

The All-Digital Camcorder — The Arrival of Electronic Cinematography

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Thirty-five millimeter motion-picture film is the yardstick for quality image acquisition in high-end television program and commercial production. The quest for a viable electronic cinematography alternative was initiated almost 20 years ago, but floundered on significant technological obstacles of that time. However, electronic imaging and recording technologies have advanced at an unprecedented pace during the past decade. Numerous technical breakthroughs have finally produced an all-digital, one-piece camcorder, incorporating advanced CCD imagers, full high-speed DSP camera processing, and a robust 10-bit 4:2:2 miniature VTR. Electronic cinematography is an important new reality.

The DVW-700 digital camcorder ranks with 35mm motion-picture film in the primary imaging characteristics of sensitivity, dynamic range, colorimetry, resolution, and highlight handling when compared to the transferred 525-line telecine digital output. It does not lay claim, however, to producing the legendary "film look," which remains bound up with those secondary imaging characteristics exclusive to 35mm and 16mm film such as 24 frames/sec, shuttered capture, and film grain.

The DVW-700 offers high-quality, first-generation 4:2:2 10-bit image capture with a battery-operated, highly compact, and mobile integrated camcorder. This image quality has a "look" of its own — one that is anticipated to extend creative options for those seeking a distinct imagery for special program content and television commercials. Electronic and film cinematography will be important allies in an era of expanding digital electronic distribution of entertainment, education, and information programming, as well as television commercial and infomercial production.

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Electronic Cinematography

The Birth of Electronic Cinematography

The concept of electronic cinematography (EC) was born in the mid-1970s with the circulation among international professional television camera manufacturers of a CBS white paper; this document described those attributes desirable in an all-electronic camera that might replace the popular 35mm film origination with telecine transfer for 525 NTSC episodic program production. Most camera manufacturers ultimately demurred, for even then the legendary "film look" preserved by the 525 telecine daunted the aspirations of the most ambitious of camera designers. Yet, a few brave efforts, centered about the still relatively new 2/3-in. format Plumbicon pickup tube, were made, including the EC-35 by Ikegami and the Panacam, a joint effort by CEI and Panavision. Neither, however, succeeded in igniting serious interest among television program producers in EC as a credible alternative to the superbly functioning motion-picture film origination. It seemed that "video" shooting would forever be destined to languish as a paltry contender to a medium of distinctly superior imaging capabilities which, although quite different from magnetically recorded televi-

sion, was still able to effectively transfer and retain the unique attributes of the film look.

It seemed also that the gap might widen in the decade of the 1980s with the advent of much-improved film emulsions based on T-grain advances and the ongoing improvements in high-end 525/625 telecine technology. By the 1990s the latter was largely employing advanced digital video processing and sophisticated secondary corrections that afforded a high degree of creative control over transferred images. Today, 525 telecines invariably deliver wide-bandwidth CCIR 601 4:2:2 component digital video at their outputs.

The Evolution of Electronic Cinematography

Five significant, and to some extent disparate, developments progressively unfolded in television image capture throughout the 1980s and early 1990s. Each ultimately made a significant contribution to the advancement of real-time electronic "shoot and capture" beyond the primitive capabilities of the mid-1970s. These developments were small-format portable camcorders, CCD solid-state imagers, high-definition television (HDTV), digital bit-rate reduction (BRR), and digital signal processing (DSP).

Before looking more closely at some of these developments, a definition of EC should first be outlined. Such a definition must begin with a concession that the film look, in all of its subtle manifestations, is not at all the desired goal. Today, few would seek a rigorous emulation of this look with an all-electronic origination system. Instead, EC aspires to achieve the physical convenience of the portable self-contained film camera, the more essential and striking attributes of motion-picture film capture, the "hands-off" nature of this largely

adjustment-free image recording system, and a degree of ergonomics and "user-friendliness" that will more readily lure the practiced film cinematographer to transfer his skills to an electronic medium now finally coming of age.

The direct digital electronic acquisition made by the "electronic cinematographer" should rank in basic performance with that first-generation digital recording made from the 525-line telecine transferring 35mm-based "film" cinematography — namely, full 4:2:2 digital component video. It is at this level that some comparisons in picture quality will be made.

Physical and Operational Specification for an EC System

The following are general specifications for an EC system:

- One-piece camcorder.
- All-digital camcorder system to ensure stability, reliability, and complete repeatability.
- Less than 25 lb total weight on the shoulder for the high-quality electronic field production (EFP) lens, battery, and viewfinder.
- Physically more compact than a 35mm film camera with magazine, with the contemporary 16mm film camera being a desirable goal.
- Direct digital 4:2:2 component video recording.
- Compact cassette with longer than 30-min recording, thus providing a distinct advantage over film cameras for unique shooting environments such as underwater and wildlife program origination.
- No "video adjustments" required on location unless specifically

sought; in other words, true "shoot and capture" in a manner akin to that of the film camera.

Picture Performances — As it Relates to Cinematography

For purposes of discussion on the relative attributes of film cinematography and EC, the renowned film look that is now so well-established can be loosely separated into two basic components. Primary picture capture characteristics are functions of the physical characteristics of film emulsion, optics, and exposure practices. These would include sensitivity, tonal reproduction, color reproduction, picture sharpness, and exposure latitude. Secondary picture capture characteristics are functions of some technical limitations considered pure artifacts by some people, but are nevertheless important creative and inherent components of the film look. These would encompass 24 frame/sec capture rate, camera 180° shuttering, and film grain.

The primary picture capture characteristics might be said to be fundamental to the high-quality image capture medium; 35mm film possesses both types of characteristics. That particularly high picture quality is a core constituent of the film look, and any attempt to rival this look electronically must first squarely confront the challenge of the superlative attributes of film with respect to these primary imaging characteristics.

But the deeper mystique of the video-transferred film look probably lies with the curious combination (from an imaging viewpoint) of the secondary imagery characteristics. A

24 frame/sec picture capture rate is technically subsampled temporally, yet it imparts a distinct look to moving pictures which, in combination with the craftsmanship of the cinematographer's manipulation of the camera movement relative to the imaging of the scene (for example, "crabbing," panning, tilting, and dollying), has evolved to what many consider an art form. Film grain is arguably of equal complexity, subtlety, and uniqueness, and it is a dimension of the film look as important to some in the art of imaging as the shuttered 24 frame/sec capture. These artistically manipulated artifacts might be said to constitute a secondary layer to the more essential layer of imaging comprised of the primary picture characteristics described earlier.

