HDTV and Film — Issues of Video Signal Dynamic Range

By Laurence J. Thorpe

The SMPTE Working Group on High-Definition Electronic Production (WG-HDEP) developed the basis of an HDTV production standard from 1984 to 1987. In September 1988, the SMPTE formally standardized the 1125/60 HDTV studio origination format, now well known as the SMPTE 240M standard. Since that time the work of the WG-HDEP has continued unabated. Prominent among the group's activities have been rigorous development of the digital representation of SMPTE 240M and a broad examination of image transfer of an HDTV production standard to 35mm film (and vice versa). In the digital work the issue of signal dynamic range emerged early as a major topic of study. The desire to better reconcile HDTV image capture with that of film (particularly if intercutting is under consideration), coupled with more efficient use of digital encoding, called for a closer look at the total transfer characteristic of the HDTV camera and how it should be preserved throughout the total system. This article is intended to describe, in tutorial form, some of the new thinking that is emerging on HDTV video dynamic range and how it relates to the perhaps better-known contrast handling capability of motion-picture film negative.

The central task of visual program origination, for a film camera or a television system, is to capture and record images as faithfully as possible on a medium that has, it is hoped, an extended life. Before discussing the dynamic range capabilities of either medium, a perspective on the magnitude of the task may be acquired by looking at what might be encountered in light levels[1] and contrast ranges in real-world scenes.

Table 1 shows typical illumination ranges (in lux) for a variety of naturally lighted environments. Any objects illuminated within these environments reflect a proportion of this incident illumination. This *object brightness* is what is seen by the camera lens and what ultimately exposes the negative film in the film camera or stimulates the image sensor of the television camera. The following discussion examines the range of contrast (from darkest to brightest object) that can actually be captured and recorded with a degree of faithfulness that ensures a believable reproduction when it is subsequently viewed.

Obviously, the object brightness range that can be encountered outdoors is potentially enormous. On a bright sunny day, objects of high reflectivity and dark objects in shadowed areas can create scene contrast ranges easily in excess of 20,000:1 (86 dB). Cameras (film or television) have limitations to their dynamic range that curtail the capture of a scene with large contrast range. This, in turn, calls for continuous creative compromising on the part of the cinematographer.

Table 2 shows typical illumination levels encountered in artificially lighted environments. They are considerably lower than the outdoors; nevertheless the contrast range can still be very high within a given environment (a studio can easily have object brightness ranging from greater than 2000 lux to less than 1 lux, providing scene contrast ratios in excess of 2000:1, or 66 dB).

Table 3 shows the vast range of scene illumination an HDTV camera deals with. Assuming the conventional studio reference for an HDTV camera (reference white level being a white object with a reflectance of 89.9%, illuminated by a light source with a color temperature of 3200 K and a light level of 2000 lux), this table indicates the degree of optical light-level control (in units of *f*-stops) or, alternatively, camera video gain control required to normalize white objects to this reference when they are viewed within the real-world range of illuminations.

Film Contrast Range Capture

The transfer characteristic of negative film is depicted by the well-known *D*-log*E* curve.[2] Figure 1 shows the characteristic curve set for the emulsion trio of the EK 5247 negative film, reproduced from the standard data sheets for this film.[3] These "tilted-S" curves plot the densities (*D*) of the exposed film's three emulsions (on the vertical axis) against the logarithm of the illumination (*E*) to which the negative film was exposed. Figure 2 shows in more detail the *D*-log*E* characteristic curve for a generic film's green emulsion. The curve has a generous linear portion that gradates into a shoulder at the high exposures — a nonlinear section that ultimately levels off — thus defining the upper recording boundary of the film. Similarly, at the lower end, where light exposures are low, the linear region curves into a toe that ultimately levels off and thereby defines the lower recording boundary.

Two expressions are common parlance among film cinematographers — *scene contrast range* (sometimes called *object range*) and *latitude*. The latitude is expressed in either camera

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Table 1 — Typical Day and Night Illumination Levels

Light	Illumination (Lux)
Day	
Bright sun	50,000–100,000
Hazy sun	25,000–50,000
Bright cloudy	10,000–25,000
Dull cloudy	2,000–10,000
Very dull	100–2,000
Night	
Sunset	1–100
Full moon	0.01–0.1
Starlight	0.0001–0.001

Table 2 — Typical Artificial Illumination Levels

Environment	Illumination (Lux)
Hospital operating theater	5,000–10,000
Television studio	1,000–2,000
Shop windows	1,000–5,000
Drafting office	300–500
Business office	200–300
Living room	50–200
Good street lighting	20
Poor street lighting	0.1

f-stops or log exposure. The latitude over the linear region is given by

$$\text{Latitude} = \log E_N - \log E_M \; (\log E \text{ units}) = \frac{E_N}{E_M} \; (\text{exposure units})$$

Maximum object contrast = max object brightness/min object brightness, which is rendered with strict proportionality between D and $\log E$.

$$1\ f\text{-stop} = 0.30 \log E$$

Latitude is often loosely regarded as the film equivalent of dynamic range in TV cameras.[4] This equivalency will be looked at more closely here.

As the curve in Fig. 2a shows, this particular film has a generous 6 to 7 *f*-stops or straight-line latitude, which ensures a linear proportionality between film density and the scene exposure. This linear curve is, moreover, an effective compressor by virtue of the slope (sometimes called gamma) of this linear region. The gamma in this film is approximately 0.6. The contrast range over the linear region is about 128:1 (7 *f*-stops $= 2^7 = 128$).

The film can clearly record considerably more than 7 *f*-stops. As the curve in Fig. 2b shows, more than 9 *f*-stops, or a contrast ratio of more than 500:1 ($2^9 = 512$), can be captured if some nonlinear compression can be accepted in the darker areas and the highlights. And such compression can indeed be accepted; in fact, it has become a well-honed artistic, creative tool in the hands of practiced cinematographers.[5,6]

Total negative film contrast range is defined as the density difference between the thinnest and densest areas;

Table 3 — Camera Control for Normalization of Video Output Level

Illumination (Lux)	Light Level Reference to Television Studio	Light Control Required to Establish Video Level (Approx. *f*-stops)	Video Gain Adjustment to Establish Reference Video Level
Bright sunlight, 100,000	×50	−5½	−34 dB
Dull cloudy, 2,000	1	0	0
Living room, 200	1/10	3½	+20 dB
Full moon, 0.1	1/20,000	14½	+86 dB

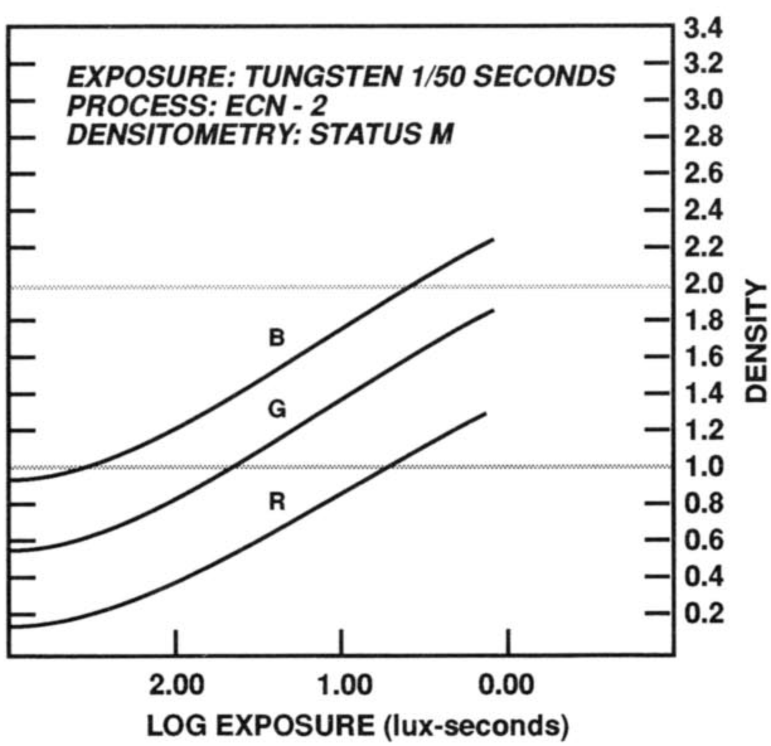

Figure 1. Characteristic curves of color negative film EK 5247 (IE: 125 tungsten, 80 daylight).

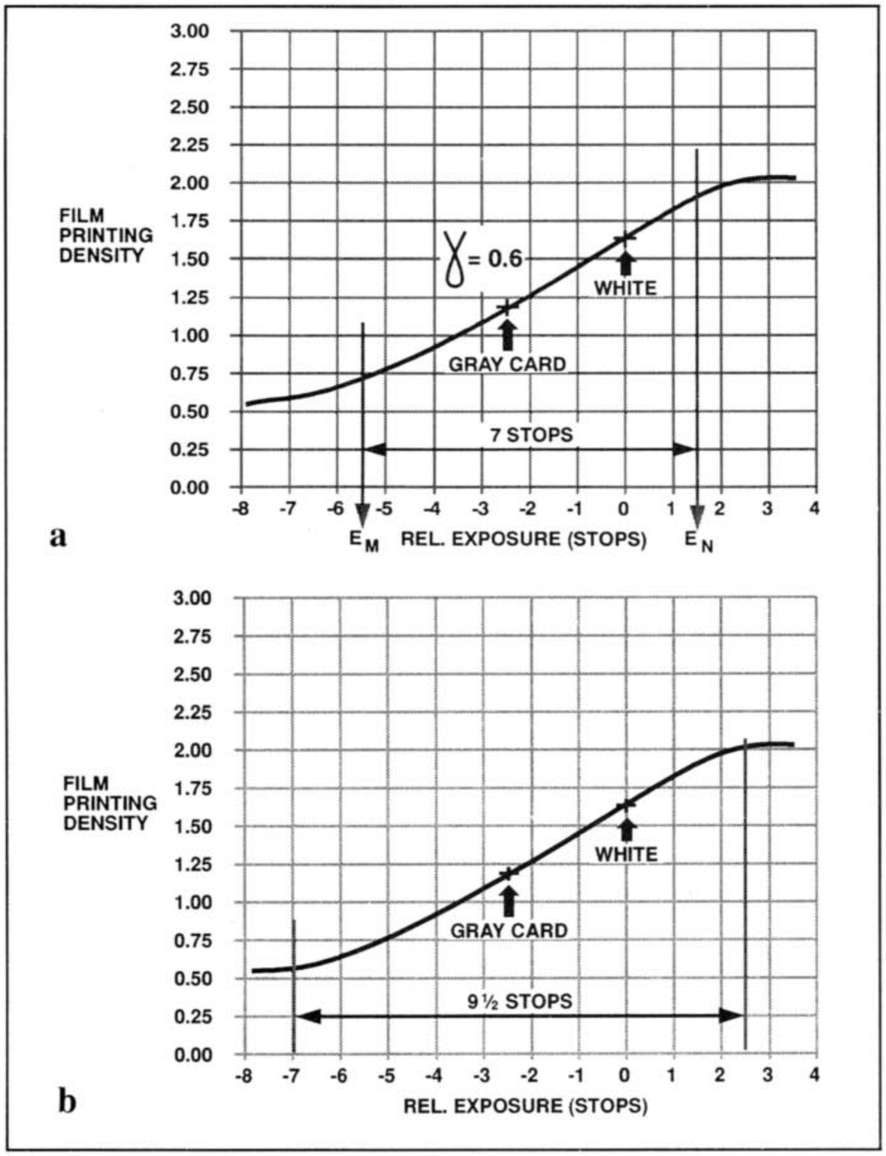

Figure 2. Latitude of Eastman color negative film (green record): (a) straight-line latitude; (b) total latitude.

