SONY

SONY HDCAM: EXPOSURE INDEX - Issues of Camera Operational Sensitivity

24P TECHNICAL SEMINAR #1

by Laurence J. Thorpe

CINEALTA

SONY HDCAM: EXPOSURE INDEX - ISSUES OF CAMERA OPERATIONAL SENSITIVITY

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ABSTRACT

The advent of 24P offers an important new acquisition tool to the cinematographer. Video cinematographers, however, are trying to adapt to a lingua franca of the film community and to operational practices long-honed in the film world. The film cinematographer, on the other hand, is trying to decipher published performance specs that are still in "video" language. It is useful, therefore, to begin our Technical Seminar series with an expose on the most fundamental aspect of any camera – namely, its sensitivity. Called Exposure Index by the film community, the sensitivity of the camera relates to its ability to capture quality pictures under a wide variety of scene lighting conditions.

The good news for all cinematographers is that the 24P camcorder is very sensitive. In film terms, it will be shown to have an effective Exposure Index (EI) range that endows a single 24P camera with the combined equivalency of very slow speed, medium speed, and high speed 35mm motion picture film.

TEN YEARS AGO, THE *SMPTE JOURNAL* PUBLISHED AN EASTMAN KODAK TECHNICAL PAPER ENTITLED:

"A COMPARISON OF COLOR NEGATIVE FILMS AND HDTV CAMERAS FOR TELEVISION PROGRAM PRODUCTION" [1]

In that paper, the authors outlined a comprehensive comparison between the performance of Sony's analog HD camera model HDC-300 and their contemporary 35mm motion picture film. The paper focused on many of the controversial parameters that are debated in traditional comparisons between HD video and motion picture film. In doing so, it shed valuable light on an approach that would be more useful in comparing video and film.

THE PAPER MADE A KEY POINT IN THE FOLLOWING STATEMENT:

"Film speed is specified by a recommended Exposure Index (EI) which the cinematographer can modify to achieve his artistic aims. The sensitivity of video cameras is specified by a minimum illumination (in Lux) required to produce a peak white signal from a 89.9% reflectance white card at a particular lens aperture."

This statement spoke directly to the video community's traditional tendency to favor signal-to-noise evaluation, compared with the far more flexible approach to camera exposure long-favored by film DPs.

The Kodak paper compared HD camera Video Sensitivity (as then published by Sony) with the Exposure Index of their films. The authors made a useful contribution to a convergence in thinking about these seemingly disparate definitions of camera operational sensitivity.

Most important, their paper also compared the electronic signal-to-noise performance of the HD camera with the Equivalent Noise for their films (scaled by Kodak from the published Granularity specifications of these same films). This facilitated an "apples to apples" comparison of the level of "grain" in the two media.

The authors then made the key point that any comparison of film and HD cameras must include the comparison of BOTH sensitivity AND noise. Taken together, the comparison of sensitivity and noise establishes the boundaries of operational sensitivity for both film cameras and electronic cinematography cameras.

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THE SENSITIVITY AND EXPOSURE INDEX COMPARISON IS REPRODUCED AS FOLLOWS [2]:

SENSITIVITY AND EXPOSURE INDEX

Image Format	Illumination* (Lux)	Exposure Index (EI)
EXR-5245 (35mm)	4300 (D)	50
EXR-5296 (35mm)	430 (T)	500
EXR-7245 (16mm)	4300 (D)	50
ECN-7292 (16mm)	690 (T)	320
HDC-300 (1-Inch)	1600 (T)	160

* Minimum Illumination @ F-4

THE NOISE COMPARISON TABLE IS REPRODUCED AS FOLLOWS:

EQUIVALENT NOISE (DB)

Image Format	EXR-5245	EXR-5296
16mm	-42	-37
Super-16	-44	-39
35mm	-49	-44
Super 35	-50	-45
HDC-300	**-46**	

As we can see, the analog HD camera of 1991 was modest in its performance when compared to film -- lying somewhere between slow and high speed 35mm film in exposure index, and between slow-speed Super16mm and 35mm in its level of "grain". The next ten years, however, would witness striking advances in High Definition CCD imager technology [2]. These advances would be further augmented by the advent of 12-bit DSP digital processing in the camera. The consequences of these technological improvements will be illustrated below.

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SENSITIVITY OF THE DIGITAL 24P CAMCORDER - A VIDEO PERSPECTIVE

In deference to those who are familiar with the sensitivity specifications of a traditional interlaced video camera operating at 59.94Hz - (hereafter rounded out to 60Hz - or 60 fields per second - for simplicity), the sensitivity of Sony's new HDW-F900 digital camcorder is as follows:

With 2000 Lux of incident illumination on an 89.9% reflectance Reference White card imaged by the camera operating in a 60i interlaced mode (a Lens aperture of F-10 producing a nominal 100 IRE video level) at the nominal 0 dB Master Gain setting. Under this camera setting, the video signal-to-noise ratio is specified as 54 dB.

A key point that needs to be made is that the long march to develop and improve video cameras has involved two parallel struggles: to lower the electronic noise level to the minimum physically possible, and to elevate the operational sensitivity. The specification quoted above is remarkable in showing what has been achieved in the HD camera over the past decade.

The sensitivity of the 1080/60i camera is identical to its sensitivity when operating in a progressive 30-frame mode, described as 1080/30P. The sensitivity of the camera when operating at the slower capture rate of 24-frame per second -- or 1080/24P (with no shuttering) -- is 1.25 times higher than 30P because of its proportionally longer exposure time. With the 180-degree shutter operation invoked, the sensitivity of the camera in the 1080/24P mode is reduced to one-half of 1.25 times that of 1080/60i.

THUS:

SENSITIVITY OF 24P OPERATION = 62.5% OF 60i OPERATION (WITH 180-DEGREE SHUTTER)

EXPOSURE INDEX OF THE 24P CAMCORDER - A FILM PERSPECTIVE

The Sony HDW-F900 digital 24P camcorder was designed according to today's international standard for HD Production: the ITU 709 standard. As such, it conforms to this standard by embodying five picture capture rates. These include three progressive scan modes of operation: 24P, 25P, and 30P -- as well as two interlaced modes: 60i and 50i.

When the camera is set up to image an 89.9% reflectance Reference white card (with 2000 Lux of incident illumination) and is operating in 24P mode with no shutter at the nominal 0 dB gain setting, then a calibrated light meter will show an EI reading of 640. This has been carefully verified with a range of lightmeters. When operating with a 180-degree shutter in the 24P mode, the nominal exposure index (as defined for the Nominal 0 dB gain setting) becomes, in round numbers: 640/2 = 320.

The most impressive aspect of the 24P camcorder, however, only emerges when its operating speed is combined with its signal-to-noise specification of 54 dB at that specific camera setting. Bearing in mind that a slow-speed low-grain 35mm EXR-5245 film has a rating of 50 ASA, with an attendant equivalent noise (film grain level) of 49 dB, the performance of the 24P camera (combining an Exposure Index of 320 with a signal-to-noise ratio of 54 dB) makes for superb low-speed operation.

It must be emphasized that this comparison based on equivalent signal-to-noise numbers does not address the subjective appearance of film grain and electronic noise. It merely speaks to the equivalent levels of "grain". In this context, Eastman Kodak pointed out [1] a general rule-of-thumb: a difference of 1 dB is just noticeable, and a difference of 3 dB is easily visible.

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THE KEY ISSUE WHEN SPECIFYING THE EXPOSURE INDEX OF THE 24P CAMERA

Eastman Kodak made the important observation that a cinematographer traditionally modifies the EI when actually operating the film camera with a given film stock. In video, on the other hand, we have traditionally specified a single number for sensitivity based upon a long-standing fixation with maximizing signal-to-noise performance.

We need to depart from that fixation when we consider the 24P camcorder in the hands of a film cinematographer -- because the cinematographer will, for creative reasons, purposefully seek to modify the effective Exposure Index. Having long experience in skillfully accommodating film grain, the film DP will be much less intimidated by the presence of a modest amount of electronic "grain." It should be kept in mind that the cinematographer chooses a particular film stock speed based upon his familiarity with the exposure index range that can be achieved and the associated levels of film grain that accompany that choice. While DP's don't think in terms of any "dB" spec for that grain level, they are still sharply attuned to its subjective visual effect.

Accordingly, it is useful to look at the HDW-F900 from the perspective that it is outfitted with an all-important operational control over its GAIN setting. To the film DP, this endows the camera with an innovative real-time control over the operational "speed" of the camera.

Again, the Nominal Exposure Index (EI) for that setting is 320 -- with an attendant "grain" level of a very low 54 dB. With that as our starting point, let us consider what the cinematographer is now free to do simply by altering Master Gain.

EQUIVALENT EXPOSURE INDEX AND EQUIVALENT GRAIN FOR THE 24P CAMERA

The following table refers to the HDW-F900 24P camcorder's performance when operating with a 180-degree shutter. It makes the simplistic assumption that there is a direct dB correspondence between the gain alterations and the attendant change in signal-to-noise performance. In practice, this assumption is reasonably accurate.

The table tracks the combined alteration of Exposure Index and Noise when the camera Master Gain control is switched over a range of settings above and below the nominal 0dB. The reference values of two film stocks specified by Eastman Kodak have been inserted in the table on the basis of their ranking in terms of equivalent signal-to-noise (equivalent grain).

GAIN SETTING (dB)	EXPOSURE INDEX (ASA)	SIGNAL/ NOISE (dB)	REFERENCE FILM STOCK
- 6	156	60	
- 3	220	57	
0	312	54	(Nominal setting)
+3	440	51	
			49 dB EXR-5245 (50 ASA)
+6	624	48	
+9	880	45	
			44 dB EXR-5296 (500 ASA)
+12	1148	42	

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THE ISSUE OF RECORDING NOISE AND DYNAMIC FILM GRANULARITY

The above discussion centered on the specification of Sony's HD digital 24P camera. Any true equivalence with film capture must, of course, factor in the performance of the associated digital recorder. While the latter has no effect on the exposure index (EI) performance of the camera, it does add a further degree of electronic noise which, in turn, modifies the "grain" level of the final 24P capture.

