ENVELOPE DELAY, PHASE DELAY, GROUP DELAY, CHROMA DELAY.... WHAT DOES IT MEAN, HOW IS IT MEASURED?

Fred J. Schulz, V.P. CATV Engineering
STERLING COMMUNICATIONS, INC.
43 West 61st Street
New York City, N.Y., 10023

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1. Introduction

The CATV industry is still growing, and in its path to maturity it is becoming more sophisticated technically. While in the early days of CATV it was sufficient to get a picture to the subscribers' TV set one is now confronted with meeting federal specifications. A number of new terms have crept into the CATV engineers vocabulary, some of which may be familiar, some of which may however have been misunderstood. The following presentation focuses on giving simple (and in some instances simplified) explanations of terms such as "envelope delay", "chroma delay", etc. An attempt will be made to explain the effects on picture quality. Appropriate test equipment, test methods and cost are explained. The explanations will be held in simple form so hopefully the average CATV engineer can follow; mathematics will be avoided.

The first part is devoted to the introduction of some necessary fundamental know how,and may be looked upon as a refresher for those already familiar with it.

2. Types of distortion

The function of a CATV system is to bring high quality undistorted pictures to a subscriber's TV set. The CATV engineer is usually familiar with distortions such as: noise, cross-modulation, second order distortion, echoes, amplitude distortion, etc. Cross-modulation and second order distortion are so called non-linear distortions. Amplitude distortion does usually not depend on signal levels; it is called a linear distortion.

Amplifiers and filters may also exhibit phase distortion, another linear distortion. Phase distortion is of prime concern in single channel and studio equipment, and will be explained here, since the CATV engineer seems to be least familiar with it.

3. Phase shift and phase delay

Phase shift is most readily explained with an experiment; let's feed a CW signal into a low pass filter and observe the input and output wave forms on a dual channel oscilloscope:

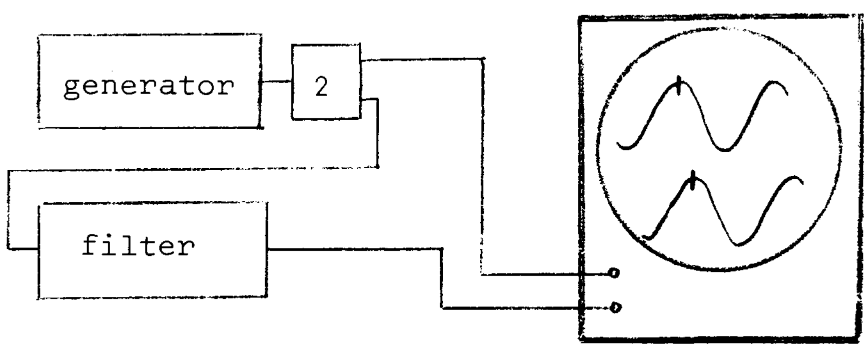

Fig.1

We find that the output waveform is not in phase with the input (the crests of the waves are shifted with respect to each other). We say there is phase shift. In this case the output lags the input wave. Phase shift is measured in degrees. One full cycle of a wave is 360°.

Phase shift occurs in any network containing capacitors and/or coils.

Another way of interpreting this effect is to say that the output is delayed compared to the input signal. Physically this makes sense, since it obviously *does* take a finite time for the signal to pass through the filter. If we express the phase shift as delay time we speak of *phase delay*. Phase delay = $\frac{\text{phase shift in degrees}}{360 \times \text{frequency}}$

TV waveforms are not as simple as the foregoing sinewave signal, but the basic principle still hold. We should be aware that the phase shift of a wave through a filter is usually not constant as the input frequency is moved through the range of the filter and particularly as the frequencies pass through the cut-off region. If we plot the phase shift versus frequency we may get a curve as follows:

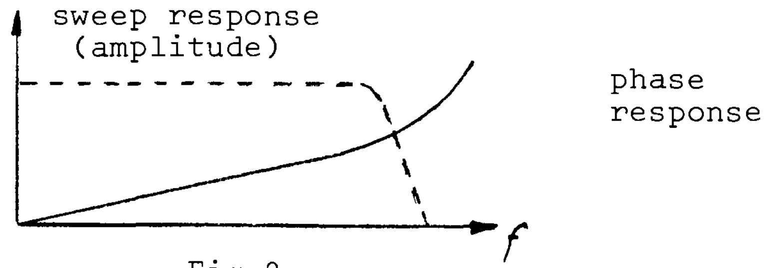

Fig.2

To be more specific we should label the sweep response amplitude response; after all the familiar sweep generator setup measures the amplitude versus frequency characteristic. The phase characteristic is seldom measured, but we believe this will become more common place in the future, particularly for single channel devices.

4. The make-up of TV waveforms

A square wave is a familiar waveform to all of us, if fed into a modulator a series of black and white bars will appear on the screen.

The square wave can be understood better if it is broken down into its components. This is called "Fourier Analysis", but let the word not frighten you, the basic principles can be well understood without the rather advanced mathematics usually associated with it.

Let us feed a square wave through a bandpass filter, one which will just pass the signal equivalent to the fundamental frequency. The resulting output is a sinewave.

