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The Engineer's Guide to Decoding & Encoding

by John Watkinson



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INTRODUCTION

The subject of encoding and decoding has become increasingly important with the trend towards the use of component technology in production.

This handbook treats the entire subject of encoding and decoding from first principles leading up to today's most sophisticated technology.

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SECTION 1 - INTRODUCTION TO COMPOSITE VIDEO

1.1 What is composite video?

This book is concerned with advanced encoding and decoding of composite video. Composite video was originally designed as monochrome compatible system for broadcasting in which subcarrier based colour information was added to an existing line standard in a way which allowed existing sets to display a monochrome picture. A further criterion was that the addition of colour should not increase the bandwidth of the TV channel. In that respect composite video has to be viewed as an early form of compression. Although designed for transmission, the baseband composite signals could be recorded on videotape. In the case of NTSC and PAL, vision mixing was also possible on composite signals. As a result early colour studios were entirely composite. There was one coder at the camera control unit and one decoder at the viewer's TV set.

Since the introduction of colour, new processes such as slow motion, standards conversion, DVEs, graphics and so on have come into being. These have in common the fact that they cannot operate upon composite signals. All processes which manipulate the image spatially will render meaningless any subcarrier based colour information. In a composite environment such devices need an input decoder and an output encoder and clearly these need to be of high quality. Television is currently in a state of change with many new transmission formats proposed. Some of these work in components, but if such formats are adopted it will be some time before composite transmission ceases. Other proposals seek to increase the performance of composite signals. In both cases a requirement for quality coding and decoding is clear. Even if a utopian component world came about tomorrow, decoding would still be necessary to view the enormous composite archives which have built up. Whilst the techniques vary, all composite signals have in common the need to include a subcarrier based chroma signal within the luminance band in such a way that it will be substantially invisible on an unmodified monochrome TV set. This is achieved in much the same way in all three systems.

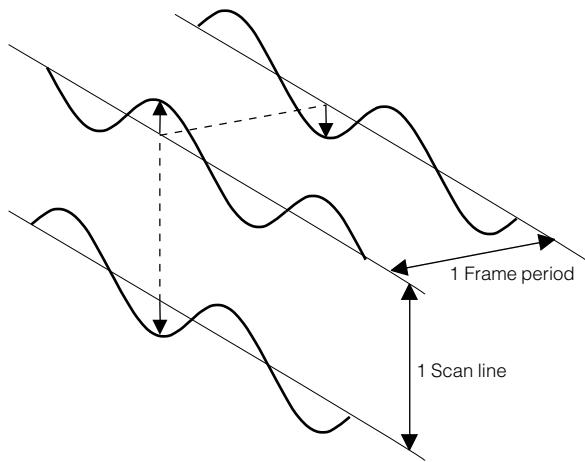


Fig 1.1.1 Chrominance superimposed on line waveform

Fig 1.1.1 shows that if a chroma signal is linearly added to a luminance signal it has the effect of making it alternately too bright and too dark. If it is arranged that the chroma is inverted on the next picture line the effect is that areas which are too bright on one line are adjacent to areas which are too dark on the next. The eye will see the average brightness of the line pairs which is the original luminance. Efforts are made to ensure that the phase of the chroma also reverses from frame to frame so that the same point on the screen alternates in brightness about the value determined by the luminance signal. Clearly the exact frequency of the subcarrier has to be carefully chosen if the effect is to work properly. NTSC and PAL modulate the phase and amplitude of the colour subcarrier so that two components can be sent simultaneously whereas SECAM frequency modulates the subcarrier and sends the components on alternate lines. The effect of composite modulation is to produce an extremely complex signal spectrum, especially in PAL. It is only by considering this spectrum in detail that it becomes clear how the components can effectively be separated.

1.2 A brief history of NTSC PAL and SECAM

The United States very nearly embarked on a field sequential colour system which would have been incompatible with the existing 525-line monochrome system. The U.S. monochrome standard had been designed by the first National Television System Committee (NTSC-1) in 1940 and 1941. The manufacturers and broadcasters re-formed the NTSC as NTSC-2 in 1950, but it made slow progress until the FCC, anxious to get things moving, stated that a sequential system would be adopted unless a better system was proposed. However, the compatible

subcarrier based NTSC-2 system won the day and transmissions began in 1954. NTSC suffered from colour instabilities due to multipath reception and transmitter imperfections which meant receivers needed a hue control to compensate. Development of the PAL system was led by Dr. Bruch in Germany. One of the goals of PAL was to overcome the NTSC instability and eliminate the hue control. It was also designed to be different to NTSC in order to keep out non-European manufacturers from the TV set market. This ploy failed when the Japanese managed to design decoders which circumvented the PAL patents by treating the signal like NTSC but decoding only every other line. France meanwhile went its own way with SECAM, with national pride having a lot to do with the decision. The three systems were adopted by the rest of the world primarily on political rather than technical grounds, except for South America, where PAL-M (Basically PAL encoding used with NTSC line and field rate) and PAL-N (625/50 PAL having NTSC channel spacing) were local compromises.

1.3 Quadrature modulation

Fig 1.3.1 shows how the ubiquitous colour bar test signal is generated. RGB square waves of identical amplitude are produced, in which one cycle fits in the active line of the green signal, two cycles fit in the active line of the red signal and four cycles fit in the active line of the blue signal. As the eye does not have a uniform response to different colours, the R, G and B components are weighted before being added to produce a monochrome equivalent signal known as luminance (Y).

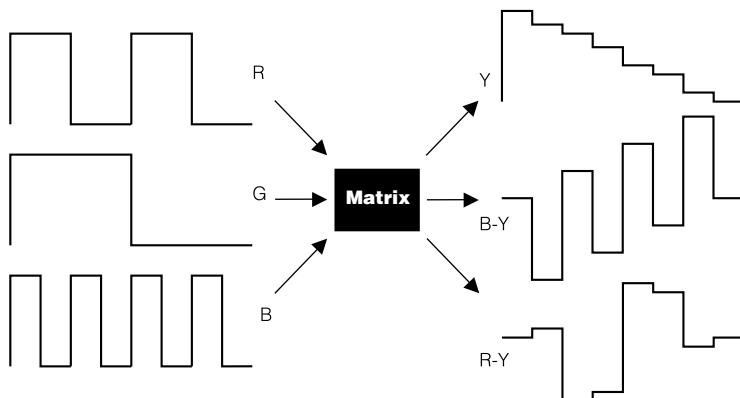


Fig 1.3.1 Red, green and blue colour bars matrixed to Y, R-Y and B-Y

This is a descending staircase which begins at peak white and finishes at black. Clearly luminance is unipolar as there is no concept of negative brightness. The luminance signal is then subtracted from the red and blue components to produce what are called colour difference signals. As they are differences, these signals are bipolar. Both signals can be displayed at once on a component vectorscope. The screen of a component vectorscope represents a constant luminance chromaticity diagram with white in the centre and saturation increasing outwards with radius. The B-Y signal causes horizontal deflection, and R-Y causes vertical deflection. It will be seen from Fig 1.3.2 that this results in a display having six peripheral dots and two central dots.

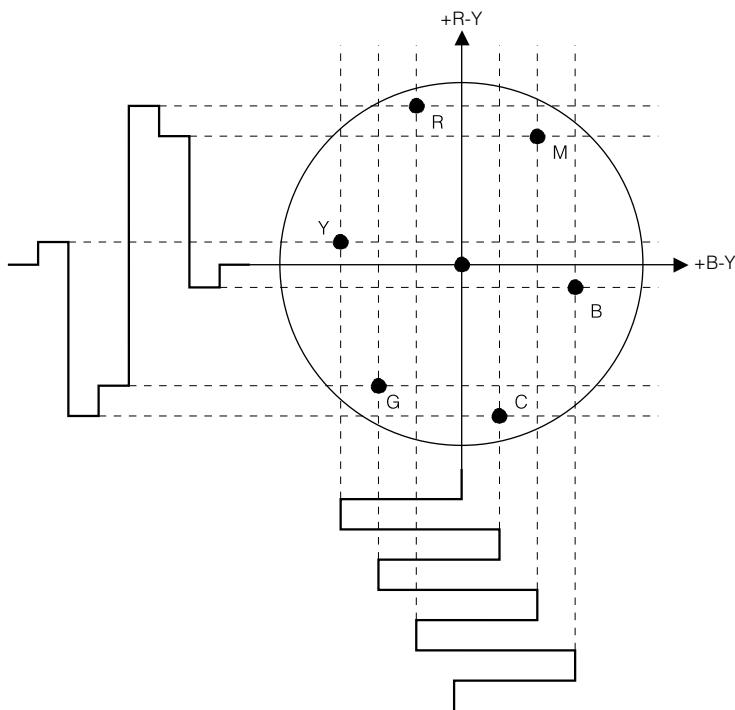


Fig 1.3.2 R-Y and B-Y component of colour bars represented vectorially

The central dots result from the white and black bars which are not colours and in which the colour difference signals are both zero. Fig 1.3.3 considers how a particular dot or colour can be reached on a two dimensional display. In component signals, the dot is reached by travelling a given distance horizontally, followed by a given distance vertically.

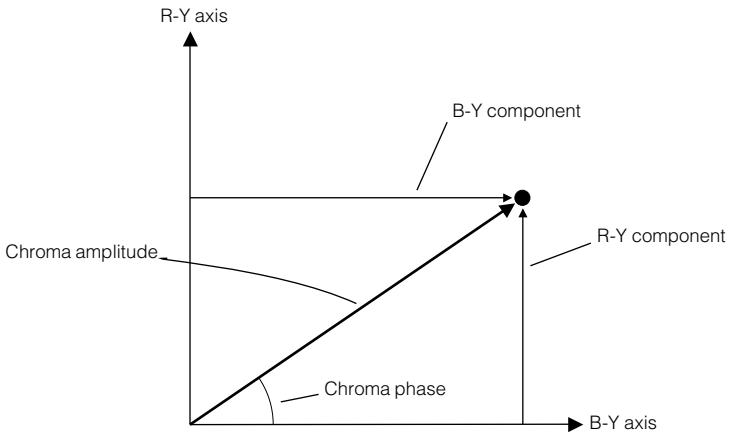


Fig 1.3.3 Component addition to produce vectors

This is the way a map reference works; mathematicians call the components Cartesian co-ordinates. It is just as easy to reach the same dot by travelling a suitable distance at the right heading or angle. Mathematicians call this polar co-ordinates. Instead of two signals, we can convey distance and angle in the amplitude and phase of a waveform. That is precisely how PAL and NTSC chroma work. The radius of the dot is the chroma amplitude which is proportional to the saturation, and the angle is the phase. The phase angle of the vector literally points to the appropriate hue in the chromaticity diagram. Simultaneous modulation of amplitude and phase is performed by a quadrature modulator.

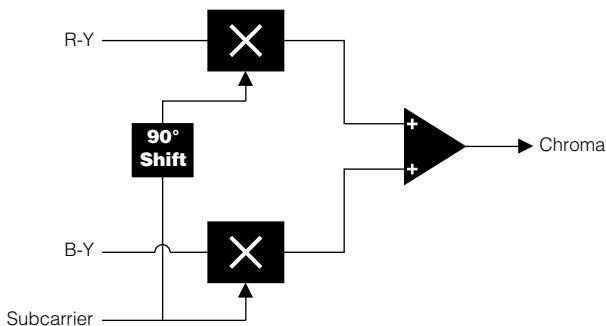


Fig 1.3.4 Subcarrier modulation

Fig 1.3.4 shows how this works. A pair of amplitude modulators (analog multipliers) are supplied with the same carriers except that one has been phase shifted by 90 degrees. The outputs of the two modulators are linearly added and the resultant signal is amplitude and phase modulated. The phase is a function of the relative proportions and polarities of the two inputs. The original subcarrier is suppressed in the output of the modulator. The picture frequencies in the baseband result in sidebands above and below the centre frequency after modulation. As a result it is incorrect to refer to the quadrature modulator output as subcarrier; the correct term is chroma. The quadrature modulated output can be decoded back to the two baseband input signals using a pair of synchronous demodulators also driven in quadrature. These need reference carriers which are identical in phase to the original pair of carriers. As there is no subcarrier in the chroma signal it is necessary to send a reference subcarrier separately. This is the purpose of the burst which is sent during horizontal blanking.

