

# A Doppler Radio-Direction Finder

*Part 1:* A radio-direction finder (RDF) is useful in locating repeater interference (intentional or unintentional) and transmitter “fox hunting.” Join in the fun with this VHF/UHF Doppler RDF project!



**R**adio-direction finding has gained a lot of interest in recent years especially on the VHF and UHF bands. There are many different approaches to determining the origin of a radio transmission. Each approach has its advantages and disadvantages. An experienced RDFer learns to make use of several methods to master the art. Directional antennas with good front-to-back ratios (such as a Yagi or quad) are simple to use and very effective in obtaining bearings from a fixed location. Because of their physical size, however, such antennas are a bit awkward to use when you're driving around in a vehicle trying to narrow the search area. Mounting a 2-meter, four-element Yagi or quad to a car window can be a safety hazard. A much more practical method of narrowing the search area uses four  $\frac{1}{4} \lambda$  mag-mount antennas and the Doppler principle.

### Theory of Operation

The classical example of the Doppler effect is that of a car approaching a stationary observer. The car's horn sounds higher in pitch (frequency) to an observer as the car approaches. The change in frequency occurs because the motion of the car shortens the wavelength. The horn sounds lower in pitch (frequency) to the observer as the car speeds away. This occurs because the car is speeding away from the observer effectively increasing the wavelength. Fewer cycles per second, hence, lower-frequency sound. A similar effect occurs when an antenna is moved

toward or away from a transmitting source. The signal received from an antenna moving toward the transmitting source appears to be at a higher frequency than that of the actual transmission. The signal received from an antenna moving away from the source of transmission appears to be lower in frequency than that of the actual transmission.

Imagine a receiving antenna moving in a circular pattern as pictured in Figure 1A.

Consider the antenna at position A, nearest the source of transmission. The frequency of the received signal at point A equals that of the transmitted signal because the antenna is not moving toward or away from the source of transmission. The frequency of the received signal decreases as the antenna moves from point A to point B and from point B to point C. Maximum frequency deviation occurs as the antenna passes through point B. The frequency of

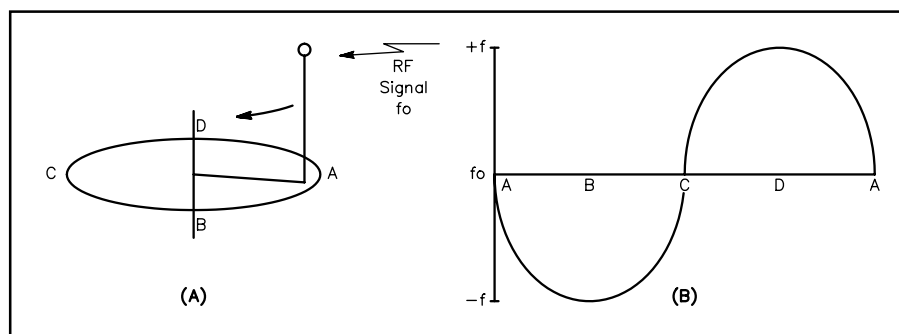


Figure 1—At A, depiction of a rotating antenna. At B, Doppler frequency shift.

### RDFing Information

If you're looking for the how-to and why of radio-direction finding, you'll want to read *Transmitting Hunting: Radio Direction Finding Simplified*, by Joseph Moell, K0OV, and Thomas Curlee, WB6UZZ. This book contains all the information you're likely to need about equipment and techniques for HF and VHF radio-direction finding. You can order your copy of this 326-page book by requesting item#2701 from ARRL Publications by telephone: 888-277-5289 (toll free), 860-594-0355, fax 860-594-0303; e-mail [pubsales@arrl.org](mailto:pubsales@arrl.org) or on the Web at <http://www.arrl.org/>.—Ed.

the received signal at point C is the same as that of the transmitted signal (no shift) because the antenna is not moving toward or away from the source of transmission. As the antenna moves from point C to point D and from point D back to point A, the frequency of the received signal increases. Maximum frequency deviation occurs again as the antenna passes through point D. The Doppler frequency shift as a function of antenna rotation is illustrated in Figure 1B.

$$dF = \frac{\omega r f_c}{c} \quad (\text{Eq 1})$$

where  $c$

$dF$  = Peak change in frequency (Doppler shift in Hertz)

$\omega$  = Angular velocity of rotation in radians per second ( $2 \times \pi \times$  frequency of rotation)

$r$  = Radius of antenna rotation (meters)

$f_c$  = Frequency of transmitted signal (Hertz)

$c$  = Speed of light

We can calculate how fast the antenna must rotate in order to produce a given Doppler frequency shift with the following equation:

$$f_r = \frac{dF \times 1879.8}{R \times f_c} \quad (\text{Eq 2})$$

where

$f_r$  = The frequency of rotation in Hertz

$dF$  = The Doppler shift in Hertz

$R$  = Radius of antenna rotation in inches

$f_c$  = Carrier frequency of the received signal in megahertz

As an example, let's calculate how fast the antenna must rotate in order to produce a Doppler shift of 500 Hz at 146 MHz, assuming the antenna is turning in a circle with radius 13.39 inches. The frequency of rotation is:

$$f_r = \frac{500 \times 1879.8}{146 \times 13.39} \quad (\text{Eq 3})$$

A rotation frequency of 480 Hz translates to  $480 \times 60 = 28,800$  or almost 30,000 r/min, which pretty much rules out any ideas of mechanically rotating the antenna! Fortunately, Terrence Rogers, WA4BVY, proposed a clever method of *electrically spinning* the antenna that works very well.<sup>1</sup> Rogers' project, the DoppleScAnt, uses eight  $1/4$ - $\lambda$  vertical whips arranged in a

<sup>1</sup>Notes appear on page 40.

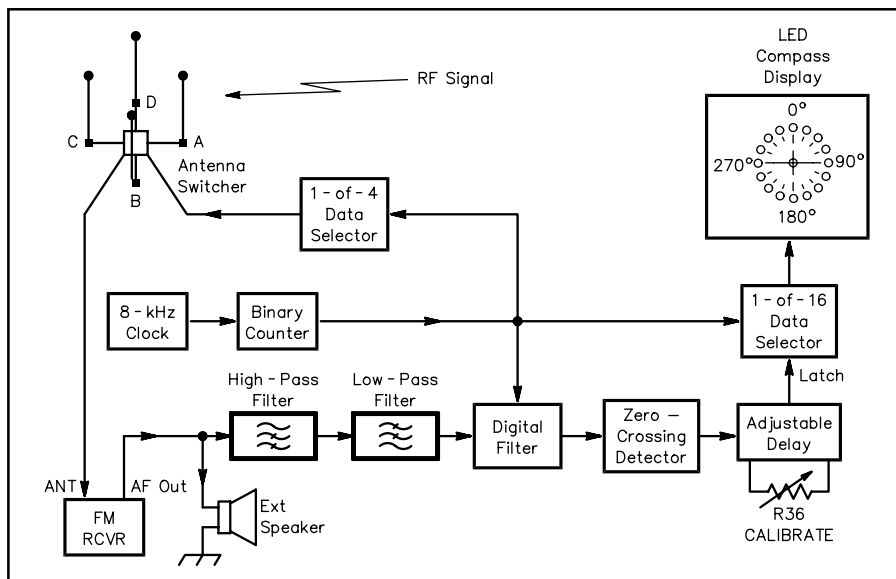


Figure 2—Block diagram of the WA2EBY Doppler RDF system.

circular pattern. Only one antenna at a time is electrically selected. By controlling the order in which the antennas are selected, the DoppleScAnt emulates a single  $1/4$ - $\lambda$  whip antenna moving in a circle. A clever feature in Rogers' design is the use of a digital audio filter to extract the Doppler tone from voice, PL tones and noise. My article in *QEX* details the operation of such switched-capacitor filters.<sup>2</sup>

Over the past 20 years, many modifications to Rogers' original design have evolved. A popular version introduced by Chuck Tavaris, N4FQ, is dubbed the Roanoke Doppler direction finder named for the Roanoke, Virginia, location where it was built and used. Modifications were later proposed to prevent false readings when the Doppler tone was too weak or too strong.<sup>3</sup> Experimentation revealed that only four antennas are needed to provide good performance. Antenna switching methods were proposed that allow the same antenna switching circuit to be used on VHF or UHF.<sup>4</sup> I set out to build a Doppler DF that has several of the improved features.

