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THE USES AND LIMITATIONS OF HF STANDARD BROADCASTS FOR TIME AND FREQUENCY COMPARISON

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ABSTRACT

The most practical methods of using high-frequency (HF) broadcasts for frequency and time comparison are reviewed briefly. Although standard broadcast and receiving equipment has improved vastly throughout the past fifty years, the HF propagation medium is no more stable today than it was a half century ago. Doppler shift resulting from changes in the effective height of the ionosphere typically limits the usable accuracy of received high frequencies to a few parts in 10^7. At locations beyond groundwave range of the transmitter, uncertainties in path delay generally restrict the usable accuracy of HF time signals to the order of a millisecond. Signal-averaging techniques are sometimes employed to extract frequency or time signals from a noisy background.

GENERAL DISCUSSION

Since 1904 or thereabouts we have witnessed increasing use of radio as a medium for dissemination of time and frequency information. Recent listings by the International Telecommunications Union and other authorities reveal that more than forty countries are now engaged in radio broadcasts of time and frequency standards. Presently, there are upwards of twenty stations transmitting frequency-time standards on regular schedules in the high-frequency (HF) band alone. Additional stations are broadcasting frequency-time standards in the low-frequency (LF) and very-low-frequency (VLF) bands.

In the United States, radio has been a principal means of transferring frequency-time standards for more than half a century. In fact, March 6, 1973 will mark the fiftieth anniversary of radio station WWV as a frequency-time service of the National Bureau of Standards (NBS).

During the first decade of its existence, WWV transmitted standard frequencies with accuracy no better than one part per million. As finer frequency-control measures were developed, the accuracy of WWV's transmissions steadily improved until it approached a few parts in 10^{12} where it remains today. Daily comparisons using the television line-ten technique ensure that the WWV time signals are synchronized within three microseconds to the UTC (NBS) scale, which in turn agrees within five microseconds to the UTC (USNO) scale at all times.

A second NBS station, WWVH, has been operating since July 1971, from near Kekaha, Kauai, Hawaii, to provide coverage for areas of the Pacific which are not served adequately by WWV. Through time comparisons via portable clocks, Loran C, and LF transmissions of WWVB, the standards broadcast by WWVH and WWV are kept in the closest possible agreement. WWVH and WWV together serve more than two-thirds of the earth's surface, although no single radio-frequency channel is likely to be 100 percent reliable under all propagation conditions. As in the case of WWV, the standard frequencies transmitted by WWVH are accurate to within a few parts in 10^{12}.

Consistent progress has been made toward improving the accuracy of frequency-time standards as actually broadcast. However, the ionosphere is no more stable now than it was during the early 1900s, as shown in Figure 1. Consequently, beyond groundwave range the usable accuracy of standard HF broadcasts is little better today than during the years of World War II.

Doppler effect arising from motion of the ionosphere still limits the typical usable accuracy of standard frequencies propagated over skywave paths to a few parts in 10^7, or perhaps a part in 10^8 under good conditions. Uncertainty in determining propagation delay generally restricts to the order of one millisecond, the best accuracy that can be relied upon for time markers transmitted on HF carriers along skywave paths. Because of the severe degradation brought about by ionospheric factors over which we have no control, I expect no further major improvements to be made in the frequency generation equipment at WWV or WWVH for their present role as HF ground-based stations.