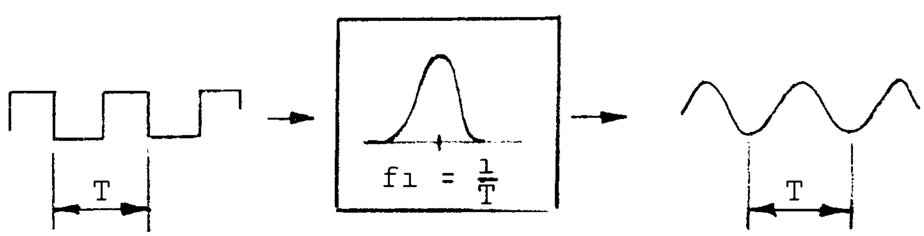

Fig.3

We also get a sinewave output if we feed the square wave through a filter with a bandpass for three times the fundamental frequency.

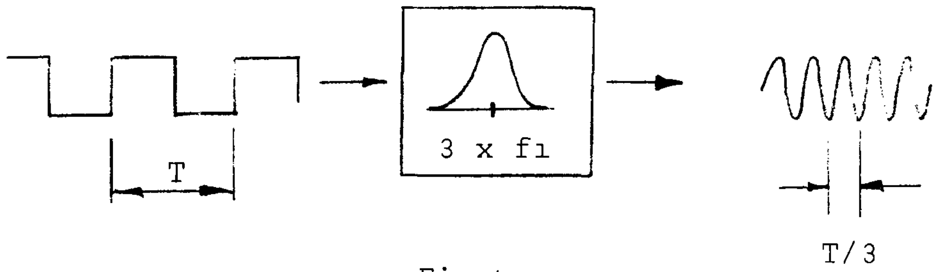

Fig.4

The same will happen if we use a filter for 5 times the fundamental, also for 7 times, 9 times, etc.

We can say that the square wave is made up of a fundamental and all odd harmonics. If the square wave has truly "sharp" corners and vertical sides we will get harmonics at <u>all</u> odd multiples of the fundamental up to infinity. The fundamental is the highest amplitude component, higher harmonics are of decreasingly lower amplitude.

We just "disassembled" a square wave into its sinewave components. Conversely we can reassemble the wave from its sinewave components. Graphically this looks like this:

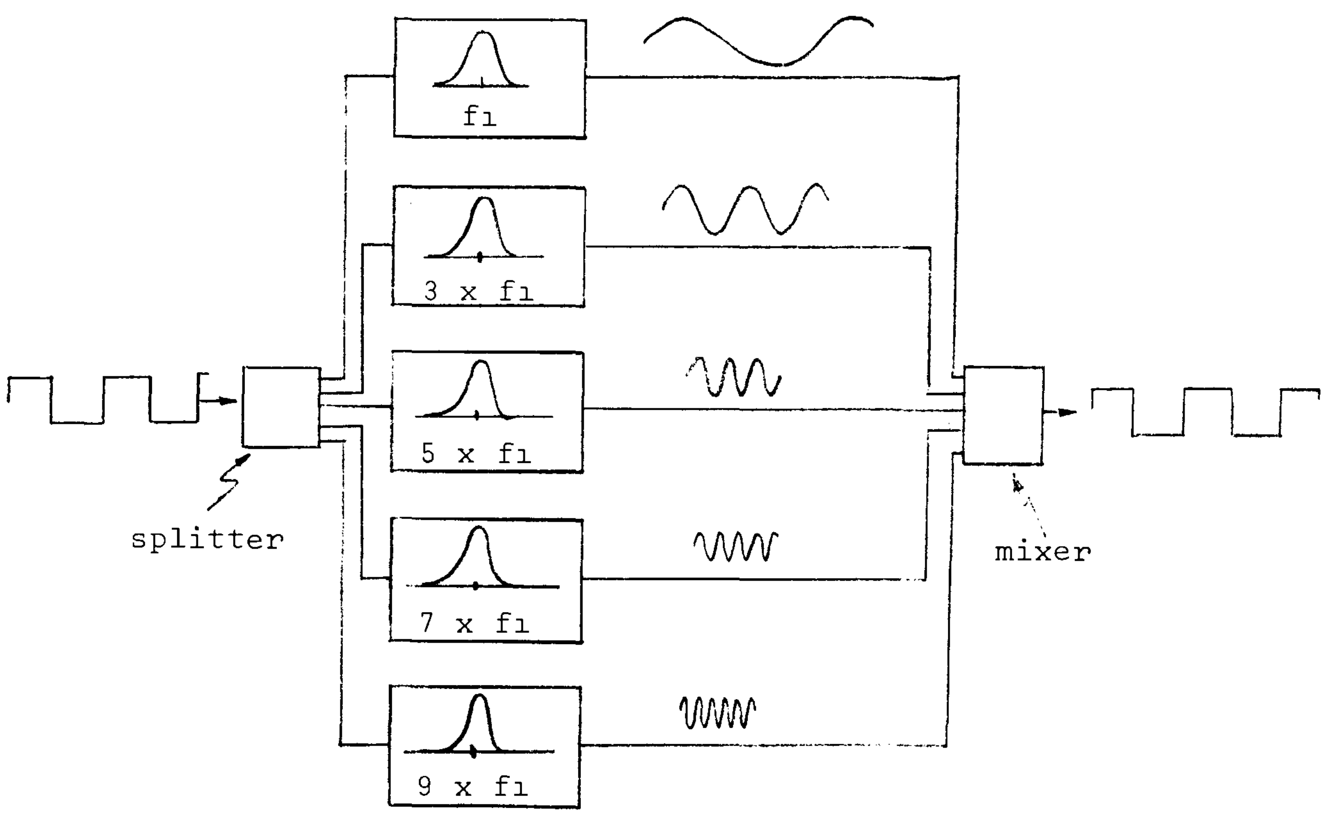

Fig.5

The following picture shows the fundamental and the first three harmonics of a square wave:

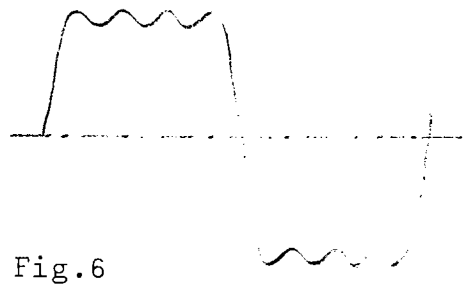

Fig.6

The result is not a very good square wave since one should also add the 9th, 11th and all other odd harmonics to make a true square wave. It should also be noted that a square wave does not contain any even, such as 2nd harmonics. The principle, however, holds.

Any waveform can be made up of harmonically related sinewaves. Another rule worth remembering is:

> " A waveform with very abrupt amplitude changes contains significant components up to many times its fundamental frequency."

5. Waveforms through filters

Let us look at the previous example again, but let us feed the signal through a low pass filter which passes only the fundamental, the 3rd and 5th harmonics, but cuts off the 7th harmonic:

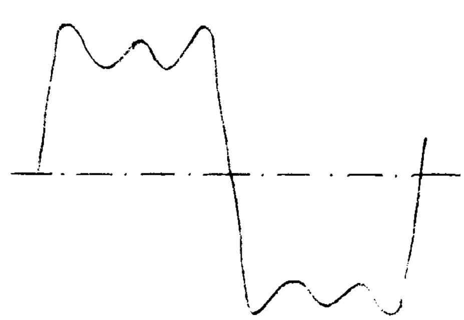

Fig.7

We see that to faithfully reproduce the input waveform one must pass all significant frequencies.

As the next experiment let us pass the signal through a filter which attenuates the 5th harmonic, such as a trap would:

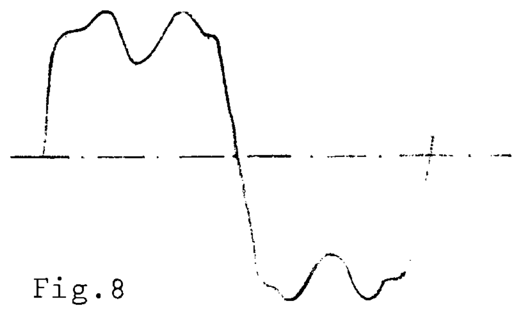

Fig.8

So far we concerned ourselves with changes in amplitude of the various frequency components only.

We indicated earlier that signals passing through a filter also get a change in phase or a delay,and further that not all frequencies may suffer the same delay. Let us pass the sample wave through a filter which shifts the 5th harmonic by 15° and the 7th by 30° with respect to the fundamental:

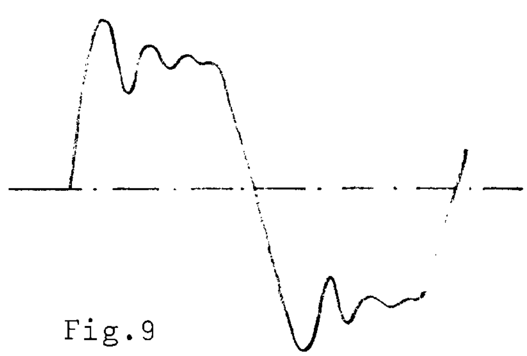

Fig.9

The output is non-symmetrical with a very pronounced ringing. As a further example let us shift the 3rd harmonic by 30°, the 5th by 60° and the 7th by 90°:

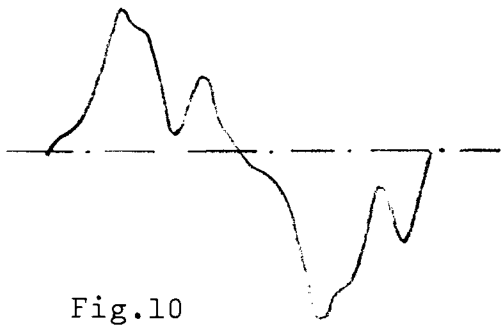

Fig.10

From these examples it is obvious that we must retain the relative positions of the signal components or distortions will result. The delay of the various frequency components, also called a group of frequencies, must be equal for distortion free transmission. If this is not the case we speak of group delay distortion or simply group delay. The group of frequencies, if applied to a modulator, will result in a carrier and associated sideband envelopes. The envelope which contains the modulation must be passed distortion free or we speak of envelope delay distortion. The terms envelope delay and group delay are generally used interchangeably.

For the sake of completeness let us also state the accepted definition of envelope delay:

> "Envelope delay is the rate of change of the phase versus frequency curve."

Mathematically expressed:

$$\text{Envelope delay} = \frac{d\phi}{d\omega}$$

Delays are usually so small that they are expressed in microseconds (millionth of a second) or nano seconds (billionth of a second).