A heavily damped phase locked loop synchronises to the burst and continues to run for the rest of the line to provide a reference for the decoder. One way of considering how quadrature modulation works is that when one of the carrier inputs reaches its peak, the other is passing through zero. At that time the signal voltage can only be a function of, say, the B-Y input. Ninety degrees later the relationships exchange and the signal voltage can then only be a function of the R-Y input. Demodulation is a question of sampling the signal every 90 degrees. Odd samples reflect the state of one component; even samples reflect the state of the other. The demodulators have the effect of inverting alternate samples. A simple low-pass filter removes the harmonics of the subcarrier frequency to recreate the input waveform.

1.4 NTSC encoding

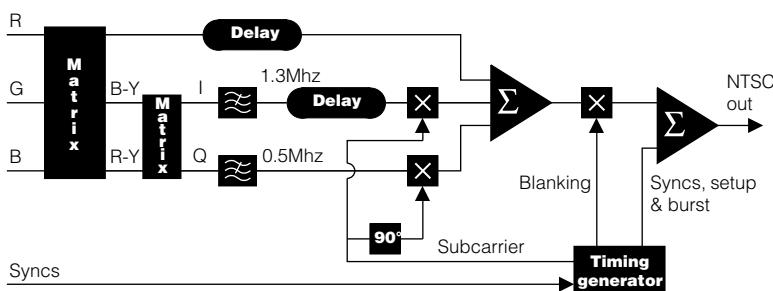


Fig1.4.1 A basic NTSC encoder

Fig 1.4.1 shows an original NTSC encoder. The RGB to colour difference matrix operates as described above to produce a luminance signal. The quadrature modulation process also operates as described above except that a psycho-visual coding scheme was used where the greatest perceived colour resolution is obtained with the minimum overall bandwidth. This is achieved by matrixing the R-Y and B-Y colour difference signals to produce new signals on different axes as shown in Fig 1.4.2.

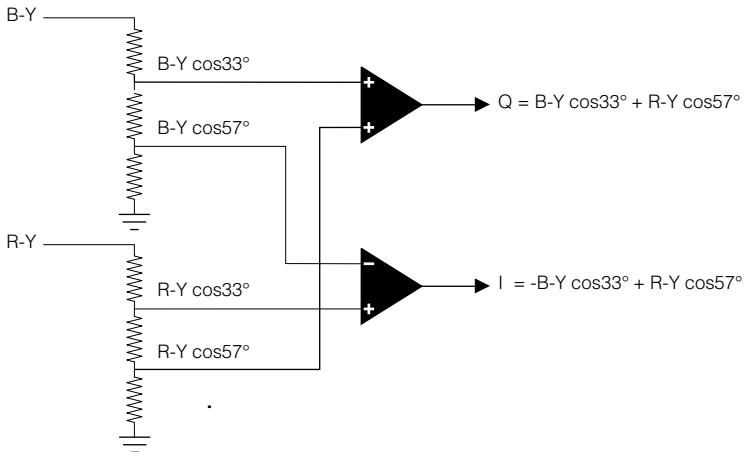


Fig 1.4.2 Derivation of NTSC I & Q axes

One axis is at 123 degrees to B-Y and the other is at 33 degrees to B-Y. The 123 degree signal is low pass filtered to 1.3 MHz whereas the 33 degree signal is filtered to only 0.5 MHz. This is possible because the latter lies upon an axis to which the eye is least sensitive. The wider bandwidth filter causes less delay than the narrow band filter, and a compensating delay is needed to time-align the filtered signals. The wide-band signal drives a subcarrier modulator and so is known as the I (In-phase) signal, whereas the narrow band signal drives the 90 degree shifted modulator and so is known as the Q (Quadrature) signal. A compensating delay is needed for time alignment of the luminance with the chroma. Adding luminance and chroma together produces the active line composite signal. The output of the sync generator produces sync pulses and set-up or pedestal level where this is used. The sync generator also produces burst gates which gate inverted subcarrier into the blanking following horizontal sync. Alternatively the burst may be produced by subtracting a burst envelope waveform from the B-Y signal. The composite signal should be band-limited to 4.2 MHz for broadcast. Whilst the above encoder fulfilled the requirements of the ideal NTSC specification, proper decoding required the demodulators to be fed I and Q references and to have reconstruction filters of

two different bandwidths followed by a matrix to return to R-Y and B-Y. However, many set manufacturers ignored the extra bandwidth and demodulated on the R-Y and B-Y axes. Similarly numerous encoder manufacturers discarded the additional complexity of the second matrix and the different bandwidths and encoded on the colour difference axes. This shifted the burst phase by 33 degrees, but as the viewer had a hue control this was of little consequence. The restricted Q bandwidth was later found to be unnecessary and the requirement was dropped, resulting in the equal bandwidth coder of Fig 1.4.3 which needs no colour difference delay.

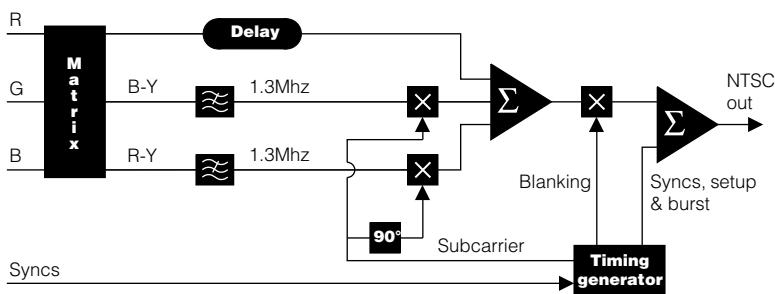


Fig 1.4.3. Equiband NTSC encoder

Although NTSC is a well thought out system, it can suffer from hue errors when signal reflections add to the direct signal. Differential phase errors, particularly in transmitters, cause the hue to vary with brightness, although later transmitter designs have reduced the effect. Differential phase is difficult to handle because there is no correct setting for the hue control; it depends on the brightness.

1.5 PAL encoding

The PAL (Phase Alternating Line) system was designed to overcome the susceptibility to hue errors inherent in NTSC and to eliminate the hue control from receivers. fig1.5.1 shows that the RGB input is matrixed as before to produce Y, B-Y and R-Y and the latter two are gain weighted and result in signals called U and V.

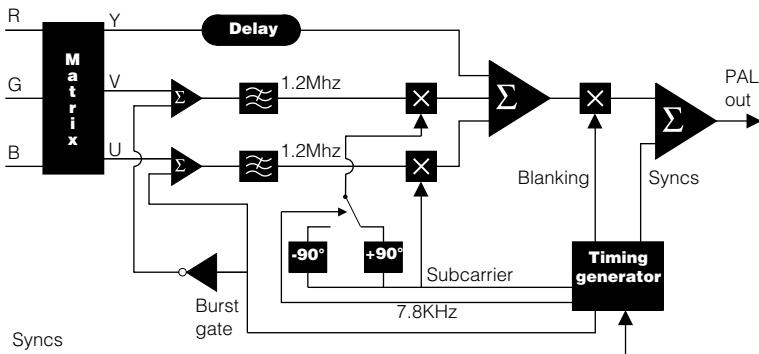


Fig 1.5.1 A basic PAL encoder

The chroma modulation system uses quadrature as in NTSC, but on alternate lines the phase of the V signal is inverted. The demodulator in the decoder has to re-invert the V signal and in order to synchronize the receiver inversion the PAL burst is arranged to swing by +/- 45 degrees with respect to -U in synchronism with the encoder inversion.

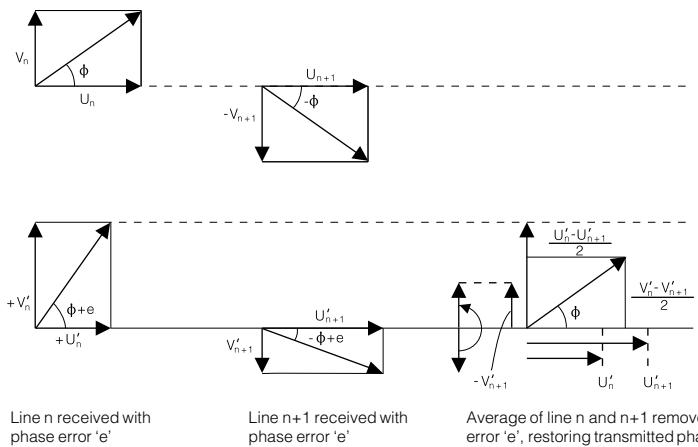


Fig 1.5.2 Removal of hue errors by line averaging in PAL

Fig 1.5.2 shows how the inclusion of V-switch allows phase errors to be rejected. If a phase error should occur, rotating the received phase, for example, clockwise, then on one line the U signal will be too small on demodulation whereas the V signal will be too large. However, on the next line the same phase error causes U to be too large and V to be too small. Thus by averaging the colour difference signals over two lines the effect of the phase error is prevented from affecting the hue. There is a small second order loss of saturation instead, but this is considerably less obvious. In simple receivers (PAL-S), the averaging is left to the viewer and severe phase errors result in brightness differences between lines which cause picture patterning known as Hanover blinds. In PAL-D receivers a one line delay is used to allow electronic averaging of the colour difference signals. This results in a loss of vertical colour resolution, but this is unimportant as the horizontal colour bandwidth has already been seriously reduced by the encoding filters to take advantage of the reduced colour resolution of the eye.

Returning to Fig 1.5.1 the PAL encoder has equal bandwidth filters for U and V. The V-switch is obtained by inverting the quadrature subcarrier on alternate lines. The swinging burst is obtained by adding an inverted burst envelope to the baseband U signal and a non-inverted burst envelope of equal amplitude to the baseband V-signal. This results in a burst of 135 degrees or -135 degrees according to the state of V-switch. The luminance signal is passed through a compensating delay before the addition of the chroma and syncs. PAL does not use set-up. For broadcast purposes the composite signal is band-limited to 5.75 MHz.

1.6 SECAM encoding

SECAM was also designed to overcome the hue instability of NTSC. Whilst PAL retained the quadrature modulation system and modified it with V-switch, the French approach was to abandon quadrature modulation altogether and to send the colour difference signals on alternate lines instead of simultaneously. The receiver requires a one line delay in order to time align the sequential signals; hence the name Séquentiel Couleur Avec Mémoire or SECAM. Line averaging is then used to obtain the colour difference signals on every line. The colour subcarrier is frequency modulated and then subject to pre-emphasis. As the colour difference signals are sent sequentially, it is necessary to synchronise the receiver so that they are not transposed. This is done by using different centre frequencies for DB ($282 \times F_h$) and DR ($272 \times F_h$). Instead of a burst for phase reference, an undeviated subcarrier of the appropriate frequency is sent at the run-in to active video to act as a reference. The centre frequencies of the two subcarriers are quite close together, and so in some versions of SECAM the vertical interval carries identification signals to help maintain colour synchronism. These consist of bursts of subcarrier which are frequency swept along the line.

The pre-emphasis causes the subcarrier amplitude to vary and the resultant envelope shape has led to them being called “bottles”. In order to reduce subcarrier visibility on monochrome receivers, the subcarrier is inverted on alternate lines. As the subcarrier is frequency modulated, this cannot be done by selecting a suitable frequency as is done in PAL and NTSC, but instead requires a switchable inverter following the frequency modulator.