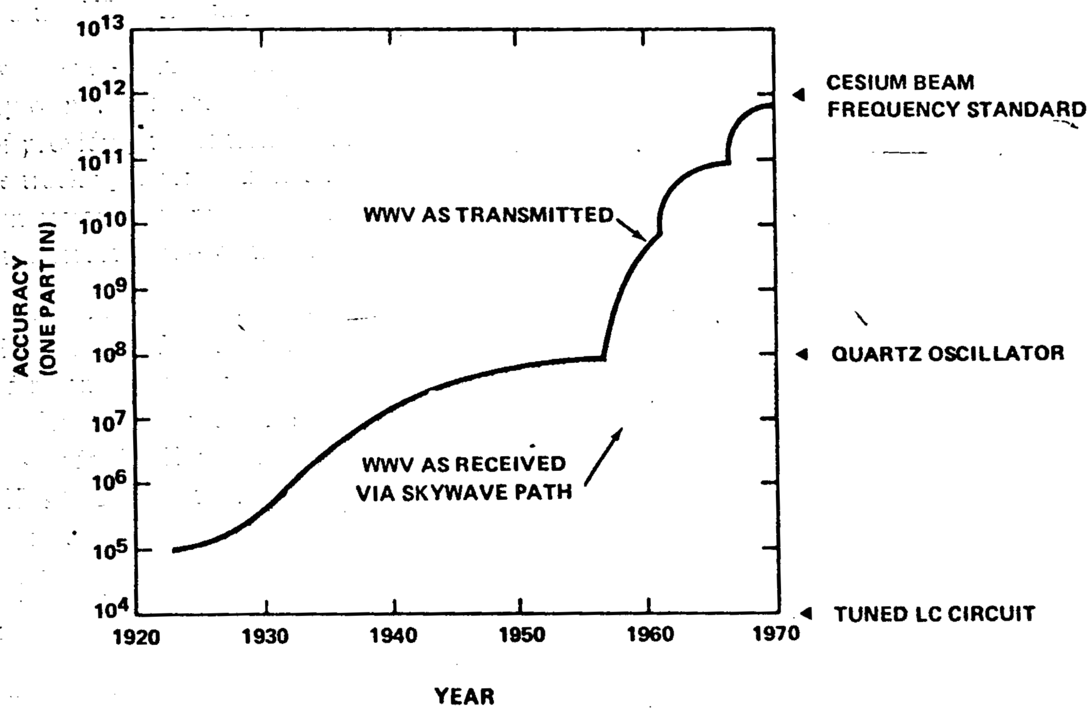

Figure 1. WWV broadcast accuracy.

Just as broadcast equipment has improved with the state-of-the-art, so too have standard broadcast formats evolved to satisfy changing needs. Beginning July 1, 1971, stations WWV and WWVH adopted totally new program formats, (Figure 2) in response to preferences registered during a nationwide survey of user requirements. Principal changes included more frequent voice announcements of time; the elimination of Morse code keying and its replacement in some cases with voice announcements; the continuous broadcast on a 100-Hz subcarrier of a binary time code very similar to the IRIG-H code; the use of male and female voices by WWV and WWVH respectively as an aid in distinguishing the broadcasts of the two stations from each other; the inclusion of 500-Hz standard audio tones in addition to standard tones of 440 Hz and 600 Hz; and the provision of certain 45-second segments every hour for voice announcements of public and scientific interest by agencies of the U.S. Government.

On January 1, 1972, further modifications were made in accordance with international agreement to eliminate the frequency offset of -300 parts in 10^{10} which had been a feature of most standard frequency broadcasts since the 1960s. Because the UTC rate is no longer changed continuously to keep in close agreement with the earth's rotation rate, UTC now departs more rapidly than before from the astronomical time scale, UT-1. To prevent this difference from exceeding 0.7 second, occasional step adjustments of exactly one second (called leap seconds) are made as directed by the International Time Bureau (BIH). The first leap second in history occurred on June 30, 1972. The next one is scheduled to occur on December 31, 1972. The leap seconds ensure approximate agreement between the UTC scale and the UT-1 scale needed by navigators and land surveyors.

Faced with ever-increasing demands for more stringent standards, researchers are exploring a variety of new methods for time and frequency dissemination. HF broadcasts fall far short of providing the extremely accurate standards required to support precision geodesy, satellite tracking, aircraft traffic control, atomic-clock synchronization, and advanced digital communications. It appears certain that no amount of money or effort can increase appreciably the effectiveness of the HF mode beyond its present capabilities.

On the other hand, the standard time and frequency broadcasts of stations such as WWV, WWVH, CHU, and JJY are more than sufficient for the everyday needs of most users. As attested by the growing number of frequency-time stations operating between three MHz and 30 MHz, the HF mode is still the most popular one for dissemination of time and frequency standards. Hardly any place in the world is outside the coverage area of one or more HF standard stations. Within the accuracy limitations previously cited, frequency calibration and clock synchronization can be achieved quite conveniently through HF standard broadcasts using relatively simple and inexpensive equipment at the receiver end.

