
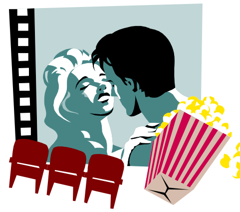
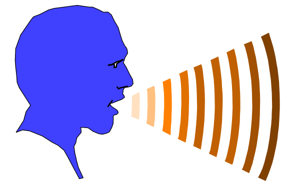
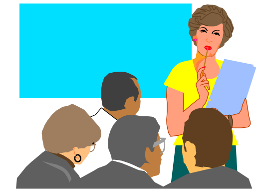

Video Processing & Communications

Basics of Video

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Outline

- Color perception and specification
- Video capture and display
- Analog raster video
- Analog TV systems
- Digital video

Color Perception and Specification

- Light -> color perception
- Human perception of color
- Type of light sources
- Trichromatic color mixing theory
- Specification of color
  - Tristimulus representation
  - Luminance/Chrominance representation
- Color coordinate conversion

Light is part of the EM wave

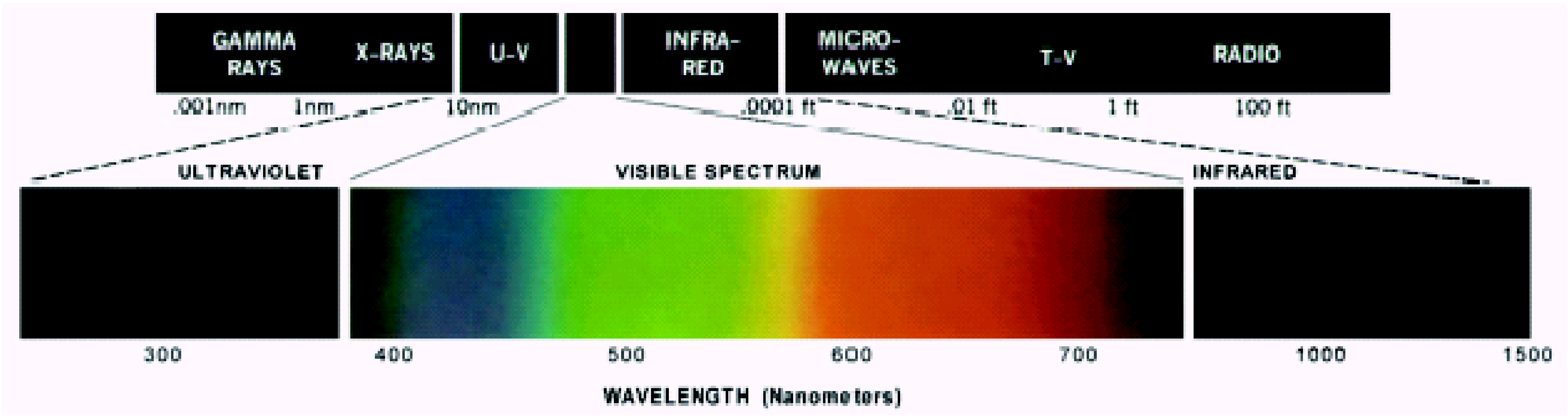


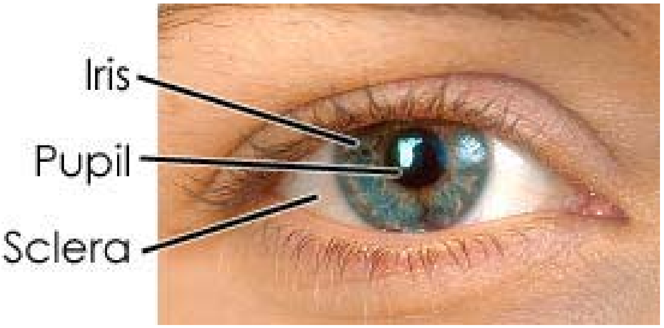
FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

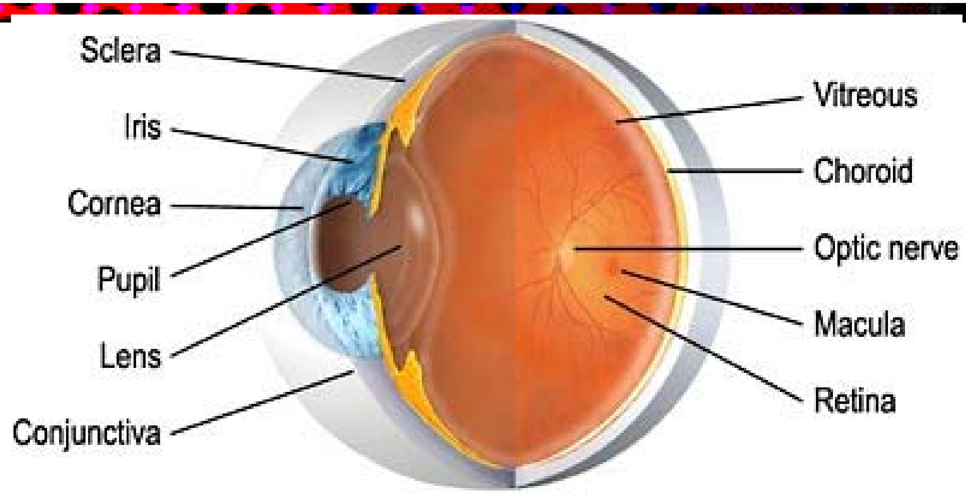
from [Gonzalez02]

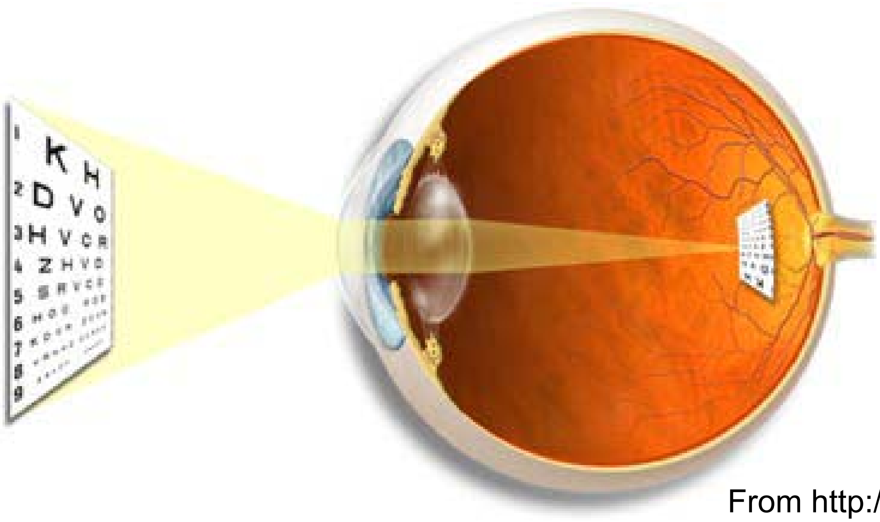
Illuminating and Reflecting Light

- Illuminating sources:
  - emit light (e.g. the sun, light bulb, TV monitors)
  - perceived color depends on the emitted freq.
  - follows additive rule
    - R+G+B=White
- Reflecting sources:
  - reflect an incoming light (e.g. the color dye, matte surface, cloth)
  - perceived color depends on reflected freq (=emitted freq-absorbed freq.)
  - follows subtractive rule
    - R+G+B=Black

Eye Anatomy

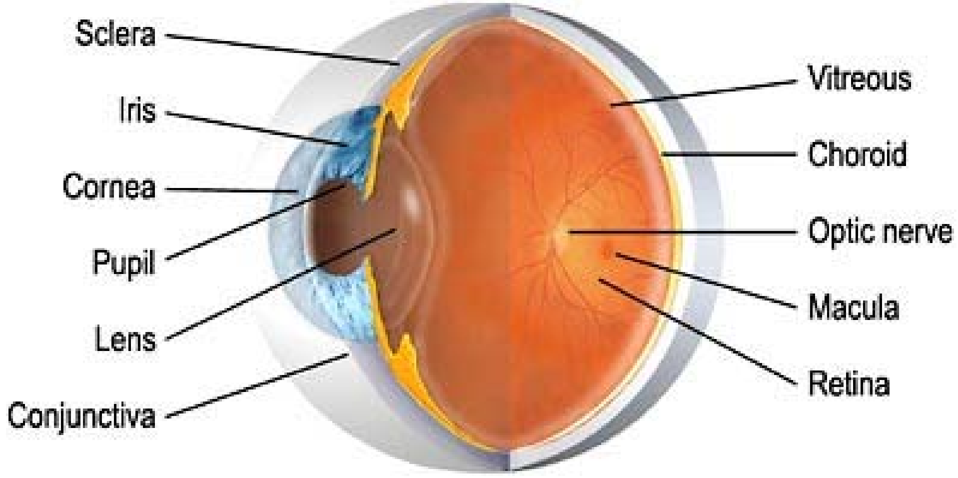






From http://www.stlukeseye.com/Anatomy.asp

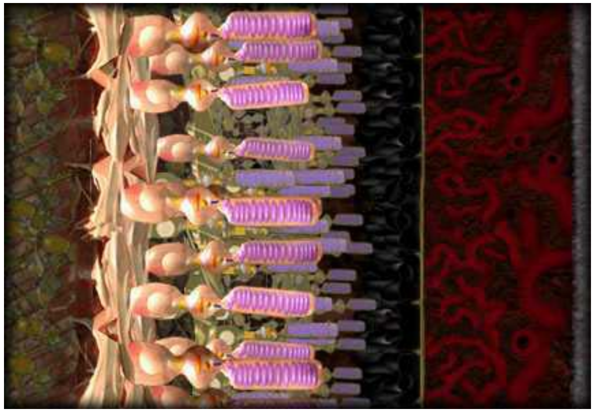
Eye vs. Camera



Camera components	Eye components
Lens	Lens, cornea
Shutter	Iris, pupil
Film	Retina
Cable to transfer images	Optic nerve send the info to the brain

Human Perception of Color

- Retina contains photo receptors
  - Cones: day vision, can perceive color tone
    - Red, green, and blue cones
    - Different cones have different frequency responses
    - Tri-receptor theory of color vision [Young1802]
  - Rods: night vision, perceive brightness only
- Color sensation is characterized by
  - Luminance (brightness)
  - Chrominance
    - Hue (color tone)
    - Saturation (color purity)



From http://www.macula.org/anatomy/retinaframe.html

Frequency Responses of Cones

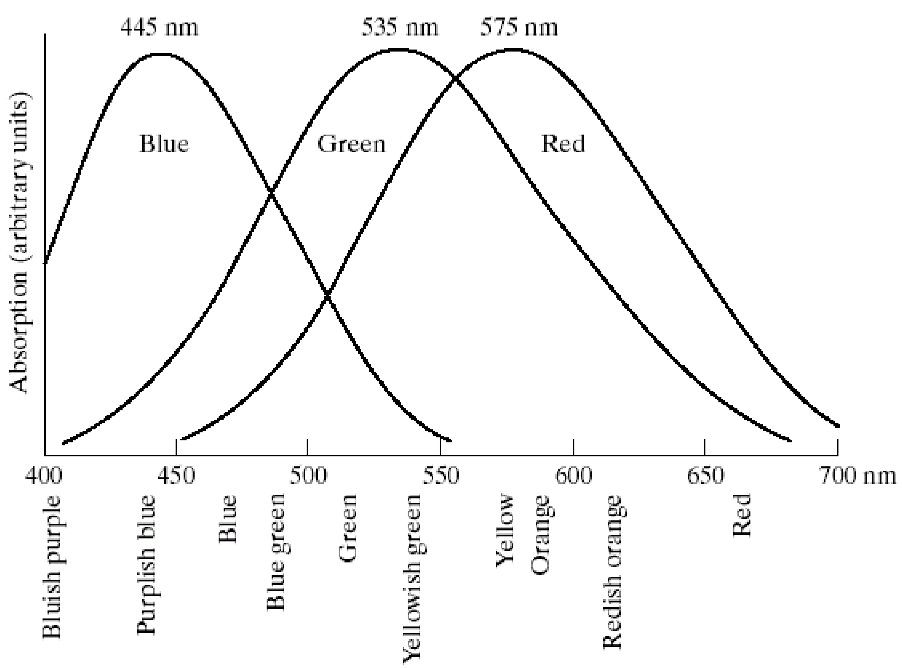
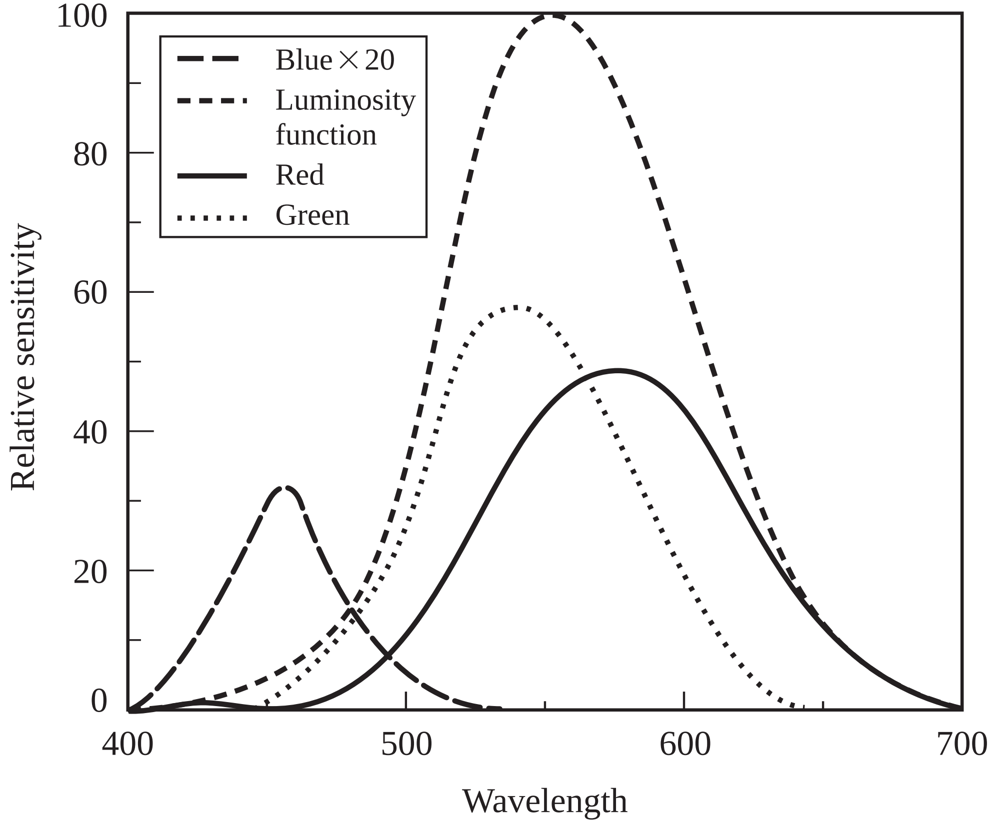


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

from [Gonzalez02]

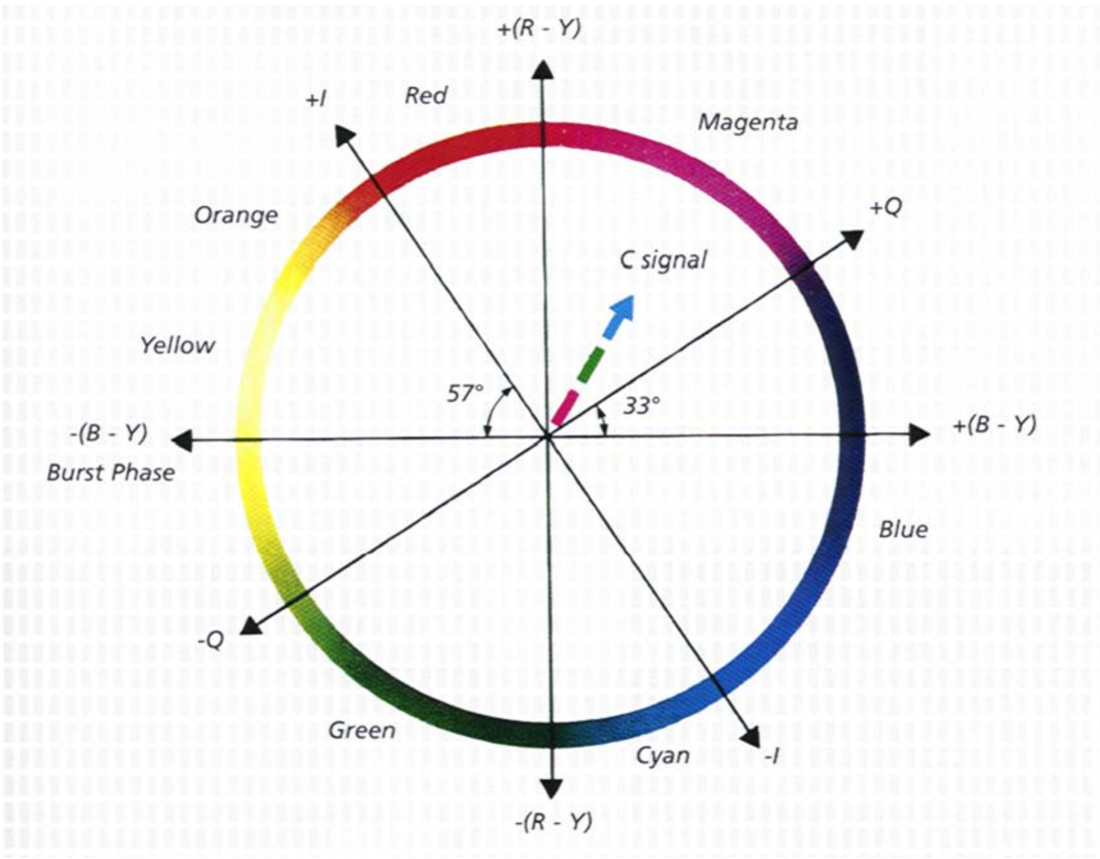
$$C_i = \int C(\lambda) a_i(\lambda) d\lambda, \quad i = r, g, b, y$$

