Characterization of the HDTV Channel in the Denver Area

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PREFACE

Certain commercial equipment, instruments, or materials are identified in this report to adequately describe the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

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CHARACTERIZATION OF THE HDTV CHANNEL
IN THE DENVER AREA

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Development and testing of various implementations of High Definition Television (HDTV) require knowledge of the multipath characteristics of the radio channel over which the proposed signal will be carried. The Institute for Telecommunication Sciences (ITS) has begun a program to measure these characteristics in locations that might represent consumer habits. This report discusses the general background of the measurement techniques and describes measurements made in the vicinity of Denver, Colorado.

1. INTRODUCTION

Wideband communication systems are subject not only to the usual additive noise but also to a multiplicative noise in which the signal interferes with itself because of multipath propagation. In the case of television the presence of "ghosts" is an obvious result of multipath; subtler effects might include synchronization problems and nonlinear distortion of the FM audio signal. In a high definition television (HDTV) system, one expects a possibly more complicated relationship between picture degradation and multipath, because of more complex modulation and data-compression schemes. Most proposed HDTV systems will need to be designed so as to cancel the effects of multipath.

To fashion such a design, it would help to know what degree of multipath distortion the system will need to combat. Unfortunately there is little quantitative knowledge about the over-the-air radio channel. This report describes a measurement program intended to acquire new data showing multipath parameters over the kind of radio link one expects in a television service. These data should prove useful in the design of systems and in devising multipath simulators for testing proposed systems.

Because we expect that different cities may have different multipath environments, our general plan is to take data in perhaps three or four geographically separated places. The data given here form the first of these sets and come from areas in and around Denver, Colorado.

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2. POSSIBLE MODELS

A good way to understand what data are required or how such data can be displayed is to relate these data to the parameters of a proposed model. Any such model will try to approximate the characteristics of the propagation channel and will therefore need to describe a function. Since we are primarily concerned with multipath, it seems most direct to use the impulse response function $h(t)$. This describes how a transmitted impulse is received—first along the direct path and then as it continues to trail along afterwards. The latter part of the signal comprises the set of "multipath components" and is presumably derived from scattering by off-path objects. Since we normally use narrowband terminology, we will need to assume that $h(t)$ is complex-valued. It is a complex signal modulating some carrier frequency.

Of course, we could also describe the channel by its spectral response function $H(v)$. Since it and the impulse response function are Fourier transforms of each other, the two should be entirely equivalent. There are, however, some practical constraints when it comes to measuring them. The impulse response can be measured only over a limited time, and the spectral response only over a limited band. Resolution of the two functions is also dependent on opposite criteria. Resolution of the impulse response requires a wide frequency band, and resolution of the spectral response requires a wide time measurement.

Also, of course, it is not the functions $h(t)$ or $H(v)$ that a model must describe, but rather the statistics of these functions. We must be able to describe more than just a single path; we must be able to describe the general appearance of all (or all suitable) paths. Terminology and the general description of these phenomena may be found in the classic paper of Bello (1963).

2.1. Discrete Impulsive Components

There are two particular models we will describe here. Their chief difference is in how they view the qualitative aspects of the train of multipath components. The first model is probably the more natural-appearing. In it, one imagines the received signal to consist of the direct signal followed by a sequence of delayed copies. The complex impulse response may then be written as

$$h(t) = S\left[\delta(t) + \sum_{k=1}^{\infty} a_k e^{i\theta_k} \delta(t - t_k) \right] \tag{1}$$

where S is the strength of the direct signal, the a_k are relative amplitudes of the delayed copies, the θ_k are relative phases, and the t_k are the delay times. We have assumed here that the direct signal arrives at time $t = 0$, that the delay times t_k are an increasing sequence of positive times, and that the a_k go quickly to zero. For any particular path at any particular time, one might imagine these parameters have specific values. In general, however, one must treat these parameters as random variables and to complete the model one must describe their statistics.

This is essentially the model proposed by Turin *et al.*, (1972). For statistics they first suggest a fairly complicated set of rules, but then settle on a somewhat simplified set. They suppose that S and the a_k are log-normally distributed with means (measured in decibels)

μ and $μ_k$ and with a common standard deviation σ equal to about 2 or 3 dB. The $θ_k$, they suppose, are distributed uniformly over $2π$ radians, and the sequence of delay times $\{t_k\}_1^\infty$ is a (modified) Poisson sequence whose mean arrival rate is given by the function of time $r(t)$. All these random variables are assumed independent. Presumably, the values of $r(t)$, and of the means of S and the a_k are all functions of the parameters of the radio path and are to be empirically determined.

2.2. A Continuum of Multipath Components

One conceptual difficulty with the model we have just described is that it makes every multipath component an exact replica of the original signal, so that in (1) they are all represented as impulses. In actuality, one expects that the scatterers involved are curved and finite in extent and that diffraction plays a major role, so that what starts as an impulse becomes spread out into a fairly smooth pulse. One way to view the result is to imagine the impulse has acquired a continuum of delay times and so has become a continuum of components.

In one extreme view, impulse responses are treated that way and, furthermore, any two of the components are assumed to be statistically independent. This forms what Bello (1963) calls the GWSSUS (the Gaussian wide sense stationary uncorrelated scatterers) channel. In a slightly modified form we can write

$$h(t) = S\left[\delta(t) + h_0(t)\right] \tag{2}$$

where S, as above, is the strength of the direct signal, where we assume the direct signal arrives at time $t = 0$, and where $h_0(t)$ is the relative amplitude of the trailing multipath components. Then $h_0(t)$ is a complex-valued stochastic process which is Gaussian distributed with mean zero and variance equal to the power curve $p(t)$, and for which any two values have zero correlation. It is something like white noise, but multiplied by a suitable amplitude function. One point to be made is that such a process is dual to the more common stationary process one likes to treat. The duality comes from the spectral response $H_0(v)$ which is stationary in frequency. It is a Gaussian process with zero mean (because the phase is random) and with autocorrelation function

$$\varepsilon\{H_0(v)H_0(\mu)*\} = P(v - \mu). \tag{3}$$

And then the Fourier transform of $P(v)$ is precisely the power function $p(t)$.

Aside from the statistics of S, the only values this model needs are those of the function $p(t)$. This is the approach taken by Cox (1973a) and by Cox and Leck (1975a, b). Their data do, indeed, seem to favor the GWSSUS channel, especially within the very small neighborhoods they examine.

This model and the previous one described in Section 2.1 are really not very different. Whether or not one can count the number of multipath components depends very much on the resolution of the measuring system. If the resolution is low, components might be smeared together and give the appearance of a continuum. Also, there is a slight difference in the assumed statistics. In (1) the a_k are supposed to be log-normally distributed, while in (2) the amplitudes, since the components are assumed to be complex Gaussian processes, are Rayleigh distributed. But a Rayleigh distribution is much like a log-normal distribution except that its standard deviation always has the value 5.57 dB.

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3. PREVIOUS MEASUREMENTS

There have been no previously collected data related specifically to the problems of over-the-air HDTV. But data do exist that were acquired for similar purposes and we will review them here.

In support of a project to design and evaluate vehicular locator devices, Turin *et al.*, (1972) have collected data from San Francisco and Oakland, over paths ranging in length from 1.5 to 10 km using the three frequencies, 488 MHz, 1.28 GHz, and 2.92 GHz. They used a system that broadcast short pulses 0.2 µs wide, and recorded received amplitudes photographically from oscilloscope traces. Using the discrete component model in Section 2.1, they were able to perform satisfactory simulations in which the means of Sand the a_k, and the values of $r(t)$ were obtained empirically from their data. Roughly, they found the mean µ of S to be 10-20 dB below free space in the Oakland area, and about 50 dB in the financial district of San Francisco. The means $µ_k$ started at 0 dB for small k and decreased to –5 dB in San Francisco and to –30 dB in Oakland. And, finally, the values of $r(t)$ began at about 7 paths per µs near $t = 0$ and fell to 1 path per µs somewhere between 3 and 6 µs.

A second group of measurements were collected by Cox (1972a, b, 1973a, b, 1977) and Cox and Leek (1975a, b). In that group, a first set came from a suburban area with the transmitter on Crawford Hill near Keyport, N. J., and the receiving locations about 4 to 5 km away. The remainder were from lower Manhattan with the transmitter near the World Trade Center but only 120 m above street level and with paths no longer than 3.5 km. The measurements were made to help with studies related to cellular telephony and the frequency used was 910 MHz in what was then a newly-released part of the spectrum.

The method for making these measurements was a new one that had been suggested by experiments carried out with the so-called Rake system of communications (see, *e.g.,* Barrow *et al.,*, 1969). In essence, the measurement system (see Cox, 1972a, and also Hufford *et al.,*, 1982) transmitted not isolated pulses, but a sequence of +1 and –1 rectangular pulses. These were arranged in a maximal shift register, or pseudonoise, sequence and used biphase shift keying to modulate the carrier frequency. On reception, the signal is decoded to obtain a simulated pulse followed by its multipath-induced copies, exactly as one wants in (1) or (2). The advantage of such a system is that the rf envelope is constant so that for a given average power the voltages are of moderate size. This is not true for isolated pulses.

In Cox's equipment there was a 9-stage shift register (hence a code length of 511 bits) which ran at a bit rate of 10 MHz. Thus he could measure multipath components to within a resolution of 0.1 µs and a delay of up to 51.1 µs. He would take a short run down a street making an impulse response measurement every 10 cm or so over a length of from 5 to 30 m. Over such short runs he found strong evidence for a GWSSUS channel and so he would often display the results of each run as a plot of the function $p(t)$ described in Section 2.2 above. He found it had values of 0 dB for $t = 0$ and decreased to –30 dB after perhaps 2 µs (in the suburbs) or after 12 µs (in New York City).

Still another set of measurements that might usefully be cited are those of Hufford *et al.*, (1982). They used equipment very similar to Cox's, but with a bit rate of 150 MHz. Presumably they could resolve multipath components to within 6.7 ns, though requiring

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a bandwidth of 300 MHz or more. They were interested in UHF mobile communications through dense forests, and on very short paths they found multipath delays on the order of 0.3 μs. This seems very short in comparison with the data we have previously described.

4. THE MEASUREMENT DESIGN

For the measurements to be described here, we combined several ideas that have been previously used. First, the NTSC television signal (the television signal used in North America and in Japan) contains a Vertical Blanking Interval (VBI) of several horizontal lines on which one can put test signals of one kind or another without affecting normal transmission. These signals are inserted into the regular video signal by readily available devices called test signal generators. Normally, the signals are used to test the fidelity of studio or transmitter equipment; but, as Vincent and Bruneau (1985) and Caron (1989) have noted, they can also be used to measure the propagation path.

If a VBI line is to be used, the next question is what form a propagation test signal should be. Of course, television uses vestigial sideband amplitude modulation, and one must realize that any signal inserted into the regular video channel will then pass through this modulation process.

One signal that is sometimes used is called the sin x/x pulse. Essentially it is an impulse passed through a 4.2 MHz lowpass rectangular filter. It seems a very natural choice to measure an impulse response. But it is a single isolated pulse with not much observable effect on the total signal—the resulting signal-to-noise ratio is not very advantageous. A better choice would be to use a sequence of rectangular pulses—perhaps an encoded arrangement of 0 and 1 bits. As Vincent and Bruneau (1985) have shown, almost any signal form can be used: after reception one can use arithmetical techniques to analyze it into multipath components. As they have also shown, however, probably the optimum signal—the one that provides the best signal-to-noise ratio—is the pseudonoise sequence of rectangular pulses used somewhat differently by Cox (see Section 3 above). A sequence of length N essentially duplicates the impulse response N times, and thus provides a processing gain of this same factor.

The final component in our measurement approach has to do with reception and analysis of the signal. While most previous work using encoded pseudonoise sequences has found a way to decode the sequence, thus producing an analog output that immediately represents the desired impulse response, our approach has simply been to record the received video signal. We record the results digitally and then subject those records to computer analysis in order to produce the final impulse responses. We lose the ability to make real time measurements, but we gain in hardware simplicity and in reliability.

The clearest advantage of this approach is that since all the component ideas are in common use today, the required equipment is commercially available. Thus the assembled system should be low cost, reliable, and able to be quickly fielded. A second striking advantage is that since we use operating television stations, the radio paths we measure will almost surely be the correct kind to represent the television broadcast service. Furthermore, we then have available the high radiated power such transmitters use and we should be able to make useful measurements at fairly large distances.

On the other hand, an obvious disadvantage is the relatively small bandwidth we can utilize and the vestigial sideband modulation our test signal must undergo. The effective bandwidth of the NTSC video signal is about 4 MHz and this, as we shall see, reduces the resolution for the system to about 0.5 µs. As we shall also see, the system as assembled sometimes has trouble synchronizing to the signal. This is particularly true when the signal is low, or when severe multipath is present.

4.1. Implementing the Test Signal

Aiming to be invisible to normal television reception, we have used specifications for our test signal that mimic those used by Teletext. The bit rate is 8/5 times the frequency of the color burst, or approximately 5.73 MHz. The rectangular pulses switch between 0 and 70 IRE units, and are shaped by passing them through a raised cosine filter with 100% rolloff.

