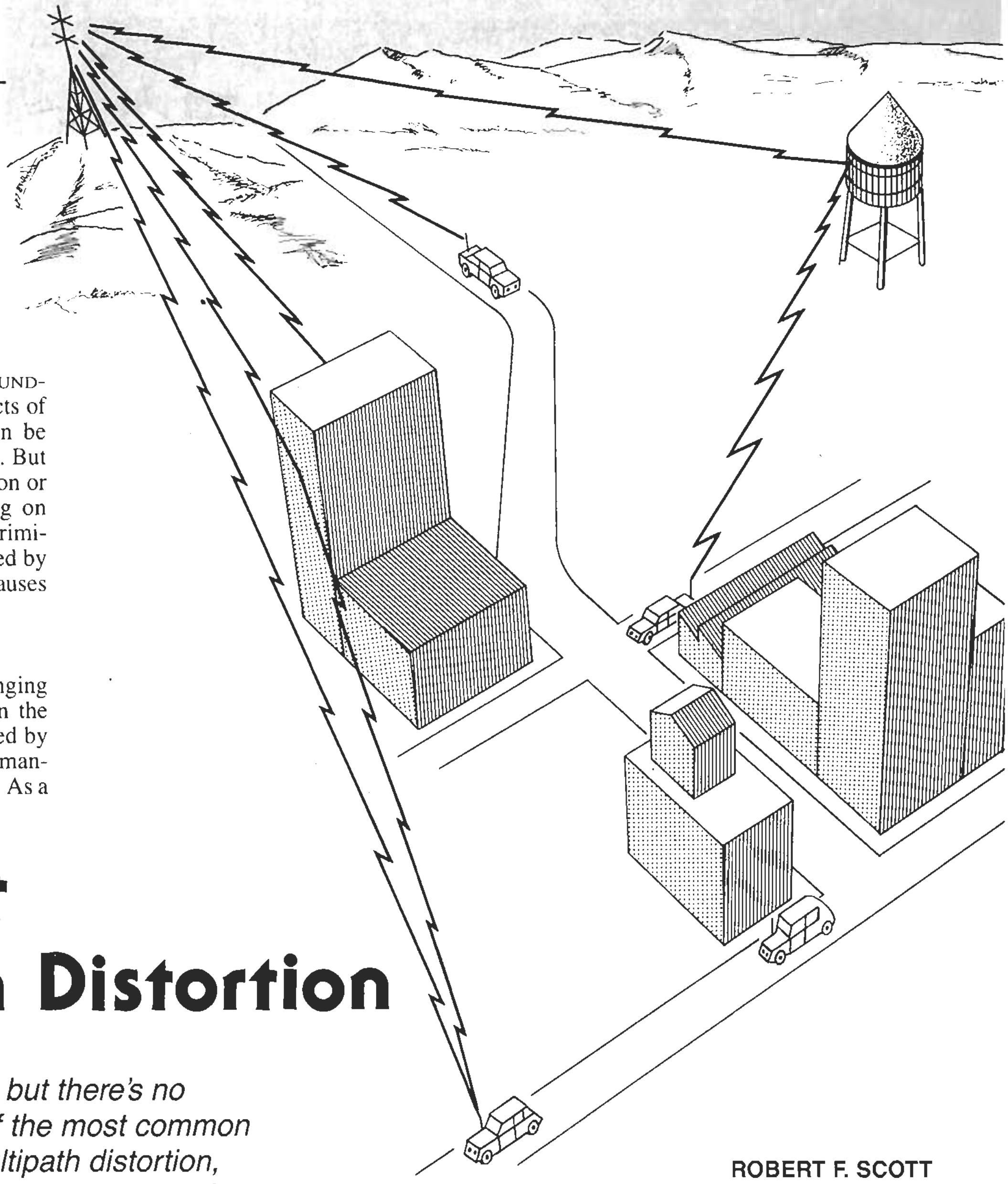

THERE ISN'T MUCH MYSTERY SURROUNDING TV "ghosts." They are the effects of multipath distortion and often can be eliminated without too much trouble. But what of FM "ghosts?" That distortion or "flutter" that you've been blaming on your receiver's tuner, AGC, or discriminator circuits may very well be caused by the same multipath reception that causes TV ghosts.