This noise level is difficult to quantify because of the nature of the real-time dynamic performance of the digital compression engine used in the HDCAM recorder. Depending on the content of each scene, the system is continually making real-time adjustments to the quantization and to the deployment of digital bits between the luminance and color difference video channels.

A reasonably accurate accounting of this VTR noise factor, based upon technical assessments of recorded pictures having a wide range of scene content, can be made by reducing all of the digital signal-to-noise figures above by 1.5dB.

It should be pointed out that motion picture film has a similar anomaly: the level of film granularity is also dynamically changing over the range of the recorded signal as it varies from black regions to overexposed highlight levels. Eastman Kodak publishes this variation in the technical data sheets for their various film stocks. To accommodate these variations in the discussions above would be mathematically daunting and Kodak made no attempt to do so in their paper.

SUMMARY

SETTING APART ISSUES OF 24P RECORDING NOISE AND DYNAMIC FILM GRANULARITY, THE ABOVE TABLE PRESENTS THE BASIC CAPABILITY OF THE 24P CAMCORDER IN RELATION TO REFERENCE 35MM FILM STOCKS.

THE 24P CAMCORDER IS SENSITIVE. THE VERY GOOD NEWS FOR THE DP IS THAT THE CAMERA IN EFFECT COMBINES THE CAPABILITIES OF SLOW-SPEED 35MM FILM, MEDIUM-SPEED FILM, AND HIGH-SPEED FILM.

- The nominal 24P camera setting -- at 0 dB gain -- yields an exposure index (EI) of 320, which is equivalent to medium-speed 35mm film but with a considerably lower grain level.
- At a lower Master Gain setting of -6 dB, the 24P camera has a slower speed, equivalent to an Exposure Index (EI) of about 150 - but it still has a higher speed than EXR-5245 slow-speed film and a grain level far lower than this 50 ASA 35mm film.
- At a Master Gain of only +9dB, the 24P camera has an exposure index of almost 900 and a grain level in the vicinity of that of 500 ASA EXR-5296 high-speed 35mm film.

  This wide range of control over Exposure Index greatly empowers a cinematographer. It eliminates the need to change film stocks of different speeds and assures constancy of tonal and color reproduction - and, of course, picture sharpness.

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1. G.L.Kennel et al., "A Comparison of Color Negative Films and HDTV Cameras for Television Program Production." SMPTE J., 100:337-341, May 1991.

2. L.J. Thorpe, "A Comparison Between HD HyperHAD Camera and Color Film for Television Program Production." SMPTE J., 103:364-376, June 1994.

SONY

SONY HDCAM: PICTURE SHARPNESS - Issues of Image Resolution

24P TECHNICAL SEMINAR #2

by Laurence J. Thorpe

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SONY HDCAM: PICTURE SHARPNESS - ISSUES OF IMAGE RESOLUTION

by Laurence J. Thorpe

ABSTRACT

On the surface, the published technical specifications of resolution for a 35mm motion picture film negative would appear to decisively eclipse the resolution specifications of a contemporary 24P digital HD camcorder. It is important, however, that the final comparison between the two media be made on a common large screen (in either the film domain or the digital HD domain). A considerable body of comparative testing over the past couple of years shows that large-screen viewing of two 35mm release prints, one produced from the film negative, the other derived by a transfer from digital 24P capture of the same scene, reveal a resolution equivalence that is remarkably close.

To understand this apparent anomaly, it is important to consider resolution from the practical perspective of what is actually perceived by the human visual system when viewing imagery on a large screen. Picture Sharpness is a term long used by film manufacturers. It is a very good term, and it implies much more than merely expressing "resolution" in another way. In order to assess the difference in perceived Picture Sharpness, we must account for the tolls taken on resolution by each element of the film processing system and the 24P digital acquisition system.

INTRODUCTION

In drawing the comparison between digital 24P HD and 35mm motion picture film, no aspect engenders more spirited discussion than that of their relative Resolution. Indeed, in a perverse twist of television history, the prevalent methodology for specifying the resolution performance of professional video cameras has evolved to a point where the published specifications of all leading camera manufacturers are no longer useful in describing the picture sharpness of the final viewed image.

The formal specification of resolution is the Modulation Transfer Function (MTF) -- the curve depicting signal output level versus the spatial frequency of a pattern of alternate black and white lines. MTF can be used to separately specify the lens, the digital camera, and motion picture film. When appropriate, MTF can even be specified separately for the horizontal and the vertical domain.

Our discussion must begin by recognizing a fundamental difference between what is recorded on a 24P tape in the digital camcorder and what is captured on the negative emulsion in the film camera.

Digital 24P is a bandwidth-limited resolution system. Analog 35mm film is a grain-limited resolution system. In this simple distinction are sown the seeds of an endless technological dialectic.

Simply stated, this fundamental difference between the two media means that, in the case of the digital 24P camera, the high MTF created by the 1920 x 1080 spatial sampling is abruptly truncated by the sharp digital filters inherent to the digital recording process. Motion picture film, being an analog medium, suffers no such truncation, and its formidable MTF characteristic extends to very high frequencies before tailing down gracefully into the film grain. This essential MTF disparity introduces considerable difficulty when we attempt to compare resolution between the two media. In fact, we can only resolve this difficulty if we reach some agreement on precisely what is being compared.

A MAN FOR ALL MEDIA

Identifying the "what" in "what is being compared" was superbly done in the 1950-60s by Otto Schade, Sr. He worked at the RCA Princeton Research Labs, and produced a legendary body of work on Image Quality [1] in the comparison between photographic film and television systems. Schade brilliantly resolved the dilemma by pointing out that a distinction must be made between Picture Sharpness and Resolving Power when assessing image resolution. He based this distinction on the interesting results uncovered following his long and close study of the behavior of the human visual system. Schade emphasized that the ultimate perceived picture sharpness of an image on a screen, whether created by film projection or television display, was a complex concatenation of the multiple MTFs inherent to both systems.

PICTURE SHARPNESS

Picture Sharpness is closely linked to the behavior of the human visual system when viewing imagery from a distance -- a form of viewing that encompasses both theatrical cinema and television. Perceived picture sharpness depends on maximizing the detail contrast within the optical pass band of the human visual system. This process is intimately related to the MTF within the range of detail frequencies that can actually be discerned at a specific viewing distance. MTF itself describes the behavior of the contrast of progressively increasing spatial frequencies.

Schade's seminal work, both mathematically and subjectively, defined the crucial importance of the shape of the MTF curve, especially at the lower end of the human visual pass band. This was shown by Schade to be radically different from the visual pass band when viewing imagery at close quarters -- where, for example, the human eye can readily discern extremely high frequency detail even when the signal level is almost buried in the film grain, especially if a magnifying glass is used. This form of viewing includes close study of reconnaissance photography, microfilm work, and examination of graphic detail content on a computer screen. In these examples, Resolving Power clearly has a very special priority. It has a lesser priority in the realm of entertainment program production.

FIGURE 1 simply summarizes the essential portions of a given MTF curve as they bear on Picture Sharpness and Resolving Power.

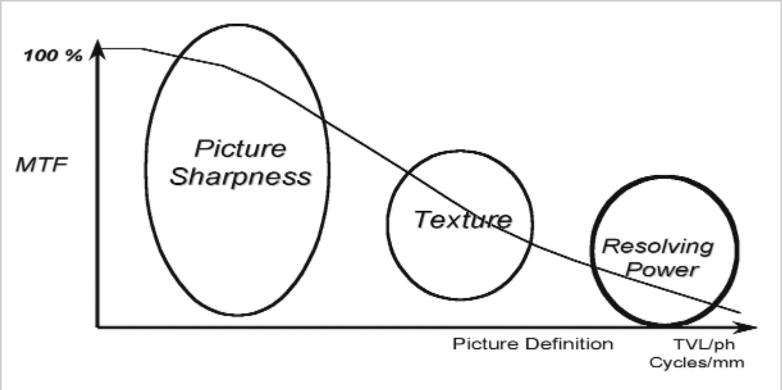

FIGURE 1 The Modulation Transfer Function (MTF) encompasses three key regions in relation to the human visual system

RESOLVING POWER — AND LIMITING RESOLUTION

On both the cinema screen and the home television screen, the upper spatial frequencies are totally invisible to the viewer. Consequently, Limiting Resolution specifications have little bearing on perceived picture sharpness. For close viewing, on the other hand, these upper spatial frequencies can have a very significant effect. This is especially significant as the eye-brain can, at close scrutiny, discern a very low level of detail contrast in these upper regions of the MTF curve, even in the presence of considerable noise or film grain.

Schade indicated that in many images there is, in essence, a "texture" overlaid on the essential image sharpness impressed upon the eye-brain. Texture is fine detail, and is a function of the lower amplitude detail contrast in the upper portion of the human visual pass band. It is extremely variable with viewing distance. This texture can be quite apparent at relatively close viewing distances -- but becomes virtually invisible at longer viewing distances.

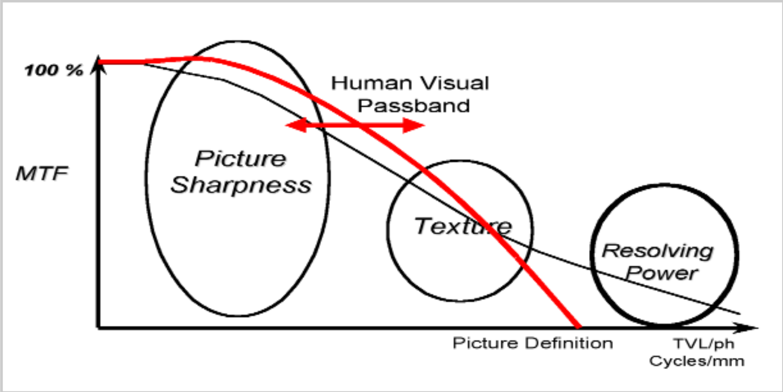

FIGURE 2 Superimposition of the variable human visual passband (variable with viewing distance) upon the MTF curve of a specific acquisition medium.

