RFI - Intermodulation

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Some old-time hams remember when VHF was quite deserted. Nearly all stations found above 50 MHz were TV and FM broadcasters. The 2-meter band was often silent, and there were relatively few VHF transmitters used by the police and businesses. With so few stations on the bands, and those stations using simple equipment (insensitive receivers), interference was unlikely.

If you use VHF today, you know that those days are gone forever. Thousands upon thousands of transmitters operate above 50 MHz for business, public service, amateur, satellite and many other uses. In addition to licensed transmitters, there are countless unlicensed transmitters, operating under FCC Part 15. It is likely that some of these radio systems will interact in undesirable ways.

When a new ham first fires up a VHF receiver and hears a few pagers in addition to the normal signals--or, even worse, hears bleeps, noises and unidentified voices across most of the band--he or she often turns to more experienced hams for an explanation. Most of these explanations blame the problem on *intermod* (intermodulation distortion, or IMD)--often with little explanation of the term.

What Is Intermod?

Communicators sometimes use the term intermod incorrectly. While intermodulation of two or more signals causes some VHF interference problems, other problems, such as front-end overload, poor IF (intermediate frequency) image rejection or IF leakage are sometimes the real culprits. Hams tend to call them all "intermod," which complicates the explanation a bit.

In a perfect world, every amplifier would amplify signals without distortion, every mixer would convert RF signals to the IF perfectly, and a radio would hear only the desired signal. In the real world, however, all of these processes are nonlinear to some degree. This results in the creation of interference.

What does "nonlinear" mean? It means that the output voltage does not follow the input voltage perfectly. Nonlinear circuits can generate harmonics and mix signal frequencies. The RF amplifier or mixer circuits in a receiver can be somewhat nonlinear, creating additional signals from the desired signal--and perhaps others--present at the nonlinear stage.

Harmonics

When a single frequency (the *fundamental)* passes through a nonlinear circuit, distortion signals appear at integer multiples of the fundamental frequency (*harmonics*, see Figure 1). We identify each harmonic by its relation to the fundamental: The second harmonic is at two times the original frequency, the third at three times the frequency, and so forth. We use frequency multiplier circuits to produce only desired harmonics. *Unwanted* harmonics can cause interference wherever they occur, ranging from HF-transmitter harmonics that interfere with a TV, to a 49-MHz transmitter's third harmonic that interferes with a 147-MHz 2-meter station (49 × 3 = 147).

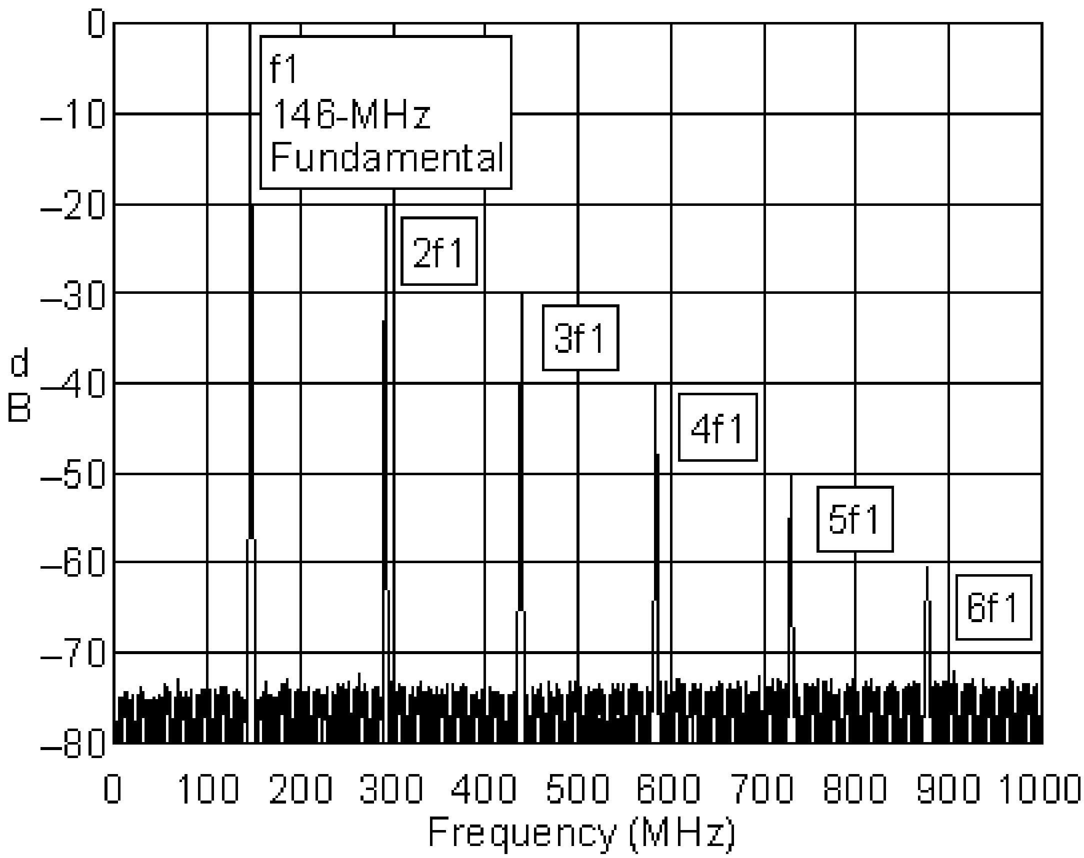


Figure 1--This 146-MHz signal contains harmonics that extend well into the UHF range.