Heterodyne Method

When high accuracy is not required, probably the simplest and fastest way of comparing the frequency of an oscillator to a broadcast standard is the familiar heterodyne or zero-beat method. To carry out this procedure a radio receiver is tuned to a standard carrier

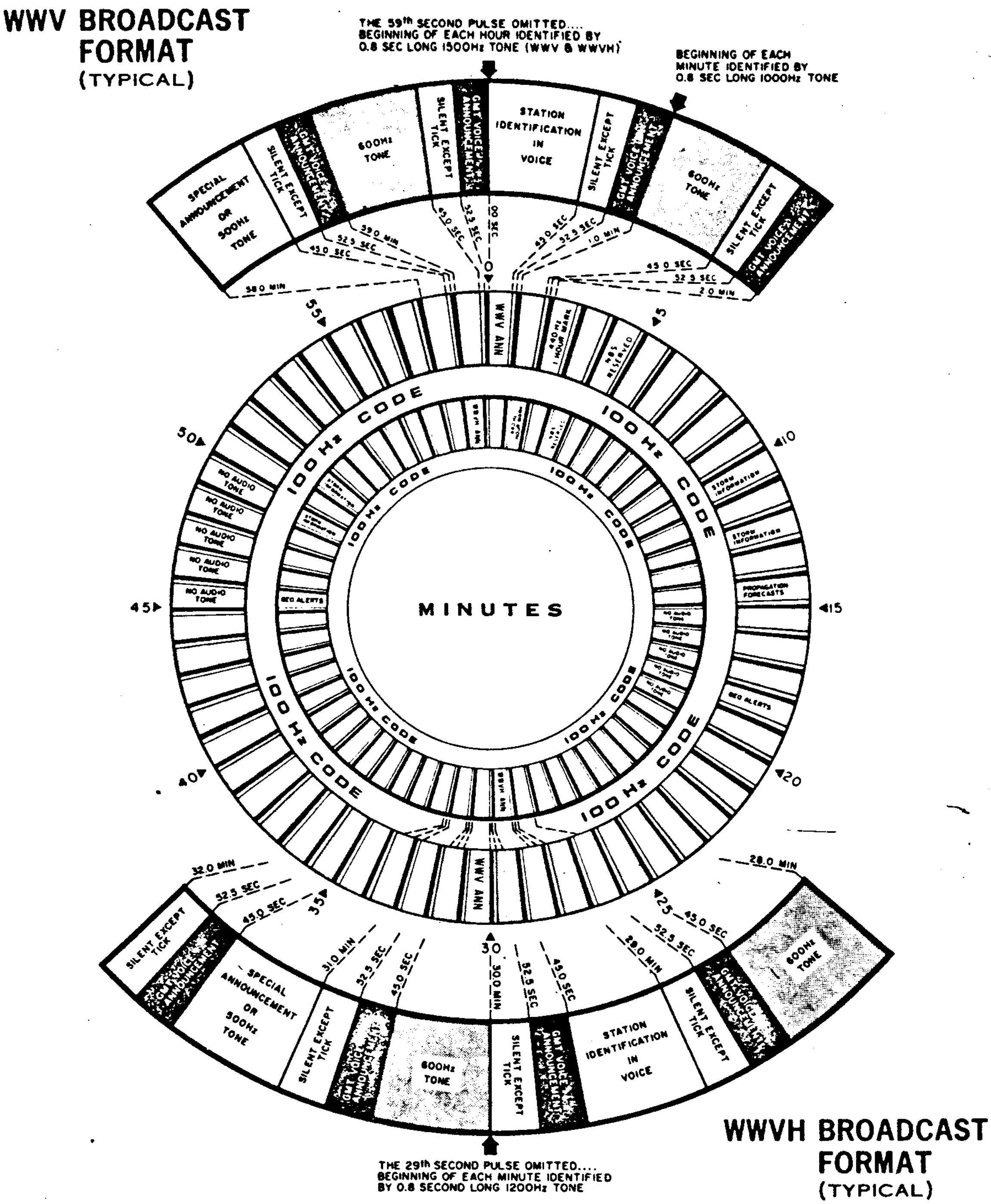

Figure 2. Typical broadcast formats.

frequency, say ten MHz, while the output of the oscillator is loosely coupled to the receiver antenna. Depending upon the fundamental frequency of the oscillator, it may be necessary to employ frequency multiplication or division to obtain a common frequency for comparison.

To achieve maximum modulation, energy from the oscillator should be adjusted so that it is approximately equal to that of the received broadcast signal. The resulting beat frequency can then be observed as a Lissajous pattern on an oscilloscope screen or can be measured directly with a counter (Figure 3). If the beat note is found to be one Hz, for example, when the comparison frequency is ten MHz, then the oscillator is off-frequency by one part in ten million, or 1×10^{-7}.