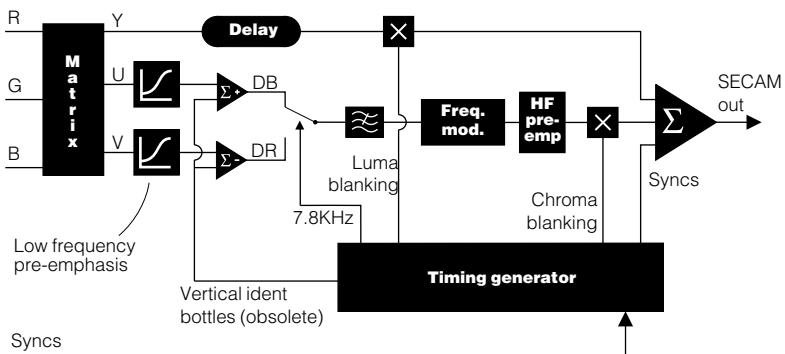


Fig 1.6.1 A basic SECAM encoder

Fig 1.6.1 shows a SECAM encoder. RGB inputs are matrixed to YUV as before. The identification (bottle) signal envelopes are added if required to make DR and DB signals. A DC offset is added to DB. DR is inverted so that it causes deviation opposite to DB. On typical program material this results in a slightly cleaner spectrum. The DR and DB signals are selected alternately at half line rate, and low pass filtered to 1.2 MHz. The baseband signals drive a frequency modulator. The DC offset in DB results in a higher centre frequency. Following the frequency modulator the chroma signal is selectively inverted. SECAM works well for transmission as the frequency modulated chroma is immune to differential gain and phase errors. This characteristic also makes it resistant to timebase errors in analog VTRs. In fact the timebase accuracy required in SECAM is no greater than in monochrome. However it is not possible to carry out any manipulation of the SECAM signal. Even a simple fade is impossible as it has no effect on the frequency of the chroma. The result is that the luminance fades and the chroma becomes noisier until it cuts out. In practice countries which use SECAM produce in PAL and transcode for transmission. It is hardly surprising that France has been at the forefront of component video development as this was a matter of necessity.

1.7 Digital encoding

Whilst analog encoders have been in use for many years, unless they are regularly adjusted to counteract drift, artifacts can result. In PAL and NTSC it is important that the modulators are driven in exact quadrature, otherwise there will be crosstalk between the colour difference signals. With an increasing amount of component digital equipment coming into use it makes sense to carry out as much as possible of the composite encoding process in the digital domain. In fact it is quite feasible to construct an encoder in which the composite analog signal emerges directly from a DAC at the output. The advantage of fully digital encoding is that the system is intrinsically stable and drift is impossible. Using digital filters for bandwidth limitation is advantageous as these filters are inherently phase linear.

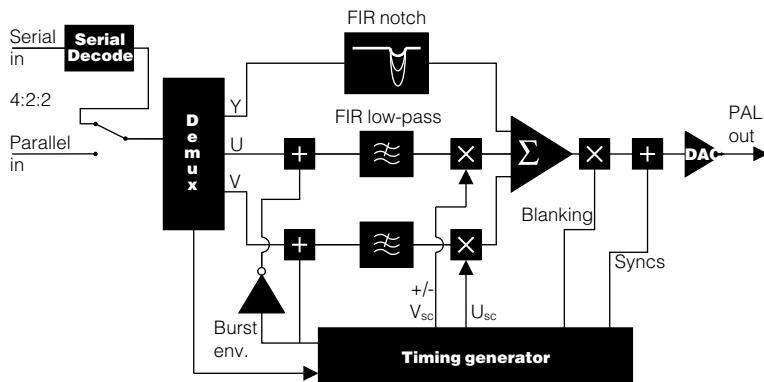


Fig 1.7.1. A digital PAL or NTSC encoder

Fig 1.7.1 shows the block diagram of a digital PAL or NTSC encoder. The input can be serial or parallel standard interface carrying component digital data in 4:2:2 format. The components are demultiplexed and the colour difference signals are subject to Finite Impulse Response digital low-pass filters to determine the signal bandwidth. The luminance signal may be subject to a FIR variable-notch filter at the subcarrier frequency. Chroma modulation is obtained in the same way as for analog encoders, except that the analog multipliers are replaced by digital multipliers and the subcarrier is no longer a waveform but a stream of numerical sample values. A binary adder is required to add the quadrature components and to add the chroma to the luminance. Digital waveform multiplication can only take place when the two waveforms to be multiplied are conveyed at the same sampling rate. The digital video input standard will determine the sampling rate and the subcarrier will have to be synthesised at the same rate. Production of the digital subcarrier for the modulators is a complex process.

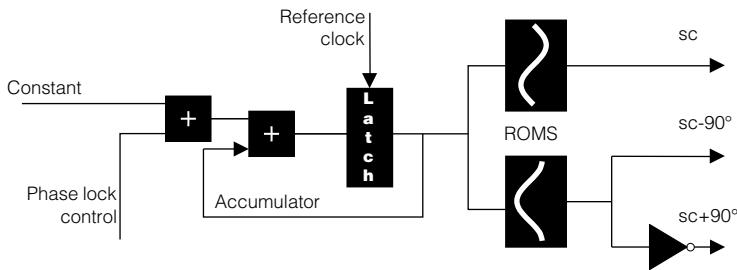


Fig 1.7.2. Digital subcarrier synthesis

Fig 1.7.2 shows one way in which it can be done. A ROM is programmed to contain one cycle of a digitized sinewave over its entire address range. If the ROM is addressed by a counter which is allowed to overflow it will produce a continuous digital sinewave whose frequency is determined by the clock rate divided by the size of the ROM. Instead of a counter, the ROM is addressed by an accumulator which adds a constant to its count on each clock. The frequency is now increased in proportion to the value of the constant. Adding a small modifier to the constant allows the frequency to be raised or lowered slightly and the result is a digitally controlled oscillator which can be incorporated in a phase locked loop so that it locks to reference subcarrier. The result is a very clean digital subcarrier having the same sampling rate as the component digital video data. A quadrature component is easily obtained from a second ROM containing a cosine wave. Clearly it is impossible for there to be any error in the quadrature. In PAL, V-switch is obtained by numerically inverting the subcarrier samples to the V multiplier. In PAL and NTSC bursts are created by adding appropriate envelopes to the modulator inputs. In SECAM a frequency modulated chroma signal is required. It will be seen that in the configuration of Fig 1.7.2 the frequency is proportional to the input constant. If the constant is replaced with a variable sample stream the result is a frequency modulator. Component digital interface signals do not carry conventional sync pulses but instead have reserved bit patterns for synchronizing. The sync generator in the encoder must recreate the original sync structure using look-up tables containing the sample values needed. The chroma, luminance and syncs are added numerically. The filtering and modulation processes extend the wordlength of sample values and so after the final addition to produce a digital composite signal the wordlength must be carefully rounded to the length suitable for the DAC in use. Simple truncation cannot be used as this will result in distortion. Following the output DAC a low-pass analog filter removes the images due to the sampling spectrum and sets the overall bandwidth of the composite signal.

SECTION 2 - SPECTRAL ANALYSIS OF COMPOSITE VIDEO

2.1 Sampling theory

The composite video systems must squeeze the colour difference signals into the same channel bandwidth as the existing monochrome signal. This is done using spectral interleaving in which frequencies which are unused in the luminance spectrum are occupied by the chroma and vice versa. Clearly the spectra of both must be fully understood if the best performance is to be obtained. As television signals describe two dimensional images changing with time they contain three dimensional information and the resulting spectra are also three dimensional.



Fig 2.1.1 Modulation of a pulse train by a sinusoid

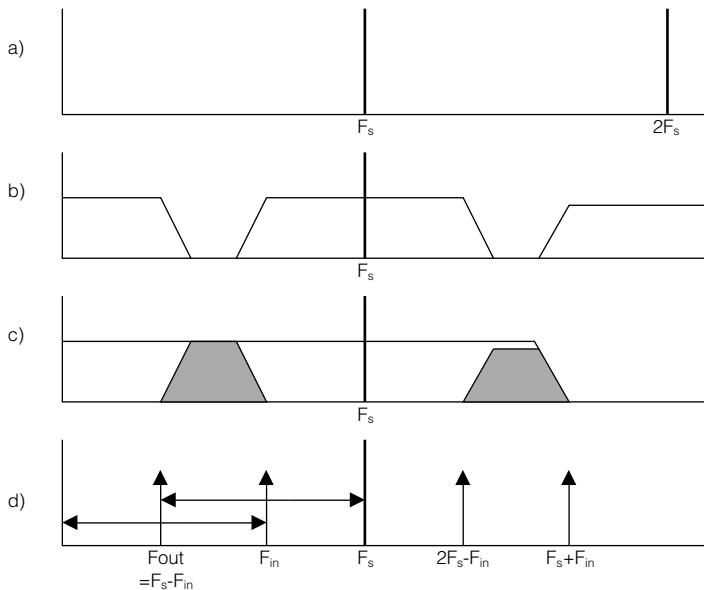


Fig 2.1.2 Effect of sidebands of differing input signals

However, careful use of sampling theory can predict exactly what takes place. Sampling is no more than the process of representing a continuous process by

periodic measurements. Television systems sample along the time axis at frame rate, and sample down the vertical axis at the line spacing. Digital systems sample along the line as well.

The sampling process originates with a pulse train which is shown in Fig2.1.1 to be of constant amplitude and period. The input waveform amplitude-modulates the pulse train in much the same way as the carrier is modulated in an AM radio transmitter. In the same way that AM radio produces sidebands or images above and below the carrier, sampling also produces sidebands although the carrier is now a pulse train and has an infinite series of harmonics as shown in Fig2.1.2a).

The sidebands repeat above and below each harmonic of the sampling rate as shown in b). The sampled signal can be returned to the continuous-time domain simply by passing it into a low-pass filter. This filter has a frequency response which prevents the images from passing, and only the baseband signal emerges, completely unchanged. If considered in the frequency domain, this filter is called an anti-image or reconstruction filter.

If an input is supplied having an excessive bandwidth for the sampling rate in use, the sidebands will overlap, (Fig2.1.2c) and the result is aliasing, where certain output frequencies are not the same as their input frequencies but instead become difference frequencies (Fig2.1.2d). It will be seen that aliasing does not occur when the input frequency is equal to or less than half the sampling rate, and this derives the most fundamental rule of sampling, which is that the sampling rate must be at least twice the highest input frequency. Whilst aliasing has been described above in the frequency domain, it can be described equally well in the time domain.

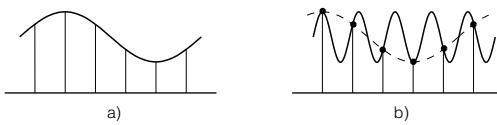


Fig 2.1.3 Adequate and inadequate sample rates

In Fig2.1.3a) the sampling rate is obviously adequate to describe the waveform, but at b) it is inadequate and aliasing has occurred. There is often no control over the spectrum of input signals and ideally it is necessary to have a low-pass filter at the input to prevent aliasing. This anti-aliasing filter prevents frequencies of more than half the sampling rate from reaching the sampling stage. In television cameras effective filters are impracticable and television signals may contain aliasing, particularly on the time axis. Temporal aliasing is commonly observed in films of rapidly revolving subjects. Stagecoach wheels are a classic example as the spoke

passing frequency can be quite high. When it reaches the frame rate of the camera the lower sideband reaches zero and the wheel appears to stop. If ideal low-pass anti-aliasing and anti-image filters are assumed, having a vertical cut-off slope at half the sampling rate, an ideal spectrum is obtained.