Early attempts at EC were beset by futile struggles to even approximately emulate the primary picture capture characteristics. These 2/3-in. format pickup tube cameras fell hopelessly short in sensitivity, at least compared to high-speed film. The exposure latitude, or effective dynamic range, of these pickup tubes hovered in the 6 *f*-stop range (compared to 9 *f*-stops for motion-picture film). Perhaps the most serious limitation lay in the inadequate handling of scene highlights, with all of the traditional photo-conductive tube impairments (comet-tailing, blooming, and image retention) distinctly setting this form of electronic image capture apart from the almost flawless highlight handling ability of film. Then there was lag — a most distinctive "footprint" of traditional video origination

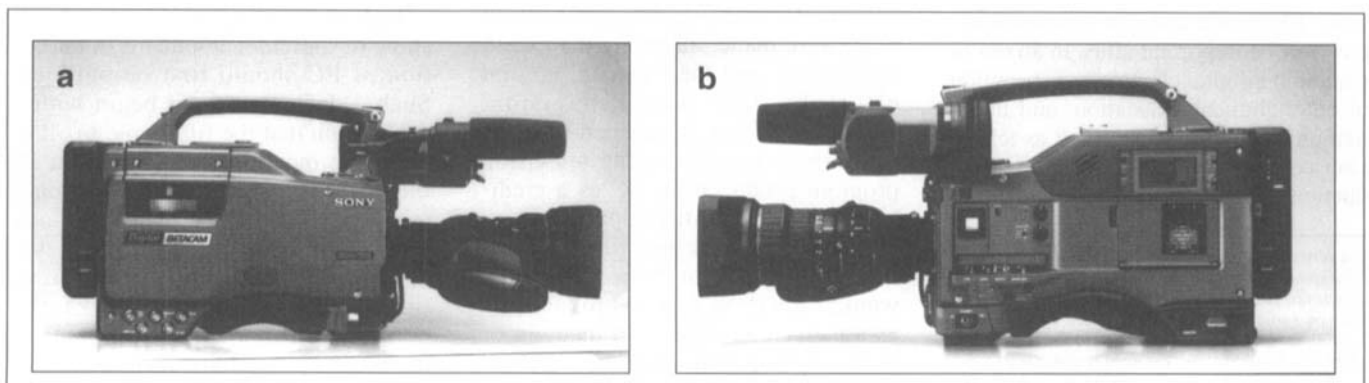


Figure 1. (a) Side profile of DVW-700 showing principal external connectors; (b) other side profile showing layout of operations controls.

— which was in itself an imaging stigma sufficient enough to forestall the electronic pursuit of motion-picture film imaging.

But much has happened during the past 20 years that electronic imaging technology has evolved. Film emulsions continued to advance steadily with the arrival of T-grain technology in the 1980s, and combined with a widening family of film stocks covering

a range of sensitivities and root mean square (rms) granularities (film grain), this allowed telecine processing to acquire even greater flexibility in the quality of imagery that could be transferred down to 525/625 television. Overall, however, the pace of electronic imaging technology was to accelerate, ultimately advancing more rapidly and on a broader front than that of motion-picture film.

The DVW-700 All-Digital Camcorder

Introduction to the Unit

Figures 1a and 1b show the new DVW-700 one-piece camcorder. This fully integrated, electronic “shoot and capture” system consists of three sections, each of which will be discussed:

- CCD imaging section, which produces

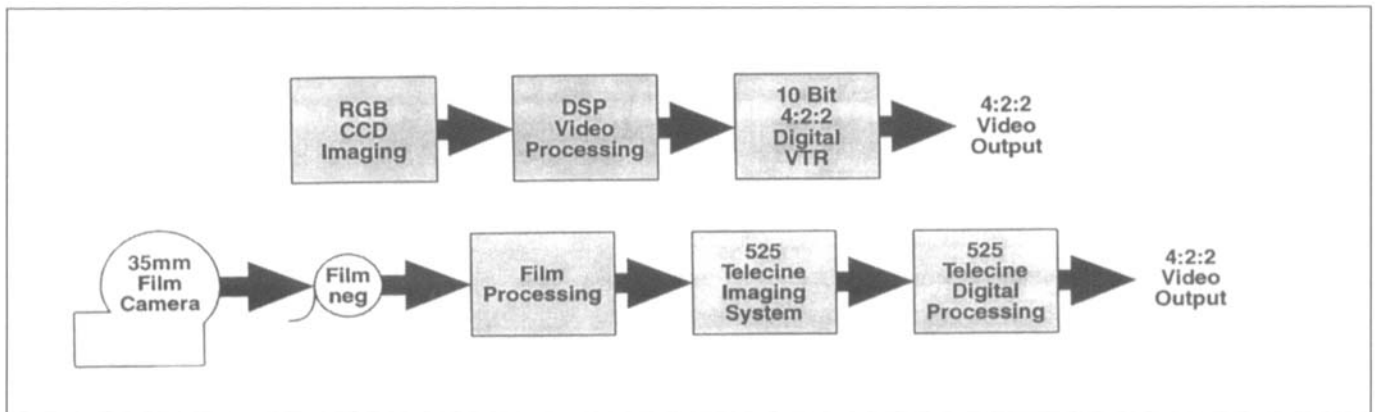


Figure 2. Picture performance of film and electronic cinematography is compared at the digital 4:2:2 component video output of each system.

Table 1 — Design Goals for Digital Camcorder with 35mm Film Transfer as Reference

Primary Imaging Performance Parameters			
DSP Camera + VTR Design Goal		35mm Film + Telecine Reference	
First-Generation 4:2:2 Digital Tape Playback		High-Quality 525-Line Telecine 4:2:2 Digital Output	
		High-Speed Film	Low-Speed, Low-Grain Film
Exposure index (sensitivity)	500	500	50
Exposure latitude (dynamic range)	9 1/2 f-stops	9 f-stops	9 1/2 f-stops
Color reproduction	SMPTE C (normal)		SMPTE C (normal)
Sharpness (resolution)			
Horiz. MTF @ 400 TVL/ph	>60%	50%	55%
Horiz. limiting resolution	465	460	460
Vertical MTF @ 400 TVL/ph	>25%	20%	25%
Highlight handling			
Blooming	none	none	none
Image retention	none	none	none
Comet-tailing	none	none	none
Lag	none	none	none
Signal-to-noise (luminance)	>60 dB	>50 dB	>56 dB

Table 2 — Primary New Features of the DVW-700 4:2:2 Digital Component Camcorder

Physical

Rugged lightweight diecast magnesium body
 Low profile
 Low center of gravity
 Total operational weight of 15 lb 7 oz (7 kg)
 Rain- and dust-resistant housing
 New cassette compartment design that increases reliability
 New lithium-ion, high-capacity, lightweight battery

Imaging

F1.4 optical system
 Three RGB Hyper-HAD 1000 FIT CCDs
 980 (H) x 494 (V) active picture sensors per CCD
 Electronic shutter 1/100 to 1/2000 (6 steps)
 Clear scan 60.1 to 7000 Hz (260 steps)
 Extended clear scan 30.4 to 58.3 Hz (248 steps)

Audio

Two channels of 16-bit digital audio recorded on two tracks
 Audio tone generator incorporated
 1-kHz reference tone recorded with color bars
 Phantom power for external microphones
 available on two XLR microphone input connectors
 48 V for external condenser microphones
 A WRR-860 UHF wireless microphone receiver can be attached
 (powered directly from DVW-700)

Table 3 — Digital Recording and Playback Features of the DVW-700

10-bit 4:2:2 digital component
 40-min recording time
 — field-proven 14- μ m MP tape
 Broadcast playback of video and audio
 — no playback adaptor or TBC
 High-speed color picture search
 Low acoustic noise

Frame accurate backspace editing
 Built-in time code generator/reader
 Real-time or preset time code recording
 — longitudinal
 — vertical interval (VITC)
 Time code regenerator
 — continuous TC recording in rec-run mode
 High-speed search
 — recognizable color pictures at ± 5 normal playback speed
 Record Review
 — auto playback of last recorded segment
 Built-in head-cleaning system (rotary and stationary)

Field playback without playback adaptor
 — full composite color; two BNC outputs
 — two audio channels (selectable); one XLR output
 Facilitates direct microwave transmission
 Provides field verification of recording (portable color monitor)
 Allows quality viewing of daily "rushes" in electronic cinematography (with high-performance color monitor)
 Luminance video playback can also be viewed in viewfinder

normalized RGB analog video voltages.