Mixers

Mixers are nonlinear devices by design. In a typical mixer used in a superheterodyne receiver, a desired signal mixes with that from a local oscillator (LO) to produce sum and difference signals. The IF circuitry selects and amplifies either the sum or difference signal. In older radios, the IF is usually the difference frequency. Modern radios, some of which use multiple conversions, sometimes use the sum frequency.

All Mixed Up

IMD, however, is a mixing process gone bad--a form of *distortion*. Whenever two or more signals are present in a nonlinear circuit at the same time, IMD creates new, unwanted frequencies from them.

The relationships between the two signals and the resultant distortion products can be quite complex. (We'll work with only two inputs, f1 and f2, to simplify our discussion.) Signals and *their harmonics* can mix together to form still more new frequencies. Any signals created in the circuit can then mix with each other and the original signals to form a complex spectrum, indeed.

The strongest IMD products are those that involve the sum and difference of the input frequencies, the harmonics of the input frequencies, and the mixing of the harmonics with each of the original input frequencies (harmonic mixing). There are higher-order mixing relationships, but they're more complicated than we want to discuss here.

IMD Product Orders

We often use the term *order* to describe a group of IMD products. Because IMD results from combining frequencies, we can identify each IMD product with an equation describing the sums and differences of the various signals involved. For example, f1 + f2, 2f1 - f2 and 3f2 - 2f1 are three such equations. An IMD product's order is the sum of the coefficients (in the term 2f1, 2 is f1's *coefficient*) of the terms in the equation. Remember that, even though you don't see it, a term like "f1" has a coefficient of 1. Table 1 shows some example IMD equations and their orders. Figure 2 shows the result of a mixer circuit (or very nonlinear amplifier) generating sum and difference products.

Table 1
Orders of Some IMD Products

IMD Product	*Order*
f1 + f2 f2 - f1 2f1, 2f2	2
2f1 - f2 f1 + f2 - f3 3f2	3
2f1 - 2f2 3f2 + f1	4

IMD is more complex than simple sum and difference second-order relationships. A nonlinear circuit creates harmonics of *all* input signals, and those harmonics mix with all of the fundamental signals plus those created by the nonlinearity. Third-order IMD between paging systems causes much of the IMD problems that plague VHF operators.

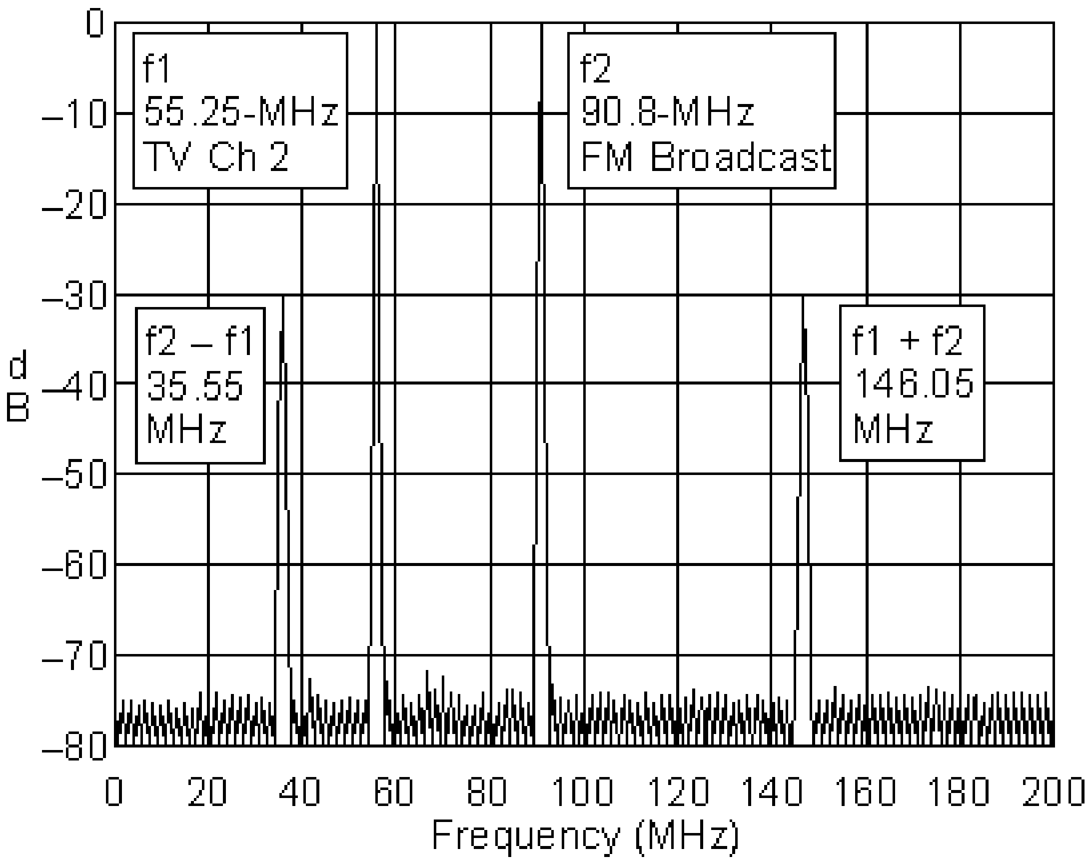


Figure 2--Here, f1 (55.25 MHz) and f2 (90.8 MHz) are present at the input of a VHF receiver, they may generate an interfering signal (f1 + f2) on 146.05 MHz.