ASSESSMENT OF PICTURE SHARPNESS

Schade's work on assessing picture sharpness of both photographic film systems and television systems showed that a crucial weighting was evident in the disparate MTF curves produced by both systems. His work demonstrated that the square of the area under the MTF curve in question -- when normalized -- produced that weighting. He showed unequivocally that picture sharpness was directly proportional to that squared area.

FIGURE 3 indicates the concept for an arbitrary MTF curve.

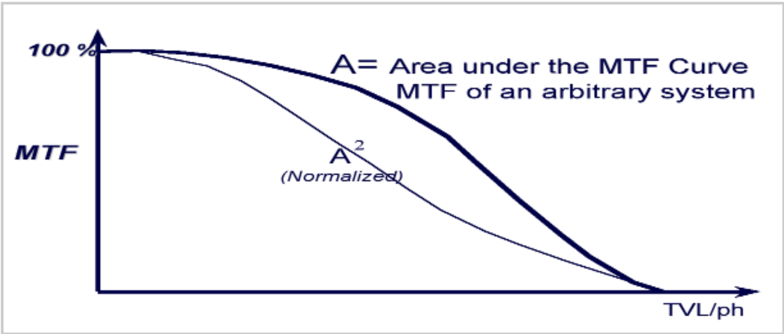

FIGURE 3. Showing the normalized Squared Area curve of Schade; as it relates to the system MTF curve -- indicating the weighting of perceived picture sharpness toward the lower spatial frequencies.

Schade then introduced a beautifully simple concept for reducing any complex MTF characteristic to a simple assessment of its relative picture sharpness. To achieve this, he superimposed upon the squared area curve a rectangle having an area equal to that of the normalized squared area curve. Where the rectangle intersects the horizontal frequency axis, Schade labelled this frequency Ne -- and he used that Ne number (quoted in TVL/ph) as a relative measurement of picture sharpness. He called Ne the Sharpness Rating.

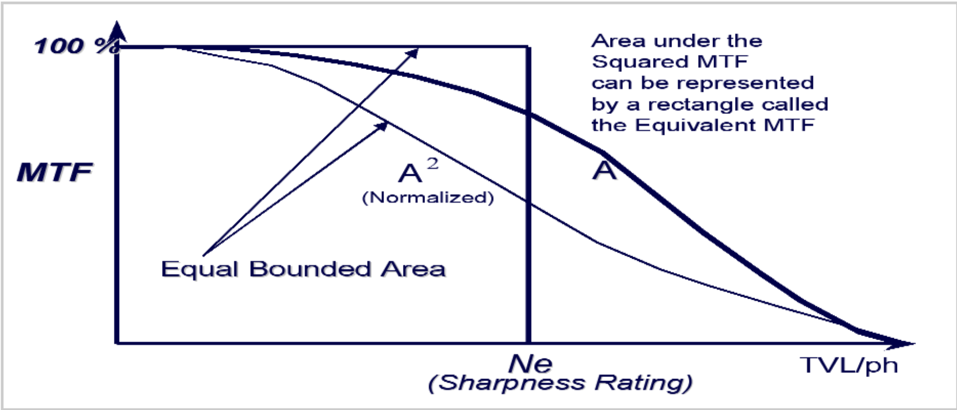

FIGURE 4 Schade's proposal for assigning a singular rating to the picture sharpness of a system having a given MTF characteristic.

SONY HDCAM: PICTURE SHARPNESS - ISSUES OF IMAGE RESOLUTION

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PICTURE SHARPNESS OF THE 24P SYSTEM AS COMPARED TO 35MM FILM

To compensate for its inherent bandwidth limitation, the 24P acquisition system effectively ignores the upper spatial frequencies and instead maximizes the contrast of all frequencies within the human pass band (for normal cinema and television viewing). This dispels the difficulty of making technical comparisons between the original 24P digital capture and the original recording on the 35mm film negative. It is more useful instead to examine the relative picture sharpness of the two media in two real-world contexts:

(a) The Film Domain -- where the digital 24P capture is transferred to a positive release 35mm film print that is directly compared to the positive release print derived from 35mm origination.

(b) The Digital Domain -- where the digital HD transferred from 35mm film on an HD Telecine is directly compared to 24P acquisition.

24P cannot yet produce the resolving power recorded on the 35mm film negative. It cannot do so because the technology of today will not support affordable digital acquisition at that level of picture resolution -- in terms of both the camera imaging and the associated digital recording data rate required to sustain that image capture. Contemporary 24P capitalizes upon the fact that nobody views the film negative. Before being viewed in the cinema, the film negative must undergo a complex series of opto-chemical processes to produce the requisite positive release film print. These processes collectively make a considerable alteration to the final MTF of the viewed positive release print. Similarly, when viewed as HD, the film negative is transferred by an HD Telecine, a different process that involves its own complex convolution of system MTFs.

MTF AND MTF AND MTF...

We will now look more closely at these two real-world approaches to comparing 24P and motion picture film. These comparisons reflect the many tests conducted by numerous workers over the past eighteen months. Some researchers were interested in assessing the potential of 24P for moviemaking -- including final theatrical release on 35mm film. Others focused on comparing the two media in the digital domain, to assess the potential of 24P as an alternative to 35mm film for high-end television production. In both cases, we will examine the individual system elements involved in producing the final imagery required for comparative viewing. And here we will quickly become immersed in the multiple MTFs of those system elements.

PICTURE SHARPNESS – COMPARISON IN THE FILM DOMAIN

Many workers chose to examine relative picture attributes in the film domain on large screen optical projection systems. While each test had its own variants, they all basically reduced to the test system depicted in Figure 5. We will examine both "paths" of this system and assess the effect of the cascading of their system MTFs.

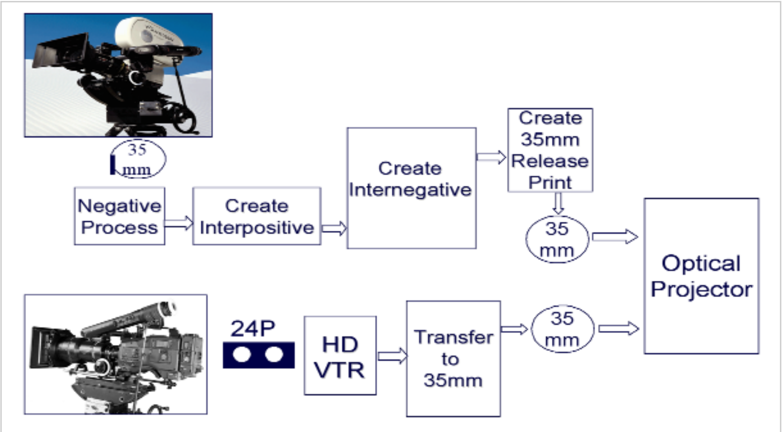

FIGURE 5 Shows the comparative testing of 35mm film and 24P picture attributes – as assessed on large screen film projection.

SYSTEM MTF – FOR THE 24P SYSTEM

Schade placed great importance on identifying and accounting for all of the system elements that ultimately formulate the final MTF -- in both the horizontal and the vertical domain (this being particularly important for the digital 24P system). In the case of the 24P system, most of these MTFs are embedded within the camera system. In the discussion to follow, we make the assumption that digital image enhancement is switched to zero in the 24P camera. Thus, the camera's DSP processing circuits make no contribution in the form of another MTF curve (the assumption being that they have a flat frequency response to the 30 MHz limit specified by the ITU 709 production standard). Figure 6 outlines the separate MTF contributions within the digital camera section of the 24P acquisition system.

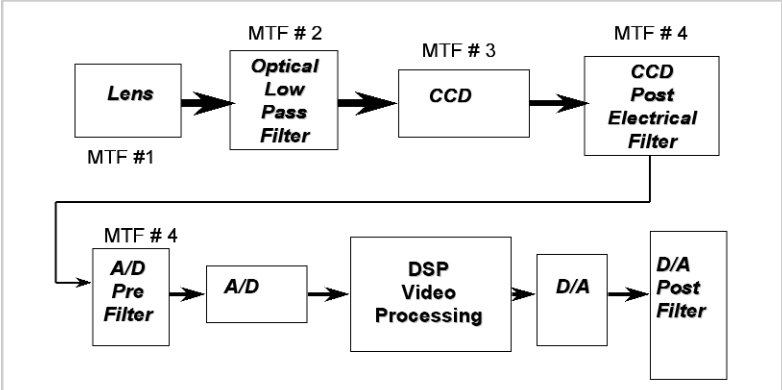

FIGURE 6 Showing the separate MTF elements that convolute to the final horizontal MTF of the 24P camera

FIGURE 7 below summarizes the collective effect of these MTFs, showing the final convolution of a camera system MTF as the bold curve.

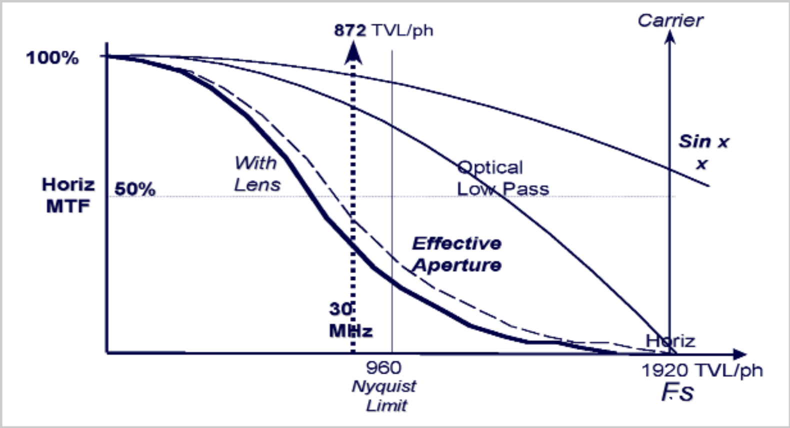

FIGURE 7 Showing the final horizontal MTF of the 24P camera with a generic HD lens (the latter is, in practice, a system MTF variable).

The system MTF will vary depending upon the quality of the lens used -- and the various tests to date do show interesting variations between the lenses of the many manufacturers involved. Each lens exhibits its own variation in how MTF characteristics alter with aperture setting. It is important to note that this lens MTF variability applies also in the case of the film camera.

