

Automotive RFI Elimination

*Modern vehicles are RF-noisy environments.
Come learn how to identify and silence
your mobile noise sources.*

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[Editor's note: Readers should check with their automobile manufacturers' EMC departments before performing any modifications that may void vehicle warranties.]

Automotive RFI can drive hams crazy and I was no exception. Even with a good noise blanker, RFI makes it very difficult—if not impossible—to hear weak stations. It is also difficult to identify noise sources using a mobile HF radio as a noise-proximity tester, that is, to obtain noise signatures by picking up other noisy vehicles, power lines, traffic lights, etc. It is theoretically possible to eliminate all automobile RFI noise.

Automotive Background

Automobile manufacturers have minimized conducted and radiated ignition, electric-motor and generator noise problems by adding inductive/resistive spark-plug wires, resistive spark plugs and judiciously placed capacitors. This was done primarily to reduce noise in the AM and FM broad-cast bands. The theory behind this is quite simple. By placing resistive and inductive distributed elements in a series circuit, voltage rise times are increased and current is decreased. In addition, a capacitor placed

between power and ground provides a low-impedance return path for low-frequency noise. The problem is the capacitor looks inductive (lead reactance) as the frequency gets higher. At some frequency, the component self-resonates. Rise time is related to the spectral content by the following approximation:

$$f_{(\text{occupied BW})} \approx \frac{0.35}{t_{(\text{rise time})}} \quad (\text{Eq 1})$$

If the rise time increases, the spectral energy content decreases. With charge flow lessened by the increased inductance and resistance, the magnitude of the radiated electromagnetic field is also reduced. These noise-reduction techniques were not intended for HF ham radios, but they do help a little. The problem is that it's not enough. Broadband noise is picked up by our HF rigs! Essentially, we drive around with spark-gap transmitters under our hoods, connected to ignition-wire antennas!

To help understand how things radiate, let's look at things in mathematical terms. The time rate of change of voltage (dv/dt) and current (di/dt) both are reduced using the previously mentioned methods. This is easily derived from the first-order differential equations for resistive or inductive spark-plug wire systems. Keep in mind that accelerating charge radiates electromagnetic energy. To understand this,

consider the following:

$$I = \frac{dq}{dt} \quad (\text{Eq 2})$$

Current flow (in amperes) is the rate of change of charge (in coulombs) per unit time. A constant dc current moves charge (electrons) through a wire and, for all practical purposes creates a static (unchanging) magnetic field. When the current is time varying, say:

$$I(t) = K \sin(\omega t) \quad (\text{Eq 3})$$

where K is the peak magnitude and $\sin(\omega t)$ describes the function of time ($\omega = 2\pi f$), things start to happen: A travelling electromagnetic wave is produced. Taking the time derivative of Eq 3's current yields:

$$\frac{d^2q}{dt^2} = K\omega \cos(\omega t) \quad (\text{Eq 4})$$

This equation represents accelerating charge that radiates electromagnetic energy. With dc current, there is no electromagnetic radiation; with a time-varying current, you get electromagnetic radiation. See the Appendix for proof.

Solutions to ignition impulse noise have already been found and successfully demonstrated in aircraft with internal-combustion engines. The VHF, AM aircraft band is especially susceptible to ignition noise. Aircraft manufacturers fixed these problems so aviators could use their AM radios. Next time you have a chance to look at an aircraft engine, observe the shield-

ing on the ignition wires.

My Mobile Rig

After getting on HF again following a long absence, I decided to install my newly purchased Kenwood TS-570D transceiver into my 1995 Toyota 4WD 4-Runner. After routing power and ground wires directly from the battery terminals and using a network analyzer to tune my ham-stick antennas (courtesy of IDAFAB's Glenn Borland, KF6VZK), I thought I was ready for my first QSO driving while hamming. I couldn't have been more disappointed. The RFI level was between S-7 and S-9. Murphy had stricken again. Oh boy—what to do?

Not long after this, back at home I heard a mobile-7 station on Interstate 10 east of Tucson working the Philippines. I just about fell out of my chair. Weeks later, I was on a one-day picnic trip to Anza-Borrego Desert State Park. With the engine turned off, I heard a station in Uganda on 10 meters and worked him! I never would have been able to hear him with the engine on: There would have been too much RFI. I realized right then that I had to eliminate the noise. Elimination of RFI noise is not black magic, but it follows theory just like everything else. It usually involves a multi-step process.