The effects of envelope delay result generally in ringing (preshoot, overshoot) producing closely spaced ghosts particularly visible on vertical black/white transitions. Another effect, color misregistration will be treated later.

6. Instruments to measure envelope delay

Envelope delay measuring equipment is built to measure the change in phase a sample signal suffers when passed through a device under test. A block diagram of such an instrument follows:

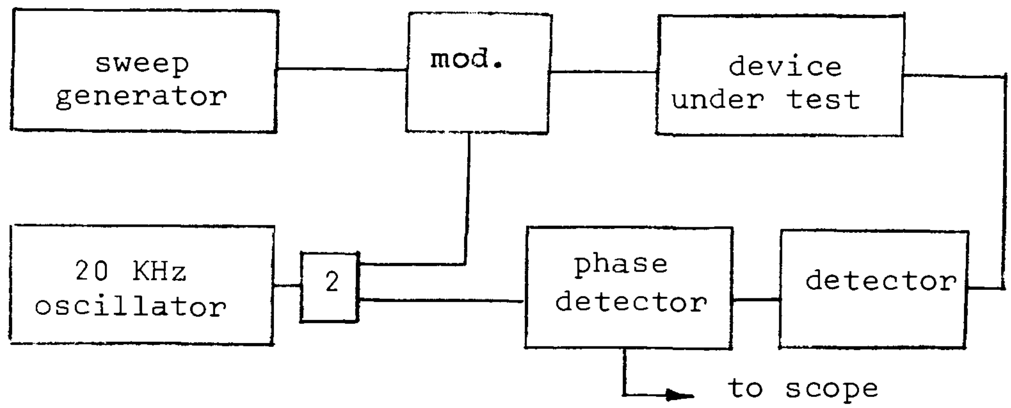

Fig.11

The following is a list of instruments now on the market with approximate prices (the list may not be complete):

1. Rhode & Schwartz - Model LFM 0.1 - 10 MHz	\$6,300.- plus sweep gen. & oscilloscope
2. Wandel & Golterman - Model LO-1 0.1 - 14 MHz	\$17,250.- complete setup
3. Datatek - Model D-700 0.05 - 50 MHz	\$3,200.- plus sweep gen. & oscilloscope
4. RCA - Model BW-8A	\$3,100.-
5. Hewlett-Packard - Model 3700 45-95MHz microwave analyzer (IF)	\$7,500.- complete setup
6. Hewlett-Packard - Model 8405 Vector Voltmeter	\$2,850.-

It should be noted that most listed equipment covers video frequencies only and additional modulators and demodulators must be used to cover RF frequencies.

It is not the purpose of this paper to give detailed information and exact cost of test equipment packages, but here are some comments on the various products.

The Rhode and Schwartz equipment package is by many regarded as the "Cadillac" of delay measuring gear. The full package to perform measurements from video frequencies to 250 MHz costs in excess of $10,000.-. Such a setup is primarily intended for lab use.

The Wandel & Golterman equipment is restricted in its frequency range to video, but can measure envelope delay where transmitter and receiver are separated such as in microwave systems.

The Datatek unit is a relatively new unit on the market and is aimed at the broadcaster since it covers the video and the new IF modulator frequencies. It contains a sync and blanking generator to make measurements in video amplifiers with DC restoration. It is also equipped to measure delay at various average picture levels and features 50 and 75 ohm impedance levels. This unit may find use in some CATV systems.

The HP microwave analyzer is aimed at testing microwave links and accomodates basically a 70 MHz IF frequency range.

The RCA unit is primarily intended for use with TV transmitters, it is one of the older designs.

The Vector Voltmeter needs additional external equipment to make it suitable for swept envelope delay measurements.

The listed equipment is intended to measure delay continuously with appropriate sweep generators. The results are displayed on an oscilloscope similar to the familiar amplitude sweep response. Most instruments allow for the simultaneous display of both amplitude and delay as shown below for a bandpass filter.

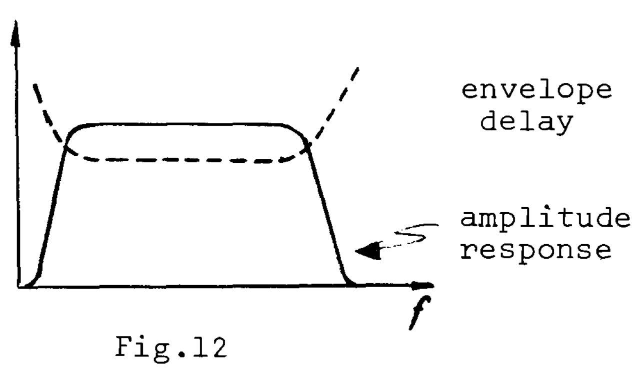

Fig.12

Delay measurements also require very good impedance matching all around; because mismatch causes reflections with resulting ghosts, and ghosts are a delay phenomena also.

To measure delay at RF frequencies one needs a modulator and a demodulator, which by themselves already exhibit some delay. The best modulator demodulator combinations available today have a residual delay of ± 20 nsec. over a 4 MHz video band pass.

