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Precise Frequency Dissemination Using the 19-kHz Pilot Tone on Stereo FM Radio Stations

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Abstract—**A continuous 19-kHz pilot tone is included as part of the modulation format of stereo FM broadcast radio stations. An experiment was performed which measures the stability of the received pilot in urban and rural environments. A mathematical analysis is presented of the phase stability of the received pilot as a function of multipath. It shows that phase changes will exist dependent upon a reflected radio signal's phase lag, relative amplitude, and the modulation index. Data are presented which indicate: 1) phase versus time of the pilot at the National Bureau of Standards (NBS) laboratory using a directional yagi and a vertical whip; 2) Allan variance measurements of σ versus τ using a directional yagi; and 3) the day-to-day phase delay of the pilot at five urban locations and three rural locations using a vertical whip. With 5 min of averaging time, the delay of the pilot at five urban sites was reproducible to within 2 μs each day over a five-day period. Delay was reproducible to within 0.8 μs at three urban sites.**

The FM Pilot as a Frequency Reference

STEREOPHONIC transmission by standard U.S. FM broadcast radio stations uses the main channel and a subchannel. The sum of left and right audio signals is contained on the main channel while the difference of the signals amplitude modulates a 38-kHz subcarrier. The subcarrier is suppressed and a 19-kHz pilot is transmitted at 10 percent of full modulation.

The pilot of a stereo FM radio station in the Boulder, Colorado, area was stabilized by a frequency standard. We examined to what extent the stability characteristics of the standard were reproducible in the radio coverage area. It is the intent of this writing to show data of the frequency dissemination potential of a stabilized pilot from a stereo FM radio station.

The Multipath Problem

One of the greatest factors influencing the stability of the received pilot is multipath. It is helpful to mathematically depict the phase delay of a single tone due to multipath. Fig. 1 is a vector diagram indicating the direct, reflected, and resultant FM radio signals at the receiver. We have direct wave:

$$e_1(t) = \cos \psi_1(t) = \cos [\omega_c(t - t_1) + \beta \sin p(t - t_1)] \quad (1)$$

and reflected wave:

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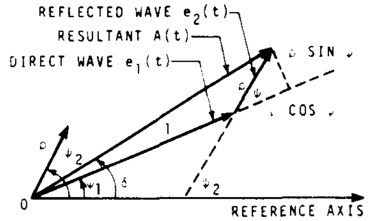

Fig. 1. Vector diagram showing direct wave, reflected wave, and resultant.

$$e_2(t) = \rho \cos \psi_2(t) = \rho \cos [\omega_c(t - t_2) + \beta \sin p(t - t_2) + \varphi] \quad (2)$$

where

- t_1 time required for the direct wave to reach the receiver;
- t_2 time required for the reflected wave to reach the receiver;
- φ angle of reflection of reflected signal;
- $\Delta\omega$ change in frequency of the carrier signal;
- p angular frequency of modulating signal;
- β $\Delta\omega/p$ = modulation index.

The demodulated output becomes

$$\Delta\omega \cos p(t - t_1) + \frac{d}{dt} \tan^{-1} \frac{\rho \sin \psi(t)}{1 + \rho \cos \psi(t)}. \quad (3)$$

The second term of the above expression represents the distortion components of the demodulated tone. The first harmonic contains a contribution to the time delay t_1 which introduces the phase error [1]. Following a derivation by Panter [2], the demodulated output (after low-pass filtering) may be written as

$$e_d(t) = \Delta\omega A \cos [p(t - t_1) - \alpha] \quad (4)$$

where

$$A = \left[\left(1 - \frac{C_o}{\beta} \sin pt_o/2\right)^2 + \left(\frac{C_o}{\beta} \cos pt_o/2\right)^2\right]^{1/2}, \qquad t_o = t_2 - t_1 \quad (5)$$

$$\alpha = \tan^{-1} \frac{(C_o/\beta) \cos (pt_o/2)}{1 - (C_o/\beta) \sin (pt_o/2)}. \quad (6)$$

C_o is an infinite series involving the coefficient of reflection ρ. Since the phase delay to be measured is pt_1, the quantity α represents a lagging phase error. Let us assume that the FM receiver is able to pick up a direct signal from the transmitter. With a given phase lag and $0 < \rho \leq 1$, it is evident from (6) that α depends upon the modulation index β. In the worst case, a reflected signal of equal strength ($\rho = 1$) makes α equal to one-half the phase lag of the reflected signal. This mathematical model is correct only for FM signals with a single tone for modulation. But it is instructive in attempting to explain the phase delay associated with the 19-kHz pilot tone which is part of total baseband modulation.