Conducted and Radiated Noise

Two different types of noise need to be considered in automobile RFI control: conducted and radiated. Conducted noise is called that because it comes through wires and other conductors directly from the noise source. Radiated noise enters the receiver at the antenna via electromagnetic fields from the source. To effectively get rid of any noise source, one must first understand if it is conducted or radiated and then determine where it's coming from. If one has no theoretical understanding, it's all the more difficult and one is left with the process of "Easter-egging." That is, you might get lucky and find the cause by adding all sorts of time-tried solutions.

The noise sources in my automobile were determined to be in the ignition system, which includes the spark plugs, wires, distributor and coil, dc motors and a noisy oil-pressure sender.

Conducted-Noise Tests

The radio amateur needs to first determine if the conducted noise on their vehicle's 12-V power system is producing noise in their rig. To determine this, do the following:

1. Start the engine and switch the rig on. This must be done without an antenna because you don't want to confuse conducted noise with radiated noise that is picked up through the antenna. Make sure the air conditioning, all fans, blowers, blinkers and windshield wipers are turned off.

2. Turn your transceiver's mode switch to AM and listen on HF, then increase the engine speed a little.

3. Do you hear any popping, whining, crackling or any other noise that increases with engine speed?

4. Turn the engine off. Now turn on the fans, blowers and air conditioning one at a time.

5. Do you hear any whining?

Did you notice any noise in steps 3 or 5? If you did, the noise you heard or saw

on the S meter is conducted through your dc bus. If no noise was heard, your rig is not susceptible to the conducted 12-V power noise. If you heard noise in steps 3 or 5 you will need to install a low-pass filter that is capable of operating with your trans-mitter's load current, typically about 20 A for a 100-W HF rig. With derating, the filter should be able to pass around 25 A or so with a low voltage drop. Obviously, the filter's dc resistance needs to be quite low or you'll get a significant voltage drop between the battery and your rig.

The ideal filter for this application would be of the L-C variety, containing a series inductor and shunt capacitor. This filter's forward voltage transfer function decreases noise on the output as a function of frequency. Dc output



Fig 1—Braid installed over spark-plug wires at distributor.

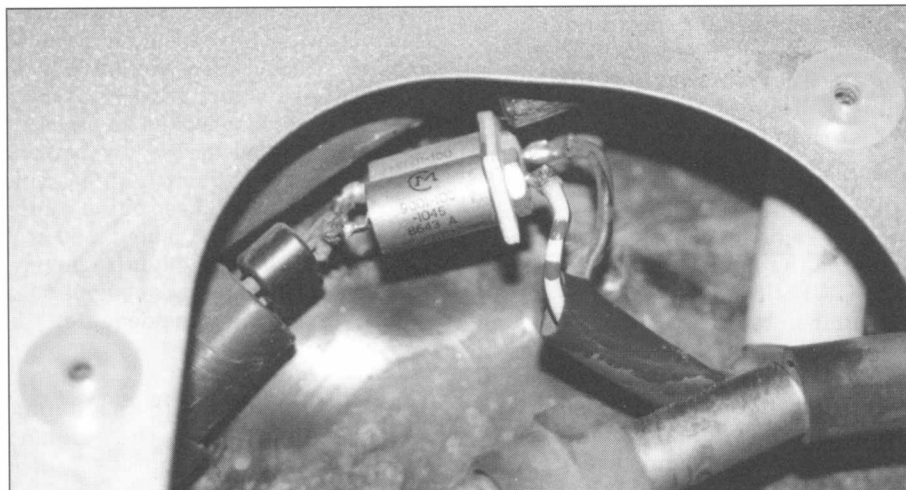


Fig 2—Filter cons installed on bracket.

current and voltage will not be affected. Do not use a pi filter here. Such a filter may couple noise from the dc bus down through the first capacitor to ground, then up through the second capacitor into your rig! The inductor side should be attached to the battery and the inductor-capacitor node to the radio side. The best type of power filter for this application is called a "filter con."