Third-Order IMD

The second harmonic of f1 or f2 can mix with the other fundamental to form a product. These products are especially important because they are low-order products, and therefore relatively strong. Also, when f1 and f2 are relatively close in frequency, these products are close to f1 and f2. These equations characterize third-order products:

2f1 - f2 (Eq 1)
2f2 - f1 (Eq 2)
2f1 + f2 (Eq 3)
2f2 + f1 (Eq 4)

The first two are probably the most important to the VHF operator because the frequencies involved are so close to the desired frequency. For example, a pager on 153.75 MHz (f1) can mix with a 160-MHz (f2) signal to produce an interfering signal (2 × 153.75 - 160 = 147.5) on the 2-meter band, according to Eq 1. Some of these frequencies are assigned to paging transmitters, which are very common in urban areas. Figure 3 shows the result of third-order IMD in a nonlinear circuit.

Higher-order products do exist. Figure 3 shows how higher odd-order products (fifth, seventh, etc) form a "Christmas-tree" pattern up and down the band.

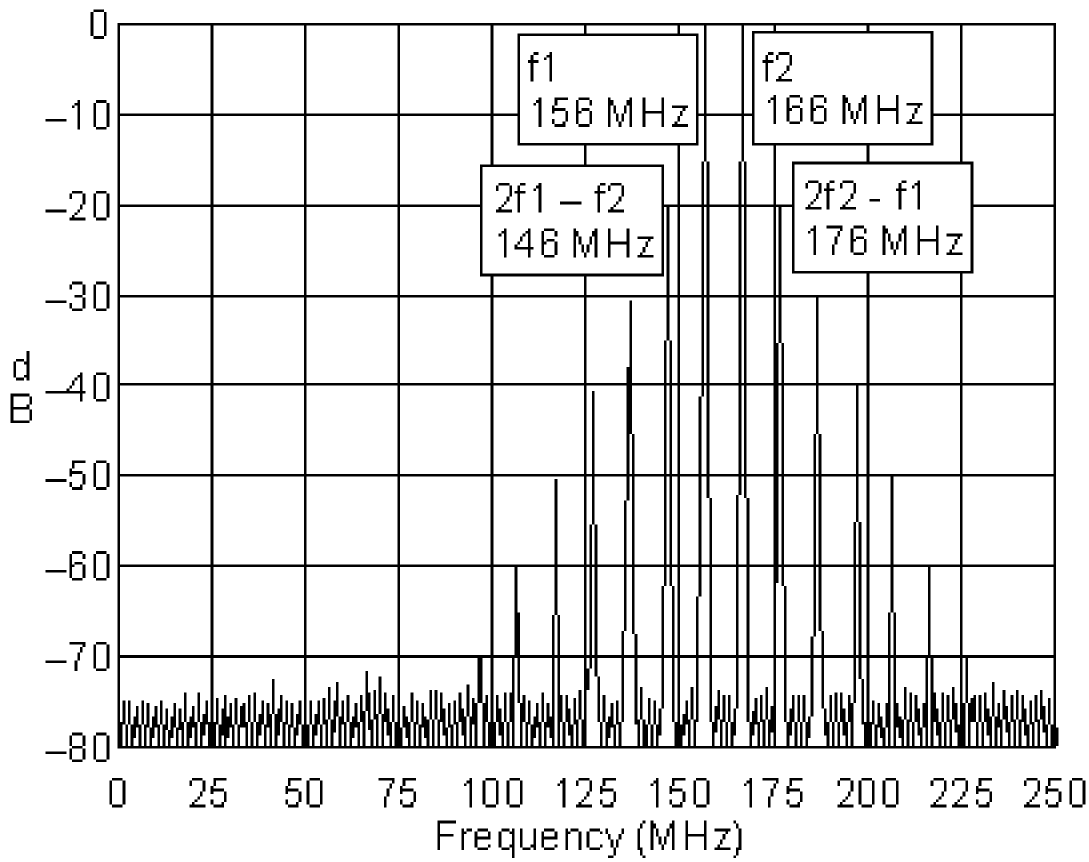


Figure 3--These pager frequencies can intermodulate to form a product in the amateur 2-meter band. If there are many pagers on different frequencies in the same area, the result can be interference across the band. This actually occurs in some major cities. This graph shows third- and higher odd-order products.

IF Response and Image Rejection

IMD is only one of the mechanisms that can create interference. Poor IF response and poor image rejection in the VHF receiver cause some problems that operators commonly blame on intermod. All superheterodyne receivers are subject to these problems. In a superhet, a mixer circuit combines the desired signal with a local-oscillator (LO) signal. The IF then selects either the sum or difference product for further processing. The presence of unwanted signals can disturb this simple scheme.