All About Multipath Distortion

FM distortion is annoying, but there's no need to put up with one of the most common types. Here's a look at multipath distortion, and how surprisingly easy it is to get rid of.

ROBERT F. SCOTT

What is multipath reception?

VHF and UHF signals, those ranging from around 50 MHz to well up in the microwave region, are easily reflected by buildings, water towers, and other manmade objects, as well as by hills, etc. As a result, at any particular location, an FM antenna may be receiving a signal on a direct, line-of-sight path, as well as via a number of reflected paths. (See Fig. 1.)

That can be an advantage in certain cases. For example, some receiving locations may be in a "shadow" area where, due to intervening buildings, hills, or heavily wooded areas, line-of-sight reception of signals is not possible. In those areas adequate reception might be possible *only* via reflected signals.

Unfortunately, not all multipath reflections are advantageous. Let's take a look at Fig. 1. That figure shows several FM receiving sites, labeled A, B, C, and D, all located about 38 miles from the transmitter. Location A receives signals over two paths. One is a 38-mile direct line-of-sight path. The other is more roundabout—40 miles to the water tower, and then 5 miles to the receiving antenna.

Radio waves travel 186,000 miles per second (0.186 mile per microsecond) or 1 mile in 5.376 µs. The multipath route is 7 miles longer than the direct path, so the reflected signal is delayed 37.63 µs (7 × 5.376 = 37.63). Though not shown, note that some of the signal reflected from the water tower also is reflected downward toward the earth. It then is reflected off the earth to the receiving antenna, forming yet another, slightly longer path. In a moment we'll see how those delays distort the received signal, but first, let's look at the other sites in Fig. 1.

Location B is a good place to receive an adequate direct signal, free from multipath interference. Locations C and D are in the "shadow" of a tall office building and cannot receive a satisfactory direct signal. The FM listener at location D has solved the problem by aiming his antenna at the water tank.

FM signal basics

When an FM transmitter is modulated, its output signal varies above and below the carrier center-frequency at a rate equal to the modulating frequency. The greater the amplitude of the modulating signal is, the greater will be the swing in carrier frequency from its assigned center frequency.

The FCC has defined ±75 kHz (a total swing of 150 kHz) as 100% modulation, ±60 kHz as 80% modulation, ±45 kHz as 60% modulation, and ±37.5 kHz as 50% modulation.

As long as the percentage of modulation is held constant, the frequency swing remains constant, regardless of the modulating frequency.

Figures 2 and 3 show the "anatomy" of an FM signal. Looking first at Fig. 2, as the modulating signal rises from zero to its maximum at 90 degrees, the carrier