- DSP camera section, which digitizes the RGB video signals and processes them in the digital domain.

- Digital Betacam VTR, a 4:2:2 digital component miniature video and digital audio recorder.

The DVW-700 is the world's first component digital professional camcorder, and as such, it constitutes the crucial missing link in a decade-old evolution to a full digital 4:2:2 program production system. A great deal of today's television programming is shot on location, and EFP has, until now, remained elusive of full component digital capture. Now for the first time, the highest quality digital field acquisition has been made both practical and cost-effective.

Design Considerations to Achieve Viable EC Picture Quality

The true measure of the picture quality criteria for EC must be evaluated at the video playback level of the acquisition system, an idea somewhat ignored in the early explorations of EC. Thus, the replay of the first-generation digital 4:2:2 recording from the DVW-700, the point at which performance goals were set, ultimately determined critical design decisions within the DSP camera and integral digital Betacam VTR. These picture-quality attributes were ranked alongside the performance characteristics of 35mm origination, but measured in the same digital 4:2:2 domain, that is, at the output of a high-quality digital 525 telecine (Fig. 2).

The performance design goals of the DVW-700 as an EC system are listed in Table 1, where they are ranked against the primary performance attributes of contemporary 35mm motion-picture film, measured at the telecine output with no color correction and no image enhancement applied in either system. The actual performance achieved will be reviewed later, following a description of the technologies employed and the overall performance specifications, which are summarized in traditional video terms.

Basic Features of the DVW-700

In addition to being an EC system,

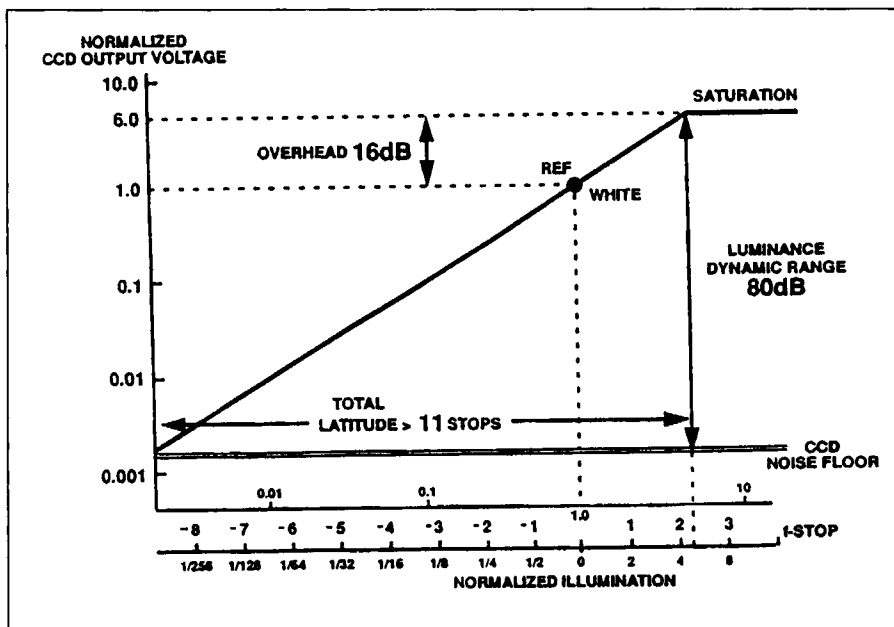


Figure 3. Dynamic range of Hyper-HAD 1000 CCD imager.

the DVW-700 is also part of a new generation of acquisition system design emanating from a broad international field acquisition experience gained over a decade of ever-evolving portable EFP and ENG camera/recorder designs. Numerous features and facilities reflect a wide spectrum of end-user requests, encompassing applications from single camera/recorder production shooting to multiple iso-recording systems. The overall goal was to achieve the very highest level of portable component digital image capture that contemporary technology would support while also addressing ergonomic and operational requirements identified over previous generations of camcorders. Tables 2 and 3 summarize the salient features of this new all-digital camcorder.

DSP Camera RGB Video Processing

CCD Video Dynamic Range and Digital Amplitude Scaling

The dynamic range of the Sony-developed Hyper-HAD CCD is about 72 dB. The imager can deliver linear signal output up to six times nominal white reference, or a little more than 2 1/2 *f*-stops of overexposure, which compares very favorably to the best 35mm motion-picture film. The high-light handling capability of this CCD

imager ensures a total absence of image retention, no comet-tailing on moving highlights, virtually no blooming on the most intense of highlights, and a vertical smear level of some -140 dB below reference white (which is essentially invisible). All of this ensures unfettered artistic freedom to exploit overexposed portions of the scene for creative purposes fully comparable to what film cinematographers have always enjoyed.

At the lower end, toward video black levels, the Hyper-HAD imager has a dark current level some ten times lower than conventional photosensors and an attendant virtual absence of fixed pattern noise. Combined with the unusually controlled level of high-frequency noise producing better than a 62-dB luminance signal-to-noise ratio

(SNR) at 0 dB gain, the DVW-700 camera has the ability to produce crisp imagery down into deeply shadowed areas. In terms of a cinematographic exposure latitude, the total operational latitude is in excess of 11 *f*-stops (Fig. 3).

In digitally coding the linear video voltage levels from the CCD preamplifiers, it is important to supply a sufficient amount of bits for each of the three RGB signals, recognizing that these video levels can travel over a very wide range. To gain a sense of the degree of demand on the quantization level assignment, it is useful to break down the video level range as shown in Table 4, which summarizes the minimum number of bits required to satisfactorily quantize a signal with 600% overexposure range.

Thus, to effectively and accurately process this extended video dynamic range in the digital domain with less than 13.5-bit quantization, a degree of analog precompression is employed in the CCD preamplifier, integral to the imagers within the CCD block itself.

Figure 4 indicates the nature of this compression curve. It is carefully designed to compress the 600% peak output of an overexposed signal down to 226% with an analog "pre-knee" actuated only on video excursions exceeding 130% of nominally exposed reference white level (or 100% video level). This compressed analog overexposed video is then applied to the three RGB analog-to-digital (A/D) converters. These are 10-bit A/Ds operating at a sampling frequency of 18 MHz. This frequency is identical to that used for the CCD sampling, which in turn dictated the 980 active horizontal picture sensors

Table 4 — Quantization Level Assignment

Video Level Range	Required Quantization Levels (No. Bits)
Nominally exposed linear video level (100%)	8
Gamma correction (x4 gain at black)	2
White balance amplifier gain (+6 dB)	1
Over exposed signal level (600%)	2.5
Total required bits	13.5

(1,038 total) in the CCD imager.

The chosen quantization level assignment is also shown in Fig. 4. It can be seen that 10 bits/sample will very effectively represent these signal levels in the digital domain. The final camera-processed component video is then fed to the digital Betacam VTR section where recording takes place, also at the 10-bit level. Thus, the excellent dynamic range generated by the CCD/DSP camera during the "shooting" process is faithfully retained in the recording (capture) process. Because the digital VTR records according to the CCIR-601 component studio standard based upon 13.5-MHz (6 x 2.25 MHz) lumi-

nance sampling frequency, the choice of 18 MHz (8 x 2.25 MHz) for the DSP/CCD camera section ensured that all of the camcorder clock frequencies were locked (thus obviating the creation of spurious beat frequencies) and that component video rate conversion (18 MHz to 13.5 MHz) in the VTR section would be simplified.