Figure 4 illustrates a 146-MHz receiver with a 10.7-MHz IF. Ideally, a signal on 146 MHz mixes with the 156.7-MHz LO to produce a difference signal on 10.7 MHz that is identical to the original signal except for its frequency. If a signal on 167.4 MHz reaches the mixer, however, that signal also appears on 10.7 MHz (167.4 - 156.7 = 10.7).

The front-end filters of well-designed radios reject (attenuate) image signals, so that users hear images only when the unwanted signal is very strong. Inadequate front-end filters can pass image responses that are as strong as the desired response. Poor image rejection is more common in receivers designed to tune over a broad frequency range. For example, a ham H-T that also receives the NOAA weather broadcasts at 162 MHz is likely to have trouble rejecting IF-image signals at 165.4 to 169.4 MHz because the images lie near the receive passband.

It is also possible to have an unwanted signal leak past the front end and mixer into the IF section. Then it's processed like the desired signal and heard in the receiver's output. Even though the sizes of IF components and conductors are small compared to the wavelength of unwanted signals, the gain of modern active parts can be extremely high. As a result, IFs can respond to unwanted signals coupled through incredibly small antennas. For example, a telephone handset can pick up HF transmissions, even with a filter in the telephone cord.

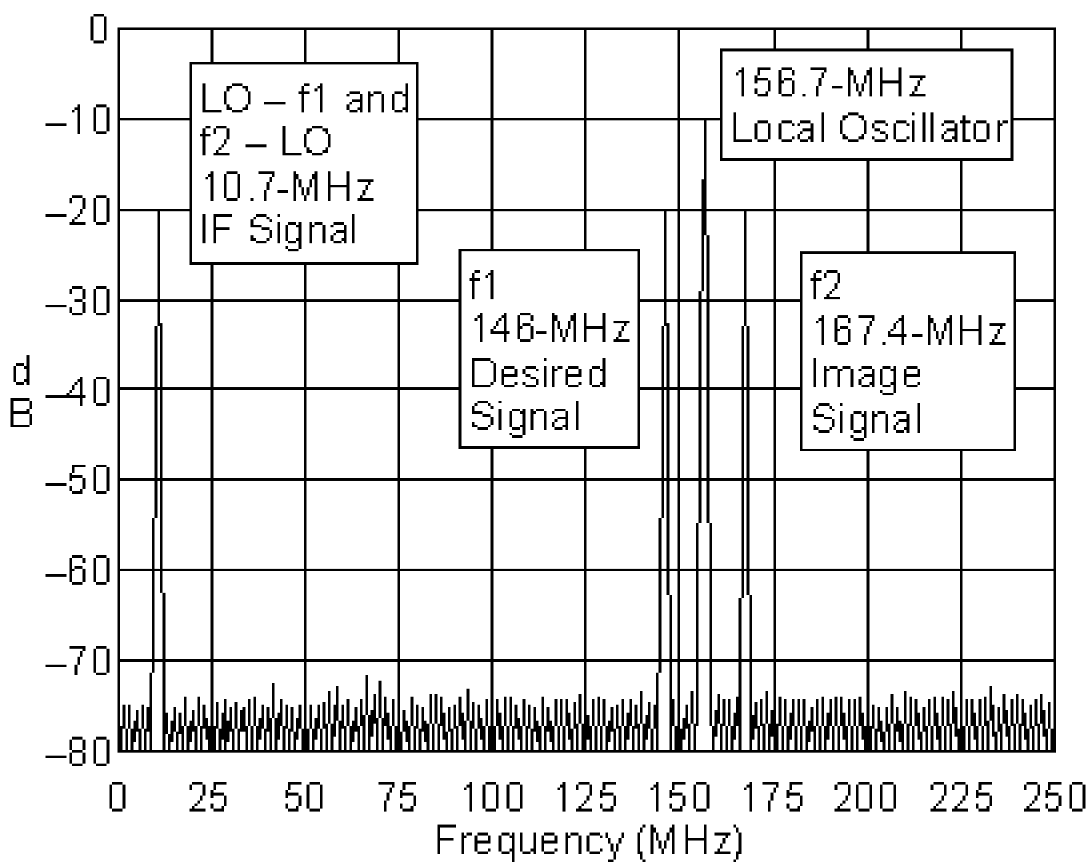


Figure 4--A superheterodyne receiver can respond to signals other than the desired signal. If the RF selectivity of the receiver is inadequate (poor image rejection), the receiver could hear the signal on 167.4 MHz in addition to the desired signal on 146 MHz.

All Radios Are Not Created Equal!

There are considerable differences in IMD performance among different radios. Many of these differences result from the radio design. A single-band radio that cannot receive frequencies outside that ham band usually offers good rejection of interference from nonham frequencies. Some radios have tracking filters in the front end that automatically pass the frequency a user selects. Other differences in performance can result from the specific design of front- end or mixer circuits.