Frequency Responses of Cones and the Luminous Efficiency Function



$$C_i = \int C(\lambda) a_i(\lambda) d\lambda, \quad i = r, g, b, y$$

Color Hue Specification



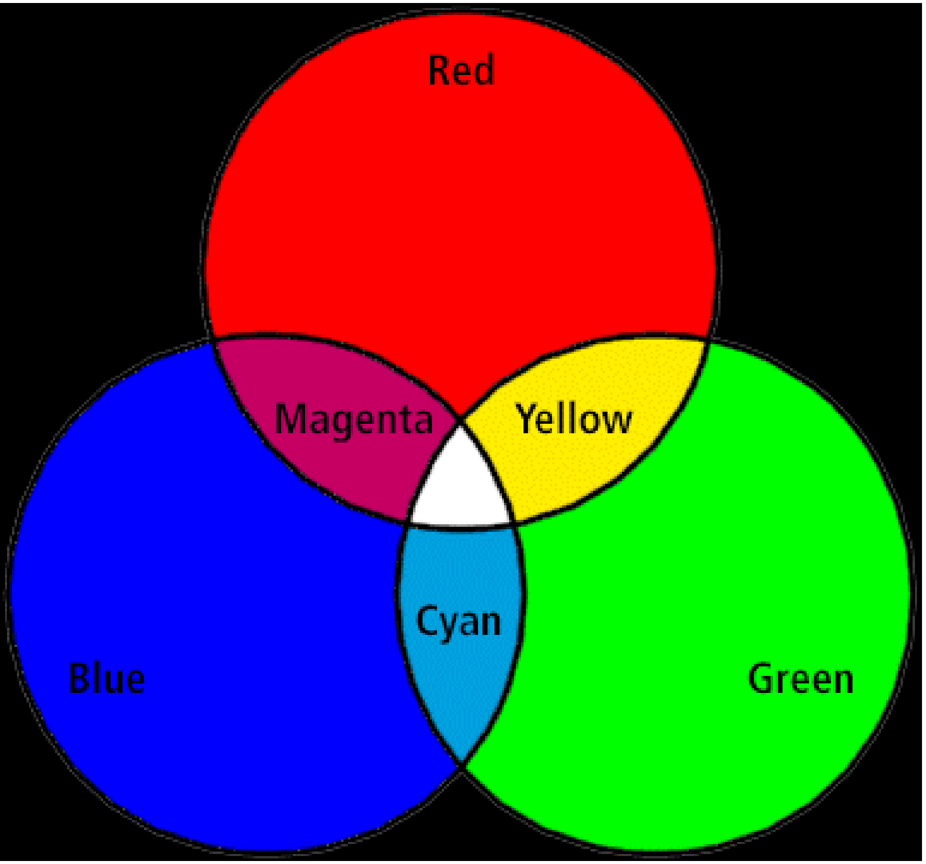
Trichromatic Color Mixing

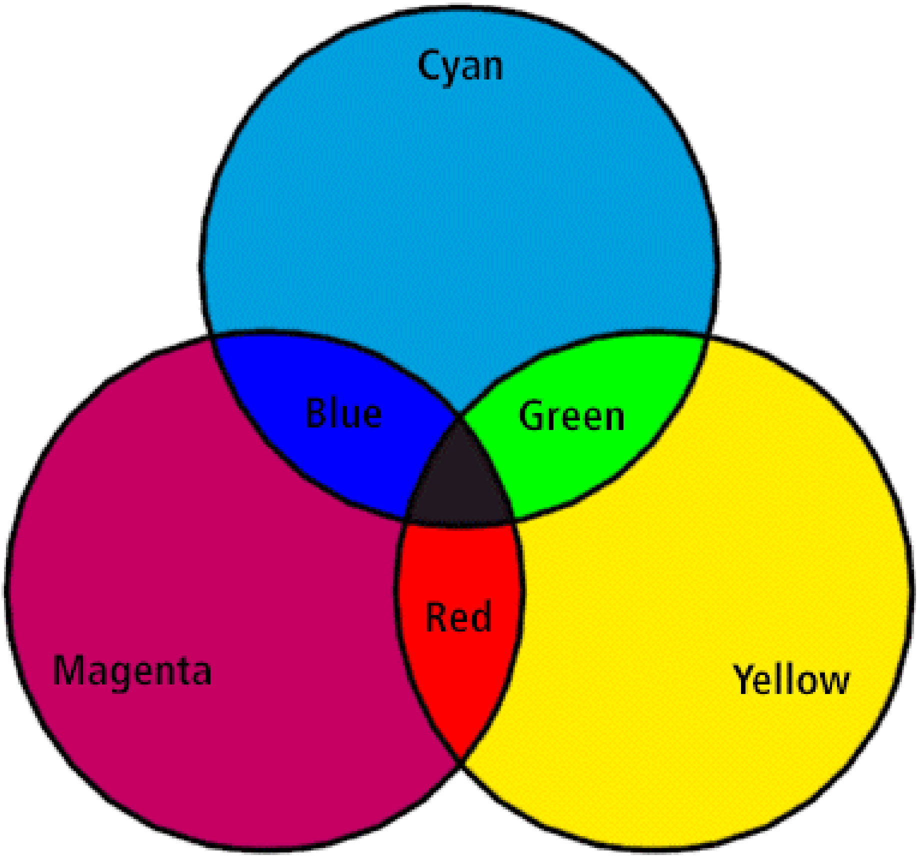
- Trichromatic color mixing theory
  - Any color can be obtained by mixing three primary colors with a right proportion

$$C = \sum_{k=1,2,3} T_k C_k, \quad T_k : \text{Tristimulus values}$$

- Primary colors for illuminating sources:
  - Red, Green, Blue (RGB)
  - Color monitor works by exciting red, green, blue phosphors using separate electronic guns
- Primary colors for reflecting sources (also known as secondary colors):
  - Cyan, Magenta, Yellow (CMY)
  - Color printer works by using cyan, magenta, yellow and black (CMYK) dyes

RGB vs CMY


Red
Magenta
Yellow
Cyan
Blue
Green


Cyan
Blue
Green
Red
Magenta
Yellow

red

Green

Blue

Color Representation Models

- Specify the tristimulus values associated with the three primary colors
  - RGB
  - CMY
- Specify the luminance and chrominance
  - HSI (Hue, saturation, intensity)
  - YIQ (used in NTSC color TV)
  - YCbCr (used in digital color TV)
- Amplitude specification:
  - 8 bits for each color component, or 24 bits total for each pixel
  - Total of 16 million colors
  - A true RGB color display of size 1Kx1K requires a display buffer memory size of 3 MB

Color Coordinate Conversion

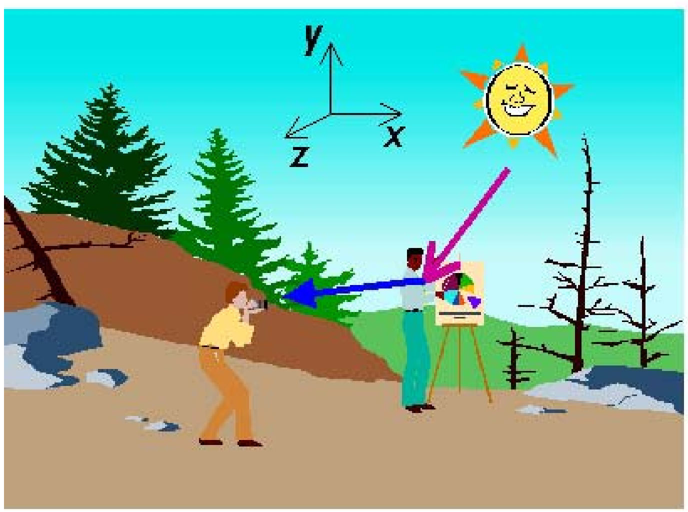
- Conversion between different primary sets are linear (3x3 matrix)
- Conversion between primary and XYZ/YIQ/YUV are also linear
- Conversion to LSI/Lab are nonlinear
  - LSI and Lab coordinates
    - coordinate Euclidean distance proportional to actual color difference
- Conversion formulae between many color coordinates can be found in [Gonzalez92]

Video Capture and Display

- Light reflection physics
- Imaging operator
- Color capture
- Color display
- Component vs. composite video

Video Capture

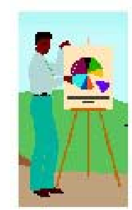
- For natural images we need a light source *(λ: wavelength of the source)* .
  - $E(x, y, z, \lambda)$: incident light on a point *(x, y, z world coordinates of the point)*
- Each point in the scene has a reflectivity function.
  - $r(x, y, z, \lambda)$: reflectivity function
- Light reflects from a point and the reflected light is captured by an imaging device.
  - $c(x, y, z, \lambda) = E(x, y, z, \lambda) \times r(x, y, z, \lambda)$: reflected light.



$\rightarrow$ $E(x, y, z, \lambda)$

$\rightarrow$ $c(x, y, z, \lambda) = E(x, y, z, \lambda) \cdot r(x, y, z, \lambda)$

Camera$(c(x, y, z, \lambda))$ =



Courtesy of Onur Guleryuz

More on Video Capture

- Reflected light to camera
  - Camera absorption function

$$\bar{\psi}(\mathbf{X},t)=\int C(\mathbf{X},t,\lambda)a_c(\lambda)d\lambda$$

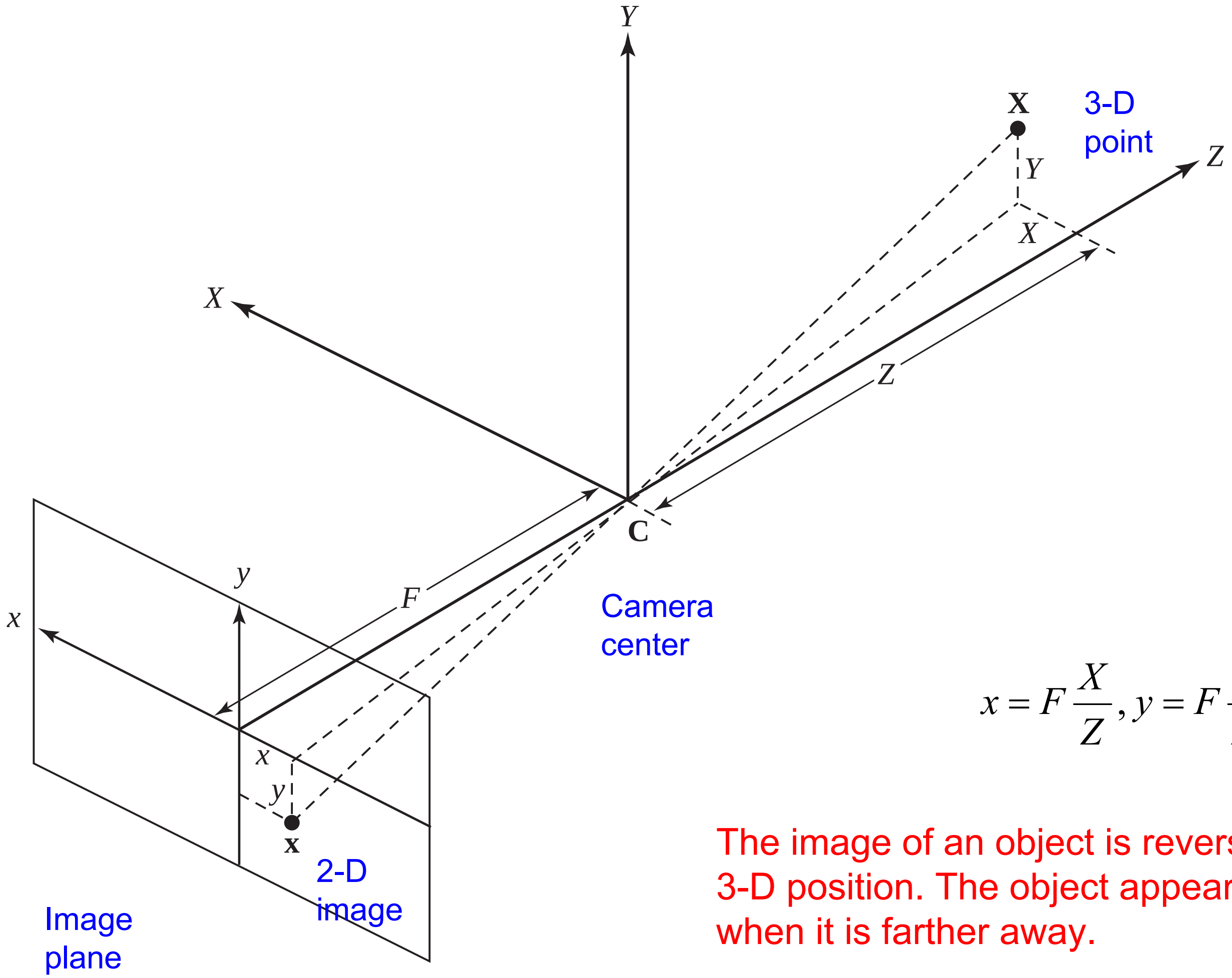
  - Projection from 3-D to 2-D

$$\mathbf{X}\underset{P}{\rightarrow}\mathbf{x}$$

$$\psi(P(\mathbf{X}),t)=\bar{\psi}(\mathbf{X},t) \quad \text{or} \quad \psi(\mathbf{x},t)=\bar{\psi}(P^{-1}(\mathbf{x}),t)$$

- The projection operator is non-linear
  - Perspective projection
  - Othographic projection

Perspective Projection Model



$$x = F\frac{X}{Z}, y = F\frac{Y}{Z}$$

The image of an object is reversed from its 3-D position. The object appears smaller when it is farther away.

How to Capture Color

- Need three types of sensors
- Complicated digital processing is incorporated in advanced cameras

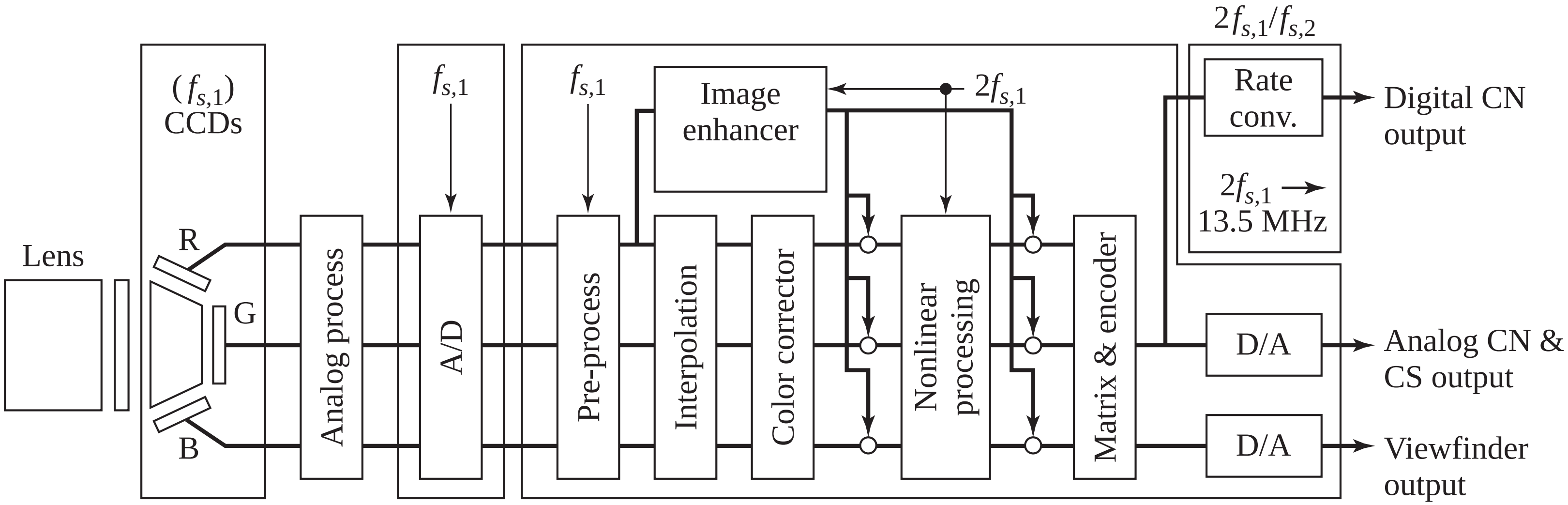


Figure 1.2 Schematic block diagram of a professional color video camera. Reprinted from Y. Hashimoto, M. Yamamoto, and T. Asaida, Cameras and display systems, *IEEE* (July 1995), 83(7):1032–43. Copyright 1995 IEEE.

Video Display

- CRT vs LCD
- Need three light sources projecting red, green, blue components respectively

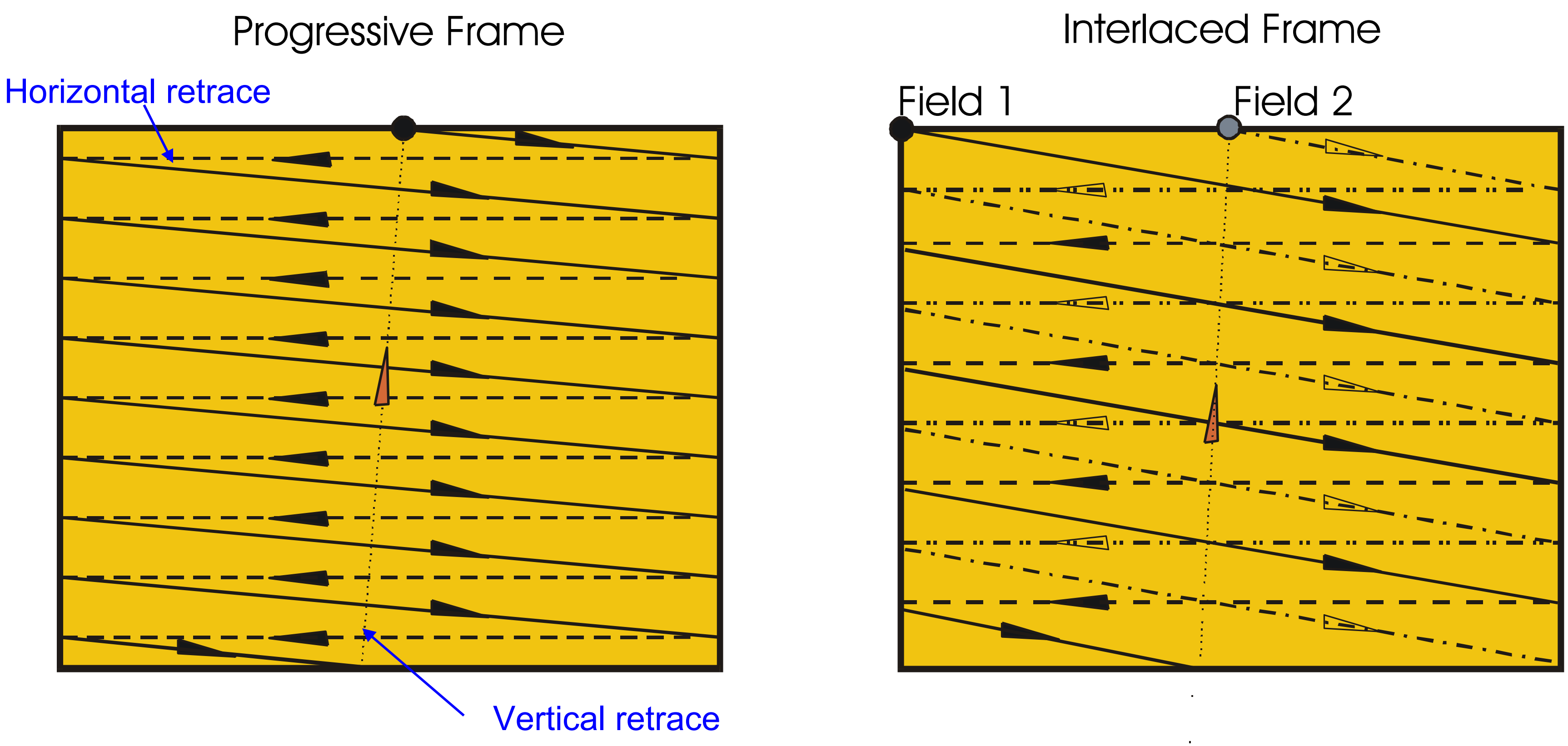
Analog Video

- Video raster
- Progressive vs. interlaced raster
- Analog TV systems

Raster Scan

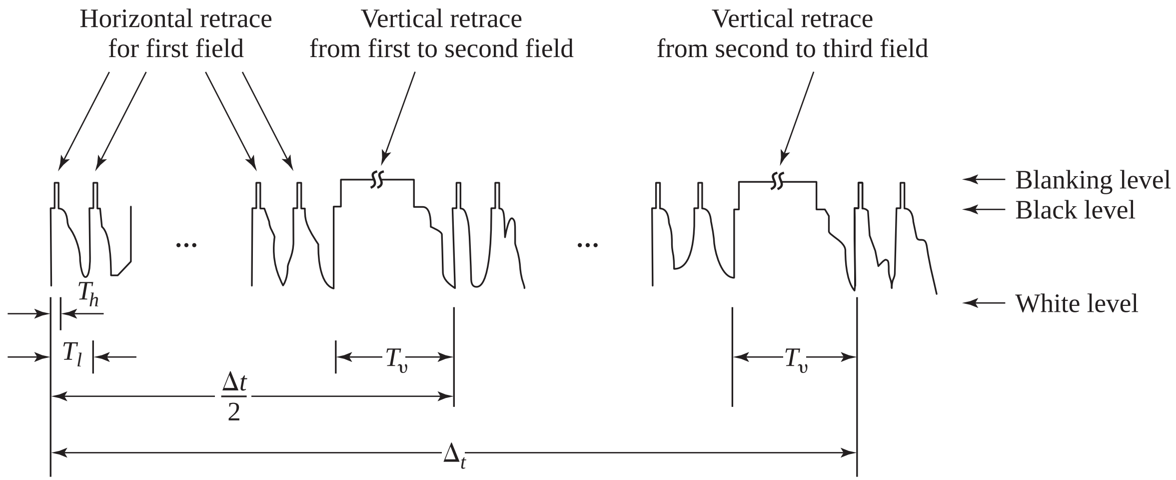
- Real-world scene is a continuous 3-D signal (temporal, horizontal, vertical)
- Analog video is stored in the raster format
  - Sampling in time: consecutive sets of frames
    - To render motion properly, >=30 frame/s is needed
  - Sampling in vertical direction: a frame is represented by a set of scan lines
    - Number of lines depends on maximum vertical frequency and viewing distance, 525 lines in the NTSC system
  - Video-raster = 1-D signal consisting of scan lines from successive frames

Progressive and Interlaced Scans

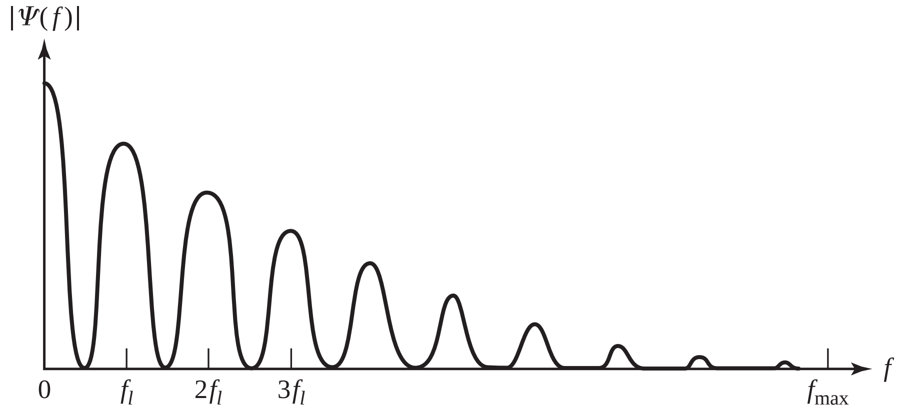


Interlaced scan is developed to provide a trade-off between temporal and vertical resolution, for a given, fixed data rate (number of line/sec).

