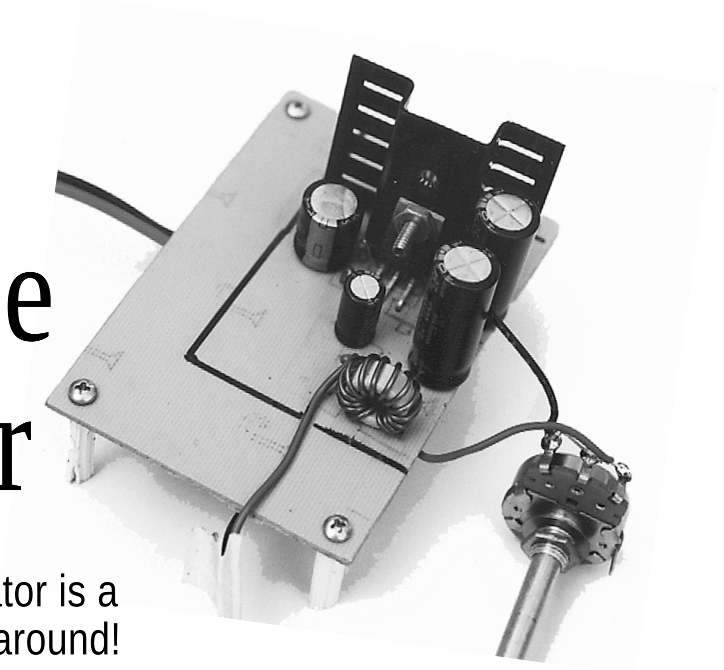
By Sam Ulbing, N4UAU

My All-Purpose Voltage Booster



This simple state-of-the-art switching regulator is a learning tool—and a handy gadget to have around!

Did you ever wish you could run your QRP rig using four NiCds instead of a heavy 12-V battery? Boating hams: Did you ever want to recharge your laptop's or hand-held's batteries from your boat's system, without having to run the engine to get a full 13.5 V? Do you need 24 V dc for that nifty relay you bought at the hamfest? Do you want to use a 6-V battery to get 12 V? With the voltage booster described here, you can do all of this.[1]

My booster gives you a dc voltage *greater* than the input dc voltage. The booster is quite flexible, efficient and easy to build. Dc-dc converters are usually built for a specific output voltage, and often for a limited output-current range. My voltage booster is different. It has an *adjustable* output voltage (up to 65 V) and works with loads drawing from less than 20 mA to over 3 A.

Why Use A Switching Regulator?

Switching regulators are becoming dominant in the electronics industry and their sales are forecast to increase markedly[2] because they offer several benefits over linear regulators. First, they are much more efficient. If you use a *linear* regulator (such as a 7805) to get 0.5 A at 5 V from your car's 12-V battery, you will find the 7805 gets *very* hot because it is dissipating 3.5 W. The efficiency of this regulator is less than 42%—the other 58% is lost as heat. *Switching* regulators, on the other hand, are usually 80% to 90% efficient. Further, switching regulators can do things no linear regulator can—such as *increase* the 5 V output of your 4-cell NiCd battery pack to 12 V!

Switching regulators are not perfect. They are noisier than linear regulators, but with proper design, the noise effects can be minimized.

Designing My Switching Regulator

Several years ago, I wanted to build a switcher so I could learn about them. But after I bought the IC, I read: "Unfortunately switching regulators are also one of the most difficult linear circuits to design. Mysterious modes, sudden, seemingly inexplicable failures, peculiar regulation characteristics and just plain explosions are common occurrences."[3] I was not exactly encouraged and gave up the project.

Then last fall, I read a comment that switching regulators were becoming smaller, more efficient and easier to build. The part that really got my attention was this: "National Semiconductor's Simple Switcher Modules for example…remove a lot of pain and aggravation for novice power-supply designers."[4] I decided to try again and see if I could design and build one. It turned out to be a piece of cake!

First I went to National Semiconductor's Web home page[5] and downloaded the data sheet for a module that appeared to do what I wanted—the LM2587. I also downloaded National's *free* design software, and within just a few days, I had designed and built a regulator that is exactly what I wanted: a general purpose step-up converter. (See the sidebar "Designing a Switching Regulator: That Was Then—This Is Now.")