Filters

To reduce RFI, one must understand filter basics. Filters can reduce or eliminate both conducted and radiated noise. Choosing the correct filter for a particular application can be a significant task in itself. Say, for instance, you want to get rid of noise on a power supply's output. You think that adding a capacitor will solve the problem; but after placing the capacitor, you find it did no good! Among other things, filter placement depends on source impedance. Noise from a low-impedance source cannot be reduced by a capacitor alone. It is simply a matter of voltage division:

$$V_{\text{out}} = V_{\text{in}} \left(\frac{Z_{\text{load}}}{Z_{\text{source}} + Z_{\text{load}}} \right) \quad (\text{Eq 5})$$

If Z_{source} is small, you can take it to zero. Then you're left with:

$$V_{\text{out}} = V_{\text{in}} \quad (\text{Eq 6})$$

The point is to think about what is happening in the circuit. The source impedance may determine what filter to add. To get good attenuation from a low-impedance source, one needs to add an L-C filter. Batteries are typically low-impedance sources!

To understand this better, think of a voltage source having zero output impedance in series with an impedance Z . Z can be resistive, inductive, or some combination of both; it represents the opposition to current flow. In the case of the lone capacitor, it had no impedance to work with. Therefore, the noise currents charged up the cap quickly because its impedance was larger than that of the source.

Power Filter Cons

Power filter cons are nice solutions to ham radio automotive noise problems for the following reasons:

1. L-C (series-L, shunt C), C-L-C (shunt-C, series-L, shunt-C, a pi network) and L-C-L (series-L, shunt-C, series-L, a T network) varieties are available at surplus and from a variety of manufacturers.
2. The filter components are hermetically sealed in a metal tube; so they can't radiate and are easily mounted

with a bracket, washer and nut.

3. The parasitic reactances have already been minimized.
4. The self-resonant frequencies of the filters are high.
5. They come in various current ratings.

Second-order filter cons typically attenuate noise at -40 dB/decade of frequency above the 3-dB point.

$$f_{-3\text{dB}} \approx \frac{1}{2\pi\sqrt{LC}} \quad (\text{Eq 7})$$

Filter cons are good up to a couple hundred megahertz. Typical series-inductance values for 25-A dc power-line filters would be in the range of 100 to 200 μH , with a shunt capacitor of about 1 to 2 μF . The break-point frequencies of these filters are about 15 kHz, or so. Essentially, this filter forms an ac voltage divider with the noise source's impedance, thus reducing ac noise at its output—more about this later. Smaller filter cons rated at 5 A or so have less inductance.

This type of filter can be large depending upon the voltage and current ratings: The inductor must not saturate. It must support the full load current, which can be up to 25 A for a 100-W transmitter—and don't forget derating. Inductor size is directly proportional to the amount current flowing through it. If the inductor saturates, you have only the wire resistance and little additional inductance. In this case, you would just have a first-order filter composed of nothing more than an R and C—not very good! Take the time to select the right filter up front.

Make sure that the ground return on your rig goes right to a solder lug on the bracket as close to the filter con as possible. After the filter is installed, repeat the above tests to see how effective it is.

Most transceivers have filters on the dc power line coming into the transceiver. In my case, the Kenwood TS-570D did not have a conducted noise problem. I did not see any indication on the S meter, nor did I hear any conducted noise. I also looked on an oscilloscope connected across my battery and noticed low-frequency ripple similar to what one would see out of a full-wave bridge rectifier: about 100 mV (P-P) punctuated with high-frequency, damped sinusoids. It was obvious that the filter in the rig was adequate.

Radiated-Noise Tests

1. Switch on your rig with an antenna connected and notice the ambient noise level with the engine off. It is better to do radiated tests on days when the ambient noise is not read-

able on the S meter.

2. Next, turn your mode switch to **AM**—with the noise blanker off—and start your engine. You'll probably hear a popping noise. Note the S-meter reading.

3. Increase the engine speed. Do you notice that the popping noise increases with engine speed? The popping noise is impulse noise from the ignition system; it is caused by the current flowing in various parts of the engine. In another words, your ignition system is radiating, and your antenna is picking it up. This is the noise problem that you should probably solve first.

If you already have resistive spark plugs and wires, the voltage and current rates of change dv/dt and di/dt should not be altered. Something else must be done. Grounding the hood will not eliminate this noise. We must attenuate the electromagnetic radiation without affecting dv/dt or di/dt , both of which are necessary for proper engine performance.

