Coherent CW — The Concept

Part 1: Would you think that you could *decrease* your transmitter output power by a factor of 10 and *increase* signal readability by the same amount — simultaneously? It's being done now.

By Charles Woodson,* W6NEY

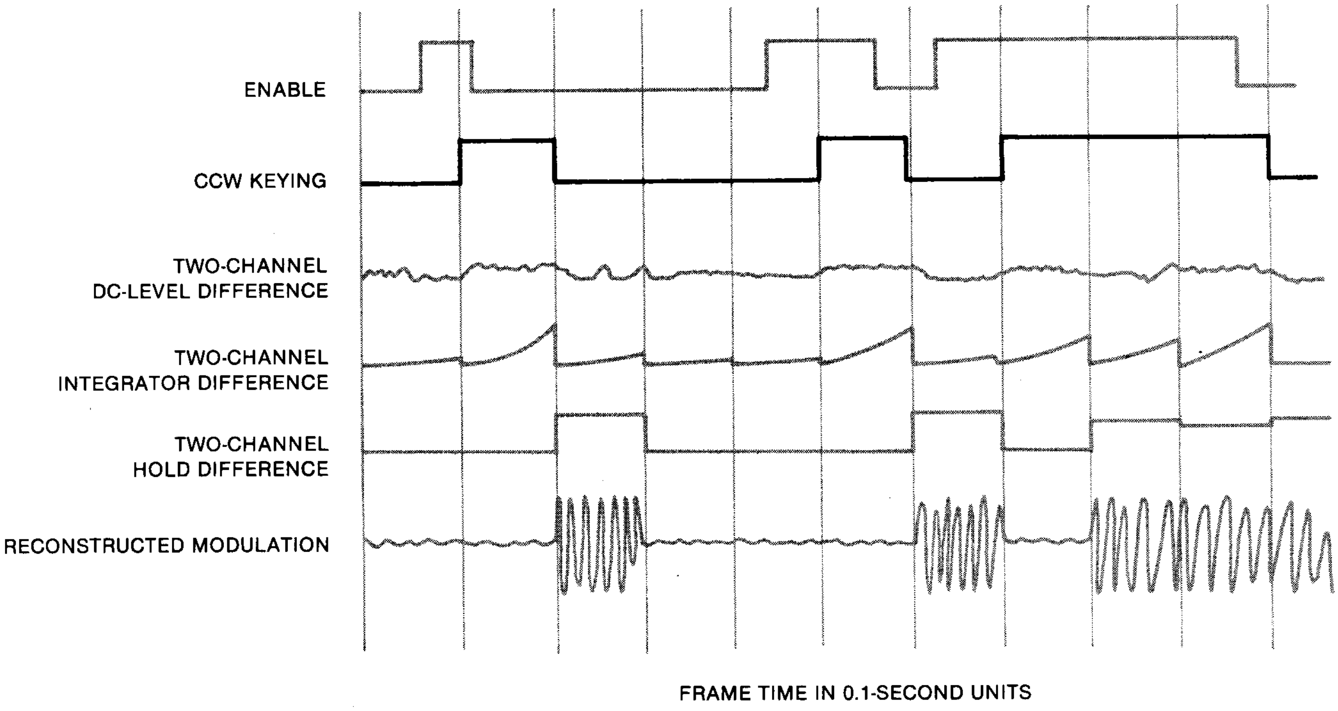

Fig. 1 — The elements of ccw communication. Frames, in 0.1-second units, are shown on the horizontal axis. The enable (top waveform) shows the closure of a manual key by the operator. When referenced to the precise frame times, it can be seen that the dots, dashes and spaces of the enable are not accurate in length. Note that with the ccw-keyer waveform a mark or space is begun only at the beginning of the frame period and continues for the full period(s). As received, the signal is mixed with QRM and QRN. The difference between the dc voltages from the switching mixers of the two channels (third waveform) is a function of the desired, but weak, signal. An integrator sums the power (voltage) received over the frame period. This sum is sampled at the end of the period and held until the beginning of the next period. The recovered modulation is used to key an audio signal for detection by ear.

The more we know about something we seek, the easier it is to find. This principle applied to Morse cw communications is called coherent cw or ccw. On-the-air trials of this technique have shown it will provide an improvement of more than 20 dB in communications effectiveness over ordinary cw methods. This same principle can be used with RTTY, ASCII and fsk signals, but this discussion will focus on cw keying.