If desired, the oscillator could be adjusted until the beat note or difference frequency is reduced to zero, at which point the oscillator frequency would be correct to within the accuracy limits of the comparison process. Usually, however, it is difficult to adjust an oscillator to exactly zero beat with an HF carrier beyond the groundwave range of the transmitter. The problem arises from rapid fluctuations in the received signal strength and from propagation flutter in the received frequency.

When reception conditions are good, the best results can be obtained by counting the beats over a continuous interval of several minutes. If severe fading is experienced, however, it may be preferable to count the beats over an interval of only a few seconds and average the results of several successive comparisons.

As a general rule low-beat frequencies can be determined more accurately with an electronic counter by measuring period rather than frequency; the accuracy can be enhanced further by using the multiple-period feature which is common in most general-purpose counters today. The more periods over which a signal is averaged, the better the resolution that can be attained. In all measurements made with an electronic digital counter, the characteristic ambiguity of plus-or-minus one count must be taken into consideration.

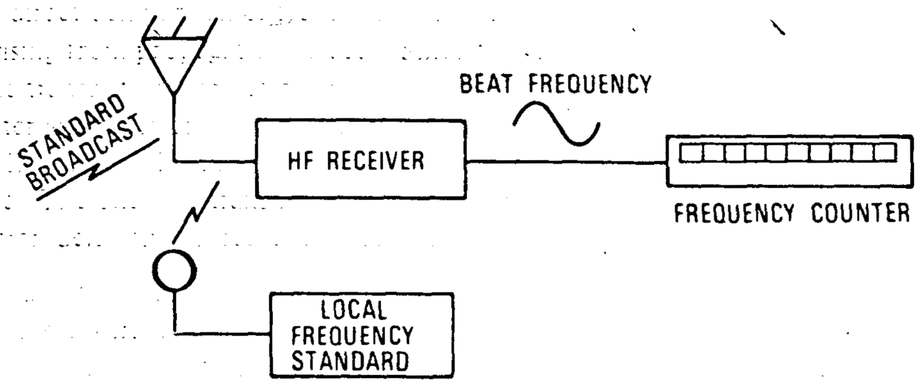

Figure 3. Heterodyne method.

As mentioned previously, skywave signals are subject to Doppler shifts brought about by vertical movement of the ionospheric layers during the course of the measurement. The error introduced by Doppler effect could be computed if sufficient data were known at the time of the measurement. The received frequency is shifted by a fractional amount equal to the rate of change in path length divided by the propagation speed of the radio wave. But ionospheric density, and hence path length, varies according to the time of day, season, sunspot cycle, geographic location, and so forth. Whereas average conditions of the ionosphere are predictable, one must realize that the conditions may deviate greatly from the norm at any particular instant.

Experience has shown that Doppler shifts of approximately three parts in 10^8 are typical for single-hop propagation via F-layer reflection. The effective change per hop increases slightly for multi-hop modes because of the higher departure angles encountered. An approximation to the overall effect of Doppler shift may be obtained merely by multiplying the estimated change per hop times the total number of hops involved, although it is very unlikely that the Doppler shift will be of equal magnitude at all reflection points along the path.

TIME-MARKER PHASING

An indirect method of frequency comparison uses standard time markers as a reference. Here the oscillator under test is used to drive an electronic clock, the output pulses of which are applied to the external trigger terminal of an oscilloscope while time markers from the receiver are applied to the vertical amplifier (Figure 4). The frequency offset of the oscillator is indicated by the rate at which the pattern drifts across the screen.

The second pulses, or ticks, transmitted by WWV consist of five cycles of 1000-Hz tone. The second pulses of WWVH comprise six cycles of 1200 Hz. In either case the duration of a complete pulse is five milliseconds with the leading edge of the first cycle on-time at its zero crossing. If the ticks are relatively free of jitter at the receiver output, time interval readings to ±10 microseconds may be resolved by expanding the sweep.

Like the direct comparison of frequencies, however, time comparisons are also subject to errors arising from propagation effects. Since the reference marker is on-time when it leaves the transmitter, corrections must be made for the propagation delay between the transmitter and receiver. A slight additional delay is encountered within the receiver itself, but for HF receivers having a bandwidth of 2000 Hz or greater the internal delay is usually negligible. The one-way transmission of time signals then requires some way of determining propagation delay time if reasonable accuracy is to be achieved.