Electromagnetic radiation of this sort *can* be greatly reduced. Maxwell's equations—the four that describe all electromagnetic waves—can yield great insight to the behavior of fields at boundary conditions. One boundary condition for E fields occurs as follows: The tangential E-field component of a propagating electromagnetic wave decreases to zero at the surface of a perfect conductor (metal) and is continuous across the boundary. That is to say: The E field shrinks to a small value across the skin depth of a metal shield, since there is no perfect conductor. The normal component of the H field passes through the metal boundary. The E-field attenuation typically will be on the order of 60 dB or so. That's a 1000-to-1 change! To greatly reduce or eliminate ignition noise, therefore, we must shield the ignition system—it's the only way. Don't worry; it's a job, but not as hard as you might think.

In shielding my ignition system, I wanted to ensure that I had good RF grounds and low-impedance current-return paths. That is, I wanted to be certain that—while each spark-plug fires—the return current travels via a shield over the spark-plug wire. The current path from the coil through the spark plug wires to the spark plug and back to the coil should be as direct and non-inductive as possible. Any other ground paths on an engine might look inductive and present a virtually open circuit at RF! The plan, therefore, was

to use flexible braid as a low-impedance ground path.

Shielding My Toyota's Ignition Spark-Gap Transmitter

My ignition system was shielded in the following manner. First, I had copper-tube spark plug covers made for all six spark plugs. They snap into place over the base of the plugs (ground potential) with a slight interference fit. I then soldered flexible braid to the outside of each spark plug's copper cover. In this way, I was able to snap

the cover over the plug at its base to provide a good ground, at the same time plugging the electrical-connection boot onto the spark plug in one motion. The copper spark-plug covers were made for me by Tooling Associates.¹

There are two common spark-plug-base sizes. Toyota spark-plugs in a 4-Runner are of the smaller-diameter. To shield them, I used 1/2-inch flexible braid (Belden #8669)² over each spark-plug wire all the way from the spark plug to

¹Notes appear on page 56.

the distributor. To increase dielectric strength, I wrapped the spark-plug wires with insulated flexible tubing before installing the braid. With ground now located so close to the wires, I sure didn't want any high-voltage breakdown. I used 3/4-inch braid (Belden #8662) to cover the larger-diameter boots at the distributor.

Belden braid comes in 50-foot lengths, so maybe a club or group purchase would be best. You can find the braid in the Newark catalogue. So far, the silicone spark plug wires have exhibited no high-voltage breakdown.

Appendix: Strength of EM Fields Radiated by Accelerating Charge

The following proof quantifies the field strengths of an electromagnetic wave as created by accelerating charge in a wire [or antenna element—*Ed.*]. This derivation begins with one of the four basic laws of electromagnetism known as Maxwell's equations. These laws were formulated as a set by Maxwell, but certain parts of them were obtained directly from the work of others such as Gauss, Ampère and Thomson.

The first law may be stated: "The work required to carry a unit magnetic pole around a closed path is equal to the total current passing through any surface that has the path for its boundary." Vector calculus says the same thing more succinctly, here in integral form:

$$\oint H \cdot dl = I_{\text{conduction}} + \frac{\partial \phi_D}{\partial t} \quad (\text{Eq 8})$$

where the left-hand side represents a line integral around a closed path, *dl* is a vector element of length along that path, *H* is the magnetic-field vector and ϕ_D is the electric flux linking the path. See Fig A. The time rate of change of ϕ_D is written as a partial derivative to show that the path of integration is not moving in space.

In a wire, there is no *E* field, so we are left with:

$$\int_0^{2\pi r} H \cdot dl = I_{\text{conduction}} \quad (\text{Eq 9})$$

$$= 2\pi rH$$

where *r* is the distance from the wire. But, current is the time rate of change of charge, *q*:

$$I_{\text{conduction}} = \frac{\partial q}{\partial t} \quad (\text{Eq 10})$$

and so:

$$\frac{\partial q}{\partial t} = 2\pi rH \quad (\text{Eq 11})$$

Now give the charge some acceleration (changing velocity). Taking the time derivative of both sides:

$$\frac{\partial^2 q}{\partial t^2} = 2\pi r \frac{\partial H}{\partial t} \quad (\text{Eq 12})$$

This shows that an accelerating charge generates a magnetic field that changes with time. A changing magnetic field is related to the electric field by Maxwell's second law, which may be stated: "The work required to carry a unit electric charge around a closed path is equal to minus the time rate of change of the magnetic flux through that path." Again using integral form:

$$\oint E \cdot dl = - \frac{\partial \phi_B}{\partial t} \quad (\text{Eq 13})$$

where *E* is the electric-field vector and ϕ_B is the magnetic flux linking the path of integration. See Fig B. We have an electromagnetic wave!