The Circuit

Figure 1 shows my voltage booster circuit and the title photo shows the prototype. The IC operates like all "boost mode" switching regulators. Pin 4 is connected to an internal switch—a high-speed MOSFET that switches on and off at about 100 kHz. When the switch is closed, supply current builds up through it and the inductor. When the switch opens, the voltage across the inductor rises above the input voltage (remember that inductors generate a back EMF to try to keep the current flowing when the connection is broken) and current is forced to flow through diode D1 to the capacitor C_{OUT}. Energy is transferred from the inductor to the capacitor, but at a *higher* voltage than the input voltage.

The output voltage is controlled by the amount of time the switch is closed: $V_{OUT} = V_{IN} \times [T \div (T - T_{ON})]$. T is the time of a cycle (0.00001 second for a 100-kHz switch) and T_{ON} is the time the switch is closed. T_{ON} is determined by an internal error amplifier and a feedback loop formed by R1 and R2. The output voltage of the circuit is regulated at $V_{OUT} = 1.23 \times (R1+R2) \div R2$, as long as the input voltage is less than the output voltage. By using the combination of a 10-kΩ potentiometer and a 5.6-kΩ resistor for R1, I was able to vary the voltage from 6 to 14.5 V.

C_{OUT} filters the switching pulses as well as storing energy from the inductor. C_{IN}, the input capacitor, reduces the current surge demand on the input source. C_F and R_F prevent the regulator from becoming unstable. C_S and L_S comprise an optional output filter that reduces the RFI generated by the circuit.

You might wonder—as I first did—how this design can be efficient when the switch shorts current directly to ground. The efficiency depends (in part) on the switch's resistance. If it were zero (a perfect switch), there would be no power lost across the switch ($P = I^2R$), so all the power must be stored in the inductor ($I^2L/2$). The regulator's internal MOSFET is designed to have a low resistance when it is *closed*. The critical part of the operation is when the switch changes from fully closed to fully open. As the switch opens, its resistance changes from very low to very high. When the switch is fully open, the current through it is zero, so there is no power loss. But *during transition*, there is a power loss due to the decreasing current flow and in-

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[1] Notes appear on page 43.

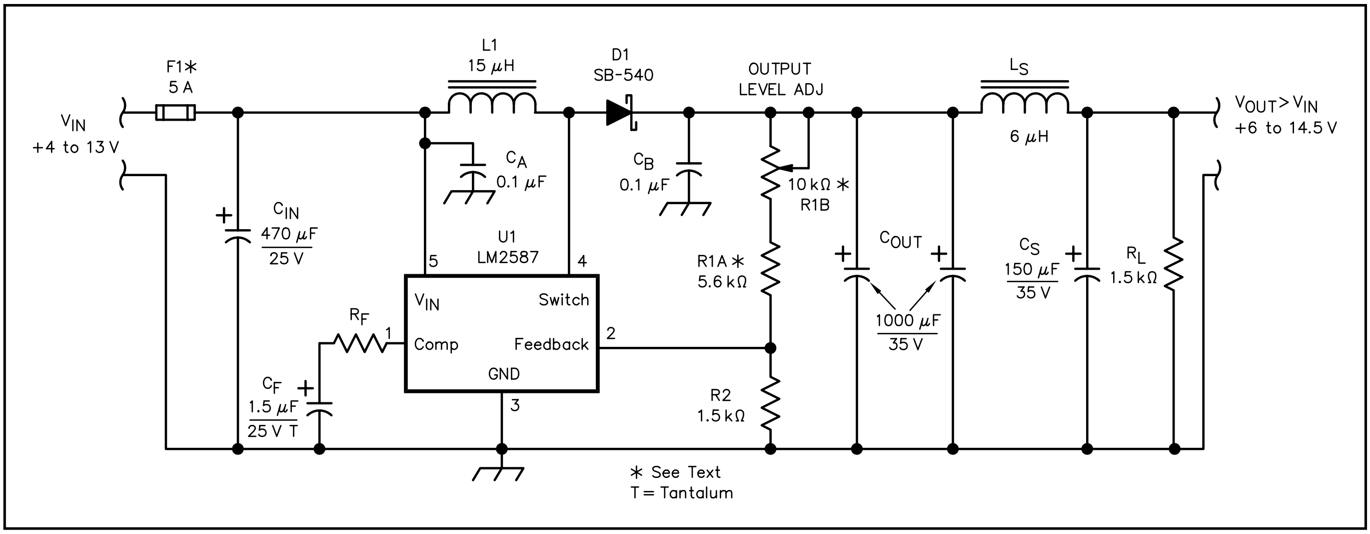

Figure 1—Schematic of the voltage-booster circuit. Unless otherwise specified, resistors are $^1/_4$ W, 5% tolerance carbon-composition or film units. Use low-ESR capacitors such as those recommended in the parts list. Equivalent parts can be substituted. Most parts are available from Digi-Key Corp, 701 Brooks Ave S, Thief River Falls, MN 56701-0677 tel 800-344-4539, 218-681-6674; fax 218-681-3380; **http://www.digikey.com**. Parts kits are available from the author (see Note 1). DK part numbers in parentheses are Digi-Key.

