GENERAL RADIO COMPANY

engineering department

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FREQUENCY—MEASURING RECEIVER SYSTEM

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Do you need a system for measuring frequencies of low-level signals from remote sources—signals usually accompanied by disturbances and noise which interfere with conventional digital counters? Then here's a possible solution: a receiver based upon superheterodyne techniques for measuring transmissions to a degree of accuracy dictated by any signal's frequency stability. Novice and expert alike will benefit by this account of past problems, new improvements, design influences and latest results with experimental apparatus.

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FREQUENCY—MEASURING RECEIVER SYSTEM

You can design frequency-measuring receivers to satisfy a wide range of requirements, most of which are set forth in Fig 1. Past systems for measuring the frequency of low-level signals in the presence of noise and interference include a simple method in which a standard frequency is combined with the signal in a detector, and the resulting beat frequency measured either by counter or by comparison with a calibrated interpolation oscillator. Another procedure, widely used, requires injection of a matching signal into the input, or antenna terminals of a receiver, followed by measurement of the matching signal frequency. This method is based on the transfer of the signal frequency to a locally-generated easy-to-measure signal source of large amplitude, free from interference and locally controlled. One receiver-type measuring system reconstitutes the input signal by successive mixing of the various local conversion oscillators with the signal from the IF amplifiers; the reconstituted signal is then applied to a digital counter. Another system converts the signal to a standard intermediate frequency by heterodyning against a known standard frequency in the first converter and against a variable-frequency second oscillator. After the signal and the standard intermediate-frequency reference are set to zero beat, a digital counter measures the frequency of the second oscillator.

All these systems suffer from one or more of seven shortcomings: requirement of a highly trained operator; involved operating procedures which must be followed exactly; manual adjustment of system throughout the measurement; inability to measure signals with poor signal-to-noise ratio; difficulty in following the freqency of a drifting signal; lack of facilities for data recording; and difficulty in achieving the measurement accuracies theoretically attainable with the signals.

A BETTER APPROACH

An improved system should operate rapidly and simply, requiring only that the operator select and identify the signal, the measurement proceeding automatically from then on. One such system uses a superheterodyne receiver arranged so that the tunable local oscillator can be phase-locked at a frequency offset from the signal frequency by the receiver's exact intermediate frequency; a digital counter measures the local-oscillator frequency. By suitably offsetting the digital counter, you can get an automatic, direct-reading of the input signal frequency. When used with amplitude-modulated signals, the locking circuit suppresses the modulation effect, extracting the carrier frequency for measurement. We chose one such system for evaluation.

Reviewing our system (Fig 2), we see that it retains some of the good characteristics of previous systems and adds features that provide improved performance. These new features are:

- Because the measured signal is generated locally, it can be made clean and of sufficient amplitude for accurate measurement by digital counter.
- System operates in a phase-locked mode, minimizing the operator skill required and permitting rapid and highly accurate measurements.
- Use of the superheterodyne receiver principle provides excellent sensitivity and selectivity.
- Local oscillator is thoroughly isolated from the antenna, permitting good RFI-free design. Since the local-oscillator signal fed to the digital counter already exists at high level in the receiver, no new problems arise from this source.
- Since the local oscillator operates without interruption, it supplies a continuous, constant-amplitude signal