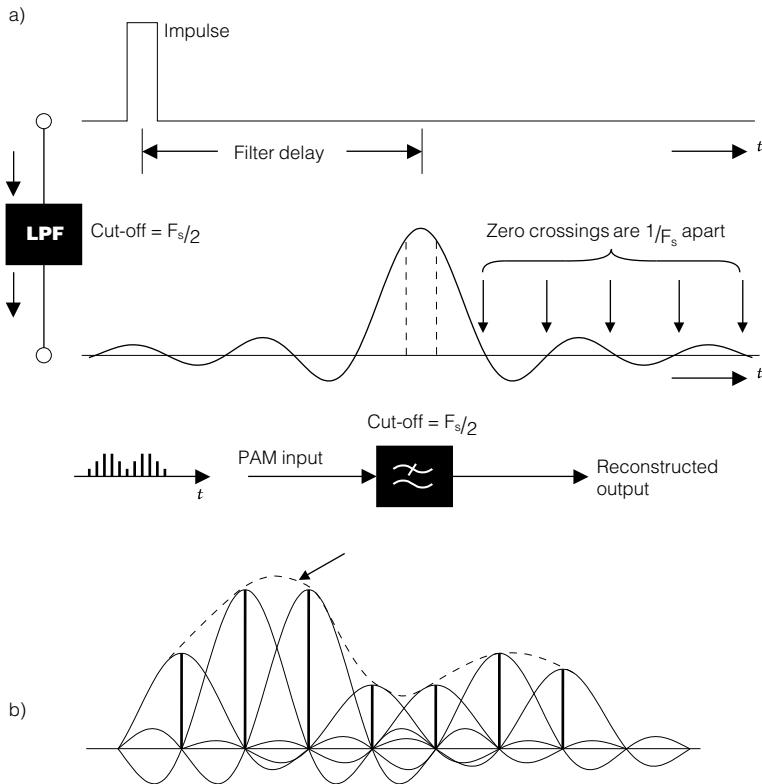


Fig 2.1.4. An ideal phase-linear low-pass filter

The impulse response of a phase linear ideal low-pass filter is a $\sin x/x$ waveform in the time domain, and this is shown in fig 2.1.4a). Such a waveform passes through zero volts periodically. If the cut-off frequency of the filter is one-half of the sampling rate, the impulse passes through zero at the sites of all other samples. It can be seen from fig 2.1.4b) that at the output of such a filter, the voltage at the centre of a sample is due to that sample alone, since the value of all other samples is zero at that instant. In other words the continuous time output waveform must join up the tops of the input samples. In between the sample instants, the output of the filter is the sum of the contributions from many impulses, and the waveform smoothly joins the tops of the samples. It is a consequence of the band-limiting of

the original anti-aliasing filter that the filtered analog waveform could only travel between the sample points in one way. As the reconstruction filter has the same frequency response, the reconstructed output waveform must be identical to the original band-limited waveform prior to sampling. The ideal filter with a vertical “brick-wall” cut-off slope is difficult to implement. As the slope tends to vertical, the delay caused by the filter goes to infinity. In practice, a filter with a finite slope has to be accepted as shown in fig 2.1.5.

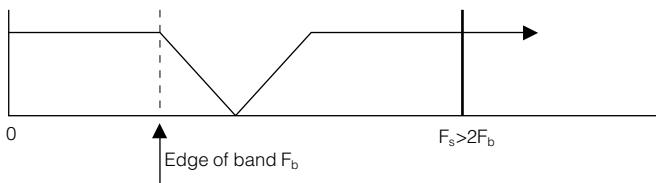


fig 2.1.5. A more achievable filter response

2.2 Aperture effect

The reconstruction process of fig2.1.4 only operates exactly as shown if the impulses are of negligible duration. In many processes this is not the case, and many real devices keep the signal constant for a substantial part of or even the whole period. The case where the pulses have been extended in width to become equal to the sample period is known as a zero-order hold system and has a 100% aperture ratio. Pulses of negligible width have a uniform spectrum, which is flat within the baseband, but pulses of 100% aperture ratio have a $\sin x/x$ spectrum which is shown in Fig 2.2.1.

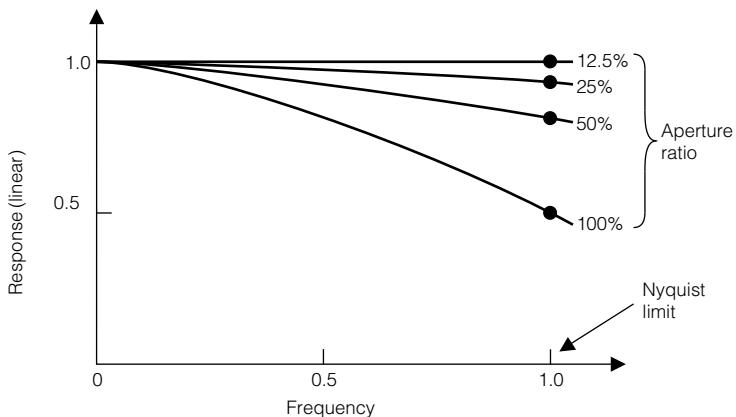


Fig 2.2.1 Sinc x/x response

The frequency response falls to a null at the sampling rate, and as a result is about 4dB down at the edge of the baseband. The aperture effect will show up in many aspects of television. Lenses have finite MTF (Modulation Transfer Function), such that a very small object becomes spread in the image. The image sensor will also have a finite aperture function. In tube cameras, the beam will have a finite radius, and will not necessarily have a uniform energy distribution across its diameter. In CCD cameras, the sensor is split into elements which may almost touch in some cases. The element integrates light falling on its surface, and so will have a rectangular aperture. In both cases there will be a roll-off of higher spatial frequencies. The temporal aperture effect varies according to the equipment used. Tube cameras have a long integration time and thus a wide temporal aperture. Whilst this reduces temporal aliasing, it causes smear on moving objects. CCD cameras do not suffer from lag and as a result their temporal response is better. Some CCD cameras deliberately have a short temporal aperture as the time axis is resampled by a mechanically driven revolving shutter. The intention is to reduce smear, hence the popularity of such devices for sporting events, but there will be more aliasing on certain subjects. The eye has a temporal aperture effect which is known as persistence of vision, and the phosphors of CRTs continue to emit light after the electron beam has passed. These produce further temporal aperture effects in series with those in the camera.

2.3 Two and three dimensional sampling spectra

Analog video samples in the time domain and vertically down the screen so a two dimensional vertical/temporal spectrum will result. In the absence of interlace there is a rectangular matrix of sampling sites vertically and temporally.

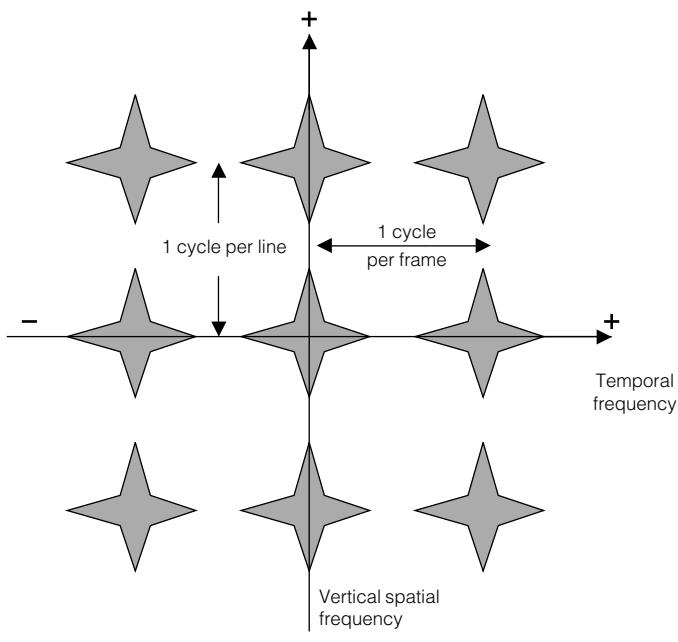


Fig 2.3.1. Vertical - temporal spectrum with no interlace

The corresponding spectrum is shown in Fig 2.3.1. The baseband spectrum is in the centre of the diagram, and the repeating sampling sideband spectrum extends vertically and horizontally. The vertical aspects of the star-shaped spectrum results from vertical spatial frequencies in the image. The horizontal aspect is due to image movement. Note that the star shape is rather hypothetical; the actual shape depends heavily on the source material. On a still picture the horizontal dimension collapses to a line. The use of interlace has a profound effect on the vertical/temporal spectrum (see Fig 2.3.2). The lowest sampling frequency on the time axis is the frame rate, and the lowest sampling frequency on the vertical axis is the number of lines in a field. The arrangement is called a quincunx pattern because of the similarity to the five of dice.

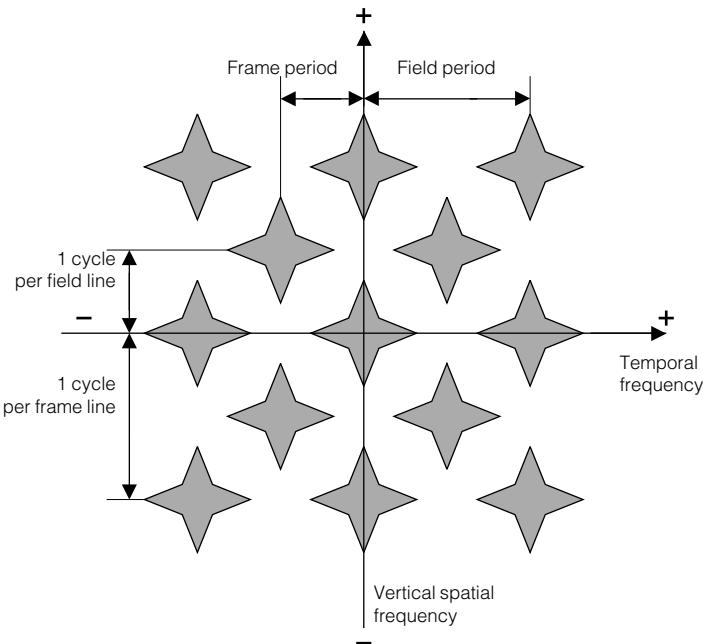


Fig 2.3.2. Vertical - temporal spectrum with interlace

The structure of the vertical/temporal spectrum of luminance is the same as the that of the two colour difference signals because both have the same field and line rates. Since both colour and luminance signals have gaps in their spectra at integer multiples of line rate vertically and integer multiples of field rate temporally, it follows that the two spectra can be made to interleave and share the same spectrum if an appropriate subcarrier frequency is selected which causes the chroma spectrum to shift by half of the spectral period in both dimensions.

2.4 Spectrum of NTSC

The subcarrier frequency of NTSC is an odd multiple of half line rate; 227.5 times to be precise. Fig 2.4.1 shows that this frequency means that on successive lines the chroma will be phase inverted.

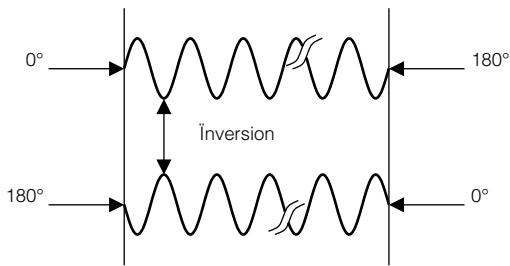


Fig 2.4.1. 2 - line subcarrier in NTSC

There is thus a two-line sequence of subcarrier, responsible for a vertical frequency of half line frequency. The existence of line pairs means that two frames or four fields must elapse before the same relationship between line pairs and frame sync. repeats. This is responsible for a temporal frequency component of half the frame rate. These two frequency components can be seen in the vertical/temporal spectrum of Fig 2.4.2.