C_A, C_B—0.1 µF, 35 V monolithic
C_F—1.5 µF, 25 V tantalum (DK P2044); Nichicon TAP155K025
C_{IN}—470 µF, 25 V electrolytic; Panasonic ECA-1EFQ471 (DK P5704); Nichicon UPL1E471MPH
C_{OUT}—Composed of two 1200 or 1000 µF, 35 V electrolytics; Panasonic ECA-1VFQ122 (DK P5746); Nichicon UPL1V102MHH
C_S—150 µF, 35 V electrolytic; Panasonic ECA-1VQ151 (DK P5732); Nichicon UPL1V151MPH
D1—5-A Schottky; SB-540 (DK SB540CT)
F1—5-A, fast-acting fuse
L1—15 µH; 17 turns #18 wire on a Micrometals T-68-52A core (Micrometals Inc, 5615 E La Palma, Anaheim, CA 92807-2019, tel 800-356-5977, 714-970-9400; fax 714-970-0400; e-mail **ironpowder@aol.com**. Micrometals has a $25 minimum order. The cores identified here are also available from Amidon Associates, PO Box 25867, Santa Ana, CA 92799, tel 714-850-4660, fax 714-850-1163; e-mail **amidon@earthlink.net**; **http://websites.earthlink.net~sold/amidon/** *—Ed.*
L_S—6 µH; 14 turns #18 enameled wire on a Micrometals T-50-18B core
R1B—10-kΩ trimmer potentiometer
R_F—2 kΩ
U1—LM2587, National Semiconductor Simple Switcher 5-A flyback regulator IC; (available from Digi-Key by special order)

creasing resistance. To keep the transition loss to a minimum, it is necessary to use a very fast switch. The rapidly changing current through the switch generates RFI; this is why switching regulators are noisier than linear regulators.

Although this is a very flexible regulator, there are limits to its use. Maximum output for this circuit (using a different value for R1) is about 17 V, although output voltages of up to 65 V are possible with only small changes to the circuit component values. The IC requires a 4-V minimum input. The switching current through the IC must be limited to 5 A, but you will not always get 5 A out. When boosting 5 V to 12 V, you can draw a maximum of 1.5 A before you exceed the 5 A switch-current limit. When boosting 12 V to 13.5 V, you can draw 3.5 A before you exceed the switching limit. Internal current and thermal limiting circuits protect the IC.

It is also important to remember that even though you can get more *voltage* out than you put in, you cannot get more *power* out than you put in. In fact, you get about 10% to 20% less. This is important to realize, especially if you plan to use NiCds as the power source. An output of 1.5 A at 13.5 V is 20 W, which needs 25 W input at 80% efficiency, or 5 A at 5 V. On the other hand, if you want 3 A output at 13.5 V (40 W) from your 12-V lead-acid battery, you need only 4.2 A input, which that battery can easily provide.

Building the Booster

To obtain efficient operation and avoid the hazards described earlier, it is necessary to carefully select the circuit components. Use good components, not junk box residents. Capacitor ESR (effective series resistance), ripple current rating and voltage rating are important. Inductors must be selected for proper saturation current, inductance value, etc. The diode must be a fast recovery type (Schottky). National Semiconductor literature advises:" . . . keep the length of the leads and traces as short as possible. Use single-point grounding or groundplane construction for best results. Separate the signal grounds from the power grounds. Keep the programming resistors as close to the IC as possible." It is a good idea

Figure 2—How to get over 14 V dc from four D-size NiCd batteries. The booster in the box does it.

Designing A Switching Regulator: That Was Then—This Is Now

It may appear that switching regulator design has become easy, but the *only* reason it is easy is because National's software does all the calculations! Data sheets I have seen from most other switcher-IC manufacturers still require *you* to do the calculations. To give you a feel for the process, let me describe my experiences. You may want to use National's software yourself, but it is not necessary for this project.