Figure 5 summarizes the digital clock system of the integrated camcorder and indicates the limiting resolution transformation that occurs because of the luminance filters associated with the digital Betacam digital-to-analog (D/A) converter. Of special note is the parity, achieved for the first time, between a camera

signal-to-noise specification and that of the recording VTR.

Full Digital Gamma Correction

Camera RGB gamma correction, operating over the nominal exposure range, combined with the nonlinear "knee" processing to compress overexposed signals according to the creative aspirations of the cinematographer are both highly complex operations having a considerable bearing on the picture quality and its artistic look. Precise long-term stability, ease of adjustment, and repeatability are essential to film cinematographers using EC as a creative alternative to film capture. Thus, implementation of these critical processing functions fully in the digital domain was central to the design concept of the DVW-700 DSP camera.

Both gamma and pre-knee, as nonlinear processes, pose a special challenge to digitization. The generation of higher harmonics, which can produce aliasing "noise," is unavoidable. To move this interference effectively beyond the visible video frequency band requires as high a digital sampling frequency in the processing section as possible.

Sony's in-house, high-speed CMOS technology can support operation close to 40 MHz. To ensure absence of contending sampling frequencies, the camera digital processing sampling was chosen to be 2 x 18 MHz = 36 MHz. For accurate resolution in these nonlinear processes, 14-bit computation is employed, thus

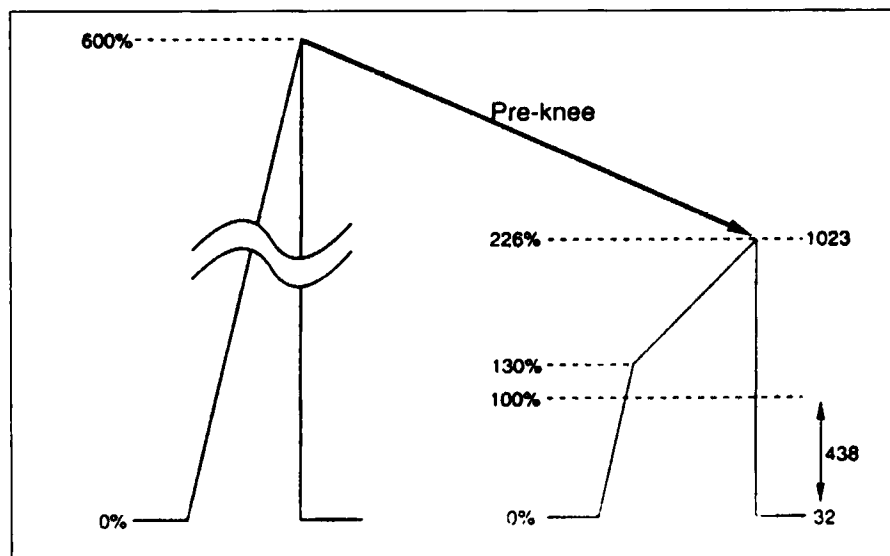


Figure 4. Pre-knee analog compression of CCD video output and subsequent 10-bit linear A/D bit assignment.

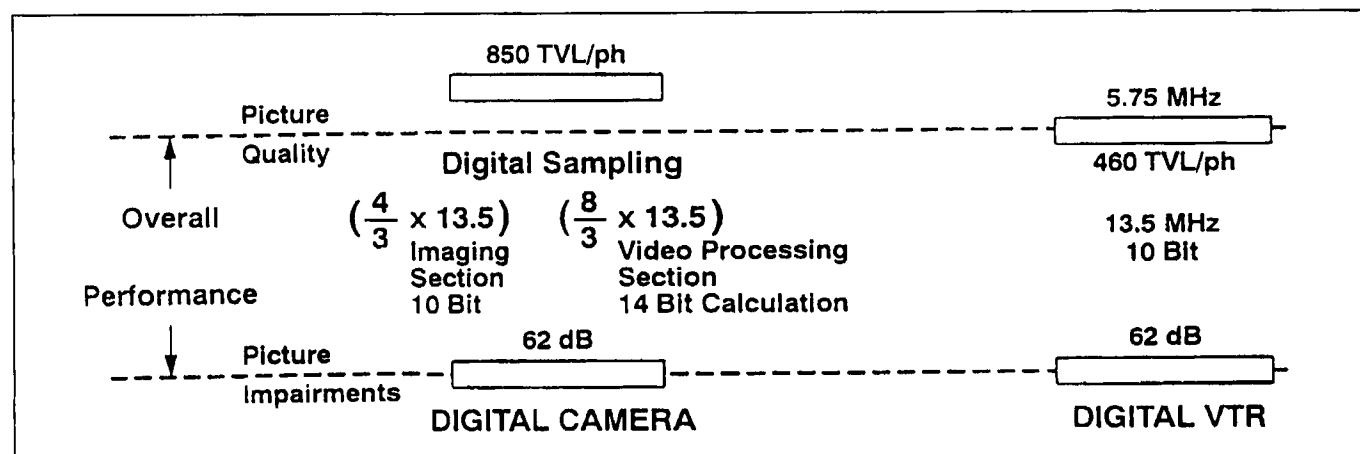


Figure 5. A representation of the digital compatibility of the DVW-700 clock frequencies and the attendant performance relationship between the CCD/DSP camera and digital VTR.

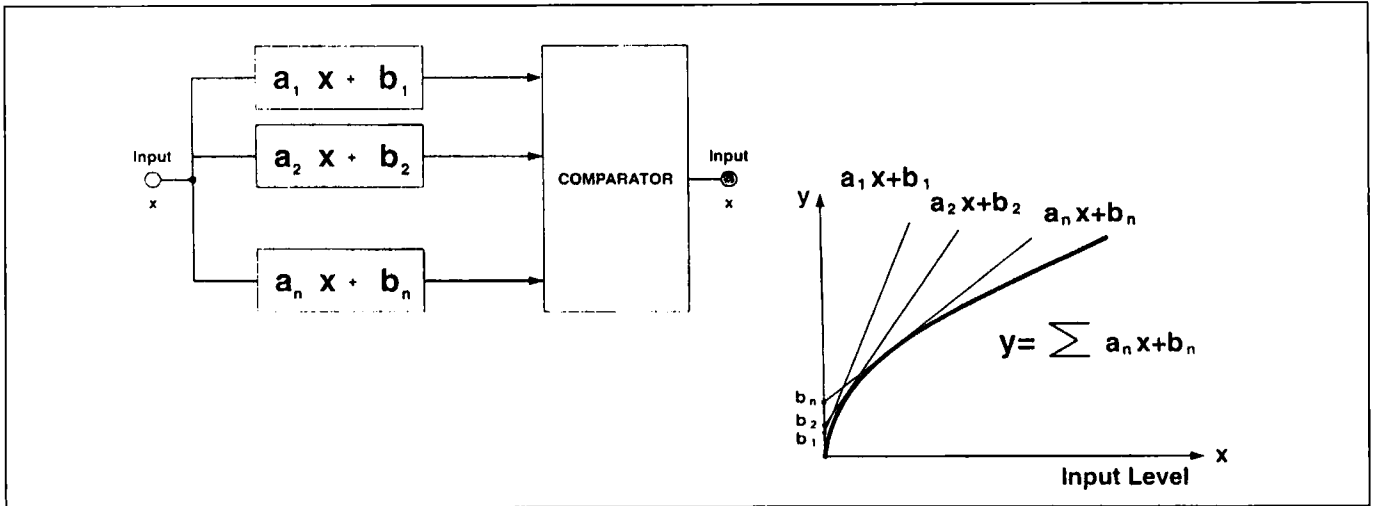


Figure 6. Traditional digital implementation of piecewise linear approximation to prescribed gamma pre-correction curve.