In summary, the contemporary 24P camera exhibits a typical horizontal depth of modulation in the vicinity of 35% at the specified 872 TVL/ph boundary (equivalent to the 30 MHz spec of the ITU 709 standard). One noteworthy aspect of the 24P system is that progressive scanning, which elevates the vertical MTF curve above its interlaced counterpart (when both are operating at 1080 lines), produces an MTF curve that is very close to the curve shown earlier for horizontal MTF (see Figure 8). Again, no digital image enhancement is involved in either the horizontal or vertical domain. This equivalence is significant in demonstrating that the 24P system is the first video system to have achieved an isotropic imagery. The present 525-line NTSC system is extremely anisotropic, with horizontal MTF far exceeding that of the vertical (which is severely curtailed by the 480 active picture samples and the further penalty associated with interlaced scanning). In producing an unsatisfying perceived resolution, anisotropic imagery plays a greater role than is generally acknowledged -- so this is good news for the 24P system.

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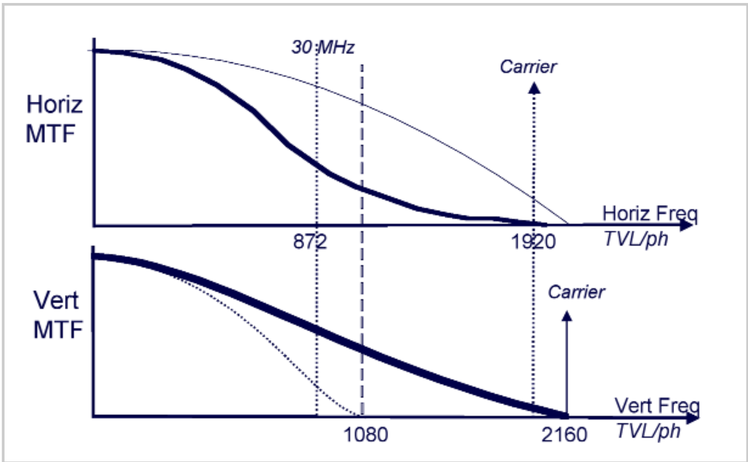

FIGURE 8 The 24P system is the first isotropic video production format

THE 24P CAPTURE PROCESS – THE DIGITAL RECORDER

Thus far, we have described the cascade of individual MTF characteristics that define a typical 24P "shoot" -- that is, the camera performance. We must now deal with the "capture" process -- namely, the digital recording of the camera video. The Sony 24P camcorder utilizes the HDCAM® recording process. Two bit rate reduction strategies are utilized to reduce the daunting 966 Mbps data rate of the camera to the 140 Mbps total sought in the recording section: digital prefiltering, followed by a 4:1 digital compression. A detailed discussion on this strategy can be studied elsewhere [2].

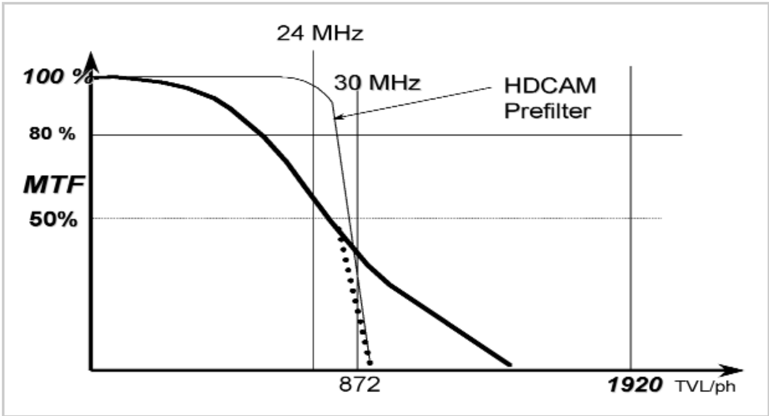

FIGURE 9 The high camera MTF is abruptly truncated by the luminance digital prefiltering in the HDCAM 24P recording; this kicks in at 24MHz

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The effect of this prefiltering is to leave the camera MTF totally untouched up to about 24MHz. A sharp cut-off filter then comes into play, truncating the camera MTF horizontal curve in the manner indicated by the dotted line in Figure 9.

We opened our examination of the resolution comparison of 24P and 35mm motion picture film by pointing out that the 24P system is a bandwidth-limited resolution system, while the film system is a grain-limited resolution system. Figure 9 graphically depicts the bandwidth limitation of the Sony 24P system. It is important to remember that the recording process has virtually no effect on the relatively high MTF of the camera over the greater portion of its pass-band -- but it does definitively determine the ultimate bandwidth limitation.

MTF SYSTEM – FOR 35MM MOTION PICTURE FILM

The MTF curves published by the film manufacturers require close study (see Figure 10). In manufacturers' brochures, film MTF is traditionally depicted on a logarithmic scale and is specified in cycles/mm, thus making an immediate comparison with 24P somewhat difficult.

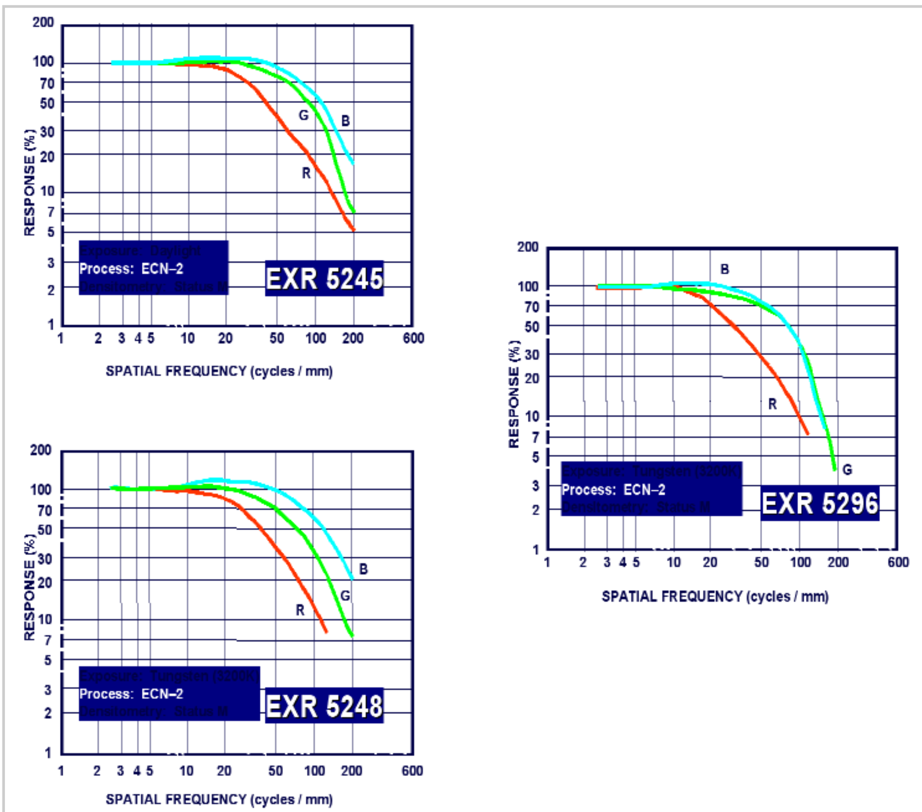


FIGURE 10 Shows the modulation transfer function (MTF) curves for different speed 35mm motion picture films – as typically published by the film manufacturers

Motion picture film is a capture medium that is inherently isotropic, and accordingly, these MTF curves apply to the film plane -- that is, they apply equally to both the horizontal and the vertical domain. Translating them to the domain of video resolution specifications -- the linear TVL/ph -- facilitates a direct comparison with 24P digital. To do this, the film plane MTF is first multiplied by the image height in millimeters to convert to cycles/picture height (c/ph), and then multiplied by two, because two TV lines are equivalent to one cycle. The resulting conversions are shown in Figures 11 and 12.

It will be noted that the emulsions themselves have a very high MTF compared to that of the 24P camera. One striking aspect of motion picture film, however, is that there are quite distinct resolution characteristics between the three emulsions on the film negative.

FIGURE 11 Showing the MTF for a typical slow speed 35mm film

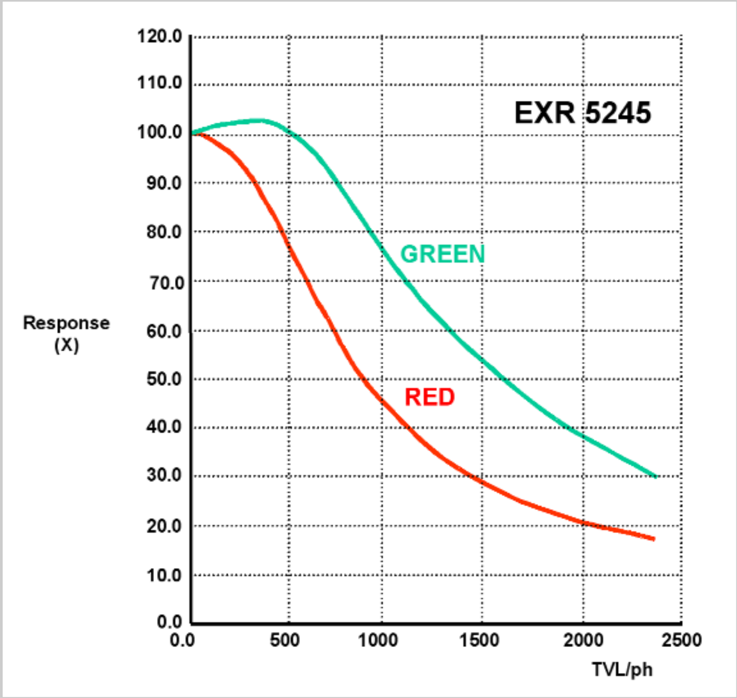
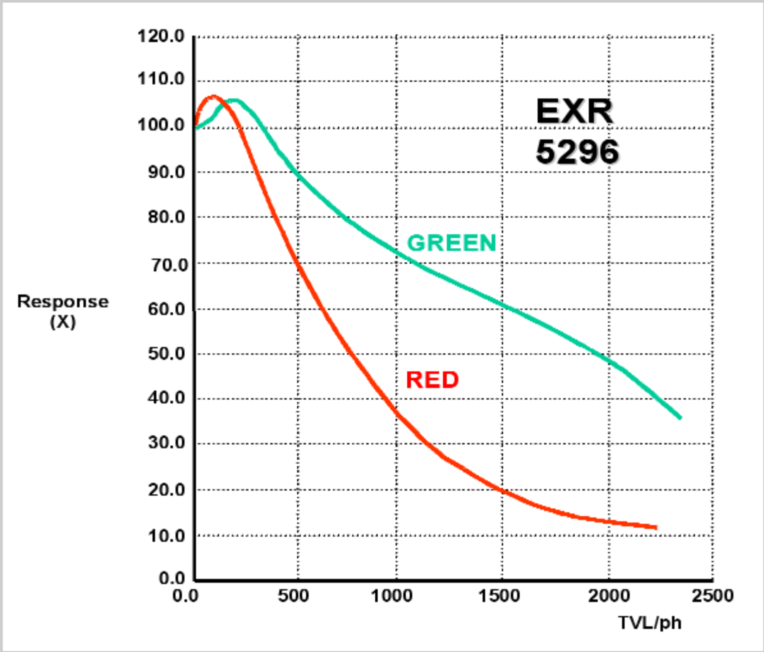