Waveform and Spectrum of an Interlaced Raster

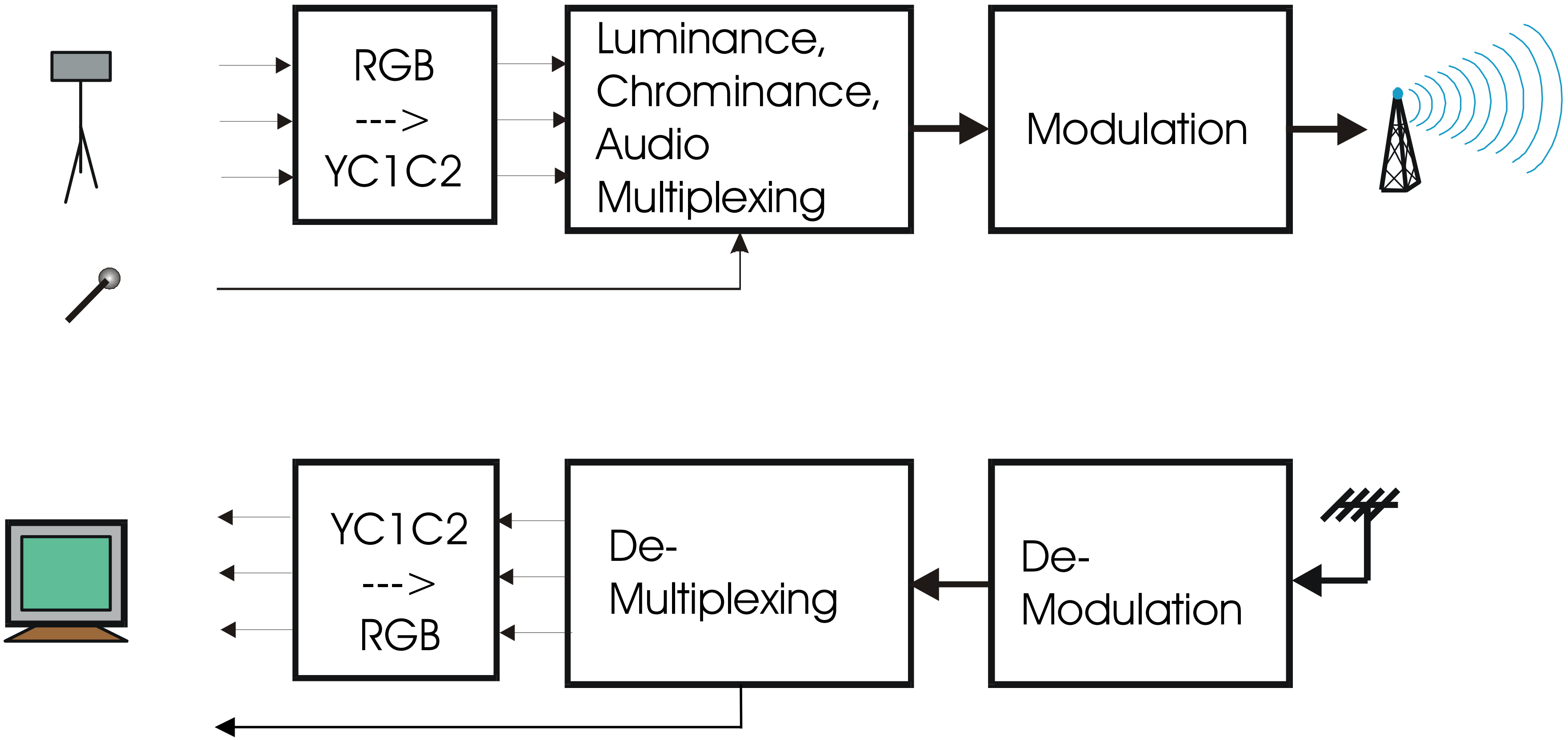


(a)



(b)

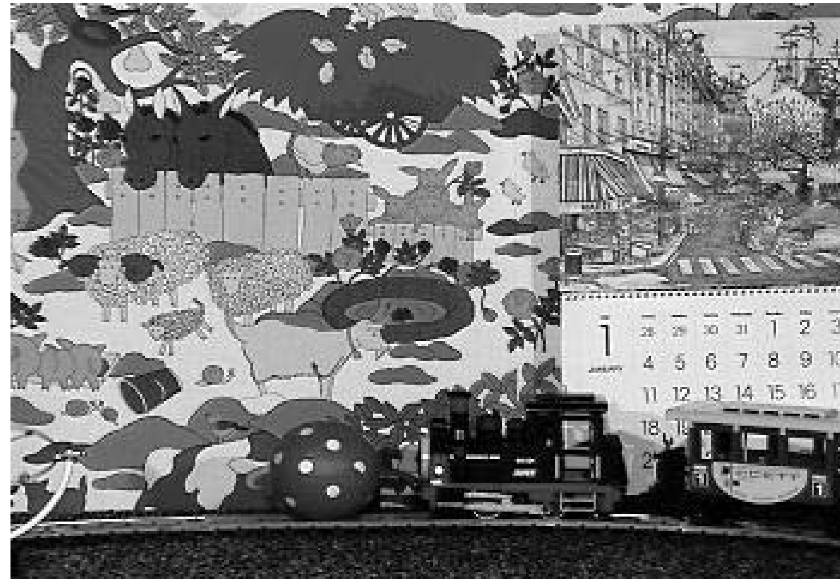
Color TV Broadcasting and Receiving



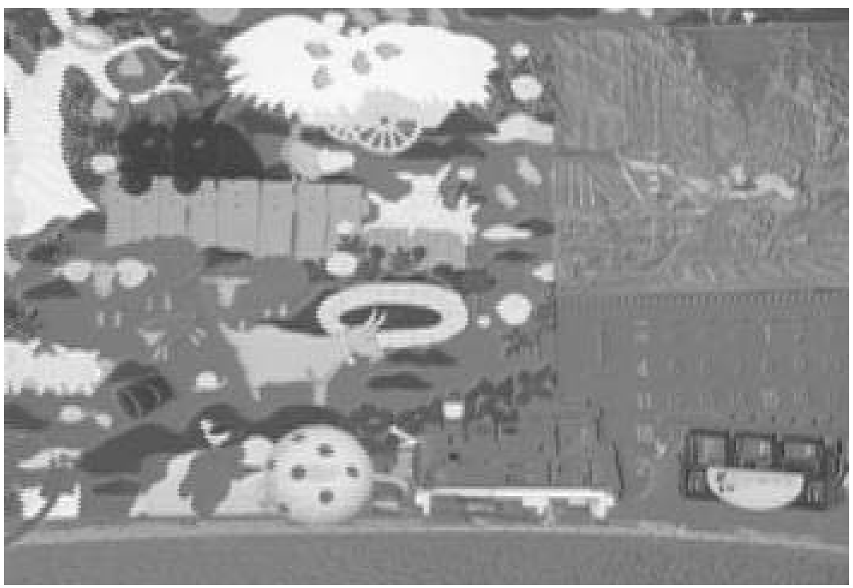
Why not using RGB directly?

- R,G,B components are correlated
  - Transmitting R,G,B components separately is redundant
  - More efficient use of bandwidth is desired
- RGB->YC1C2 transformation
  - Decorrelating: Y,C1,C2 are uncorrelated
  - C1 and C2 require lower bandwidth
  - Y (luminance) component can be received by B/W TV sets
- YIQ in NTSC
  - I: orange-to-cyan
  - Q: green-to-purple (human eye is less sensitive)
    - Q can be further bandlimited than I
  - Phase=Arctan(Q/I) = hue, Magnitude=sqrt (I^2+Q^2) = saturation
  - Hue is better retained than saturation

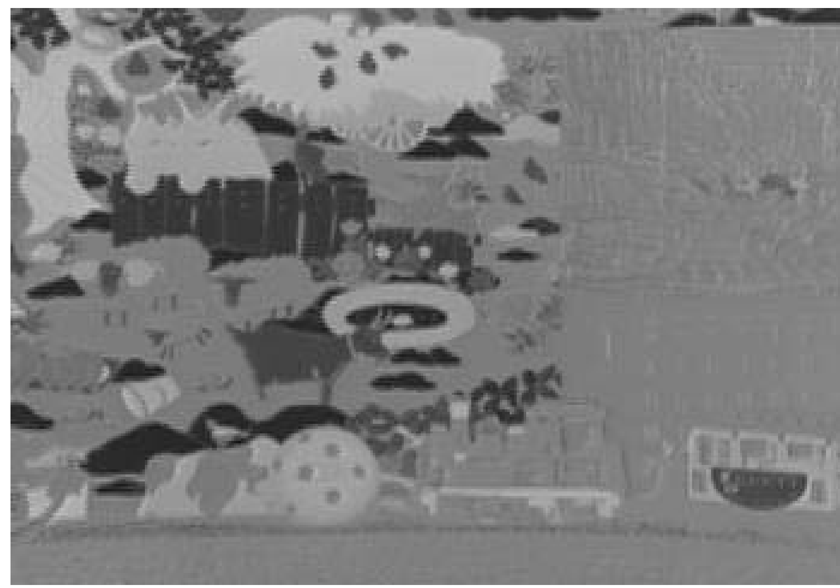
Color Image



Y image

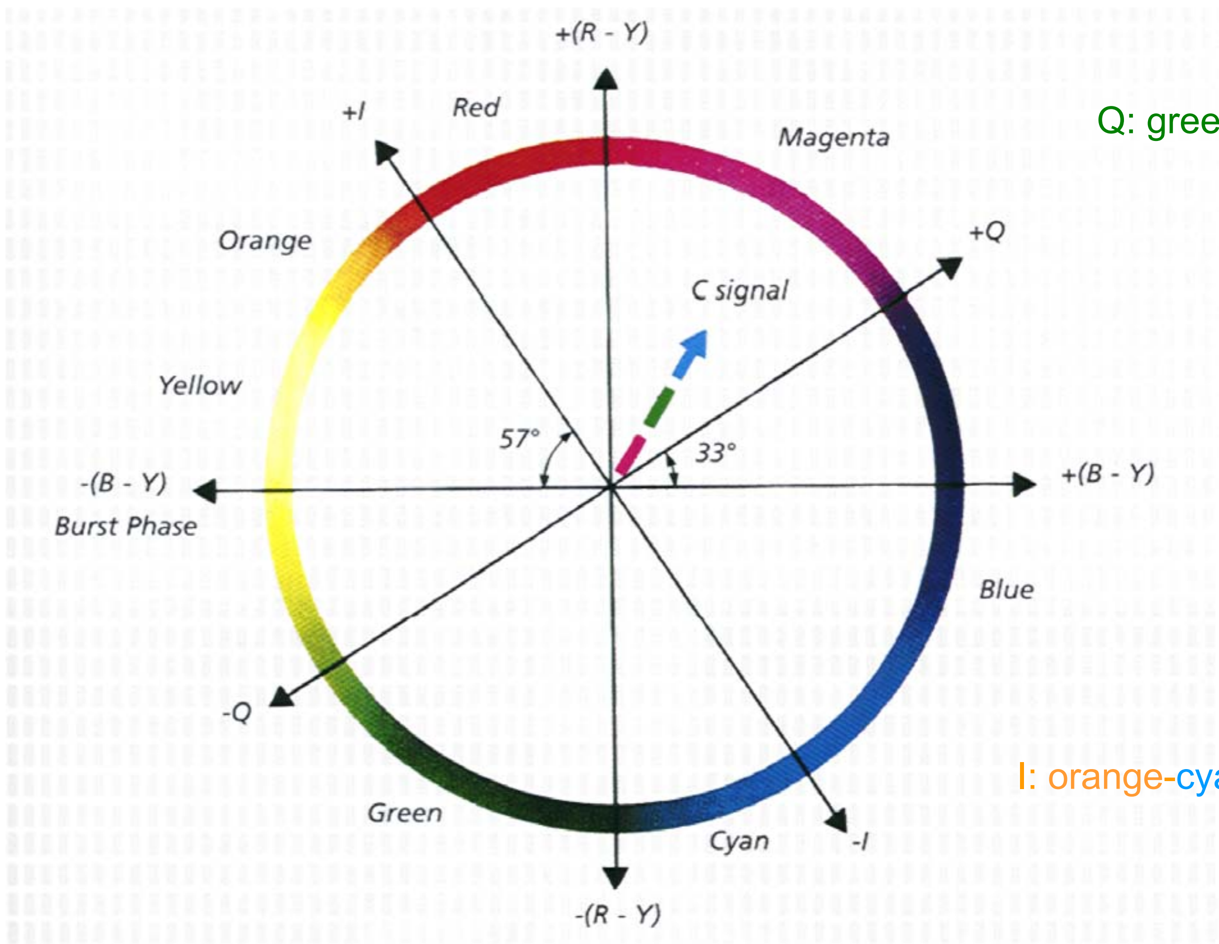


I image (orange-cyan)



Q image (green-purple)

I and Q on the color circle



Q: green-purple

I: orange-cyan

Conversion between RGB and YIQ

- RGB -> YIQ

$$
\begin{aligned}
Y &= 0.299\ R + 0.587\ G + 0.114\ B \\
I &= 0.596\ R - 0.275\ G - 0.321\ B \\
Q &= 0.212\ R - 0.523\ G + 0.311\ B
\end{aligned}
$$

- YIQ -> RGB

$$
\begin{aligned}
R &= 1.0\ Y + 0.956\ I + 0.620\ Q, \\
G &= 1.0\ Y - 0.272\ I - 0.647\ Q, \\
B &= 1.0\ Y - 1.108\ I + 1.700\ Q.
\end{aligned}
$$

TV signal bandwidth

- Luminance
  - Maximum vertical frequency (cycles/picture-height)= black and white lines interlacing

$$f_{v,\max} = Kf'_{s,y}/2$$

  - Maximum horizontal frequency (cycles/picture-width)

$$f_{h,\max} = f_{v,\max} \cdot \mathrm{IAR}$$

  - Corresponding temporal frequency (cycles/second or Hz)

$$f_{\max} = f_{h,\max}/T'_l = \mathrm{IAR} \cdot Kf'_{s,y}/2T'_l$$

  - For NTSC, $f_{\max} = 4.2\ \mathrm{MHz}$

- Chrominance
  - Can be bandlimited significantly
    - I: 1.5 MHz, Q: 0.5 MHz.

Bandwidth of Chrominance Signals

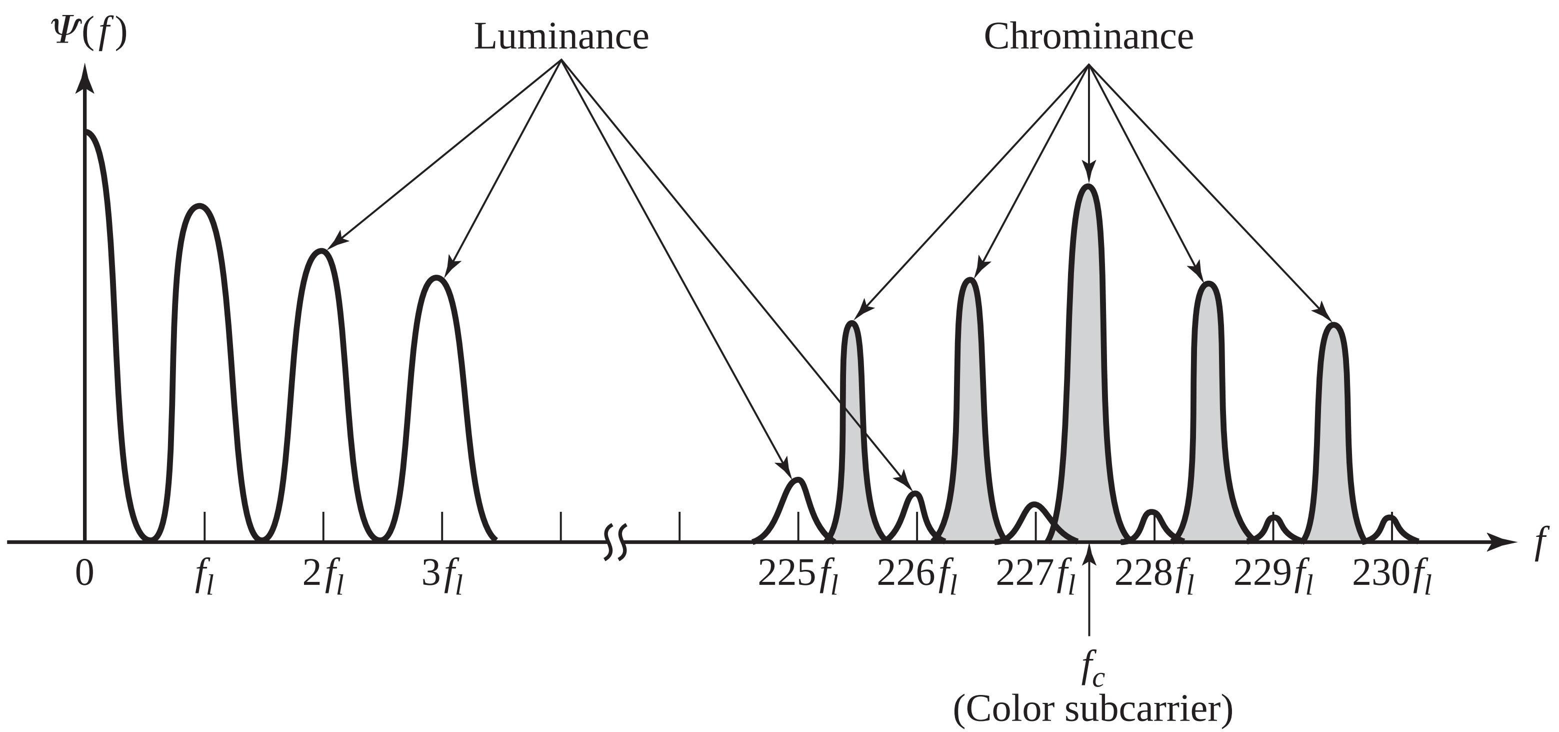
- Theoretically, for the same line rate, the chromiance signal can have as high frequency as the luminance signal
- However, with real video signals, the chrominance component typically changes much slower than luminance
- Furthermore, the human eye is less sensitive to changes in chrominance than to changes in luminance
- The eye is more sensitive to the orange-cyan range (I) (the color of face!) than to green-purple range (Q)
- The above factors lead to
  - I: bandlimitted to 1.5 MHz
  - Q: bandlimitted to 0.5 MHz