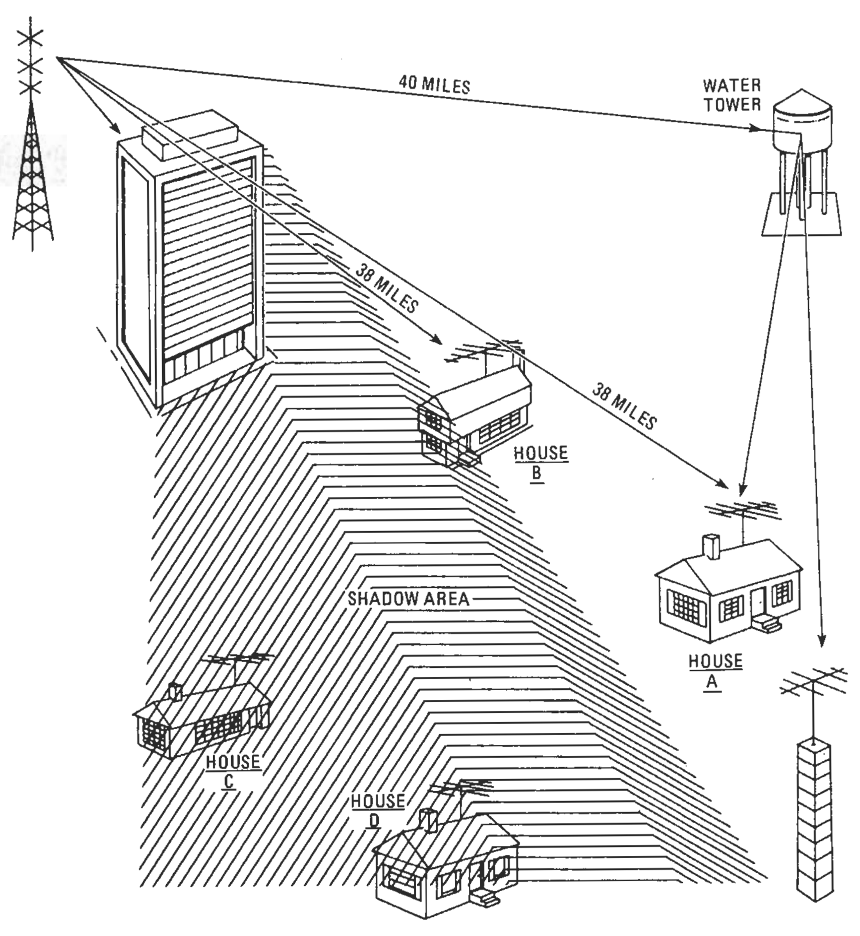

FIG. 1—SOME LOCATIONS RECEIVE direct signals, reflected signals, or a combination of both. In locations where both direct and reflected signals are received, multipath distortion can occur.

frequency swings from its resting (unmodulated) center frequency to a maximum determined by the percentage of modulation.

As the modulating signal passes 90 degrees, the carrier frequency decreases until it returns to the center frequency when the modulating carrier reaches 180 degrees. As the modulating signal swings in the negative direction, the carrier swings from its center frequency toward its minimum (once again determined by the percentage of modulation). Once the modulating signal passes 270 degrees, the carrier frequency begins to rise until it is once again at the center frequency at 360 degrees (0 degrees).

Figure 3 shows the effects of the modulating signal on a carrier signal. Figure 3-*a* is the modulating audio signal, while Fig. 3-*b* shows the corresponding effect on the carrier frequency. Figure 3-*c* shows the modulating signal superimposed on the carrier. In those illustrations the modulation polarity and its relationship to carrier frequency is such that a positive-going modulating signal causes the carrier frequency to increase while a negative swing in modulating voltage cause the carrier frequency to decrease. That polarity relationship is not mandated by FCC regulations or by FM transmitter design.

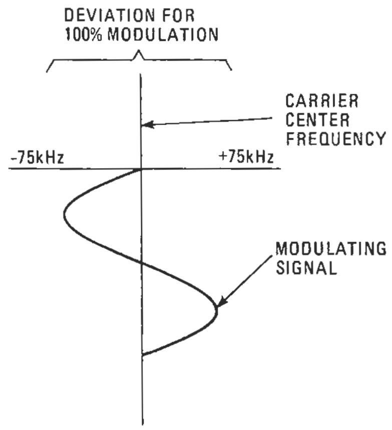

FIG. 2—FOR 100% MODULATION, the carrier frequency will swing ±75 kHz.

An FM transmitter can just as easily be operated with negative polarity where a positive-going modulating wave causes the carrier frequency to decrease.

Causes of multipath distortion

We have seen how a reflected signal takes a longer path and is delayed in reaching the receiving antenna. The chart in Fig. 4 can be used to compare typical delays with differences in the lengths of the direct and reflected paths.