In Figure 1 is a plot showing how the VBI line should appear when it carries our pseudonoise (pn-) code. Following the horizontal synchronizing pulse and the color burst, the encoded signal is placed in the middle of the remainder of the line. It is generated by a 7-stage shift register, and the resulting code of 127 bits is inserted twice in the line. It appears twice because the multipath components generated by the first half will then occupy their proper places in the second half. If delay times are not too long the second half will appear as it would if it were part of an infinite repetition of the code. When we decode the signal we treat only the second half and we do that by using a straightforward circular correlation process.
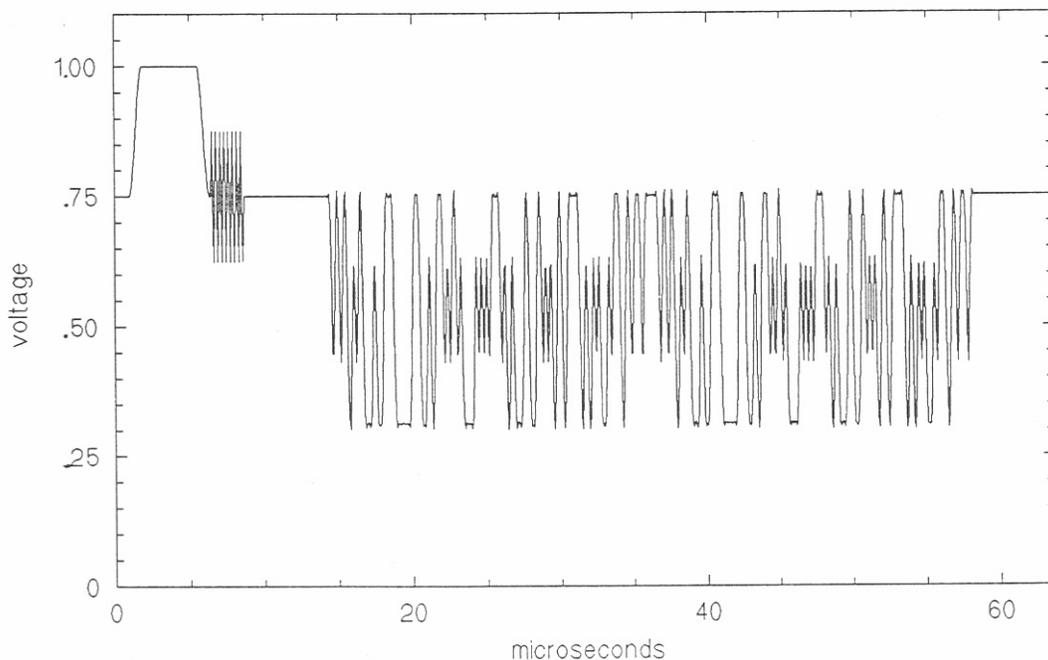

Figure 1. Appearance of the test line showing the synchronizing pulse, the color burst, and the pn-code.

When the signal is received it is demodulated and the resulting video signal is digitized. We have chosen a digitizing rate equal to 4 times the color burst frequency (*i.e.*, 14.3 MHz) and so 5/2 times the bit rate of the pn-code. This is a satisfyingly oversampled rate which is still easily attainable. The fact that there are a fractional number of samples per bit is an inconvenience, but the fact that the bit rate and the sampling rate are closely tied together and are synchronous with the color burst introduces many simplifications. The factor of 4 was chosen because it is easy to produce and because it is used elsewhere in the television industry. Our test signal generator, for example, uses that sampling rate to describe its test signals.

The receivers involved use synchronous demodulation. One reason is that the resulting video signal is then linearly related to the transmitter input, which must be the case if the measurement is to be faithful. Another reason is that we need both in-phase and quadrature components of the received signal. Although amplitude modulation would, in itself, produce no phase changes, a multipath component probably will. As the models in Section 2 would maintain, such components will arrive with an entirely random phase. If this phase is in quadrature with the direct signal, then it would be completely absent from the in-phase part of the received signal, although very definitely a contributor to the total phenomenon.

Furthermore, the vestigial sideband modulation adds other complications. A good synchronous demodulator will provide a faithful reproduction of the original signal in the in-phase channel. In the quadrature channel, however, one obtains what is essentially a smoothed version of the Hilbert transform of the original signal. Unfortunately, we cannot simply ignore this channel; if a multipath component arrives in quadrature, then the roles of the two channels are reversed: the quadrature channel contains the faithful copy and the in-phase channel the Hilbert transform.

In Figure 2 we show how this whole process functions. It pictures an actual received signal that is fairly clean. At the top are plotted the in-phase and quadrature components of the received pn-code. In the middle graph are plotted the results after the correlation process. It thus shows the superimposed in-phase and quadrature components of the measured impulse response. The bottom graph is just the resulting amplitude—the square root of the sum of the squares of the two components. It is in this bottom form that we will normally imagine our final results are represented. For comparison, Figure 3 shows the same sequence of graphs, but this time for a signal that is subject to fairly severe multipath.

In Figure 4 we have re-plotted the pulse of Figure 2. This is essentially the basic pulse generated by the system. Note that it has a base width of about 1 μs and that the corresponding resolution between pulses is perhaps 0.5 μs. The curve in Figure 5 is the power spectrum of the (complex) impulse response of Figure 4. One sees in that curve the effects of the lower sideband cutoff and of the raised cosine filter.

4.2. The Measurement System

As assembled the system uses commercially available devices connected in a fairly straightforward way. At the transmitter, a Tektronix 1910 Digital Test Generator inserts our special test signal into a selected one of the VBI lines. This test signal is the pn-code of Figure 1 and is represented in digitized form in a part of the ROM of the test signal
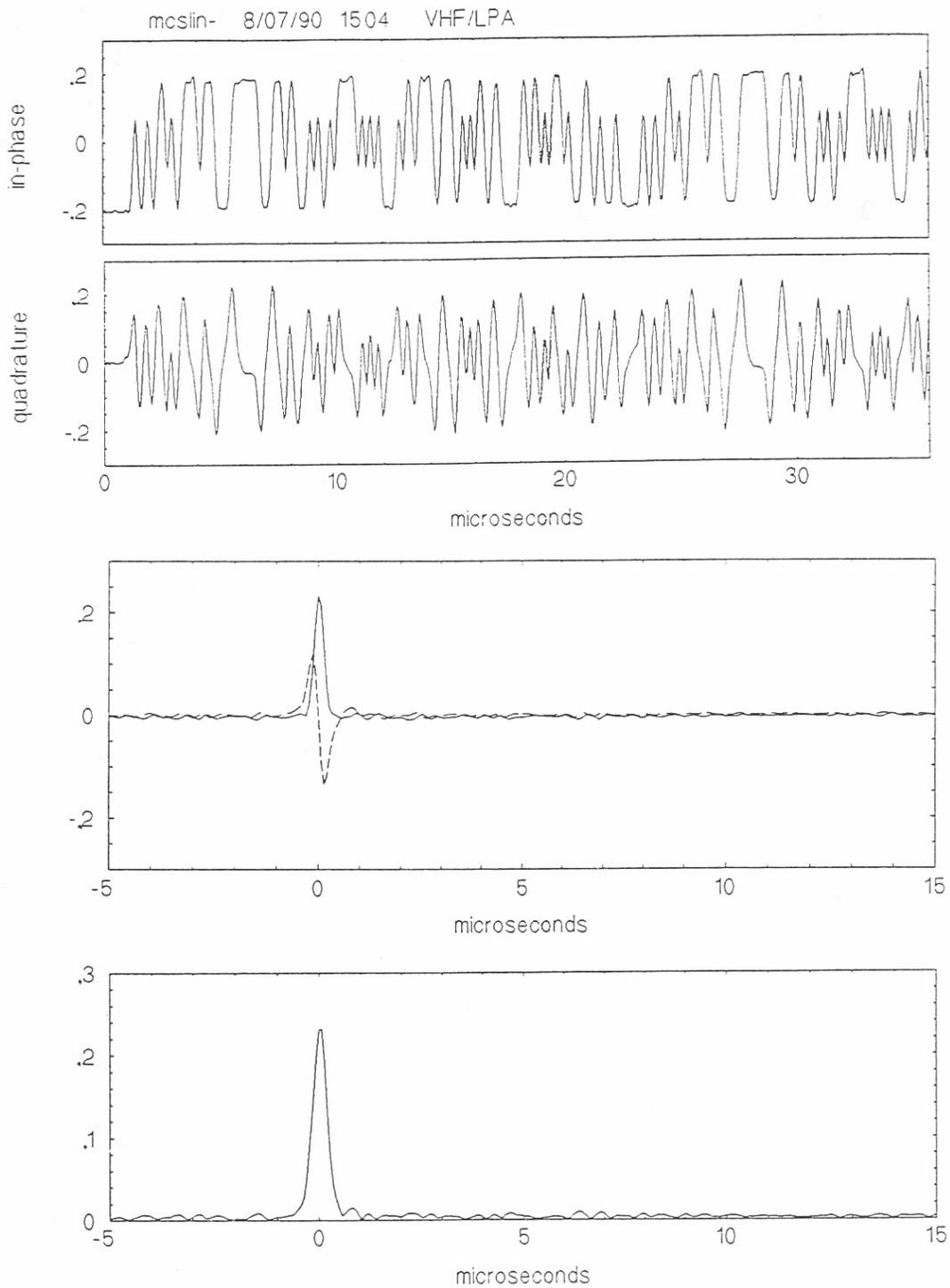
Figure 2. The measurement of a clean signal. At top is the pn-code as received; in the middle, the components of the complex impulse response after the correlation process; and at bottom, the resulting amplitude of the impulse response. In all cases the vertical axis is a consistent, but not very meaningful, voltage.
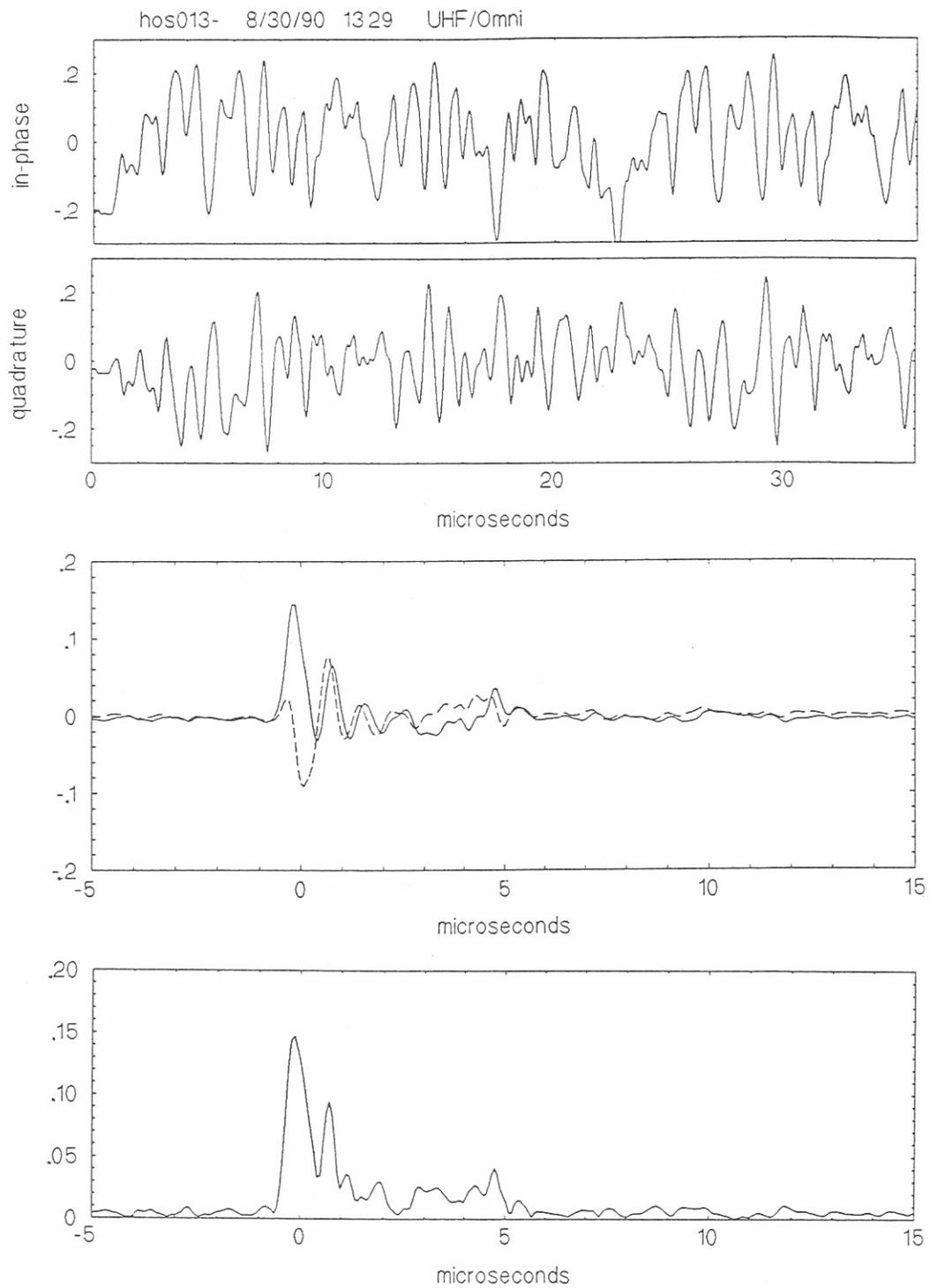
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Figure 3. The measurement of a signal subject to severe multipath. The graphs have the same meaning as those in Figure 2.
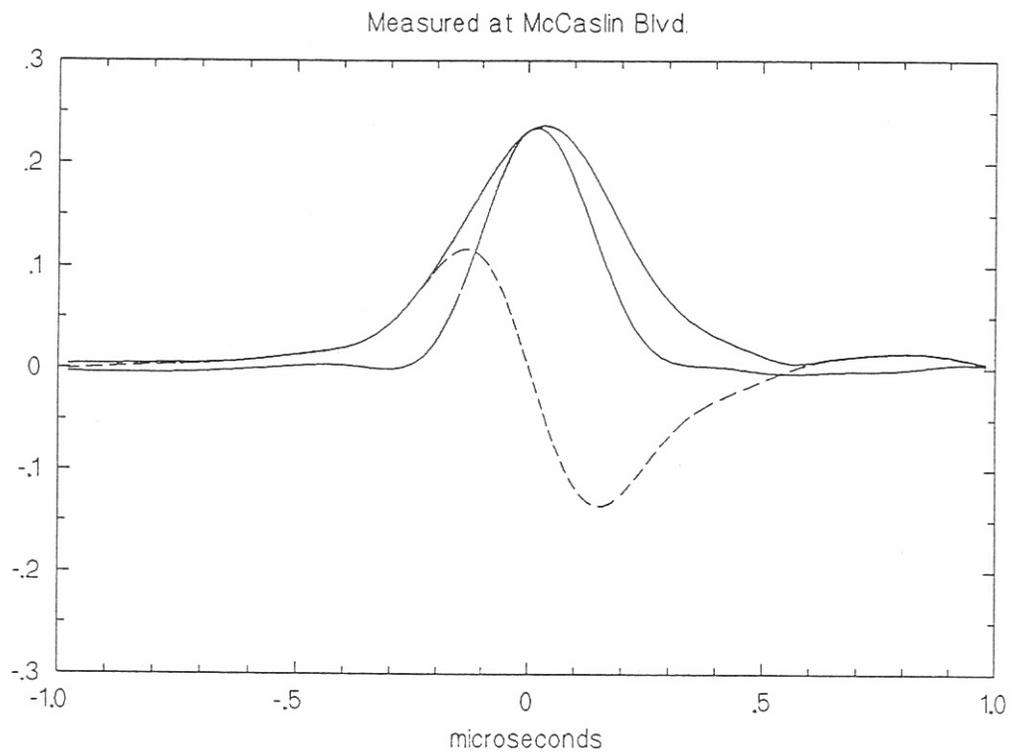
Measured at McCaslin Blvd.
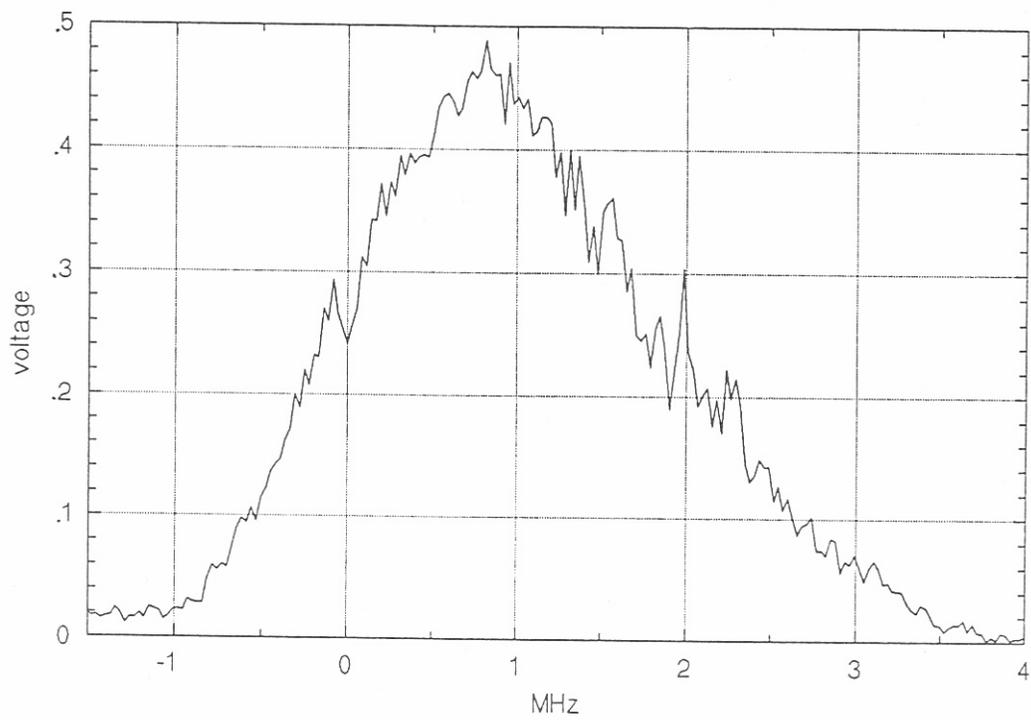

