

# 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

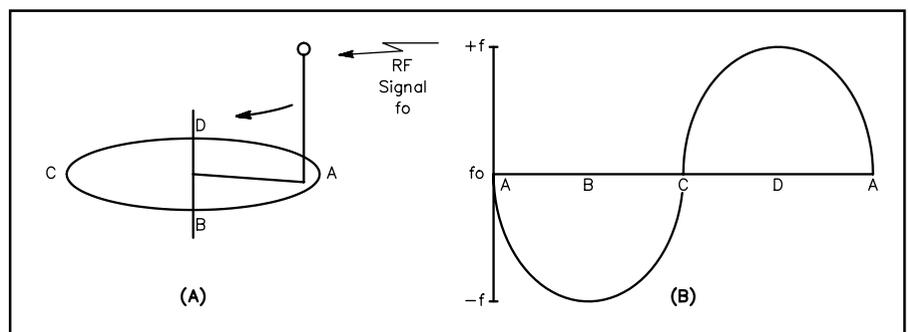


Figure 1—At A, depiction of a rotating antenna. At B, Doppler frequency shift.

## 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.

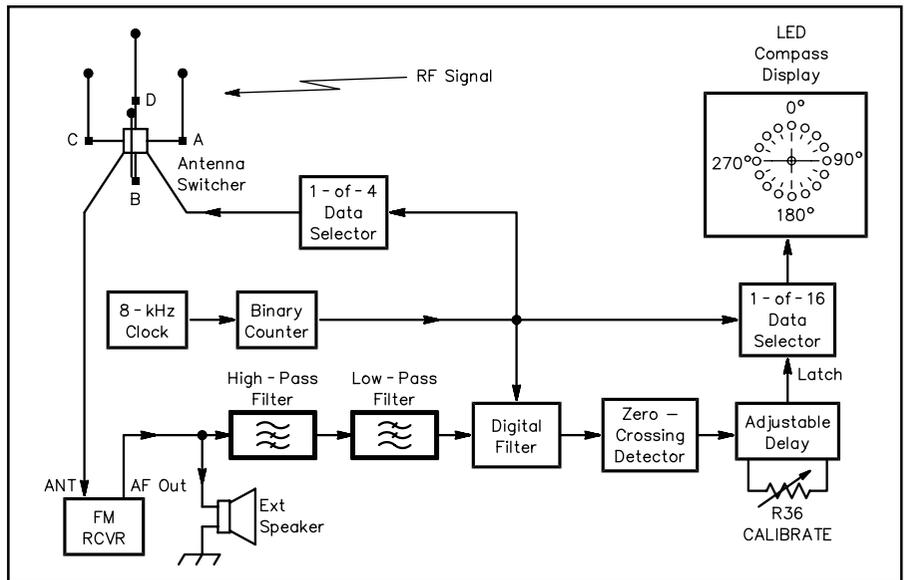


Figure 2—Block diagram of the WA2EBY Doppler RDF system.

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.

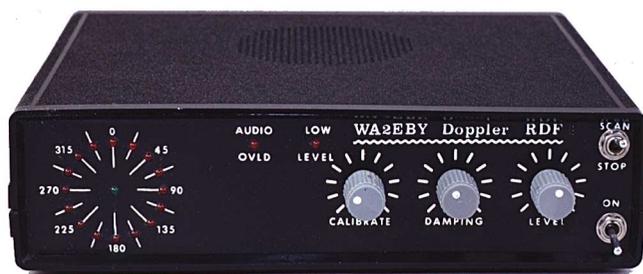
A careful review of the Roanoke design revealed use of somewhat obsolete 4000 series CMOS logic circuits that require CMOS-to-LED display drivers to operate the LEDs. These IC drivers are still

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.