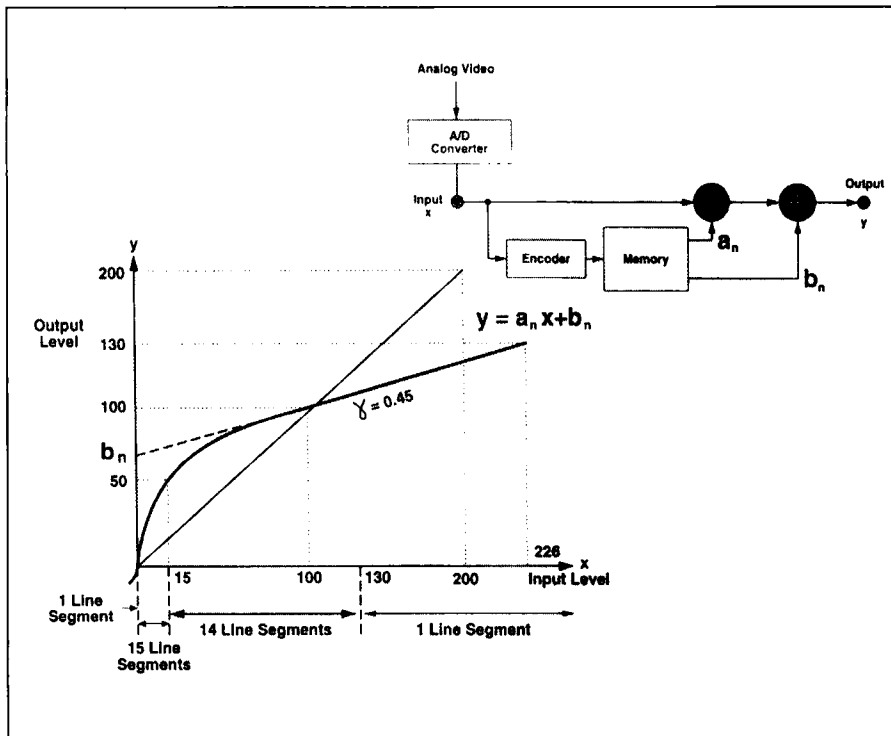


Figure 7. Sony-patented digital gamma pre-correction circuit showing high precision of synthesized curve.

avoiding rounding errors throughout.

Traditional gamma correction circuits employ piecewise linear approximation to synthesize the desired non-linear characteristic. In the analog domain it was not unusual to employ five or six stages to achieve a smooth implementation of the desired curve. In the digital domain a digital emulation of this technique is generally utilized, having the form shown in Fig. 6.

In this approach, the so-called

“mapping system,” the gamma correction characteristic is stored in memory and the output signal is read out of memory by using the digital input video data as the readout address. This embodiment generates a series of polygonal lines used to synthesize the desired shape of the gamma correction characteristic, with five or six lines typically being the limit because of the extensive digital memory required and the number of

multipliers and adders. This large memory capacity is a practical handicap, particularly when it is desired to implement the gamma correction circuit as an integrated circuit (IC) gate array. Moreover, the need to implement variable RGB gamma controls demands that the entire memory must be rewritten.

An alternative approach was sought to reduce the digital memory requirements and to facilitate easy differential adjustment of the three RGB gamma correction circuits. By subtracting the curve representing input uncorrected digital video data from a desired gamma correction characteristic, multiplying this result by coefficient data, and adding this result to the input digital video data, the desired gamma corrected output is generated (Fig. 7).

RGB Black Level Control

A perennial problem in color-camera RGB video processing is attaining adequate stabilization of the three video black levels; this has preoccupied camera design engineers for decades. The requisite degree of precision is an ever-moving target as camera master gain ranges approach 30 dB and new black stretch circuits are incorporated to further extend creative flexibility. Time and temperature excursions have always resulted in the inability to maintain an adequate stability in black color balance (between RGB) and in the absolute master black setting. Achievement of

the highest precision and stability of RGB black setting, black shading, and balance is crucial to full exploitation of the superb dynamic range of the Hyper-HAD CCD imagery because it is at the low end of the luminance scale — in dark shadowed scenes — that contemporary EC offers distinct advantages over motion-picture film. Figure 8 shows that, at nominal 0-dB gain, the exposure latitude of the DVW-700 extends more than 2 *f*-stops below modern T-grain film emulsion. This can only be fully exploited in capturing color-rich

and accurate imagery in deep shadows if the RGB three back levels are held absolutely stable.

To achieve this degree of stability in the DVW-700, a novel digital feedback clamp circuit was developed (Fig. 9). The video channel black level is sampled in the digital domain within the IC CDX-8353 detector and compared with a digital number corresponding to the desired black setting of that specific channel. This reference setting, placed in digital memory, is ultrastable and impervious to long-term drift or temperature effects.

The output of the digital comparator is converted to an analog voltage and sampled by the clamp pulse in an integrated sample and hold circuit, whose output is then highly amplified and fed back to the input of the video channel A/D converter, thus closing the controlling feedback loop.

The DSP camera exploits digital techniques to the fullest when dealing with RGB channel black shading. When auto shading is selected via the digital menu-control system, the raster is sampled in some 30,000 individual zones (114 x 228). This is accomplished within the detect digital large-scale integration (LSI), and each zone generates a compensation shading correction by digital comparison akin to that described for black level setting. The resulting zonal signals are fed to a digital-to-analog (D/A) converter and filtered to produce the complex waveform, which is added to the appropriate video channel in the input video amplifier prior to A/D conversion.

Camera Digital Signal Processing — Partitioning into LSI

Figure 10 is an overall block diagram of the DSP camera (shown within the shaded area). Clearly all the critical RGB video processing

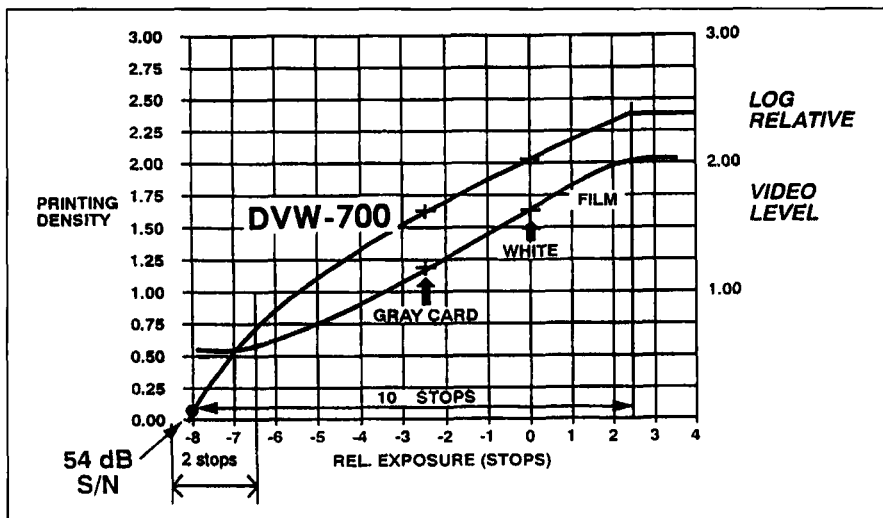


Figure 8. Comparison of exposure latitude of DVW-700 with that of contemporary slow-speed 35mm film (green emulsion).