Cw signals may be analyzed as a series of digital units, all of which have (at least approximately) a unit of time in common. For convenience, I'll call this time unit a "frame." Each frame contains either a "mark" (key down) or a "space" (key up). Fig. 1 illustrates this concept.

Ordinary cw dots, dashes and spaces begin at somewhat arbitrary times, depending on when the operator happens to press the key. Thus, the frame length varies to a considerable degree, and you can't predict when each frame starts and ends. With ccw, all dots, dashes and spaces are exact multiples of the basic time unit and occur within predictable time frames. This includes any pauses during transmission. When received, ccw signals sound like any other cw signal except that they are being sent very precisely, as with

*2301 Oak St., Berkeley, CA 94708

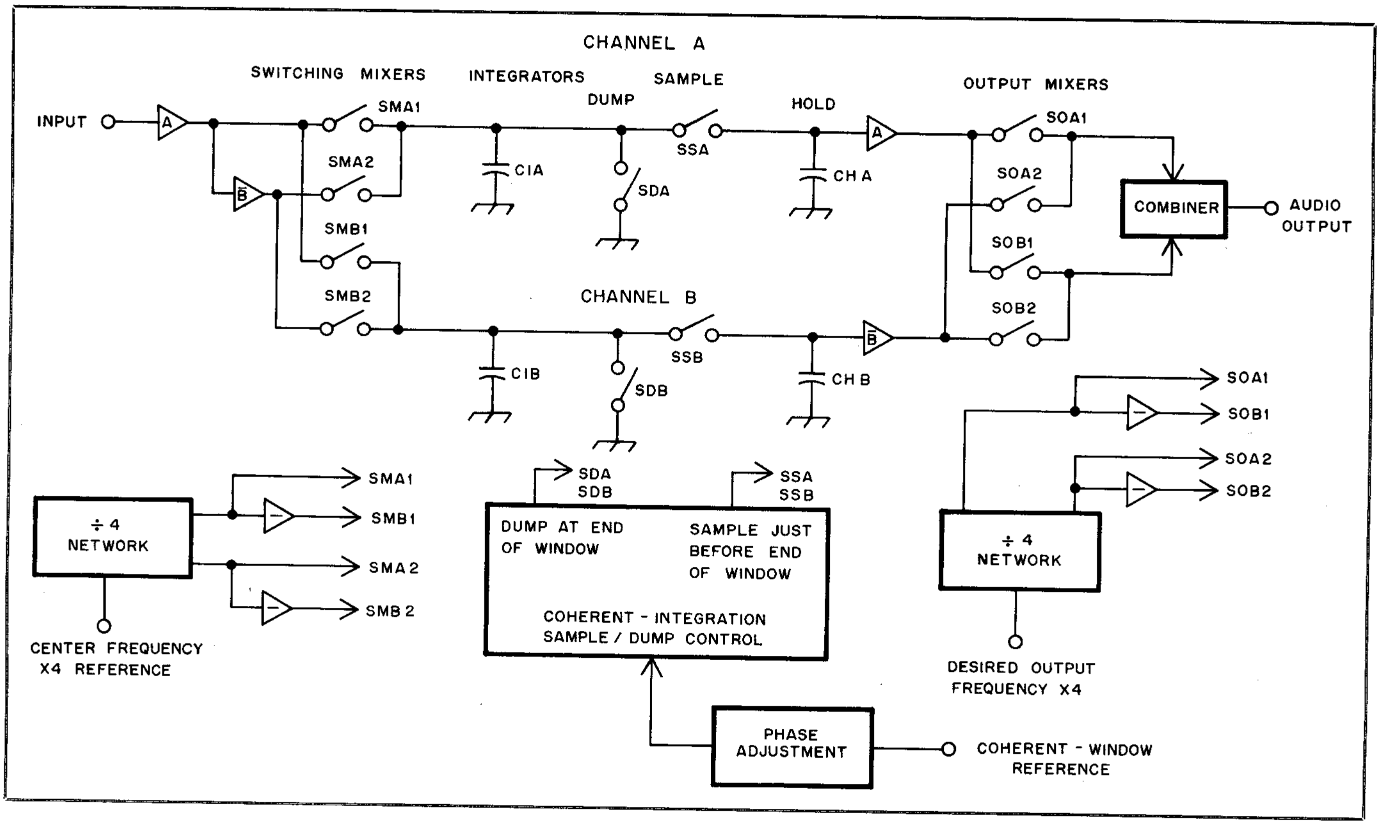

Fig. 2 — Block diagram of a ccw filter.

a perfect "fist." This characteristic is utilized to permit the use of very narrow bandwidth filters.