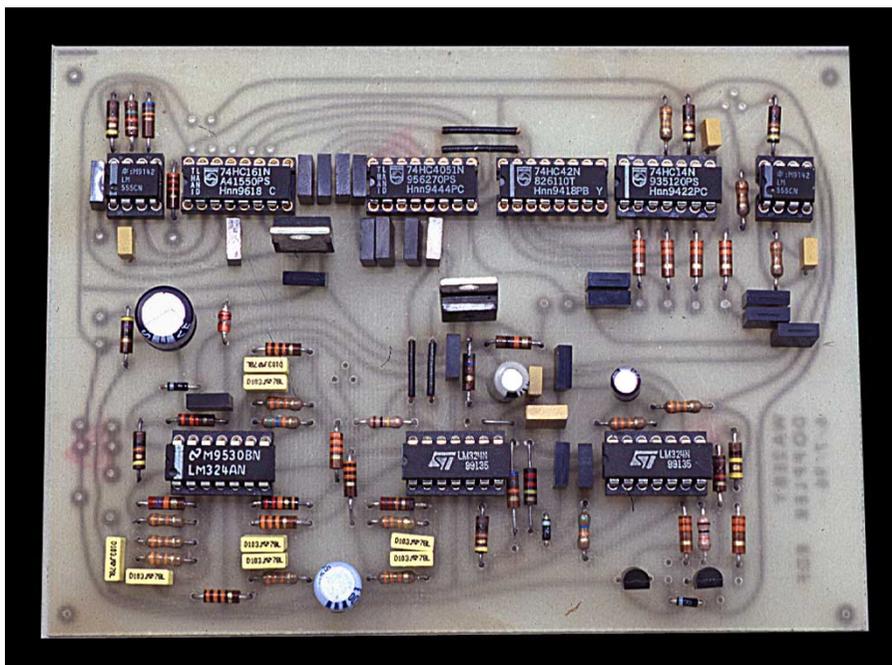
The output of the digital filter represents the actual Doppler frequency shift described in Figure 1B. Zero crossings of the Doppler frequency shift pattern correspond to the antenna position located directly toward the source of transmission (position A) or directly opposite the source of transmission (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