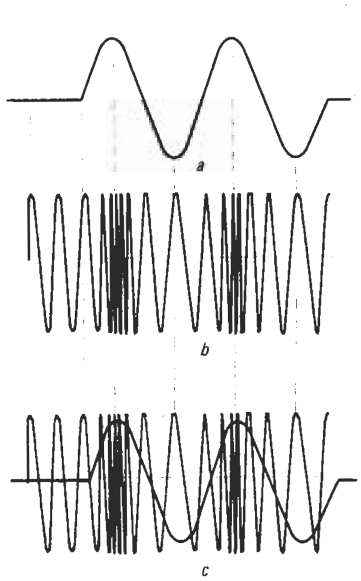

FIG. 3—ANATOMY OF AN FM SIGNAL. The modulating signal is shown in *a*, and its effect on the carrier frequency is shown in *b*. The two signals are shown superimposed in *c*.

When an FM signal is reflected, it usually undergoes a 180-degree phase reversal. So, when the reflected path is a whole number of wavelengths longer than the direct path, the signals at the antenna are out-of-phase; and the strength of the signal at the receiver depends on the relative strengths of the two signals. Complete cancellation can occur when the signals are 180 degrees out-of-phase and of equal amplitude.

When the difference in path lengths is an odd number of half-wavelengths, the signals are in phase. The result is that the signal strength at the receiver will actually be higher than if only the direct signal were being received.

But, most often the difference in path lengths will be something other than an odd or even multiple of the wavelength. Since the carrier frequency of an FM signal is constantly changing, in those instances there will be constant changes in the instantaneous phase and frequency differences in the direct and multipath signals. Thus, the resultant signal at the receiver will contain both phase-modulated

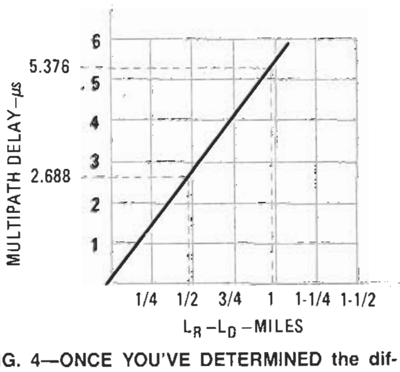

FIG. 4—ONCE YOU'VE DETERMINED the difference in length between the direct path (L_D) and the reflected path (L_R), this chart can be used to find the multipath delay in μs.

and amplitude-modulated distortion components that were not present in the original signal.

Let's take a look at the distortion caused by multipath reception of the FM signal at location A in Fig. 1. The multipath signal travels 7 miles farther than the direct signal, so its arrival is delayed 37.63 µs. Let's assume that, at a given instant, the FM transmitter is 100% modulated by a 5-kHz tone. The period of a 5-kHz sinewave is 200 microseconds. Since, as we've seen, a frequency-modulated carrier reaches its maximum deviation in one direction at the 90-degree point of the modulation cycle, and maximum deviation in the opposite direction at 270 degrees, how much will the carrier swing during the 37.63-µs delay?

Since the period of the signal is 200 µs, we know that at 50 µs, the signal has swung through ¼ of a cycle, or to 90 degrees. That allows us to set up the following proportional relationship:

$$\frac{50\ +\mu S}{90^\circ} = \frac{37.63\ +\mu S}{X}$$

$$50X = 3386.7^\circ$$

$$X = 67.73^\circ$$

To find the percent of modulation at that point:

$$\sin 67.73^\circ = 0.9292$$
$$0.9292 \times 100\% = 92.52\%$$

The carrier swing thus is 92.52% × 75 kHz, or 69 kHz. Thus, when the reflected signal arriving at the receiver passes through the center frequency, the direct signal has advanced 67.73 degrees or 69 kHz.

At that instant the direct and multipath signals interact to produce a 69-kHz beat. That signal is not audible, but it can produce annoying interference as it beats with other components of the composite FM direct and multipath signals.

Similarly, with the same 37.63-µs delay, a 1-kHz tone produces a 17.25-kHz beat, while an 8.75-kHz beat is produced when the FM carrier is modulated by a 500-Hz tone.