To get my design, I started by entering the input and output voltages, the required current draw and percentage of allowable ripple. The program gave me a circuit design. Because the program is so easy to run, I started playing with it, trying other parameters. I soon found many parameter sets delivered similar designs, ie, the same inductance value, but slightly different capacitor values. I discovered that I could force the software to use component values other than it offered, so I changed the values that were different between the designs and made them equal. The program identified the acceptable operating limits for each component change. By using different component-value combinations, it soon became apparent that with a 15-µH inductor, a fixed set of capacitors and resistors, and a potentiometer at R1 (of Figure 1), I could build a regulator that works over a wide range of currents and voltages. My All Purpose Voltage Booster was born!

Compare this process with what was required *without* the software:

That Was Then

The 76-page Application Note (AN) that came with the IC was full of equations and graphs.[*] I had to learn about pulse-width modulators, error amplifiers, frequency compensation, output diode losses, inductor and transformer design.

Inductor: Trade-offs are size, maximum output power, transient response, input filtering and, in some cases, loop stability. The AN gave eight pages of equations to "help" me select the proper inductor!

Output Capacitor: Criteria are "low ESR . . . a reasonable procedure is to let the reactance of the output capacitor contribute no more than $^1/_3$ of the total peak-to-peak output voltage ripple."

Frequency Compensation: Three pages of instructions including comments such as: "Inject a signal and check the 'phase margin'; several large-signal dynamic tests should also be done; check the startup overshoot."

This Is Now

The data sheet for the LM2587 is 25 pages long but, instead of having a lot of equations, there are some suggested circuits with *specific* parts recommended for building them. Better yet, the software gave me specific answers:

Inductor: Use a T-68-52A toroid core with 17 turns of #17 wire.[†]

Output Capacitor: two Panasonic ECA-1VFQ122 in parallel.

Frequency Compensation: C_F = 1.5 µF tantalum; R_F = 2 kΩ, $^1/_4$ W.

As you can see in the photo, my booster is not particularly small. That's because I wanted it to handle a lot of power. Had I wanted a smaller regulator, I could have designed for a lower maximum current and the software would have specified smaller capacitance and inductance values.

The software did not help me with *circuit layout,* but the data sheet noted that layout is "very important" because "CMOS devices ...can cause incredible noise.... typically made up of crosstalk, power supply spiking, transient noise and ground bounce." In the process of building my switcher, I tried six different PC board layouts. They all worked well, but the ones with the least EMI were those that minimized the "switching loops" and reduced the length and area of the connections at the ICs switching node (pin 4). As all hams know, loop antennas are efficient radiators and, in the case of my booster, there are two major loop antennas. The *output* loop consists of the diode, output capacitor and the IC switch. The *input* loop is the inductor, input capacitor and IC switch. For boost-mode regulators, the output loop is the most critical. By reducing this loop size and connecting the diode and inductor as close as possible to pin 4, I was able to make significant reductions in RFI.

A post filter consisting of C_S and L_S made a significant RFI reduction when I put it on a breadboard, but when I moved it to the PC board, the noise returned. I found this was because I was using the PC board groundplane instead of a direct (point to point) return to pin 3 of the IC. I corrected this with a jumper wire, and the noise went away (I guess layout is important!). To reduce leakage from the toroid, I rewound it with #18 wire and kept the windings tight to the core and spaced evenly. This also reduced RFI. While #18 wire has 25% greater resistance than #17, I felt it was not significant (the resistance increased from 8 milli-ohms to 10 milliohms) except at the highest load currents, and it was much easier to bend the wire and get it close to the core. Some literature suggests using several small-diameter wires in parallel for the windings as another way to get better conformation to the toroid, but I have not tried this.

Designing Other Switchers

Using the software, you can modify my regulator to get 24 V at 300 mA from 12 V by simply changing the values of L1 and some resistors. You can get up to 65 V out, but be sure to use capacitors and a diode with higher voltage ratings. National Semiconductor makes several switcher ICs optimized for different functions. The IC used for my voltage booster can also be used in a *flyback* configuration to provide more than one output voltage. For instance, you can build one that gives positive and negative voltages. Other switchers, such as *buck regulators*, let you *reduce* voltage efficiently. If you want to try one of these, all the data is available at National Semiconductor's home page. The software specifies commercial transformers for flyback designs. Such transformers are sometimes difficult to locate, although the serious experimenter can usually obtain a sample from the manufacturer.[†] Since all the pertinent design data is specified by the software, it is also possible to wind your own toroid transformer if you know how to select the proper toroid-core material. I don't, but perhaps a technically gifted *QST* reader can help me (and others) by explaining—in *simple* terms—how to select the proper core given the required inductance, peak current, power output, etc.—*Sam Ulbing, N4UAU*

[*] Linear Technologies, *Applications Note 19.*

[†] Odd wire sizes are available from motor repair shops.