CW Filters

In general, receiver filters with bandwidths much wider than that of the desired signal are less effective because they allow reception of additional noise and undesired signals. At 12 wpm a cw signal occupies about 10 Hz of the spectrum, yet 500- or 2300-Hz-wide filters are frequently used for cw reception. With a 500-Hz filter, one hears the 10-Hz-wide desired signal and 490 Hz of noise and QRM! By analogy, an ssb operator using a similar approach would listen to 100 kHz of the band at one time!

High-Q analog cw filters are not useful at the narrow bandwidths approaching the bandwidth of a 12-wpm cw signal. Such filters, with bandwidths less than 500 Hz, tend to "ring" or produce an output after the signal ceases. The human ear is confused by such ringing. Also, the receiver stability and resetability required in conjunction with the filter, on the order of a few hertz, is difficult to achieve.

Phase-locked loop (PLL) filters with time constants long enough to produce bandwidths of only a few hertz unfortunately take tens of seconds to achieve lock. PLLs also tend to lock on the strongest signal in the passband and are, therefore, sensitive to QRM. PLL filters have their place of importance, but not with the bandwidths required here.

The filter we need will provide a bandwidth of only a few hertz without ringing and without a tendency to lock on the QRM. Such a filter improves the signal-to-noise ratio dramatically. A 1-W signal copied through a 10-Hz bandwidth filter is comparable to a 50-W signal heard through a 500-Hz filter or a 230-W signal heard through a 2300-Hz filter.

The CCW Station

Typically, ccw stations agree on an operating frequency (e.g., 14,049,000 Hz ± 2 Hz) and a frame length (usually 0.1 second, the speed of 12 wpm), and acquire the "framing" — when each frame starts and ends — as part of the signal-tuning process. Thus, the frequency, frame length and frame phase are all known at the receiving end and are used to advantage in the detection process.

To achieve the necessary frame-length accuracy and to get on the operating frequency within the narrow tolerance of the filter, all frequency-determining oscillators in both the transmitter and receiver of the ccw station must be highly stable and accurate. The stability and accuracy requirements are obtainable by using carefully built crystal oscillators which are compared to a reference frequency such as WWV. Time discipline for the transmitted signal is determined by a reference oscillator which is divided to provide a 10-Hz synchronizing signal for the transmitter keyer. The ccw filter at the receiving station uses timing signals derived from the station reference oscillator. These timing signals tell the receiver filter when to expect a frame to begin and end.

The Coherent Integrating Filter

Fig. 2 shows a block diagram of the filter which makes possible the efficient reception of a ccw signal. The major blocks of each of the two filter chains are: input mixers, integrators, sample-and-hold circuits, output mixers and the timing and control circuitry. The reason for the two chains will be examined later; for now, we'll follow the signal through one chain.

The Mixer: The first part of each filter chain is a switching mixer where the desired signal (along with adjacent QRN and QRM) is mixed with a reference signal of the same frequency as the desired signal. (Solid-state switching is performed in the actual circuit, but for simplicity, mechanical contacts are shown in Fig. 2.) The reference signal is obtained from a stable source such as the timing and control circuitry, and it determines the center point of the ccw filter. A signal at the desired frequency comes out of the mixer as a dc voltage — the stronger the signal, the larger the voltage. An off-frequency signal, however, comes out of the mixer as a low-frequency ac voltage. We mix the incoming signal right down to zero beat. Undesired signals will be distinguished from the desired signal because they are not exactly zero beat.

The Integrator: An op-amp integrator comprises the second part of each filter chain. We use the integrator to distinguish the desired signal (the zero-beat dc voltage) from the undesired signals (low-frequency ac voltages) coming from the mixer. The integrator may be thought of as a moderately large capacitor. A synchronizing "dump" signal from the timing and control circuitry shorts out this capacitor at the start of each time frame. Any desired signal (dc voltage) during the time frame causes the capacitor to charge. The resulting voltage at the end of the time frame is a function of the strength of the desired signal received during that frame.

QRM and QRN, being off frequency, appear as ac signals to the integrator capacitor. These charge the capacitor for part of the time frame, but discharge it for other parts of the same period. Consequently, signals off frequency do not have as great an effect on the integrator output as do signals exactly on the desired frequency. That is how the ccw filter achieves its selectivity.