It was by chance that we assigned the distances to the direct and reflected paths shown in Fig. 1. Had we assigned values where there was only a half-mile difference, the delay would have been 2.688 µs in the two signal paths. The 5 kHz, 1 kHz, and 500 Hz modulating tones then would have produced beats of 6.3 kHz, 1.26 kHz, and 630 Hz, respectively.

Note that the preceding discussion is based on signals strong enough to modulate the carrier 100% and drive it to full ±75-kHz deviation. If, in the examples above, the carrier is modulated only 50%, maximum deviation is only ±37.5 kHz and the beat interference frequencies would be half of those given above.

The interference frequencies given in the above examples are generated when the modulating signal contains but a single frequency. But typical FM signals contain a variety of frequencies, and the multipath distortion caused by them can be exceedingly complex and constantly changing.

Reducing multipath distortion

Generally, multipath distortion can be reduced to an acceptable level, or completely eliminated, by any method that can be used to insure a 40- to 50-dB difference in the strengths of the direct and reflected signals. Usually, the approach would be the same as that used to eliminate TV ghosts. That is, install a highly directive receiving antenna that has a good front-to-back ratio, a sharp frontal lobe, and a minimum of spurious side and back lobes. An antenna rotator would be used to aim the antenna at an interference-free direct signal—keeping the direct signal well within the main portion of the forward lobe while causing the unwanted reflected signal to fall in a null in the response pattern.

If your FM receiver has a signal-strength meter, you can swing the antenna and measure the angle between the direct and reflected signals. If the multipath signal is arriving from 20–30 degrees right or left of the direct signal, it may be possible to eliminate it by stacking two identical high-gain antennas, one above the other, one-half wavelength apart. In addition to increasing direct-signal pickup by 2.5 to 3 dB, stacking sharpens the forward lobe—possibly enough to completely eliminate multipath interference.

If the reflected signal arrives from the rear of the antenna and is not sufficiently attenuated by conventional vertical stacking (as described above) try stagger stacking, as shown in Fig. 5.

Stagger stacking provides a 10- to 20-dB improvement in the front-to-back ratio, while still providing a substantial increase in forward gain. In stagger stacking, the antennas are spaced 0.67 to 0.7 wavelengths apart vertically, and the upper antenna is spaced one-quarter wavelength ahead of the lower one. The coax line between the upper antenna and the coupler is one-quarter wavelength longer than the coax connected to the lower antenna.

Because of the one-quarter wavelength horizontal stagger between the antennas, the wavefront of the incoming direct signal reaches the upper antenna one-quarter wavelength (90°) before it reaches the bottom one. However, the extra one-quarter wavelength section of coax from the upper antenna delays the signal 90 degrees so it will be in phase with the signal from the bottom antenna when the two combine in the coupler. That provides an added 2.5 to 3 dB gain.

The wavefront of the reflected signal arriving at the rear of the antenna array reaches the upper antenna one-quarter wavelength after it has reached the bottom antenna. The signal at the upper antenna is delayed an additional 90 degrees by the added quarter-wave section of coax downlead. Thus, the reflected signals from the top and bottom antennas arrive at the coupler 180 degrees (one-half wavelength) out-of-phase, so they will cancel. The rejection of the reflected signal is typically −20 dB, and may be −30 dB with careful design and construction.

When designing a stacked antenna array, remember that FM signals travel slower in cable than in free space (or the atmosphere). Because of that, the wavelength of the signal in cable is shorter than