The standard FM broadcast format calls for a maximum deviation of $\pm$ 75 kHz. The 19-kHz pilot tone causes deviation of nominally $\pm$ 7.5 kHz. Therefore, the modulation index β_{pilot} equals 0.395 ($\beta = (\Delta\omega \text{ pilot})/p = (7.5 \text{ kHz})/(19 \text{ kHz}) = 0.395$). Excluding the pilot tone, β_{audio} will vary from 0 to around 100, depending upon the modulation. When measuring the phase delay of the pilot tone, one must consider the other signals comprising the total baseband modulation. This is because the tone is subject to deviations equivalent to maximum, since it is linearly added to the total baseband audio. We have

$$\Delta\omega_{\text{total}} = \sum_{n=1}^{m} \Delta\omega_n = \Delta\omega_{\text{pilot}} + \Delta\omega_{\text{audio}}. \tag{7}$$

With multipath and a nonzero phase lag in the reflected signal, we may infer that the phase of the pilot tone will be related to the total baseband modulation.

Experiment

A portable cesium atomic frequency standard was installed at the transmitter site of a stereo FM station. The output of the atomic standard fed a synthesizer whose 76-kHz output was used as the reference for the transmitter's stereo multiplex generator and pilot. The effective radiated power of the transmitter was 30 000 W; its antenna was a six-bay circularly polarized array with elements along the side of a 60-ft vertical pole.

The complete receiver setup is shown in the block diagram of Fig. 2. At the receiver, the front end and IF amplifier were taken from a low-priced consumer model. The local oscillator frequency was synthesized from a cesium standard reference. The sensitivity of the receiver was sufficient for full quieting (better than 50 dB S/N) throughout the geographic area of interest. The phase versus frequency plot of the IF amplifier is shown in Fig. 3. It shows the average phase change over the 150-kHz passband to be less than 100 ns. The relative intensity of the multipath at the receiver was measured by observing the amplitude versus frequency of the FM carrier using an oscilloscope. High multipath produced a large amount of amplitude modulation along

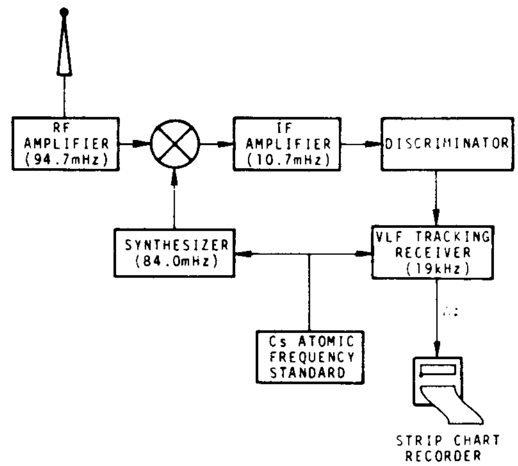

Fig. 2. Block diagram of the receiver setup.

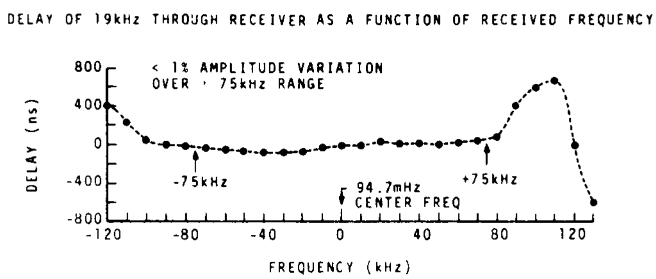

Fig. 3. Phase versus frequency plot of receiver. Phase stability was within 100 ns for a 150-kHz bandwidth.

with the frequency modulation. Fig. 4 describes how relative multipath was monitored. The output of the discriminator fed a tracking receiver tuned to 19 kHz and referred to the cesium frequency standard. The tracking receiver was able to monitor small phase changes of the pilot and indicate them on a strip chart recorder. The tracking receiver bandwidth was about 0.2 Hz.