As an example, consider an interfering carrier which is 10 Hz above or below the desired signal. Following the switching mixer, this QRM appears as a 10-Hz ac voltage. If the filter is set to the ccw standard frame length of 0.1 second, then the 10-Hz interfering signal goes through one complete cycle during the integrating period. At the end of the time frame, the QRM-produced voltage at the integrator output is zero. Thus, the ccw filter has a null just 10 Hz above and below its center frequency. There are also similar nulls at other 10-Hz multiples.

Sample-and-Hold and Integrator Reset: At the end of each time frame, a "sample" signal from the timing and control circuit transfers the voltage at the integrator output to the sample-and-hold circuit. That circuit "remembers" that voltage for the following interval. Once the sample-and-hold has acquired the integrator output voltage, a dump signal from the timing and control circuitry shorts out the integrator capacitor. It does this by means of a CMOS analog switch connected across the capacitor. This allows the integrator to start over again with zero voltage at the start of the next time frame.

Resetting the integrator at the end of each time frame lets the ccw filter avoid the ringing (or intersymbol interference) common to other narrow-bandwidth filters. Note that this is possible only because the ccw filter "knows" when each time frame begins and ends. It is here that the time discipline of the transmitted signal is used to advantage in the detection process.

Output Mixer: This last block of the filter chain is much like the input mixer: it functions as an amplitude modulator, using the sample-and-hold output voltage to control the amplitude of a sidetone. The purpose of this mixer is to construct a sidetone for the human operator to hear.

Why Two Channels?

If the incoming signal is in phase with the center reference, then the mixer output is always positive. The integrator which follows will see a positive dc voltage. If the signal is out of phase with the reference, then the mixer output is always negative. The integrator will see a negative dc voltage. The positive or negative dc voltage charges the integrator capacitor, the sample-and-hold "remembers" that charge during the next time frame, and the output mixer generates a sidetone whose amplitude is proportional to the voltage on the sample-and-hold capacitor. But if the signal is 90° out of phase with the reference frames, then the mixer output will at times be positive and at other times be negative during a given input cycle. This output will be averaged to zero by the integrator. The result is no filter output from this channel.

The situation is different for each channel because the A channel input mixer is operated by a reference which is 90° out of phase with the B channel reference. Thus, if a signal is 90° out of phase with the A channel, it will be in phase (or 180° out of phase) with the B channel. At all phase differences between the two channels, the product of the two channels is always the desired signal despite the phase relationship between the center frequency reference and the incoming signal.

If the desired signal is graphed as a phasor (as in Fig. 3) one might say that the B channel picks up the X component of that phasor, and the A channel picks up the Y component of the phasor. The two-channel output mixers are also driven with signals 90° out of phase. That way, the output tones combine vectorially. The result is that the combined output is a tone whose amplitude reflects the amplitude of the desired signal, regardless of the signal phase. The phase of the output tone also reflects the phase of the desired signal.

The theoretical response curve of the filter may be developed. We won't go into the mathematical details except to say that the amplitude response is a sin x/x curve, like that in Fig. 4. For a 0.1-second frame length, the nulls in the filter response occur every 10 Hz either side of the center frequency. The 3-dB points on this curve are 9 Hz apart; the 6-dB points are 12 Hz apart.

Fig. 5 compares the ccw filter (0.1 second frames) with an ordinary 500-Hz cw filter and a 2700-Hz ssb filter. On this scale it is impractical to show the numerous nulls in the ccw-filter response; shown instead is the envelope of the primary response.

How Much Improvement?

One way of comparing ccw with the ordinary cw method is to consider the filter noise bandwidth. This is the bandwidth of

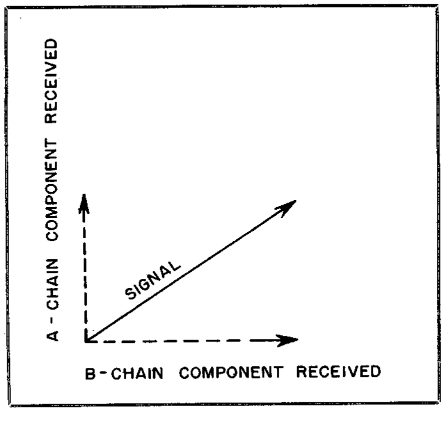

Fig. 3 — The desired signal considered as a phasor.