Figure 4. A closeup of the pulse in Figure 2.

Figure 5. The spectrum of the pulse in Figure 4.

generator. The rest of the transmitting system is simply the transmitter and antenna of the cooperating television station.

The receiving system includes a log-periodic directional antenna (beamwidth about 65°) and two omnidirectional antennas (for each of two channels) that feed two commercial television demodulators (Tektronix 1450) providing in-phase and quadrature outputs for the two channels. A line monitor (Tektronix 1480) provides synchronization with the VBI line containing the pn-sequence. A video processing amplifier provides an output which is phase-locked to the transmitted color burst subcarrier. This is then multiplied by four by a phase-locked oscillator to provide a clock for two analog to digital converters operated by a microcomputer. The computer then collects and stores some 32 sweeps of the proper line, all of which takes a little more than one second.

Figure 6 is a simplified block diagram of the receiving system. The equipment is installed in a standard-size van with a 9 meter pneumatic mast for the antennas. A view of the van being prepared for a measurement episode is in Figure 7. In general, the plan involved driving to a selected receiver site, erecting the antenna mast, and then recording data for the two frequencies and the two antennas. The omnidirectional antenna provides a more accurate picture of all multipath signals arriving at a site while the directional antenna might be more representative of actual television usage. Most measurements were made with the directional antenna pointing towards the transmitter.

5. DENVER DATA

Denver is a medium sized city located in the high Colorado plains. It has a tightly clumped island of tall buildings, some of them over 200 m high. On the northern edge of this island is an industrial area with fairly extensive railroad yards, stock yards, and an oil refinery. In other directions are first, a region of 3- to 5-story apartment houses, hospitals, and office buildings, and then an extensive area of residences, often shaded by mature trees. This extensive area is spotted with more or less isolated clumps of high buildings and commercial neighborhoods. The suburbs stretch north and south for approximately 50 km.

About 25 km to the west, the Front Range of the Rocky Mountains rises abruptly out of the plains with some of the highest mountains in the contiguous United States. Most of the television and FM radio transmitters serving Denver are in an antenna farm on Lookout Mountain, one of the foothills of the Front Range. This site has an admirable view of the city and the surrounding plains. Even modest towers provide stations with heights above average terrain that, in the direction of Denver, exceed 600 m.

Our measurements used two of these television stations. One, a VHF station, was KMGH-TV on channel 7, and the other, a UHF station KDVR-TV, on channel 31. Both are full power stations; channel 7 has an effective radiated power of 316 kW and channel 31 has 5 MW.

In choosing receiver sites we went into kinds of areas where we expected the multipath behavior to be statistically homogeneous. We call these areas *archetypes* of multipath environments. The idea is that if we know the statistics of multipath behavior within each archetype, and if we know the abundance of the archetypes in a given region, then we
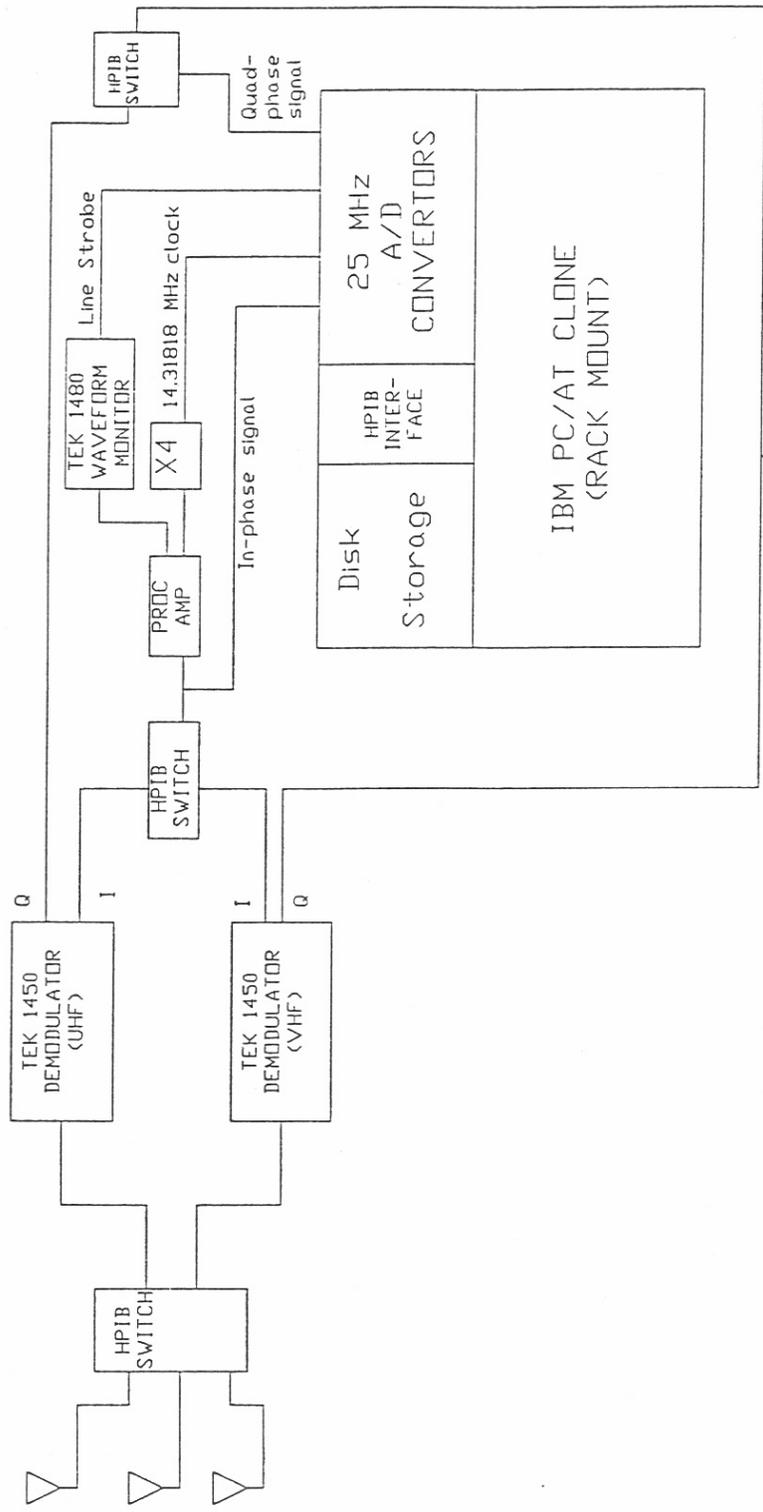
Figure 6. Block diagram of the receiving system.

Figure 7. View of the receiving van being prepared for a measurement.

will know the statistics of multipath behavior throughout the region. Figure 8 is a map showing the general Denver region and the locations of several of these archetypal areas.

5.1. Examples of Multipath Data

We have gone to approximately 160 sites in the Denver area and attempted a complete measurement sequence at each. The measurements were usually successful, although there were a few failures which seemed to be caused either by very low signal levels or by severe multipath. In such situations the system was unable to find the proper synchronizing pulse.

Two examples of these measurements have already been shown in Figures 2 and 3. The clean signal in Figure 2 was obtained at the site pictured in Figure 7, a rural site about 20 km north of the transmitters on Lookout Mountain and within clear view of them.

The site of Figure 3 was an area about 1 km east of the tall buildings in downtown Denver. In relation to the transmitters, it is "behind" downtown and about 22 km distant. It is an area of office buildings, hospitals, and residences; and it is the one area we examined where severe multipath appeared consistently.

The streets in the downtown area are at about 45° to the general east-west direction and the walls of the buildings look like large reflecting surfaces which then present this same angle to rays coming directly from the transmitters. To examine whether reflections actually take place, we chose an area about 5 km north of downtown and measured impulse responses such as that in Figure 9. Assuming a reflected ray from downtown we compute a path length difference of from 3 to 4 km (depending on what part of downtown is assumed) and a delay time of from 10 to 13 μs. This is displayed quite well in Figure 9.