The receiver setup was installed in a van. A vertical whip antenna was used. By making the equipment transportable, measurements could be made in a variety of locations. The van was driven to eight locations each day for five consecutive days. Five locations can be considered as being in an urban area and three in a rural area. The National Bureau of Standards (NBS) Boulder laboratory was used as a reference point for the eight sites. The nearest and farthest points to the transmitter were 4 and 9 mi, respectively.

Data

Fig. 5(a) shows a strip chart record of phase versus time of the pilot measured at the NBS lab using a directional yagi about 150 feet above ground. It shows the peak-to-peak phase instability due to all causes is less than 100 ns for a 6-min sample. Fig. 5(b) is the same measurement using a whip antenna. The changes in phase (α) accompanied changes in β. By observing the multipath indicator, we noted that the severity of

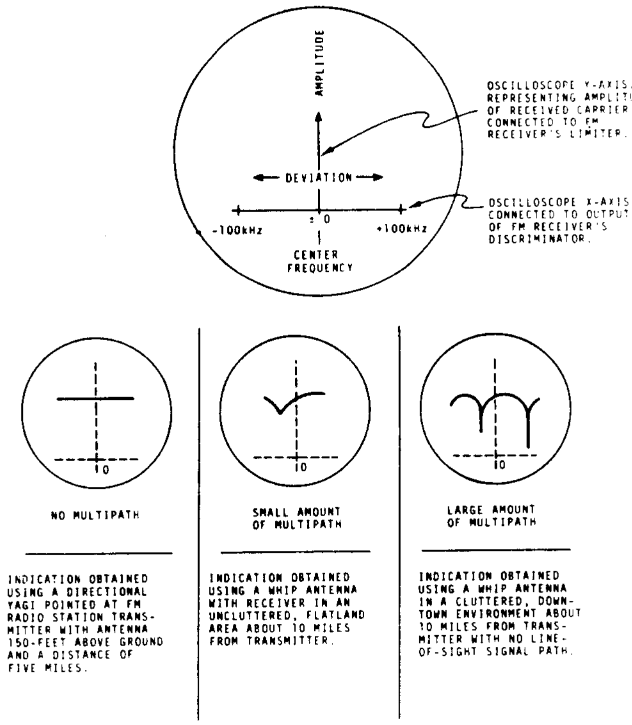

Fig. 4. Relative intensity of the multipath was measured on an oscilloscope by observing the amplitude versus frequency of the FM carrier.

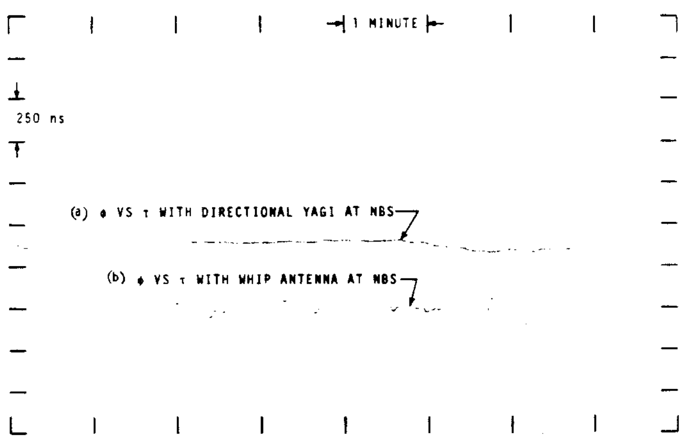

Fig. 5. Phase versus time at the NBS laboratory. (a) Using directional yagi. (b) Using vertical whip antenna. With multipath, the phase of the pilot changes with the modulation index.