Characteristic	Desirable Performance	Experimental Results
Sensitivity:	Wide range of input levels	0.1 µv to above 1 v (at approx. 100Ω level) for satisfactory readout on CW or A-M carrier.
Accuracy:	±0.1~, or better	±0.1~normally, ±0.01~possible (if signal is stable).
Frequency Range:	A-M B/C to lower edge of VHF TV (540 kc/s-54 Mc/s.)	540 kc/s-7.4 Mc/s (7.4-14.8 Mc/s preliminary data)
Selectivity:	Adjustable, with good skirt rejection, -70 dB at ±10 kc/s. 500~ min b/w for CW signals	a. Greater than 70-db rejection of signals more than ±10 kc/s removed from desired signal. b. Crystal filter provides narrow-band selectivity. 500~ and 1300~b/w usable. (200~ b/w unstable lock).
	Lock to be maintained with good capture ratio.	c. Lock is not disturbed except by large noise pulses. Capture ratio not measured.
Cross-modulation:	Reject all cross-modulation.	Not measured; receiver design governs.
Intermodulation:	Relatively unimportant for frequency measuring.	Not measured; receiver design governs.
Stability of Local Osc. (unlocked):	$\pm 1 \times 10^{-6}$ in 10 minutes $\pm 3 \times 10^{-6}$ per hour (approx.)	Satisfactory for unattended recording after lock-on in lowest frequency bands (AM broadcast). HF bands require supervision.
Capture Range:	Manual scanning, ± 10~or wider.	Excellent performance >±100~
Hold-in Range:	Sufficient to stabilize local osc vs drift & track signal frequency.	Adequate. (±150~-±400~). Quantitative values for hold-in performance are difficult to give since it depends on the signal. You can measure mark and space frequencies of FSK telegraph signals. Fitler adjusted experimentally to explore possibilities.
Radiation from Receiving System:	No radiation detectable.	No radiation observed.
Recording Facilities:	Facilities for digital or chart recordings.	Standard digital counter accessories used.

Fig 1—Frequency-measuring receiver characteristics.

to the digital counter even though the received signal may be keyed or amplitude modulated.

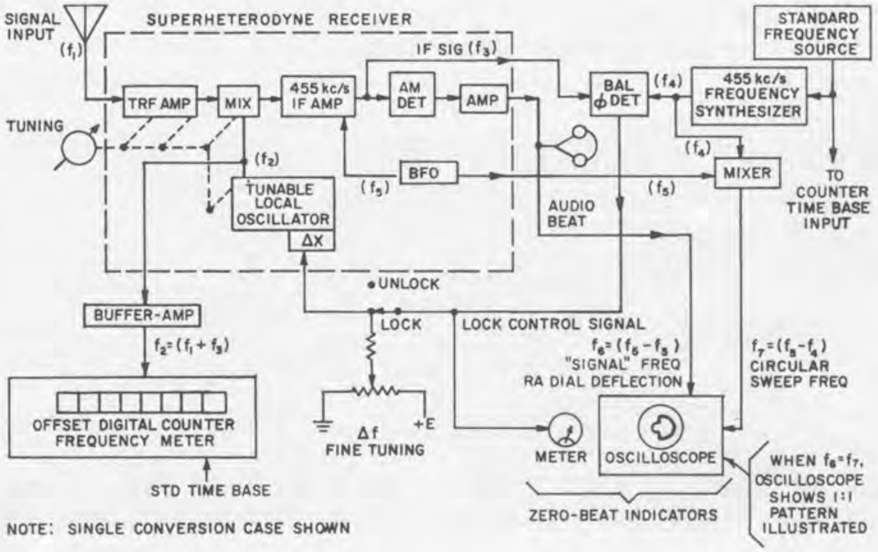
- The three-fold beat and lock indication system aids measurement of signals which are of such an intermittent nature that only approximate frequency limits can be assigned to their spectra by measurement.

Precision frequency measurement of intermittent suppressed-carrier signals is always difficult, and sometimes impossible. Such measurements are probably limited to power density or percent interference time logged on a given frequency in a given bandwidth, and they are not provided for directly in the experimental receiver. They could be obtained by adding a frequency synthesizer to serve as a stabilized local oscillator, and a dc level recorder to record the amplitude of the signal at the second detector.

You can measure single-sideband, suppressed-carrier telephone or voice-frequency teletype signal frequencies by setting the dial for receiving these signals without using the phase-lock circuit, and simply reading the digital frequency meter. Even in the absence of a signal, the frequency meter indicates the frequency to which the receiver is tuned, since it registers the frequency of the local oscillator offset by the intermediate frequency. In this respect, the digital frequency meter is a self-calibrating precision dial of high overall accuracy.