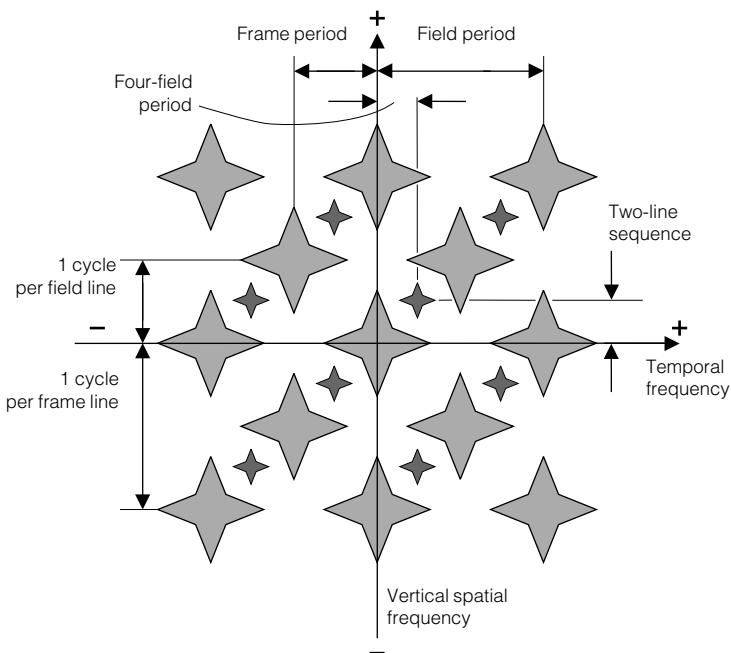


Fig 2.4.2. Luma - chroma interleave in the vertical - temporal domain

The chroma thus interleaves with the luminance spectrum in two dimensions. The effect of the chroma added to luminance is to make the luminance alternately too dark or too bright. The phase inversion causes this effect to cancel over pairs of lines and over pairs of frames, minimising visibility on monochrome receivers. The half frame rate component is responsible for the familiar four-field colour framing sequence. When editing NTSC recordings, this four field sequence must not be broken. The spectrum of Fig 2.4.2 does not show the whole story, because the luminance and chroma do not have the same horizontal frequency. Fig 2.4.3 shows a vertical/horizontal spectrum in which it will be seen that the chroma is displaced on the horizontal frequency axis by the subcarrier frequency.

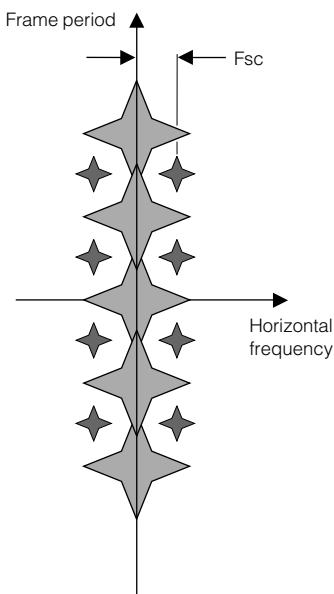


Fig 2.4.3. As Fig 2.4.2 but showing the horizontal- vertical spectrum

If Fig 2.4.2 is considered whilst viewing Fig 2.4.3 it will be possible to imagine the chroma components being displaced above and below the plane of the diagram. It is useful to consider the spectrum of the actual video waveform in the area where the chroma and luminance overlap in Fig 2.4.3. The video signal as displayed on a spectrum analyzer has a one dimensional spectrum. This results from the temporal sampling spectrum being itself sampled by a vertical sampling process at the line rate. The situation is inevitably complicated by interlace. Considering luminance only, the fundamental temporal sampling rate is 60 Hz.

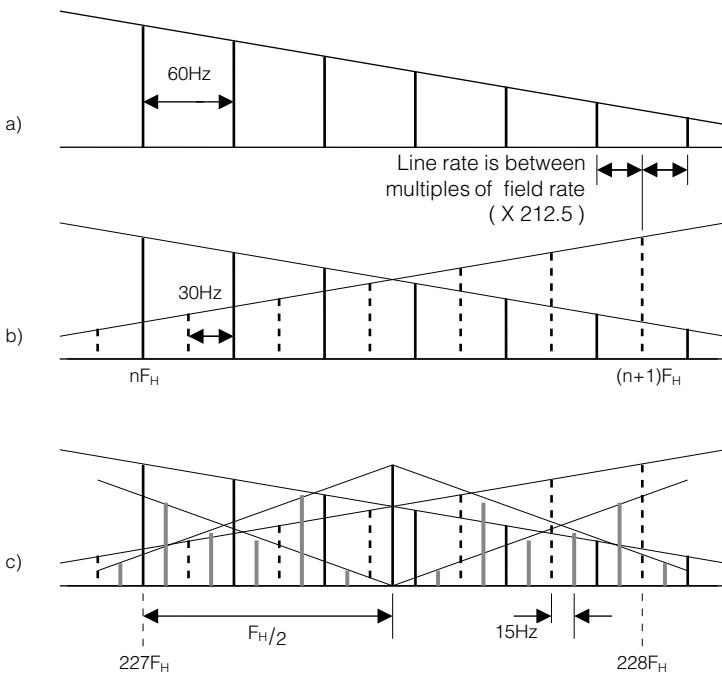


Fig 2.4.4. Temporal sampling spectrum of NTSC

The temporal sampling spectrum thus contains multiples of 30 Hz as shown in Fig 2.4.4a). In an interlaced system there is an odd number of lines in the frame and so the line frequency is not a multiple of field rate. The effect of interlace is that the line rate is positioned half way between multiples of field rate as shown in Fig 2.4.4b). The sidebands at 60 Hz spacing mesh with the 60 Hz spacing of the baseband to produce a signal which has spectral entries repeating at 30 Hz which is, of course, the frame rate. There is a coarse spectrum repeating at line rate, and a fine spectrum repeating at frame rate. The colour difference components in NTSC have the same spectral structure as they are sampled in the same way. The subcarrier frequency must be such that the resulting chroma spectrum meshes with luminance on both the coarse and the fine scale. This means that the subcarrier frequency must be as far as possible from multiples of line rate and field rate. A frequency half way between multiples of line rate also falls half way between the 30 Hz spaced fine spectral entries. In practice 227.5 times line rate is used. It will be seen from Fig 2.4.4c) that this allows the luminance and chrominance spectra to mesh on both the coarse and fine scales. The fundamental spacing in the spectrum is now 15 Hz which is responsible for the four-field sequence of NTSC.

2.5 Spectrum of PAL

The periodicity of the vertical temporal spectrum of the U signal is identical to that of luminance. However, in PAL the hue instability of NTSC is overcome by the inversion of V on alternate lines. This makes the V spectrum different to that of the U signal. V-switch causes a two line sequence which is responsible for a vertical frequency component of half line rate. As the two line sequence does not divide into 625 lines, two frames elapse before the same relationship between V-switch and the line number repeats. This is responsible for a half frame rate temporal frequency component.

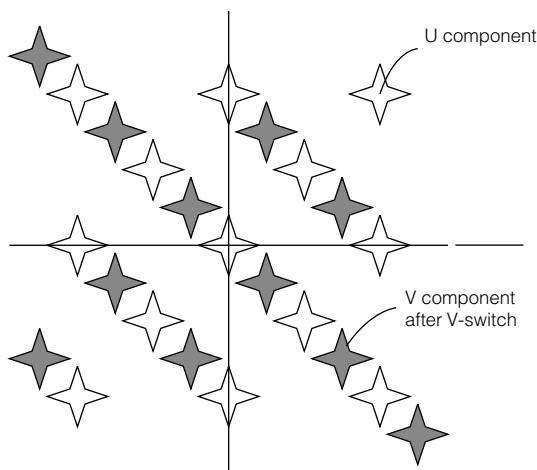


Fig 2.5.1. Vertical - temporal spectrum of baseband PAL colour signals

Fig 2.5.1 shows the resultant vertical/temporal spectrum of PAL baseband colour difference signals after V-switch. The two frame sequence of V-switch moves the V spectrum horizontally between the U spectral entries, and the two line sequence moves the V spectrum vertically in the same way. The effect of both is that the V component has shifted diagonally so that its spectral entries lie half way between the U component entries. Spectral interleaving with a half cycle offset of subcarrier frequency as in NTSC will not work, as Fig 2.5.2 shows that this only interleaves the U component properly.

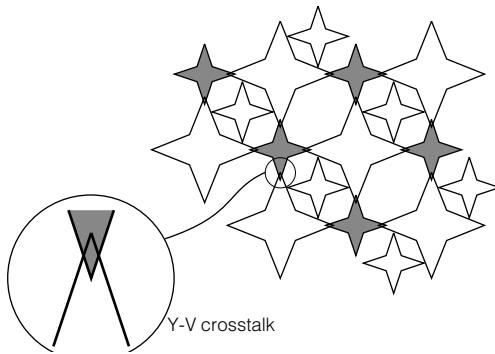


Fig 2.5.2 Luma -V axis crosstalk

As V-switch has halved the spectral repeat rate of chroma, the solution is to shift the chroma not half way between the luminance spectral entries, but one quarter and three quarters of the way. In order to obtain this spectrum it is necessary to adopt a subcarrier frequency with a quarter cycle per line offset. Multiplying the line rate by $283\frac{3}{4}$ allows the luminance and chrominance spectra to mesh as in Fig 2.5.3.

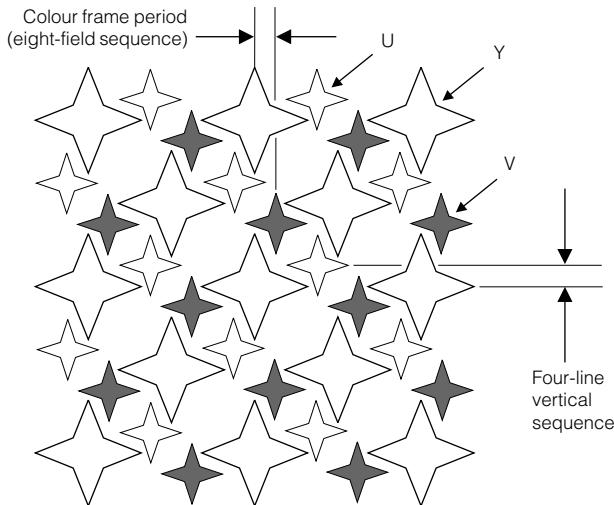


Fig 2.5.3 Interleaving of Y,U and V in PAL

The quarter cycle offset produces line quartets instead of line pairs, and this is necessary to obtain the vertical frequency component of one quarter of line rate which is needed for spectral interleaving. Furthermore four frames or eight fields have to elapse before the same relationship of subcarrier to frame timing repeats. This results in a temporal frequency component of one quarter of frame rate which is also visible in the figure. This component is also necessary for spectral interleaving, but restricts the way in which PAL recordings can be edited. Note that there is an area of the spectrum which appears not to contain signal energy in PAL. This is known as the Fukinuki hole. The three-quarter cycle offset of subcarrier also means that the line pair cancellation of NTSC is absent, and another means has to be found to achieve visibility reduction. This is done by adding half frame rate to subcarrier frequency, such that an inversion in subcarrier is caused from one field to the next. Since in an interlaced system lines one field apart are adjacent on the screen, cancellation is achieved.

The penalty of this approach is that subcarrier phase creeps forward with respect to H-sync at one cycle per frame. The eight field sequence contains 2500 unique lines all having the subcarrier in a slightly different position. Observing burst on an H-triggered oscilloscope shows a stable envelope with a blurred interior. Once more the vertical/temporal spectrum only shows part of the story.

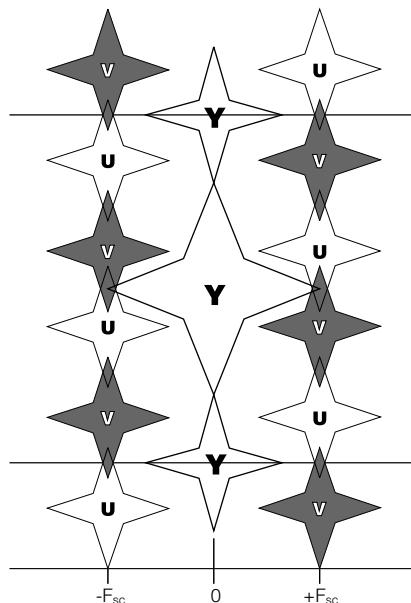


Fig 2.5.4. PAL vertical-horizontal spectrum

Fig 2.5.4 shows the vertical/horizontal spectrum in which it will be seen that the chroma is separated on the horizontal frequency axis by the subcarrier frequency.