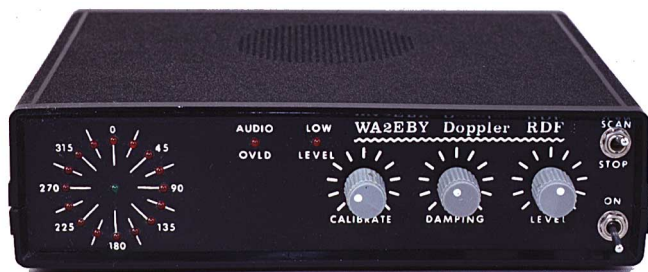
A careful review of the Roanoke design revealed use of somewhat obsolete 4000 series CMOS logic circuits that require CMOS-to-LED display drivers to operate the LEDs. These IC drivers are still

available, but are a bit expensive (\$15 for the three). Another costly aspect of the project is the use of four  $1/4$ - $\lambda$  mag-mount antennas for the array. The cheapest mag-mount antenna I could find cost \$15 each. Multiply that times four, and you have spent \$60 before you add any electronics!

My design offers slightly improved audio filtering, 74HC-series logic circuits capable of driving the LED display directly and a wideband VHF/UHF antenna switcher that you can make for about \$40—including the four  $1/4$ - $\lambda$  mag-mount antennas! High-quality PC boards and parts kits are available that make building this project simple and economical.<sup>5</sup> Total project cost is about *one-third* the cost of purchasing a commercial RDF unit—and building the project is a lot more educational!

### How it Works

To understand the operation of the Doppler RDF circuit, see the block diagram of Figure 2. An 8 kHz clock oscillator drives a binary counter. The output of the counter performs three synchronized functions: "spin" the antenna, drive the LED display and run the digital filter. The counter output drives a 1-of-4 multiplexer that spins the antennas by sequentially selecting (turning on) one at a time in the



Main unit front panel



Main unit rear panel

order A, B, C, D, A, etc, at 500 times per second. The counter output also drives a 1-of-16 multiplexer used to drive the LED display in sync with the spinning antenna. The RF signal received from the spinning antenna is connected to the antenna input of a VHF or UHF FM receiver.

The spinning antenna imposes a  $\pm 500$  Hz frequency deviation on a 146 MHz received signal. A 146 MHz FM receiver connected to the spinning antenna's RF output demodulates the  $\pm 500$  Hz frequency deviation and sounds like a 500 Hz tone with loudness set by the 500 Hz frequency deviation. The receiver audio, including 500 Hz Doppler tone, is processed by a series of audio filters. A high-pass filter rejects PL tones and audio frequencies below the 500 Hz Doppler tone. A low-pass filter rejects all audio frequencies above the 500 Hz Doppler tone, and a very narrow bandwidth digital filter extracts only the 500 Hz Doppler tone.

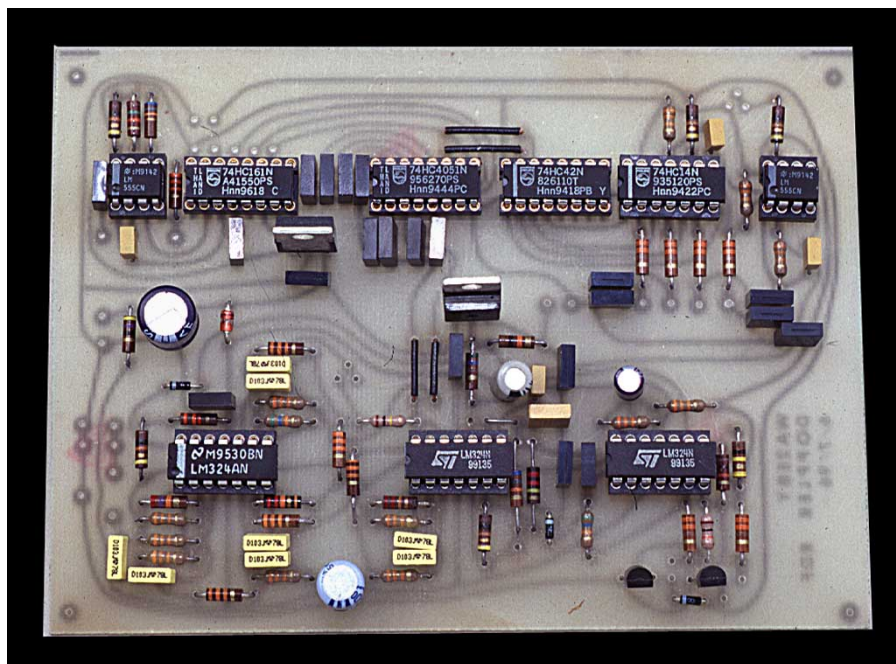
The output of the digital filter represents the actual Doppler frequency shift described in Figure 1B. Zero crossings of the Doppler frequency shift pattern correspond to the antenna position located directly toward the source of transmission (position A) or directly opposite the source of transmission (position C). The zero-crossing signal passes through an adjustable delay before it latches the direction-indicating LED. The adjustable delay is used to calibrate the LED direction indicator with the actual direction of the transmission.

### Circuit Description

Figure 3 is a schematic of the WA2EBY Doppler RDF. The heart of the system is an 8 kHz clock oscillator built around a 555 timer, U4, configured as an astable multivibrator. C26 and R27, and R28 and R29 determine the multivibrator's oscillation frequency. R28 and R29 are series connected to allow fine-tuning the oscillation frequency to 8 kHz. It's not critical that the clock frequency be exactly 8 kHz, but I recommend that it be adjusted to  $\pm 250$  Hz of that frequency for reasons that I'll discuss shortly. The 8-kHz output of U4 provides the clock for 4-bit binary counter U7. The 3-bit binary coded decimal (BCD) output of U7 is used to operate three synchronized functions.

#### Three Synchronized Functions

The first function derived from binary counter U7 is antenna array spinning. This is accomplished by using the two most-significant bits of U7 to run 1-of-4 multiplexer U8. The selected output of U8 (active low) is inverted by buffer U12. The buffered output of U12 (active high) supplies current sufficient to turn on the antenna to which it is connected. (The details of how this is done will be covered later.) Buffer outputs U12A, U12B, U12C and U12D are sequenced in order. The corresponding buffer selects antennas A, B, C, D, A, B, etc. Driving multi-



Main PC board

plexer U8 with the two most-significant bits of counter U7 divides the 8 kHz clock by four, so each antenna is turned on for 0.5 ms. One complete spin of the antenna requires  $0.5 \text{ ms} \times 4 = 2.0 \text{ ms}$ , thus the frequency of rotation is 2 ms or 500 Hz. An FM receiver connected to the spinning antenna's RF output has a 500 Hz tone imposed on the received signal.