What are the relative advantages of the wide-range, high-frequency tunable local oscillator followed by fixed IF amplifiers, compared with a stepwise-settable stabilized high-frequency oscillator and tunable IF stages? The problem has many aspects. Obvious advantages of the present experimental receiver, which uses a wide-range tunable oscillator include the reduction of spurious signals or "birdies" and the unique determination of the oscillator output signal to the digital counter. In part, the principal disadvantages of this approach are that the stability of the HF oscillator may not be adequate for unlocked-mode transfer oscillator use, and that the digital counter has to count higher frequencies than a second-conversion oscillator. For phase-locked mode operation, the stability of the experimental receiver HF oscillator appears to be adequate, i.e., after an appropriate warm-up time, the oscillator stays locked if the signal frequency remains constant. For unlocked-mode or transfer oscillator measurements, the stability is marginal, and the oscillator plate supply and mixer loading effect need improving to make the experimental receiver generally satisfactory. Extension of the operating frequency range above the HF band usually requires one or more standardized frequency conversion opera-

Fig 2—Block diagram of the system we chose for evaluation. Signal f_1 is applied to the antenna input terminal of the receiver, which we tune manually to select the signal properly. Setting the Lock switch, we adjust the tuning until the zero-beat indicators show that locking has been achieved. At this point the tunable local oscillator is locked at a fixed frequency offset from the incoming signal frequency. If the lock is solid, $f_2 = f_1 + f_3$, $f_3 = f_4$, and $f_6 = f_7$ showing "zero beat" in the scope indicator. Incoming signal frequency is indicated by the digital counter which measures the frequency of the tunable local oscillator, f_2. Since the counter is offset by 455 kc/s, the amount of the intermediate frequency f_4, we were able to make a direct reading of the signal frequency by arranging the offsetting to subtract 4,550,000 from a 10-sec-count total in the experimental receiver.



tions. You can do this by beating against known standard frequencies and evaluating the residue or interpolation frequency as in the present system.

Superheterodyne receivers may use double, triple, or other multiple conversion systems, in which case you must use the proper offset in the digital counter to restore direct-reading. For example, the experimental receiver makes use of a double-conversion system in the higher frequency ranges to enhance image rejection; to obtain direct reading you would have to phase-lock the second-conversion oscillator at 3500 kc/s and change the digital counter offset to 3955 kc/s. In addition, you would have to change the offset, or reset numbers by displacing the digits appropriately right or left if the counting time is changed in decade steps. We neglected these complex arrangements in favor of operating time with the single-conversion system. Changes in the counting time were handled by exchanging the counting decade.

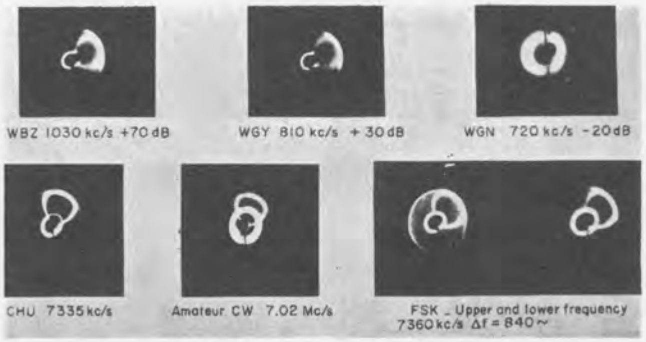


Fig 3—Oscilloscope photographs of receiver measurements.

DESIGN FACTORS

Choice of experimental receiver was based on these assumptions:

- Receivers exist for the frequency range concerned.
- Performance exhibited by the existing receivers is satisfactory in the detection, selection and processing of the signals concerned.
- Measurement will be manually supervised, at least for signal identification.
- Frequency measurements will be subject to limitations arising from the basic stability of the incoming signals,