Multiplexing of Luminance and Chrominance

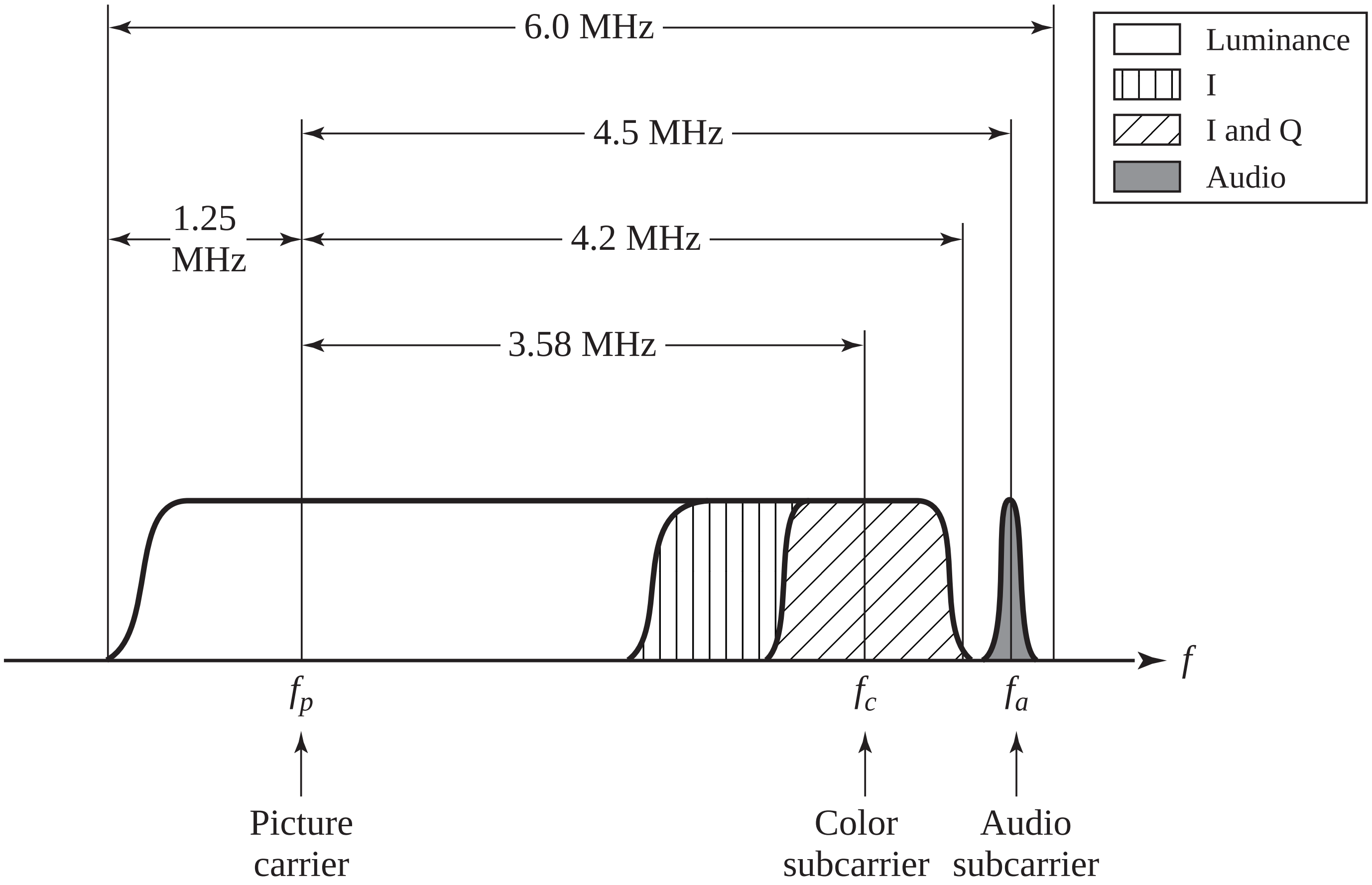
- Chrominance signal can be bandlimited
  - it usually has a narrower frequency span than the luminance and the human eye is less sensitive to high frequencies in chrominance
- The two chrominance components (I and Q) are multiplexed onto the same sub-carrier using QAM
  - The upper band of I is limited to 0.5 MHz to avoid interference with audio
- Position the bandlimited chrominance at the high end spectrum of the luminance, where the luminance is weak, but still sufficiently lower than the audio (at 4.5 MHz=286 f_l)
- The actual position should be such that the peaks of chrominance spectrum interlace with those of the luminance

$$f_c = 455 f_l / 2 \ \ (= 3.58 \ \text{Hz for NTSC})$$

Spectrum Illustration

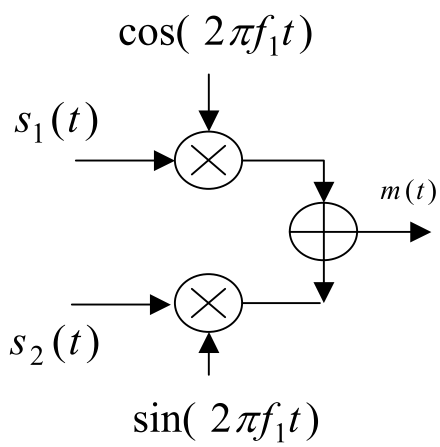


Multiplexing of luminance, chrominance and audio (Composite Video Spectrum)

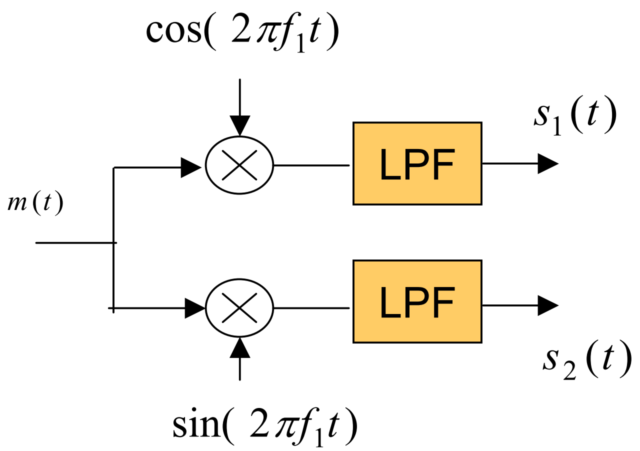


Quadrature Amplitude Modulation (QAM)

- A method to modulate two signals onto the same carrier frequency, but with 90° phase shift

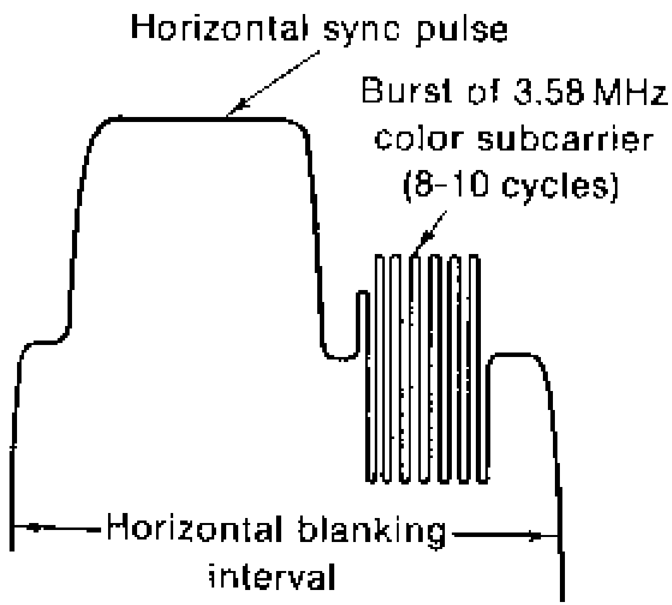


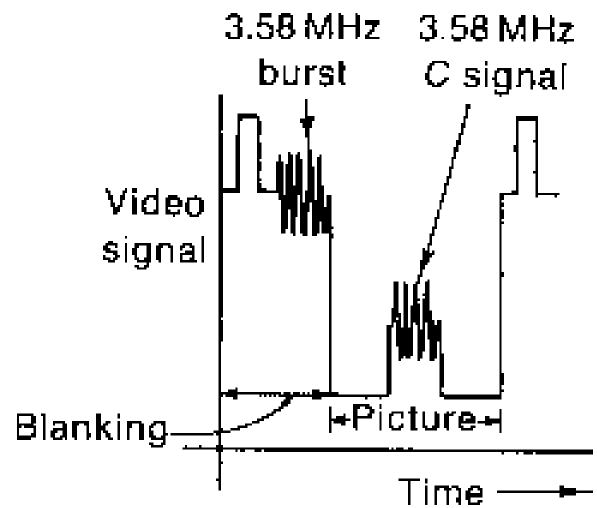
QAM modulator



QAM demodulator

Adding Color Bursts for Synchronization

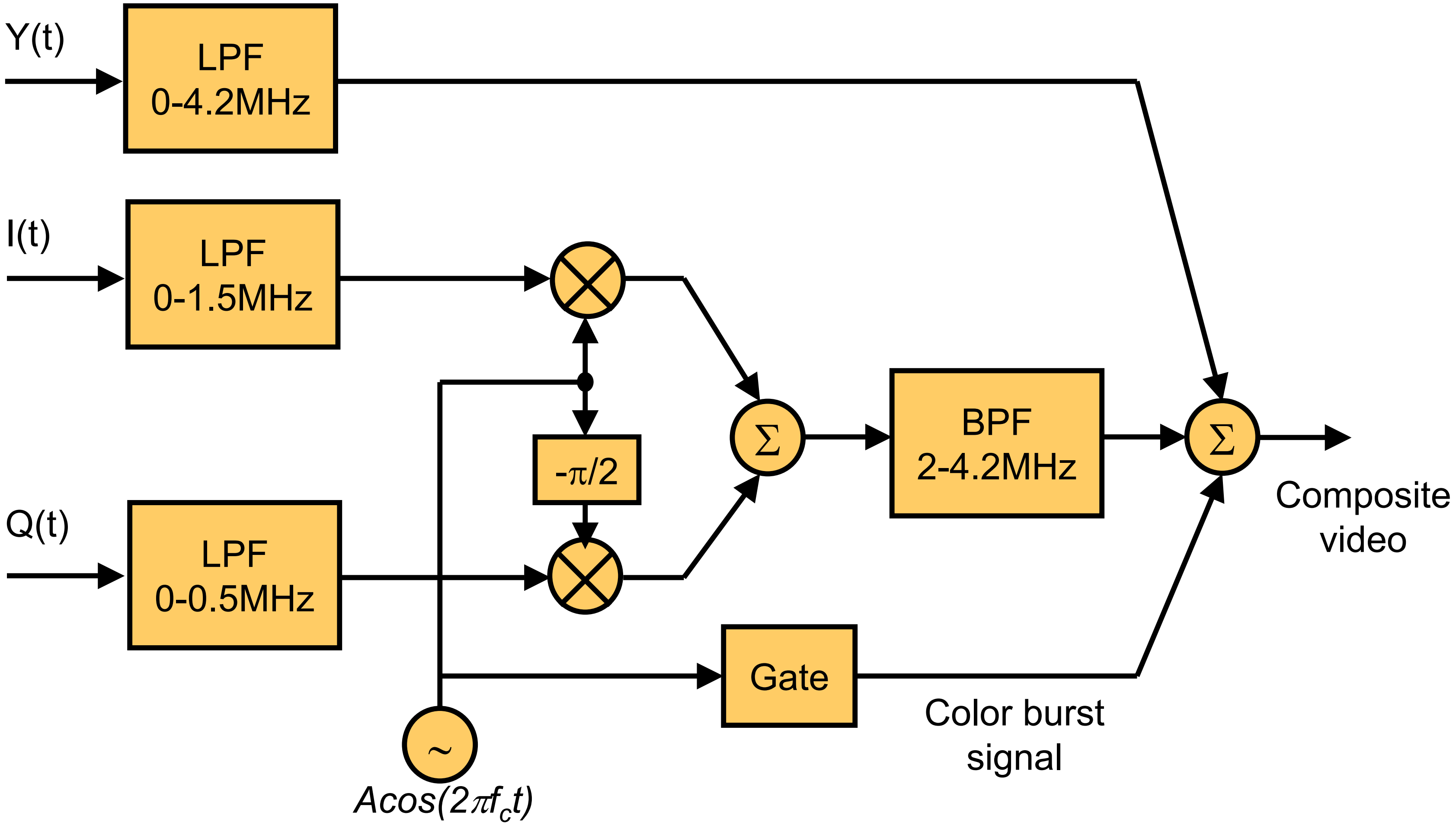




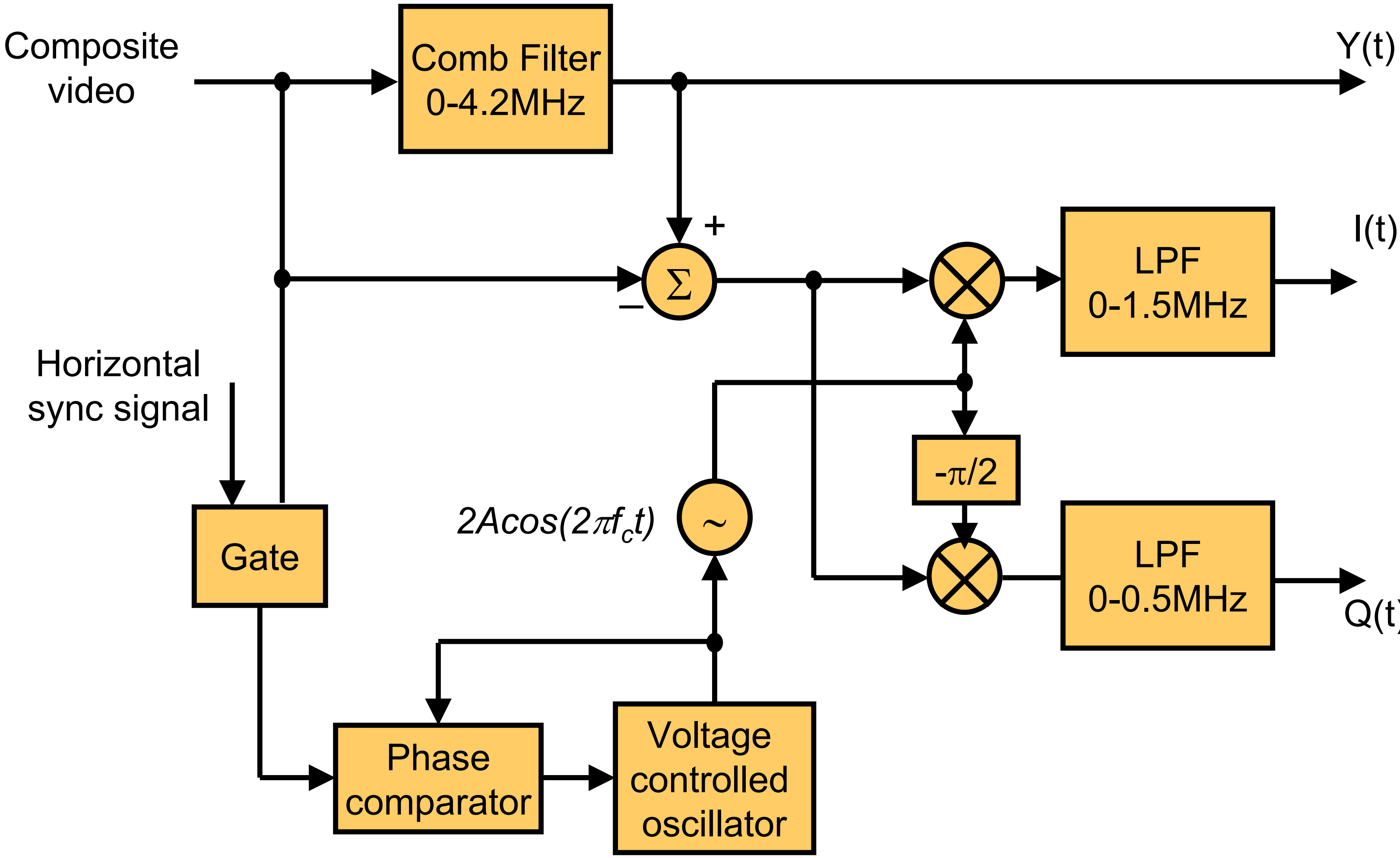
For accurate regeneration of the color sub-carrier signal at the receiver, a color burst signal is added during the horizontal retrace period

Figure from From Grob, Basic Color Television Principles and Servicing, McGraw Hill, 1975
http://www.ee.washington.edu/conselec/CE/kuhn/ntsc/95x417.gif

Multiplexing of Luminance and Chrominance



DeMultiplexing of Luminance and Chrominance



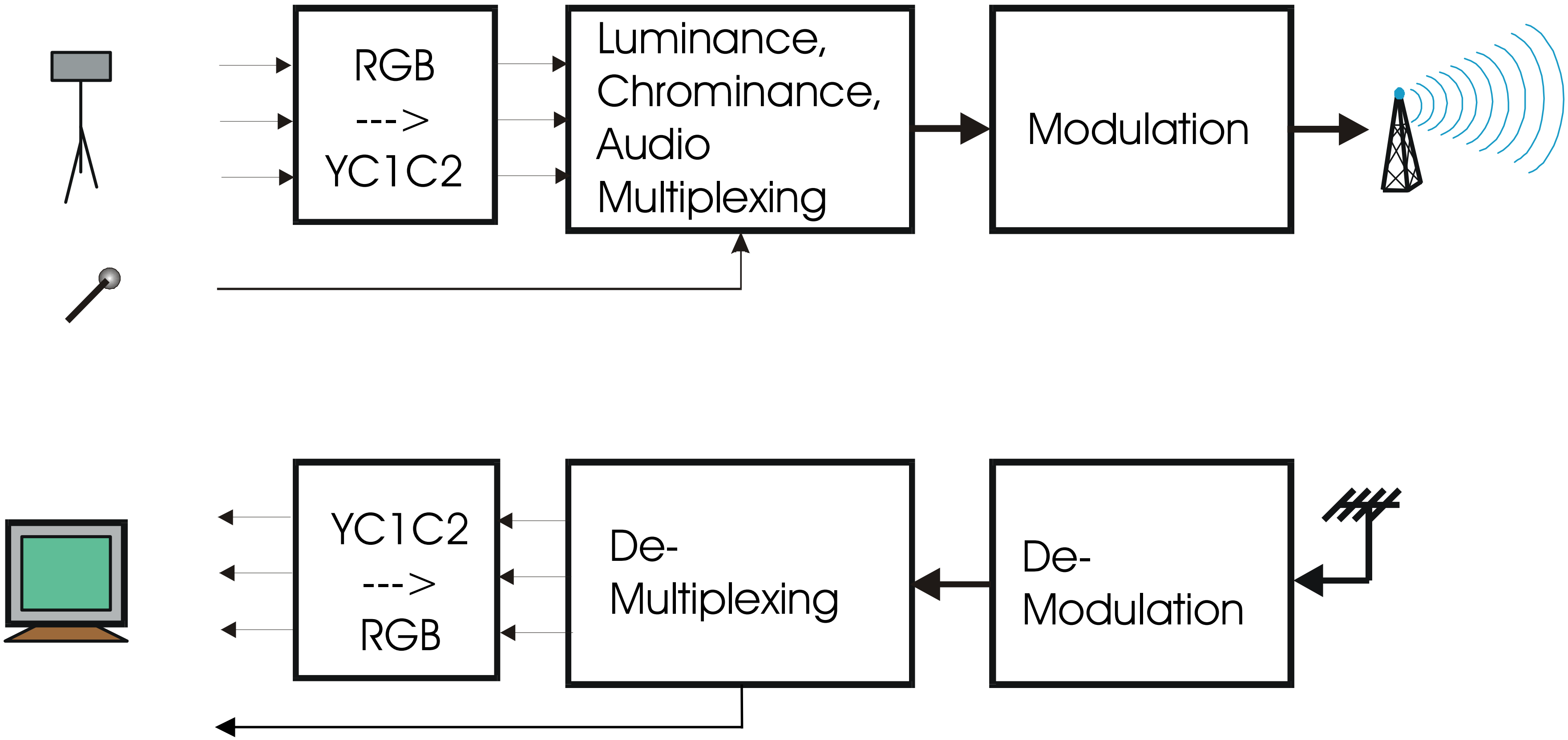
Luminance/Chrominance Separation

- In low-end TV receivers, a low pass filter with cut-off frequency at 3MHz is typically used to separate the luminance and chrominance signal.
  - The high frequency part of the I component (2 to 3 Mhz) is still retained in the luminance signal.
  - The extracted chrominance components can contain significant luminance signal in a scene with very high frequency (luminance energy is not negligible near f_c)
  - These can lead to color bleeding artifacts
- For better quality, a comb filter can be used, which will filter out harmonic peaks correspond to chrominance signals.
- Show example of comb filter on board