FIGURE 11 shows this for a slow-speed 35mm film stock, and Figure 12 for a high-speed film stock. In both cases we have, for simplicity, removed the Blue emulsion -- which typically has a higher MTF than the Green -- in order to highlight the more dramatic difference between the Green and Red emulsions. Clearly, the effective luminance MTF will be a matrix of the two (along with blue), which will lower its effective MTF. However, the MTF of negative film still remains very high.

FIGURE 12 Showing the MTF curves for a typical high speed 35mm film



GETTING TO THE POSITIVE RELEASE PRINT

The MTF convolution for the film scenario is more complex than that of the 24P camcorder. This is particularly true in the case of the creation of the first generation 35mm positive print as earlier shown in Figure 7.

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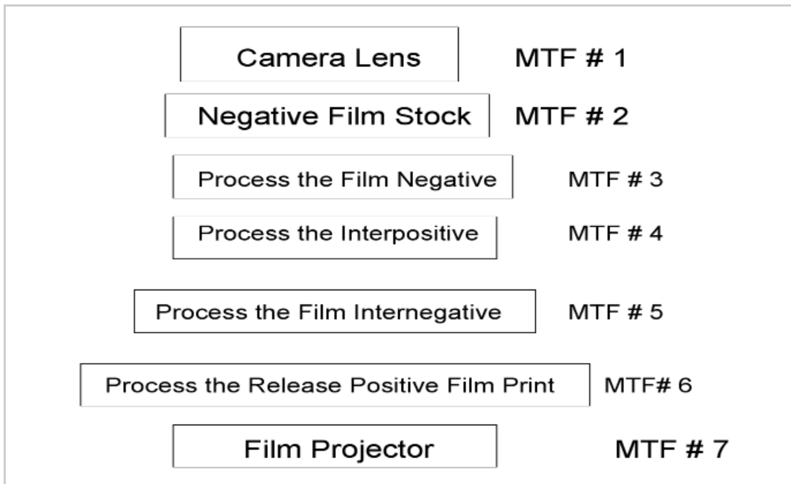
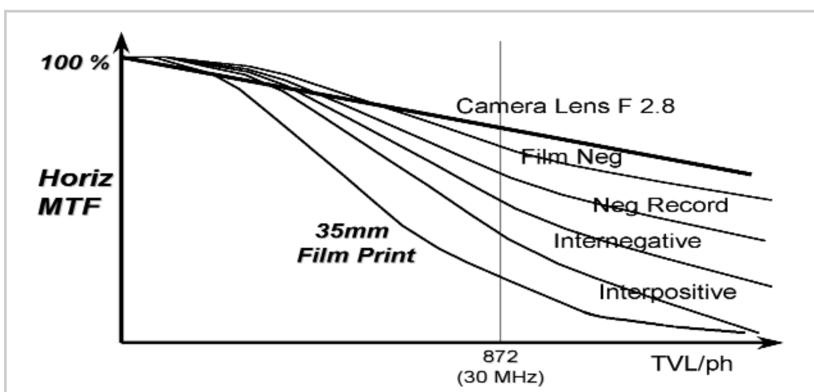
FIGURE 13 The sequential processes involved in creating the final positive release print used for theatrical projection of motion picture film.



The final MTF of the 35mm positive release print is indicated in Figure 14. Every step of the serial opto-chemical process takes its inexorable toll on resolution. It should also be noted that each step takes a small, but cumulative, toll on the lower frequency in-band MTF.

FIGURE 14 Summarizing the individual MTF characteristics associated with each stage of the opto-chemical process involved in the creation of a contemporary 35mm positive release print.



TRANSFERRING THE DIGITAL 24P TO A 35MM FILM RELEASE PRINT

To complete the comparison of the 24P and 35mm film in the domain of optical projection, the digital 24P edited master must first pass through its own multifaceted process of transfer to the theatrical film release. There are a number of technologies to do this – Electron Beam Recording (EBR) and Laser Recording being two contemporary techniques employed today.

The EBR [3] has the advantage of being a very high-resolution approach by virtue of the fact that the initial transfer from digital tape to film is done in non real-time via an exceedingly fine electron beam directly exposing a low-grain slow-speed high resolution black and white negative – all within a meticulously controlled vacuum system. Because no optical system is entailed in this process, the MTF of the 24P recording is transferred virtually unimpaired across to the very high MTF of the film negative. The RGB digital frames are transformed to sequential monochrome RGB frames on that film negative. A subsequent optical step-printing process (involving appropriate color filters) then photo-optically creates an internegative 35mm film from which the release print is then printed. The concatenation of that photo-optical MTF and that of the release print are the dominant MTFs that determine the final convolution of the 24P system MTF on the release print. In total, this process takes a lesser toll on MTF than that described for the film system.

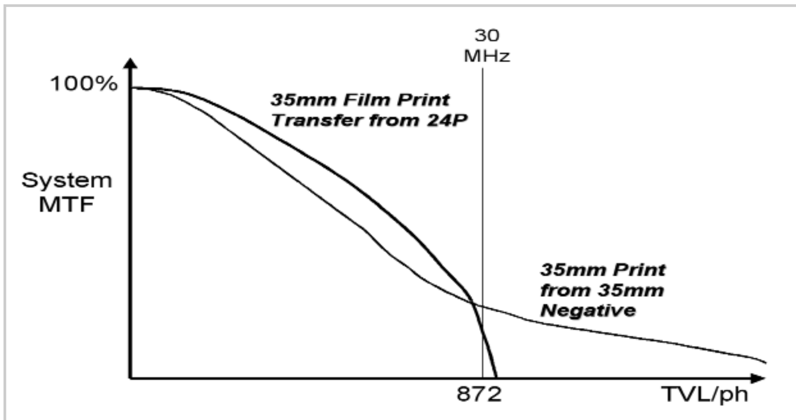
The 24P camera does embody some very sophisticated digital enhancement controls, which can be used to alter the final system MTF. This enhancement does not come for free -- it will raise the noise level proportionally. However, confining this to a modest three dB boost will make a considerable enhancement to both the horizontal and vertical MTF, and the noise increase (at a normal 0 dB camera gain setting) will be almost imperceptible. Optimum deployment of digital image enhancement in the 24P camera should be carefully tailored to counter these transfer-to-film MTF losses to the degree possible – and this does involve a systematic pre-testing of the system.

The alternative Laser recording transfer system utilizes very high resolution RGB laser direct exposure of the three emulsions that constitute a 35mm internegative film. From this film the release 35mm positive is printed. This system is also an inherently high-resolution system that creates an internegative film with high MTF.

COMPARISON OF THE FINAL MTF OF 24P AND 35MM FILM

When the final 35mm film MTF is superimposed on the final recorded MTF of the digital 24P system when transferred to 35mm film by EBR or Laser recording (see Figure 15 below), two distinct differences become apparent. First, the 24P MTF characteristic typically has a higher "belly" in its curve, at the lower end of the passband; contemporary digital tape to film recorders have quite flat response up to high frequencies. Second, in the upper frequency region, the bandwidth-limited 24P system MTF conversely terminates more rapidly than the 35mm all-film system's positive print, which extends to higher spatial frequencies (albeit at a considerably lower MTF than the original 35mm negative recording). The 24P curve is the curve inherent to the camera-recording system, without any image enhancement.

FIGURE 15 Showing the MTF curve for the 24P digital transfer to 35mm film positive and the 35mm positive release print derived from the 35mm film negative.



Shade's technique now allows these disparate curves to be compared based upon the premise of the Ne Sharpness Rating. By squaring the above two curves and then constructing the associated equivalent Area MTF rectangles, a direct comparison of picture sharpness Ne is possible -- as shown in Figure 16.

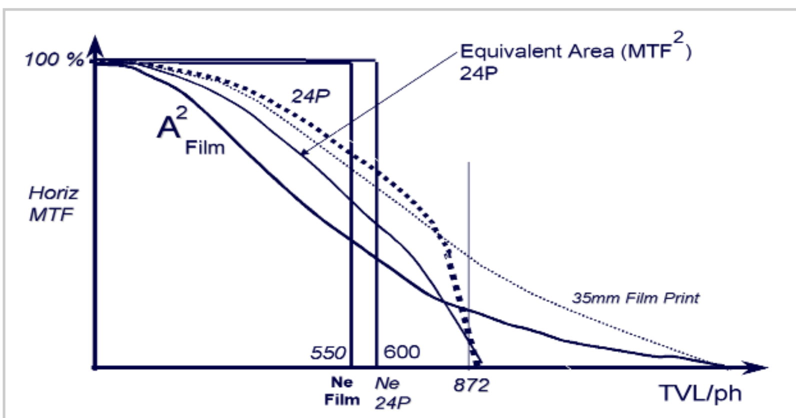


FIGURE 16 The Picture Sharpness Ratings for the 35mm positive release print transferred from the 24P system and the 35mm release print derived from the original negative film

It has been noted, during various tests conducted with the 24P camcorder shooting side by side with 35mm motion picture film, that when a comparison was made at the 35mm film positive release print stage, the 24P image was often judged to be sharper. The technical explanation for this is outlined above: that the more complex MTF concatenation in the case of the 35mm all-film system erodes more of the lower detail frequencies, and, as taught by Schade, this impairs perceived picture sharpness at normal viewing conditions. It should however, be noted that each system involves many elements, any one of which is a variable. For example, just lens variations could reverse the final results, as could different film stocks and film processing behaviors.