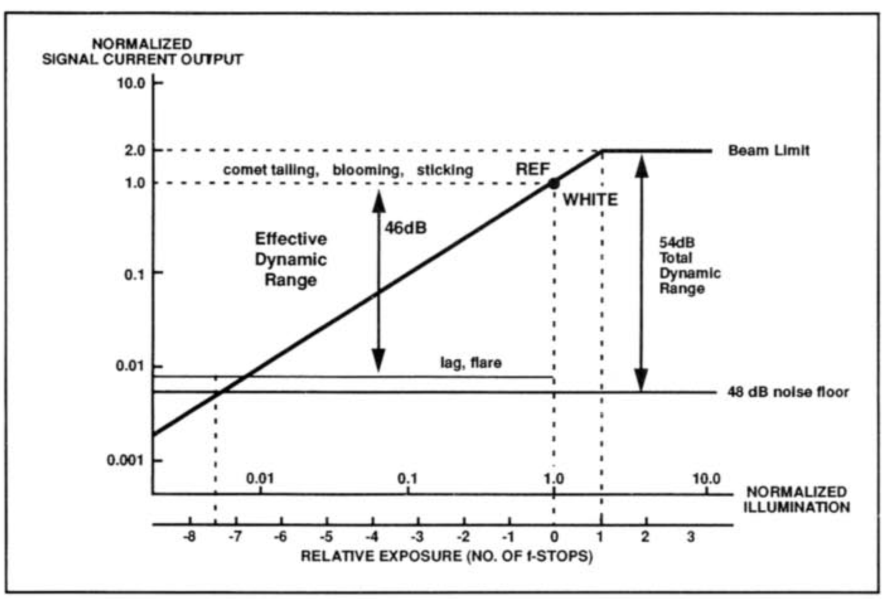

Figure 3. Total dynamic range and effective dynamic range of early pickup tubes.

it is called the density range. Density range is determined by

- Scene contrast range
- Camera settings, namely in setting lens iris opening and exposure time, which establish the placement on the range of log$E$ axis
- Shape of the negative film characteristic curve, determined by emulsion composition and developing conditions

Maintaining good tone scale (tone reproduction, or gray scale in video terms) is dependent upon optimally mapping a suitably chosen scene contrast range through the film's characteristic curves and onto the final display medium, such as print film, or onto a cathode ray tube (CRT) display for telecine transfer from film origination to television output.[7,8]

Video Dynamic Range — Limitations of the Camera Imaging Section

As the SMPTE WG-HDEP progressed in its studies of the requirements for HDTV dynamic range, it was recognized that many of the issues encountered are also considerations in our current 525-line television.[9] The basic challenge centers on the recent rapid and dramatic progress in the signal-handling capability of television cameras and the new attention that consequently must be directed to the VTR and to the post-signal-handling systems.

The explosion of color camera development that began in the late 1960s with the widespread adoption of color television was further fueled in the late 1970s by the advent of electronic news gathering/electronic field production (ENG/EFP) portable cameras. The popular 30mm and 25mm Plumbicon television studio cameras of 1965 to 1980 conventionally had a sensor dynamic range limited at the upper end by practical boundaries of the pickup tube's beam reserve (typically 2:1 above nominal white exposure) and at the lower end by the noise floor (cameras at that time had about a 48-dB signal-to-noise ratio (SNR)). This limited the total dynamic range to about 54 dB, as shown in Fig. 3.

However, an effective dynamic range (less than the total) limited actual operating practices as program producers struggled to generate images free of camera sensor artifacts. Most severe at the upper end, such artifacts as sticking (image retention), blooming, and comet tailing — stimulated as the pickup tube tried to deal with high object-brightness levels — simply could not be tolerated on certain high-quality programs. At the lower end, flare and lag often marred the image in low-light scenes, sometimes even more than noise. A typical effective dynamic range was probably in the vicinity of 46 dB.

Dynamic Range — Lower Boundary of SNR

At low-light-level illuminations of the scene, the limitation to acquiring a useful picture for broadcast applications is determined primarily by the SNR. Here we have to rely on the inherent photosensitivity of the tube (always less than the theoretical 100% quantum efficiency) and ensure low noise in the camera tube and associated preamplifier. Modern Plumbicon and Saticon tubes have negligible noise in the target compared to the noise in the preamplifier system.

In the mid-1980s, however, striking advances in both pickup tube and preamplification design were steadily contributing to an increase in this dynamic range. A 60-dB SNR was becoming typical of contemporary ENG/EFP and ⅔-in. studio cameras. The smaller image-tube formats lowered lag, and improvements in optical design (and electronic flare-correction circuits) significantly reduced flare effects.

Upper Boundary — Highlight Problem

In the early days of the Plumbicon cameras, without doubt the most vexing artifacts to be contended with were the highly visible and objectionable blooming and comet-tailing effects surrounding the inevitable highlights that often constituted only a small area of an otherwise normally exposed scene.

Those highlights (which can extend considerably beyond the average scene illumination) exceed the normal beam reserve of the pickup tube and result in the subjectively distracting artifacts of blooming and comet tailing. These effects can be alleviated by elevation of the beam current (to a degree), but only at the expense of reduced resolution and increased lag that invariably accompany any increase in beam reserve. Typically, tube beam reserve of about 2:1 above nominal white exposure represented a general industry compromise. That is, about 1 f-stop of excess highlight could be accommodated, sufficient to handle a small overexposure but totally inadequate for discharging severe highlights.

ACT Tube

The advent of the anti-comet-tail (ACT) tube in the early 1970s brought a novel solution to the problem.[10] Specially constructed tubes, with additional electrodes and associated ACT pulse-driving circuits, allowed an innovative compromise of handling normal scene illumination with a beam reserve of perhaps ½ f-stop; the new tube design actually introduced a knee characteristic at this level. However, excessive highlights, beyond the knee, are separately handled by neutralizing the highlights (returning target potential to that of the cathode) with a greatly boosted beam current during flyback. The tube adjustment consists in arranging for normal exposures to be handled by the forward readout beam current (with knee) and for any highlight areas on the target to be separately handled by the far larger flyback beam current. State-of-the-art 25mm ACT Plumbicons commonly handled almost 5 f-stops of highlights above normal exposure with substantially reduced blooming and comet tailing. ACT guns were confined almost exclusively to 25mm and 30mm Plumbicons, and they enjoyed an era of popularity in outside broadcast cameras.

Tube Dynamic Beam Control

A more recent solution, in the early 1980s, was heralded by the introduction of dynamic beam control (DBC), more commonly called automatic beam optimization (ABO). These were circuits that operated with conventional tubes but attained a particularly high degree of success with diode-gun tubes[11] because of their novel grid voltage-cathode current transfer characteristic. In this system a special feedback circuit monitors the target signal current, and when a sharp increase is encountered (indicative of the beginning of an attempt to discharge a highlight charge pattern on the target), this circuit controls the grid voltage of the tube in a manner that sharply boosts the beam reserve. This is an automatic action, calling for enhanced beam reserve (by driving the forward beam scan) only when demanded by the presence of a highlight. The large beam reserve of the diode-gun tube, combined with the high slope of the beam current-grid

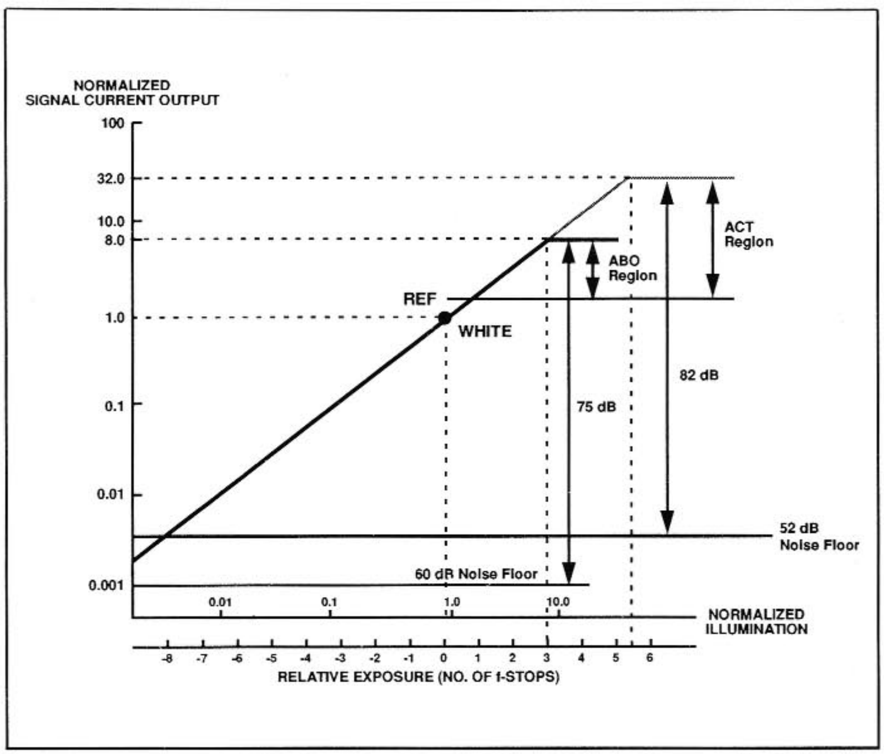

Figure 4. Dynamic range of ACT tube and ABO tube.

voltage characteristic curve, rendered ABO circuits remarkably effective, particularly with the ⅔-in. pickup tubes of the 1980s. ABO circuits incur some compromises in their capability as a consequence of precautions that must be taken to avoid potential instabilities that can be encountered in what is, in essence, a positive feedback system.

Typically, ABO circuits can handle about 3 *f*-stops of excess highlight with modest blooming and comet tailing. While not as formidable as the ACT tube, the ABO enjoys virtually universal employment in modern ENG/EFP and studio cameras – and HDTV cameras – because of the cost-effectiveness of the tube and the compactness of the DBC circuits.

A comparison of the total dynamic range capabilities of a typical 25mm ACT Plumbicon tube camera of the late 1970s and that of a modern 18mm Plumbicon tube camera employing ABO techniques is shown in Fig. 4. The dynamic range can be assessed, in video terms, by the output video signal range between the upper and lower boundaries (vertical scale, typically quoted in dB). Alternatively, the signal-handling capacity of the television imager can be measured in terms of total latitude of the scene capture (horizontal scale, quoted as *f*-stops of input scene latitude). The latter method is adopted here to facilitate a later comparison of the HDTV camera with the film camera.

It must be stressed that the techniques of ACT and ABO merely alleviate the beam-related artifacts at the upper end of video capture; they do not allow high-quality video reproduction in this region of overexposure. In this sense it must be said that the more graceful upper limitation of film (the shoulder characteristic, which is virtually free of highlight-related artifacts) remains superior to that of any pickup tube camera.

HDTV and Film Systems

A very rudimentary comparison of the total HDTV and film systems[12] is shown in Fig. 5. Each system has a shoot-and-capture front end, the output of which is a recorded image ready for delivery to the subsequent system. In HDTV, the recording is a first-generation VTR playback video signal; in film, it is the processed negative. There are common parameters for image quality (often uniquely labeled) in each medium shown in Fig. 5. This article concerns the first three: (1) total contrast range, (2) gray scale transfer characteristics, and (3) noise and granularity.

The importance of understanding the synergy between the two media, and the significance of relationships between image parameters, was fully recognized by the SMPTE Working Group on High-Definition Electronic Production. Figure 6 illustrates the multimedia system possibilities available today that can address a range of imaging applications in future ATV systems and in the motion-picture, corporate, medical, printing, and publishing industries, as well as other diverse businesses and industries.

An understanding of the technical imaging parameters involved will facilitate the effective image transfer required between media. Central to this understanding are the issues surrounding image dynamic range.