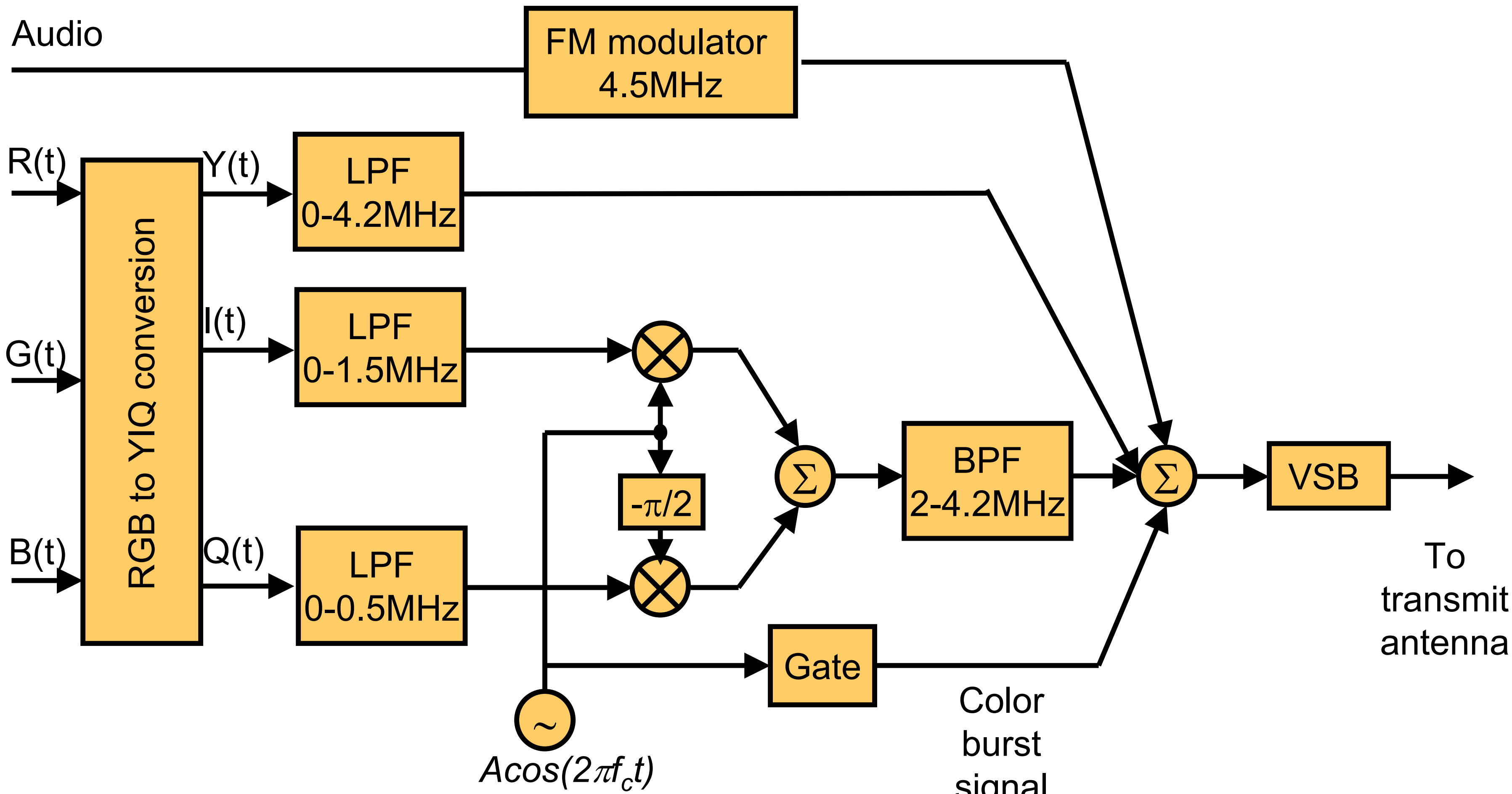
What will a Monochrome TV see?

- The monochrome TV receiver uses a LPT with cut-off at 4.2 MHz, and thus will get the composite video (baseband luminance plus the I and Q signal modulated to f_c =3.58 MHz)
  - Because the modulated chrominance signal is at very high frequency (227.5 cycles per line), the eye smoothes it out mostly, but there can be artifacts
  - The LPF in Practical TV receivers have wide transition bands, and the response is already quite low at f_c.

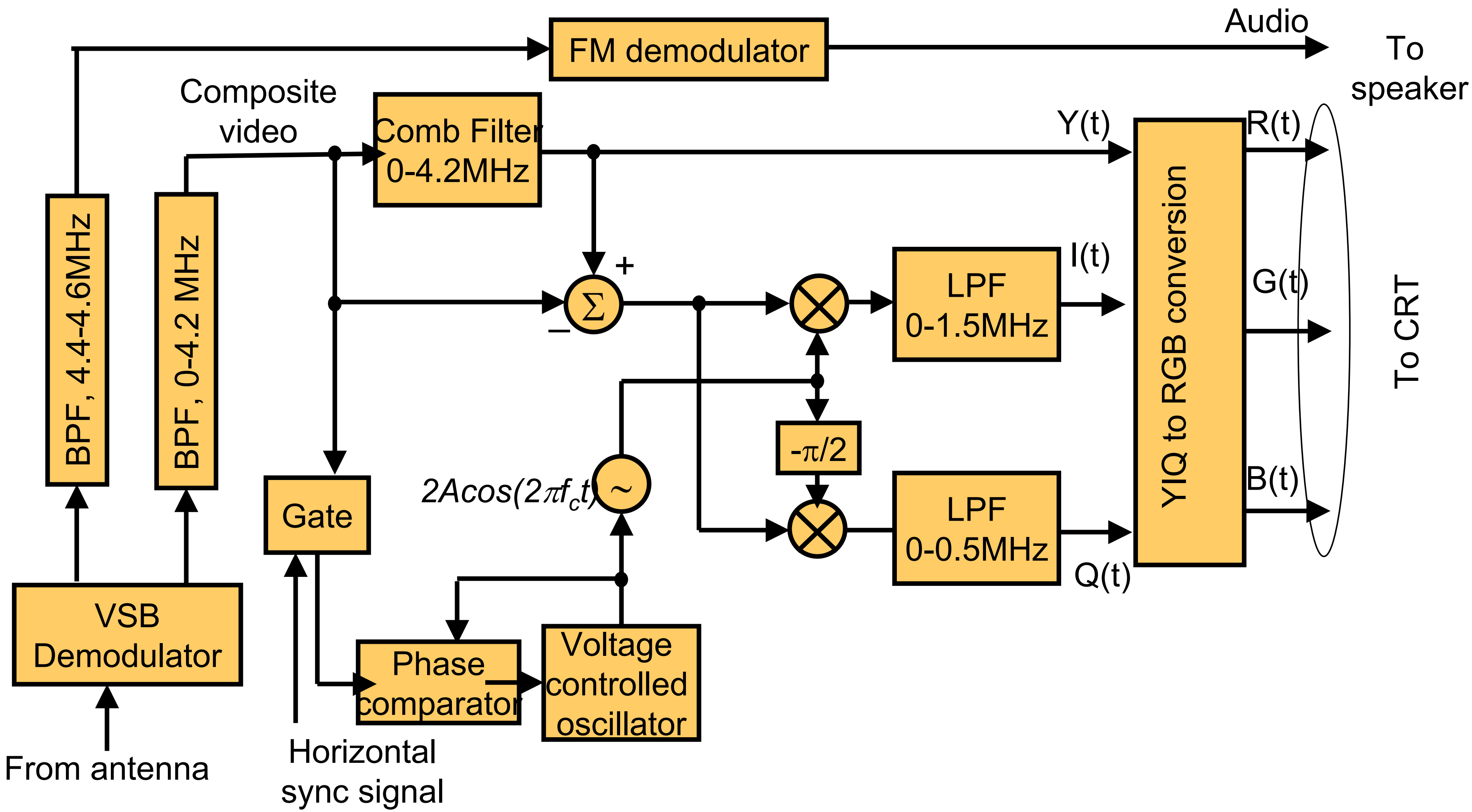
Color TV Broadcasting and Receiving



Transmitter in More Details



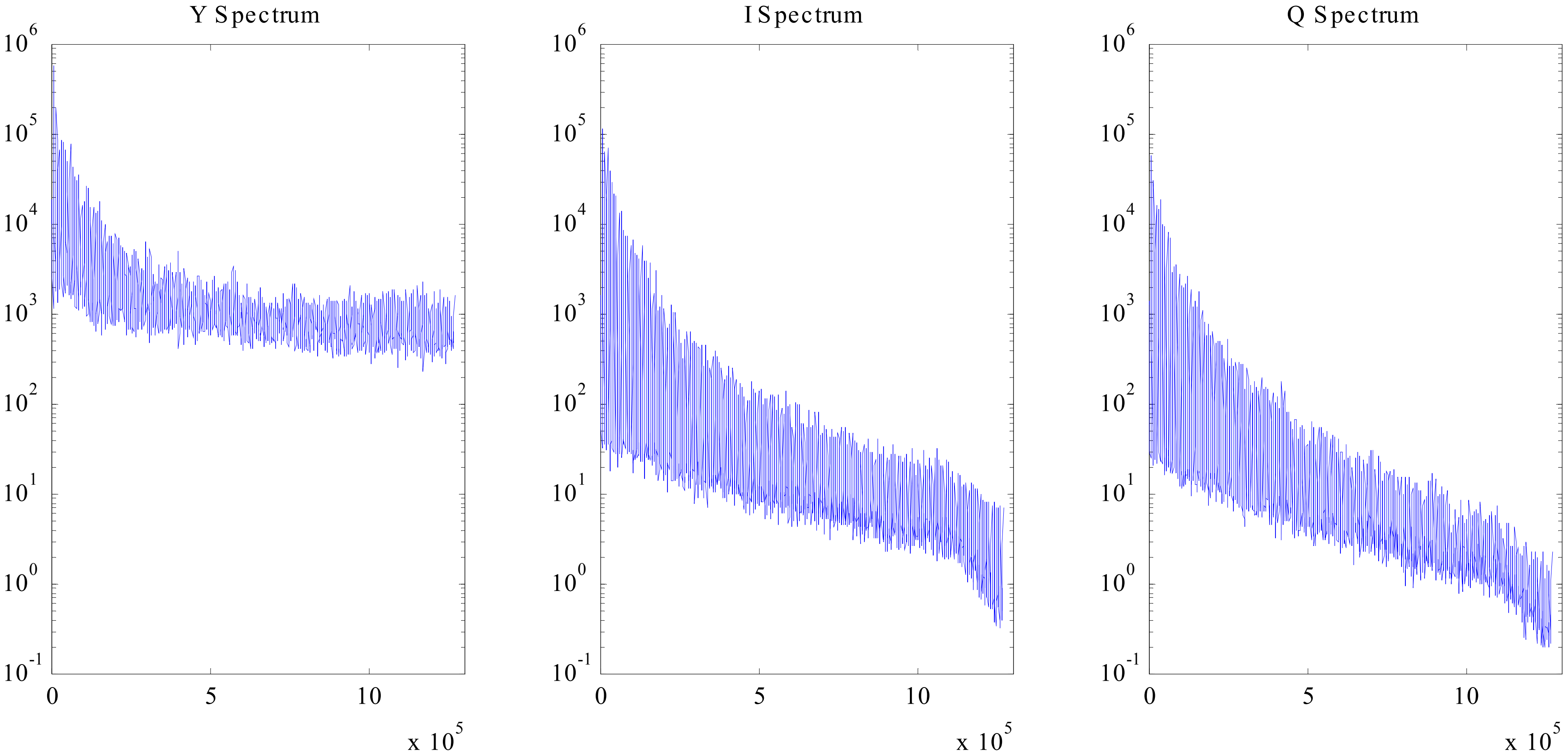
Receiver in More Details



Matlab Simulation of Mux/Demux

- We will show the multiplexing/demultiplexing of YIQ process for a real sequence ('mobile calendar')
  - Original Y,I, Q frames
  - Converted Y,I, Q raster signals and their respective spectrums
  - QAM of I and Q: choice of f_c, waveform and spectrum
  - Multiplexing of Y and QAM(I+Q): waveform and spectrum
  - What wil a B/W TV receiver see:
    - W/o filtering vs. with filtering
  - What will a color TV receiver see:
    - Original and recovered Y,I, Q
    - Original and recovered color image
    - Spectrum and waveforms

Spectrum of Y, I, Q

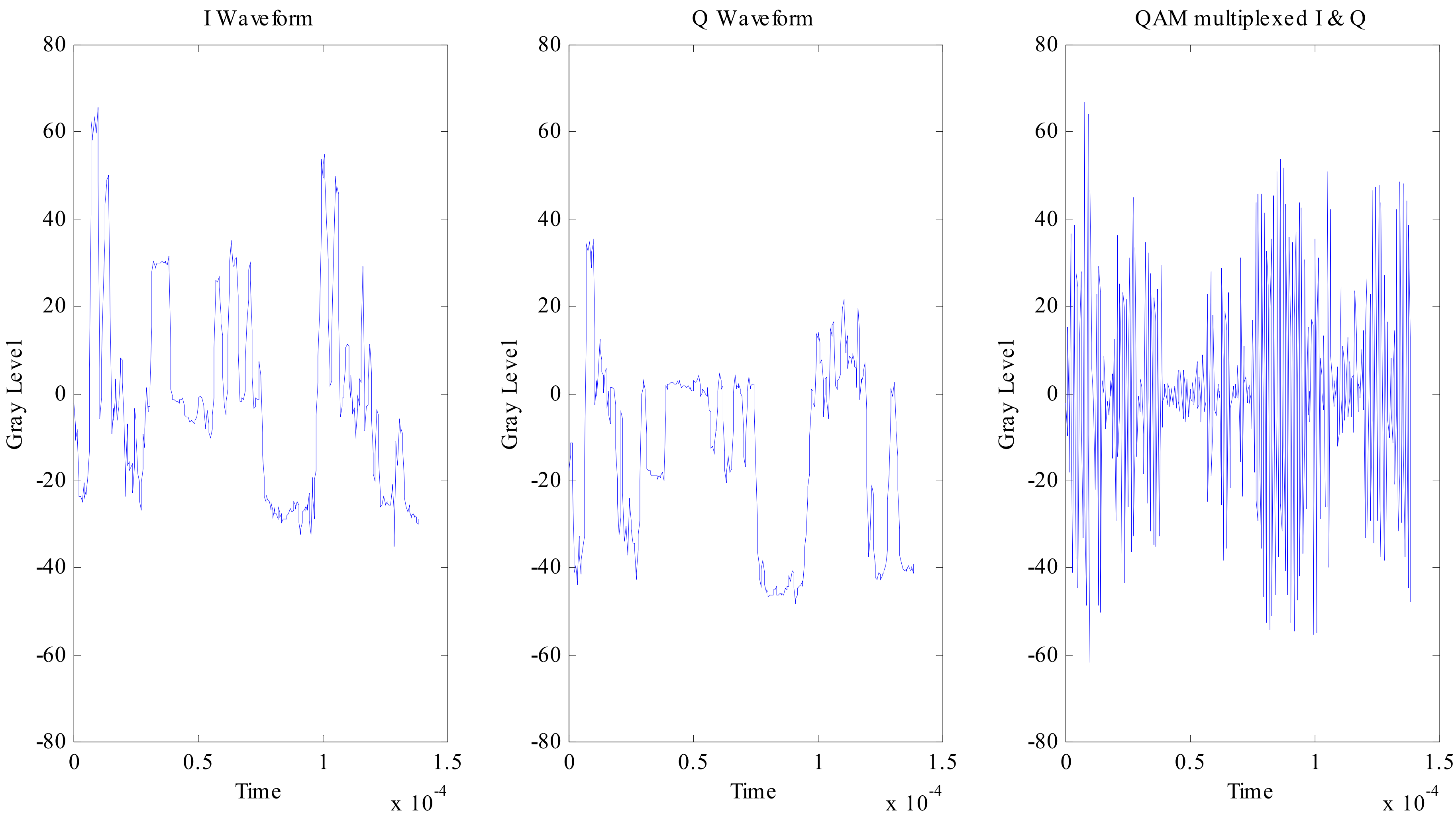


Spectrum of Y, I, and Q components, computed from first two progressive frames of “mobilcal”, 352x240/frame

Maximum possible frequency is 352x240x30/2=1.26 MHz.

Notice bandwidths of Y, I, Q components are 0.8,0.2,0.15 MHz, respectively, if we consider 10^3 as the cut-off magnitude.

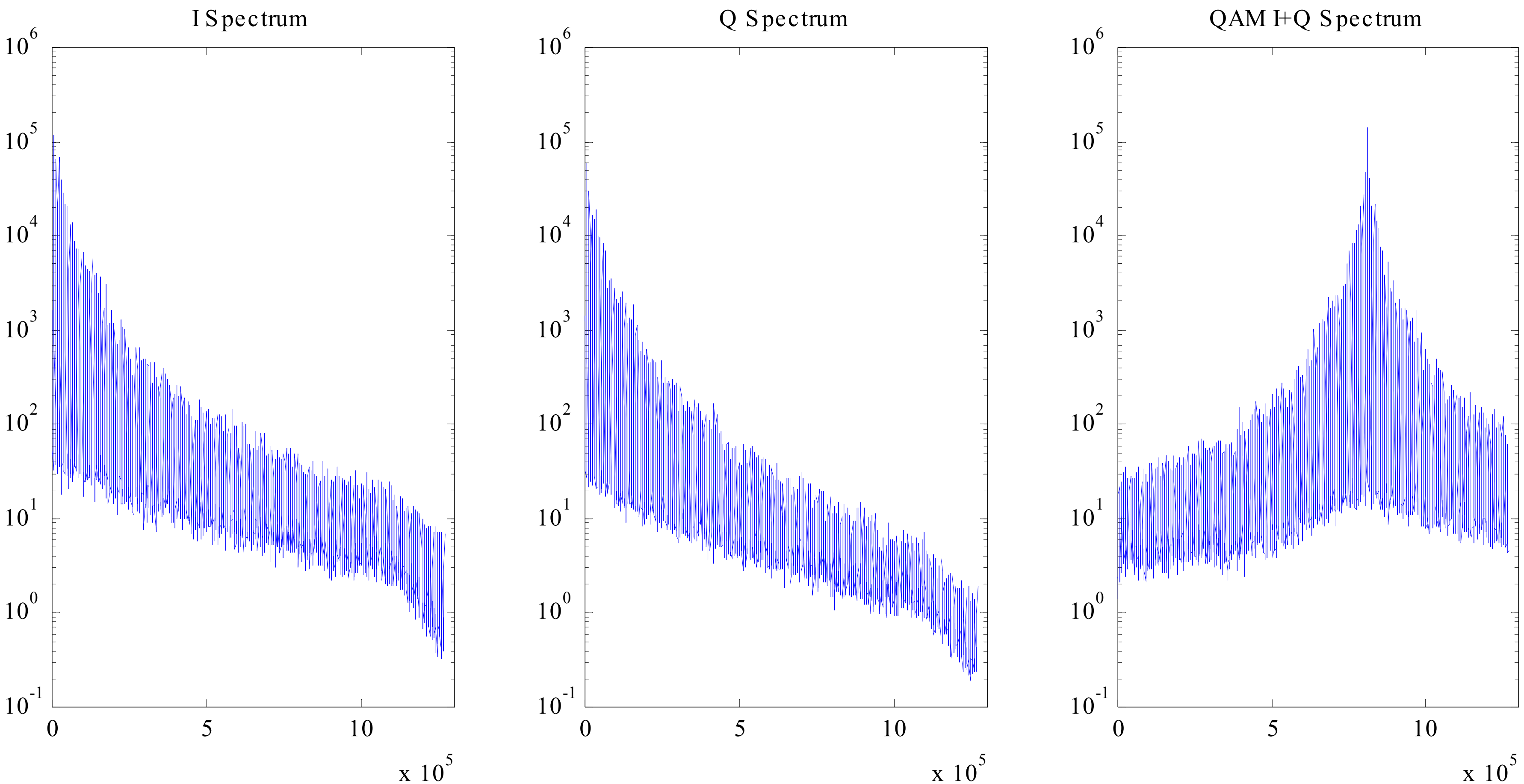
QAM of I and Q: Waveform



Line rate f_l=30*240; Luminance f_{max}=30*240*352/2*0.7=.89 MHz, The color subcarrier $f_c=225*f_l/2$=0.81MHz.