Boulder is a fairly large suburban community about 30 km north of the transmitters and northwest of Denver. While much of Boulder seems to be relatively free from multipath, Figure 10 shows the strong multipath observed in the downtown commercial area. There is also a region of Boulder, up against the foothills, that is locally known to suffer from bad multipath. We attempted measurements there, but had a particularly difficult time finding the synchronizing pulse.

On one excursion we tried to find how far the system could reach. We ended at Fort Morgan, Colo., some 135 km northeast of the transmitters, and made the measurement shown in Figure 11. Note that despite the distance the impulse response is fairly clean. What looks like noise is indeed just that, as becomes apparent when the one scan shown is compared with the rest of the 32 scans.

The same trip included the measurement shown in Figure 12. This was made within the town of Hudson, Colo., about 65 km from the transmitters. The marked appearance of multipath is probably due to the large grain elevators that overlook this town.

This section's recital of measured examples serves to show that our measurement system produces reasonable results and that there are instances of strong multipath that need documenting. We might also report some other qualitative observations: Sometimes the UHF channel seemed to have more multipath on it and sometimes the VHF channel; only rarely did there seem to be any correlation between the two. And it quite often happened that multipath that seemed apparent with the antenna down in its travelling position would disappear when the antenna was raised.
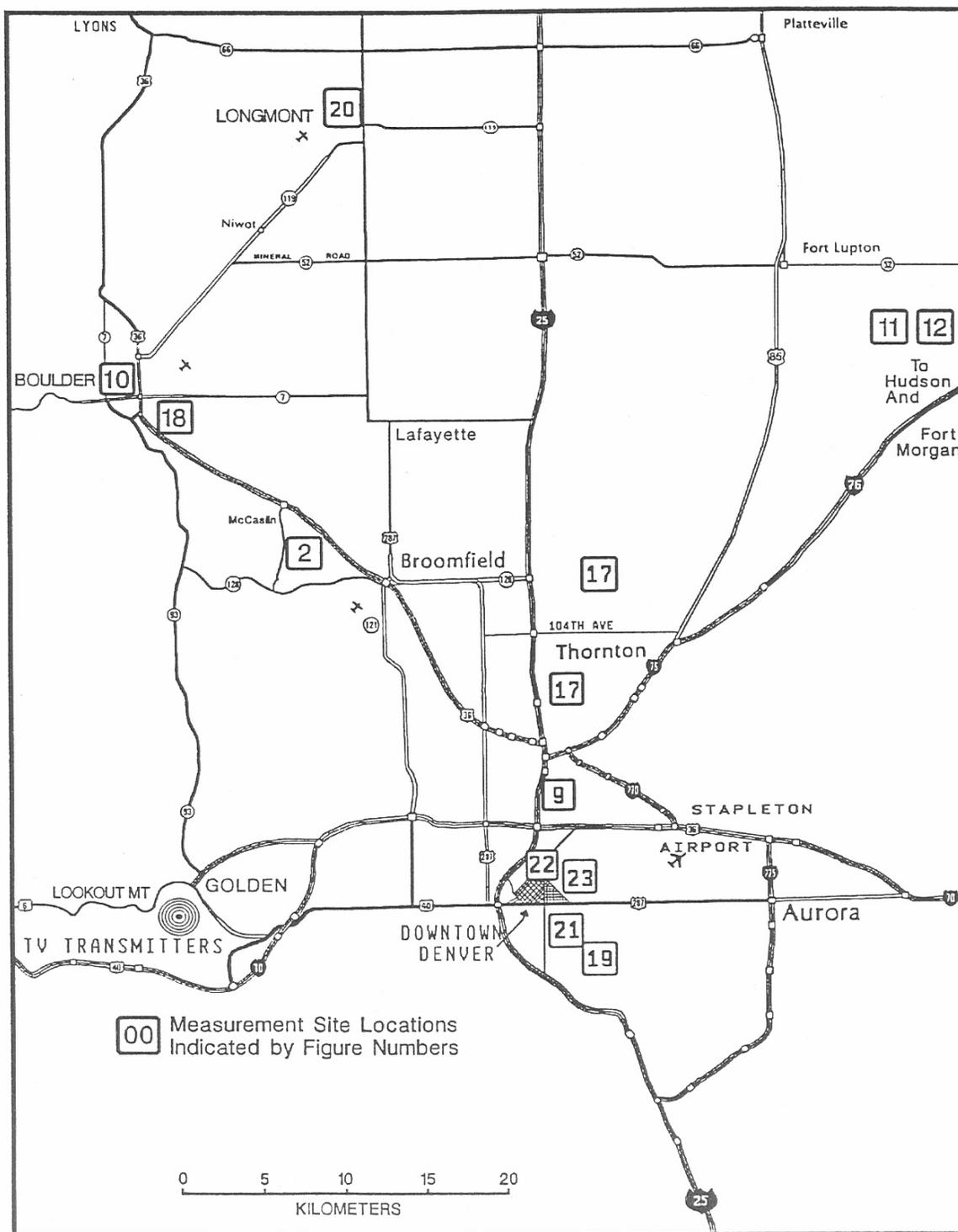
Figure 8. The general Denver region and several of the measurement areas.

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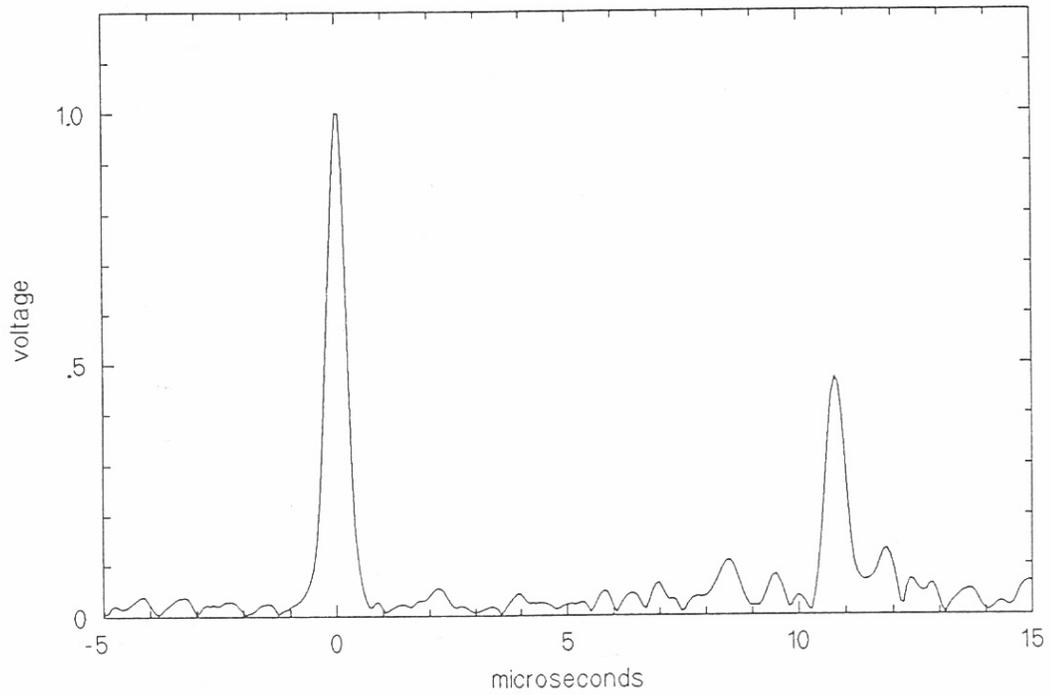Figure 9. An impulse response with a strong reflection from downtown Denver.
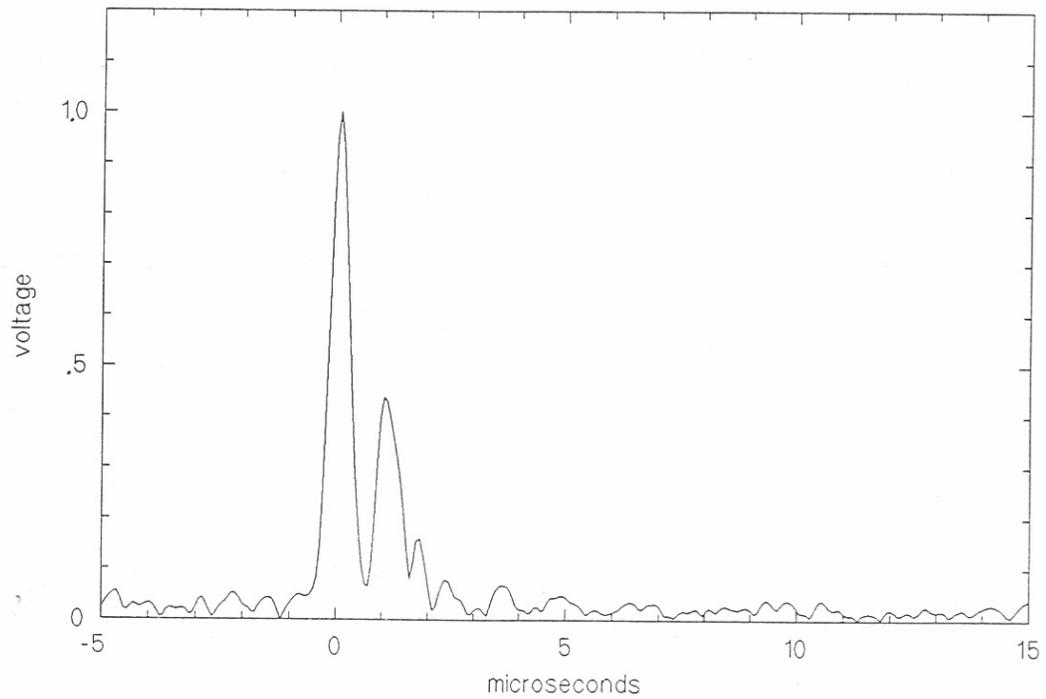
Figure 10. In downtown Boulder.

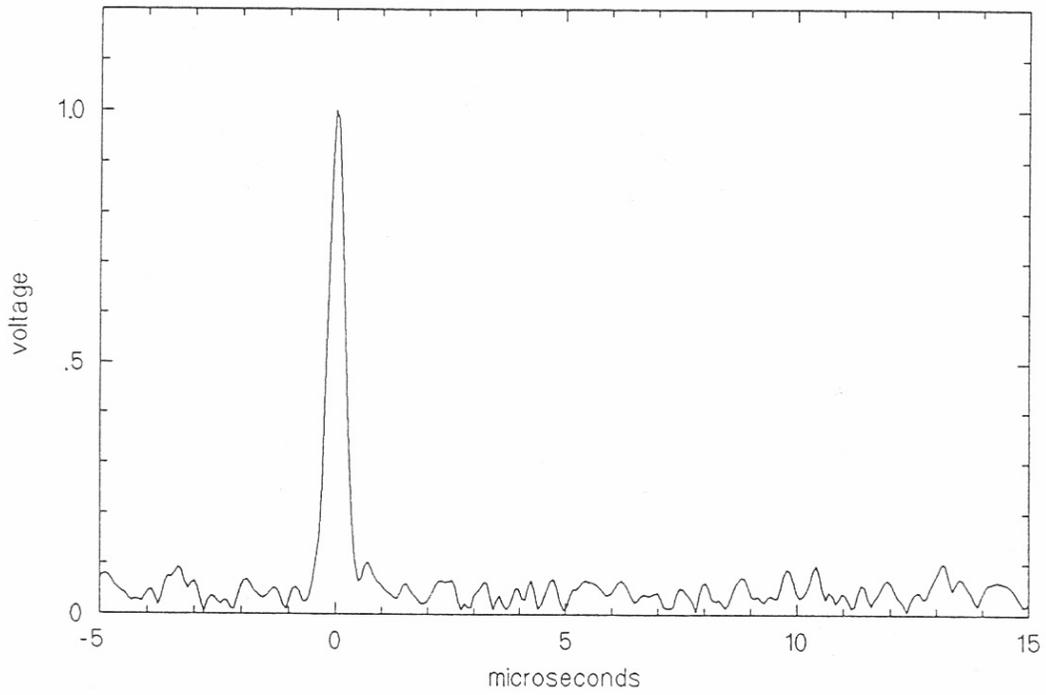trp006-   8/27/90 13:58 UHF/LPA

Figure 11. At Fort Morgan, Colo., 135 km from the transmitter.
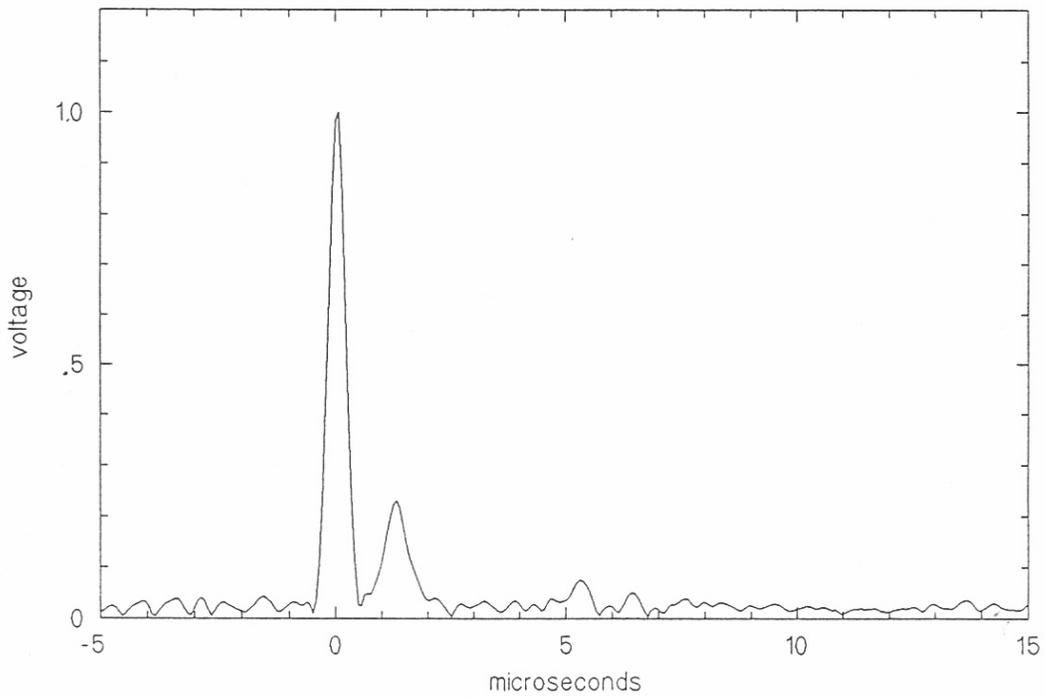
trp002-   8/27/90 11:37 UHF/Omni

Figure 12. At Hudson, Colo., near large grain elevators.