Propagated at the speed of light, the time markers will arrive three milliseconds late for every 1000 kilometers traveled between the transmitter and receiver. Because HF groundwave propagation is confined to distances of only 160 kilometers or so, we will assume skywave propagation for the more general case. Except during the daytime when E-layer reflections sometime occur, long-distance HF reception usually results from F-layer reflection at an average virtual height of about 350 kilometers.

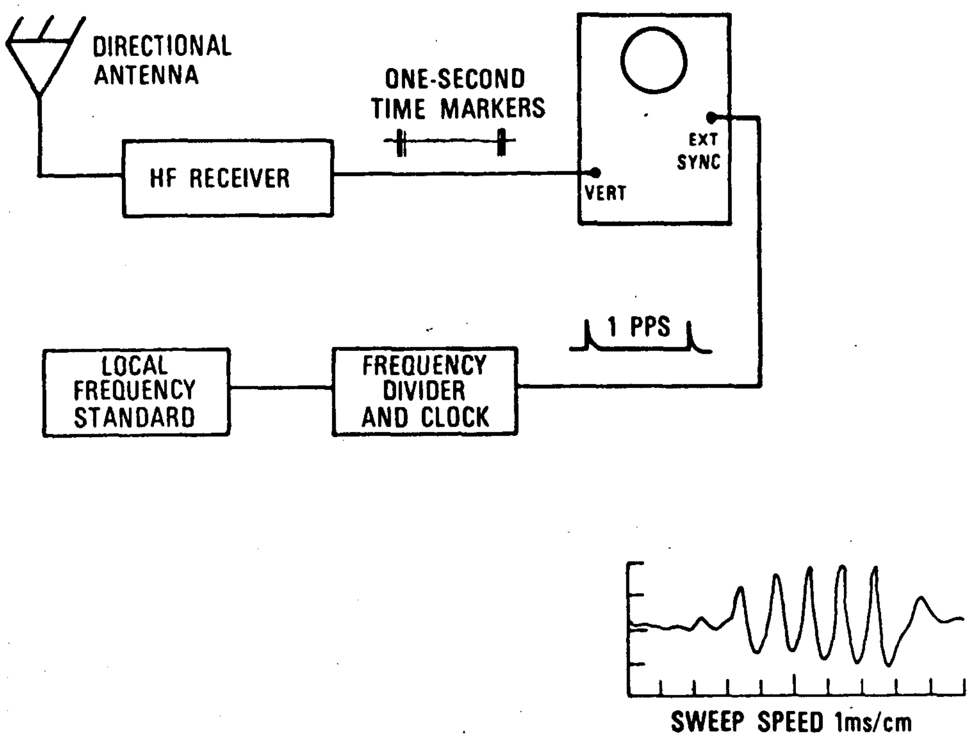

Figure 4. Time-marker phasing.

The maximum distance that can be spanned by F_2 reflection is about 4000 kilometers. For great-circle distances greater than 4000 kilometers, therefore, it is apparent that more than one reflection must generally occur. The fewest number of hops between the transmitter and receiver sites is the integer higher than the great-circle distance of 7000 kilometers. Division by 4000 yields a quotient of 1.75, which rounds off to 2 as the next higher integer. Thus two hops can be predicted for the shortest probable path. The same type of calculation leads to a prediction of three hops for great-circle distances from 8000 to 12,000 kilometers and four hops for distances between 12,000 and 16,000 kilometers. Once the number of hops is established, the distance traveled by the HF wave can be computed from the estimated height of the reflecting layer and the geometry of the path.

If several modes are being received, as indicated by jitter or the appearance of multiple ticks on the oscilloscope display, one should consider only the pulse with the earliest arrival time. Round-the-world echoes and interference from other frequency-time stations may cause problems unless a highly directional antenna is used with the receiver. Interlayer reflections, ionospheric turbulence, scattering, and other propagation anomalies may also cause excessive jitter.

The effects of jitter and the precision of measurement can be minimized by making observations over a long period of time. Fairly good results can be obtained with a long-persistence oscilloscope which permits several pulses to be superimposed and viewed together.

From such a display the operator can readily discern the pulse of earliest arrival. Similar results can be obtained from a multiple-exposure photograph of the oscilloscope display.