Date	Time	Channel Frequency	Call	City	Measured Frequency	Signal Level (db vs 1 μv)
10/21/65	0859 EDST	540 kc/s	WDIC	Islip, N.Y.	539,997.4~	−3 to +6 (≈ 1 μV)
	0905	550	WXTR	Pawtucket, R.I.	550,001.9	+40 (≈ 100 μV)
	0906	560	WHYN	Holyoke, Mass.	560,001.5	+55
	0907	570	WMCA	New York City	570,000.9	+40
	0909	580	WTAG	Worcester, Mass.	580,000.1	+70
	0910	590	WEEI	Boston, Mass.	590,000.4	+70
	0912	600	WICC	Bridgeport, Conn.	600,000.2	+30
	0913	610	WGIR	Manchester, N.H.	610,008.1	+45
	0916	620	WLBZ	Bangor, Maine	620,001.9	+25 (fades with beat)
	0919	630	WPRO	Providence, R.I.	629,998.9	+50
	0920	640	CBN	St. John's, N.B.	640,003.3	−8 to −10
	0921	650	WSM	Nashville, Tenn.	649,999.0	−5
	0923	660	WNBC	New York City	660,000.0	+52
	0924	670	WMAQ	Chicago, Ill.	670,002.1	−4
	0925	680	WNAC	Boston, Mass.	680,000.5	+60
	0926	690	CBS	Montreal, P.Q.	689,999.6	−6
	0927	700	WLW	Cincinnati, Ohio	700,000.0	+20
	0928	710	WOR	Newark, N.J.	710,001.1	+45
	0929	720	WGN	Chicago, Ill.	720,000.4	−2
	0933	730	WACE	Springfield, Mass.	729,998.4	+55
	0939	740	WXHR	Cambridge, Mass.	739,993.3	+59
	0940	750	WHEB	Portsmouth, N.H.	750,003.6	+42
	0941	760	WJR	Detroit, Michigan	760,000.9	−10
	0943	770	WABC	New York City	770,000.3	+35
	0944	/80	WBBM	Chicago, Ill.	780,001.0	−5
	0946	790	WEAN	Providence, R.I.	790,001.9	+48
	0948	800	WCCM	Manchester, N.H.	799,999.9	+58
	0951	810	WGY	Schenectady, N.Y.	810,018.2	+40
	0953	820	WOSU	Columbus, Ohio	820.001.0	−20, or less
			or WAIT	Chicago, Ill.	820,000.6	
	0956	830	WNYC	New York City	830,000.4	+10
	0957	840	WRYN	Newington, Conn.	839,999.5	+25
	0959	850	WHDH	Boston, Mass.	849,999.6	+45
	0959	860		Canada?	860,002.6	+10 (fades, beats)
	1002	870	WHCU?	(Ithaca, N.Y.)	870,000.0	−20 (fades, beats very weak)
	1016	880	WCBS	New York City	880,007.4	+42
	1018	890	WLS	Chicago, Ill.	889,998.8	−25 (in noise)
	1020	900	WOTW	Nashua, N.H.	900,002.3	+52
	1022	910	WRCH	New Britain, Conn.	910,003.2	+30
	1025	920	WJAR	Providence, R.I.	920,001.9	+38
	1026	930	WRNH	Rochester, N.H.	929,997.6	+40 (heavy beating)
			WBEN	Buffalo, N.Y.		
	1052	940	WIND	Brookfield, Mass.	939,998.6	−5 } beats,
			(?)	(————————)	940,001.0	−3 } of course
	1055	950	WORL	Needham, Mass.	949,993.7	+50
	1057	960	WFGM	Fitchburg, Mass.	960,000.5	+35
	1100	970	WESO	Webster, Mass.	970,001.7	+42
	1105	980	WCAP	Lowell, Mass.	979,998.6	+55

Fig 4—Partial listing of the carrier frequencies of standard AM broadcasting stations logged at Bolton, Mass. to a precision of ±0.1 c/s. Calibrated accuracy of the frequency standard used for reference is always better than $\pm 3 \times 10^{-9}$ versus WWV UTC frequency. All channel frequencies in the AM broadcast band, with only two exceptions, were logged at the rate of approximately 20 stations in 30 minutes, and at least two 10-sec counts were observed in each case to assure specified measurement validity. This performance indicates that the initial goal of rapid, accurate measurement capability has been achieved.