Sequencing the 16 LED display is the second synchronized function derived from binary counter U7. This is done by using the binary output of counter U7 to select 1-of-16 data outputs of U11. The selected output of U11 goes low, allowing current to flow from the +5 V supply through current-limiting resistor R51, green CENTER LED, D16, and direction-indicating red LEDs D17 through D32. Each antenna remains turned on as the LED display sequences through four direction-indicating LEDs, then switches to the next antenna. Each direction-indicating LED represents a heading change of  $22.5^\circ$ .

The third synchronized function is operating the digital filter responsible for extracting the Doppler tone. The 500 Hz Doppler tone present on the receiver audio output is connected to an external speaker and AUDIO LEVEL ADJUST potentiometer R50. The signal is filtered by a two-pole Sallen-Key high-pass filter<sup>6</sup> built around op amp U1A. It filters out PL tones and audio frequencies above the 500 Hz Doppler tone. Next, a four-pole Sallen-Key low-pass filter using U1B and U1C band-limits audio frequencies above the 500 Hz Doppler tone. The band-limited signal is then applied to the input of a digital filter consisting of analog multiplexer U5, R18, R19 and C10

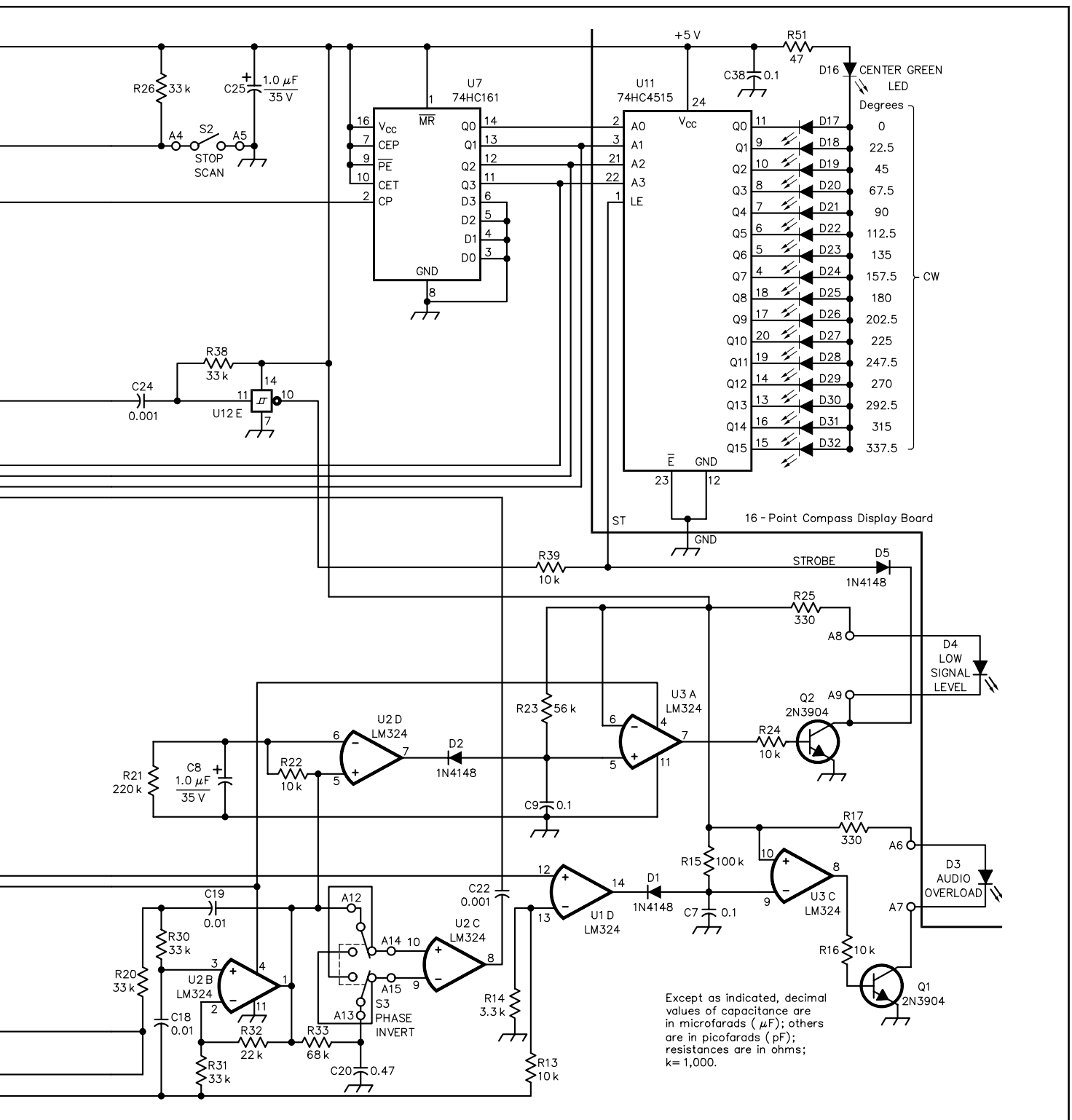
through C17. (Readers interested in the detailed operation and analysis of this fascinating digital filter are encouraged to review my QEX paper; see Note 2.)

### The Digital Filter

Using the three most-significant bits of U7 to drive the digital filter divides the 8 kHz clock by two, making the digital-filter clock rate 4 kHz. The center frequency of the digital filter is determined solely by the clock frequency divided by the order of the filter. This is an 8th-order filter, which makes the center frequency of the filter  $4 \text{ kHz} / 8 = 500 \text{ Hz}$ . This is the exact frequency at which the antenna spins, hence, the same frequency of the Doppler tone produced on the receiver audio connected to the spinning antenna. This is truly an elegant feature of the Doppler RDF design. Using the same clock oscillator to spin the antenna and clock the digital filter ensures the Doppler tone produced by the spinning process is precisely the center frequency of the digital filter. Even if the clock oscillator frequency drifts, the Doppler tone drifts accordingly, but the center frequency of the digital filter follows it precisely because the same clock runs it. Excessive drift in the 8 kHz clock should be avoided, however, because the analog high and low-pass filters that precede the digital filter have fixed passband centers of 500 Hz. A drift of  $\pm 250 \text{ Hz}$  on the 8 kHz clock corresponds to  $\pm 62.5 \text{ Hz}$  ( $250 / 4$ ) drift in the Doppler tone produced. This value is acceptable because of the relatively low Q of the analog band-pass filter.