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to add a fuse (5 A) to the input circuit. Although the IC has many safety features, a dead short at the output will cause dc to flow directly from the power source through the inductor and diode to the output. For heavier loads, use a heat sink on the IC. I originally put the regulator in a metal case for shielding (see Figure 2). Later, I moved it to a plastic box so I could add an inexpensive DVM to display the output voltage.

Using the Booster

I have used my booster in a number of situations and it works as promised. When I used NiCds to power my NorCal 40A QRP rig, I had this voltage booster three inches away from the rig and heard no noise. The station I was working said my signal sounded good and my antenna tuner indicated I was putting out the full power. By changing the booster voltage from 12 to 13.5 V, I could see the output power increase. (Remember, I was powering my rig from four D-cell NiCds!) The booster has also worked well powering my Switched Capacitor Audio Filter[6] and Uncle Albert's Keyer[7] with no noise.

My tests show some noise is apparent on the higher bands at higher loads, but generally this noise is not very objectionable as long as I use good RFI grounding techniques. At lighter loads, the noise is hardly noticeable. While drawing 2.5 A for an extended period, the booster stayed cool with a small heat sink on it (see the title photo). One nice feature of this IC is that it has a "soft start" feature, which limits the initial current inrush that is common with older regulators.

Finding the Parts

Most of the parts for this project are not hard to find. Digi-Key and other large suppliers have most of them. My greatest difficulty was locating the proper inductor. Inductors and transformers for circuits such as these are often available only directly from their manufacturer and sold only in quantities of hundreds or thousands. That's one reason I selected the LM2587 for my booster: The software indicated that I could wind the inductor on a toroidal core. I had learned how to do this while building QRP rigs and knew where to get toroids.

Summary

It may take you a little while to get used to thinking in terms of *boosting* rather than *dropping* voltage, but once you do, you will realize this switching regulator has many uses. At home with an inexpensive 5-V computer power supply at its input, you'll have a power supply variable up to 17 V (or more, with minor changes). Think about using the booster as a lamp dimmer for a 12-V lamp, or as a motor-speed controller. In the field, you can use NiCds or other low-voltage batteries as a power source. If you want to design a different regulator, all the data you need is available at the referenced locations. Keep in mind that switching regulator technology is improving very rapidly, so you may find faster, smaller, more-efficient modules available. I am interested in hearing the thoughts, ideas and experiences of anyone who does explore this area.

Notes

[1] A PC board, all board-mounted parts and detailed instructions for this project are available from the author for $21, plus $2 for shipping in the US and Canada, $4 elsewhere. Foreign orders please include an international money order or a check in US currency payable at a US bank. Charge cards are *not* accepted. Foreign orders are shipped by air, small packet. Florida residents please add sales tax. A template package is *not* available.

[2] *Electronic Business News*, Oct 28, 1996, p 24.

[3] Linear Technologies *App Note 25*, Sep 1987; **http://www.linear-tech.com**

[4] *Electronic Engineering Times*, Sep 30, 1996, p 28.

[5] To obtain the free software and get more information on the LM2587 and other Simple Switcher modules, visit the following National Semiconductor Web page: **http://www.national.com/sw/SimpleSwitcher/0,1043,0,00.html**; you can download the individual software versions from **http://www.national.com/sw/switch/sms421.exe** and **http://www.national.com/sw/switch/sms33.exe**. Also see **http://www.national.com** and **http://www.nsc.com**, or contact them via e-mail **support@tevm2.nsc.com**. —*Ed.*

[6] Sam Ulbing, N4UAU, "An Active Audio CW Filter You Can Build," *QST*, Oct 1992, pp 27-29.

[7] Sam Ulbing, N4UAU, "Uncle Albert's Keyer," *QST*, Jan 1994, pp 42-44.