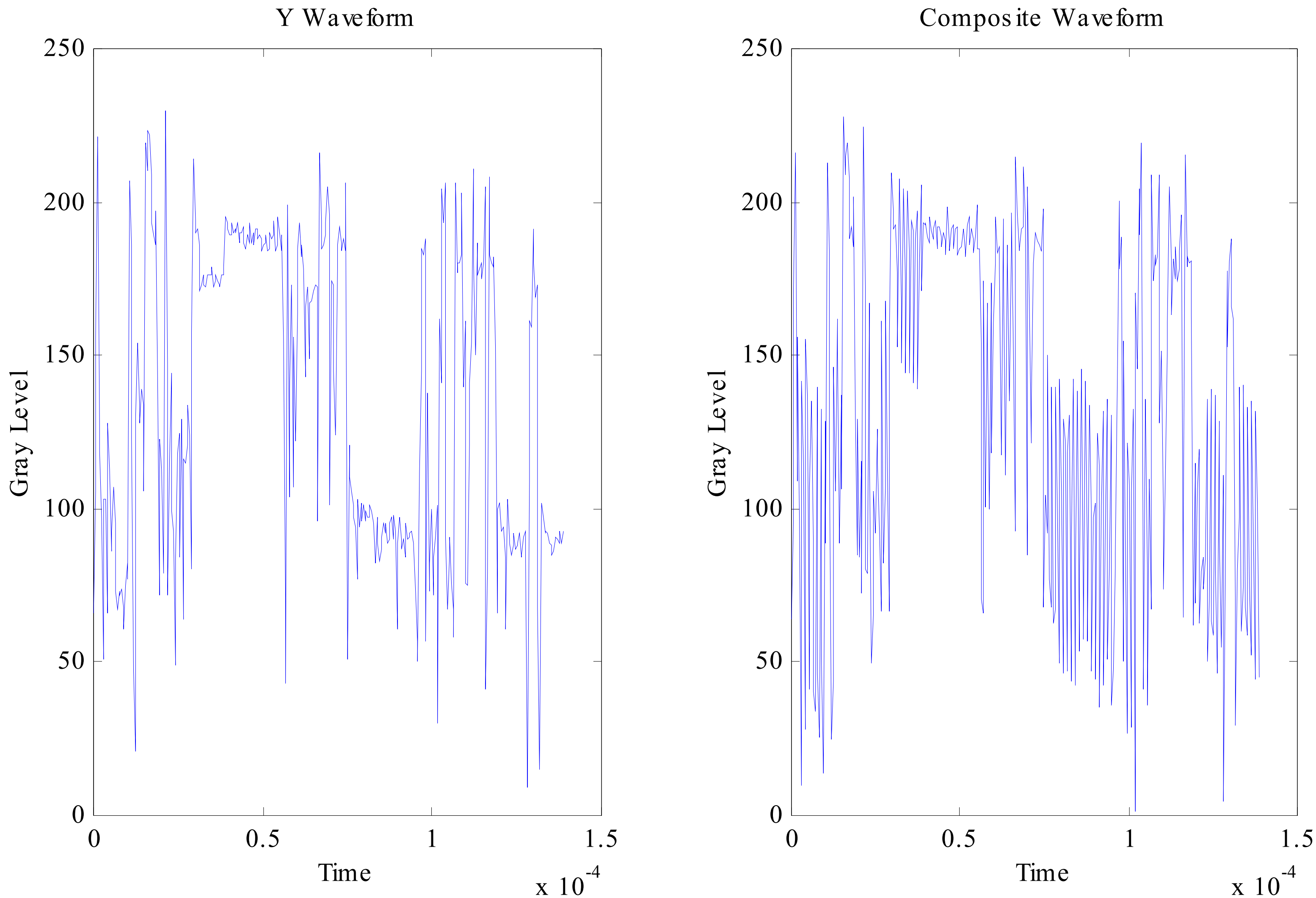
$M(t)=I(t)*\cos(2\pi f_c t)+Q(t)*\sin(2\pi f_c t)$

QAM of I and Q: Spectrum



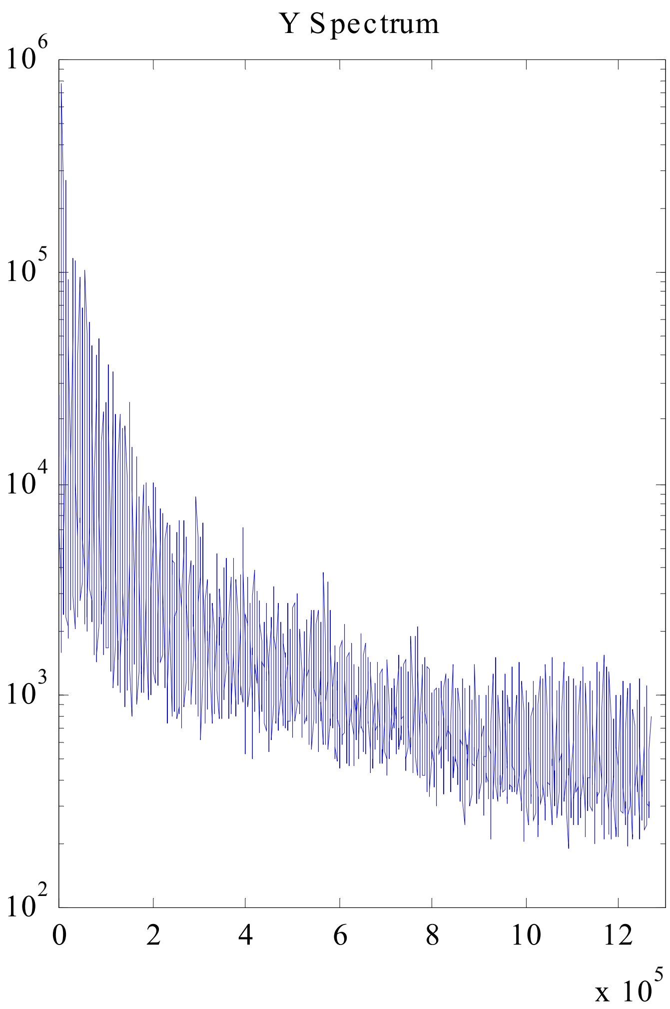
Spectrum of I, Q, and QAM multiplexed I+Q, fc=225*fl/2=0.81 MHz

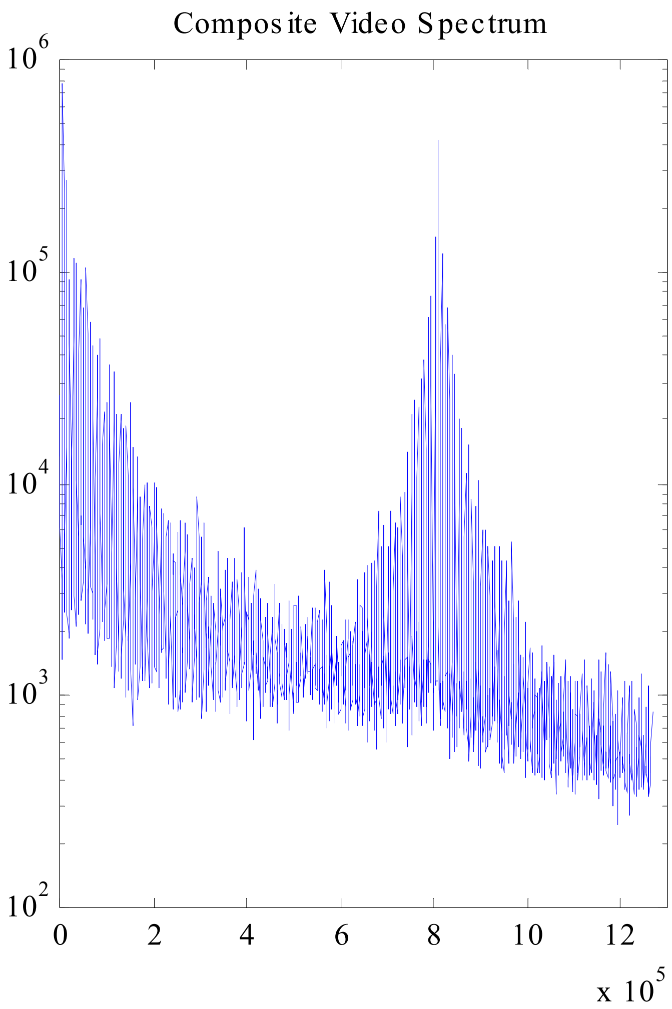
Composite Video: Waveform



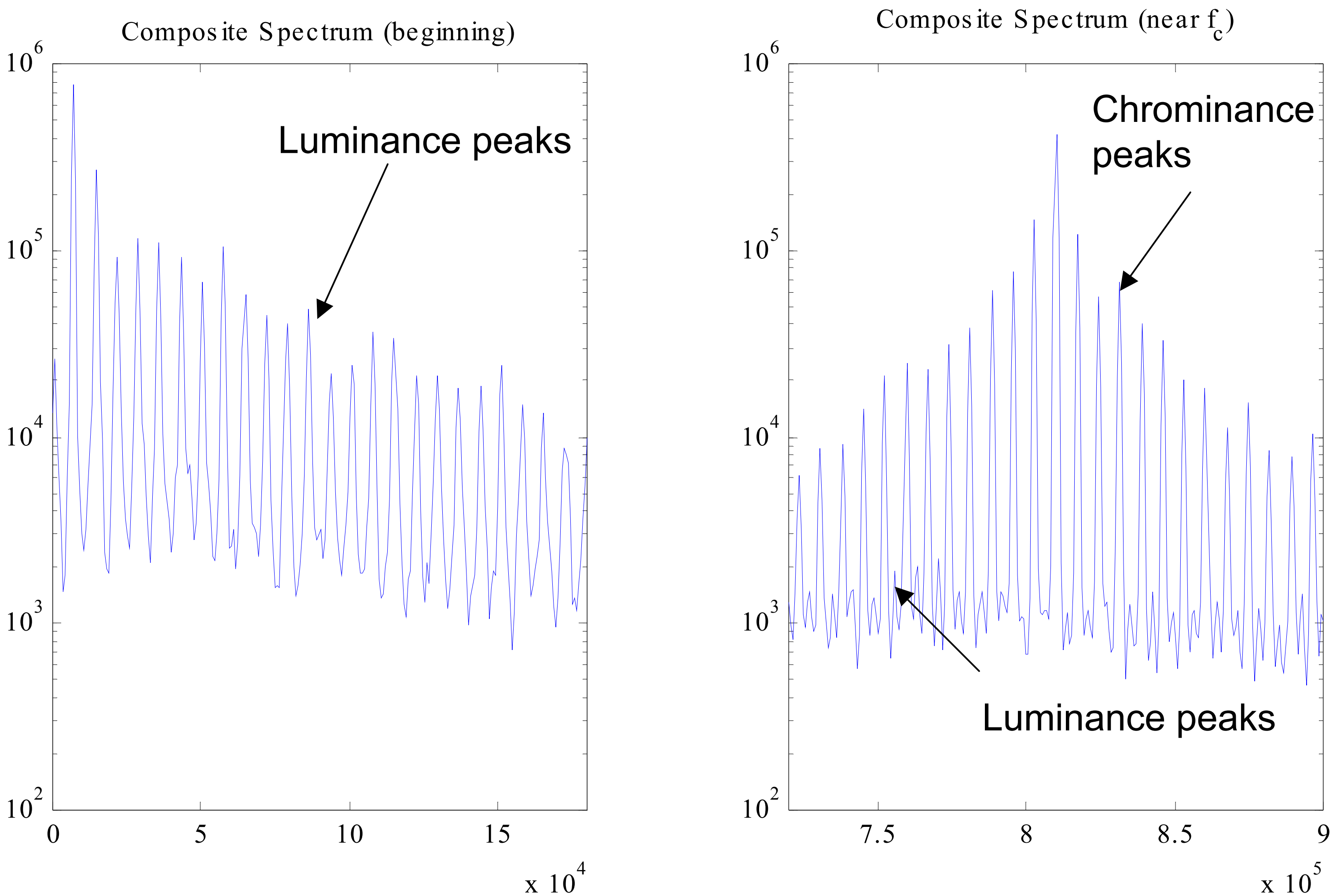
Waveform of the Y signal *Y(t)* and the composite signal *V(t)=Y(t)+M(t).* 1 line

Composite Video: Spectrum





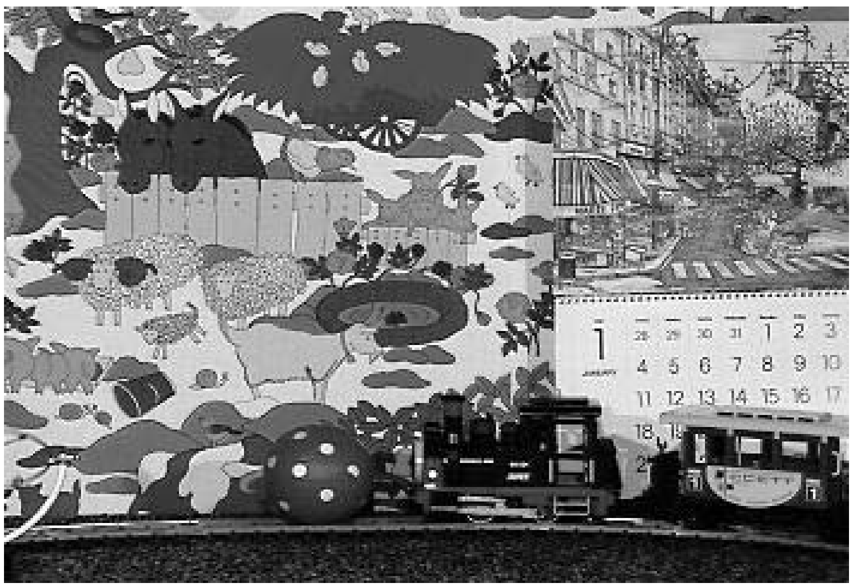
Blown-up View of Spectrum



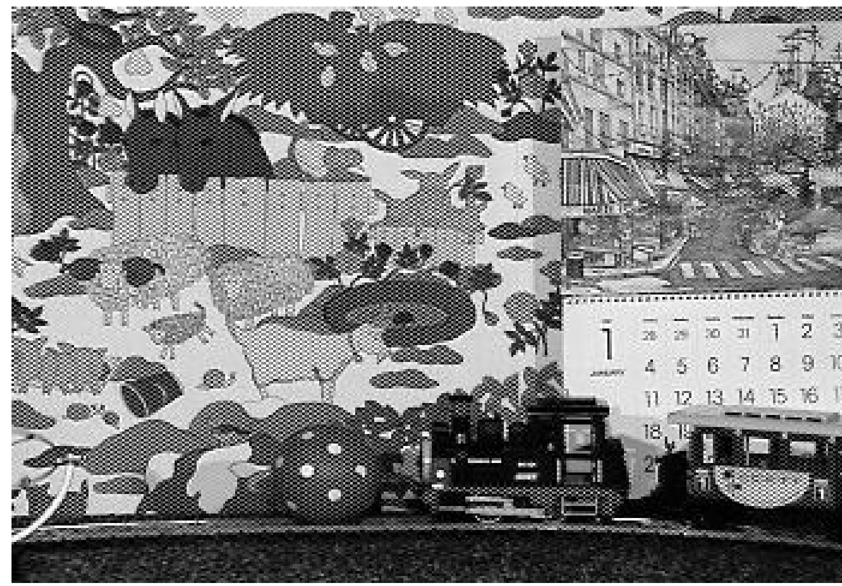
Notice the harmonic peaks of Y and M interleaves near fc

Composite Video Viewed as a Monochrome Image w/o filtering

Original Y



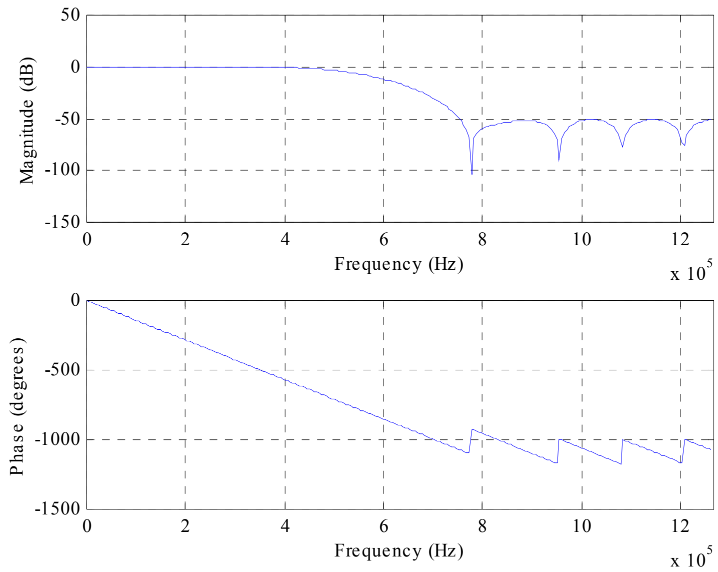
Composite Signal as Y



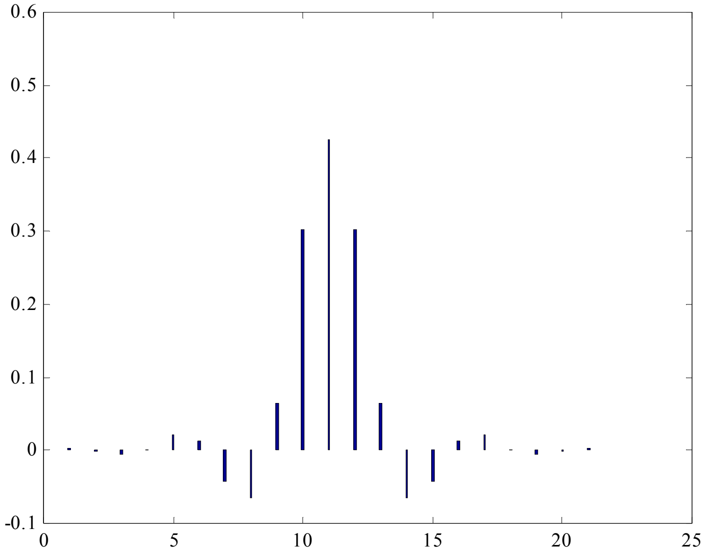
On the right is what a B/W receiver will see if no filtering is applied to the baseband video signal

Low-Pass Filter for Recovering Y

Frequency response



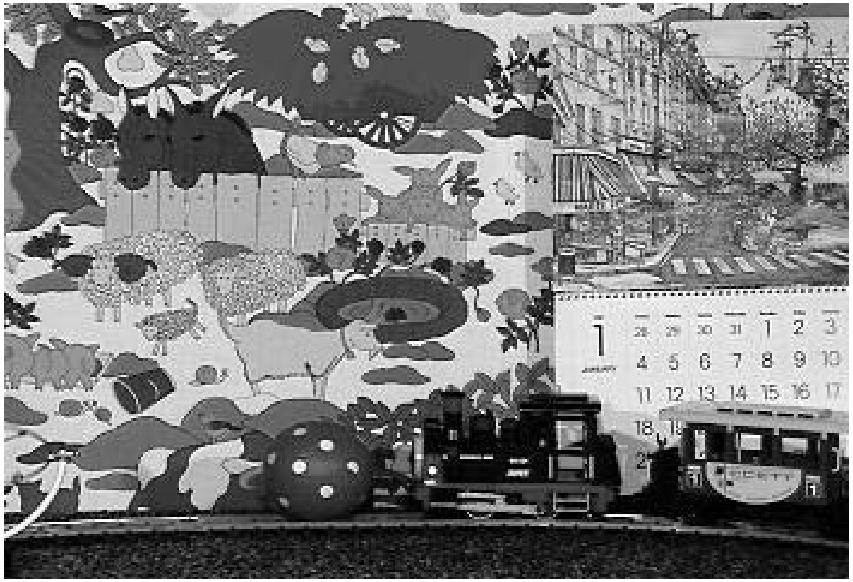
Impulse response (filter coefficients)