Maxwell's equations may also be written in differential form. An excellent book that explains this vector calculus stuff in understandable ways is H. M. Schey, *Div, Grad, Curl and All That*, 3rd edition, ISBN 0-393-96997-5.

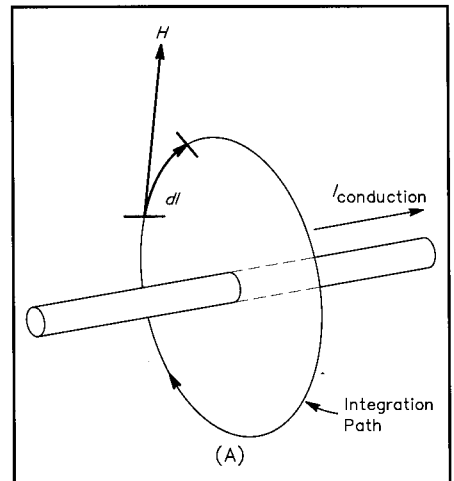


Fig A—The situation of Eqs 8 through 12.

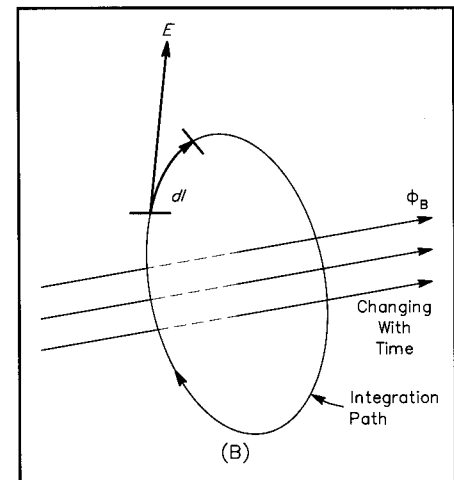


Fig B—The situation of Eq 13.

Second, the distributor was zinc "flame-sprayed" to create a volumetric metal enclosure (shield) only a few mils thick, but still thick enough that the E field exponentially dies off and meets the E-field boundary criteria. This could also have been done with the coil. Flame Spray, Inc of San Diego³ graciously sandblasted and flame-sprayed the distributor. The distributor had to be masked so that the metal did not cover areas where its was not needed. Plastic parts are routinely sprayed for EMI/RFI protection in military and commercial applications, and the flame-spray people are in this business.

Taping of the distributor can be a task; otherwise high-voltage arcing can occur. I taped the coil myself with 1-inch-wide, 1-mil-thick copper tape, which was supplied by Chomerics of Woburn, Massachusetts.⁴

Third, I used narrow hose clamps to connect the ends of the braid to the wires to the distributor and coil below the insulating boots. It worked quite well. See Fig 1.

After completely shielding the ignition wires, coil and distributor, I studied the ignition circuitry for *sneaky* RF paths. Next, I put two filter cons between the +12-V power line, the igniter and the coil. I mounted them on a bracket with a good RF ground next to the coil and igniter. The reason for this was simple: I did not want broadband RF energy in the wire from the distributor to the coil to get into my 12-V power line and radiate.

All coils and transformers are self-resonant and start to look capacitive—rather than inductive—at some frequency. The Toyota's high-voltage ignition coil is no exception. Remember that all current—even RF—wants to return to its source. Why not give it a low-impedance path by making the path short? Minimizing the current-loop size minimizes the radiated energy, as well.

Ah, but what kind of filter con should I select? In this case, an L-C filter con was the optimum choice because the output capacitor shunts the dc power at the coil and igniter right at its source, creating a very short return path for RF. The series inductance presents a large inductive reactance that keeps RF off the +12-V power line.

Judging from the wire gauge from the battery to the igniter and coil, the dc current must be on the order of a couple of amperes. Therefore, I used a 5-A filter con that's about the size of a fat pencil and about 1-inch long. Its dc working voltage is 50. See Fig 2.