Transfer Characteristic of SMPTE 240M

In developing the SMPTE 240M standard,[13] colorimetry and transfer characteristic were carefully examined from three system viewpoints:

- Producing an HDTV production system that would provide an adequate display of picture contrast range on a reference HDTV studio monitor (direct-view CRT), implementable with today's CRT technology.
- Developing a system approach that recognized the inevitability of

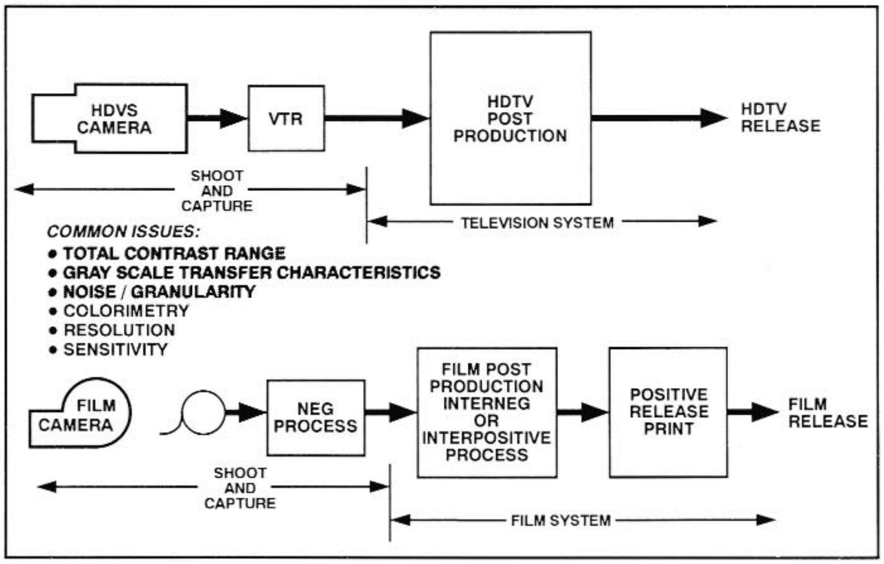

Figure 5. HDTV and film systems.

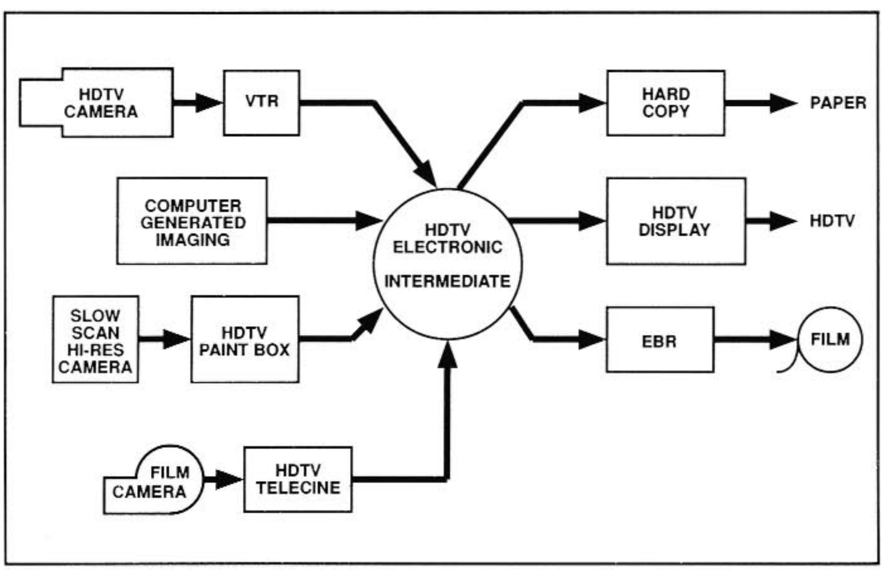

Figure 6. Multimedia in business and industry.

continuing evolution in HDTV display, both direct-view and projection. This would require the ability for the display system itself to encompass the different colorimetric transformation and gamma correction appropriate to the particular display technology in question (CRT, laser, LCD, plasma, etc.).

• Extending the system approach to allow the HDTV capture on videotape to be subsequently transferred to 35mm film. This, too, entailed consideration of colorimetric transformations and transfer characteristics tailored to the different film emulsions that would be encountered.

Thus, the requirement for downstream system video processing, involving different colorimetric transformations and appropriately tailored nonlinear transfer characteristics, introduced the concept of incorporating the capability to linearize[14] the HDTV video component signals, somewhere in the post-production process. Impetus was further lent to this need by the anticipation of digital image manipulation that might also form a part of the post-production process. Such digital processing is better accomplished with linear video signals.

High-Definition Television System

A simplified block diagram of a total HDTV system, from studio production to the home, is shown in Fig. 7. This corresponds to our established 525-line NTSC television system today. There were two considerations of the SMPTE WG-HDEP: (1) in the early days, HDTV studio monitors and home receivers would be conventional in the sense that they would rely exclusively on nonlinear precorrection in the HDTV camera (gamma correction) to compensate for their nonlinear display transfer characteristic; and (2) in the future, manufacturers would have the option of incorporating nonlinear video processing in studio reference monitors and, possibly, even in future sophisticated home HDTV receivers. A block diagram of such a system is shown in Fig. 8.

Facilitating such a dual-system approach required

• Incorporating in an HDTV camera a nonlinear precorrection that would adequately (if not entirely accurately) compensate for the CRT transfer characteristic.

• Standardizing a camera precor-

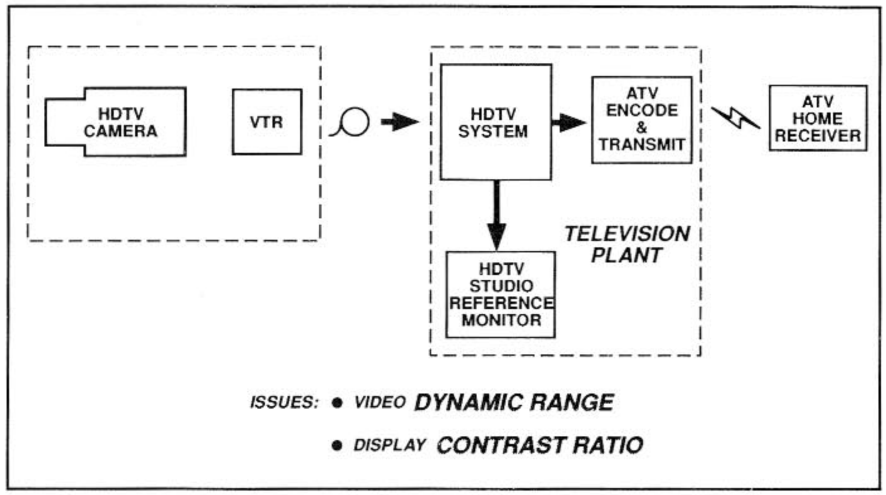

Figure 7. High-definition television system.

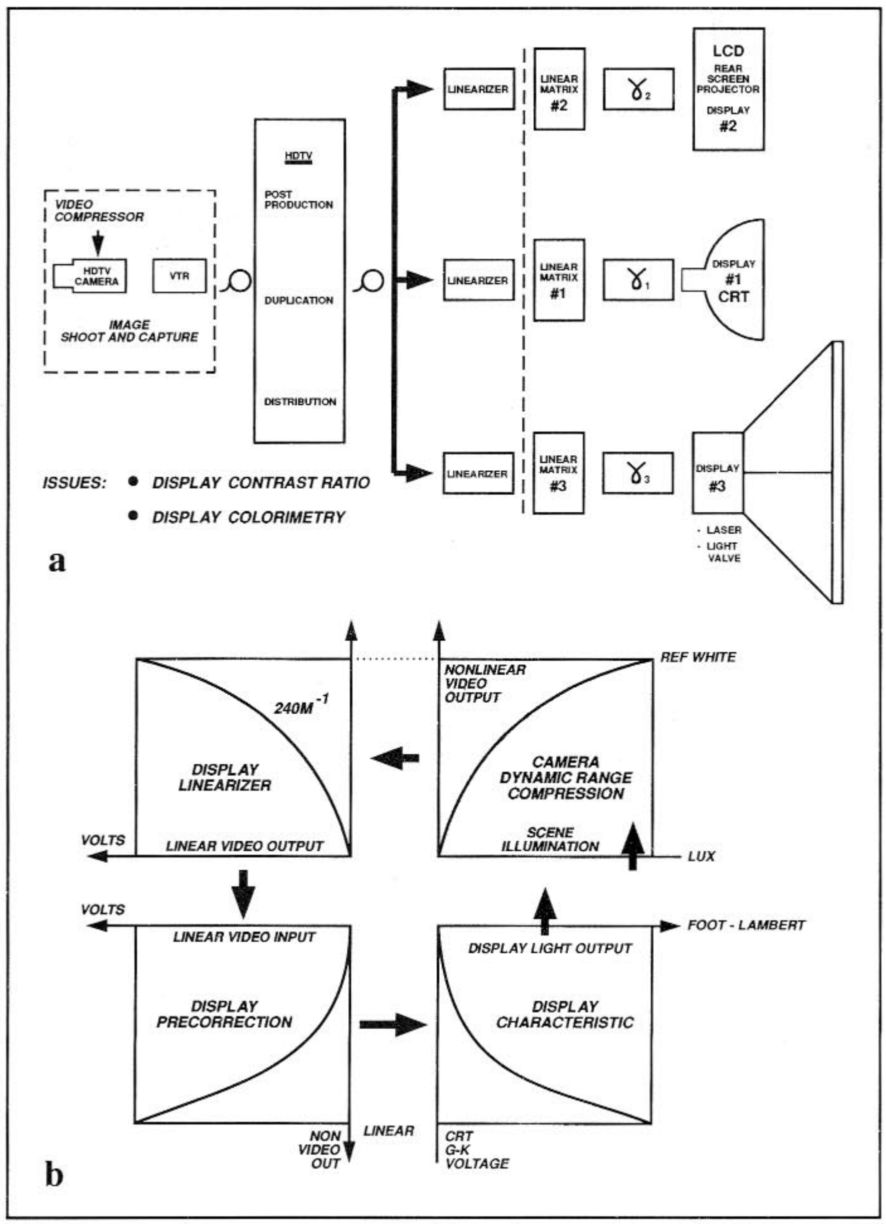

Figure 8. HDTV system employing linear matrixing and gamma correction circuits in the display systems: (a) different HDTV systems; (b) convolution of camera compression curve, display linearizing curve, and display gamma correction curve.

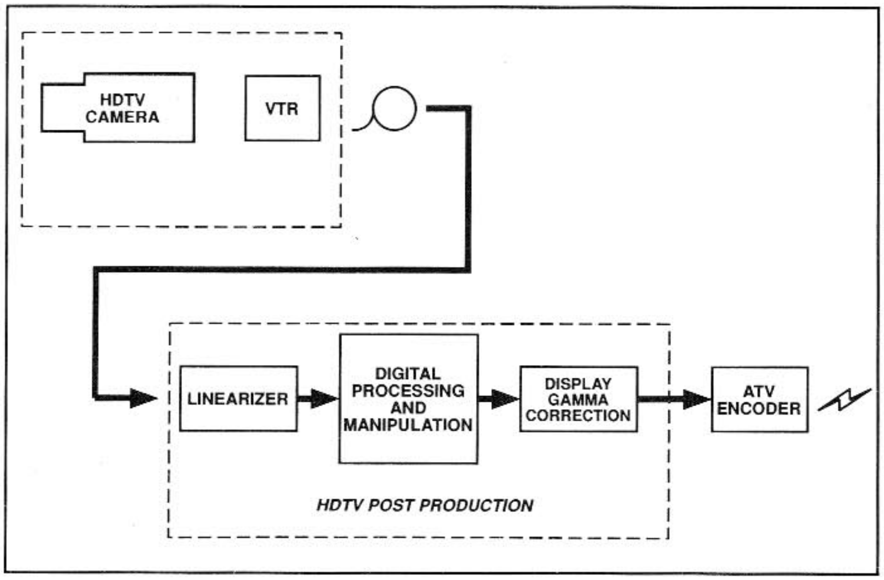

Figure 9. Digital post-production.