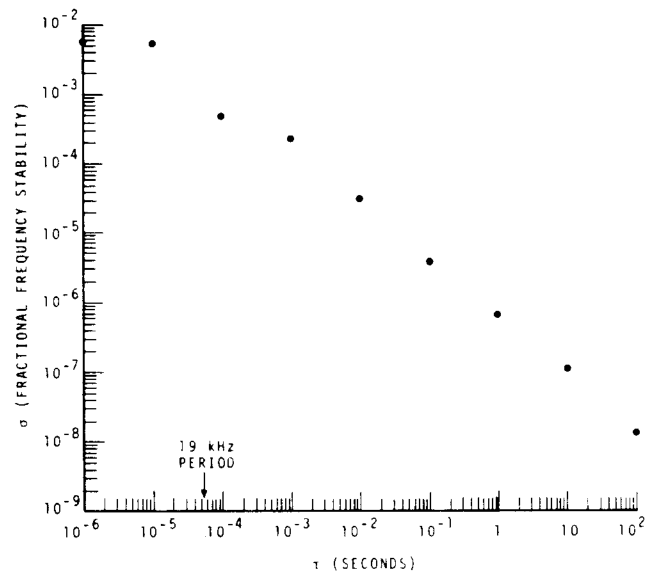

Fig. 6. The σ versus τ plot using a directional antenna shows the statistical stability of the received pilot is about seven parts in 10^7/s. $\sigma_f(\tau)$ data were derived from a computing counter with a quartz crystal reference ($\tau = 1\ \mu s \rightarrow 10$ s; $N = 2$; $10^4 \rightarrow 10$ sets).

the multipath at the receiver showed substantial correlation to the amount of phase change in the pilot.

Fig. 6 shows σ versus τ data of the demodulated pilot using the Allan variance [3]. Measurements were at the NBS lab using a directional yagi. The stability data closely approximates $1/\tau$ flicker of phase noise characteristics. One sees that with 1-s averaging time, it is possible to calibrate a remote oscillator to an accuracy of about 7 parts in 10^7.

Fig. 7(a) is a graph indicating the average delays in microseconds at five urban sites for 5-min averaging at each site. The rms phase instability is also noted at

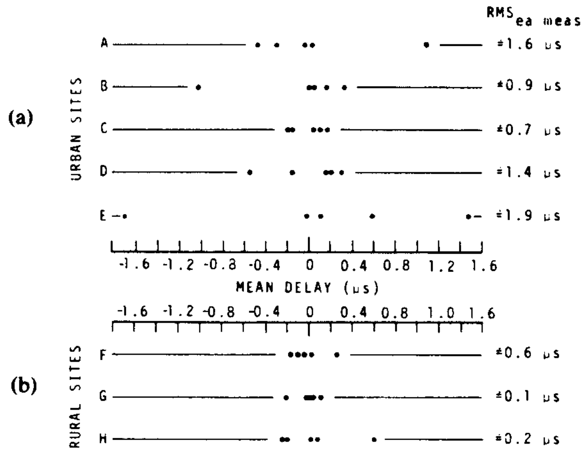

Fig. 7. Scatter of delay measurements around the mean for each site. The 5-min averaging for each data point. The rms phase instability is approximate for each measure and the average value for each site is shown on the right. "*A*" is the closest location at 3 mi from transmitter; "*H*" is farthest at 9 mi. All urban measurements fell within 2 μs of mean. Rural measurements were within 0.8 μs of mean.

each site. Fig. 7(b) shows the same measure but for three rural locations. Of the entire sample of phase versus time records, the least peak-to-peak phase jitter was 100 ns and the most was about 10 μs. The characteristics of the multipath effects were very nearly identical from day to day at each site. Day-to-day variations in multipath were observable only at points "*F*" and "*H*," the farthest from the transmitter at 8 and 9 mi, respectively.

Conclusion

We have shown that the pilot tone on a stereo FM radio station may be used for calibration of oscillators within the radio coverage area to about seven parts in 10^7/s. The accuracy of calibration is as good as the frequency standard used to generate the pilot. We have observed a change in the phase delay of the received pilot which was predominantly attributed to multipath. We measured multipath by noting the amplitude versus frequency of the received FM carrier. From a mathematical model using a single tone for FM modulation, we inferred that the amount of phase change was related to the modulation index β of the total baseband audio. Using a whip antenna, we have measured β-dependent phase changes in the pilot tone of nearly 10 μs at some locations. The least phase jitter was 100-ns peak-to-peak. Typically, it was less than 2 μs peak-to-peak in an urbun environment. With 5 min of averaging time, the delay of the pilot at five urban sites was reproducible to within 2 μs each day over a five-day period. Delay was reproducible to within 0.8 μs at three urban sites. Day-to-day changes in the multipath were not significant but were more noticeable as the distance to the transmitter increased.

Acknowledgment

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