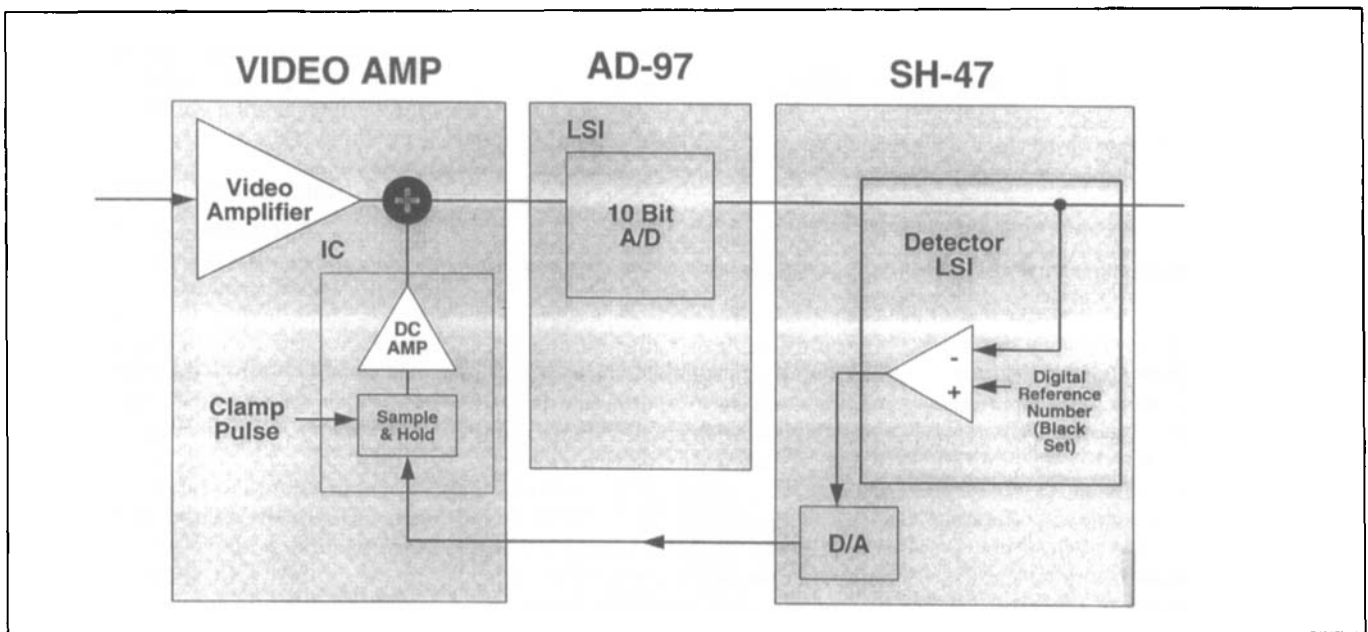


Figure 9. Digital feedback clamp system employed in each RGB channel to ensure high stability of black levels.

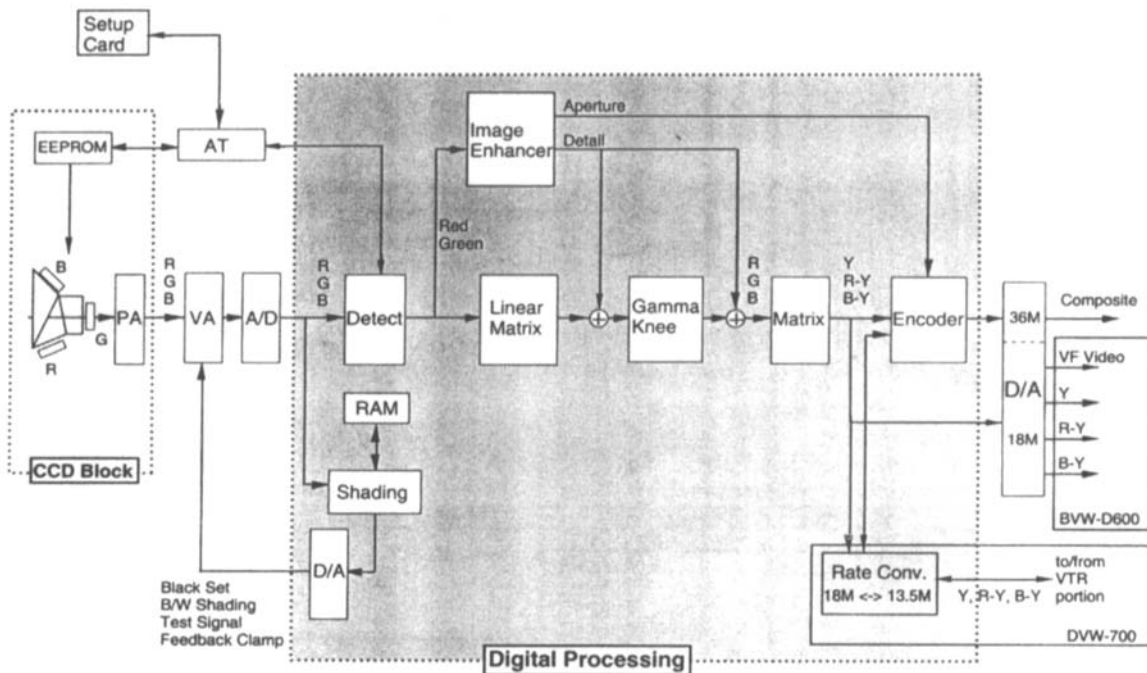


Figure 10. Simplified block diagram of the DVW-700 camera showing the RGB video processing accomplished in the digital domain.

contributing to accurate color reproduction, color balance, and tracking are accomplished entirely in the digital domain. It should be noted that this same DSP camera is employed in the sister camcorder to the DVW-700 described in this paper; the BVWD600 utilizes an analog Betacam SP VTR. Thus, Fig. 10 shows the alternative system connections for both VTRs.

A key part of the complex video processing required in a high-performance camera is the image enhancement system. Picture sharpness is multidimensional, and different pictures often require different degrees of sharpness to satisfy various creative aspirations. A high degree of creative flexibility in separating precise control of both the horizontal and vertical aperture responses was deemed crucial in allowing the subtle form of image enhancement that is attractive to film cinematographers.

Figure 11 shows the extent of the digital image enhancement system of the DSP camera and Table 5 summarizes the operational controls available for the systems. Table 6 summarizes the LSI circuits that make up DSP camera

processing, outlining their functions, technologies, and packages. Figure 12 shows four of the five LSI circuits used in DSP camera processing.