The ARRL Laboratory performs an extensive battery of tests on all equipment featured in the Product Review column. One of those tests is a wide-band dynamic-range test on VHF equipment, using two strong signals just outside the amateur band (usually the abode of nearby pager transmitters). This test is a good indicator of relative IMD performance. *QST* lists the result in the Product Review table as "Two-tone, third-order dynamic range, 10-MHz offset."

The November 1995 Product Review column (available from the Members Only Web site, pr9511.pdf, [Adobe PDF file, 1,183,154 bytes]) compared eight dual-band FM H-Ts. The 10-MHz dynamic range varied quite a bit from radio to radio, ranging from 73 dB to 91 dB.

Why are they different? Many factors combine to affect a radio's IMD performance. Most VHF receivers are designed to be very sensitive because they will be used with inefficient "rubber ducky" or short mobile whip antennas. Unfortunately, this sensitivity can make the receivers prone to overload, especially when used with good outdoor antennas in urban areas.

Band-Pass Versus Broadband Designs

Radios designed to receive only ham-band signals contain a band-pass filter in the RF stages. This filter significantly reduces out-of-band signals, such as those from pagers. Most ham-band-only equipment is fairly immune to IMD problems.

Many hams want to use their VHF equipment as general-coverage VHF receivers, however, to monitor the police, fire and aircraft bands. Although this is convenient, it usually means that these receivers have broadband front ends. A broadband front end offers little protection against many interfering signals. It may be nice to have a radio that tunes from "dc to daylight," but that convenience may come with an unwanted price: The resultant combination of harmonic distortion, poor IF-image rejection and IMD problems can make the radio unusable in some areas.

Some receiver designs combine the best of both worlds: *Tracking* front ends automatically tune the RF stage to pass the desired frequency. Thus, when you use the receiver on 146 MHz, the front-end filter passes 146 MHz and offers some rejection to paging signals near 152 MHz, for example.

External Filters

External filters can significantly improve the IMD performance of existing radios. These filters are usually either band-pass or band-reject (notch) designs. Several companies sell filters designed to solve IMD problems.

Band-Pass Designs

Band-pass filters do just what the name implies--they pass a band of frequencies and attenuate all others. A well-designed filter can exhibit less than 1 dB of loss inside the passband and up to 60 dB or more attenuation outside the passband. Figure 5 shows two commercial band-pass filters. (Any of these filters will help reduce IMD problems.) The large filter at the top of the photograph is a helical band-pass filter made by DCI. [1] The ARRL Laboratory measured 0.8 dB insertion loss (a fraction of an S unit) and about 55 dB of attenuation at pager frequencies. This filter would make an excellent IMD filter for a base or mobile station. It is much too large to use with a H-T, however. Its band-pass characteristics are similar to those in Figure 6. It filters on transmit as well as receive, offering some additional EMI prevention as a bonus.

MFJ Enterprises sells the smaller filter shown in the lower left of Figure 5. [2] It requires an external dc power supply, and you must switch it off line manually or via the built-in RF-sensing circuit before transmitting. It has 6 dB of insertion loss on receive and offers up to 55 dB of attenuation at pager frequencies. It is small, and its BNC connectors mount it to an H-T easily. It is relatively easy to find the 30 mA of dc current required to operate the RF switch and internal relay.

Although up to 6 dB of insertion loss may seem excessive, most local FM signals are much stronger than 6 dB above the local noise. They will still fully quiet the receiver even when reduced 6 dB by the filter. More important, the filter removes third-order IMD from 150 to 160-MHz signals, allowing successful contacts on an otherwise unusable radio.