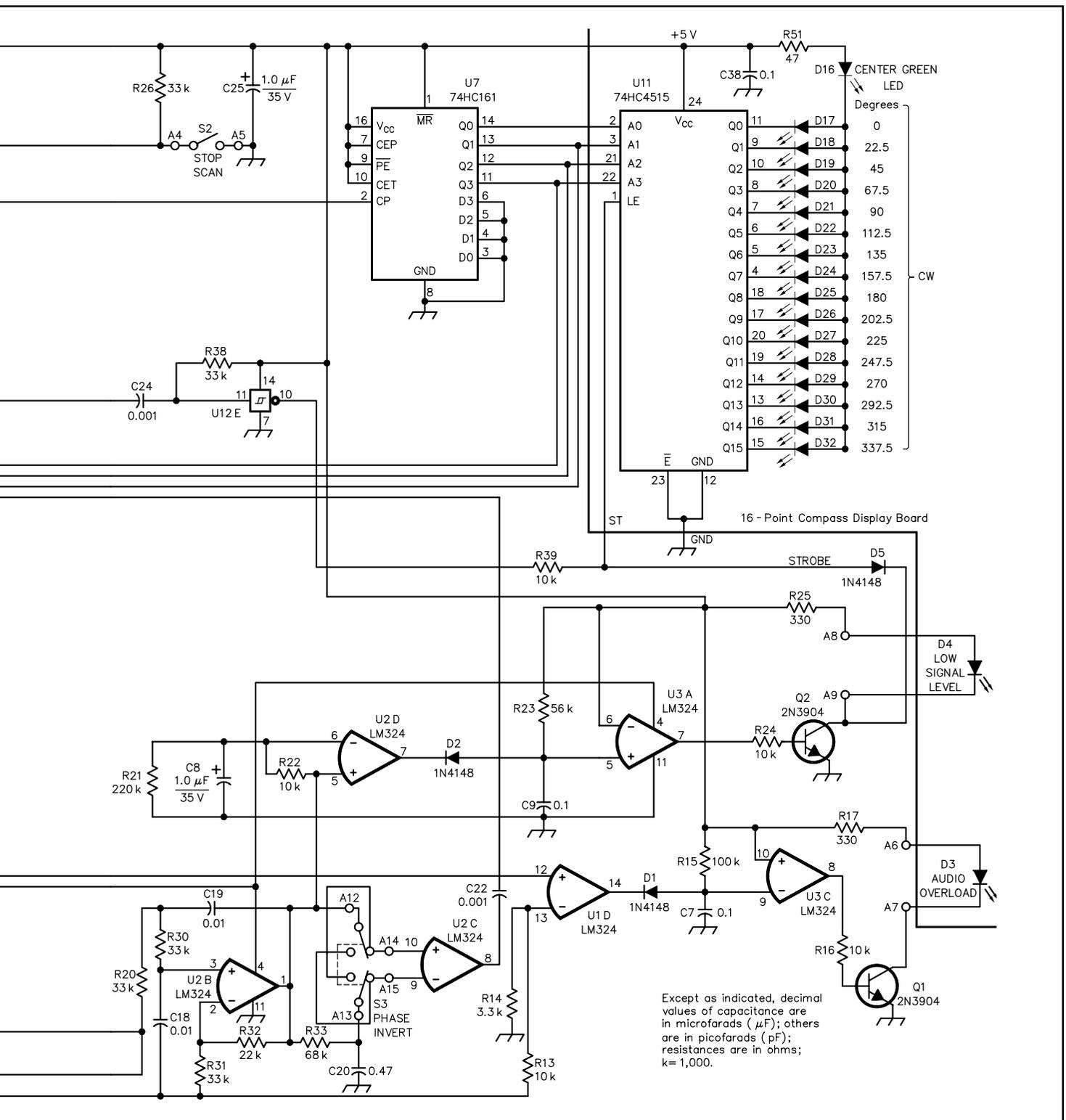
through C17. (Readers interested in the detailed operation and analysis of this fascinating digital filter are encouraged to review my *QEX* paper; see Note 2.)

### 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)

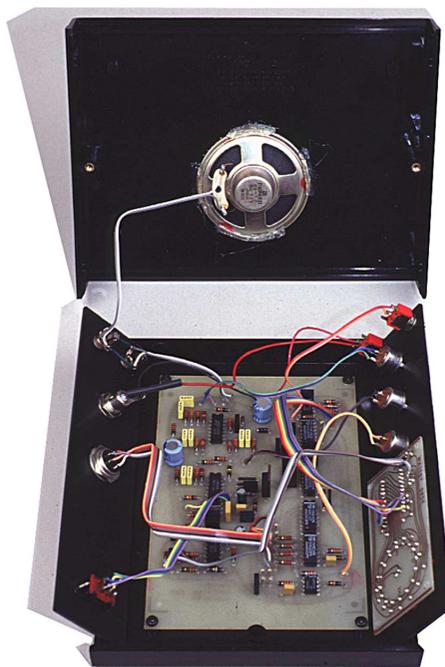
- Enclosure Pac-Tec Model #CM86-175 (616-69206)
- Knobs, three required (450-2023)
  - Main PC board (371-MAINPCB)
  - Display PC board (371-DISPLAYPCB)

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.

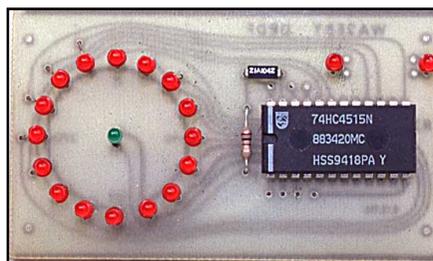
A digitized representation of the Doppler tone is provided at the digital filter output. A two-pole Sallen-Key low-pass filter built around U2B filters out the digital steps in the waveform providing a near sinusoidal output corresponding to the Doppler shift illustrated in Figure 1B. The zero crossings 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).

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See Feedback in July 1999 *QST*.