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5.2. Statistics of Multipath Data

We turn now to a study of statistics of the impulse responses of archetypal sets. One way to display the major trends and the variability within such a set is to plot all the measured data at once as a kind of scatter plot. We have done this in Figures 13 and 14. In Figure 13 we show the results using the UHF channel with nondirectional antenna in one particular area that we will call a "wooded residential" area. (It is in Longmont, Colo., an older suburban community about 50 km from the transmitters.) Figure 14 shows a similar scatter plot from the area "behind downtown Denver." This was described in the previous section as being about 1 km away from the downtown area and on the opposite side from the transmitters. Indeed, the response shown in Figure 3 is one of those included in Figure 14.

Note that we have changed the scale in these new figures from simple voltages to decibel values. We think that voltages give a better understanding of the processes involved but that decibels provide better engineering information. We have also normalized the measured impulse responses so that the peaks of the direct signals are at 0 dB and 0 µs.

Because of this normalization, the leading edges of the first pulse all fall in the same place in these figures, making that first pulse an obvious feature. But also note in Figure 13, a similar feature appears shortly after 5 µs delay time. This same structure appears in all the UHF impulse responses and we suspect it must be a spurious artifact of the system. Whether it derives from something in the transmitter or in the receiver, we do not presently know. At any rate we are confident it does not belong to the propagation path, and that while examining our data one should try to ignore it. In Figure 13, for example, one should simply agree that the impulse responses have all disappeared into the noise before 4 µs delay time.

A more readable display describing a whole set of data might be a simple plot of the first one or two moments. Following the ideas in Section 2.2, we will use powers (that is, squares of voltages) as the basic values and calculate power averages and standard deviations. Then, expressing these averages and standard deviations in decibel values we draw curves like that in Figure 15. That figure summarizes the jumble of Figure 13; the solid curve is the average, and the dashed curve the standard deviation.

In Section 2 we hinted that the impulse response amplitudes might very well be Rayleigh distributed. If that were so, a consequence would be that the standard deviation of power is equal to the average, so that two curves in Figure 15 would coincide. Since the important part of the average curve here begins at the trailing edge of the direct pulse and continues until it disappears into the noise, it is encouraging to find the curves in this region are so similar.

In Figure 16 we have drawn an expanded version of the same power average curve, and have superimposed on it the undistorted system pulse. Presumably, if we could subtract out this curve (which represents the normalized direct signal) the remainder would be exactly the function $p(t)$ of Section 2.2.

Completing this study of the Denver data, the next several figures (Figures 17 through 23) comprise a catalog of the averages and standard deviations obtained for the principle archetypal sets. We present them here with only brief comments.
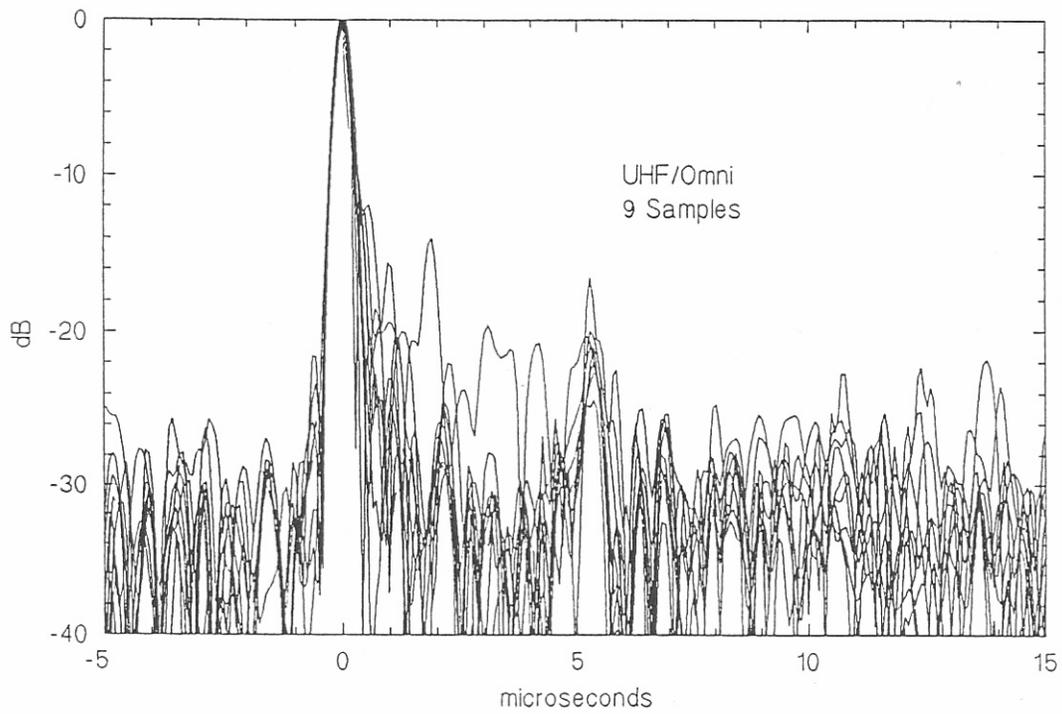
Figure 13. A scatter plot of impulse responses in a suburban wooded residential area.
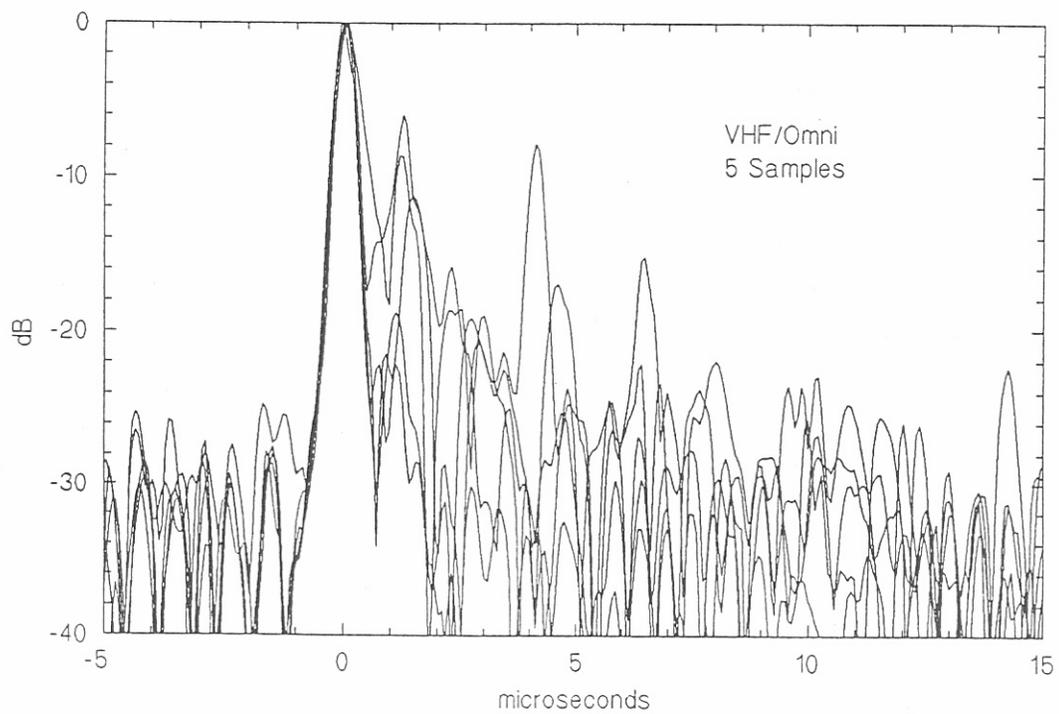

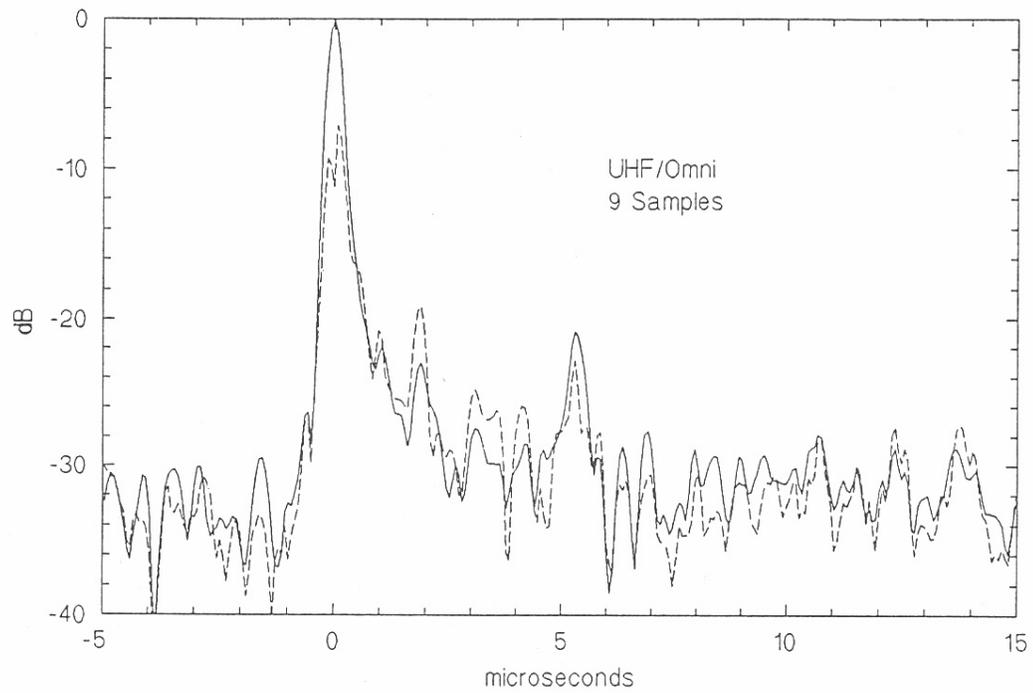Figure 14. A scatter plot from an area behind downtown Denver.