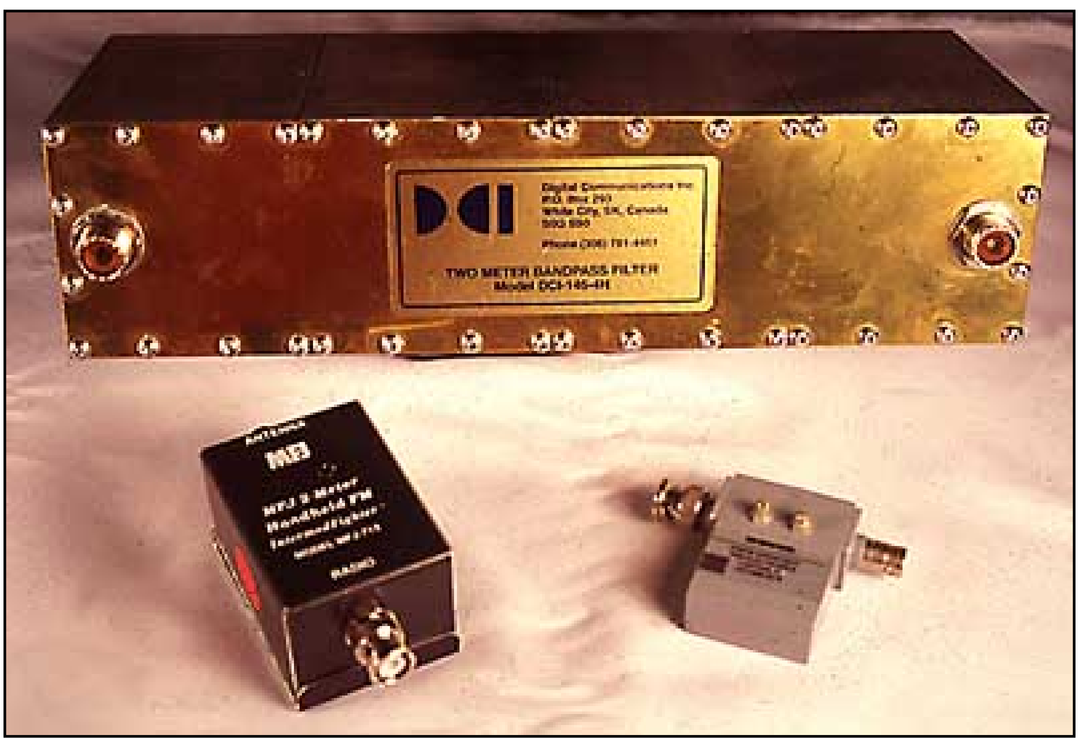


Figure 5--Two of the three shown are band-pass filters. One of them is a notch filter. All three are commercial.

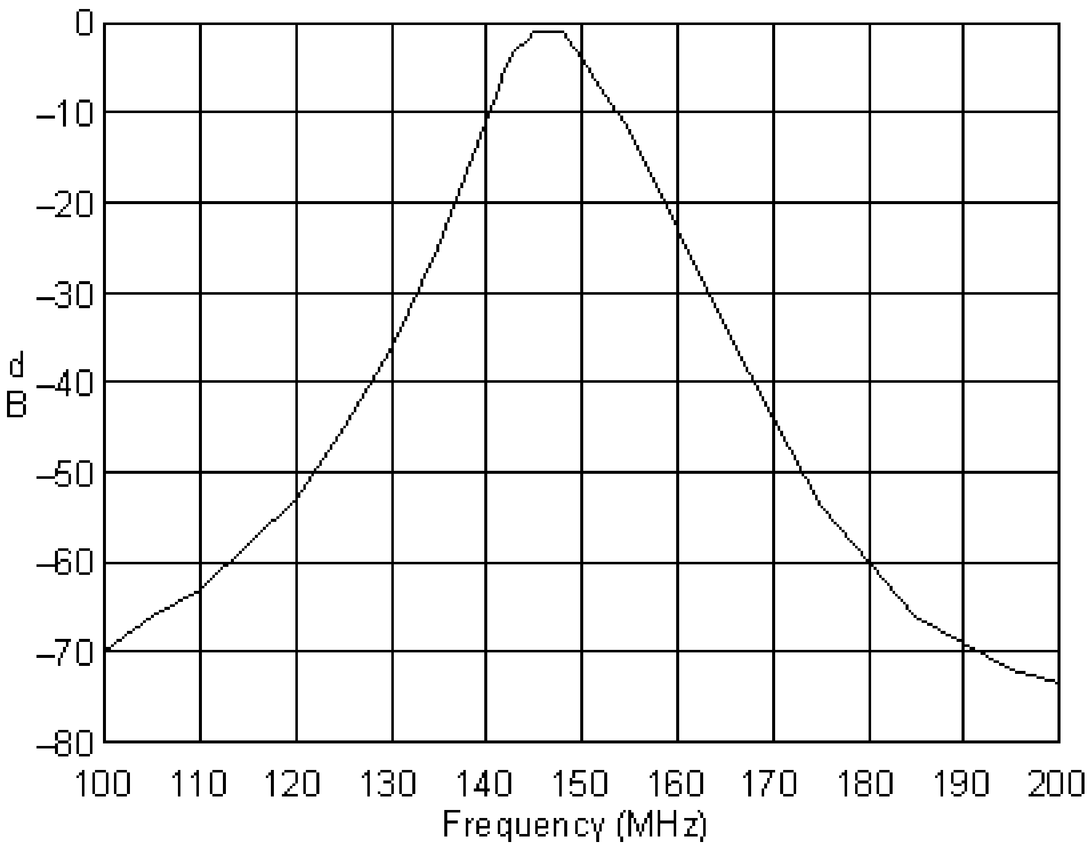


Figure 6--The frequency response of a typical band-pass filter. This filter's passband centers near 147 MHz. Its 3-dB bandwidth is about 7 MHz (143 to 150 MHz).

Notch Filters

Most 2-meter IMD problems are true IMD cases: third-order distortion from pager transmitters. Pagers near 2 meters operate from 152 to 156 MHz. If these are your only problem, a notch filter on your receiver will eliminate the IMD interference. Figure 5 shows a notch filter made by Par Electronics at the lower right. [3] It has 0.2-dB insertion loss on 2 meters and 45-dB attenuation at 152 MHz. It is entirely passive and suited for use with H-Ts, base or mobile equipment. It does not protect against interference problems caused by transmitters other than 152 to 156-MHz pagers, though.

If you like to build your own accessories, see the sidebar "A 2-Meter Notch Filter You Can Build."

Attenuation

In some cases, a simple attenuator can help reduce IMD problems. Third-order IMD has an unusual property: When you reduce the level of a signal causing a third-order product by 1 dB, you reduce the third-order product by 3 dB. In cases where the desired signal fully quiets the receiver and yet is masked by IMD, a 10-dB attenuator placed between the receiver and antenna reduces the desired signal by 10 dB and the IMD by 30 dB! In many cases, a 10-dB reduction of the desired signal won't matter, but a 30-dB reduction of the IMD product makes the contact possible.