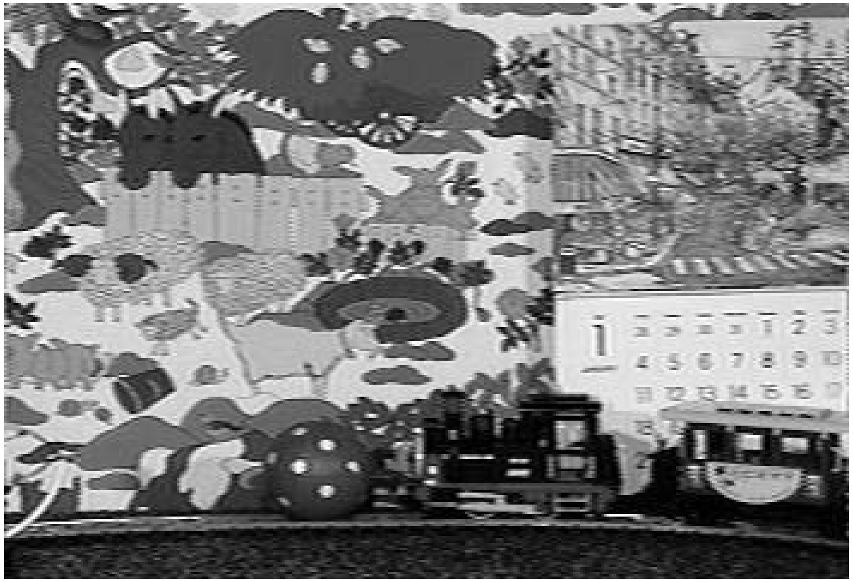

```
f_LPF=30*240/2*150=0.54MHz; fir_length=20;
LPF=fir1(fir_length,f_LPF/(Fs/2));
```

Recovered Y with Filtering

Original Y



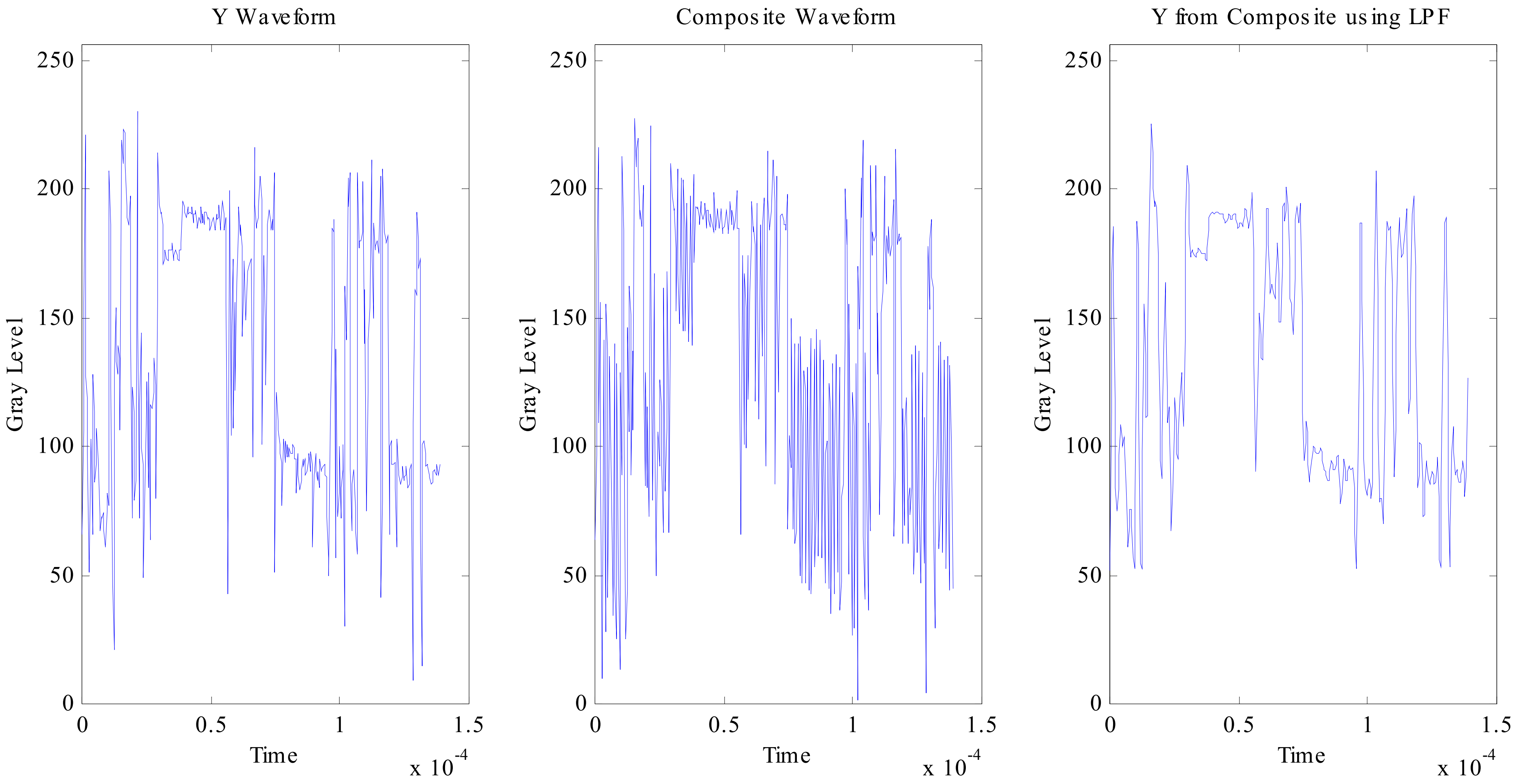
Recovered Y



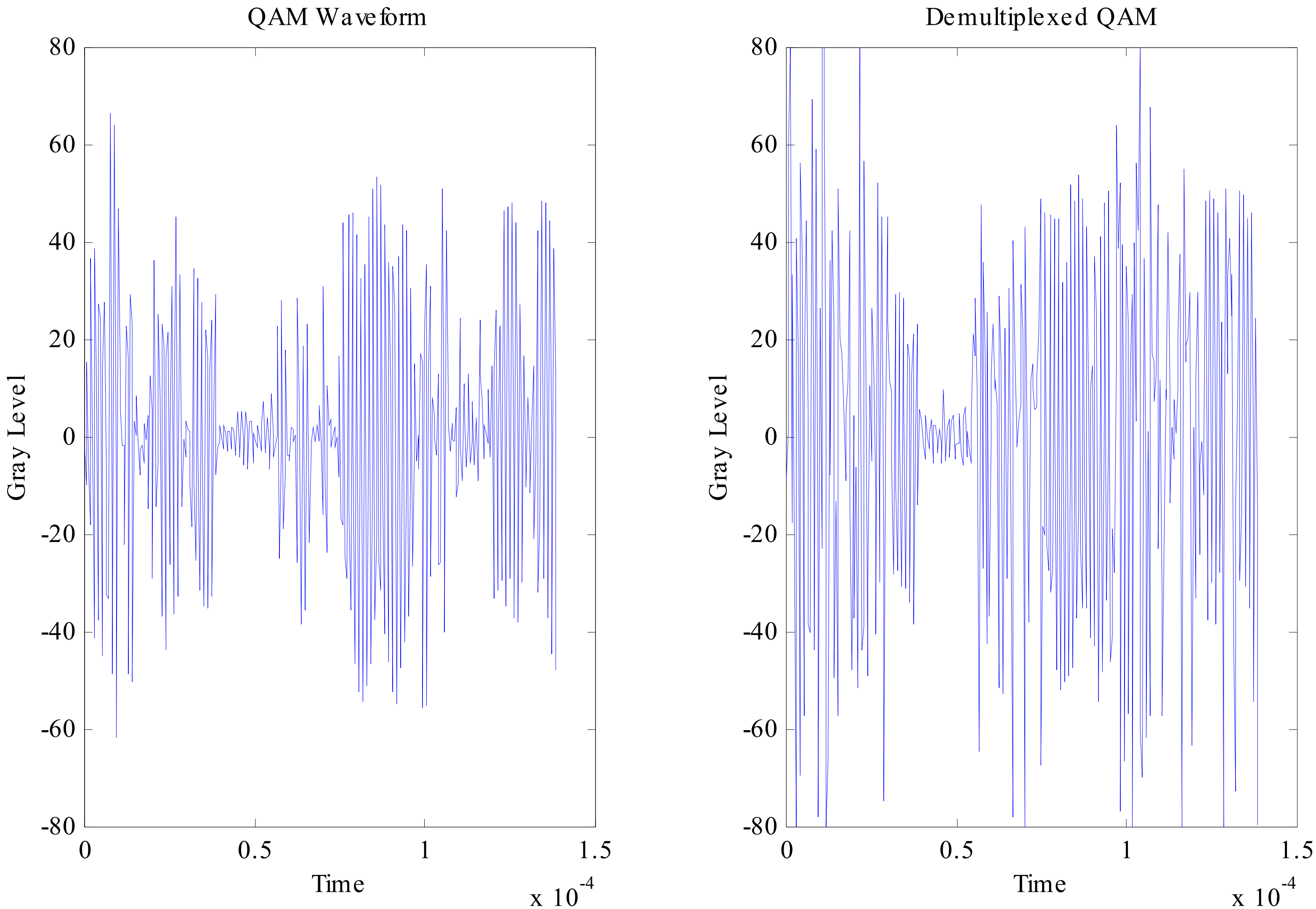
On the right is what a B/W receiver will see if a lowpass filter with cutoff frequency at about 0.75 MHz is applied to the baseband video signal. This is also the recovered Y component by a color receiver if the same filter is used to separate Y and QAM signal.

$$Y'(t)=conv(V(t),LPF(t))$$

Y Waveform Comparison



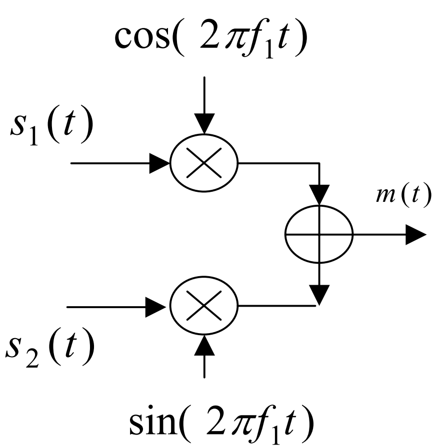
Demux Y and QAM(I,Q)



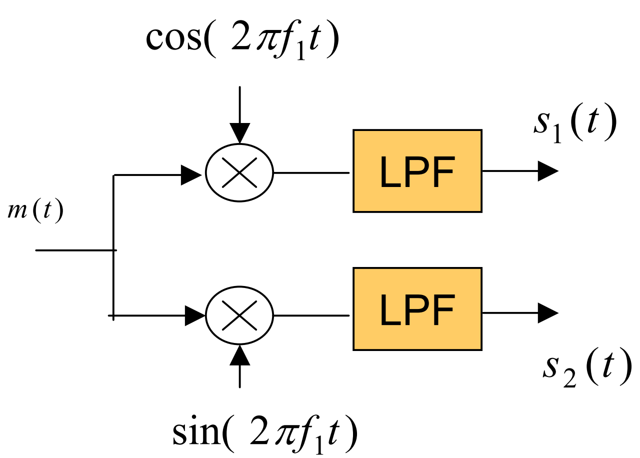
$M'(t)=V(t)-Y'(t)$

QMA Modulation and Demodulation

- Modulated signal:
  – $M(t)=I(t)*\cos(2\pi f_c t)+Q(t)*\sin(2\pi f_c t)$
- Demodulated signal:
  – $I'(t)=2*M(t)*\cos(2\pi f_c t)$, $Q'(t)=2*M(t)*\sin(2\pi f_c t)$
  – I'(t) contains I(t) at baseband, as well as I(t) at $2f_c$ and Q(t) at $4f_c$
  – A LPF is required to extract I(t)



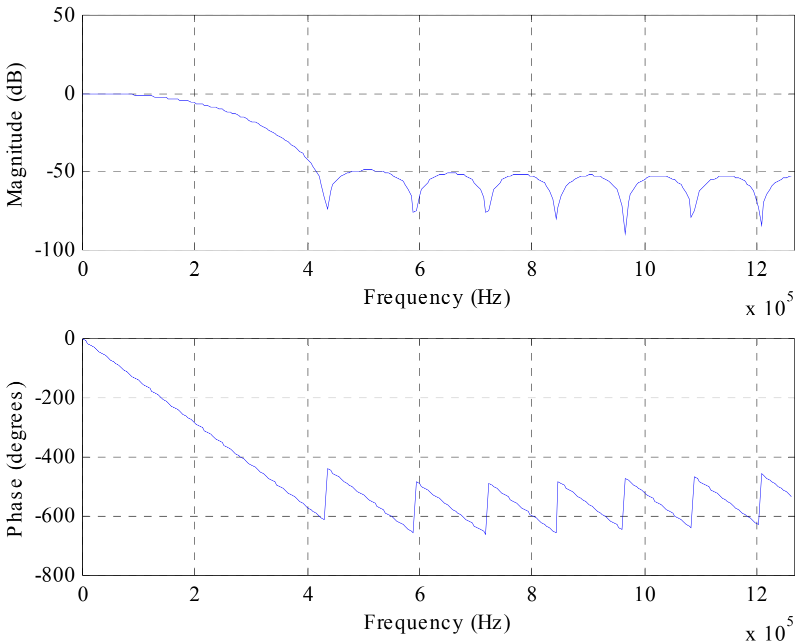
QAM modulator



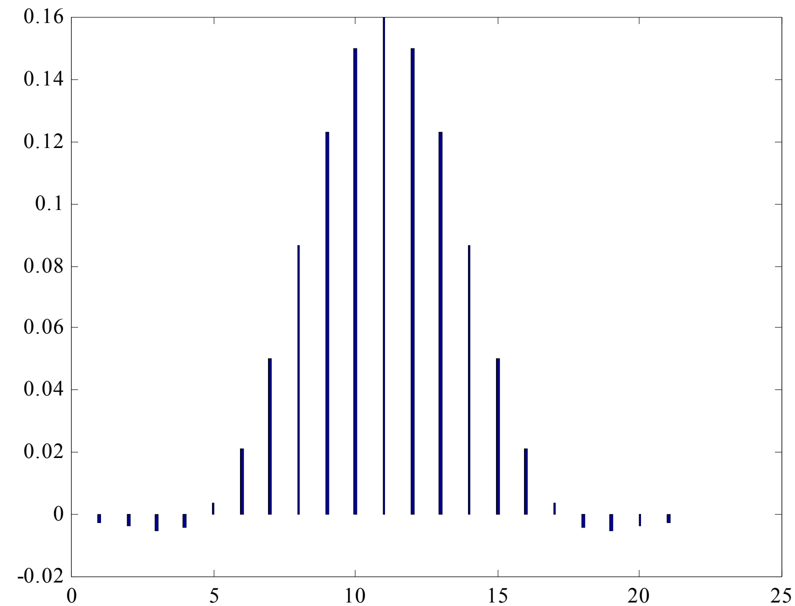
QAM demodulator

Lowpass filter for Extracting QAM(I+Q)

Frequency response

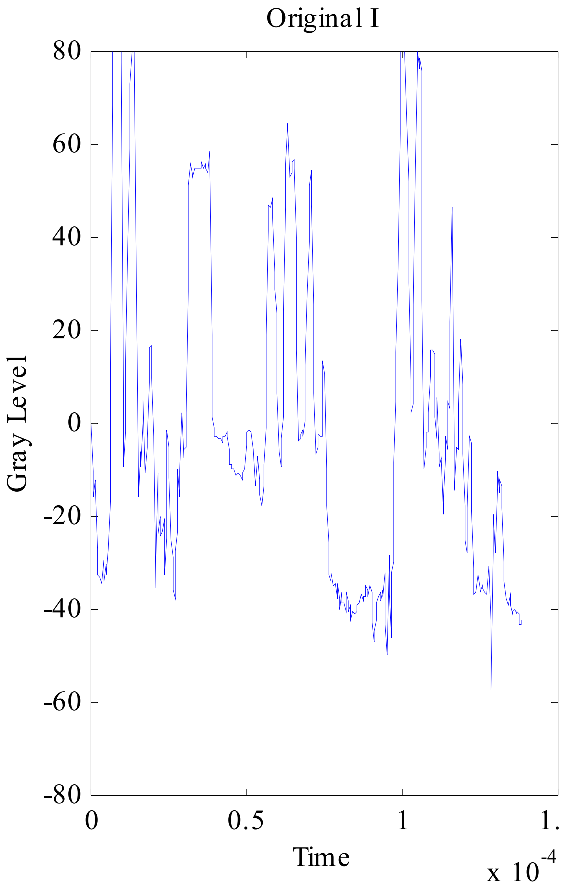


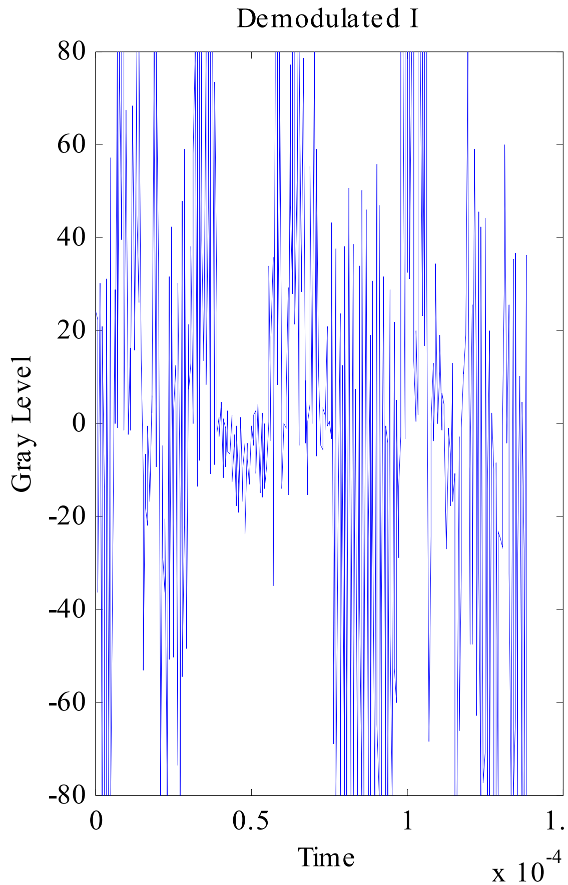
Impulse response

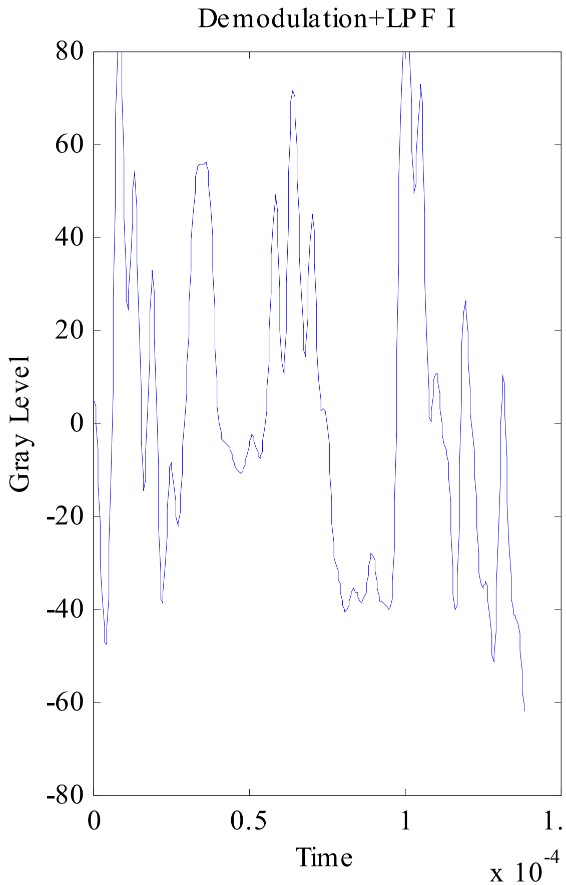



```
f_LPF=0.2MHz; fir_length=20;
LPF=fir1(fir_length,f_LPF/(Fs/2));
```