Digital filter Q is calculated by dividing





- R4—27 k $\Omega$  (29SJ250-27K)
- R8, R32—22 k $\Omega$  (29SJ250-22K)
- R12, R23—56 k $\Omega$  (29SJ250-56K)
- R13, R16, R22, R24, R27, R37, R39—10 k $\Omega$  (29SJ250-10K)
- R14—3.3 k $\Omega$  (29SJ250-3.3K)
- R15, R18—100 k $\Omega$  (29SJ250-100K)
- R17, R25—330  $\Omega$  (29SJ250-330)
- R19, R36—500 k $\Omega$  linear-taper pot (31CN505)
- R21—220 k $\Omega$  (29SJ250-220K)
- R28—15 k $\Omega$  (29SJ250-15K)
- R33, R29—68 k $\Omega$  (29SJ250-68K)

- R42, R51—47  $\Omega$  (29SJ250-47)
- R46, R47, R48, R49—470  $\Omega$  (29SJ250-470)
- R50—10 k $\Omega$  linear-taper pot (31CN401)
- U1-U3—LM324 (511-LM324N)
- U4, U6—LM555 (570-LM555CN)
- U5—74HC4051 (570-CD74HC4051E)
- U7—74HC161 (511-M74HC161)
- U8—74HC42 (511-M74HC42)
- U10—LM7805 (511-L7805CV)
- U11—74HC4515 (570-CD74HC4515E)
- U12—74HC14 (511-M74HC14)

- Miscellaneous
- F1—0.5 A fuse (5761-51500)
  - J1—6-pin DIN receptacle (16PJ224)
  - J2—3.5 mm audio jack (16PJ011)
  - P1—Coaxial dc receptacle (163-4305)
  - S1, S2—SPST (1055-TA1320)
  - S3—DPDT (1055-TA1360)
  - SP1—8  $\Omega$  speaker (253-2120)

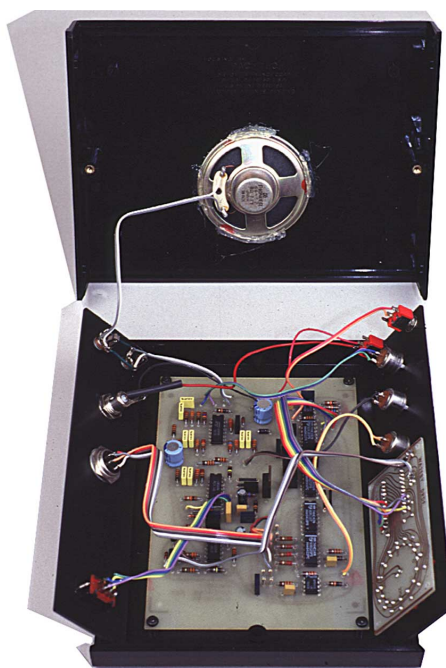
- Enclosure Pac-Tec Model #CM86-175 (616-69206)
- Knobs, three required (450-2023)
  - Main PC board (371-MAINPCB)
  - Display PC board (371-DISPLAYPCB)

the filter's center frequency by its bandwidth ( $Q = f / BW$ ) or  $500 \text{ Hz} / 4 \text{ Hz} = 125$ . It's very difficult to realize such a high- $Q$  filter with active or passive analog filters—and even more difficult to maintain a precise center frequency. The slightest change in temperature or component tolerance would easily de- $Q$  or detune such filters from the desired 500 Hz Doppler tone frequency. The digital filter makes the high  $Q$  possible and does so without the need for precision-tolerance components. By varying **DAMPING** pot R19, the response time of the digital filter is changed. This digital filter damping helps average rapid Doppler-tone changes caused by multipath-reflected signals, noise or high audio peaks associated with speech.

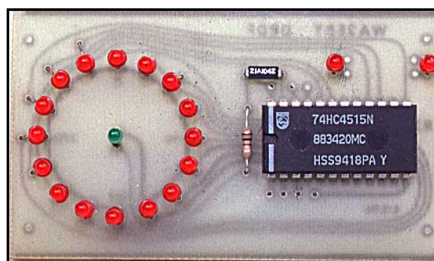
A digitized representation of the Doppler tone is provided at the digital filter output. A two-pole Sallen-Key low-pass filter built around U2B filters out the digital steps in the waveform providing a near sinusoidal output corresponding to the Doppler shift illustrated in **Figure 1B**. The zero crossings of this signal indicate exactly when the Doppler effect is zero. Zero crossings are detected by U2C and used to fire a monostable multivibrator (U6) built around a 555 timer. U6's output latches the red LED in the display corresponding to the direction of transmission with respect to the green **CENTER** LED, D16. Calibration between the actual source of transmission and the red direction-indicating LED latched in the display is easily accomplished by changing the delay between the Doppler-tone zero crossing (firing of U6) and the generation of the latch pulse to U11. C23, R36 and R37 determine this delay. Increasing or decreasing the delay is achieved by increasing or decreasing the value of the **CALIBRATE** potentiometer R36.

### Low-Signal-Level and Audio-Overload Indicators

Two useful modifications included in this design are the **LOW SIGNAL LEVEL** lockout and **AUDIO OVERLOAD** indicators. U2D continuously monitors the amplitude of the Doppler tone at the input to the zero-crossing detector. U2D's output goes low whenever the Doppler tone amplitude drops below 0.11 V peak. This is done by referencing the negative input of U2D to 2.39 V, 0.11 V below the nominal 2.5 V dc reference level output of U2B by means of voltage divider, R21 and R22. U2D's output remains high when the Doppler tone is present and above 0.11 V peak. C9 discharges via D2 whenever U2D goes low, causing U3A's output (pin 7) to go high, turning on Q2 via R2 and illuminating **LOW SIGNAL LEVEL** LED, D4. D4 remains on until the Doppler tone returns with amplitude above 0.11 V peak and C9 recharges via R23. The LED display remains locked by disabling U11's strobe input whenever the Doppler tone is too low for an



Inside view of main unit



Display PC board

accurate bearing. This is done by pulling pin 1 of U11 low via D5 when Q2 is turned on.

**AUDIO OVERLOAD** indicator D3 tells you that audio clipping of the Doppler tone is occurring. Clipping results if the signal level from the digital filter is too high and can produce an erroneous bearing indication. The output of U1D goes low whenever the output of the digital filter drops below 0.6 V as the amplitude of the Doppler tone approaches the 0 V supply rail. C7 discharges via D1 and causes the output of U3C to go high, turning on Q1 via R16 and illuminating **AUDIO OVERLOAD** LED D3. I elected not to lock the LED display on audio overload; doing so, however, only requires connecting a diode between the collector of Q1 and pin 1 of U11, similar to the low-level lock-out function.

### Phase Correction

If the audio output of the Doppler RDF FM receiver is incorrectly phased, S3, **PHASE INVERT**, can fix that. (If phasing is incorrect, LED direction indications are

180° opposite that of the actual signal source.) Moving S3 to the opposite position corrects the problem by letting U2C sense the trailing edge. This is particularly useful when switching between different receivers. S2 disables the 8 kHz clock to disable the antenna spinning. This helps when you're trying to listen to the received signal. Presence of the Doppler tone in the received audio makes it difficult to understand what is being said, especially with weak signals.

### Power Supply

Power is delivered via a 1/2 A fuse (F1) and **ON/OFF** switch S1. D6 provides supply voltage reverse-polarity protection by limiting the reverse voltage to 0.7 V and allowing sufficient current to flow to blow fuse F1. U10 provides a regulated 5 V dc to all digital ICs. C29 through C33 are bypass filters. U10's 5 V dc output is dropped 2.5 V by resistive divider R43 and R45. Noninverting voltage follower U3B buffers the 2.5 V source to provide a virtual ground reference for all analog filters and the digital filter. Using a virtual ground 2.5 V above circuit ground allows op amps to process analog signals without the need of a negative power-supply voltage. Analog voltages swing from near 0 V to near +5 V with the virtual ground level right in the middle, 2.5 V.

### Next Month

In **Part 2**, I'll discuss the antenna switcher, construction and calibration.