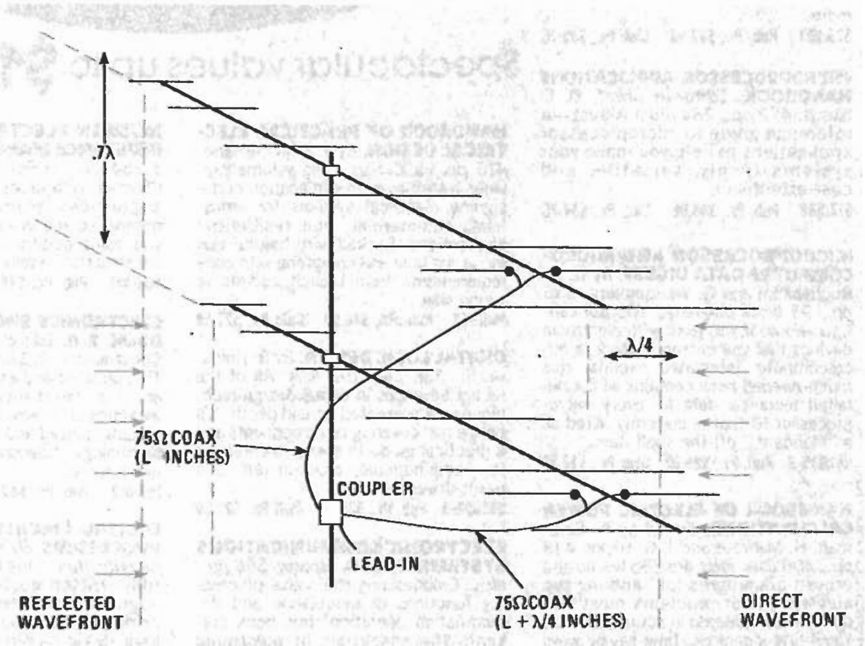

FIG. 5—WITH STAGGER STACKING, the upper antenna is mounted so that its elements are located ¼ wavelength ahead of the corresponding elements of the lower antenna.

the wavelength of the signal in free space. Therefore, when calculating the length of a section of transmission line, you must compensate for a characteristic called velocity of propagation. For solid-dielectric coax, the velocity factor is 0.66; the velocity factor is 0.85 for foam-dielectric coax. Thus a piece of solid-dielectric coax that is one wavelength long will be only 66% as long as the wavelength of the signal in free space.

Let's next calculate the dimensions of the array shown in Fig. 5. We'll use 100 MHz, the center frequency of the FM band, as our design frequency. In free-space:

$$\lambda = 11{,}700/f \text{ inches}$$
$$\lambda/2 = 5850/f \text{ inches}$$
$$\lambda/4 = 2925/f \text{ inches}$$

where λ is the wavelength and f is the frequency in MHz. At 100 MHz, one wavelength is 11,700/100, or 117 inches. Vertical spacing between the antennas is 81.9 inches (117 × 0.7) while the horizontal offset or staggered dimension is 2925/100, or 29.25 inches. The solid-dielectric coax connecting the antenna array to the coupler consists of two lengths. The shorter length, which measures L inches, connects the bottom antenna to the coupler. The other section is a quarter wave longer, so it measures L + 19.3 inches (66% × 117/4).

Horizontal stacking

When the reflected signal arrives from an angle to the right or left of the direct signal, two high-gain directional antennas can be stacked horizontally (side-by-side) and aimed for maximum pickup of the direct signal. Their center-to-center spacing can be adjusted to develop a null in the pattern corresponding to the angle of arrival of the reflected signal. Figure 6-*a* shows that at some spacing, H, between the antennas, the reflected signal arrives at an angle corresponding to one of the minor lobes in the pattern. In that situation, multipath distortion will be severe.

To minimize that distortion we can "warp" the response pattern so the reflected signal falls at a null between the major and minor lobes as shown in Fig. 6-*b*. When that occurs, the reflected signal "sees" half-wave or 180° spacing between the two antennas. When that happens, the signal voltages induced in the two antennas are 180° out of phase, so they cancel at the coupler.

On the other hand, the antennas are oriented so that the direct signal reaches both simultaneously. That means that the signals are in phase. The overall result is a 3-dB increase in the strength of the direct signal and the cancellation of the reflected signal.