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PICTURE SHARPNESS – COMPARISON IN THE DIGITAL 24P DOMAIN

A great percentage of prime time television and television commercial production still originates on 35mm motion picture film. A considerable number of side-by-side tests have been conducted over the past year and a half to assess the performance of the 24P system as a possible alternative for such program origination. Figure 17 summarizes the nature of these tests.

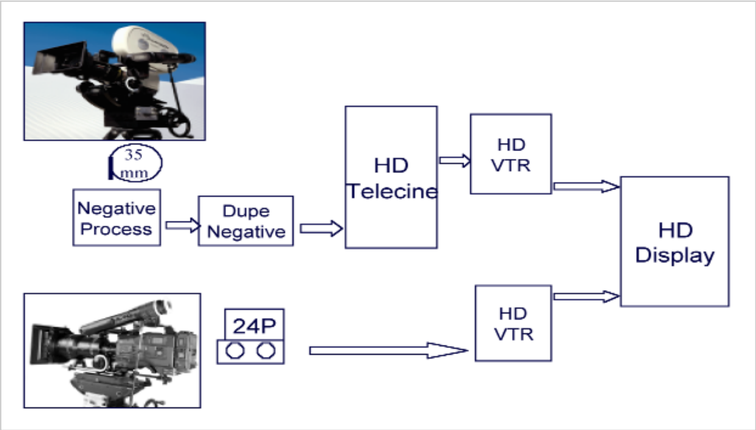

FIGURE 17 Outlines the comparative 24P and 35mm film tests that sought picture quality assessments between the two media (including picture sharpness) in the electronic domain – some on large screens and others on high performance HD studio monitors.

35MM FILM AND THE HD TELECINE

FIGURE 18 shows that the system originating with a 35mm film shoot subsequently transferred to 24P digital HD involves a considerable number of system elements each with their own MTF characteristic.

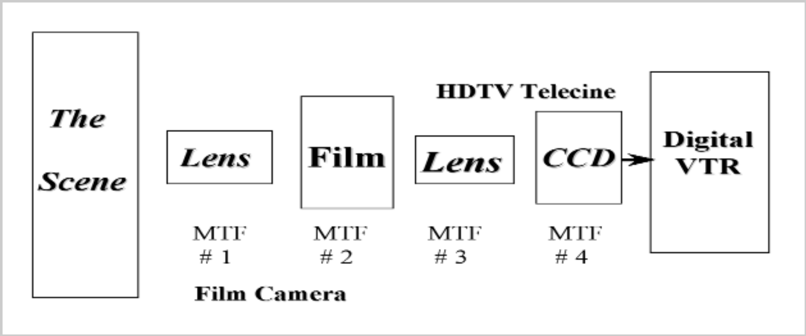

FIGURE 18 Indicates the 35mm Film-Telecine process

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This process involves multiple factors: the concatenation of the MTF characteristics of two lens systems, the MTF characteristics of the film process (the number of these MTFs is variable depending upon whether a dupe negative or an interpositive transfer is being made), and finally, the complex MTF processes of the Telecine itself. In the case of the Sony Vialta™ Telecine system, the MTF concatenation can be assumed to be identical to that of the 24P camera described earlier (the Vialta system employs 22:22:22 CCD spatial sampling using the same area array imagers as the 24P camera). Other Telecines utilize 22:11:11 CCD spatial sampling, and this fact would need to be accounted for in the system MTF assessment.

As a consequence of the increased number of contributing MTF elements, it is obvious that the film-through-Telecine process will incur a slightly higher loss in overall MTF than the same original scene captured directly by a 24P camcorder. This will be the case when the 24P camcorder and Telecine both do not employ image enhancement, and the resolution assessment is made using the Ne Sharpness Rating. However, it should be pointed out that the situation could very easily be reversed with the application of only a modest degree of image enhancement in the HD Telecine. The same can, of course, be utilized in the 24P camera. So it is safe to conclude that parity in picture sharpness can be realized between 24P and a 35mm film transferred on an HD Telecine.

SUMMARY

The wonderful work done a half-century ago has finally come into its own. Otto Schade, Sr., was comparing an embryonic 1950-vintage television system with an established photographic film system. Even then, however, he was able to demonstrate the potential of electronic imaging (his lab work included a prototype high-resolution television system). More important, he quantified the electronic imaging specifications that needed to be sought in order to achieve image quality parity with 35mm motion picture film.

It is only today, in an era of digital HD video, that the full import of his work can be brought to bear on advances in imaging. Schade's legacy lies in the ability we now have to objectively assess the realities of resolution in contemporary digital HD and film imaging systems. A matter that might appear intuitive -- based upon published specifications and attendant conjecture -- in fact turns out to be far more complex.

A great deal of global discussion is underway today in the broad quest to define the specifications for an all-digital "cinema" system -- from acquisition, through postproduction and distribution, to final display on very large screens. Sharp divisions exist between the aspirations of various parties involved. If Otto Schade Sr. taught us anything, it is that electronic bandwidth is a commodity to be carefully nurtured. Today, this translates into the associated digital data rate -- and in the context of an overall Digital Cinema system, digital data rate is a precious commodity indeed. A proper understanding of Picture Sharpness, as it affects both digital cinematography and digital cinema distribution/display, can enormously aid in the pragmatic disposition of digital data rates.

To date, the news is very good. The first-generation 24P system, with all of its necessary pragmatic design compromises, has proven far better than some had anticipated. Specifically, in terms of perceived picture sharpness, the 24P system has surprised many who have viewed 35mm film transfers from this digital origination on very large screens. Indeed, some recent tests involving transfers of 24P to large-format 16-perf 65mm film have been cause for even greater surprise. This has stirred a new interest in mobilizing the 24P digital system as an adjunct in large-format film productions, using 24P as a more compact and mobile acquisition package for shooting difficult scenes where camera size and weight might be a logistical issue.

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2. L.Thorpe et al, "The HDTV Camcorder and the March to Marketplace Reality", SMPTE J. 107:164 – 177, March 1998

3. L.Thorpe et al, "HDTV Electron Beam Recording", SMPTE J. 97:833 – 843, October 1988

SONY

SONY HDCAM:
EXPOSURE LATITUDE -
Issues of Dynamic Range

24P TECHNICAL SEMINAR #3

by Laurence J. Thorpe

CINEALTA

SONY HDCAM: EXPOSURE LATITUDE - ISSUES OF DYNAMIC RANGE

by Laurence J. Thorpe

ABSTRACT

For decades, motion picture film had enjoyed one indisputable advantage over video imaging – namely, a marvelous ability to capture very high contrast scenes. The medium has always inherently boasted an extensive dynamic range, or, as is commonly quoted in film parlance – a wide Exposure Latitude. Until recently, that is.

During the past decade, the contemporary digital camera has forged ahead of the best of the traditional video cameras that served the broadcast and production industries from the 1940s to the early 1990s. Propelled by stunning advances in solid state CCD imager technologies, flanked by digital signal processing circuits having impressive video processing prowess, the digital 24P high definition acquisition system will be shown to have an Exposure Latitude that rivals that of the 35mm motion picture film negative.

DYNAMIC RANGE

Dynamic Range is a topic that has attracted increasing interest within the world of digital cinematography. With the advent of the new generation of 24P acquisition systems, it has emerged as a central topic -- and has also caused considerable confusion.

In the July 2001 edition of "In Camera," published by Kodak Entertainment Imaging, Mr. Tom Wallis, their Chief Technical Officer, made the following statement: "The best HD and other digital cameras offer a capacity for recording a dynamic range of about 100:1." If a high-level technical expert believes this about contemporary digital acquisition, it is little wonder that so many in the production community also retain some misunderstandings.

Certainly, there was a time when video acquisition fared poorly when its dynamic range was compared to that of motion picture film. That day is long gone. The stunning advances in CCD image sensor capabilities -- their abilities to capture scenes containing unusually wide contrast ranges -- have spurred a closer examination of how best to process the acquired video in order to optimize its ultimate tonal reproduction on an electronic display. Different considerations arise when the same digital 24P HD video is to be processed preparatory to a transfer to motion picture film for theatrical release.

DYNAMIC RANGE IN VIDEO CAMERAS

For decades, video acquisition suffered from serious limitations in dynamic range capabilities. A variety of the imaging artifacts of photoconductive pickup tubes conspired to cloud tonal reproduction at the lower end of the video-output/light-input transfer characteristic. These artifacts included electronic noise of various forms, optical and imager flare, black shading aberrations, and highly problematic motion-related problems such as image lag. Any attempt to extract picture detail from deeply shadowed areas of a scene were severely impaired by the cumulative "masking" of these low-light picture impairments.

The upper end of the transfer characteristic -- the highlight handling region -- was also hampered by separate difficulties largely associated with the imager itself. Pickup tubes had severe electron beam limitations, which served to abruptly "clip" any overexposed content. Prior to the onset of such clipping, however, other image artifacts such as blooming, black halos, and comet-tailing combined to badly mar the reproduction quality of overexposed sections of the picture. Indeed, it became an established norm to resort to all sorts of expedients to avoid the imaging of overexposed scenes. More than anything else, this problem definitively separated earlier video imaging from motion picture film imaging.

The advent of the solid-state CCD imager greatly reduced artifacts in the light transform of an electronic signal. With the advent of the CCD, tonal reproduction within the video medium acquired a whole new meaning. The capture "window" was dramatically opened. Today, even contemporary consumer camcorders exhibit remarkable exposure latitudes. The days of video cameras with "100:1 dynamic range" are ancient history.