### Notes

- <sup>1</sup>Terrence Rogers, WA4BVY, "A DoppleScAnt" *QST*, May, 1978 pp 24-28.
- <sup>2</sup>Mike Kossor, WA2EBY, "A Digital Commutating Filter," *QEX*, May/June 1999.
- <sup>3</sup>Joseph Moell, K0OV and Thomas Curlee, WB6UZZ, "Transmitter Hunting—Radio Direction Finding Simplified," (Blue Ridge Summit, PA: TAB Books, 1987) Chapter 9, pp 120-141.
- <sup>4</sup>Joe Moell, K0OV, Homing In, "A Good Doppler Gets Better" *73 Magazine*, Apr 1995 pp 68-73, and Joe Moell, K0OV, Homing In, "Wide Band Doppler, Part 2," *73 Magazine*, Jun 1995, pp 54-58.
- <sup>5</sup>PC boards and parts kits are available from Mouser (Mouser Electronics, 958 N Main St, Mansfield, TX 76063-4827; tel 800-346-6873, 817-483-4422, fax 817-483-0931; [sales@mouser.com](mailto:sales@mouser.com); <http://www.mouser.com>): main PC board and PC board components kit (371-2771CF), \$50; display PC board and PC board components kit (371-2771D1), \$20; main PC board only (371-MAINPCB), \$15; display PC board only (371-DISPLAYPCB), \$6; switcher PC board and components kit (371-2771-D2), \$32; switcher PC board and four mag-mount PC boards (371-SWITCHERPCB), \$15. Add shipping to all prices.
- <sup>6</sup>Don Lancaster, *Active-Filter Cookbook*, (Indianapolis: Howard W. Sams & Co, 1975).

You can contact Mike Kossor, WA2EBY, at 244 N 12th St, Kenilworth, NJ 07033; [mkossor@lucent.com](mailto:mkossor@lucent.com).

See Feedback in July 1999 *QST*.

# A Doppler Radio-Direction Finder

*Part 2*—In this installment, I'll discuss the antenna switcher, construction of the PC boards, calibration and checkout. Construction data is supplied for using the unit on three bands.<sup>7</sup>

## Antenna Switcher

Figure 4 is the antenna-switcher schematic. Antenna 1 is selected when +5 V is applied to J1 pin 1. Current flows through RF choke L5, D11, D7 and RF choke L1 to ground. This current forward biases diodes D11 and D7, increasing their junction capacitance. The high junction capacitance (low reactance) allows RF signals present on antenna 1 to pass easily through D7, the 12-

inch-long coaxial line, D11, C49 and on through the line to the FM receiver. C49 is a dc blocking capacitor.

J1 pins 2, 3 and 4 remain at 0 V dc while antenna 1 is selected. Without forward bias, D8, D9 and D10 exhibit very low junction capacitance and effectively isolate antennas 2, 3, and 4 from the circuit. Thus, D7 through D14 function as RF switches. They are considered closed when forwarded biased and open without forward bias. Emulating a spinning antenna in the pattern of antenna 1, 2, 3,

4, 1 is achieved simply by applying 5 V dc sequentially to pins 1, 2, 3, 4, 1.

It is absolutely essential that all unselected antennas be isolated from the circuit and circuit ground. Grounding unselected antennas has the undesired effect of adding parasitic antenna elements, which could distort the received-signal direction indication.

ECG-555 or MPN3404 PIN diodes are usually recommended for switching diodes D7 through D14. However, they are expensive compared to ordinary 1N4148 switch-

<sup>7</sup>Notes appear on page 40.

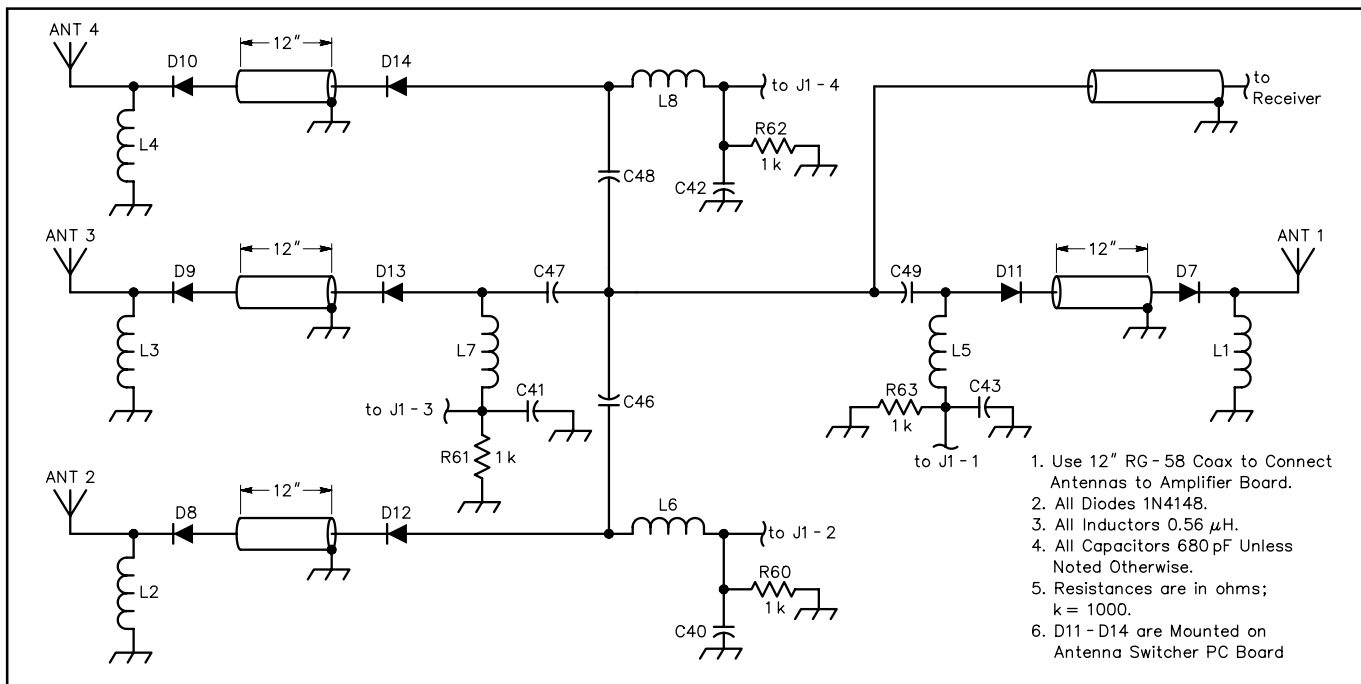


Figure 4—Antenna switcher schematic. Unless otherwise specified, resistors are 1/4 W, 5% tolerance carbon-composition or film units. Part numbers in parentheses are Mouser (Mouser Electronics, 958 N Main St, Mansfield, TX 76063-4827; tel 800-346-6873, 817-483-4422, fax 817-483-0931; [sales@mouser.com](mailto:sales@mouser.com); <http://www.mouser.com>). Equivalent parts can be substituted; n.c. indicates no connection. Switcher PC boards only (371-SWITCHERPCB); includes switcher PC board and four mag-mount antenna PC boards.