Figure 15. Power averages and standard deviations for the curves in Figure 13. The solid curve is the average, and the dashed curve the standard deviation.
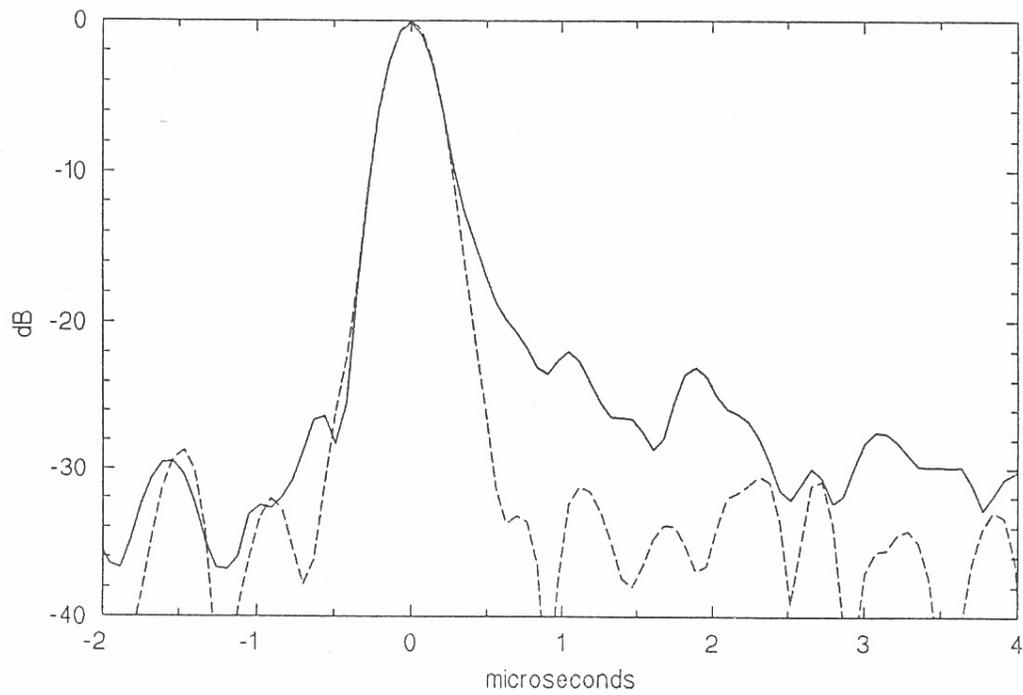

Figure 16. A closeup of the average in Figure 15, together with a copy of the undistorted system pulse.
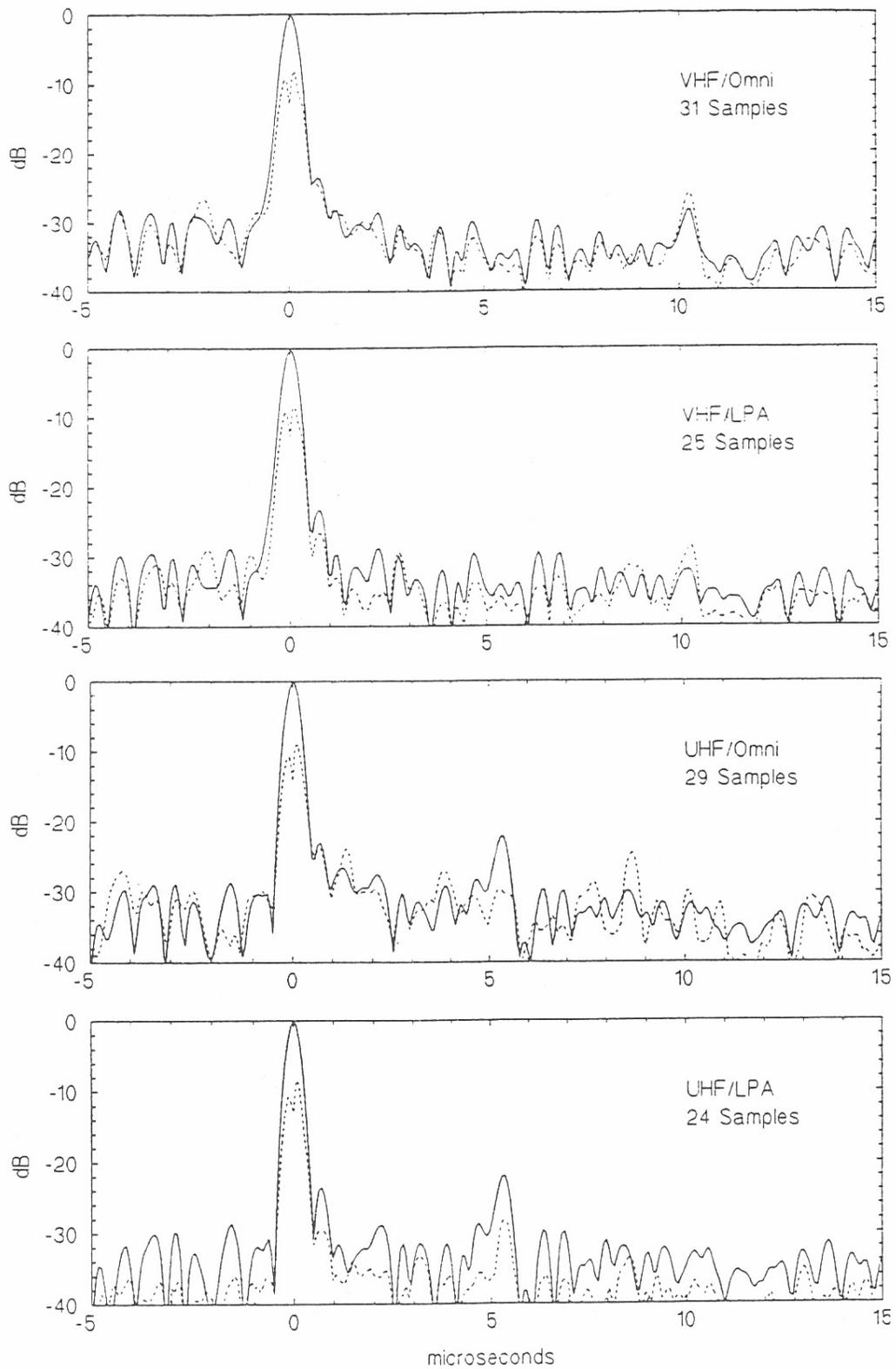
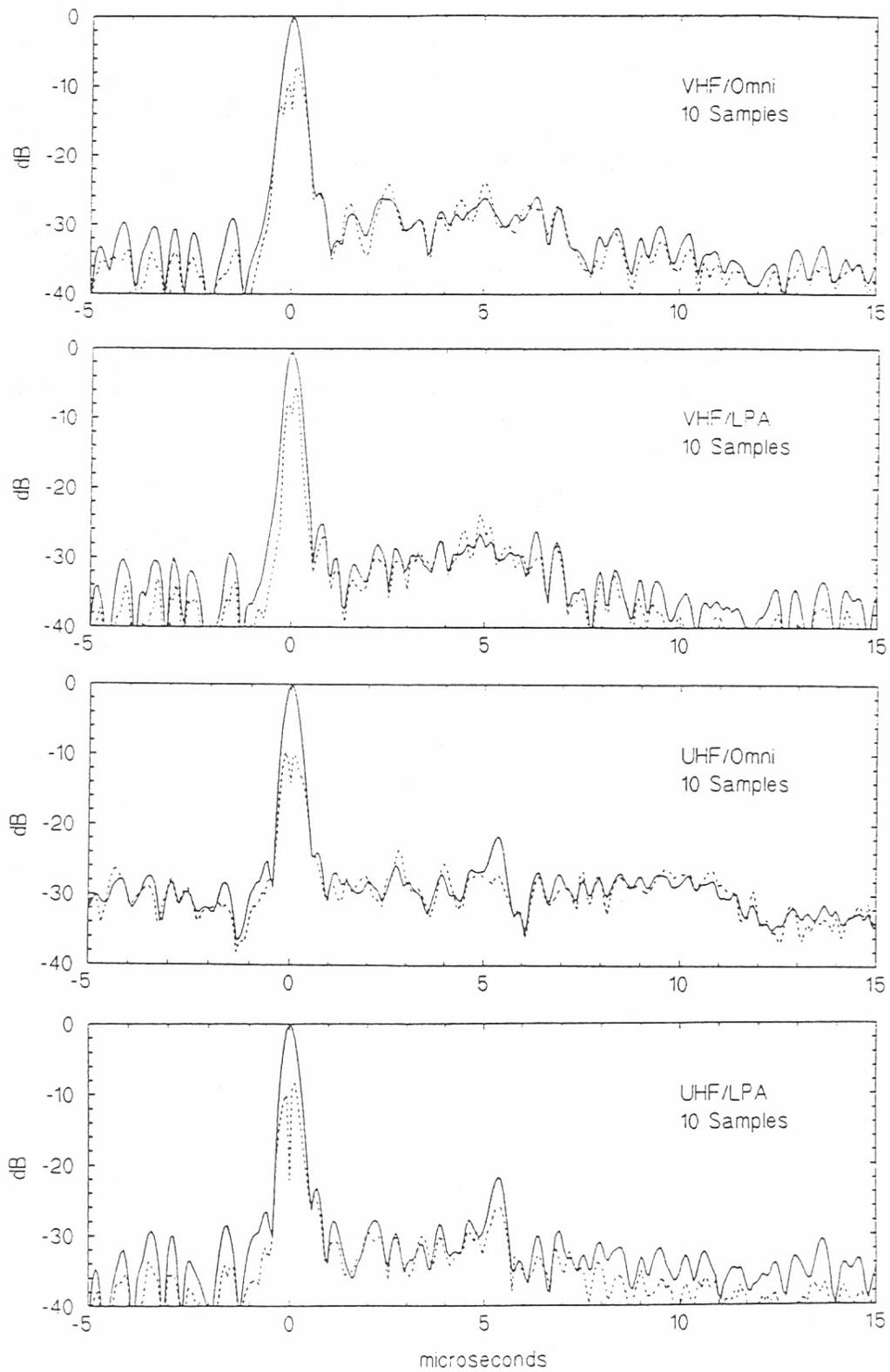Figure 17. An open residential area in Thornton, Colo.

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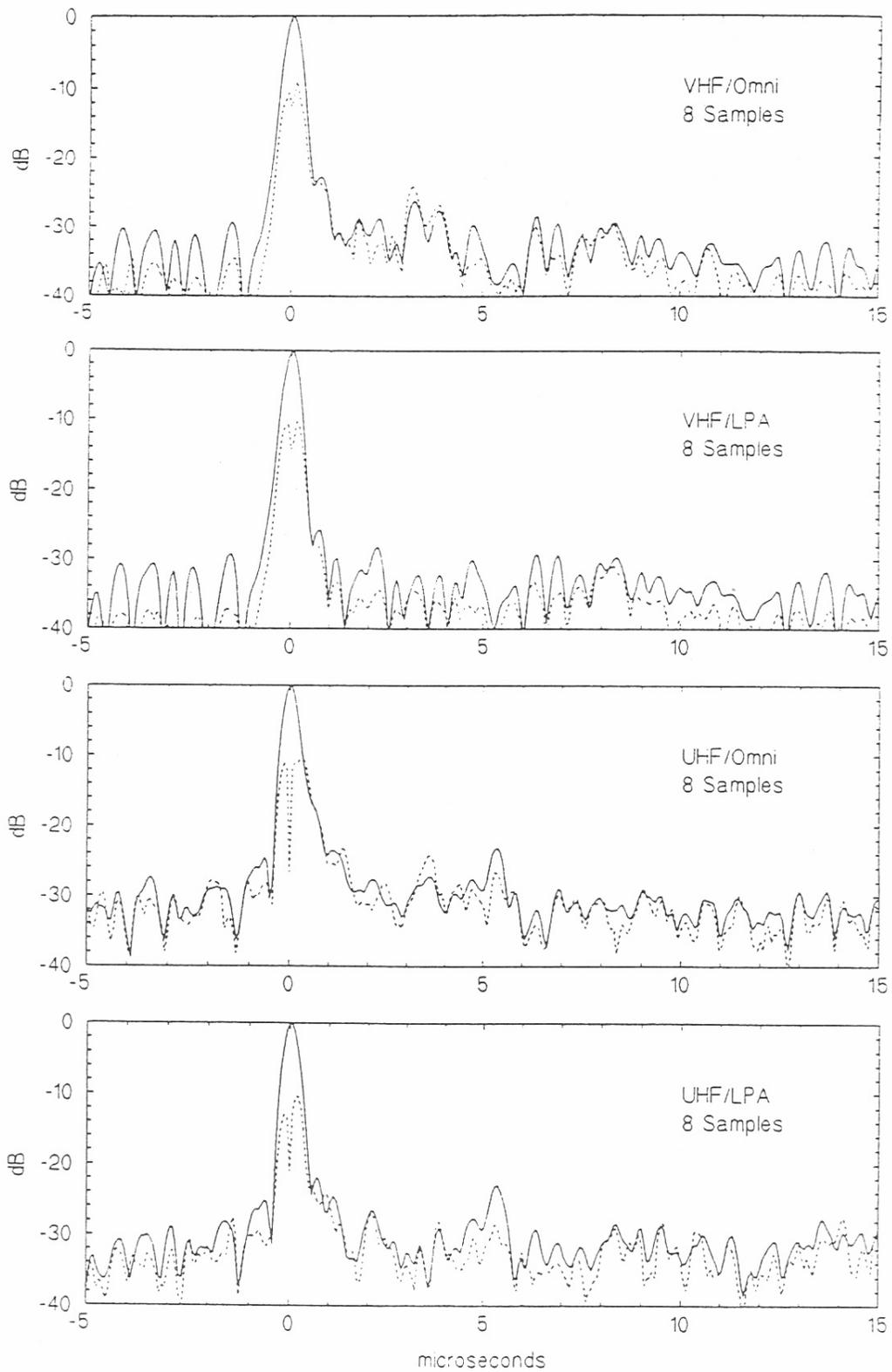Figure.18. An open residential area in Boulder, Colo.