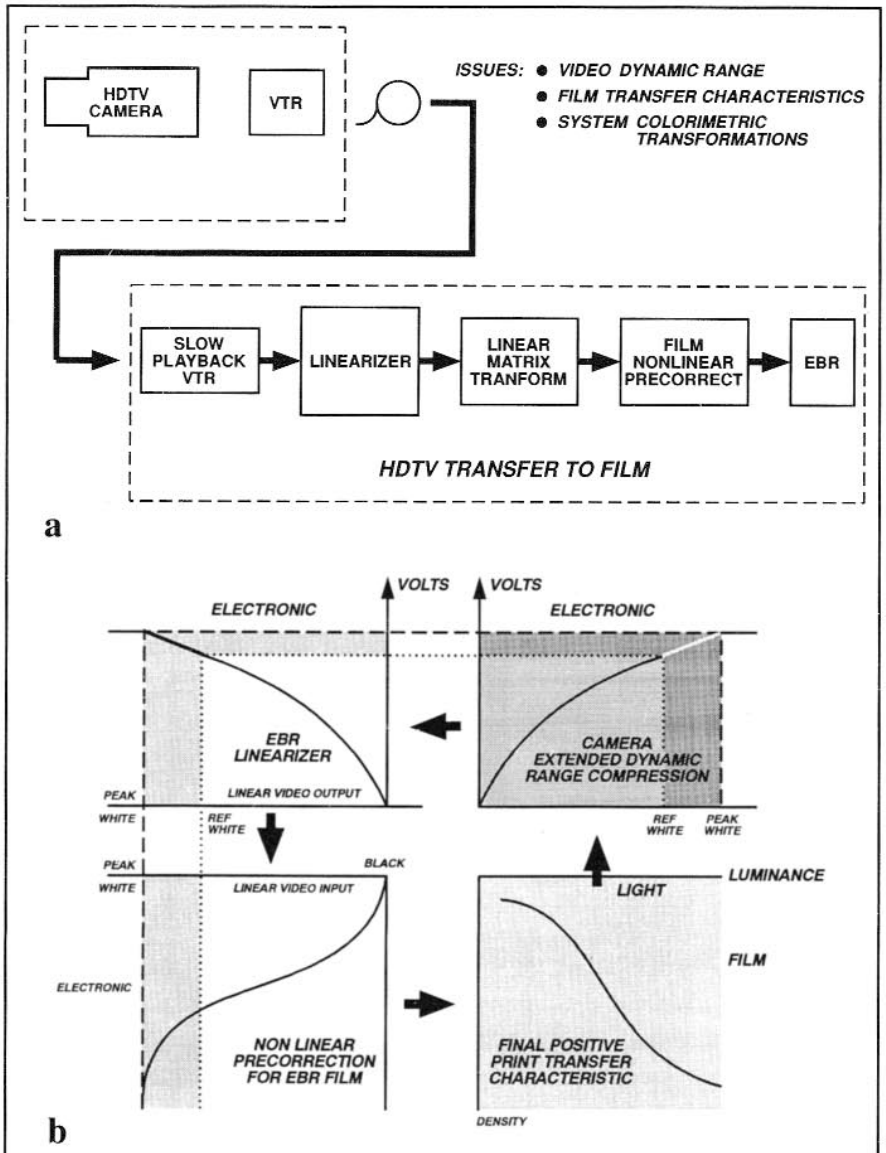

Figure 10. HDTV transfer to film: (a) total process; (b) transfer characteristics in the system.

rection curve with a shape that could be easily implemented with hardware and, perhaps more important, easily linearized downstream with high accuracy. This entailed designing a curve described with high mathematical precision and shaped for easily implemented hardware in a wideband (30-MHz video) system and allowing for an equally easily implementable downstream linearizing circuit.

The SMPTE 240M precorrection curve meets these requirements quite well.

HDTV Origination with Digital Post-Production

Figure 9 shows a block diagram depicting HDTV shoot and capture followed by post-production. Post-production will take many forms in HDTV, depending upon the application. It might well embrace all that is now done with digital video effects, electronic paint boxes, and 3-D image manipulation — all for picture embellishments intended for future home entertainment and commercials. It may also involve complex manipulation of HDTV images used in non-entertainment applications — in business and industry, corporate communications, and medical, educational, scientific, and military work. Many have expressed the opinion that complex digital manipulation will be better accomplished on linear video signals. Thus, a linearizer (most likely digitally implemented) will be required in post-production, as illustrated in Fig. 9. After the requisite digital processing/manipulation, the video signal components can then be gamma corrected before being encoded for transmission, or possibly for closed-circuit large-screen display. This gamma correction could take the form of a repeat of the SMPTE 240M precorrection curve, or it could be another curve more accurately optimized to the particular display (direct-view CRT, projection, etc.) and viewing environment. In particular, the latter can call for system gammas ranging from 1.0 to 1.5, depending on the viewing ambient lighting.

HDTV Origination with Subsequent Transfer to Film

HDTV origination with subsequent transfer to film is similar to the procedure for linear digital post-production. The block diagram in Fig. 10a shows the HDTV component video signals again linearized in post-production. The transfer to 35mm film requires considerable signal preconditioning,[15] which must begin with linear signals. As Fig. 10a shows, the first correction (which must take place with linear signals) is that of a matrix transformation to alter the SMPTE 240M colorimetry to one appropriate to the film emulsions being used. This is followed by a nonlinear precorrection also tailored to the characteristics of the film (Fig. 10b).

The primary role, therefore, of the nonlinear precorrection in the camera (precisely specified according to SMPTE 240M) is one of dynamic range compression. That is, all that can be captured by the HDTV camera sensors (Saticon, Plumbicon, and CCD all being imagers with linear light transfer characteristics) must be compressed to accommodate the limitations of digital quantization and noise in VTRs, transmission systems, and post-production systems.

Television Visual Contrast Range

As the object brightness in the scene is progressively lowered, the brightness of the television display correspondingly lowers. A point is finally encountered where the display fails to portray to the viewer's eye any discernible lowering in the brightness, despite a continuing diminution of the scene object brightness. This point constitutes the lower threshold of the contrast range of that particular television system. Conversely, at the upper end – as the object's brightness is progressively raised – the system reaches a point where the display portrays no further incremental increase in apparent brightness. This can occur because of overloading of the display mechanism or because of an upper boundary in the capability of the imager in the television camera. The upper threshold divided by the lower threshold defines the contrast handling range of that television system.

A total television system includes the scene (which has a certain contrast range defined by the upper and lower levels of object brightness), the television camera and subsequent electronic system (which have a defined video dynamic range), the final viewing display (which also has its own unique contrast range), and the viewer, who also possesses a finite capability in discerning brightness increments. Figure 11 depicts this total visual system.

The "rules" of human vision are still a topic of considerable investigation and debate. However, as far back as the early 1700s, Pierre Bouguer revealed that the average human being could distinguish between two adjacent surface brightness levels if their contrast ratio was higher than about 1.015.[16] This work was later refined by the further discovery that the human eye responds linearly to logarithmic (or geometric) changes in light level. This is known as the Weber-Fechner Law.[17] This still-debated law will be accepted for the analysis here, and a slightly more conservative assumption is made (based on Pierre Bouguer) that two adjacent brightness steps on a television test chart are indistinguishable if their brightness ratio is less than 1.02.

SMPTE 240M Transfer Characteristic and Display Contrast Range

A television test chart, appropriately illuminated and viewed by the HDTV camera, is depicted in Fig. 12. There are 16 steps in this chart, each differing from the preceding step by a ratio of 1.414. Alternatively, every second step is half the brightness of the reference step, or one *f*-stop lower. If we directly view this chart, according to our laws of vision, each step appears to be of equal contrast in relation to its two neighbors. As shown in Fig. 12, the contrast range of this test chart is $(\sqrt{2})^{16}$ or 256:1.

The test chart's brightness levels corresponding to the enumeration of the individual steps appear in Table 4. As shown, the vertical brightness scale is logarithmic. The table lists all 16 brightness levels, assuming a nonspecific maximum brightness level normalized to 100 "brightness units"; it constitutes the object brightness inputs to the HDTV system. Now a word about the display before examining what the eye might actually see on an HDTV display in an HDTV system designed according to the SMPTE 240M standard. A direct-view HDTV CRT will be assumed because this

Table 4 – HDTV Camera Test Chart Brightness Levels

Brightness Levels		Step Number	Relative *f*-Stop
100		0	0
	70.711	1	
50.000		2	1
	35.355	3	
25.000		4	2
	17.678	5	
12.500		6	3
	8.839	7	
6.250		8	4
	4.419	9	
3.125		10	5
	2.210	11	
1.563		12	6
	1.105	13	
0.781		14	7
	0.522	15	
0.391		16	8

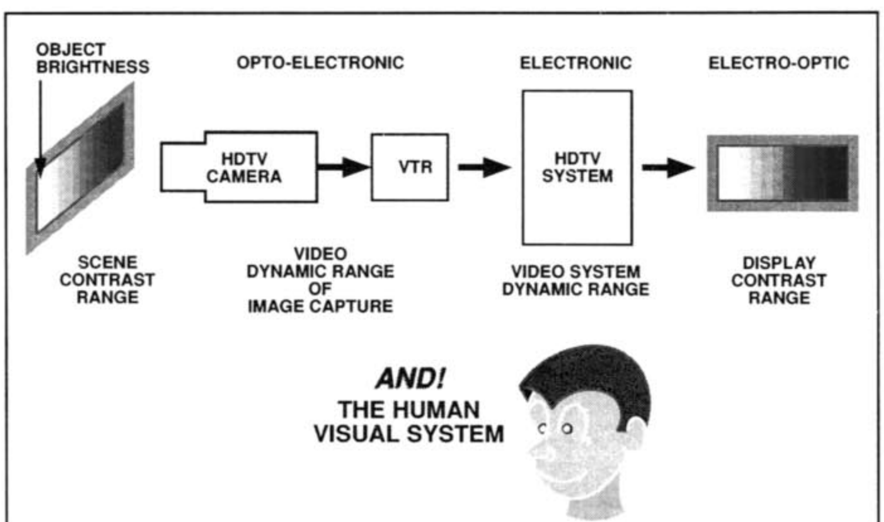

Figure 11. Television system contrast handling range.