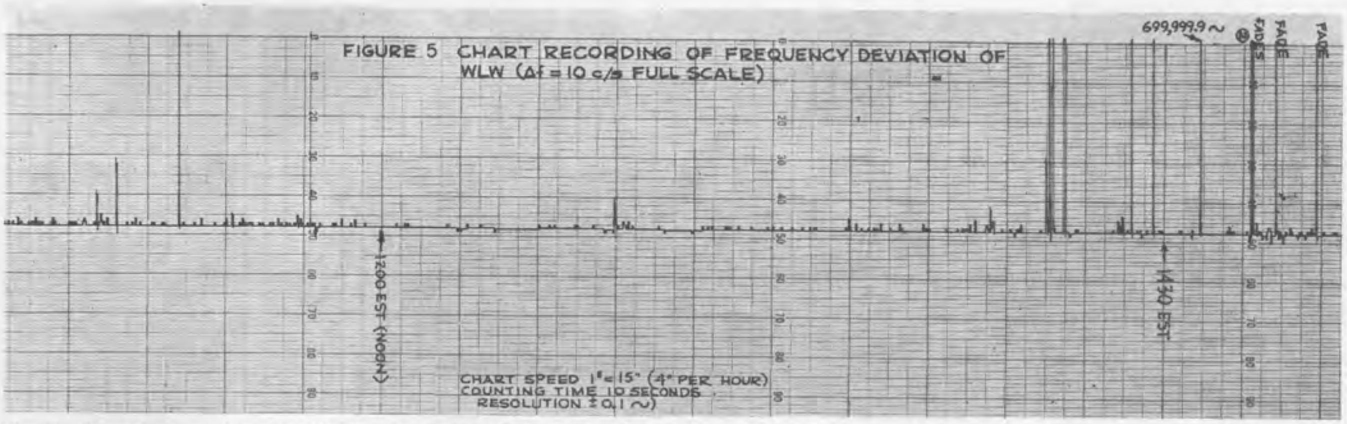


Fig 5—Sample recording of WLW's frequency deviation, using a 10-sec counting time; Δf = 10 c/s full scale. Indicated frequency deviation of the received signal is approximately ±0.1 c/s from the mean value of 700,000.2 c/s, except for periods of severe noise bursts from industrial equipment in the vicinity of the receiver and a few severe fades which caused the receiver to lose coherence with the incoming signal. Subsequent measurements, using 100-sec counting time, confirmed the low deviations observed. Generally, the receiver stays locked until the signal drops below 0.1 μv at the antenna terminals. At this level, no modulation can be understood, and only a little evidence of zero beat is left on the oscilloscope display and meter indicator. The recorded frequency provides the most conclusive evidence of lock, although the stable beat note in the headphones is usually detectable by ear. Above this signal level the indicators give positive assurance of lock.

modified by additional factors such as interfering signals, noise and propagation variations. On this basis, we estimated that a resolution of ±0.1 c/s would be adequate for most measurements in the MF and HF bands.

After deciding to modify experimentally a standard communications receiver for evaluating this measuring system, we chose a receiver which incorporated many of the desired output connections. Adapting the receiver's local oscillator to provide voltage-controlled tuning in 4 of the coil ranges, we attached to the receiver the coherently synthesized 455 kc/s IF reference signal, a balanced phase detector with limiter driver stage, and various experimental filter networks in the locking loop. To bring out the oscillator frequency, f_2, we installed a coupling loop, and modified a digital counter for reset to the complement of 0455,000.0, instead of to 0,000,000.0, for use with a 10-sec counting period and 455 kc/s IF. An oscilloscope indicator and meter gave zero beat and phase-lock indication, and headphones enabled audible identification of the signal and helped detect the phase-locked condition. Fig 3 shows photographs of the oscilloscope display for several types of signals.

Frequency measurement of intermittent or keyed signals, as well as that of continuous and amplitude-modulater carriers, requires a dynamic phase-lock indicator with good precision and fast response. An important feature of the present system is the inclusion of the previously-mentioned three simultaneous lock-indication checks. These three indications come from the audible beat note between the IF signal and the BFO, a circular-sweep oscilloscope display, and a zero-center microammeter indication of phase-detector error signals. Since the three indications are easy to interpret and self-explanatory, most people quickly become "skilled operators."

HOW IT PERFORMED

Performance of the experimental system, evaluated by measurements of signals from standard AM broadcasting stations (see Fig 4), has been gratifying. Measurements of some AM stations over fairly large distances during daytime conditions (sunrise-to-sunset) indicated that both the frequency stability of the RF carriers and the propagation velocity uniformity are quite high. In particular, WLW, Cincinnati, Ohio, 700 kc/s, and WMAQ, Chicago, Illinois, 670 kc/s, have been received with reasonably good stability during daylight hours (Fig 5).