FIGURE 1 shows the dynamic range performance of the CCD imager employed in the new Sony HDW-F900 high definition camcorder -- when it is operated in the 50 or 60 Hz interlace mode. This chart shows the input light range to the camera expressed in F-stops, as well as the resulting video signal levels from the CCD imager.

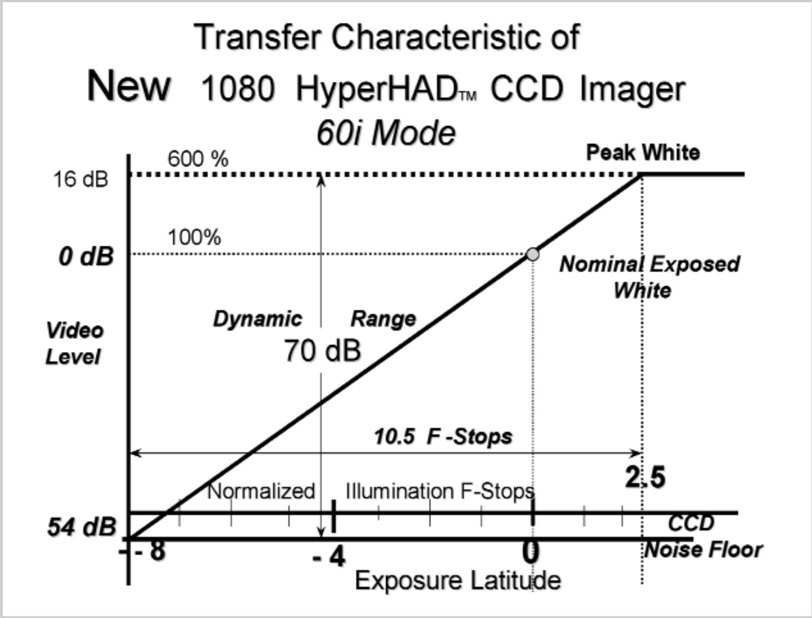

FIGURE 1. Showing the dynamic range of the 1080 CCD in the interlace mode

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The CCD has an unprecedented dynamic range of 70 dB -- or 2500:1. The challenge to the camera designer lies in digitally processing that extraordinary dynamic range to formulate a signal ready for subsequent digital recording.

Switching the same CCD to operate in 24, 25 or 30 Hz progressive capture loses the double pixel row summation inherent in the interlace mode of operation; as a consequence, the dynamic range is lowered by 6dB (SEE FIGURE 2).

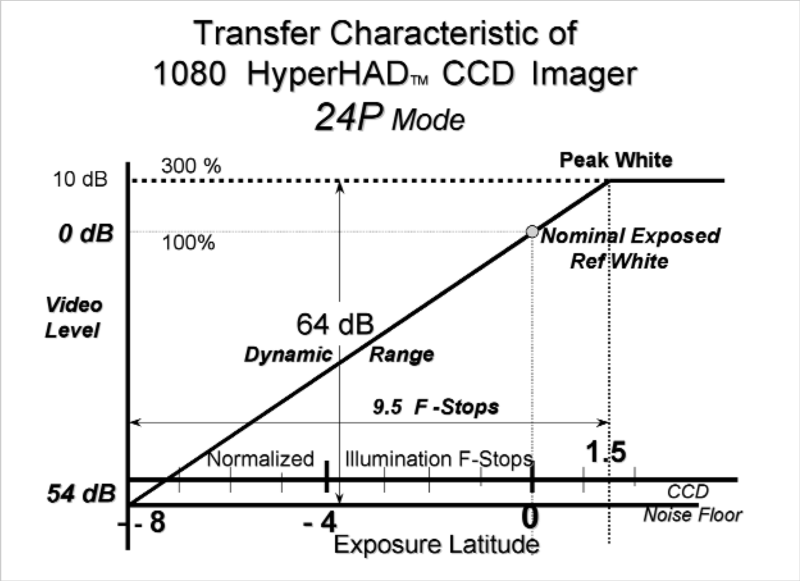

FIGURE 2. Showing the 6dB reduction in dynamic range when the same CCD is operated in the progressive scan mode

CAPITALIZING UPON IMPROVEMENTS IN DYNAMIC RANGE PERFORMANCE

As the picture capture "window" of contemporary CCD imagers has progressively opened at both extremes, the camera design task has become one of optimally shaping the overall video transfer characteristic. Technically, this is necessary to ensure that the wide exposure latitude of the video signal initially created by the CCD imager can be properly accommodated within a variety of digital processes. It is also an artistic necessary, in order to achieve on the final display(s) the specific tonal reproduction sought by a specific production team.

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THE TECHNICAL CONSIDERATIONS INCLUDE:

- A/D Conversion: required to digitize the analog video output from the CCD imager prior to Digital Signal Processing within the cameras (this has today expanded to 12-Bit).
- Digital Video Recording: a challenge associated with the limited Bit-depth of contemporary HD video recorders (8-Bit being a current norm in HD camcorders).
- Digital Fiber Link: in the case of a 24P HD studio camera system, digital transmission from the camera head to the Camera Control Unit (CCU) must be considered.
- Postproduction Processes: such as color correction, transfer characteristic manipulation, etc. (to optimize the signal for presentation on electronic projection systems, where different projection technologies have their own unique transfer characteristics).

IMPLEMENTING A DESIRED TRANSFER CHARACTERISTIC

In these early days of digital 24P HD cinematography, two distinctly different philosophies have emerged with respect to the desired final transfer characteristic:

1) Emulating the tonal reproduction of a specific film stock.

2) Achieving a tonal reproduction unique to the new digital medium (and distinctly different to that of film).

These differences are a consequence of:

a) Some producers making the transition to digital acquisition from motion picture film (and seeking to preserve a familiar imagery).

b) Other producers recognizing the advantage of 24-frame operation for international distribution (its easy conversion to 50Hz and to 60Hz), and having no specific allegiance to film-based imagery.

In terms of how desired transfer characteristics are achieved, there are also two divergent philosophies:

1) Programing the camera's nonlinear DSP circuits to achieve the specifically desired overall tonal reproduction directly in-camera

2) Programing the camera to achieve the widest possible exposure latitude -- and later, manipulate the transfer characteristic in postproduction to achieve the desired tonal reproduction.

The in-camera approach relies on predetermining the desired transfer characteristic and carefully pre-programming this characteristic into the relevant DSP sections. The postproduction approach focuses on scrupulously capturing the most possible picture contrast information -- in the primary exposed "middle" regions as well as within the deep-shadowed areas and the over-exposed areas of the particular scene being imaged.

PRESENCE OF THE HD MONITOR ON THE CAMERA SET

Both the in-camera and the postproduction approach are compounded by divergent philosophies on using or not using an HD picture monitor on the set. Many directors and DPs have not only come to feel comfortable with the on-set monitor, but actually claim an empowerment in achieving the pictures they seek. Others completely shun such an on-set display.

Using an on-set monitor to determine the final image composition -- both in terms of the transfer characteristic and the color reproduction -- requires a disciplined technical setup of the monitor itself as well as a carefully controlled viewing environment. Work to date strongly reinforces the belief that pre-testing can facilitate a very successful implementation of this practice. Clearly, it is easier to implement in the studio than in the uncontrolled lighting conditions of the outdoor set.

With respect to location shooting, some producers have resorted to the use of a small truck that houses a digital control room to achieve the carefully adjusted viewing conditions required. When the postproduction suite is the planned venue for final adjustment of the transfer characteristic, the task on the camera set becomes one of adjusting the camera transfer characteristic to favor adequate capture of both highlight and lowlight scene content under all encountered shooting conditions. Having a known transfer characteristic (one that allows adequate capture) programmed in the camera DSP circuits will make it easier to predict the subsequent manipulation required to achieve a desired effect.

TRANSFER CHARACTERISTIC – THE BROADCAST TELEVISION MODEL

Traditionally, the setting of video camera RGB processing circuits followed the decades-long "broadcast television" orientation. Broadcasters sought to maximize the signal-to-noise ratio of the normally exposed image and sharply curtail any signal levels above that -- in order to avoid downstream circuit overloading, especially overloading of the television transmitter. This approach, in turn, dictated setting the reference scene white (as defined by the 89.9% white chip on a standard television grey scale chart) at the maximum video level -- the well-known 100 IRE level on the measuring waveform monitor. All signals exposed above the 100 IRE level were of secondary importance, and typically were eliminated by a white clipping circuit set some few percent above that level. Cameras had their lens iris adjusted in real-time throughout the shoot to maintain scene white as close as possible to the 100 IRE level -- a continual intervention in order to sustain the optimum video S/N ratio.

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FIGURE 3 illustrates the principle of choosing different transfer characteristics for widely varying conditions of scene illumination. In a studio situation, where lighting is carefully controlled to eliminate, or minimize, specular highlights, the traditional "broadcast video" transfer characteristic can be employed (see Curve A). The ITU 709 HD standard precisely prescribes such a curve. This allows the camera to be exposed in a manner that places reference white at 100 IRE (on a standard television waveform monitor). This exposure would maximize the signal-to-noise ratio. Note: curves are generic and are intended to be illustrative.

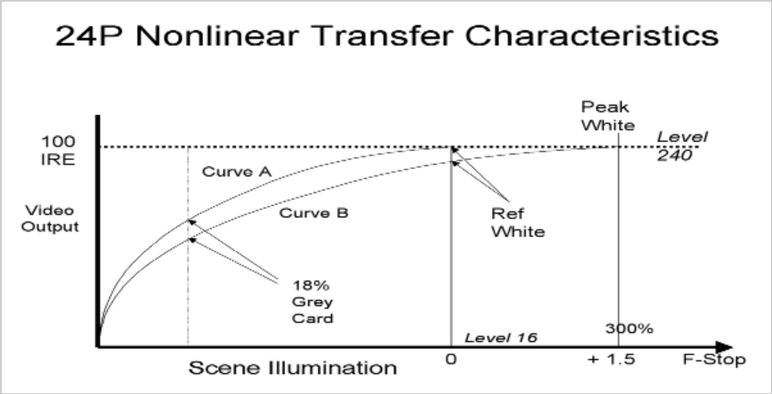

FIGURE 3. Curve A is the specified ITU 709 Gamma Curve for a nominally exposed camera; Curve B is an alternative extended range characteristic for handling scenes with 1 1/2 F-stop overexposure. Note the attendant drop in level of reference white level.