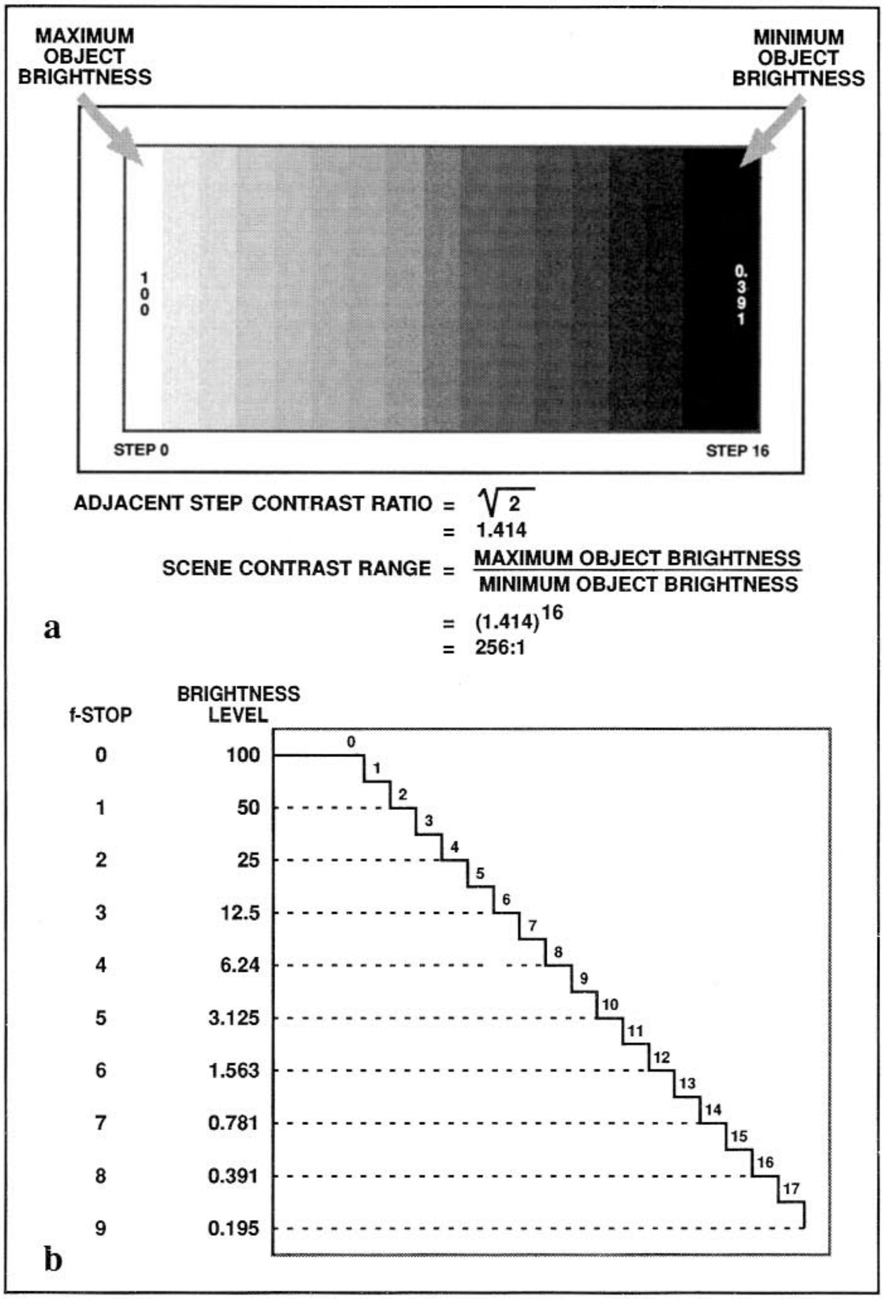

Figure 12. HDTV camera test chart: (a) scene contrast range; (b) brightness levels.

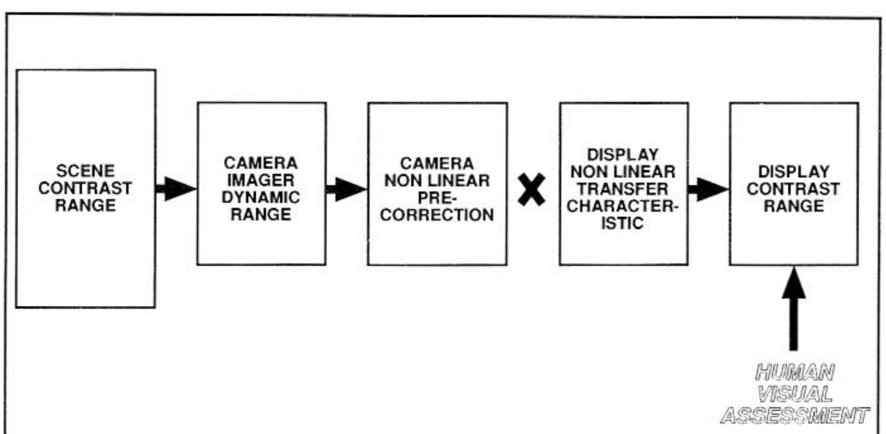

Figure 13. Television imaging system.

constitutes the contemporary studio reference monitoring system (and is expected to continue as such for quite some time). The CRT display has an upper and lower brightness threshold, each of which is bounded by the following physical criteria:

1. Maximum highlight brightness
   - Phosphor efficiency
   - Gun current
   - Gun/electron optics
2. Low-level brightness
   - Halation effects
   - Internal light reflections in CRT
   - CRT light reflecting back into itself
   - External ambient light

To facilitate the analysis, the generally accepted power law of 2.22 will be assumed to describe the nonlinear transfer characteristic of the CRT.

Figure 13 delineates the essential elements to be considered in assessing the imaging ability of this total HDTV system. The display characteristic has been described, and the camera's nonlinear electrical precorrection is according to that defined in SMPTE 240M and reproduced in Fig. 14.

The optoelectronic transfer characteristic of 240M is described mathematically on the left of Fig. 14, and the corresponding transfer curve is reproduced on the log-log scale shown. This mathematical expression is really describing two curves: one is a straight line depicting a constant gain of 4.0 (or 12 dB) at the lower end; the second is a power curve beginning at the top right of the graph (the reference white level input), which is based on a power law of 0.45, but it has been mathematically modified to ensure a smooth tangential interception to the linear curve at the bottom left. The conceptual point of interception is described by the factor 0.0228 in the mathematical expression and is shown as the vertical dotted line from the horizontal camera light input axis. This corresponds to a brightness input level of 2.28 brightness units, or a level that is slightly under 5½ *f*-stops below the reference white input. This level and the limiting gain of 4.0 (12 dB) in the lower light level region were two pivotal design decisions made by the designers of the SMPTE 240M standard. These were pragmatic choices based upon the practical capabilities of contemporary HDTV cameras and displays. They still stand as good choices.

A computer program was developed that applied the input brightness levels of Table 4 to the SMPTE 240M nonlinear transfer characteristic and, further, applied the result to the nonlinear power law of the CRT display. In effect, this mathematically computed the multiplication of the total system transfer characteristics represented in Fig. 13. Some significant modifications to this convolution were added, however. In this analysis, all the contributing unwanted components hampering low light reproduction in the CRT were computed as one factor, described as total display flare. Various levels of flare are examined, each intended to represent three types of viewing conditions relevant to the total HDTV environment. A level of 1% flare is taken to be representative of "ideal" viewing conditions such as might be encountered in a darkened laboratory. A level of 5% is typical of a semidark control room in a television station or editing room in a post-production house. Finally, the bright ambient level of typical home viewing is taken to be reasonably represented by a 15% flare level.

The computer program output was structured to reproduce the kinescope display as a series of curves (one for each system flare level) depicting the equivalent contrast ratio of adjacent test chart steps (vertical axis) portrayed against the identified steps themselves (horizontal axis). Figure 15 shows these display outputs for an HDTV system employing the SMPTE 240M camera precorrection. Superimposed on these curves is the significant "Pierre Bouguer line," at a contrast ratio of 1.02, which defines the threshold of visibility.

These curves allow immediate assessment of what the average human visual system will "see" on an HDTV CRT display for the three viewing conditions described. The points above the threshold of visibility line represent test chart steps that are visible to the human observer on the CRT. That the system portrayal is nonlinear is evident. But then, it always has been. Television camera designers have never implemented electronic precorrection in the camera (conventionally known as gamma curve) that precisely complemented the CRT nonlinear power law. This was never possible for two reasons: (1) the significant difficulties of actually implementing wideband nonlinear circuits with very large differential gain extremes (in the white and black regions) and (2) far more important, the consequent intolerable elevation of camera noise, flare, and lag effects representing visual penalties that could not be sustained in real television systems.

So camera precorrection has always been a pragmatically shaped curve that sought a balance between reasonable portrayal of contrast range on the CRT and control of the noise and low-level artifacts on the same display. Historically, camera manufacturers separately determined their own "optimized" gamma implementations, based on their individual experiences (often separately acquired by working with major broadcast end users having their own internal criteria). SMPTE 240M represents a historical break-

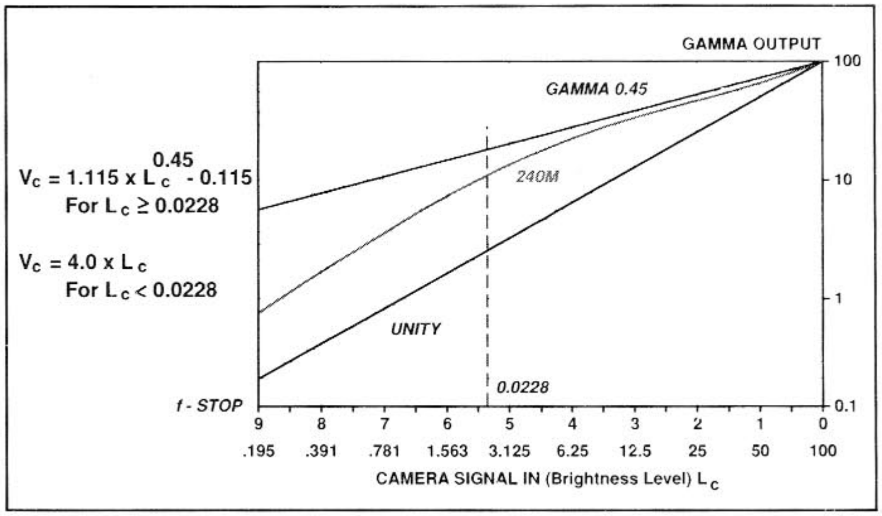

Figure 14. HDTV camera precorrection transfer function, 240M gamma.

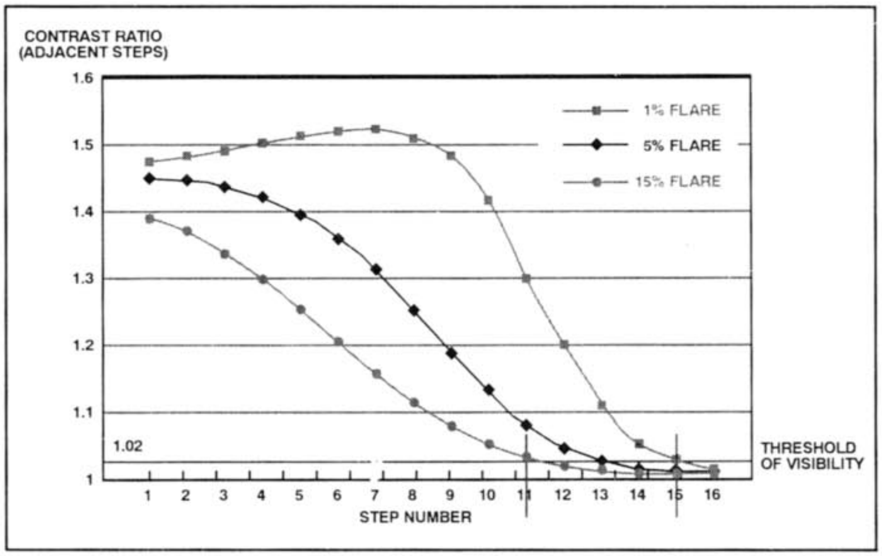

Figure 15. Gray-scale behavior of kinescope with HDTV camera using SMPTE 240M gamma correction.