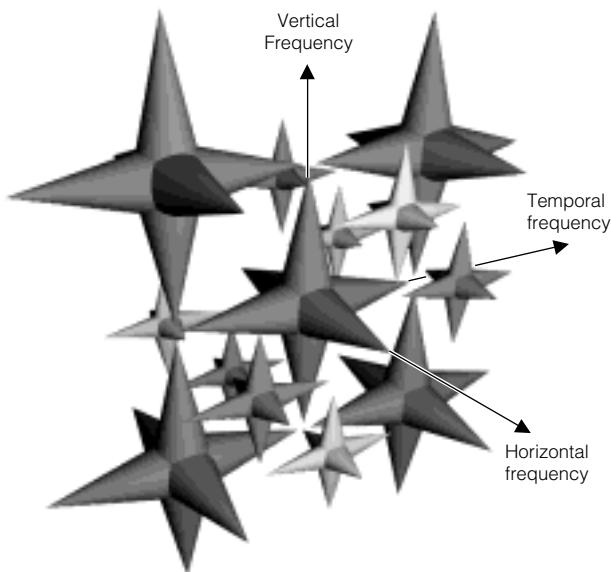


Fig 2.5.5. A 3-dimensional representation of the PAL spectrum

Fig 2.5.5 shows a perspective representation of the three dimensional spectrum of PAL. The one dimensional spectrum of the PAL signal in the area of the subcarrier will now be considered. Beginning with the luminance signal, as for NTSC the effect of interlace is that there is a coarse spectrum based on multiples of line rate and a fine spectrum repeating at multiples of 50 Hz as shown in Fig 2.5.6b).

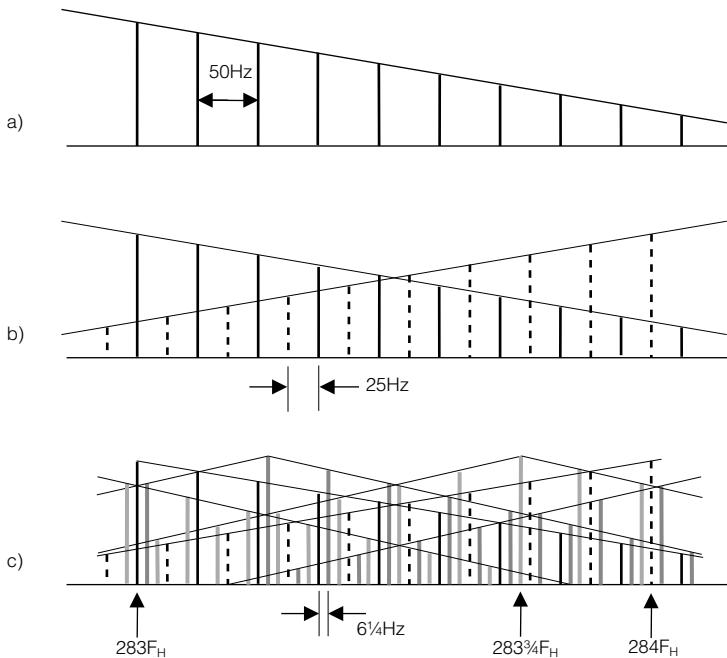


Fig 2.5.6 Temporal sampling spectrum of PAL

PAL, the presence of V-switch alters the spectrum in comparison with NTSC. The U-signal is unaffected and has the same spectrum as luminance. However, V-switch effectively modulates a half-line-rate square wave with the V signal. The result is that the V spectrum is displaced by half line rate such that the line rate multiples of V fall between the line rate multiples of U as shown in Fig 2.5.6c). The half line rate offset of NTSC clearly cannot be used as this would cause the V-component spectrum to have identical frequencies to luminance. Instead a three-quarter line rate offset must be used. Fig 2.5.6c) shows that on a coarse scale the U component resides at three quarters of the way between luminance line rate multiples and the V component resides one quarter of the way. Meshing is also achieved on the fine spectral scale. The fundamental spectral spacing here is $6\frac{1}{4}$ Hz, which is responsible for the eight field sequence. Note that the addition of 25 Hz to the subcarrier frequency does not affect the meshing of the coarse or fine spectra. The 25 Hz component neither causes nor affects the eight field sequence.

2.6 Colour framing and Sc-H phase

Composite video was originally designed purely for transmission and all three systems work well in that role. However, the low temporal frequencies resulting from the deliberate measures to render the chroma invisible caused some difficulties when editing composite video recordings was attempted. Monochrome editing requires only that the line and frame synchronizing is unbroken at the edit, but the presence of chroma adds the requirement that the low frequency components continue across the edit. VTRs require a colour framing signal in the control track to specify the field in which the lowest frequency begins a cycle. Digital timebase correctors attempt to make the offtape chroma sequence the same as in the reference. The timebase corrector will re-phase the low frequency components of non-colour framed edit by moving the picture vertically or horizontally as required and in some cases these picture shifts will be visible. In composite vision mixers the most critical aspect of the signal is that the subcarrier phase of all inputs should be the same. Timebase correctors are designed to align subcarrier phase with reference so that tapes can be mixed with other sources. If the Sc-H phase on the tape is not the same as that of the reference the picture is once more shifted horizontally by the TBC. A further problem is that certain Sc-H phases make it impossible unambiguously to identify the field in which the lowest frequency begins a cycle and colour framing is not then possible. As a result definitions of acceptable Sc-H phase have been produced which specify the time relationship between a zero crossing of subcarrier and the 50% point of sync on a specified line. In order to meet the specification subcarrier has to generated with a mathematical relationship to sync.

SECTION 3 - ADVANCED DECODING

3.1 Introduction

Composite decoding requires two main processes, which are usually carried out sequentially. One is to separate the chrominance signal from the luminance; the other is to demodulate the chrominance into the original colour difference signals. In NTSC and PAL it is not necessary to perform these processes in a particular order. The quadrature demodulation process requires multiplication by a subcarrier and is indistinguishable from a modulation process. Thus demodulating composite video without prior Y/C separation has the effect of modulating luminance to new frequencies which can later be filtered from the colour difference signals. In many standards converters the interpolation filter which changes the scanning parameters has a subsidiary task of suppressing residual chroma in luminance.

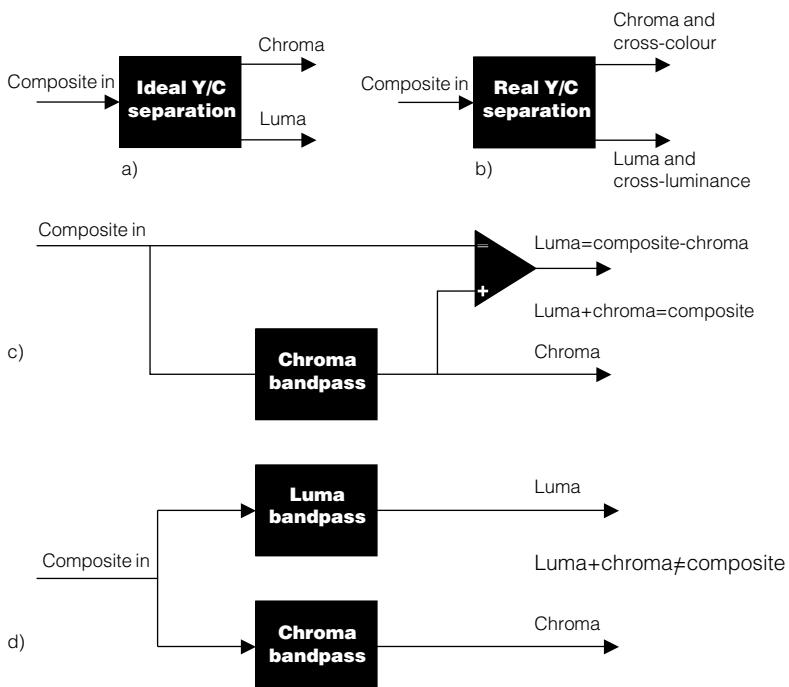


Fig 3.1.1. Y-C separation

Fig 3.1.1a) shows an ideal Y/C separator whereas Fig 3.1.1b) shows what happens in practice. Ideal separation is impossible and there is always some crosstalk. The luminance signal contains some residual chroma which is called cross-luminance and the chroma signal contains some cross-colour. If the decoded

components are subsequently re-encoded to composite, it is possible to return the cross-colour and cross-luminance to their original places in the composite spectrum provided that the subcarrier used in the second encoder has the same relationship to syncs as the subcarrier in the original signal. If this relationship is not maintained, artifacts will result. This is the reason why component video recorders still have colour framing systems; it allows them to record composite inputs using simple decoders and correctly to re-encode the original composite signal on replay. This effect is only obtained if the filtering is complementary. A complementary Y/C filter is defined as one whose outputs when linearly added will recreate the original input waveform exactly. This is easily achieved in practice by constructing a filter as shown in Fig 3.1.1c) which selects chroma from the input. This chroma signal is simply subtracted from the composite input to produce luminance in which case the outputs are complementary by definition. In practice simple decoders need to be complementary so that re-encoding can be used, whereas in high quality decoders will achieve sufficient separation to make complementary operation unnecessary. In fact the requirement for complementary signals is a restriction in advanced decoder design and is undesirable as well as unnecessary. A non-complementary filter is shown in Fig 3.1.1d). Each output is obtained by a separate filtering process. It was shown in section 2 that in ideal PAL and NTSC signals the chroma resides in a different space to the luminance and so it is theoretically possible to make a filter which separates them. In NTSC the I and Q signals share the same spectrum and can only be separated in the quadrature demodulation process. In PAL, the U and V signals also reside in different spaces to one another and so it is also possible to separate U and V spectrally prior to demodulation. This theory does not tell us how to design such a filter or how complicated it will be. In practice real picture material can result in non-ideal spectra where the components may overlap. In this case ideal separation is impossible. However, there is a possibility that suitable pre-filtering may be used before or during composite encoding to ensure that no such crosstalk is allowed in the composite spectrum. In this case effective separation would be possible with all types of picture material. At the moment such pre-filters are uncommon, and as a result colour artifacts are generated by certain luminance patterns. Herringbone suits and zebras at the right distance from the camera can both produce luminance frequencies which extend into and are indistinguishable from chroma frequencies. Without pre-filtering, the decoder produces false colours.

3.2 Simple Y/C separation

Early decoders were rather crude and simply contained a notch filter centred around subcarrier frequency which removed chroma from the composite signal as well as removing high frequency luminance. The resulting picture was quite soft but when displays were small and of moderate performance this was acceptable except when highly saturated colours or sharp detail were present when cross effects would be evident. A bandpass filter centred on subcarrier was used to produce the chroma

signal. In the presence of luminance detail this contained a great deal of cross luminance. Such performance is totally unacceptable for production purposes. In NTSC and PAL more sophisticated filters can be used based on the predictable phase changes of chroma from one line or field to the next. These cannot be used for SECAM because the chroma is frequency modulated and the phase becomes arbitrary. SECAM Y/C separation must use a notch filter. Cross colour is less of a problem in SECAM because the colour information is carried in the frequency of the chroma. Line and field based separation cannot be used on PAL or NTSC signals unless they are perfectly stable. Unstable signals such as from colour-under VCRs can only be separated with a notch filter. For applications like this and for SECAM, an improvement can be obtained if the notch filter in the luminance channel is programmable in depth and width and varies according to the chroma content.