A directional antenna, such as a Yagi, is an "attenuator" solution to IMD problems that is sometimes overlooked. This solution is useful when the IMD source and desired signal come from different directions. Orient the antenna for either maximum desired-signal strength or minimum IMD.

External IMD

So far, I've discussed only IMD that occurs in an overloaded receiver. In rare cases, IMD can happen outside of the receiving system. Although a repeater receiver is prone to the same IMD problems as any other receiver, the repeater duplexer usually offers some protection from overload. (However, it may not be enough for pagers located on the same site!) Because of this protection, IMD to repeater systems sometimes comes from sources external to the receiver. Any nonlinear system or device can act as a mixer, generating harmonics and IMD. Once IMD is generated, any significant conductor connected to the nonlinear device will act as an antenna and radiate the signals, perhaps over a large area.

When talking about external IMD, most hams immediately think of the "rusty-bolt effect." Any poor electrical joint between two conductors can act as a diode mixer, so many hams blame rusty towers, gutters and downspouts for external IMD. In reality, this is rarely the case. Look for external IMD very close to one or both of the transmitters and then very close to the receiver. Locate external problems with direction-finding techniques.

One or more transmitters at a site can be the source of the problem. Strong signals from the antenna can mix in a transmitter output circuit, then be radiated from the antenna. Transmission-line stubs or additional filter cavities can reduce the unwanted signals. [4]

The ARRL has two books that pick up where this article leaves off. *The ARRL RFI Book* covers a wide range of interference problems. *Transmitter Hunting explains a number of direction-finding techniques that can be applied to external IMD problems.*

Notes

[1] DCI Digital Communications, Inc, PO Box 293, White City, SK, Canada, S0G 5B0; tel 306-781-4451; e-mail dci@dci.ca; Web site: http://www.dci.ca.

[2] MFJ Enterprises, PO Box 494, Mississippi State, MS 39762; tel 800-647-1800; fax: 601-323-6551; e-mail: mfj@mfjenterprises.com Web Site: http://www.mfjenterprises.com/

[3] Par Electronics, 6869 Bayshore Dr, Lantana, FL 33462; tel 407-586-8278; fax 407-582-1234; e-mail par@magg.net; Web site: http://www.rf-filters.com/

[4] For more information about tuned stubs, look in *The ARRL RFI Book*. You'll find them in the index under "Filters: Tuned stubs." A basic discussion of cavity (transmission-line) filters appears in the *ARRL Handbook*.

A 2-Meter Notch Filter You Can Build

Having trouble with VHF pager interference? The notch filter in Figure A can remove signals just above the 2-meter amateur band, without significantly degrading 2-meter signals. As a bonus, it notches out some FM broadcast signals as well. The filter has a notch depth of 27 dB, with 0.5 dB of insertion loss.

The design is fairly straightforward. L1 and C2 form a 152-MHz series-resonant circuit to reflect 152-MHz signals. C2 sets the notch frequency. As the frequency decreases below 152 MHz, the circuit becomes capacitive. We prevent the capacitive circuit from disturbing 2-meter signals by adding inductive reactance to form a 2-meter parallel-tuned circuit. We could do this with a tunable inductor, but a variable capacitor and a transmission-line section (C1/TRL1) are more practical. As a bonus, the capacitor and transmission line form another series-resonant circuit, which rejects signals in the FM broadcast band.

This design assumes that you want a notch above the 2-meter band. For a notch below the 2-meter band, the unwanted reactance would be inductive, which would require only a capacitor to obtain parallel resonance. This would eliminate TRL1.