- C40-43, C46-49—680 pF, 25 V chip capacitors (140-CC502B681K)
- D7-D14—1N4148 silicon diode (583-1N4148)
- L1-L8—Surface-mount inductor, 0.56 μH (434-07-R56K)
- R60-R63—1 kΩ chip resistors (71-CRCW1206-1.0K)

- Miscellaneous**
- 4—1/2 inch brass hex spacers (534-1450C)
  - 1—6-pin DIN plug (171-0276)
  - 4—#4-40 × 1 inch flat-head screws
  - 12—#4-40 star lock washers
  - 12—#4-40 nuts
  - 4—1/16 diam × 36-inch-long copper welding

1. Use 12" RG-58 Coax to Connect Antennas to Amplifier Board.
2. All Diodes 1N4148.
3. All Inductors 0.56 μH.
4. All Capacitors 680 pF Unless Noted Otherwise.
5. Resistances are in ohms; k = 1000.
6. D11 - D14 are Mounted on Antenna Switcher PC Board

- rod (Lincoln R45)
- 5—Magnet strips 3 1/2 × 3 1/2 inches
- 4—Soda bottle caps (pop tops) for antenna bases
- 10 feet of RG-58 coax, 95% shield
- 10 feet of 6-conductor #24 AWG shielded wire

ing diodes. I decided to compare the difference between expensive PIN diodes costing as much as \$10 each with common 1N4148 switching diodes costing as little as four cents each. I tested a pair of each diode type in the same test circuit using a network analyzer to measure the insertion loss through both diodes and return loss. (Return loss is a measure of how close the input impedance is to the ideal 50  $\Omega$ .) A 0 dB return loss corresponds to an infinite SWR (open or short circuit) while a -20 dB return loss corresponds to a good SWR of 1.2:1. The diodes were turned off by not applying any forward bias and turned on with 15 mA of forward current. The test results are presented in [Table 1](#).

Not surprisingly, the most expensive PIN diode performed the best. I was a little surprised, however, to find that the popular ECG-555 has very poor isolation (4.5 dB) at UHF. This makes it totally unacceptable for use on 446 MHz. The ECG-553 is a better choice for VHF and UHF applications, but it costs considerably more than the switching diodes without providing a significant improvement in performance. I chose to use the Rectron 583-1N4148 and obtained excellent results with it.

## Construction

### Main Board

I used PC board construction for the main Doppler RDF board because of the large number of interconnections. Point-to-point wiring can be used if you have the patience and are a stickler for detail. Part placement is not critical, but use care to isolate digital and analog grounds. The main PC board fits nicely inside a 2  $\times$  8  $\times$  6.25-inch (HWD) plastic Pac-Tec enclosure. The **CALIBRATE**, **DAMPING** and **AUDIO LEVEL** controls and the **ON/OFF** and **SCAN STOP** switches are mounted on the front panel for easy access. Dc power input, Doppler tone **PHASE INVERT** switch S3 and the audio inputs and outputs are located on the rear panel. I mounted the external speaker inside the enclosure and drilled speaker holes in the top.

### Display Board

A PC board simplifies construction and provides a uniform circular pattern for the LED display. Point-to-point wiring can be used if desired; part placement is not critical. I made my own LED standoffs from #20 wire insulation. Strip the wire, removing a single tube of plastic insulation six inches long. Then cut 16 equal-length pieces, 0.20 inch long. Install the standoff on each LED's anode (longer) lead. The PC-board hole spacing varies to facilitate layout. Keep the anode lead straight at all times, and bend the cathode lead as necessary to reach the wide-spaced mounting holes. The standoffs ensure all display LEDs are the same distance from the board. Repeat the same procedure for LEDs D3, D4 and green **CENTER** LED, D16.

### Antenna Switcher

Double-sided PC board construction with plated through holes is used for the antenna

**Table 1**

### On and Off Performance of Various Diode Types

Diode Number And Type		146 MHz		446 MHz		Cost (Each)
		Return Loss (dB)	Insertion Loss (dB)	Return Loss (dB)	Insertion Loss (dB)	
HP3077-745	Off	0.16	66.00	0.03	49.50	\$10
PIN	On	23.00	0.44	15.10	0.79	
NSMP-3820	Off	0.10	47.30	0.10	27.00	\$1
PIN	On	25.20	0.21	18.20	0.44	
ECG-553	Off	0.10	48.00	0.05	27.60	\$2
PIN	On	21.40	0.76	19.10	1.00	
ECG-555	Off	0.10	29.10	2.80	4.50	\$2
PIN	On	25.30	0.23	16.40	0.51	
MPN-3404	Off	0.10	42.70	0.30	20.30	\$1.25
PIN	On	24.20	0.23	14.40	0.57	
1N914A	Off	0.10	56.30	0.20	37.10	\$0.12
Switching	On	16.70	1.82	17.80	2.42	
1N4454	Off	0.06	49.00	0.28	29.50	\$0.05
Switching	On	24.50	0.76	22.90	1.15	
1N4537	Off	0.05	48.00	0.27	30.80	\$0.05
Switching	On	25.50	0.66	22.70	1.24	
333-1N4148	Off	0.10	50.50	0.37	33.40	\$0.04
Switching	On	24.10	0.93	24.40	1.40	
583-1N4148	Off	0.04	47.10	0.27	29.00	\$0.04
Switching	On	26.70	0.62	22.30	1.09	



Antenna switcher close-up

switcher circuit. Microstrip transmission lines are employed to minimize impedance discontinuities and route signals to the summing point. Double-sided PC boards are also used to make each of the four  $1/4\lambda$  antennas (see [Figure 5](#)). Each 2.5  $\times$  2.5-inch antenna PC board contains an antenna-mounting stud, one switching diode and an RF choke connected to a microstrip line. A thin, flexible magnet attached to the bottom surface of each board makes it a mag-mount antenna. Business-card size magnetic material is available from office-supply stores. This material has an adhesive backing. It also helps make an excellent, low-cost mag-mount antenna! To add support to the antenna-mounting stud, I use plastic soda-bottle caps (pop tops). Drill a hole in the center of a cap for the whip-mounting screw and notch one side of the cap to pass the coax, as illustrated in [Figure 5](#). For this reason, I dubbed my homemade mag-mount antenna the Pop Top Mag-Mount. A 12-inch length of RG-58 coax connects each antenna to the antenna switcher PC board. Take care to make the lengths of all four coax lines exactly equal: This ensures the accuracy of the RDF bearing indication. Use hot-melt glue or epoxy to secure the RG-58 to the antenna-switcher PC board and each Pop Top Mag-Mount PC board. Larger fruit and sports

drink caps work well to protect the antenna switcher electronics.

Detachable antenna whips are made from 1/6-inch-diameter copper-plated-steel welding rods (Lincoln R45) and available from welding supply stores. The rod is easily soldered halfway into the zinc-plated #4-40  $\times$  1/2-inch hex standoffs. Install a #4-40  $\times$  1/2-inch screw in one end of the standoff to prevent solder from flowing more than halfway into the standoff. Insert the antenna whip into the other end and solder it in place. Remove the screw when the solder has cooled. Caution: All plastic pop tops are not created equal. Because their height varies, screw the antenna whip into the pop-top mag-mount base *before* cutting it to length. [Table 2](#) provides the whip lengths for 146, 223 and 446 MHz operation. The whip length is measured from the top surface of the Pop Top Mag-Mount base to the whip tip. You'll notice that the whip lengths are somewhat longer than that calculated using the formula  $l = 234/f$ . The extra length is required to compensate for the capacitive coupling between the mag-mount base and the car top.