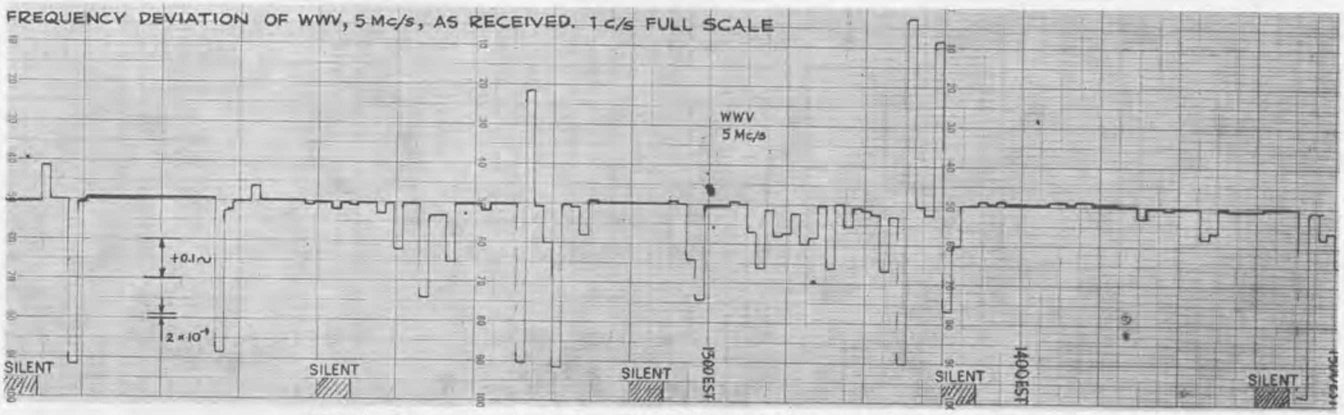


Fig 6—Frequency deviation of WWV, 5 Mc/s, (1 c/s full scale).

Frequency
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For measuring carrier frequencies buried in noise, the receiver's performance is indicative of results obtainable by using a phase-locked loop to extract a relatively stable signal frequency from a noisy background. However, in many locations, the receiver performance would be improved by the addition of a pulse interference blanker or IF noise silencer. Operation of the receiver with fixed gain improves locking operation on weak signals. Very large impulse noises saturate the receiver, causing ringing of the tuned circuits and disturbing the locking loop, especially when AGC is used with weak signals. This phenomenon shows up strongly for long counting times such as 100 sec. Large impulse noises produce temporary frequency deviations in the local oscillator which are more likely to occur during a 100-sec than a 10-sec counting time. Also, if a recording of frequency deviation is made, the counting circuits hold the erroneous value on a chart recorder as if it had occurred *for* 100 sec, not just *within* a 100-sec interval, thereby exaggerating the apparent error. This behavior arises from the needed capacity for tracking unstable signals as well as stable ones, and it could be greatly improved if stable carriers alone had to be measured. Because the present experimental system is not designed for such precise measurements, it responds fairly rapidly to frequency changes. The minimum effective bandwidth of the experimental system is approximately ±50 c/s.

We have used the experimental receiving system to measure keyed CW (Morse-code) signal frequencies, and to measure both the mark and space frequencies of frequency-shift keyed (FSK) teletype signals, where the FSK shift is great enough to unlock the receiver. With the FSK signals, stabilities of the indicated frequencies appear to be between ±5 c/s and ±80 c/s; the best Morse-code signals show about the same stability. Both signal types suffer from the presence of actual "chirp" deviation at the transmitter plus "chirps" implied by the lock-on process in the receiver. Even with the chirp deviations, the actual transmitted frequencies are probably fairly close to those indicated.

Recordings made of the apparent received carrier frequencies on WWV on 2.5 Mc/s and 5 Mc/s prove that the frequency of the received HF signals may deviate as much as a few parts in 10^7 from the nominal value. The local reference frequency standard is calibrated by routine time comparison over several days, and occasionally checked on VLF. An example of the frequency deviation of WWV as received on 5 Mc/s with a resolution of ±0.01 c/s, given in Fig 6, is representative of a "good" day. □

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