Sam Ulbing, N4UAU, has contributed a number of project articles to QST, QEX *and* 73 Amateur Radio Today Magazine. *Most of these articles have been low-power, 12-V-based projects. This is because Sam is one of the growing number of sailors who like to take their ham gear along when they sail.*

Sam became a ham after spending a winter on his sailboat in the Bahamas and meeting other boaters who are hams. The advantages of having a ham radio on board were immediately apparent: Hams are able to get vital information such as weather reports daily on nets like the Waterway Net. In addition, Sam found that boaters who have their ham stations on board tend to become much closer friends because they can keep track of each others' location and are thus able to meet often. Sam reluctantly uses SSB. His favorite mode is CW, which—with its low power consumption—is ideal for use on a boat. When he's not on his boat, you can contact Sam at 5200 NW 43rd St, Suite 102-177, Gainesville, FL 32606; e-mail* **n4uau@afn.org**.

Photos by the author.

* *The Waterway Radio and Cruising Club meets daily on 7268 kHz at 0745 Eastern.*

New Books

RADIO-FREQUENCY ELECTRONICS CIRCUITS AND APPLICATIONS

By Jon B. Hagen, KP4I

Published by Cambridge University Press, North American Branch 40 West 20th St, New York, NY 10011-4211. Order direct at 800-872-7423. First edition, 1996, hard cover, 8×10$\frac{1}{4}$ inches, 358 pages B&W illus, with many equations, ISBN 0-521-55356-3, $49.95.

Reviewed by Paul Danzer, N1II
Assistant Technical Editor

Jon Hagen, a former Raytheon engineer, is currently the director of laboratory operations at the National Astronomy and Ionosphere Center at Cornell University. He is also a ham, and his long-term amateur experience shows through in this book.

Hagen wrote this as a textbook, and I am rather glad that I did not have to take this course. I suspect it would be rather like covering world history from Adam to atom, all in just one semester. However, the large number of topics covered in very little space is just what might make it an attractive addition to your book shelf.

The book takes a very interesting approach—in most areas it first explains a topic and then gives the basic mathematics that apply. The chapter on phase locked loops is typical, taking five pages to paint a word picture—including a mechanical analog—before the first schematic and equations. You can stop right there, and probably understand the operation of most common PLLs. But if you want, you can continue to tour the next pages of design equations and additional information. For perpetual students, or those very interested in a topic, each chapter ends with a small set of problems and exercises.

The book's organization is particularly interesting. After introducing and defining RF and narrowband signal ideas (Chapter 1), it jumps to impedance matching (Chapter 2) and then to linear amplifiers (Chapter 3). At this point you are ready for processing signals in filters and various RF circuits.

The book than proceeds through the parts of radio receiver, including the circuits and the modulation concepts needed to understand radio communication. Even switching converter power supplies are covered. A really nice inclusion in the switching converter chapter is the operation of those pesky feedback power supplies commonly found in today's TVs. Now if someone could only publish a book on how to troubleshoot and fix those beasts!

The small-signal RF amplifier chapter is particularly interesting. Would you believe there are only two equations in the entire chapter? But somehow the concepts of small signal amplifiers, including dynamic range (one nicely done figure), come though clearly.

Another highlight of the book is Chapter 22, Transformers and Baluns. It has more equations than found in most chapters, but it remains comprehensible, and even if you skip some of the math you will probably still get a clear understanding of the topics. There is also a paragraph and drawing of the mechanical analog of a perfectly coupled transformer—rather unusual way to explain this idea.

A set of very clear drawings highlight the waveguide circuits chapter. The equations here are brief, and you can either study them or just look at their form, which will often explain what is going on.

Hagen introduces his chapter on TV with an interesting drawing of a Nipkow rotating disk TV system, which he uses to lead into the sequential signal idea of all analog TV transmissions. Included here are several drawings of the video interlace time sequences and the commercial channel subcarrier standard—excellent reference material for TV repair and TVI troubleshooting.

One chapter is devoted to radar pulse modulators. Even if you have no interest in radar, the chapter will give you some good ideas on how to generate very short pulses.

Each of the 34 chapters run between 5 to 12 pages each, so the book is really the basis of a survey of its title, *Radio-Frequency Electronics*. For a ham, it has concise word explanations of most of the common items you might want to know more about. Although you'd be hard put to design circuits from the equations given, they do act as a solid introductory step to the ideas behind topics you might not be familiar with.

As a reference book, it may serve you very well. The publisher suggests it would be "an ideal textbook for junior and senior courses in electrical engineering." Unfortunately, if you are interested in using it as a textbook, the publisher also tells us there is no instructor's guide or manual that contains the answers to the book's various learning exercises.