## Check Out

### Basic Testing

It is wise to review your workmanship, looking for circuit shorts or opens prior to applying power. Use an ohmmeter to measure the resistance between power and ground; the value should be greater than 2 k $\Omega$ . Apply 12 V dc to the RDF unit with the power-supply current limited to 150 mA to prevent damage in the event of a problem (normal current drain is 100 mA). Verify the presence of the following supply voltages: +5 V on the output of U10, pin 16 of U8, pin 8 of U4, pin 8 of U6, pin 16 of U7, pin 24 of U11, pin 16 of U5. Verify +2.5 V on pin 14 of U3, verify +12 V on pin 4 of U1 and U2. This completes the basic testing of the Dop-

pler RDF circuit. The following tests are recommended to identify and troubleshoot problems, but don't worry if you don't have all the necessary test equipment. Satisfactory performance can usually be achieved without performing these tests.

### Functional Testing

Before connecting the antenna switcher, verify the operation of clock oscillator U4 by connecting an oscilloscope to pin 3. The output should be a square wave with an amplitude of 5 V and a period of 125  $\mu$ s (8 kHz). Use a frequency counter to verify the clock frequency is 8 kHz  $\pm$ 250 Hz for best performance. If necessary, the values of R27 and

R28 can be changed to adjust the clock frequency. Verify that closing switch S2 disables the clock. Open S2 (**SCAN STOP**) and verify the operation of BCD counter U7 by connecting the oscilloscope sequentially to pins 14, 13, 12 and 11. The signal frequency on these outputs should be approximately 4, 2, 1 and 0.5 kHz, respectively. Verify the presence of a square wave signal on pins 2, 4, 6 and 8 of buffer U12.

### Signal-Level Indicators

The following test uses an audio-signal generator to simulate the presence of the Doppler tone. Disconnect the speaker from **AUDIO LEVEL** control potentiometer R50 to

prevent loading the signal generator. Connect an audio-signal generator to the receiver audio-input terminal. Set the generator to apply a 500 Hz sine wave with amplitude 1 V P-P. Rotate R50 until the **AUDIO OVERLOAD** LED D3 illuminates. Then, adjust R50 until **LOW SIGNAL LEVEL** LED D4 lights. Adjust R50 so that LEDs D3 and D4 are off, set **CALIBRATE** control R36 to the center of its range and adjust **DAMPING** control R19 for minimum damping (fully CCW).

### Direction Indicator

Adjust the frequency of the audio generator very slowly around 500 Hz while observing the LED display. You should see the direction-indicating LEDs around the green center LED illuminating. The LED illumination should rotate *clockwise* when the frequency of the generator is set slightly *lower* than the antenna rotation frequency. (Only one LED will be on when the frequency of the generator equals the antenna-rotation frequency.) The display should rotate *counterclockwise* when the frequency of the generator is slightly *higher* than the antenna-rotation frequency. Because the digital filter is sharp, the transition between clockwise, stationary and counterclockwise directions is very abrupt. The audio generator must be capable of very fine frequency adjustment in order to observe the transition. All LEDs in the display may appear to be on if the signal generator frequency is just 10 Hz different from that of the antenna-rotation frequency determined by U4. It is interesting to observe the sharpness of the digital filter on pin 1 of U2 on the oscilloscope as the display makes the transition from clockwise to counterclockwise. You can see the simulated Doppler tone of the generator come out of the noise, peak and return into the noise as the transition takes place.

### Calibration Control

Verify the function of the **CALIBRATE** control by adjusting the audio generator equal to the antenna rotation frequency. At this point, only a single LED will illuminate. Rotate the **CALIBRATE** control through out its range and observe the direction-indicating LED "move" around the display. The range of movement should be more than 360°. The direction-indicating LED may move slightly if the generator frequency drifts. It is very difficult to keep the generator frequency synchronized exactly, but that's not necessary in this test. Disconnect the signal generator and reconnect the speaker to the receiver audio-input terminal.

### Antenna Switcher

Verifying proper operation of the antenna-switcher sequencing circuit requires only a dc voltmeter. Connect the antenna switcher to the Doppler RDF unit and position the four mag-mount antennas on a table. Do *not* install any of the whip antennas for this test.

It is essential that the antennas be turned on in sequence to emulate an antenna spinning in a circular pattern for the Doppler RDF

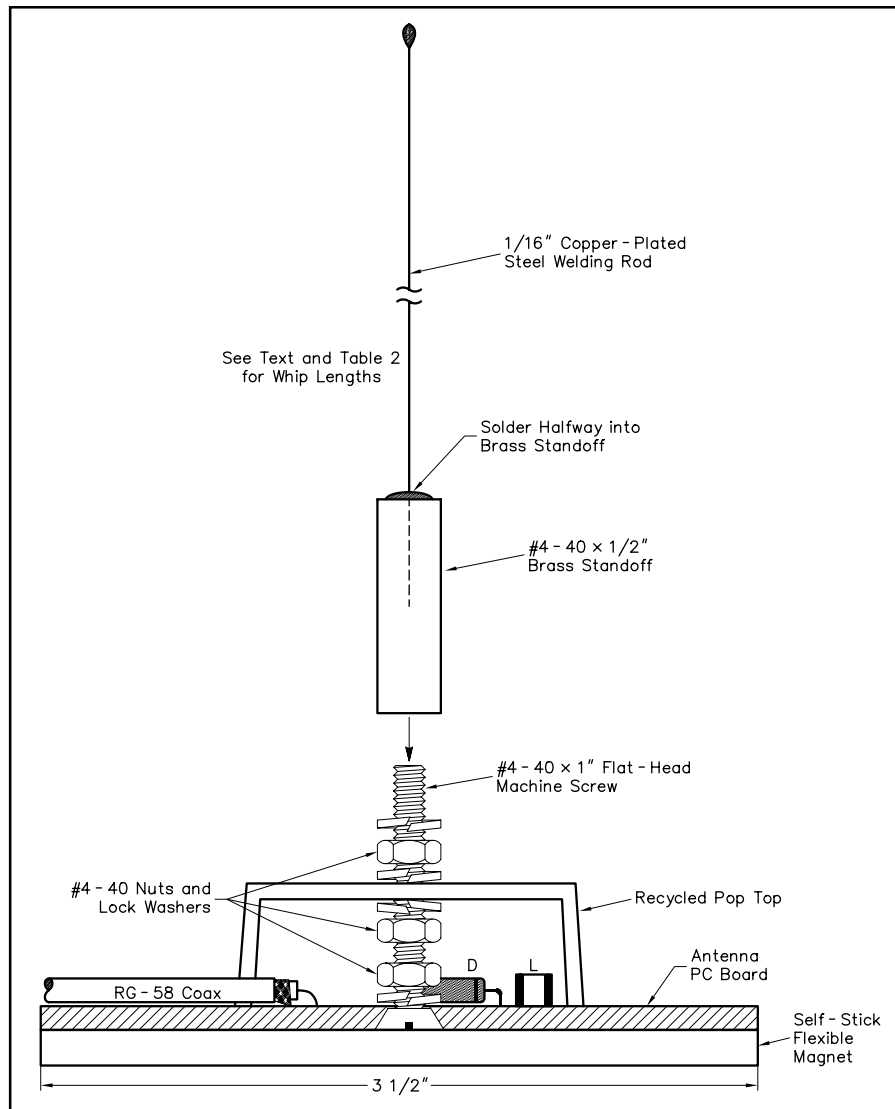


Figure 5—Assembly drawing of one of the four Pop Top Mag-Mount antennas. Dimensions for the whip lengths for three bands are given in Table 2.