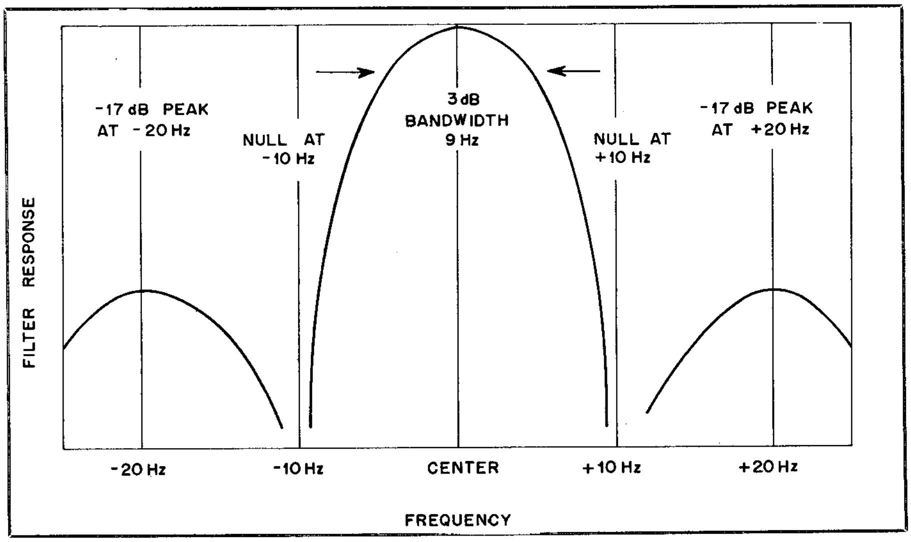

Fig. 4 — Filter-response curve for a 10-Hz bandwidth ccw filter.

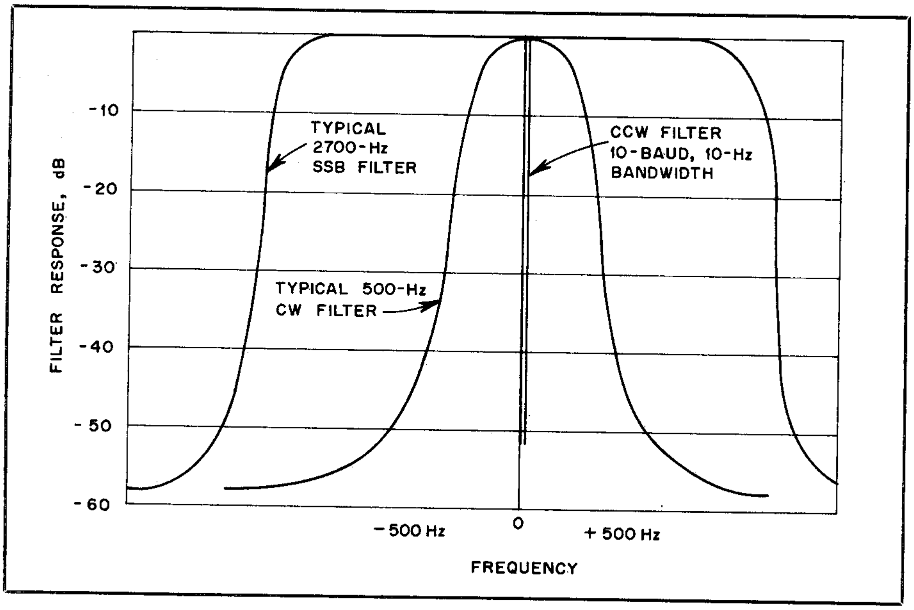

Fig. 5 — A comparison of three filter-response curves.

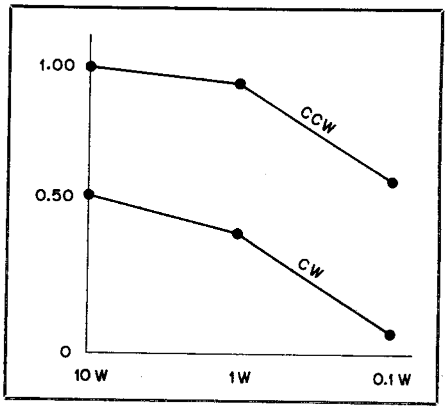

Fig. 6 — A graph of the average proportion of copy made by four operators of simultaneously sent cw and ccw signals. Three different power levels were used. See text.

an ideal steep-sided filter which would pass the same amount of random noise as the filter being considered. For 0.1-second frame length ccw, the filter noise bandwidth is 10 Hz. This equates to an approximate superiority of 17 dB over a 500-Hz cw filter and about 24 dB over a 2300-Hz filter. Such estimates should be reasonably accurate with respect to noise, but when QRM is present, the ccw filter probably does even better. Using a ccw system of 0.1-second frames with ground wave in the presence of natural noise, and adjusting power for matching readability, I have measured an approximate 16-dB improvement over a 470-Hz crystal filter; this is close to the theoretically expected value.