Success in cancelling the reflected signal depends on how precisely we know the value of θ, the angle between the direct and the reflected signals. When the location of the reflecting surface is not known, you can measure θ by first orienting the antenna for best reception of the direct signal and then repositioning it for best reception of the reflected signal. The spacing between antennas, H, can be determined from:

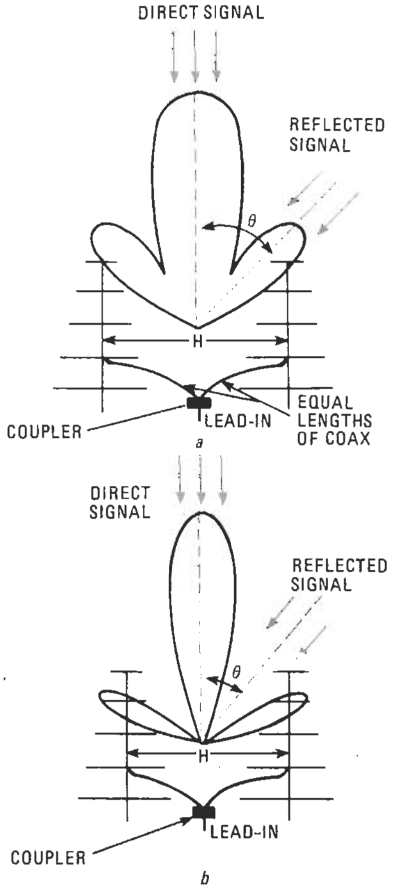

FIG. 6—WITH HORIZONTAL STACKING, at some spacing, H, the reflected signal will arrive at an angle corresponding to one of the antenna system's minor lobes; that is shown in *a*. It is possible to alter the spacing between antennas so that the reflected signal comes in at an angle corresponding to a null between the lobes; that is shown in *b*.

$$H = (\lambda/2)\sin\theta$$

where H and λ are in inches.

Let's see how that formula is used to calculate H by looking at an example. Let's assume that the carrier frequency of the incoming signal is 100 MHz, and that the angle θ between the direct and the reflected signals is 40°. First, λ is equal to 11700/100 = 117. Plugging into the equation, $H = (117/2)\sin\theta = (117/2)0.6428 = 117/1.285 = 91.4$ inches.

The graph in Fig. 7 shows the relationship between θ and the center-to-center spacing, H, in wavelengths. Note that as θ increases beyond 30 degrees, the spacing is quite small, and the antenna elements may touch or overlap. In such cases, space the antennas an odd multiple of H apart. That allows clearance without changing the response pattern.

Diversity reception

While eliminating multipath distortion for a home receiving setup presents relatively few problems, the same can not be said for car setups. There, the directional signal path between the FM transmitter and the moving car is constantly changing. At times the received signal is severely attenuated or completely blocked, causing fading and "drop out." At other times, the car's antenna picks up signals reflected from the ground, buildings, hills, etc. As the car moves, the phase relationships between the direct and reflected signals are constantly changing, adding and then subtracting at random rates to vary the instantaneous signal strength, producing a multipath distortion called "flutter" or "picket-fencing."

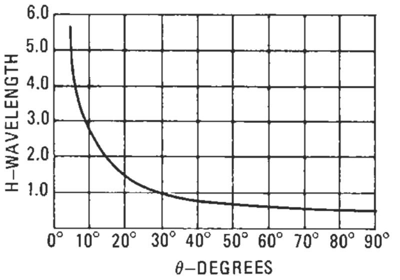

FIG. 7—THIS CHART shows the relationship between the angle θ and the proper spacing in wavelengths between antennas in a horizontally stacked system.

It was discovered many years ago that signal strength at a particular moment may be quite different at antennas spaced just a few wavelengths apart. A technique to eliminate the above mentioned receiving problems, called diversity reception, takes advantage of that phenomenon by feeding an FM receiver from two antennas. The theory being that as the signal strength is fading on one antenna, it will be constant, or even increasing on the other. A diversity receiver is designed to determine which antenna is providing the strongest signal at a particular moment and to switch to that antenna.

