order to our perceived universe.

We have a relatively common malady up here, especially on 20 meters.⁵ We often experience conditions in which rotating a high gain Yagi clear around the compass has no effect on an incoming signal's strength. This is especially prominent on incoming Northern European stations. The signal seems to come from everywhere at once.

The answer is rather simple, once one recognizes that those signals are circularly polarized. Actually it's coming from straight overhead. This is what happens when you have a low angle signal bouncing off an ionosphere that's tilted at a 60° angle. This isn't rocket science, it's just geometry. Well, the ionospheric tilt only explains part of it. By rotating the Yagi, shouldn't there be some cross polarization effects on a downward arriving signal? Not if the signal is circularly polarized. A horizontal Yagi has no way of knowing what the polarization is of a circular signal coming in broadside.

Probably a little closer to home for most hams (the above is an Alaskan weirdness, after all) is the matter of circular polarization in the FM broadcast business (and to a limited degree in TV broadcasting). Has it ever occurred to you why nearly every FM broadcast station in the past 40 years has transmitted a circularly polarized signal? Is it because the vast majority of FM listeners have circularly polarized antennas? Not likely. Is it because about half the listeners use vertical polarization, and half use horizontal polarization? No, it's still about 80% in favor of horizontal polarization, even with car radios. Industry specialists who have major financial interests in getting the correct answer to this question have known the answer for years.

The real reason for using circular polarization in FM broadcasting, as delineated in the very FCC documents that authorized its use, is solely for the reduction of multipath distortion — primarily in the form of phase cancellation. How does this work? A linearly polarized signal, after being reflected from a surface, will generally be out of phase with the incident signal. If this reflected signal is recombined in the receiving antenna, along with a direct signal, the chances of phase cancellation, to some degree at least, are very good.

On the other hand, if a circularly polarized wave reflects off a surface, it remains circularly polarized, but its sense is reversed. Statistically, this has a much lower chance of causing phase cancellation, regardless of the polarity of the receiving antenna. Additionally, if the receiving antenna should use circular polarization (as exceedingly rare as this might be in consumer circles) the chance of phase cancellation would be nearly zero.

**“This isn't
rocket science,
it's just geometry.”**

Now, could it be within the realm of possibility that some of these effects, though naturally of different scale from those on HF, could be used to some advantage? Why not? Furthermore, could this account for some otherwise inexplicable behavior of certain HF signals? Quite likely. At the very least, would this merit further investigation?

Building a CP antenna to at least investigate these possibilities is so simple, there's no excuse for the enterprising ham to not at least give it a shot. It's a great field for experimentation. Still not convinced about this whole X and O business? Good. I invite you to build a circularly polarized antenna and find out for yourself. The sidebar describes how to make a simple one for yourself. In so doing, you will prove the physicists (and yourself) right. I'm so confident of this that I will give you the weapons to do this in the associated polarimeter projects, one simple (on the QST-in-Depth Web site) and one quite fancy.⁶ Both methods will use WWV as the reference transmitter, since it has such well controlled characteristics.

Notes

¹The more pedantic radio amateur (and mathematician) is apt to remind us that the circle is merely a special case of the ellipse, that is an ellipse with an ellipticity of 1. At the other extreme, an ellipse with infinite ellipticity, is the line. This, of course, covers all possible cases of any radio wave, which may seem to largely dilute the impact of the first paragraphs of this article.

Once one actually does the experiments, however, one finds that the degree of roundness of ionospheric signals is amazingly good. One of the best indications of the degree of circularity is the degree of incorrect sense signal rejection. Up to 3 S-units (on the order of 15-18 dB) is typical for most haphazardly installed HF CP antennas. Such figures would not be possible if the waves had a high degree of ellipticity. With careful alignment of the antenna “on bore” much higher degrees of rejection are realizable.

Although there is no theoretical maximum value for the cross-polarization discrimination of a CP antenna, there's no point in trying to achieve particularly high degrees of discrimination. The limiting factor for this application, as mentioned above, is the lumpiness of ionospheric reflections, anyway.

²Extracted from US Bureau of Standards' Letter Circular LC-375, “The Ionosphere and Radio Transmission,” QST, Mar 1940, pp 32-35, 88-92.

³The *High Frequency Active Auroral Research Program* (HAARP), an ionospheric research program funded by the US Air Force, the US Navy, the University of Alaska and the Defense Advanced Research Projects Agency.

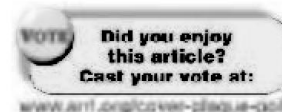
⁴There is a further exacerbating cause up here, somewhat unrelated to this topic — that of a tilted ionosphere. Most models of ionospheric propagation make a couple of assumptions, and those are huge assumptions. The first is that the ionosphere is flat, and the second that the ionosphere is horizontal. Neither of these conditions prevails in Alaska, but again, this is a separate issue.

⁵I don't know precisely why 20 meters is so pronounced in this regard — we haven't solved *all* the mysteries. This is where every ham can contribute to the state of the radio art.

⁶www.arri.org/qst-in-depth

Eric P. Nichols, KL7AJ, has written numerous QST and QEX articles over the past 30 years, with a strong emphasis on RF design and techniques. He worked as a broadcast engineer for a quarter century, later applying his RF experience to experiments conducted at HIPAS (High Power Auroral Stimulation) Observatory and HAARP, as well as designing instrumentation for the UCLA Plasma Physics Department. His first novel, Plasma Dreams, was published in 2005. His upcoming book, The Opus of Amateur Radio Knowledge and Lore, is slated to be published sometime in the not too distant future. Eric can be reached at PO Box 56235, North Pole, AK 99705 or at eric.nichols@cielson.af.mil.

QST



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