3.3 Field combs

It has been mentioned above that on still pictures the temporal spectrum collapses to discrete lines. In this case it is possible to perform Y/C separation using a comb filter which is based on field delays.

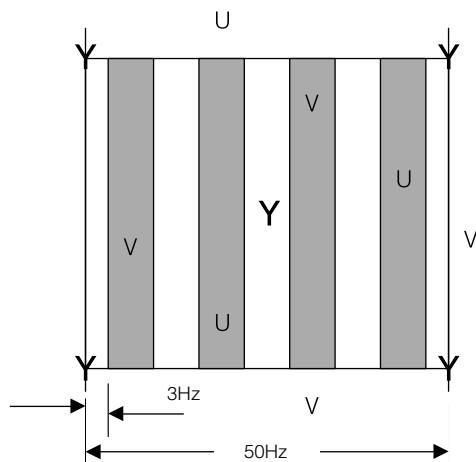


Fig 3.3.1. Vertical - temporal response of a field comb

Fig 3.3.1 shows the response of a field comb with respect to the vertical/temporal spectrum. With still images separation is perfect. However, even the slightest image motion will result in cross effects and blur. In PAL temporal frequencies due to motion are only rejected up to 3 Hz. Such frequencies are easily reached even by the motion of undetailed areas.

3.4 Line combs

The repetitive nature of the composite spectrum suggests the use of comb filters. The luminance repeats at multiples of line rate with the chroma between.

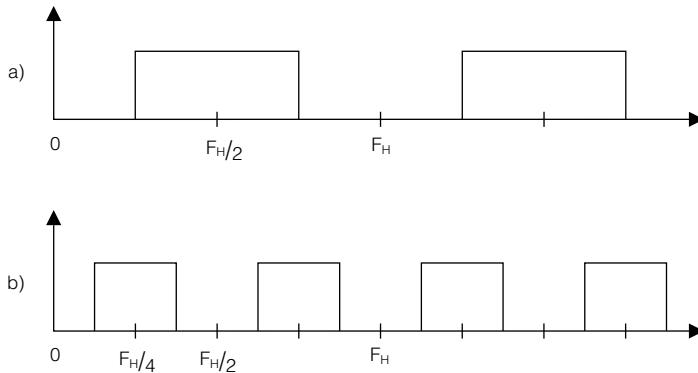


Fig 3.4.1. Ideal responses for comb filters a) for NTSC and b) for PAL

Fig 3.4.1a) shows the ideal frequency response of a comb filter for NTSC and b) shows the ideal response for PAL in which the “teeth” are spaced half as far apart. The ideal square teeth shown cannot be achieved in practice because the number of points in the filter has to be infinite. In practice little more than the fundamental frequency of the teeth will be obtained.

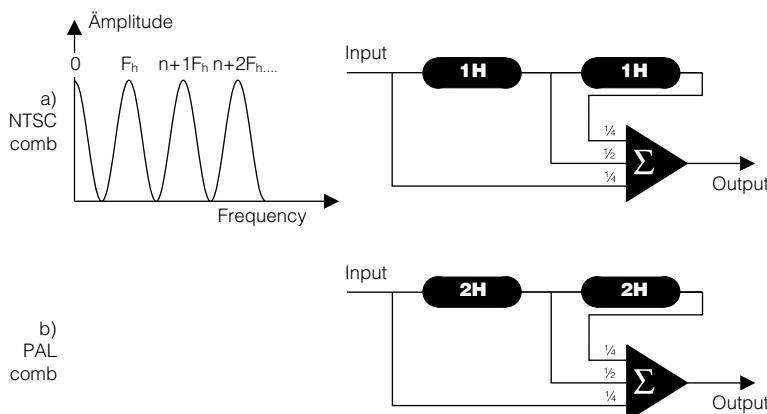


Fig 3.4.2. Frequency response of line combs

Fig 3.4.2a) shows a simple line comb for NTSC and its frequency response. The delays needed are of one line period. The configuration for PAL is shown in b) in which the delays need to be of two line periods. Line combs work quite well in NTSC but less well in PAL. The reason can be seen in Fig 3.4.3 which shows the response of a comb filter superimposed on the vertical/temporal spectrum.

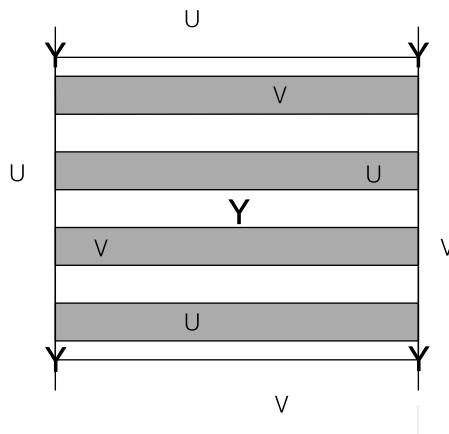


Fig 3.4.3. Vertical - temporal response of comb filter

Quite a lot of vertical luminance resolution is being lost, and becoming cross luminance, particularly in PAL. Similarly, high vertical frequencies in chroma become cross colour. Some of this resolution loss can be overcome by restricting the combing to a bandpass region as shown in Fig 3.4.4a)

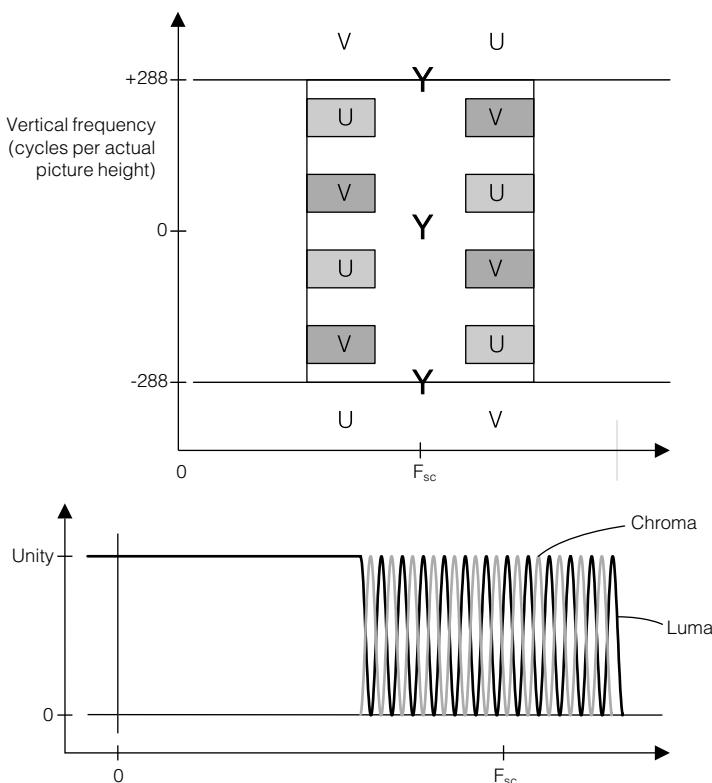


Fig 3.4.4. Vertical -horizontal spectrum of PAL comb

The result can be seen in b) which is a vertical/horizontal spectrum. At low horizontal frequencies the full vertical resolution is restored and the loss of vertical resolution only occurs at high horizontal frequencies. Although the full luminance bandwidth is available, this is restricted to picture detail having vertical edges. Man-made subjects such as buildings give good results, but more natural scenes containing diagonal edges are less successful.

3.5 Adaptive filters

Possibly the main drawback of the line comb is the cross colour due to high vertical frequencies in the colour difference signals. Fig 3.4.3 showed how these frequencies are accepted by the luminance passband. It is possible to visualise how this cross colour occurs by considering how the comb filter handles chroma. The

line comb effectively adds lines together. In NTSC the chroma inversion between lines and in PAL the inversion over two lines results in chroma cancellation. However, this is only true if the chroma phase is the same on the three lines being added. Whilst the subcarrier inverts as required, there is no subcarrier in chroma.

If there are vertical colour changes in the image, there will be chroma phase changes from line to line and the chroma cancellation will break down. This is known as comb mesh failure and the result is that uncancelled chroma breaks through onto the luminance signal and causes dots at vertical transitions. In practical line combs, it is necessary to revert to simple Y/C separation when comb mesh failure occurs. A low-pass filter is used to produce narrow-band luminance which is free of dots. Circuitry is added to the comb which compares chroma phase over the line delays to predict when failure will occur. A tuned circuit may also be provided in the comb luminance output which produces a signal if comb failure actually occurs. Either of these systems can switch the luminance output to the narrow-band signal. Y/C separators have also been made which switch between field combs and line combs on an adaptive basis. The switch between operating modes can be visible in an adaptive filter. It is particularly noticeable on moving objects where the difference between static and dynamic resolution becomes clear. It is difficult to detect the conditions in which one or other mode should be selected because of the complex spectrum of real signals. Additionally there will always be signals which will not be handled well by any mode. Noisy signals may result in undesirable frequent mode switching.

3.6 Multi-dimensional filtering

Conventional line or field comb filters are not the ideal solution to Y/C separation, particularly in PAL as they only work in one dimension at a time. The reason this fails is the strong diagonal distribution of chroma in the vertical/temporal domain. However, the shortcomings of these filters can largely be overcome by designing filters having two-dimensional responses which can follow the diagonal chroma structure. Caution is necessary because of the vertical and temporal phase (and V-switch in PAL) changes in composite signals. If composite signals are to be combined in a multi-tap filter it may be necessary to invert or phase shift certain taps before adding in order to avoid corrupting the chroma. In the case of PAL it may be necessary to have two filters, one feeding the U demodulator and one feeding the V demodulator so that lines containing opposing states of V-switch can be added in one case and subtracted in the other. In a filter which is designed to reject chroma from luminance this is unnecessary as it is only required to remove the correct frequencies. It will be clear that if such techniques are used, the Y/C separation will not be complementary. However, if the performance is good enough this is not a concern.

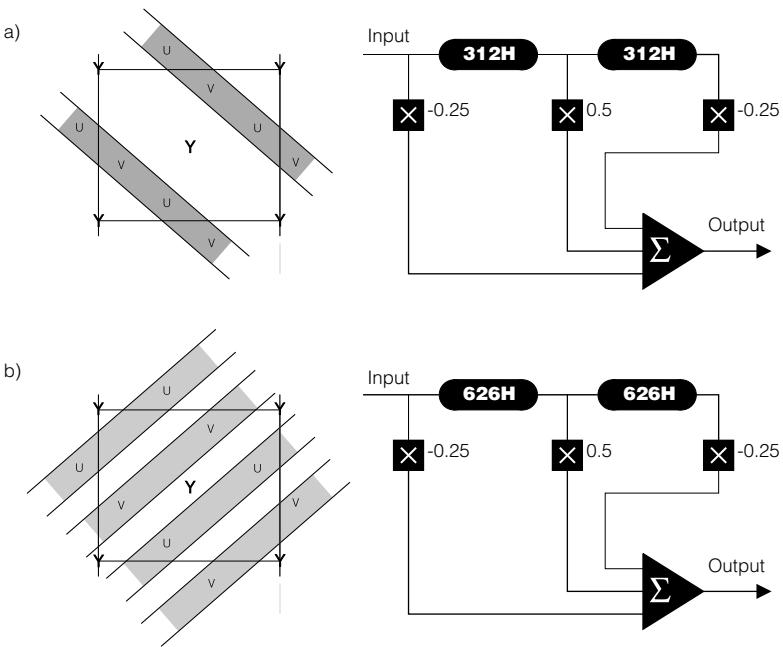


Fig 3.6.1(a&b). Diagonal comb filters

Fig 3.6.1a) shows a diagonal comb filter based on 312-line delays and the corresponding vertical/temporal response. 312 lines is one field period to the nearest line. A delay of 312 lines has the same state of V-switch on input and output so can meaningfully be combined to create chroma. Owing to interlace, summing three points at a spacing of 312 lines places the impulse response diagonally on three different picture lines vertically and in three different fields temporally, hence the diagonal response. A second comb filter having a spatio-temporal response at right angles to that of Fig 3.6.1a) is required, but the spacing of the comb “teeth” must be halved because of the periodicity of U and V energy. A comb filter based on 313-line delays has a response in the vertical/temporal diagram with the opposite slant to that of the 312 line comb but the period is too great and the delay has to be doubled to 626 lines as shown in Fig 3.6.1.b).