In particular, the horizontal detail system has been made particularly flexible both in terms of the peaking frequency (variable from 2.0 to 6.5

Table 5 — Flexible Digital Control Over Numerous Image Detail Enhancement Processes

Total horizontal and vertical detail enhancement control level	
White clip	(±99 steps)
Black clip	(±99 steps)
Crispening	(±99 steps)
Level dependence	(±99 steps)
Knee aperture	
Horizontal detail control	
Horizontal peak frequency	(2 to 6.5 MHz in 10 steps)
Vertical detail control	
Level	
Black clip	
Skin tone detail	
Reduces level of image enhancement for skin tone objects in the scene	
Selected skin tone area can be shown as "zebra" pattern in viewfinder (or as monochrome on color monitor)	
Controls	
Skin tone detail level	
Saturation center	
Saturation range	
Hue center	
Hue range	

Table 6 — Summary of Five Digital LSIs that Constitute the DSP Camera System

DVW-700 DSP Camera LSI	Function	Number of Gates	Number of Package Pins	Technology
1 Detect	Measurement peak video level Measurement average video level Flare correction CCD APR circuit	67,000	160	0.5 μ m 3.3 V
2 Shading	Multizone black shading compensation for RGB channels RGB black set measurement Multizone white shading compensation for RGB	60,000	208	0.8 μ m 3.3 V
3 Processor	Digital linear matrix Digital gamma correction Digital knee and white clip Comb filter for enhancement	220,000	208	0.5 μ m 3.3 V
4 Encoder	Digital matrix RGB to Y/R-Y/B-Y Composite NTSC encoding	105,000	208	0.5 μ m 3.3 V
5 Rate Converter	Rate conversion of Y/R-Y/B-Y from 18 MHz to 13.5 MHz (for digital Betacam recording)	82,000	160	3.3 V 0.5 μ m

MHz) and the various nonlinear processes employed to treat that detail signal. The specific requirements for these can be very dependent upon scene content and can also be a purely aesthetic judgment on the part of the director or the cinematog-

rapher. Direct digital operational control can vary the effective horizontal peak frequency by appropriate adjustment of the coefficients a, b, and c (Fig. 13), thus providing an unusual degree of creative control over picture sharpness.

Salient Performance Specifications of the DVW-700 Camcorder

Table 7 summarizes the primary performance specifications of the digital camcorder in terms of CCD camera imaging and the digital VTR recording of both video and audio. These specifications are written in traditional television terms. The performance of the camcorder compared to film cinematography is reviewed later in this paper.

Digital Control of the DSP Camera

Modern color cameras embody a wide range of engineering alignment and user-operational control adjustments. The great strength of the DSP camera is that all of these controls can be relegated to digital numbers, the settings of which can be adjusted by an up-down switch and stored in digital memory. Multiple potentiometers and analog reference voltages are eliminated. This digital storage of camera alignment facilitates a new flexibility that can offer a choice between two operational modes: the videographer mode, in which a wide

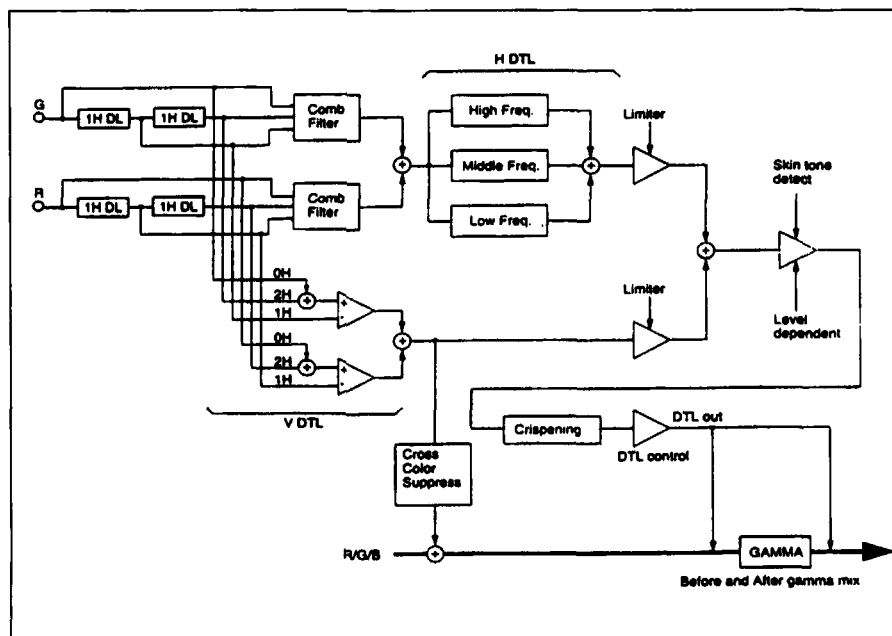


Figure 11. Block diagram of the all-digital image enhancement system; all except the 1H delay circuits are contained within the PR LSI chip.

variety of controls can be readily accessed on location to perform real-time optimization of a particular look; and the film cinematographer mode, where all adjustments for a particular look can be preprogrammed, thus rendering the camcorder adjustment-free on location (a close emulation of prechoosing a film stock).

The up-down switch control of camera settings is aided in the DVW-700 by a menu screen displayed either in the viewfinder or in an external monitor. Three levels of digital menu-assisted controls are provided, as shown in Fig. 14.

BSC-1 Setup Card

A small IC electronic memory card (Fig. 15), measuring only 1 3/8 in. x 7/8 in., is provided with the DVW-700. This plug-in card functions very much like a "smart card" and can store the camera setting data in its entirety. This data can be easily written to and read from the setup card; the data writing is accomplished by inserting the card into the small receptacle on the right side panel of the DVW-700 and activating the up-down switch under appropriate menu control. Write protection and ID editing for the setup card are facilitated. Almost 180 preset switches; mode selects; and technical, operational, and continuously variable controls are all accessible to the engineer aligning the cameras; all can be stored on the set-up card.

Having loaded a particular set-up with the data from a camera follow-

Table 7 — Imaging and Recording Performance Specifications for the DVW-700

Imaging	
Sensitivity (3200°K incident light on 89.9% reflectance white)	2000 lux @ f-8
Minimum illumination (with f1.4 lens and +30-dB gain)	1.9 lux
Signal-to-noise ratio (luminance)	62 dB
Resolution horizontal MTF @ 400 TVL/ph limiting horizontal resolution	70% (with high-quality lens) 850 TVL/ph
Video Component Recording	
Bandwidth Y	5.75 MHz ± 0.5 dB
R-Y and B-Y	2.75 MHz ± 0.5 dB
K-Factor (2T pulse)	<1%
Y/R-Y/B-Y delay	<15 nsec
Signal-to-noise ratio	62 dB
Digital Audio Recording	
Sampling frequency	48 kHz
A/D and D/A quantization	16 bits/sample
Frequency response	20 Hz to 20 KHz +0.5 dB - 0.8
Dynamic range (emphasis on)	> 85 dB
Head room	20 dB
Wow and flutter	Below measurable limit

ing its full technical alignment, the card can then be used to copy that alignment into another camera or multiple system of cameras (Fig. 16a). Digital precision inherent in the DSP video processing chips will then ensure a very tight degree of matching among all cameras. Thus, rapid picture matching on a multicamera

shoot is expedited to a degree not available in former analog cameras.