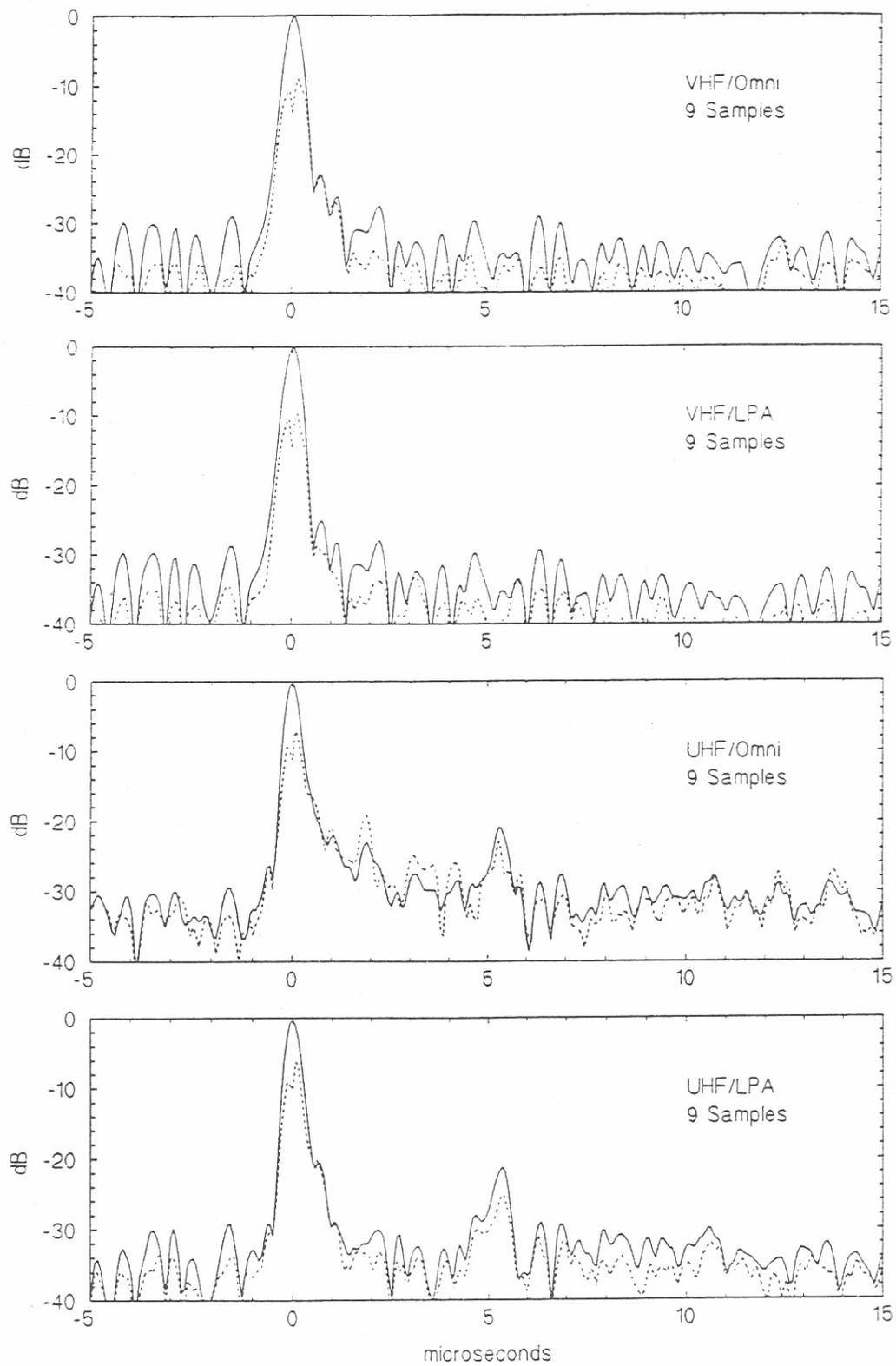Figure 19. A wooded residential area in Denver.

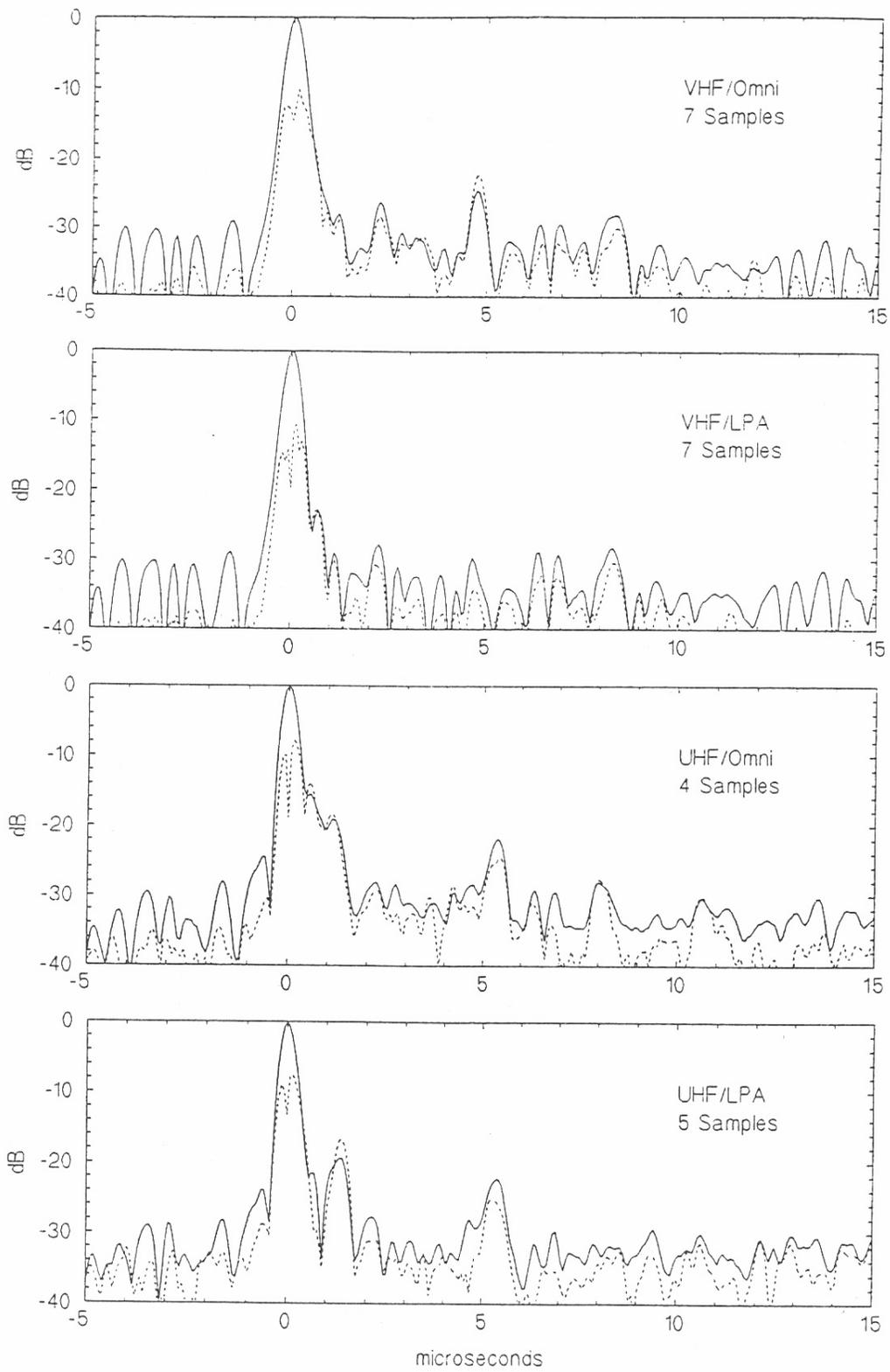Figure 20. A wooded residential area in Longmont, Colo.
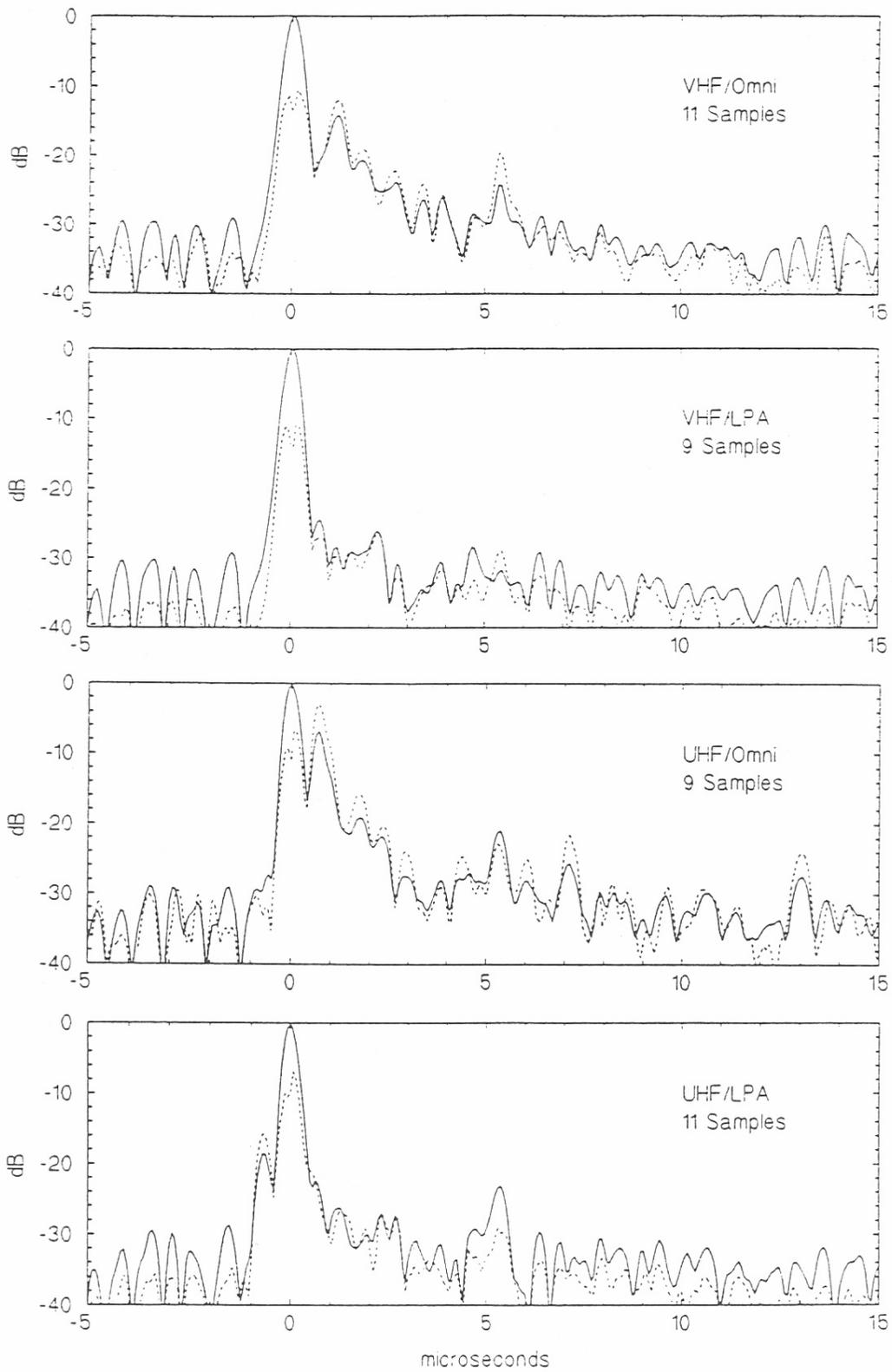
Figure 21. An urban area with low buildings.

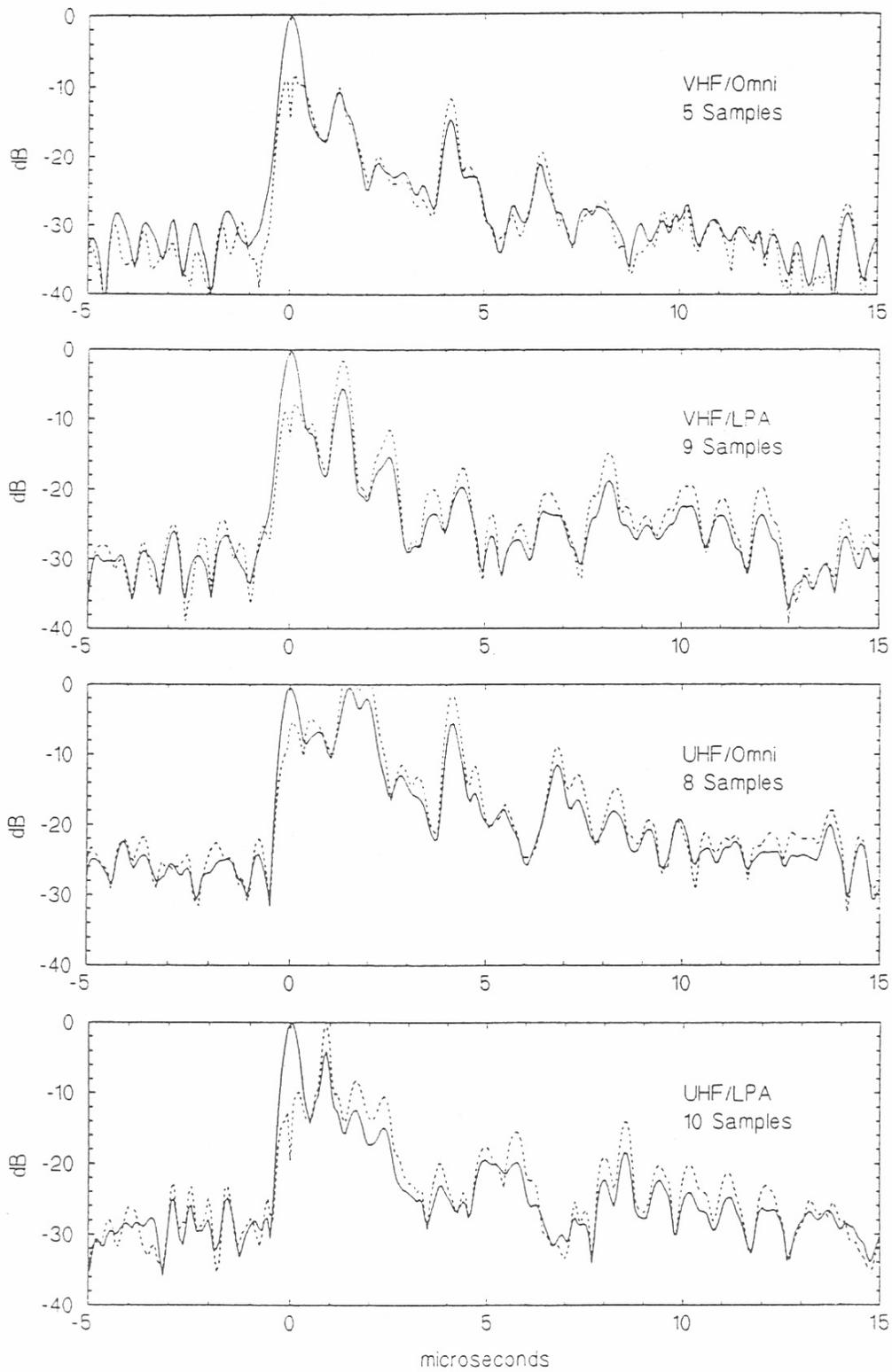25

Figure 22. An area to the side of downtown Denver.