7. Chroma delay

A standard color TV picture consists of a high definition black and white picture with a low definition color picture added to it. The color information is carried at the upper end of the video spectrum around a 3.58 MHz color subcarrier. The frequency distribution looks like this:

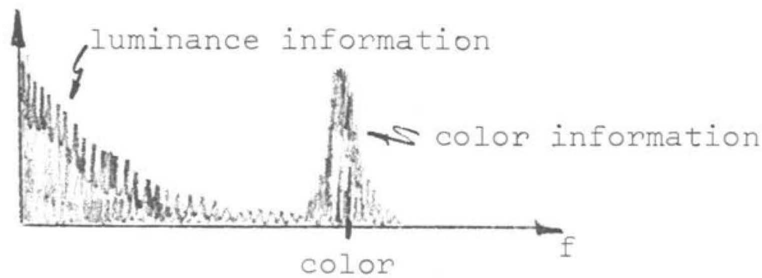

Fig.13

It is important that the color information arrives at the picture tube at the same time as the black and white picture or the color will be out of registration. This error can be called chroma delay. In reality it is simply the envelope delay between the low frequency black and white picture components and the delay of the color information around 3.58 MHz, as shown below:

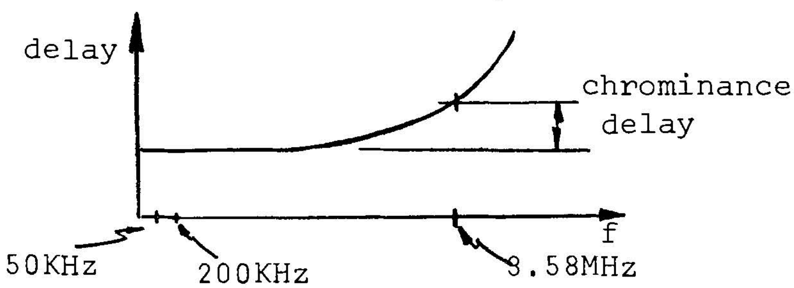

Fig.14

Chroma delay is one of the most visible effects of envelope delay and methods to measure it rapidly have been developed.

The 20T pulse has gained wide acceptance for measuring chroma delay; it is a low frequency pulse modulated with 3.58 MHz color subcarrier signal. Its shape and frequency components are pictured below:

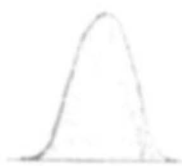

Fig.15

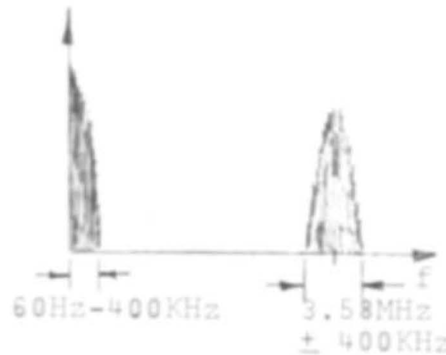

Fig.16

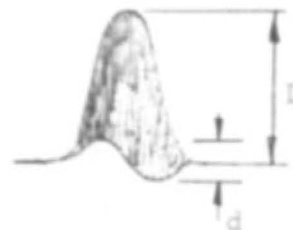

Fig.17

The base line of this pulse gets distorted when the signal is passed through a device with chroma delay. It is possible to determine the delay by measuring pulse height (as referenced to the bar signal level) and the base line excursion using graphs or formulas.

Several manufacturers offer instruments that allow the introduction of delay of opposite polarity and of 3.58 MHz gain/loss to straighten the base line; the introduced delay is then a direct measure of the chroma delay. Instruments to generate 20T pulses cost around $1,500.- usually coupled with generation of other test pulses. The cost of the special receiver described above is approximately $1,500.-. The 20T pulse was originated in Europe and is in wide use there; U.S. networks are not using it yet for transmission over the air.

Tektronix is now featuring a 12-1/2T pulse which yields a wider frequency spectrum around the color subcarrier to be more representative of the actual color information bandwidth and to yield easier computation of the chroma delay from the measured base line excursion.

Tektronix has introduced a way to measure chroma delay using the color bar test pattern. This method makes use of the fact that the chroma signal transition between the green and the magenta bars is easily identifiable because the phase changes 180°, and the luminance changes level as well. The delay can then be measured on a waveform oscilloscope. Luminance/chrominance cross talk effects are also eliminated if Tektronix generator, model 146, is used, since the chrominance and luminance signals are available separately. A scope presentation looks like this:

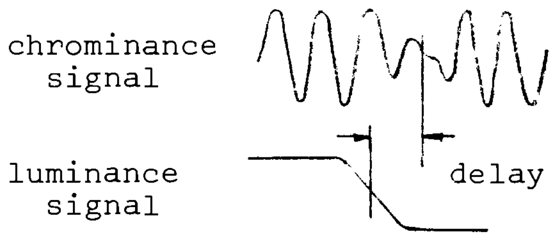

Fig.18

The 20T (or 12-1/2T) pulse measures the "average" delay between the low luminance frequencies and the color subcarrier region. Some people have reported good agreement between 20T pulse measurements and continuous measurements with swept envelope delay equipment, others have found discrepancies. Discrepancies may possibly happen when the delay curve is very non-symmetrical about the color subcarrier. Another effect of non-symmetrical delay is color quadrature cross-talk, which results in color boundary effects.