Table 2

### Antenna Whip Lengths and Antenna Spacings for Use on Three Bands

Frequency (MHz)	Whip Length (inches)	Antenna Spacing per Side (inches)
146	20 <sup>1</sup> / <sub>16</sub>	18.25
223	13	11.5
446	6 <sup>11</sup> / <sub>16</sub>	5.75

unit to operate correctly. A single antenna turned on out of sequence is enough to produce a bogus RDF reading. It does not matter if the antenna spins clockwise or counter-clockwise. For this test, we'll assume the antenna spin is clockwise.

**SCAN STOP** switch S2 stops the antenna from spinning. Close and open S2 until the voltage on terminal J1 pin 1 of Figure 3 reads +5 V. Pins 2, 3, and 4 should all read 0 V. Pin 1 is the antenna-enable signal for antenna 1. Label the corresponding mag-mount antenna on the table as antenna 1. Close and open S2 until the voltage on terminal J1 pin 2 reads +5 V. Pins 1, 3, and 4 should all read 0 V. Pin 2 is the antenna enable signal for antenna 2 and should be positioned to the right of antenna 1 as viewed from the center of the antennas for a clockwise spin. Close and open S2 until the voltage on terminal J1 pin 3 reads +5 V. Pins 1, 2, and 4 should all read 0 V. Pin 3 is the antenna-enable signal for antenna 3 and should be positioned to the right of antenna 2 as viewed from the center of the antennas. Close and open S2 until the voltage on terminal J1 pin 4 reads +5 V. Pins 1, 2, and 3 should all read 0 V. Pin 4 is the antenna enable signal for antenna 4 and should be positioned to the right of antenna 3 as viewed from the center of the antennas.

Testing the RF operation of the antennas is quite simple. Place all four mag-mount antennas around the center of the car roof, placing each antenna at the corner of an 18.25-inch-square pattern for operation on 146 MHz. Do not install any of the whip antennas yet. Connect the RF output of the antenna switcher to an FM receiver or transceiver tuned to a strong NOAA weather broadcast signal. *Caution:* Make sure you disable transmit mode if you are using a transceiver!

Apply power to the RDF unit and open S2 to stop the spinning process. Take one whip antenna and touch it to the mounting screw on each of the mag-mount antennas. Only one antenna should provide a signal strength reading similar to it being connected directly to the FM receiver. Remove the whip from the selected antenna and touch it to each of the other three antennas. The NOAA signal should be weak or nonexistent. Close and open S2 until another antenna is selected and repeat the same test. Continue the process until you have verified each antenna can be turned on while the other three remain off.

## Operation

Checking performance of the RDF unit is best done in a large, empty area away from tall buildings; a parking lot will do. Use caution at all times during open-road operation of the RDF unit. Use a minimum of two people for all testing and operation of the RDF unit: one to operate the vehicle and the other to operate the RDF unit. As a safety measure, secure each Pop Top Mag-Mount with 20-pound fishing line when operating the vehicle at highway speeds.

Attach all four whip antennas to the mag-mount antenna bases placed about the center of the car top. Connect the RF output of the



Single antenna base

antenna switcher to a FM receiver or transceiver tuned to a strong NOAA weather broadcast signal. *Caution:* Again, make sure you disable transmit mode if you are using a transceiver!

Adjust the receiver's audio to a comfortable level in the external speaker. Apply 12 V to the RDF unit and spin the antenna by closing switch S2. As soon as S2 is closed, you should hear a 500 Hz tone imposed on the receiver audio. Rotate **AUDIO LEVEL ADJUST** control R50 so that **LOW SIGNAL LEVEL LED D4** and **AUDIO OVERLOAD LED D4** are extinguished. *Never trust bearing indications if D3 and/or D4 are illuminated.* The direction-indicating display should be relatively constant with a single LED lit, or one or two adjacent LEDs alternately illuminating. Adjust **CALIBRATE** control R36 so that the direction-indicating LED is consistent with the general direction of the NOAA transmission with respect to your location and the position of the car.

Have the driver slowly circle while you observe the display. You should see the direction-indicating LED move in the opposite direction as the car is turning in a circle. The position changes relative to the changing direction of the car; however, the direction indicated from the center of the circle the car is driving around should remain fixed. If the display turns in the same direction as the car, flip **PHASE INVERT** switch S3 to the opposite position to correct the 180° phasing offset. This completes the rough calibration procedure.

## Final Calibration

A more accurate calibration can be achieved while the car is in motion. Position a volunteer with an H-T in a safe spot on the side of a long, straight and vacant roadway about 1/4 to 1/2 mile away. Have them transmit on low power (0.5 W) while traveling towards them. The RDF operator should calibrate the RDF display to indicate 0° as straight ahead. The display should change to 180° indicating the signal is coming from directly behind the car as the vehicle passes the transmitter. The moving calibration procedure functions to average out false reflected signals caused by multipath propagation.

You may notice that the Doppler tone changes as the car moves about. The Doppler tone will sound like a pure, undistorted 500 Hz sine wave in the absence of reflected or multipath interference. Direction indications are most reliable under these conditions. When reflected or multipath signals

are present, the Doppler tone will sound raspy and distorted. These signal components may arrive from different directions causing false bearing indications. The LED display tends to jump around randomly under these conditions. Avoid taking bearing information when the Doppler tone sounds raspy for this reason. You can minimize display jitter by slowing the response time of the digital filter. This is accomplished by increasing **DAMPING** control R19. With a little time, you can master the art of Doppler RDFing.

## RDFing on Other Bands

The wide-bandwidth antenna switcher can be used for DFing on other bands, provided the proper antenna whip lengths and antenna spacings are used. Arrange the antennas in a square pattern. Typical antenna spacing is  $0.22 \lambda$  per side. Table 2 provides the whip lengths for use of the DFER on 146, 223 and 446 MHz. Whip lengths are measured from the top surface of the mag-mount PC-board base to the tip of the antenna.

Other band-limiting components associated with the antenna switcher are the inductors L1-L8. The recommended inductor for the antenna switcher in the parts list is a 0.56  $\mu\text{H}$  unit with a self-resonant frequency of 440 MHz. This inductor presents an impedance of more than 500  $\Omega$  from 146 MHz to 446 MHz. Part substitution is permissible, providing the inductor has a inductive reactance of at least 500  $\Omega$  and a self-resonant frequency greater than the highest frequency at which the antenna switcher will be used.

## Summary

This project incorporates several useful features developed over the years into a single, compact design. The wide bandwidth antenna-switcher design introduced here can be built using commonly available components, significantly reducing the overall cost of the project. In constructing this project, you have the opportunity to learn about analog, digital and RF circuits—and have a great deal of fun organizing and participating in “fox hunting.”

## Acknowledgments

I want to thank Harry Randel, WD2AID, for capturing the schematic and parts layout of this project, and my brother, Dave, KC2BDL, for assisting with field testing. My thanks also to these members of the Tri-County Radio Club (TCRA): Gerry Miller, AA2ZJ, Bob Grassmann, KB2BBD, Ed Grassman, N2TDM, and Dick Montgomery, N3DV, for providing the opportunity to hone my RDFing skills with many memorable hours of fox-hunting.

<sup>7</sup>Part 1 of this series appears in *QST*, May 1999, 35-40.

Note: In Part 1, Figure 3, page 38, the input pin of U12A should be shown as pin 9, not pin 4. Also, the author's mailing address is 244 N 17th St, Kenilworth, NJ 07033.

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See Feedback in July 1999 *QST*.