Table 5 — SMPTE 240M Transfer Curve (Noise-free Example)

	1% Flare	5% Flare	15% Flare
Final distinguishable step number			
n	15	13	11
Display contrast range	$(1.414)^{15}$	$(1.414)^{13}$	$(1.414)^{11}$
$(\sqrt{2})^n$	180:1	90:1	45:1

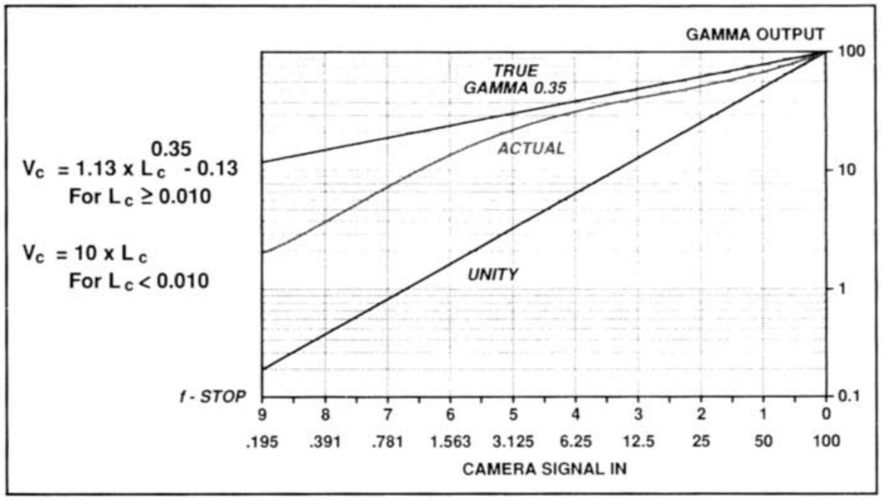

Figure 16. Transfer function of HDTV camera with 0.35 gamma-extended characteristic.

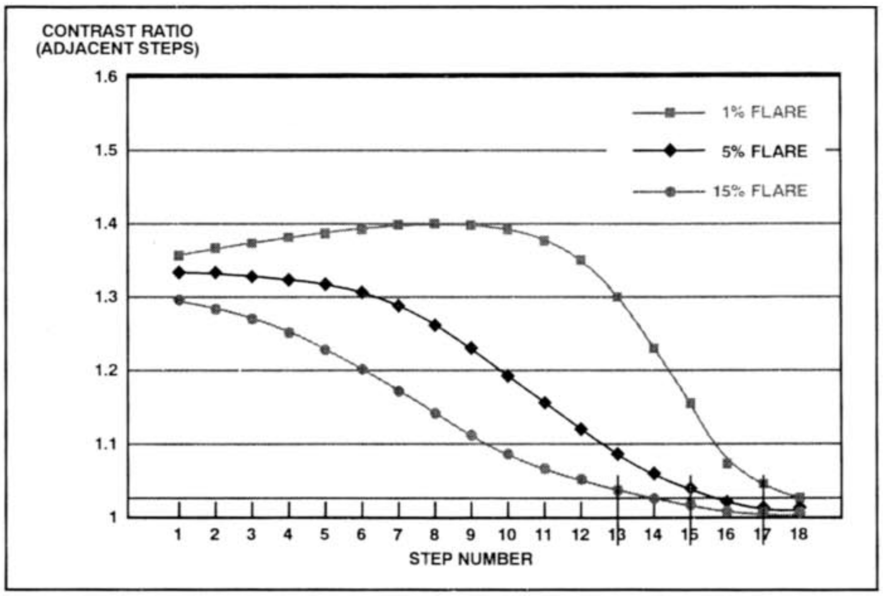

Figure 17. Gray scale behavior of kinescope with HDTV camera with 0.35 gamma-extended characteristic.

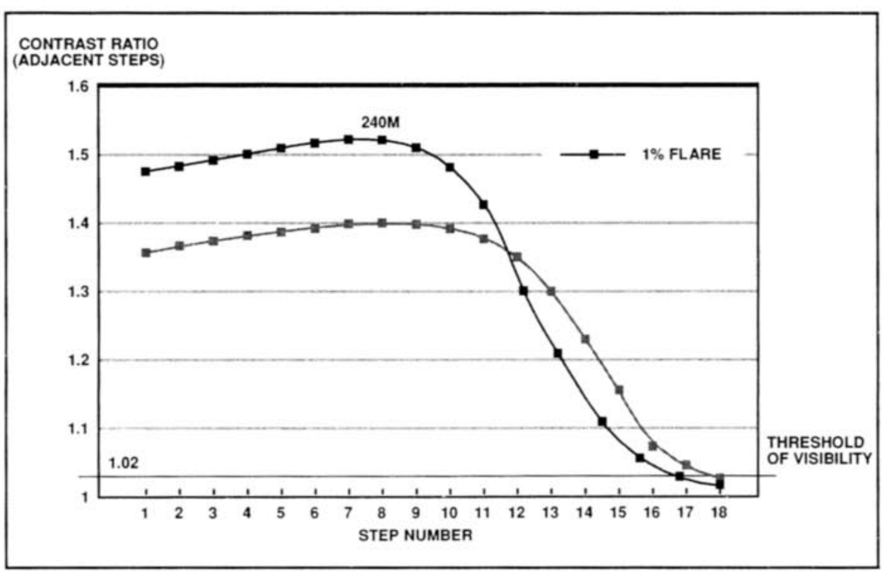

Figure 18. Comparison of display gray-scale behavior with two different HDTV camera precorrection curves.

through in standardizing a precise mathematically described curve that finally brings a sensible convergence to this important element of a total television system design. Incidentally, the driving force was the desire to converge on a standardized colorimetry (the display of which is profoundly affected by camera gamma).

Only a totally noise-free system has been considered so far in this analysis. Figure 15 allows an assessment of the picture contrast ratio as seen by the viewer, summarized in Table 5 for the three different viewing environments.

Many proposals have been made regarding the implementation of improved camera precorrection.[18-21] To further illustrate the design flexibility available to HDTV system designers, a second, more radical camera precorrection curve is examined. Here three significant changes have been made to better complement the CRT transfer characteristic:

1. The limiting gain at black has been raised from 4.0 to 10.00 (from 12 dB to 20 dB).
2. The point at which this limit is encountered is lowered to even darker regions – about 7 *f*-stops down on reference white level.
3. A lower power law of 0.35 is used as the "base" curve instead of the 0.45 of 240M.

This extended, 0.35-gamma curve is portrayed in Fig. 16, and the consequences on the display contrast ratios are shown in Fig. 17, again for three levels of flare.

To graphically compare the difference between the SMPTE 240M curve and the extended gamma curve, Fig. 18 illustrates a direct comparison of the CRT displays for the singular case of the 1%-flare "ideal" viewing condition. At the upper brightness levels, the 240M curve exaggerates the contrast ratios of adjacent steps (should be 1.414) from step 1 through step 11; whereas the extended curve gives a better approximation to a linear system (1.414 contrast relationships) from step 1 through about steps 11 and 12. In the darker regions, however, both systems quickly become nonlinear. Both curves for this noise-free example allow the human visual system to distinguish essentially the same number of brightness steps, albeit with more clarity for the extended curve.

To understand the real choices facing the camera designer, the critical lower region of the curve – specifically that defining the limiting low-light gain of the system – must be examined in light of the realities of television imaging. The effect of camera front-end noise must now be considered.

Dynamic Range of the HDTV Camera

To return to the front end of the television system, we take a closer look at another highly significant impediment to achieving a large system imaging contrast range in present-day HDTV systems. It's useful to examine the video signal in the camera at the earliest stage possible, the first available measuring point in the video chain, the imager preamplifier output. This is before any nonlinear precorrection in the camera.

Figure 19 shows a comparison of the total dynamic range capabilities of a second-generation HDTV camera employing state-of-the-art 25mm pickup tubes with that of a typical 525-line NTSC 18mm tube ENG/EFP camera when both employ a static beam reserve of 2:1. The horizontal axis represents the light input from the scene and is shown both as a normalized illumination on a logarithmic scale and as corresponding *f*-stops referenced to a normally exposed reference white level (89.9% reflectance white illuminated by 2000 lux at 3200 K). The vertical axis is also a logarithmic scale showing the output of the pickup tube's signal current (could also be normalized video peak-to-peak voltage at the first stage preamplifier output). The noise floors are the measured SNRs of the respective cameras when they are capped. The conventional definition of a pickup tube imager output dynamic range is from the beam overload level (6 dB above nominal white signal current) to the noise floor.

Clearly, the 525-line NTSC camera, with its relatively narrow bandwidth, has a significantly greater dynamic range than the 30-MHz HDTV camera – some 16 dB greater – which is entirely attributable to the greater noise level of the latter camera (a penalty of the triangular noise spectrum of pickup tube preamplifiers).

The dynamic range can also be evaluated on the basis of the input to the system. If the enhanced highlight handling (due to modern ABO capabilities) is factored in, then the dynamic range of pickup tube cameras can be compared in the manner shown in Fig. 20. The terminology of the film cinematographer is introduced in the form of exposure latitude, measured in *f*-stops. A direct comparison of a second-generation Sony HDTV camera (the current HDC-300) and the last Sony 525-line NTSC Plumbicon camera[22] – before replacement by charge-coupled devices (CCD) cameras – (the BVP-30) is depicted on the basis of dynamic range measured as input exposure latitude. This method of assessing an imager's dynamic range will be helpful when comparing HDTV and film camera performance.

So far, noise has been looked at as a lower boundary, a noise floor, when the camera is capped (i.e., no light input). It may be useful to take a look at the significance of noise when the camera views the reference test chart in Fig. 12. If the preamplifier voltage output, corresponding to this light input, is viewed on an oscilloscope, a stair-step waveform will be evident, with the riser amplitudes decreasing rapidly in a geometric ratio. At some particular riser amplitudes, the level of rms noise present will essentially equal that of the riser. For that particular riser step, the SNR becomes 0 dB (Fig. 21).

An SNR of 44 dB in an HDTV camera corresponds to 6.3-mV rms noise voltage, as shown in Fig. 22. This

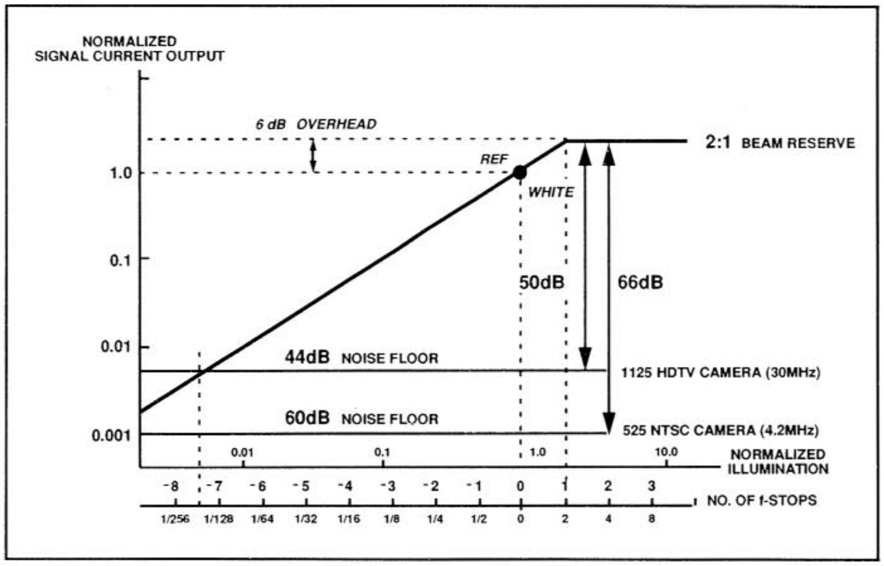

Figure 19. Dynamic range of pickup tube cameras.