If, however, the camera is on location, where uncontrolled scene illumination can contain highlights in excess of reference white, the transfer characteristic can be programmed to produce a light-input/video-output relationship as represented by a generic Curve B.

The 24P camera exposure can be further altered (by using ND filters or closing down the lens) to ensure that even higher scene highlight information is captured, further lowering the level of the reference white. Figure 4 shows a hypothetical scenario where the scene peak white is 2 1/2 F-stops above reference white in the example shown.

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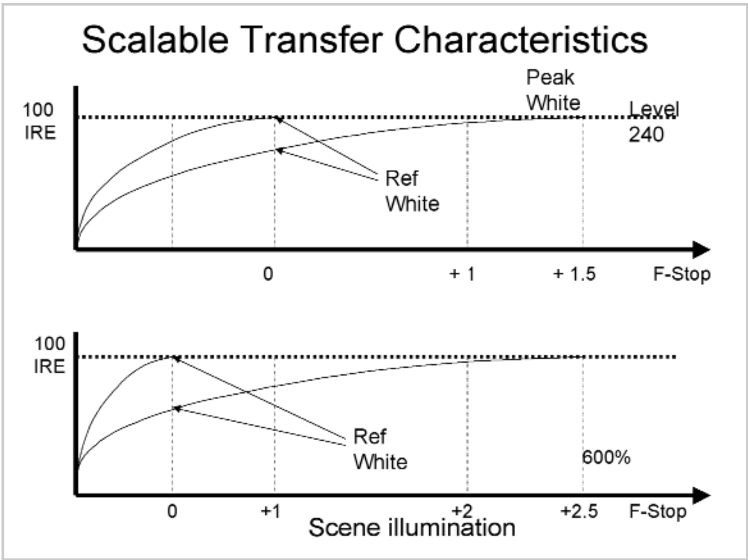

FIGURE 4 shows a hypothetical scenario where the scene peak white at 2 1/2 F-stop above reference white in the example shown. Note: curves are generic and intended to be illustrative. The first set of curves depict the principle of a transfer characteristic intended to capture signals exposed to 1 1/2 F-stops above reference white; the second set of curves show how this might be altered to capture up to 2 1/2 F-stops above reference white.

In this scenario, the low-light level information is somewhat disadvantaged; however, the high S/N of the 24P camera can readily accommodate this. The low-light information can still be satisfactorily restored in postproduction. When the camera is used to image scenes with even greater levels of overexposure, the limitations of the progressive scan imager must be taken into account.

TRANSFER CHARACTERISTIC AS A MEANS TO OPTIMIZE DYNAMIC RANGE CAPTURE

As shown in our earlier seminar on operating sensitivity, the contemporary 24P digital camera has a quite high Exposure Index (EI). This "overhead" in sensitivity can be exploited to allow the S/N of the nominally exposed portion of the signal to vary widely in order to capture the widest possible dynamic range. In this approach, the reference white level is allowed to drop lower than the prescribed 100 IRE level and the DSP nonlinear circuits are manipulated accordingly to favor assignment of the transfer characteristic to overexposed signals (those that lie above reference white). Scene lighting is adjusted where possible to set the peak white extremities of any given scene to just below the white clipping level in the three RGB circuits. If the transfer characteristic has been set to a nominal known curve, then all of the information recorded can be linearized in postproduction.

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When the original capture is subsequently linearized (perhaps in a computer or color corrector), it is a relatively simple process to superposite any desired replacement characteristic (for example, the Cineon color space standard) in postproduction;.see **FIGURE 5**. Note: curves are generic and intended to be illustrative.

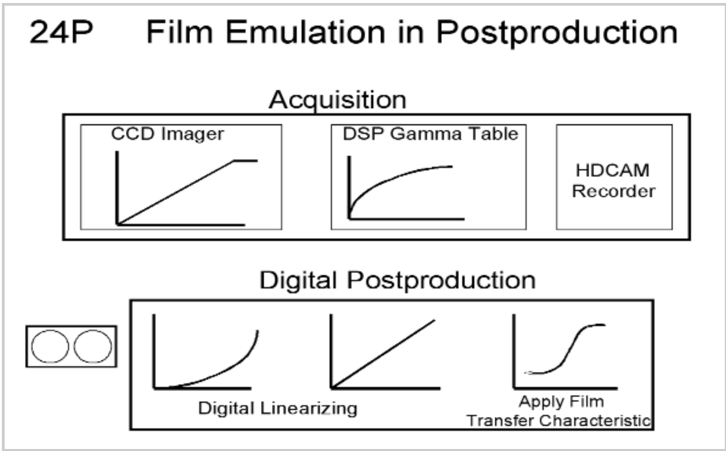

FIGURE 5. Showing application of the desired transfer characteristic in postproduction

TRANSFER CHARACTERISTIC AND DIGITAL BIT SAMPLING DEPTH

To faithfully capture a satisfactory tonal reproduction over the entire dynamic range of the imaged scene, it is important to consider the relationship between the prescribed transfer characteristic and the bit sampling in the associated digital recorder. Satisfactory transmission of the wide dynamic range signal through an 8-bit or 10-bit system (fiber or Triax etc) is equally important.

There can be considerable confusion on this issue. That is why we need to look more closely at the sampling of a camera video signal that has been pre-corrected according to the nonlinear transfer characteristics discussed earlier. We will first consider the case of a scene with a 7 1/2 F-stop exposure latitude, then the more taxing case of a scene with exposure latitude of 9 1/2 F-stops.

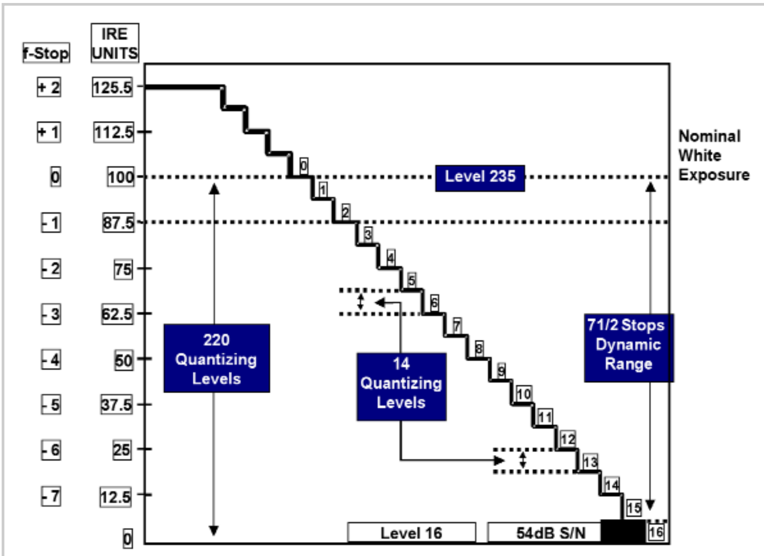

FIGURE 6. The waveform monitor depiction of a 7 1/2 F-stop dynamic range capture where reference white is set to 100 IRE units

The lower boundary of this reproduction is assumed to be that final grayscale step where the S/N ratio is unity -- in other words, where noise totally masks the step, defining the lower limit. This "black" level is assigned digital coding level 16. The camera has been exposed so that the reference 89.9% white chip is at the nominal 100% level -- or 100 IRE units on the standard waveform monitor -- and this is assigned digital coding level 235, to allow overhead. With a nonlinear Gamma precorrection prescribed by the ITU-709 standard, the camera output would be as shown in Figure 6. Note that under these conditions, each step of the grayscale chart is amplitude-sampled by no less than 14 coding levels -- more than enough to accurately reproduce the steps over the entire luminance scale.

Now consider the same camera exposing the grayscale chart and an additional 2 1/2 F-stops of highlights above reference white. When this peak white level is adjusted (by lens aperture or ND filter) to the 100 IRE video level, the resultant waveform applied to an 8-bit A/D converter would be as shown in Figure 7.

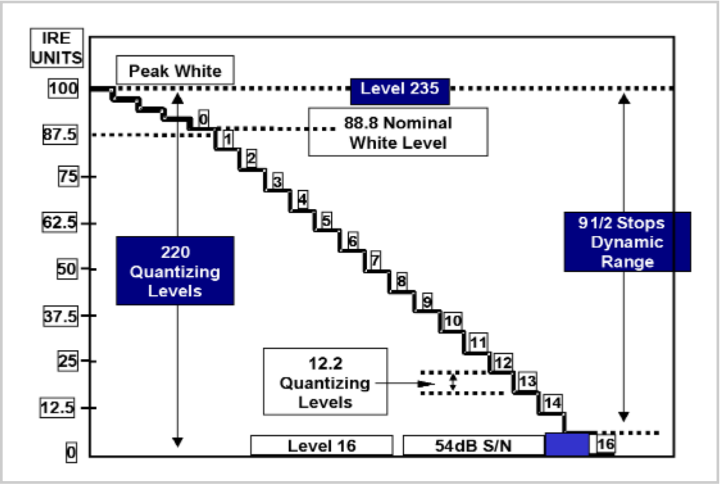

FIGURE 7. Showing a 9 1/2 F-stop scene dynamic range applied to the 24P camera when this is carefully exposed to set the peak white level to 100 IRE

Note that in this case, reference white has been lowered to the 88.8 IRE level and that there are now just over 12 amplitude samples of each step of the grayscale -- again, more than adequate to accurately capture each level.

We conclude that 8-bit recording is more than adequate to faithfully capture a dynamic range of 9 1/2 f-stops when a signal with wide dynamic range is exposed in the manner prescribed (with overexposed peak white signals carefully set to the 100 IRE level), provided that this signal has been pre-compressed according to the principles outlined above.

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