Fuel-Pump Noise

When I finished the job, I started the motor, switched the radio to **AM** and noticed that the ignition noise was gone! Now I heard another noise that had been masked by the first noise source: a whine that did not change with engine speed. What was it? —Some kind of motor that was radiating! Since all other motors and fans were turned off, it could only be the fuel-pump motor inside the gas tank. With the engine on, I pulled the fuse to the fuel system. The noise stopped—I had found it!

Again, I thought about EM theory. I knew it was motor noise and that every motor has a rotor and a stator. I thought there must be some sort of brushes making sparks. Since sparks make broadband noise and rotors and stators can self-resonate, I theorized that the RF energy must be coupling capacitively through the rotor or stator and looping back through my power system. After some ground testing, I found two ground returns for the fuel pump system: one through the vehicle ground and one via a power-return wire! I wanted to put the filter cons right at the source, but that was going to be tough unless I removed the gas tank—which I did not want to do. As it turned out, there was an access panel on top of the gas tank, accessible through the back seat. Again, I wanted to short out any RF return currents and short out the sneak path.

The place to do this was at the top of the gas tank. I mounted two 5-A filter cons on a bracket, in turn connected to a tab through a self-tapping screw made for holding the gas-tank wires to the top of the tank. Fuel-pump power and return passed through both of the filter cons. By now, you're probably wondering what kind I used. I used a low-pass pi network. It worked! When I turned the engine back on, the noise from the fuel pump was gone!

Oil-Pressure-Sender Rheostat Noise

Well, by now I had spent considerable effort eliminating noise problems, but I wasn't going to quit now! With the engine running for a while, I noticed that I had no noise for a couple of seconds—then all heck broke loose. The next noise did not whine but crackled. When I increased the engine speed, it stayed nearly constant. When I decreased engine speed, it went away for a couple of seconds, then came back. I wondered what would cause this.

I took out my scope and looked on the

+12-V bus. I saw some noise but thought it was too low in frequency to cause what I was hearing. Obviously, the real source was something that switched on shortly after engine start and changed after decreasing engine speed. I thought it might be the sender in the fuel pump and therefore pulled the gauge fuse, opening all sender circuits. The noise stopped! I then knew it was some sort of sender, but which one?

Then it hit me: Oil pressure rises when the engine is first started, until it reaches its proper value and it changes again with engine speed—some sort of rheostat. I pulled the connector from the oil-pressure sender and the noise stopped! I looked at my S meter. There was no noise indication, and I could not hear any vehicle noise! I removed the sender unit from the engine. With help from Glenn Borland, KF6VZK, I cleaned the sensor body of "chem" film and soldered a filter con onto it. We used a high-power soldering iron for this because we wanted the job done quickly to avoid damaging the sender. This requires a large, hot thermal mass. There was no good place to put a bracket. Best was to mount the filter con directly onto the sensor and that's what we did.

Shake-Down Test

Since I had put many hours into solving my RFI problems, Janice and I decided to go to Anza-Borrego Desert State Park for a picnic and a hike. The HF rig went along too, although it was in the back seat. (Never put the rig on the right-front seat with the girlfriend or wife along—it might find its way onto the highway!)

With the engine on, there was no noise indication on the S meter in the **AM** mode. I quickly turned to SSB. I could hear all kinds of stations—even weak ones; I worked several stations and thought how nice it was to be able to finally use my rig to its full potential without limiting RFI. We hiked up Palm Canyon and were rewarded a sighting of a bighorn sheep—a borrego. It was a great day!

Notes

¹Contact Pete Bird, 15570 Corte Montanoso, San Diego, CA 92127; tel 619-672-1949.

²Belden Wire & Cable Co, PO Box 1980, Richmond, IN 47374; tel 765-983-5200, fax 765-983-5257; <http://www.belden.com/>.

³Flame-Spray Inc, 4674 Alvarado Canyon Rd, San Diego, CA 92120-4304; tel 619-283-2007; contact Gary Logan.

⁴Chomerics Division, Parker Hannifin Corp, 77 Dragon Ct, Woburn, MA 01888-4014; tel 781-935-4850, fax 781-933-4318; <mailto:mail@chomerics.com>; <http://www.chomerics.com/>. Contact Dennis Hennigan, WA1HOG, extension 4140. □□