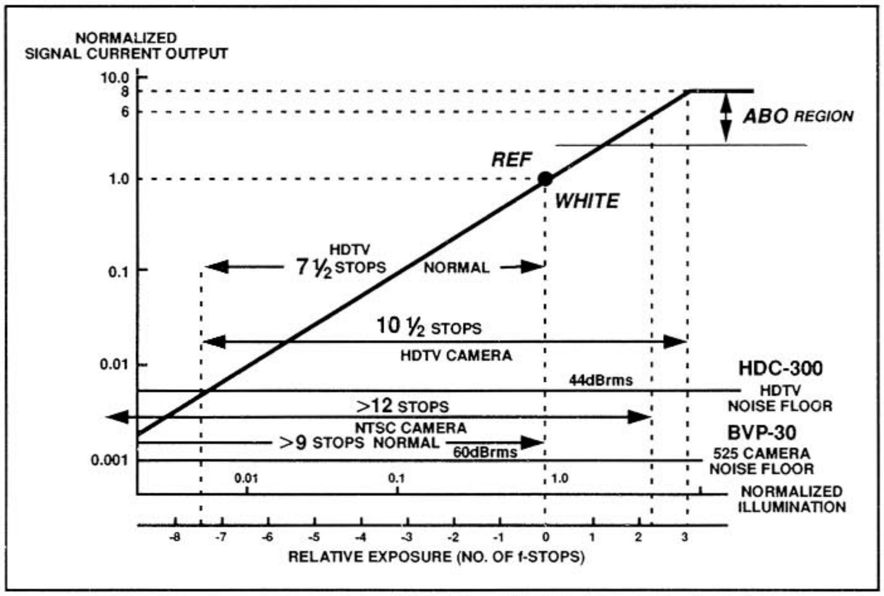

Figure 20. Dynamic range comparison of HDTV and NTSC pickup tube imaging systems.

approximately corresponds in amplitude to the riser descending into step 13 of the stairstep. That is, at this particular input brightness level (or 6½ *f*-stops down from reference white level), the imager output has a 0-dB SNR. The step thus cannot be effectively distinguished from the noise, and the lower boundary of the imager's video dynamic range has been determined. Note that the television system's dynamic range, and ultimate viewing contrast range, have been determined before any encounter with the camera nonlinear precorrection.

Table 6 summarizes the effective consequences of this input limitation on the displayed contrast ratio for the HDTV system using the SMPTE 240M precorrection curve. Under ideal lab conditions the last step that is distinguishable on the display is step 13, and thus we view an effective contrast ratio of 2^{13}, or 90:1. Camera noise limits effective portrayal of a wide dynamic range, as do the limitations of the display CRT itself and the incompatibility between camera nonlinear precorrection and the CRT transfer characteristic. Also, at the higher flare levels the flare factor dominates noise as the ultimate limitation to viewable contrast range.

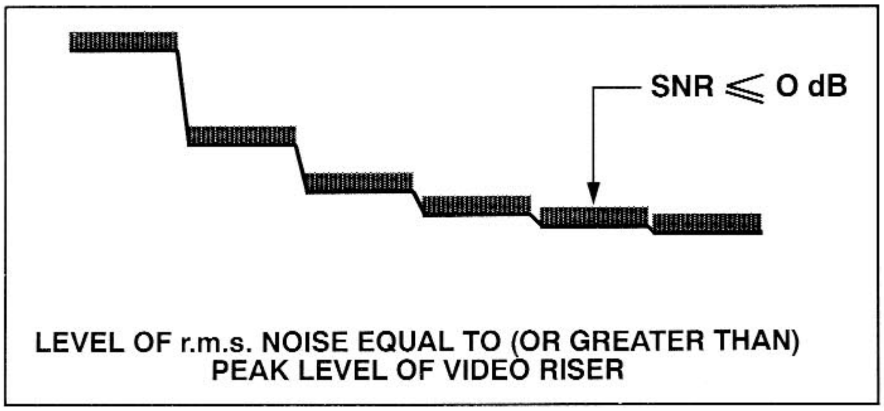

Figure 21. Noise limitation to video dynamic range.

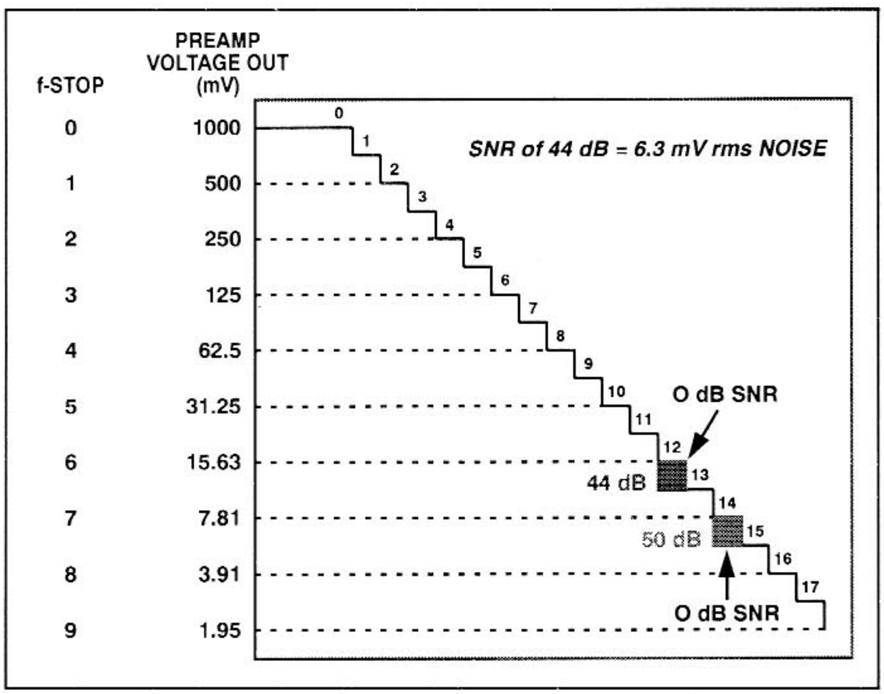

Figure 22. HDTV camera linear imager output.

Table 6 — SMPTE 240M Transfer Curve (Luminance SNR of 44 dB)

	1% Flare	5% Flare	15% Flare
Final distinguishable step number			
n	13	12	11
Display contrast range	$(1.414)^{13}$	$(1.414)^{12}$	$(1.414)^{11}$
$(\sqrt{2})^n$	90:1	64:1	45:1

If the dynamic range of the HDTV video signal is bounded at a lower input light level of 6½ *f*-stops (below reference white) then this must represent a critical design factor in the camera's subsequent nonlinear precorrection. There can be nothing gained by implementing a correction curve with high amplification in the region below this lower boundary; the camera is simply not reproducing any discernible signal that could even be made visible on a display. It was this stark reality that guided the framers of SMPTE 240M to settle for the very modest limiting gain of 12 dB in the standardized precorrection curve. As Fig. 14 shows, the limiting gain (12-dB) region of the SMPTE 240M curve is effectively below 5½ *f*-stops down from the reference white level. This fits very nicely with the 6½ *f*-stops lower boundary defined by contemporary HDTV cameras. Note that the SNR is not affected by the SMPTE 240M curve; that is, both the signal and the rms noise are amplified by 12 dB in the lower regions.

Noise in Film

Film has much the same difficulty with noise limitations at the lower end of the light transfer characteristic as does the television camera.[9,23,24] The latter exhibits a noise spectrum (triangular for the pickup tube – it increases linearly with higher frequencies) that is generally specified as an rms noise voltage related to the peak video voltage corresponding to the reference white level. Film noise is called granularity. It is measured with a scanning microdensitometer with a standardized aperture of 48 μm.

In order to compare television noise and film granularity, some correlation must be established. Generally this takes the form of scaling the measured film granularity according to an aperture that is calculated to produce an "equivalent aperture" related to the bandwidth of the television system being compared and to the width of the film frame of the particular film image format under consideration. Such a technique was described in an Eastman Kodak paper.[25]

Figure 23 shows the characteristic transfer curves and film granularity curves for two new high-performance films,[26] Eastman high-speed EXR 5296 and slow-speed EXR 5245. The dotted-line trios shown in each describe the relationship between film granularity for each emulsion layer and the input exposure. Interpreting such curves is, of course, difficult for video engineers. However, the technique described in Ref. 25 was used to prepare Table 7, which compares equivalent film noise (expressed as unweighted rms noise level referenced to nominal white level and calculated at a picture luminance level equivalent to the reference object) with that of the Sony HDC-300 HDTV camera. Some caution must be expressed in depicting such a comparison in this manner. As can be seen from the film data curves, film granularity varies with exposure, so the visible "noise" in film can vary quite a bit (and is further a function of the subsequent printing process). At best, therefore, Table 7 should be interpreted as indicating approximate magnitudes.

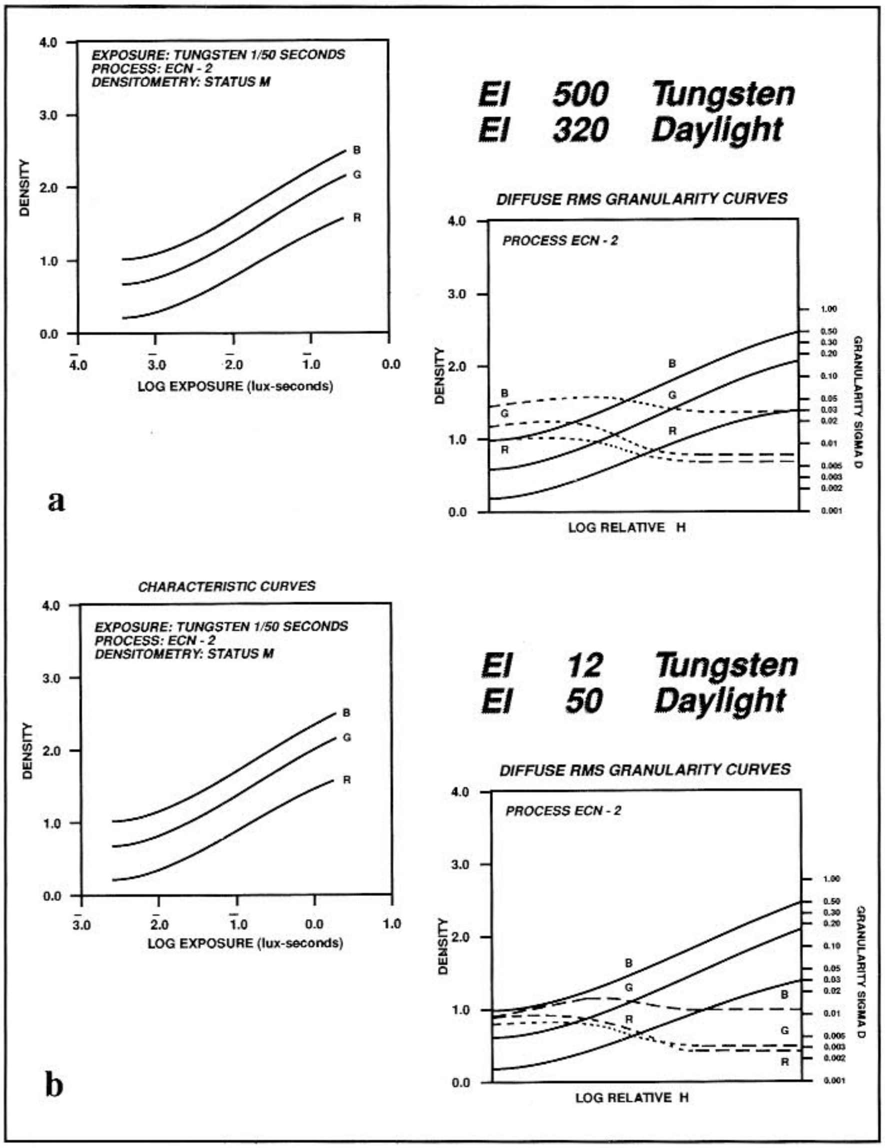

Figure 23. Characteristic transfer curves and film granularity curves: (a) Eastman color negative film EXR 5296; (b) Eastman color negative film EXR 5245.