Narrowing the ccw bandwidth by using longer frame times provides an additional signal-to-noise advantage at the price of slower information transmission rates. A 0.1-second integration period gives about 24 dB improvement over a 2300-Hz crystal filter: a 1-second integration period (1.2 wpm), 34 dB; a 10-second period, (0.12 wpm), about 44 dB. These speeds are slow, but the improvement in effective communication with lower power is quite fascinating.

The improvement gained by long-frame ccw is limited by phase modulation introduced by the propagation path. For 14-MHz signals, motion in the F layer typically produces 2 or 3 Hz of phase (or frequency) modulation for a JA to W6 path.[1] (We have also observed what appears to be propagation time delays under poor band conditions.) When the filter passband becomes so narrow that this modulation exceeds the filter bandwidth, further improvement in signal-to-noise ratio cannot be obtained by narrowing the filter passband.

In evaluating filter effectiveness, noise bandwidth does not tell the whole story; there are psychological considerations, too. The human ear is frequency sensitive, and the human brain can focus on particular cw signal frequencies amid the noise and QRM. Skillful cw operators use this capability well. My observations have led me to conclude that this skill is worth at least a 6-dB margin when using a 2300-Hz filter. QRM, however, is often a confusion factor and therefore causes more degradation of copy than an equivalent amount of random noise. These psychological factors are difficult to quantify, but probably reduce the advantage of ccw over ordinary cw.

Fig. 6 shows graphically the results of on-the-air comparisons between cw and ccw made in 1975. Transmissions were made on 14,049,000 Hz from JR1ZZR at power levels of 10 watts, 1 watt and 0.1 watt using ccw and a vertical ground-plane antenna on a four-story building. A three-element beam was used for reception at W6BB. The ccw signals were received simultaneously as cw and ccw signals, and were recorded on separate channels of a stereo cassette recorder. We selected sample periods from the cassette recording and played back the signals to four moderately experienced cw operators. The average proportion of copy shown on the graphs is based upon words considered copied. The copy content was taken from radio journals. Extrapolation of these data indicate an estimated 13-W cw signal as equivalent to a 0.1-W ccw signal in communications effectiveness, or a 24-dB superiority for ccw.

Concluding Remarks

The ccw technique appears to be most promising, especially where signals are weak compared to the noise and QRM. Under high absorption and QRN conditions (as often experienced on 80 and 160 meters) the additional selectivity of ccw would be helpful; we don't have data on that yet however.

Ccw might be used for EME communication, but the problem is complicated because of lunar-motion Doppler effects. One might need a computer to calculate the frequency at which the signal is expected to return. Also, achieving the necessary frequency stability of 1 or 2 Hz is more difficult at the higher frequencies used for EME.

Some of the simplest rigs are the easiest to convert for ccw operation. To obtain the full advantage of the ccw mode, however, receiver quality should be high. In Part 2, I will describe the equipment and methods used for communicating by ccw. QST

References

Petit, "Coherent CW: Amateur Radio's New State Of The Art?", *QST*, September 1975.

Sekine, "Coherent CW Wa Nandesuka (What is Coherent CW?)", Japanese *Ham Radio Journal*, January, 1976.

Weiss, "Coherent CW — The CW Of The Future," *CQ*, June and July, 1977.

Petit, "Fundamentals of CCW," CCW Newsletter 75:7. Note: Back copies of volumes of the Coherent CW Newsletter (CCWN) are available from CCWN, 2301 Oak St., Berkeley, CA 94708: 1975, $5; 1976, $5; 1977, $10; 1978, $10. Volumes 75 and 76 are well summarized in the Weiss article in *CQ*. Most of volumes 77 and 78 are summarized in this article. Further volumes of the CCWN are not planned, but a book on ccw is being assembled by Petit. This article has benefited from suggestions by: Jim Maynard, K7KK; Ray Petit, W7GHM; Keitaro Sekine, JA1BLV; and Ed Johnson, W2ZWA/JA1YVW.

---

[1] [Editor's Note: The amount of "signal spreading" is determined in large measure by the earth's geomagnetic activity (A-index), which is more severe under disturbed conditions.]