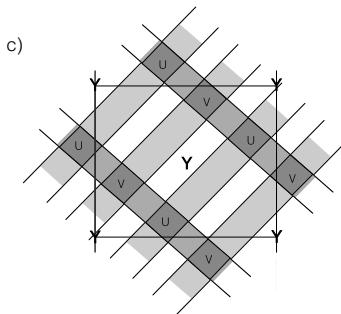


Fig 3.6.1(c). Combined diagonal comb filters

Combining the two filters as in c) has the effect of selecting diamond shaped areas in the two dimensional spectrum in which the U and V signals reside. Another way of looking at this result is to consider that the diagonal spectrum of video is due to interlace in the first place and it is intuitive that a filter having points on an interlaced scan is bound to have a diagonal response. Using a three tap comb filter it is only possible to obtain a sinusoidal frequency response. Increasing the number of taps allows more terms in the Fourier series to be admitted and the response can be improved to make the passband flatter and the cut-off steeper. However, this increase cannot be taken too far.

Firstly, the cost of the filter rises dramatically with the number of points, particularly when increasing the impulse response window along the time axis requires additional fields of storage which also cause the filter delay to rise. Secondly a large number of points on the time axis can result in the response becoming too sharp in which case ringing will occur due to the filter ripple. This is evident as multiple images of moving objects. Similarly an excessive number of vertical points can result in spatial ringing particularly on horizontal edges between coloured areas. The selection of the number of filter points is thus a compromise, but to keep matters in perspective the final result is considerably better than in any simpler approach. A particularly desirable result in spatio-temporal filters of this kind is that the need for adaptation is eliminated.

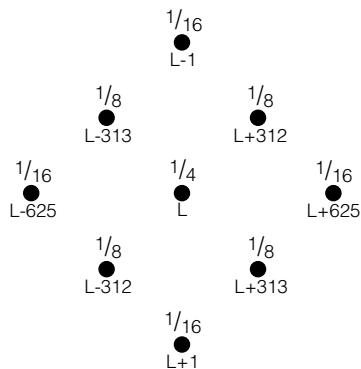


Fig 3.6.2(a). Location of points in a nine-tap PAL filter

Fig 3.6.2a) shows the location of points in a nine tap PAL filter and the structure of such a filter is shown at b).

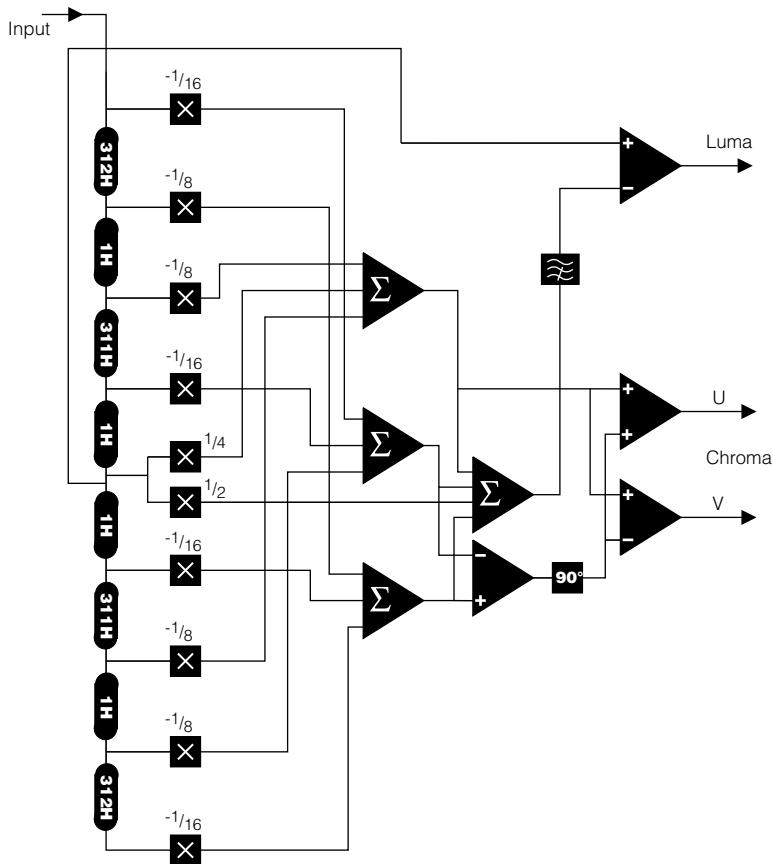


Fig 3.6.2(b). Block diagram of nine-tap PAL filter

Note that this is not a complementary filter; the luminance signal is obtained by producing a two dimensional chroma passband regardless of V-switch and subtracting it from luminance. The U and V outputs are obtained after a 90 degree phase shift to counteract the effects of subcarrier quadrature from line to line. Separate additions and subtractions are used to produce U and V signals allowing for the effect of V-switch.

3.7 Chroma Demodulators

In SECAM the colour difference signals are sent on alternate lines on a frequency modulated subcarrier. Following Y/C separation the chroma will be decoded to baseband colour difference signals. Fig 3.7.1 shows that there are two frequency discriminators, one for each centre frequency.

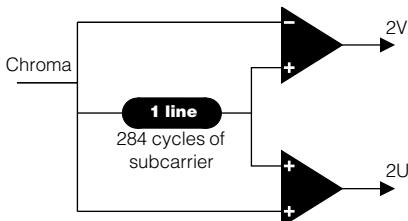


Fig 3.7.1. SECAM demodulator

Input chroma is passed through a one line delay. As the colour difference signals are sent alternately, when one type of signal is entering the delay, the other type will be coming out. The demodulator will lock to the two line sequence by using the unmodulated subcarrier at the beginning of each line and will use the sequence to operate a two pole changeover switch which ensures that the correct colour difference signal is always fed to the appropriate discriminator. Following the discriminators are two low-pass filters which remove any residual subcarrier in the baseband output. The DR signal is re-inverted to oppose the inversion in the encoder. The luminance signal has been obtained by passing the composite input through a notch filter and a compensating delay which time-aligns luminance with the demodulated colour difference signals. If RGB is required, a further matrix can be used.

3.8 NTSC demodulation

Fig 3.8.1 shows an NTSC demodulator. The composite input is Y/C separated. A sync separator recognises horizontal sync edges and produces a burst gate which allows input bursts into the burst locked oscillator which is used to locally regenerate subcarrier.

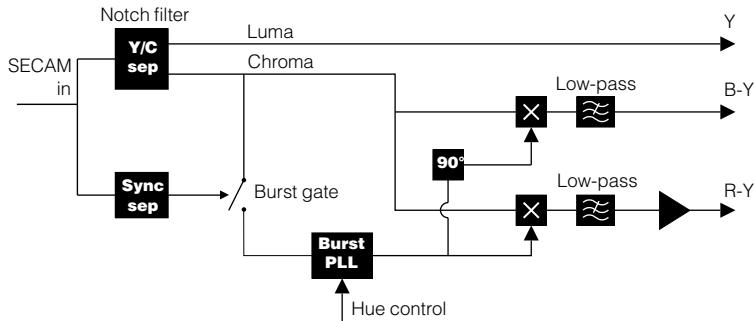


Fig 3.8.1. NTSC demodulator

The hue control changes the phase of the local oscillator with respect to burst. The oscillator output is provided with a quadrature phase shift for one of the demodulators. Following the demodulators, low pass filters of 1.3 MHz bandwidth are used to remove residual subcarrier frequencies from the baseband colour difference signals. Luminance passes through a compensating delay.

3.9 PAL demodulation

Simple PAL demodulation can be obtained by a slight modification to Fig 3.8.1 which is shown in Fig 3.9.1

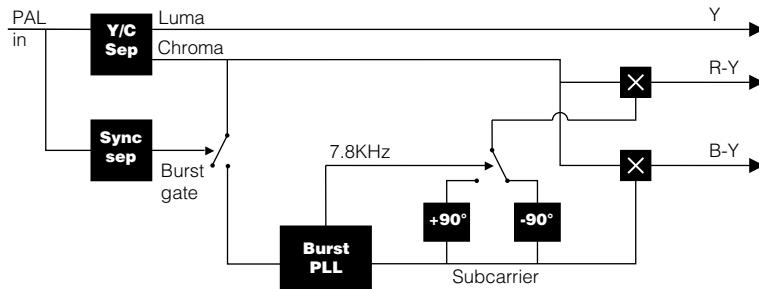


Fig 3.9.1. PAL demodulator

The burst locked oscillator is heavily damped and runs at the average phase of burst. As a result, burst swing will cause a phase error at the oscillator which has a frequency of 7.8 kHz. This is the V-switch signal and it is used to invert the V-signal

on alternate lines. This can be done by switching the quadrature reference between plus and minus 90 degrees, or by switching in and out an inverter in the baseband V signal. This simple demodulator relies upon the eye to average out phase errors and if these are serious, the result will be Hanover blinds. The proper PAL decode (PAL-D) requires the colour difference signals to be averaged over two lines. This requires a one line delay which is best implemented before demodulation where the signal contains fewer octaves. The delay is slightly increased from one line to make it a whole number of cycles of subcarrier long.

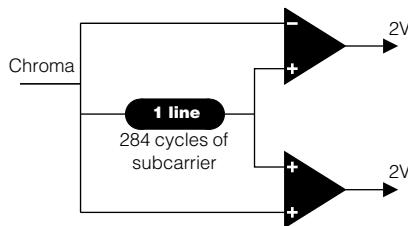


Fig 3.9.2. PAL delay line averager

Fig 3.9.2 shows the configuration of the line averager. As the U signal is unswitched, after a delay of 284 cycles it will have the same phase. Adding the input of the delay to the output results in reinforcement of the U signal but cancellation of V. On the other hand V-switch means that after a delay of 284 cycles the V signal will be inverted. Adding the inverted input to the delay output reinforces the V signal but cancels U. These signals are both the average of two lines and so phase errors will have been cancelled. The separated U and V signals are fed to a pair of demodulators followed by low-pass filters to remove residual subcarrier. In early PAL-D TV sets the accurate 284 cycle delay was an expensive item. In the digital domain it is much easier to implement.

3.10 Digital decoders

In practice the multi-tap filters required in advanced spatio-temporal decoders can only be implemented in the digital domain where the rigid control of the time axis prevents unwanted phase shifts due to drift. A sampling rate which is locked to subcarrier helps in this respect and also allows standardized composite digital inputs to be decoded. In the case of analog inputs a suitable ADC will be required. The composite digital standards sample at four times subcarrier and thus take four samples per cycle. As the sampling clock is subcarrier locked, the composite sampling process is actually a form of demodulation but prior to Y/C separation. Following Y/C separation in a digital filter, the emerging chroma samples are already demodulated by the 4FSc sampling and it is only necessary to selectively invert and matrix chroma samples to produce colour difference signals decoded on the desired axes. The matrixing is needed because digital NTSC samples on the I and Q axes whereas digital PAL samples at +/- 45 degrees to the colour difference axes.

Following demodulation the colour difference signals need to be low-pass filtered to the appropriate bandwidth. As a sampling rate convertor also requires a linear phase low-pass characteristic it is possible to combine both functions in one stage. The sampling rate convertor allows 4Fsc input data to be output at the line-locked sampling rates used in the standard digital component interface. Sampling rate conversion will be required for both components and luminance prior to multiplexing into the 4:2:2 data stream. If only analog outputs are required the sampling rate conversion can be omitted and DACs are driven directly.

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