Comparison of HDTV and Film Dynamic Range

Figure 24 superimposes the transfer characteristic of the green recording of a typical film (EXR 5245) onto that of the Sony HDC-300 HDTV camera. The comparison of effective dynamic range is made on the basis of input exposure latitude; therefore, the video is measured as the luminance output (following the SMPTE 240M nonlinear precorrection), but with the white clipper and variable knee circuit removed. The film's output (printing density) is a log scale, shown on the left abscissa. The luminance video output has been transformed to an equivalent log scale, shown on the right abscissa. The input to both media is also a log scale. The HDTV camera's dynamic range is bounded at the lower end by the 44-dB SNR limitation discussed, and its upper region (above reference white) is bounded by the limitations of the ABO circuit — 2½ to 3 *f*-stops of highlight-handling capability.

As shown, the two media have total picture dynamic range capabilities that are remarkably close — of the order of 9 *f*-stops (HDTV) to 9½ *f*-stops (film). Again, however, some significant qualifications to this comparison

Table 7 — Equivalent Noise Performance of HDTV and Film (p-p signal to rms noise in dB)

	Film		HDTV
Image Format	EXR 5245	EXR 5296	Sony HDC-300
16mm	−42	−37	
Super 16mm	−44	−39	
25mm			−44
35mm	−49	−44	
Super 35mm	−50	−45	
65mm	−54	−49	

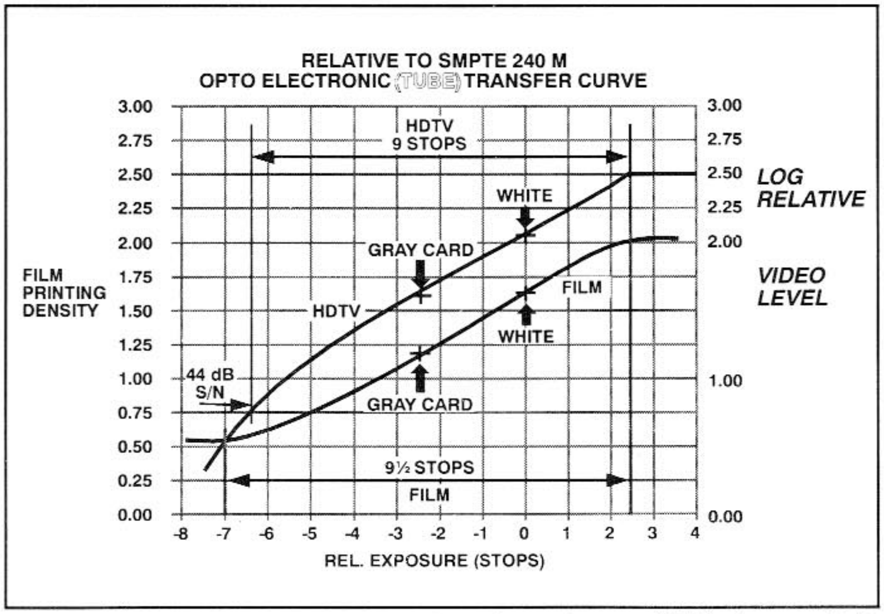

Figure 24. Comparison of SMPTE 240M optoelectronic transfer curve (HDTV tube camera) with transfer curve of Eastman color negative film (green record).

must be made. For HDTV the quality of the image capture in the upper region does not equal that of film. HDTV can capture images up to 3 *f*-stops above reference white, but they are marred by comet tailing, blooming, and some loss of resolution. Film, on the other hand, is flawless in regard to such artifacts; it merely introduces a nonlinearity to the upper tone reproduction (generally used to great effect in artistic image capture).

At the lower end, the HDTV floor is quite predictable, as described. Film, however, becomes a little more nebulous. Two factors militate against film's portraying good contrast in the lower region. One is the toe of its transfer characteristic, which compresses the lower steps of the test chart; the other is film noise. I hesitate to define a noise floor for the film because granularity is a function of a number of factors. It's probably true (based on the granularity curves of Fig. 23) that the noise in the lower region is worse than the 44 dB of HDTV (certainly for EXR 5296), and this film noise rides on top of a visual image that is being progressively compressed. So at the lower end, the HDTV camera actually retains a small advantage over film. However, this holds true only when we speak of total dynamic range. Cinematographers know well how to slide effective exposure latitude up and down the total film transfer characteristic to overcome any such limitations when dealing with a desired visual effect in real-world image capture.

Promise of the CCD Imager in an HDTV Camera

The CCD imager is rapidly replacing photoconductive pickup tubes in virtually all categories of 525/625-line broadcast and professional television. Its advantages over its tube predecessor are, on the whole, overwhelming. In particular, the effective dynamic range of these television cameras has been dramatically extended with the advent of the solid-state sensor. This is demonstrated in Fig. 25, which shows the transfer characteristic of Sony's current high-end CCD[27] (in the BVP-70 portable camera). This sensor — a frame interline transfer (FIT) CCD with hole-accumulated diode (HAD) technology in the photosensor — has a dynamic range of the order of an outstanding 80 dB. This results in an effective input exposure latitude of almost 12 *f*-stops. And unlike the pickup tube, the 16 dB of signal overhead above reference white level incurs no penalties in the form of highlight-related artifacts. This CCD exhibits no lag, blooming, comet tailing, or image retention. And the signal is linear above white. In this respect, especially in the lower black regions, this sensor is distinctly superior to film. It has nothing like the superb image spatial resolution of negative film, however, so any direct comparisons with film in overall image quality are almost meaningless. But an HDTV CCD imager is something else.

The HDTV CCD imager is now under active development in at least half a dozen major international labs. Technical papers published so far describing these R&D projects suggest

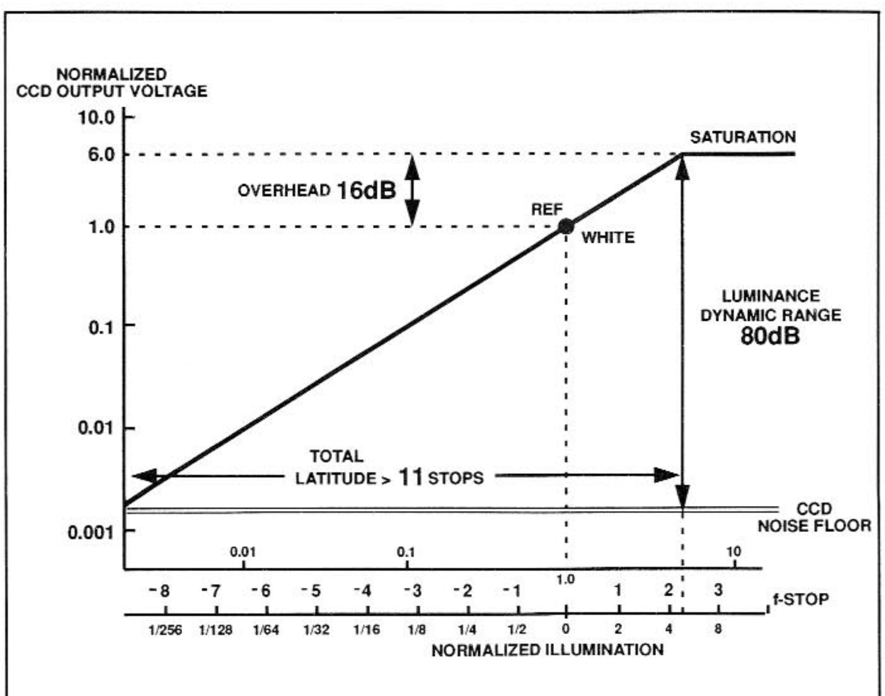

Figure 25. BVP-70 hole-accumulated diode (HAD) CCD sensor.

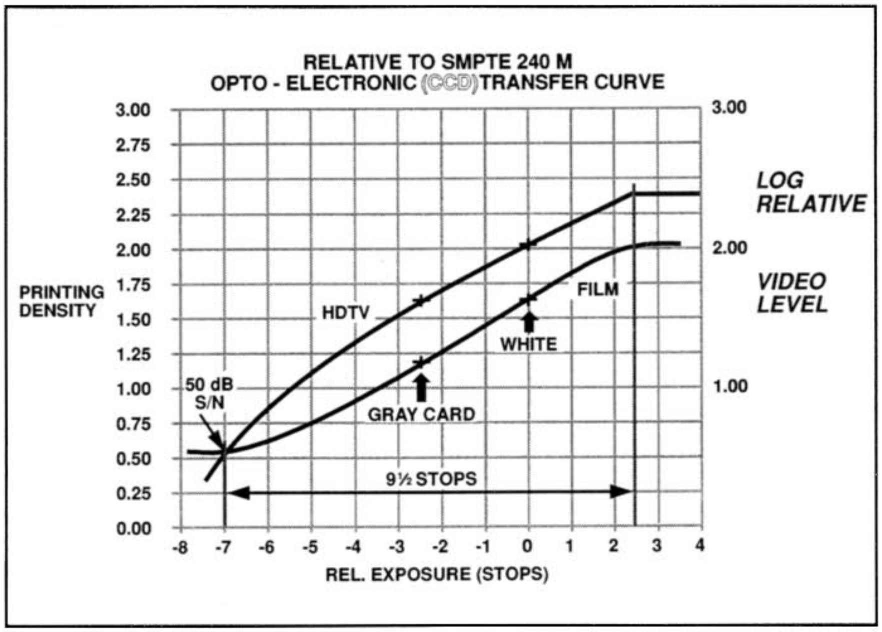

Figure 26. Comparison of SMPTE 240M optoelectronic transfer curve (HDTV CCD camera) with transfer curve of Eastman color negative film (green record).

that the first generation of HDTV CCD (of the order of 2 million pixels) will target a 50-dB SNR performance, some 6 dB better than the pickup-tube counterpart.[28,29] As Fig. 26 shows, such an improvement would extend the camera dynamic range to an equivalent 9½ *f*-stops exposure latitude.

If the HDTV CCD imager has a fixed-pattern noise (FPN) that is of the same order of magnitude as current 525/625-line HAD, the significance of the 50-dB SNR is that the HDTV sensor clearly outperforms most films in the lower black regions. At the upper end they will be essentially equivalent (about 2½ *f*-stops of latitude above reference white).

Conclusion

The comparison here of HDTV and film imaging relates primarily to the HDTV camera front-end imaging system and the processed film negative. The differences in dynamic range are not as great as has been suggested; most of the confusion is attributable simply to difficulties in relating the two media on a sensible and fair technical basis. Both media have their own characteristics and trade-offs. Television imaging has advanced at an astonishing pace during the past decade, particularly since the advent of the solid-state CCD imager. Indeed, it is the HDTV CCD imager that will thrust high-resolution real-time television imaging forward to be a tenable companion to 35mm film imaging. Film itself will, of course, continue to evolve separately.

The attributes of the SMPTE 240M transfer characteristic and its role, both as a precorrection for CRT display now and as a video dynamic range compressor in the future, are examined here. The topic of the "extended" transfer characteristic is now under study in the SMPTE WG-HDEP. The goal of this work is two-fold:

- To define a family of knee curves (suitably tailored to the basic SMPTE 240M curve) to more usefully treat HDTV video information in the 3 *f*-stop region above reference white
- To reconcile the entire extended dynamic range capabilities of HDTV cameras with the digital processing that follows (VTRs, digital video effects, digital transmission, etc.), particularly regarding the desired number of bits per sample, quantization law, and video-level coding

It is hoped that these issues can be examined and the further progress of the SMPTE WG-HDEP and the inevitable fast-paced developments of related HDTV production equipment can be reported on soon.

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