Color misregistration is also called funny paper effect. Opinions on how much chroma delay is tolerable vary widely in industry. A figure of 200 nano seconds results in a shift of the color by approximately 1/16" on a 23" TV set. At least one CATV manufacturer considers this tolerable. A major test equipment manufacturer feels that 250 nano seconds yields an untolerable mis-registration. A member of the Philips research laboratories considers 50 nsec. chroma delay just perceptible under studio conditions. The subject matter is of great importance. Shift of red letters on white background are more readily visible than e.g. blue letters on white. A recent study made by Bell Laboratories, showing color slides on a video monitor to a group of trained observers found that 100 nsec. of flat delay or 180 nsec. of shaped delay was just perceptible. For no objectionable impairment the figures were 260 nsec. for flat delay and 480 nsec. for shaped delay. Shaped delay means delay gradually rising (or falling) from the low frequencies towards the color subcarrier region. Flat delay means constant delay over the subcarrier region; color processors, which separate luminance and chrominance signals may exhibit flat delay.

About the only thing everybody agrees to is that it is highly desirable to keep the delay as small as possible, since delays are additive.

8. Effect of delay

We already treated the special case of chroma delay. Delay effects at other frequencies result mainly in waveform distortions. We saw earlier that a waveform can be distorted by deleting higher frequency harmonics or by delays. A pulse which is representative of an actual picture waveform as produced by the scanning beam in a TV camera, and which does not contain frequency components above 4 MHz is the so called 2T sine squared pulse. This pulse is transmitted by many TV stations as a vertical interval test signal. The pulse is 250 nsec wide at half amplitude. When envelope delay is present, the pulse gets distorted as follows:

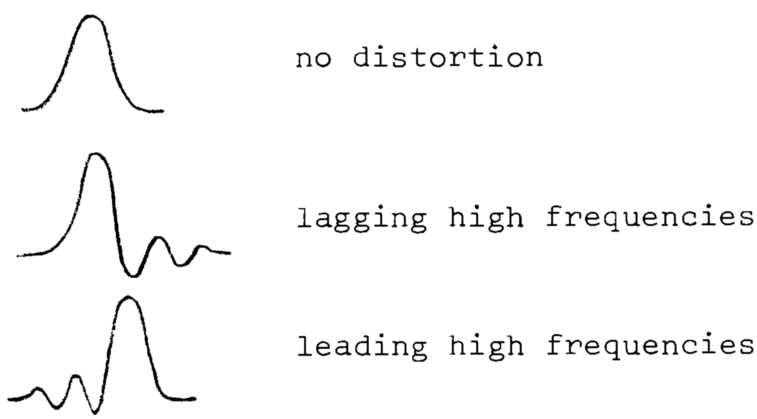

Fig.19

A multitude of distortion patterns are possible. To judge the acceptability of a distorted pulse, a frame or window has been devised, the so-called K-factor graticule.

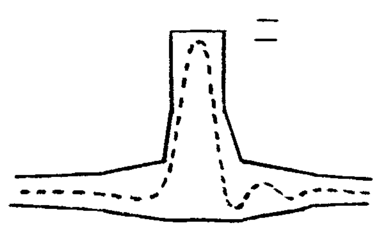

Fig.20

If a pulse is within the outlines of a 2% graticule it is considered very good, 4-6% is acceptable. There is no total industry agreement on the K-factor and a tie-in with actual numbers of envelope delay has not been possible. The K-factor has been treated extensively in the literature.

9. Delay effects in 2-way filters

Two-way filters are in essence a combination of a low pass and a high pass filter with a sweep (amplitude) response as follows (both LP and HP sections shown together).

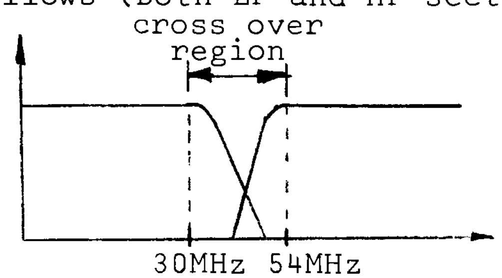

Fig.21

We stated earlier that sharp amplitude response changes are likely to bring delay changes with it. It is easily seen that the narrower the cross over region is made,the sharper the cut-off rate must be. A narrow cross-over region is desired to make the sub-channel return band as wide as possible.

A compromise between usable bandwidth and tolerable envelope delay at the edge channels must be made. There is some specmanship taking place, but most manufacturers feel that 30 MHz is the highest usable sub-channel frequency. Delay effects are cummulative, 50 amplifiers with filters at the input and output result in 100 filter delays all added. If we consider 200 nsec of chroma delay tolerable, each filter cannot contribute more than 2 nsec. The designers of two-way gear are well aware of this problem. To get more reliable measurements one tests a number of filters in cascade, commercially available delay test gear cannot resolve nano second delays very accurately. A fair number of systems have used sub-channels to feed signals back to the head-end by using either Blonder-Tongue model MSVM, Jerrold FCO-47 or similar filters. These filters have a very narrow cross-over region and should not be cascaded in large numbers. A B-T model MSVM was measured at 8 nsec chroma delay at channel 2.

Most of the cross-over filters are of a design with a smooth envelope delay curve so it seems that the chroma delay is a good indication of delay performance. This is not the case with sharp band pass filters however, where the delay may vary in a ripple like fashion.