Figure 8 is a block diagram of a diversity receiver. As is shown, such a receiver features two antennas, two tuner front ends, two IF amplifiers, two FM detectors, a common local oscillator, and a comparator. Clarion Corp. of America (5500 Rosecrans, Lawndale, CA 90206) sells a diversity receiver, the Audia *DTX-1000* shown in Fig. 9. In that receiver, a common local oscillator tunes both tuners to precisely the same frequency. The signals in the two IF-amplifier systems are rectified separately to develop signals consisting of a direct-path voltage and a multipath voltage.

Amplitude modulation (AM) and phase modulation (PM) components develop when an out-of-phase multipath signal is combined with the direct signal. The AM components of the multipath sig-

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nal and the direct signal are amplified by the same gain factor and then rectified to produce DC voltages.

The comparator/control circuit compares the levels of the DC voltages derived from the two IF signals and immediately selects the antenna and tuner combination with the lowest DC voltage from the AM component of a multipath signal. The control circuit switches the input of the audio amplifier to the output of the tuner providing the better signal. Switching occurs as rapidly as necessary to ensure that the listener gets the signal with the least interference and distortion.

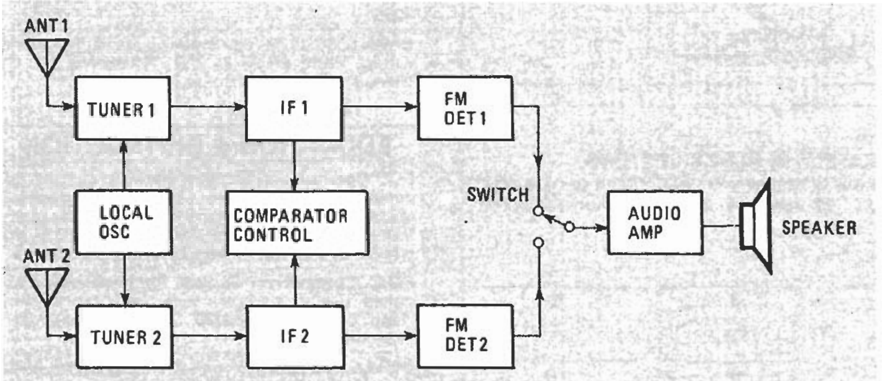

FIG. 8—BLOCK DIAGRAM of a stereo diversity reception stereo receiver. Note that it has two independent front ends.

FIG. 9—THE AUDIA *DXT-1000* diversity receiver from Clarion.

Other manufacturers use different techniques to reduce multipath distortion in automotive FM receivers. One such technique makes use of the fact that, for a given signal strength, a stereo FM signal is inherently noisier than a mono one. For adequate reception, a receiver requires a signal that is above a given threshold level. As the signal drops toward that level, interference and distortion is first noticed as noise and hiss in the treble range. A further drop causes garbled sound and random dropouts. Mono signals have a higher high-frequency content than stereo signals, which results in better masking of noise and hiss.

Some car stereo makers use that fact to reduce multipath distortion. When multipath reception causes the incoming signal to fall below a given level, control circuits automatically switch the receiver from stereo to mono. In some sets, the switching from stereo to mono is rather abrupt and quite noticeable. In others, such as Pioneer's (5000 Airport Plaza Dr., Long Beach, CA 90815) receiver models *KE-A630*, *KE-A430*, and *KE-A330* (see Fig. 10) the transition from stereo to mono is achieved by a gradual blend of the left- and right-channel signals. As the FM signal gets stronger, the effect is gradually reversed.

FIG. 10—THE *KE-A330* stereo receiver from Pioneer automatically switches to mono when the signal strength drops below the level required for acceptable stereo reception.

In some receivers multipath distortion under weak-signal conditions is made less noticeable by rolling-off the high-frequency response when the incoming signal does not have enough treble content to over-ride hiss and noise. Usually that is done by feeding the recovered audio signal through a highpass filter and rectifier to a logarithmic amplifier that develops a DC voltage that is proportional to the high-frequency content of the signal. That DC voltage controls the bandwidth and roll-off of a variable highpass filter—cutting the high-frequency response so noise and hiss are eliminated. **R-E**