Under typical conditions it may be necessary to record data from an HF standard station for several days to average out the anomalies and approach high precision. For an observation period of 24 hours, the precision may be on the order of one part in 10^8; for a week to ten days, one part in 10^9; and for a month, one part in 10^{10}. In the HF spectrum the limit of accuracy is established by the propagation medium regardless of the duration of the observation interval. After plotting the measurement results for several days or weeks, one should disregard those points which do not conform with the others, or else correct the measurements to a more likely propagation mode.

Best results can generally be attained by tuning the receiver to the highest frequency that provides consistent reception. The optimum working frequency seems to be at about 85 percent of the maximum usable frequency. Operation at the optimum working frequency serves to reduce interference from high-order modes and usually results in the best reception over the greatest possible distance.

Because the density of free electrons in the ionosphere is greater during the day than at night and also greater in summer than in winter, it follows that the critical frequency is likely to be highest at noon and during midsummer. Throughout periods of peak sunspot activity the critical frequencies become abnormally high.

It is evident that in the interest of accuracy, the time or frequency comparisons should be made when the ionosphere is most stable. This condition generally prevails when the entire path of propagation is in total darkness or total daylight, that is, when midnight or noon occurs approximately midway between the transmitter and receiver sites. Because of Doppler effect, received frequencies are slightly high in the early morning hours when the path length is decreasing, and slightly low in the evening while the path is extending.

By carefully choosing the frequency, the mode of propagation, and the time of day for a measurement or comparison, an observer can obtain optimum results with HF time standards. Under ideal conditions the attainable accuracy may be ± 0.1 ms or better. At the opposite extreme, if the propagation path is highly disturbed the accuracy may deteriorate to worse than ± 10 ms. The nominal accuracy is ± 1 ms.

Several instrumentation variations are possible. A more elaborate arrangement might include a time comparator in conjunction with the oscilloscope. In lieu of the oscilloscope it is usually feasible to use a digital counter capable of time-interval measurement. If a continuous record of the comparison is desired, the counter may be outfitted with a digital-to-analog converter and recorder.

INTERFERENCE AND FADING

Mutual interference by two or more stations on shared channels is more serious now than ever before. In the HF spectrum, however, it is not unusual for a single station to interfere with itself. Multipath reception often leads to alternate constructive and destructive interference at the receiver location without a second broadcast station being involved. The result is fading and distortion of the received signal.

Fadeouts may also result from other factors, such as ionospheric storms, solar flares, magnetic storms, and sporadic E-layer reflection. Nuclear explosions at altitudes between 15 and 60 kilometers have been reported as causing HF blackouts for periods of several minutes within a few hundred kilometers of the detonation site.

Interference problems can be attacked at the receiver most economically by using a directional antenna that favors the preferred signals azimuth and angle of arrival. Additional precautions may be taken by scheduling measurements for a time when the undesired signals are known to fade out.

Diversity receiver systems have long been used to combat the effects of fading in the field of radio communications. Such systems take advantage of the fact that if two or more receivers are separated by space, by frequency, by antenna polarization, or by angle of arrival, the fading often occurs independently at each receiver. Although diversity receivers are available for HF channels, the technique has not been widely exploited for frequency-time applications. Perhaps the added cost has been a deterrent.

NOISE

Additive noise has reached serious proportions throughout the HF spectrum. Atmospheric noise is generally high during the spring and summer months; but man-made noise may predominate at any time, especially in urban areas. As more radio stations increase their effective radiated power in an effort to overcome electromagnetic noise levels, the interference problem is compounded. Signal-averaging is an effective means of extracting time signals or other periodic waves from random noise.

For our present purposes random noise is considered to be that form of noise for which the average amplitude at any particular frequency is zero. Now let us assume a uniform periodic event, such as a time tick, that occurs in the presence of random noise. If the same point on the periodic pulse is examined every time the pulse recurs, an average voltage could be associated with that point. This follows from our assumption that the true signal amplitude at the point is constant whereas ultimately the random noise voltage at that point must average out to zero. The time required for the average signal voltage to emerge depends upon the extent and nature of the noise.

A signal-averager examines numerous points on the periodic wave and stores the instantaneous voltage of each point in a memory bank. Each time the wave recurs the same points are examined and the respective voltages are stored in the same memory elements. Eventually each memory element will contain the average voltage from its associated point on the waveform. At some prescribed moment the memory elements are strobed sequentially and the stored voltages displayed on an oscilloscope. The result is a reconstruction of the average waveform without the distracting noise. The waveform is composed of many discrete voltage levels read out from the memory bank.

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