10. Measured delay curves of some CATV equipment

Fig.22 shows amplitude and envelope delay of a sharp band-pass filter with a trap for the adjacent upper picture carrier. Fig.23 shows a band-pass filter without an adjacent channel trap. It should be noted that the amplitude response over the channel looks reasonably identical for both filters, the delay curves however, do not. The delay distortion below the picture carrier has not received as much attention as the delay at the upper band edge. There seems to be a new awareness of this fact and future equipment designs will take this into account. Delay errors below the picture carrier can produce leading pre-shoot and a following slow approach to final value at sharp video transitions, resulting in a smearing effect on vertical edges.

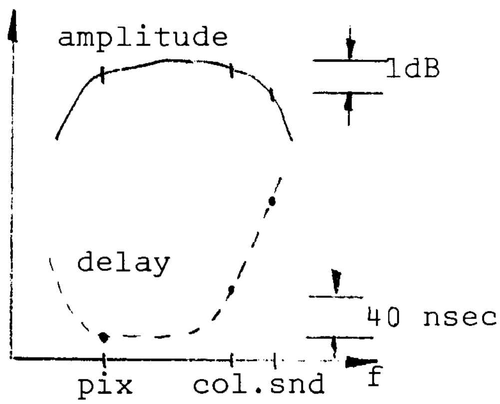

Fig.22

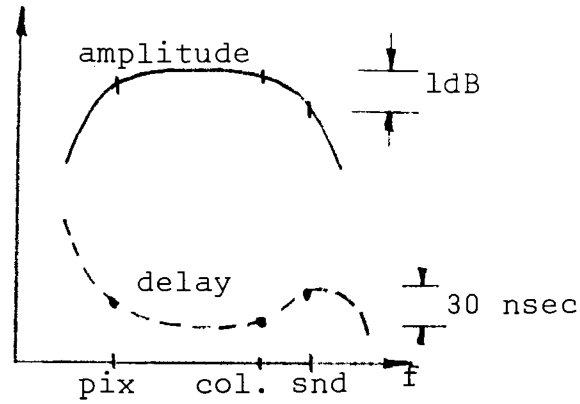

Fig.23

Fig.24 shows the amplitude and delay response of a strip amplifier with less selectivity than the previous band-pass filters. Envelope delay is very small. Fig.25 shows the delay of a narrow band trap tuned for maximum signal rejection (60dB down). Tests on this trap showed a great variation in envelope delay with very small changes in tuning. The same is true for sharp band-pass filters. Test equipment found in the average CATV shop is not good enough to align sharp filters reliably.

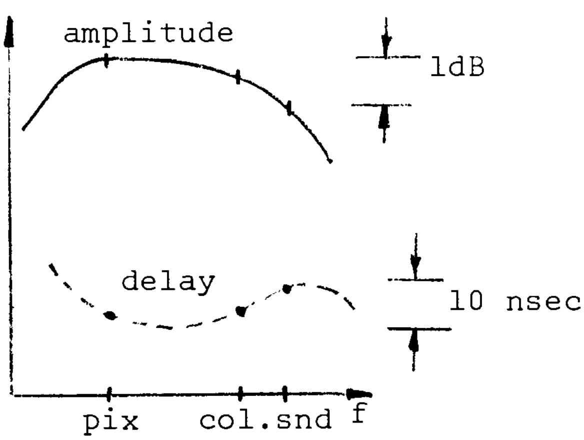

Fig.24

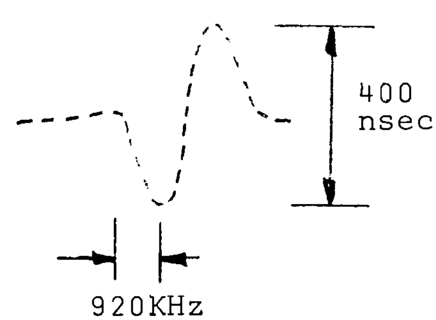

Fig.25

11. The broadcaster and envelope delay

Filters with sharp cut-off have particularly bad envelope delay problems unless compensated for by using extra filter sections. Compensated filters are costlier.

A TV set IF amplifier must be reasonably "sharp" to suppress adjacent channels, it also contains a sound trap, plus traps for the suppression of adjacent channel carriers. The IF does introduce a certain amount of envelope delay. When the currently used color system was proposed by the National Television Standards Committee (NTSC) in the early 1950's, it was proposed to pre-distort the transmitted signal rather than to include costly delay equalizers in every TV set. The recommendations resulted in the currently used transmitter delay curve shown below:

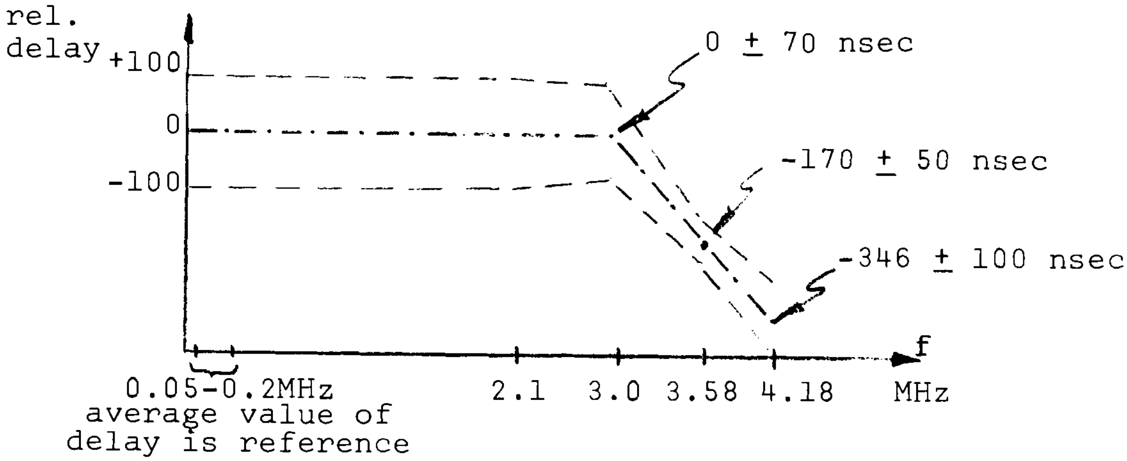

Fig.26

This pre-distortion is exactly the opposite of a "typical" TV set, which has a rising delay curve from approximately 3 MHz to the upper band limit of 4.18 MHz. There were relatively few color TV sets measured to arrive at the so called "typical" receiver delay curve. The response characteristic of a TV receiver is not covered by regulation nor by industry standards. Recent measurements on a number of receivers has indicated a wide range of envelope delay curves. TV receivers are usually designed for a good compromise between selectivity, transient response, color response, cost and other factors. Some people feel that the present transmitter delay curve should be changed; however, until so done one must adhere to it.

A broadcaster is obliged to pre-distort the radiated signal per FCC specs. This pre-distortion is taken care of by type accepted filters and by measurements during the manufacture of the transmitter. Proof of performance measurements, made when a transmitter first goes on the air do not require the measurement of delay. Many broadcasters use adjustable equalizers to make up for delay deficiencies in the transmitters. Equalizers of this kind cost several thousand dollars.

All video signals fed to the transmitter are automatically pre-distorted, however, the signal may suffer delay distortion in the studio or on its way to the transmitter. There are no rules on the maximum allowable delay distortion for signals leaving the studio. It is then perfectly possible that an over distorted signal is transmitted. Color processors used in studios often separate the luminance and chrominance signals with the possibility of introducing delay (or advance) in either luminance or chrominance. Video tape recorders can be a source of delay distortion. Many of you undoubtedly have observed delay effects only on some programs of a given channel and not on others. Efforts are currently underway by broadcasters to tighten color broadcasting standards.

12. Envelope delay in FM equipment

FM receivers should have linear phase response (no envelope delay) otherwise FM signals are distorted. Some recently introduced FM gear payed particular attention to delay response in the IF amplifier with resulting superior performance, such as low harmonics and intermodulation. The achieved performance would probably be noted by the real Hi-Fi bug, but not by the average listener. Present FM head-end gear is designed along more conventional lines with typical Hi-Fi gear performance.

13. Delays in trunk and distribution plants

It was pointed out earlier that delay distortion and rapid amplitude changes such as found in single channel equipment go hand in hand. A CATV plant is wide band and accordingly has little envelope delay. Jerrold showed the following delay curve of an 18-amplifier cascade.

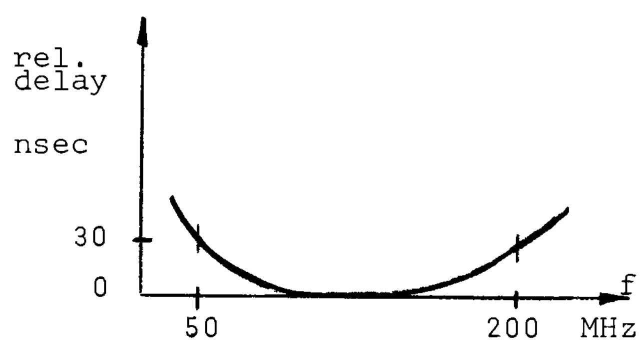

Fig.27

Hewlett-Packard in their appl. note #92 show the delay of a single CATV amplifier as 2 nsec from 54 to 120 MHz, and within 1 nsec from 120 MHz to 216 MHz.

14. Regulations

The proposed technical standards for CATV do not mention envelope delay specifically. The standards however, clearly indicate that the FCC wants the CATV system to faithfully reproduce the received signals at the subscriber's set.

The recently enacted Canadian standards require local origination signals to be pre-distorted per DOC (Canadian equivalent of the FCC) specs and that head-end processors must retain the original pre-distortion. Type approval of gear is considered since it is recognized that not every CATV operator will be able to purchase envelope delay measuring gear.

It is my opinion that it is only a matter of time before the FCC will take a similar stand.

Manufacturers will probably be required in the future to certify modulators, demodulators and signal processing equipment as to envelope delay and other types of distortion.

It may be of interest to realize that some TV studio specifications call for ± 25 nsec envelope delay.

15. Summary

An attempt has been made to explain "delays". It should be understood that delays can cause but one of the many distortions a signal can suffer from scene to TV set. For single channel equipment envelope delay measurements are a necessary complement to the more familiar amplitude response. Both amplitude and delay responses must be performed under all encountered signal level conditions.

16. Acknowledgements

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