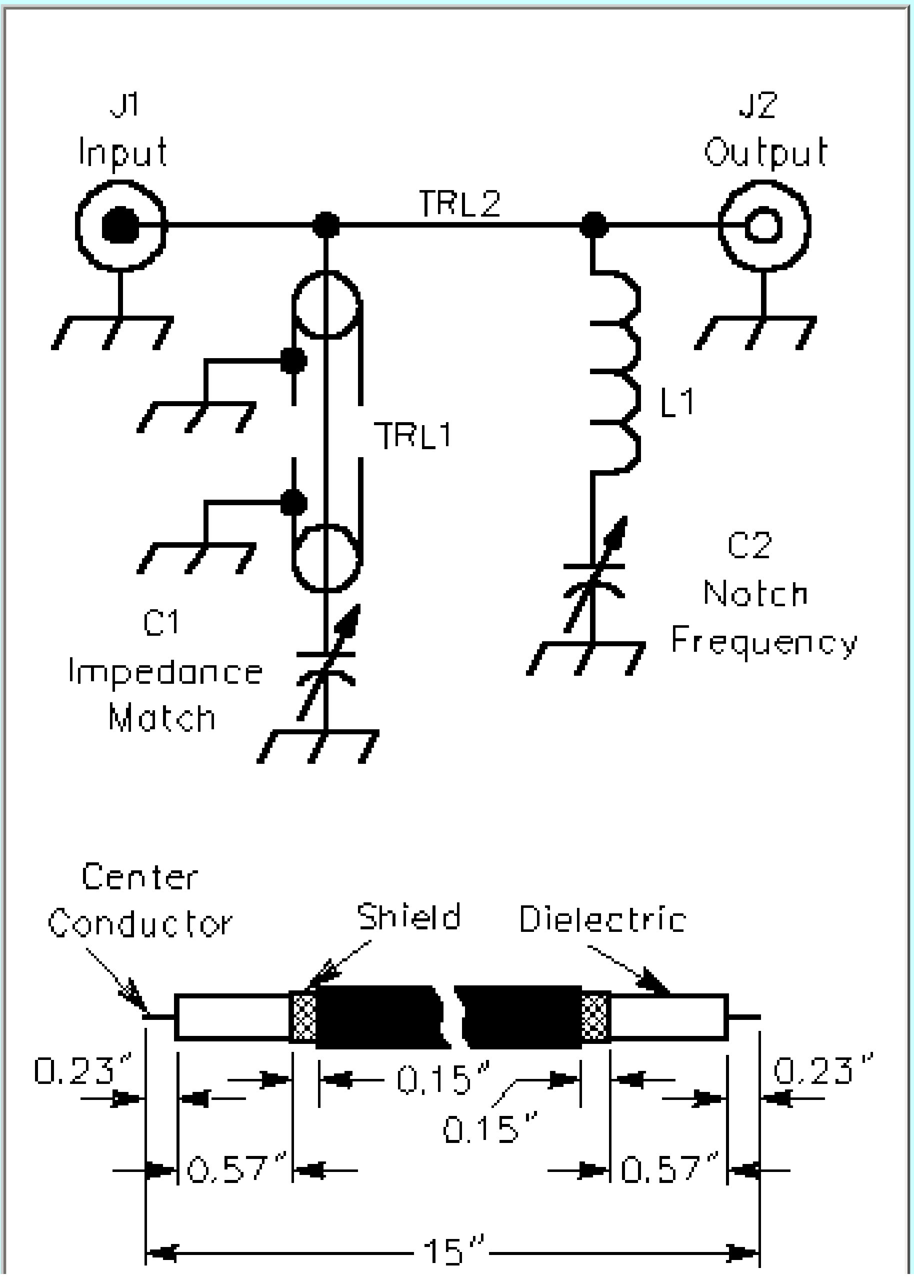
The filter is bidirectional--it works both ways. I have assumed that you would attach it directly to a BNC connector on an H-T.

Construction

If cost isn't a factor, build this circuit in a Pomona 2391 die-cast aluminum box that comes with male and female connectors (available from Newark Electronics). [*] Male BNC panel-mount connectors can be difficult to locate.

RF grounding is important. To establish good electrical contact to the capacitors, I first removed the paint by lightly drilling the chassis with a Black and Decker 5/16-inch "bullet" drill bit. I then enlarged the holes (with an ordinary 1/4-inch drill bit) to mount the capacitors. Similarly, scrape off the paint underneath the connectors for good electrical contact. I prepared RG-188 Teflon coax for TRL1 as shown in Figure B. RG-174 will work just as well, but it is easy to melt the RG-174 dielectric and short the cable while soldering.

Figure A--This simple notch filter is easy to tune and uses available components.



TRL1 End Detail

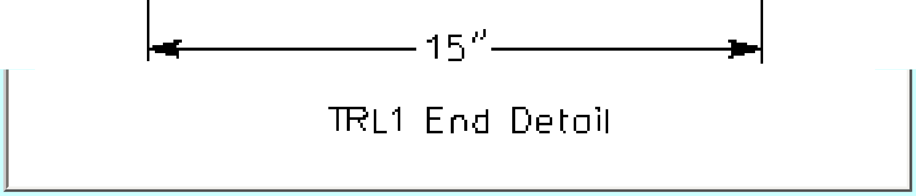


Figure B--Schematic of a pager notch filter that allows undisturbed 2-meter reception.

C1, C2--1 to 14 pF 5402PC Johanson air-dielectric variable capacitors (Newark No. 17F161; minimum Q is 3000 at 100 MHz).

J1--Male BNC connector. See text.

J2--Female BNC connector.

L1--8 turns #18, 5/16-inch diameter air wound, space equally.

TRL1--15 inches RG-188 Teflon coax with ends prepared as shown.

TRL2--1.75 inches, #18 AWG enameled wire between coaxial jacks (to hook the connectors together).

Alignment

C2 controls the notch frequency; adjust it first. Even with an expensive piston trimmer, the notch in tuning is rather sharp--use a high-quality capacitor. Next, tune C1 for best SWR. It should not affect the notch frequency, although C1 may need retuning if you change the notch frequency. Use an H-T and an SWR meter or return-loss bridge to tune C1. [**] --*Zack Lau, W1VT, ARRL Senior Lab Engineer*

[*] Newark Electronics, Inc, 4801 N Ravenswood Ave, Chicago, IL 60640-4496; tel 773-784-5100; http://www.newark.com/.

[**] A suitable return-loss bridge circuit appears in the April 1996 *QST* on page 76.

Web Links

TCS Intermodulation Software - Version 2.0 (Beta B)
Provides an easy approach to calculation intermodulation distortion frequencies.