QAM Demodulation: Waveform



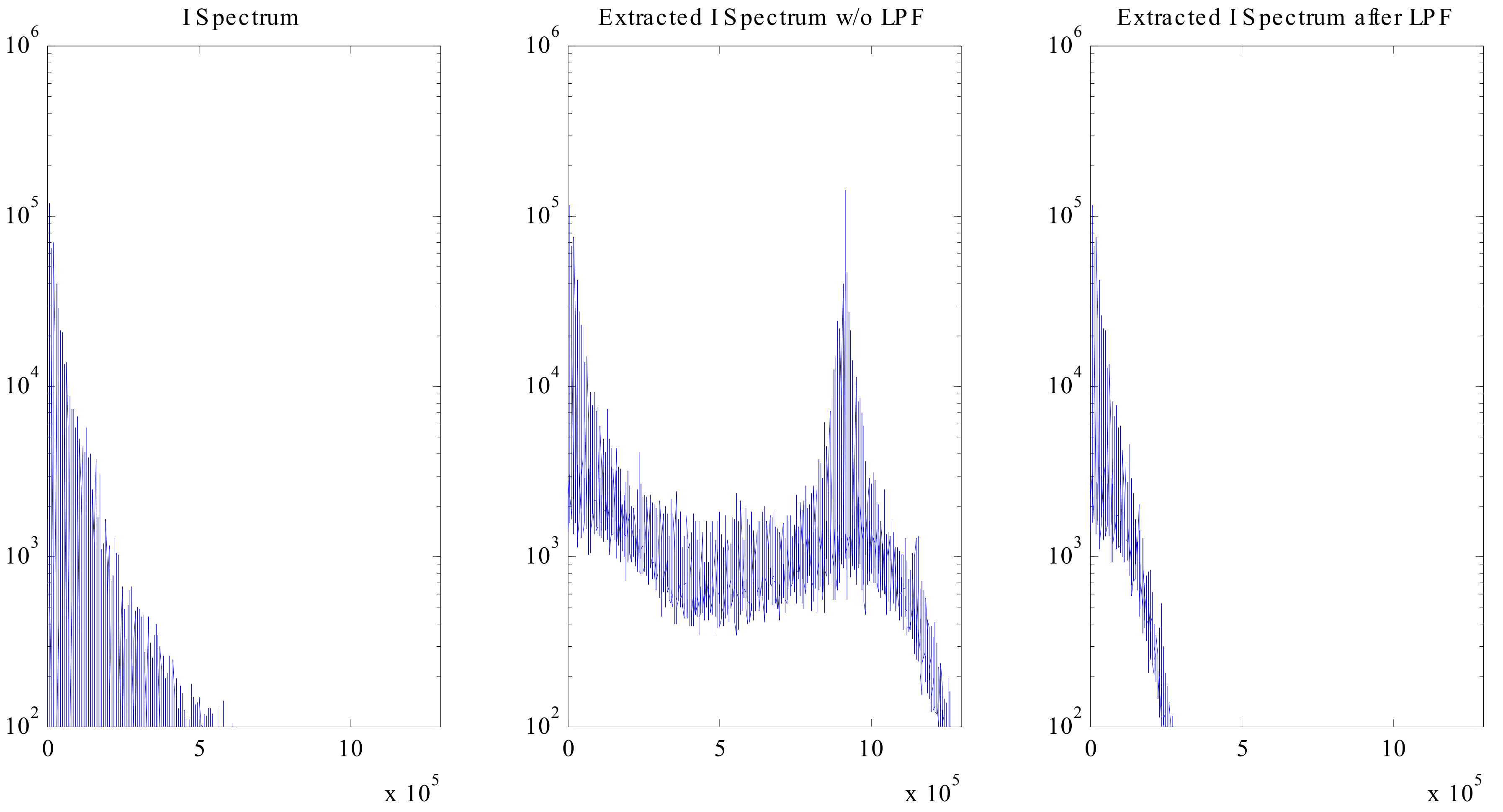


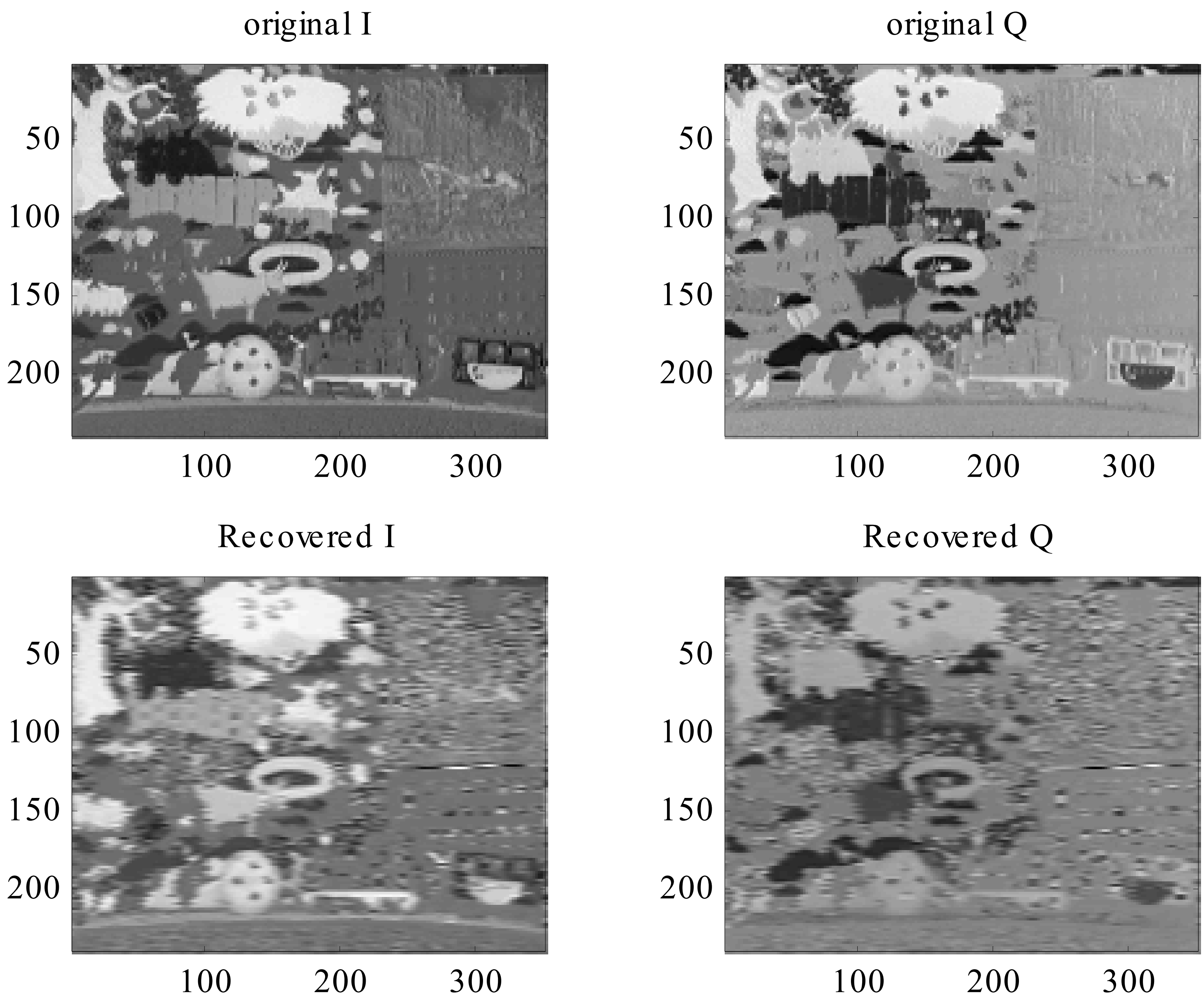


$I'(t)=2*M(t)*\cos(2\pi f_c t)$

$I''(t)=\mathrm{conv}(I'(t),LPF(t))$

QAM Demodultion: Spectrum




original I
original Q
Recovered I
Recovered Q
50
100
150
200
100
200
300

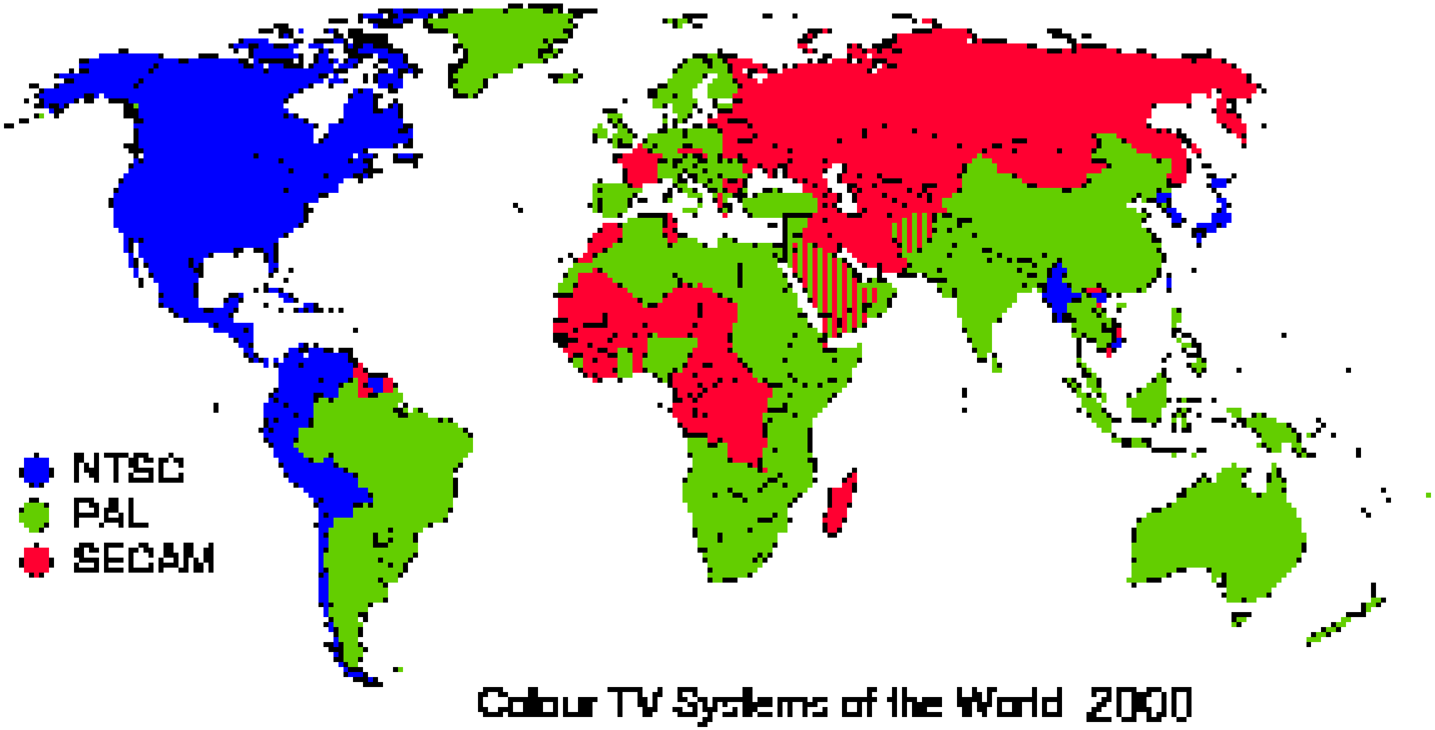
Original color frame

Recovered color frame

Different Color TV Systems

Parameters	NTSC	PAL	SECAM
Field Rate (Hz)	59.95 (60)	50	50
Line Number/Frame	525	625	625
Line Rate (Line/s)	15,750	15,625	15,625
Color Coordinate	YIQ	YUV	YDbDr
Luminance Bandwidth (MHz)	4.2	5.0/5.5	6.0
Chrominance Bandwidth (MHz)	1.5(I)/0.5(Q)	1.3(U,V)	1.0 (U,V)
Color Subcarrier (MHz)	3.58	4.43	4.25(Db),4.41(Dr)
Color Modulation	QAM	QAM	FM
Audio Subcarrier	4.5	5.5/6.0	6.5
Total Bandwidth (MHz)	6.0	7.0/8.0	8.0

Who uses what?



From http://www.stjarnhimlen.se/tv/tv.html#worldwide_0

Digital Video

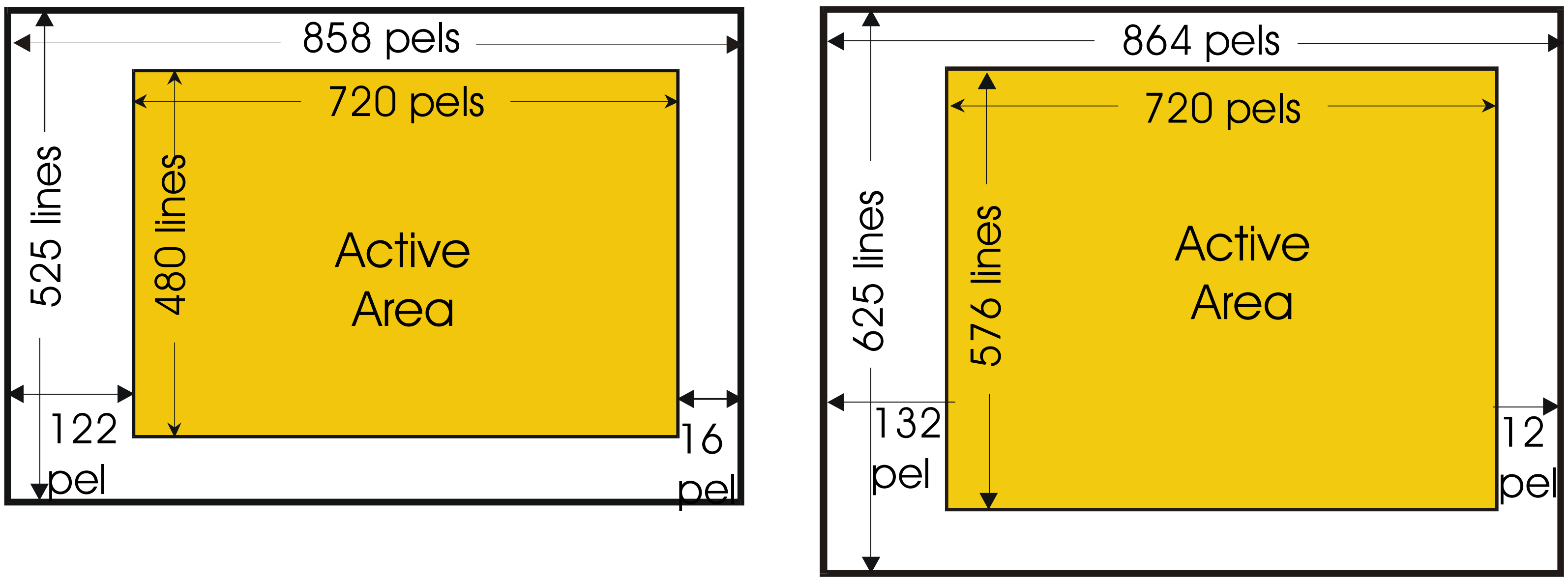
- Digital video by sampling/quantizing analog video raster → BT.601 video
- Other digital video formats and their applications

Digitizing A Raster Video

- Sample the raster waveform = Sample along the horizontal direction
- Sampling rate must be chosen properly
  - For the samples to be aligned vertically, the sampling rate should be multiples of the line rate
  - Horizontal sampling interval = vertical sampling interval
  - Total sampling rate equal among different systems

$$f_s = 858 f_l (\text{NTSC}) = 864 f_l (\text{PAL/SECAM}) = 13.5 \ \text{MHz}$$

BT.601* Video Format



525/60: 60 field/s

625/50: 50 field/s

* BT.601 is formerly known as CCIR601

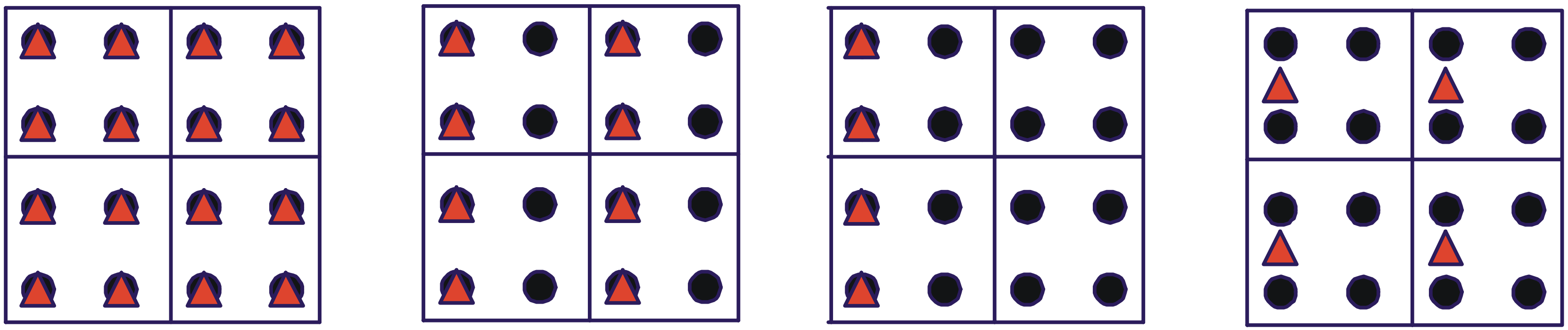
RGB <--> YCbCr

$$Y_d = 0.257 R_d + 0.504 G_d + 0.098 B_d + 16,$$
$$C_b = -0.148 R_d - 0.291 G_d + 0.439 B_d + 128,$$
$$C_r = 0.439 R_d - 0.368 G_d - 0.071 B_d + 128,$$

$$R_d = 1.164 Y_d' + 0.0 C_b' + 1.596 C_r',$$
$$G_d = 1.164 Y_d' - 0.392 C_b' - 0.813 C_r',$$
$$B_d = 1.164 Y_d' + 2.017 C_b' + 0.0 C_r',$$

$$Y_d' = Y_d - 16,\ C_b' = C_b - 128,\ C_r' = C_r - 128$$

Chrominance Subsampling Formats



4:4:4
For every 2x2 Y Pixels
4 Cb & 4 Cr Pixel
(No subsampling)

4:2:2
For every 2x2 Y Pixels
2 Cb & 2 Cr Pixel
(Subsampling by 2:1 horizontally only)

4:1:1
For every 4x1 Y Pixels
1 Cb & 1 Cr Pixel
(Subsampling by 4:1 horizontally only)

4:2:0
For every 2x2 Y Pixels
1 Cb & 1 Cr Pixel
(Subsampling by 2:1 both horizontally and vertically)

● Y Pixel

▲ Cb and Cr Pixel

Digital Video Formats

Video Format	Y Size	Color Sampling	Frame Rate (Hz)	Raw Data Rate (Mbps)
HDTV Over air. cable, satellite, MPEG2 video, 20-45 Mbps				
SMPTE296M	1280x720	4:2:0	24P/30P/60P	265/332/664
SMPTE295M	1920x1080	4:2:0	24P/30P/60I	597/746/746
Video production, MPEG2, 15-50 Mbps				
BT.601	720x480/576	4:4:4	60I/50I	249
BT.601	720x480/576	4:2:2	60I/50I	166
High quality video distribution (DVD, SDTV), MPEG2, 4-10 Mbps				
BT.601	720x480/576	4:2:0	60I/50I	124
Intermediate quality video distribution (VCD, WWW), MPEG1, 1.5 Mbps				
SIF	352x240/288	4:2:0	30P/25P	30
Video conferencing over ISDN/Internet, H.261/H.263, 128-384 Kbps				
CIF	352x288	4:2:0	30P	37
Video telephony over wired/wireless modem, H.263, 20-64 Kbps				
QCIF	176x144	4:2:0	30P	9.1

Video Terminology

- Component video
  - Three color components stored/transmitted separately
  - Use either RGB or YIQ (YUV) coordinate
  - New digital video format (YCrCb)
  - Betacam (professional tape recorder) use this format
- Composite video
  - Convert RGB to YIQ (YUV)
  - Multiplexing YIQ into a single signal
  - Used in most consumer analog video devices
- S-video
  - Y and C (QAM of I and Q) are stored separately
  - Used in high end consumer video devices
- High end monitors can take input from all three

Homework

- Reading assignment:
  - Chap. 1.
- Problems:
  - Prob. 1.5.
  - Prob. 1.6.
  - Prob. 1.7.
  - Prob. 1.8.
  - Prob. 1.9.
  - Prob. 1.10
  - Prob. 1.11
  - Prove mux/demux with QAM will get back the original two signals