Figure 23. An area behind downtown Denver.

Figures 17 and 18: Two "open residential" areas. Figure 17 is from Thornton and Figure 18 from Boulder. Both areas are fairly new developments with planted trees that have not yet grown to their full heights. Thornton overlooks Denver and has a clear line-of-sight view of the downtown area about 12 km away. The Boulder area surrounds an isolated clump of three 12-story buildings.

Figures 19 and 20: Two "wooded residential" areas. Figure 19 is from the middle of Denver (about 3 km from downtown) and Figure 20 from Longmont (about 50 km from the transmitters).

Figure 21: An "urban with low buildings" area. This figure is from an area with 3- to 5-story apartment houses. It is southeast and only about 1 km away from the downtown Denver area. Despite being so close, we think it is well shielded and probably unaffected by the tall buildings.

Figure 22: A "to the side of downtown" area. This is from an open area about 3 km northeast of the downtown Denver area. Figure 23: A "behind downtown" area. This is the area discussed before in Figures 3 and 14.

One can determine the approximate area affected by severe multipath by estimating the percentage of each archetype that is present. The high-rise center and adjacent areas will be those with the worst multipath, especially the area on the opposite side (with respect to the transmitter location) of the high-rise center. Any groups of large buildings or isolated ones will also produce multipath in the immediate vicinity, but a detailed survey of the city would be necessary to locate all of these. We estimate that 15 to 20% of Denver is affected by severe multipath.

In Figure 24 we present plots of the data for all seven archetypes combined. It is an average of incompatible data and so is probably not very meaningful. One reason we attempted this combination was the hope that the many peaks from individual measurements would average out to some smoother curve. This did not happen, and note that the pattern of peaks here strongly corresponds to the pattern in the severe multipath area behind downtown Denver shown in Figure 23. What has happened is that the set of combined signals is completely dominated by these particularly strong ones. Note, too, that the standard deviation is unusually high indicating again that the data are not consistent. At most, these graphs might serve as a measure of the performance of our system.
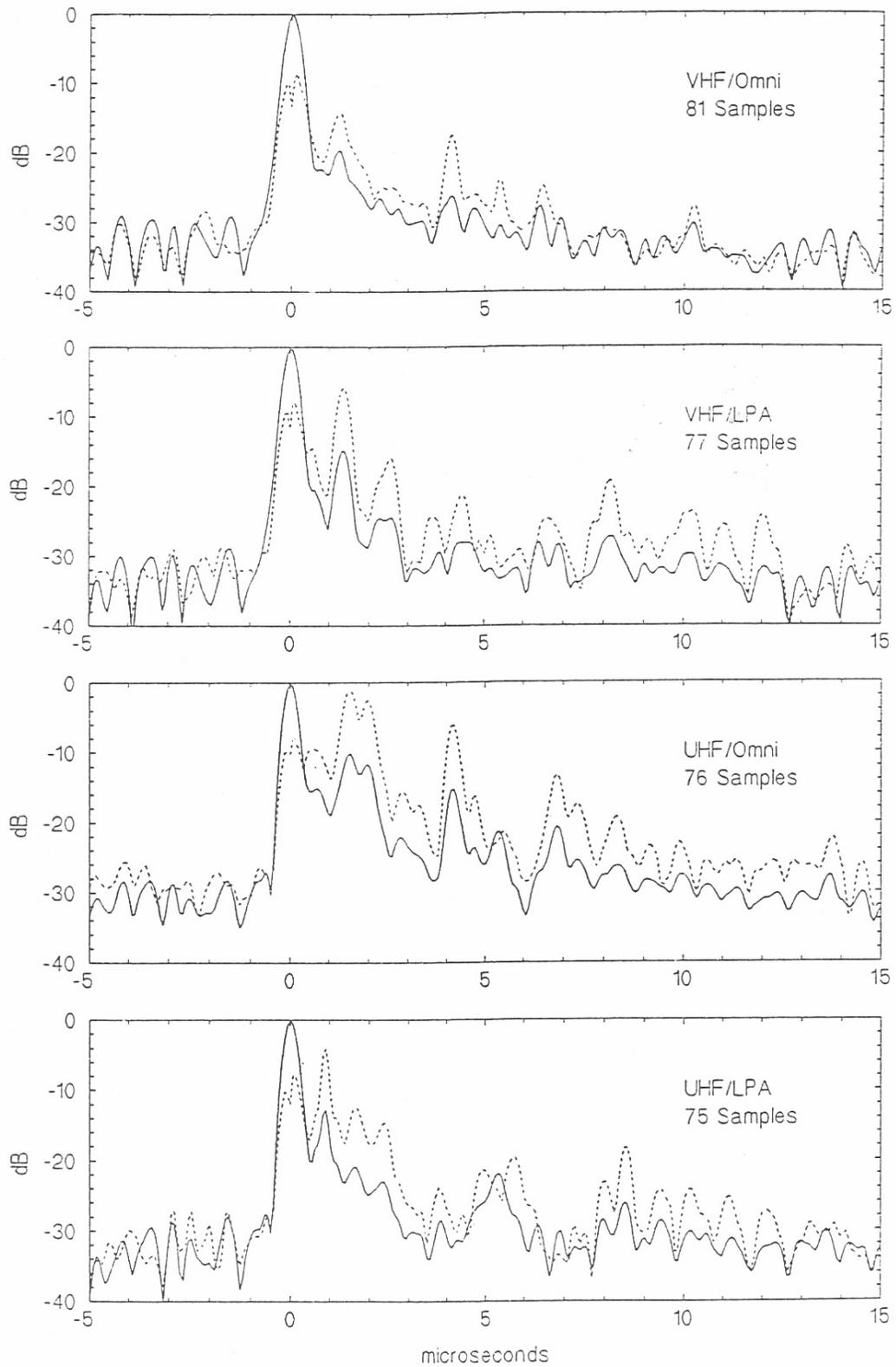
Figure 24. All archetypes combined.

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6. CONCLUSIONS

In the last several figures (Figures 17 through 23) we have summarized almost all our data. (We have left out only those measurements made for specialized experiments.) From them, one can deduce a useable model. The curves provide the function $p(t)$ as defined in Section 2 for the indicated archetypal areas. One then arrays a set of multipath components at increasing delay times with strengths given by this function. When deciding how thickly these components should be arrayed, it is probably fairly reasonable to treat the channel as a GWSSUS channel, and so place the components continuously. For practical purposes on a 6 MHz channel, one would suppose that about 5 components each microsecond would be sufficient. Perhaps their positions should be dithered somewhat or, if it seems advisable, perhaps Turin's notion of a Poisson process should be adopted.

In just about every measurement we made, it seemed possible to detect signs of multipath. Sometimes these signs were very weak and almost inseparable from the noise— and so perhaps they are not of much importance. In this regard, we might point out that there have been studies of how multipath echoes affect NTSC pictures. Figure 25 shows results from one of them (Lessman, 1972). This study involved a panel of observers, an average of results for three different scenes, and a scoring scheme that went from "not perceptible" to "extremely objectionable" in 7 steps. In the figure the solid curve gives echo strengths that 80% of the observers found not yet objectionable, while for the dashed curve, 80% found the echoes at most just perceptible. We see from these results that echoes 20 or 30 dB down may still be of concern.
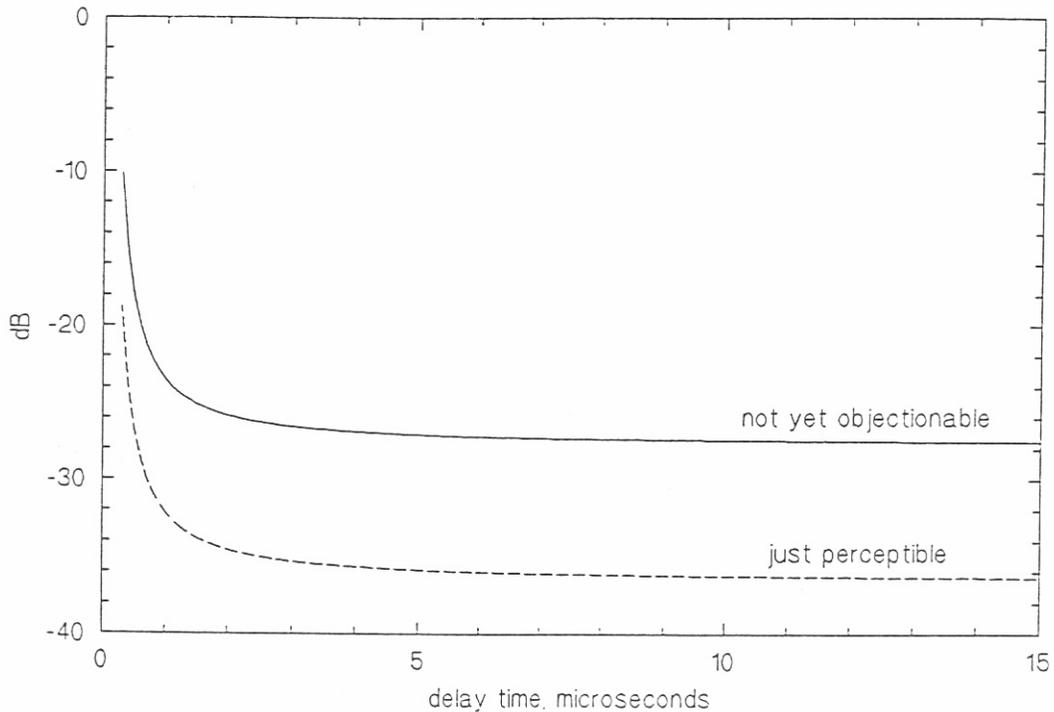

Figure 25.   Some results from a panel study of observable multipath echoes; echo strength versus delay time.

The sites where we found strong multipath seemed always associated with buildings or other manmade structures. In general, there was more multipath at UHF than at VHF, more with omnidirectional antennas than otherwise, and more with low antennas than with high. But these rules describe only trends; at individual sites they were often violated.

These remarks only confirm what has been the common wisdom; indeed, the single surprise here is that the multipath tail can go on for what seems like a long time. Note also that our measurements have included areas at widely different distances. And yet when one compares, say, Figures 19 and 20, there does not seem to be any trend. If the multipath characteristics have a distance dependence, it is rather subtle.

Our system for measuring impulse responses has several shortcomings. It has a small bandwidth and hence a low resolution; its maximum delay time is perhaps a little short; and there may be some degree of distortion as in the extra pulse observed in the UHF channels. Most distressing, when multipath is severe we often cannot obtain synchronization. For most of these problems, however, we expect to find solutions. In general, the system performs quite well and can be used to collect the data for which it was designed—the characterization of the 6 MHz HDTV channel. We have already made many measurements in the Denver area, and the raw data are available and easily accessible for further studies.

7. ACKNOWLEDGEMENTS

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Development and testing of various implementations of High Definition Television (HDTV) require knowledge of the multipath characteristics of the radio channel over which the proposed signal will be carried. The Institute for Telecommunication Sciences (ITS) has begun a program to measure these characteristics in locations that might represent consumer habits. This report discusses the general background of the measurement techniques and describes measurements made in the vicinity of Denver, Colorado.

16. Key Words *(Alphabetical order, separated by semicolons)*

Channel characterization; delay spread; high definition television; impulse responses; multipath; pseudonoise codes; radio propagation

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