Alternatively, the set-up card system can be employed in a single camera operation to instantaneously realign the total set-up of that camera. Employing a number of preloaded cards, each carrying digital data corresponding to a total

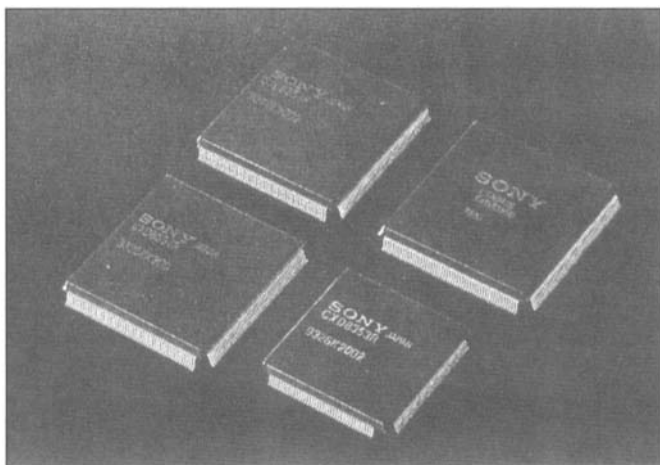


Figure 12. Four of the digital LSI circuits used in the DSP camera.

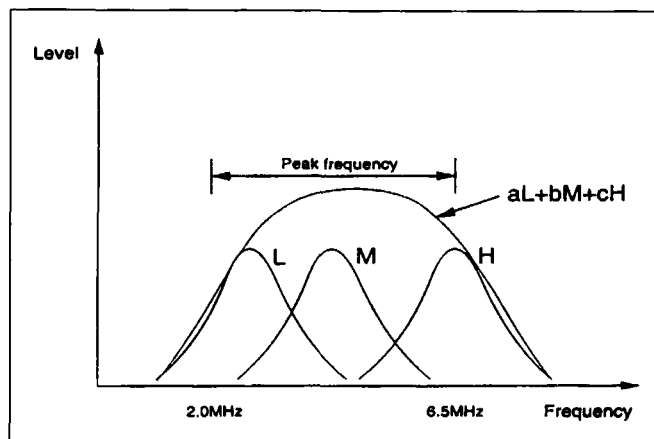


Figure 13. Variable horizontal peak frequency of the DSP image enhancement system.

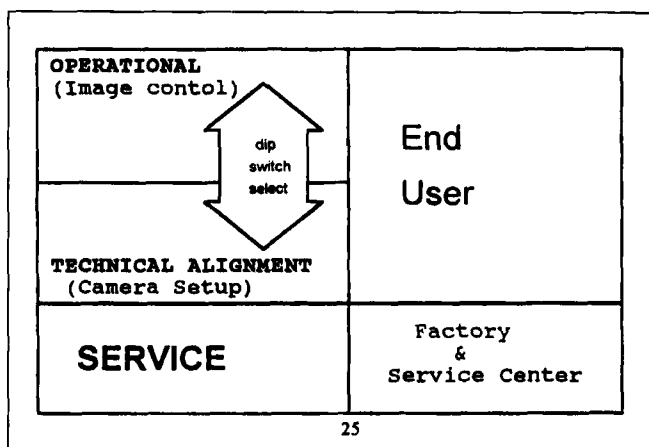


Figure 14. Up-down control of multiple camcorder functions has separate access for operational and servicing needs.

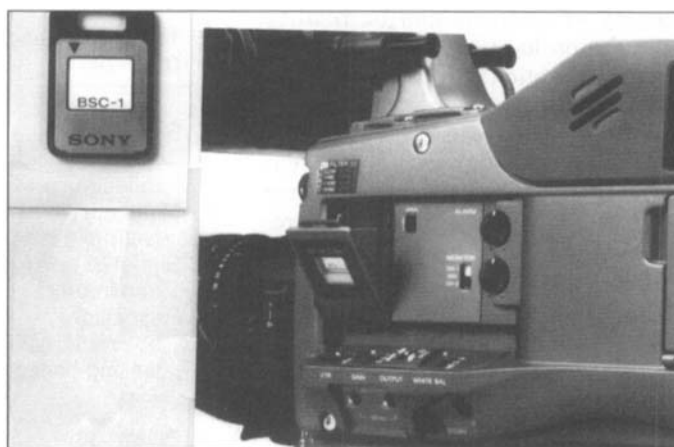


Figure 15. Set-up card BSC-1 and card receptacle (located on the right side of the DVW-700).

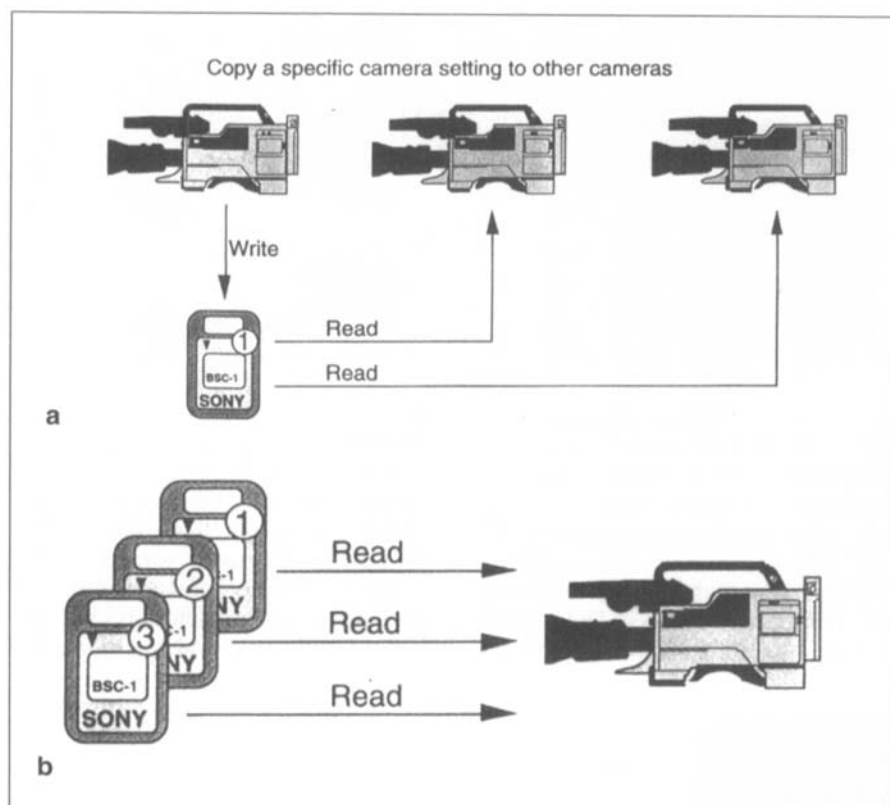


Figure 16. (a) Set-up card used to copy a specific camera alignment to other cameras; (b) multiple preprogrammed set-up options to instantaneously achieve different image looks in a single camera.

alignment carefully set to achieve a specific image look, the camera can be instantly and precisely customized to a desired imagery merely by substituting the appropriate plug-in card (Fig. 16b).

Rental houses and production facilities can prepare set-up cards for a wide variety of such customized image-making choices. Over a period

of time involving various shooting experiences, the particular look sought by a film cinematographer or videographer can be readily supplied in the form of an appropriately identified set-up card.

A major step in eliminating "video-tweaking" during location shooting is provided by this unique electronic card system, bringing the video cam-

corde a large step closer to the adjustment-free operation of a film camera. Digital EC is thus rendered more friendly to the skilled film cinematographer.

The IC card uses about 2 kbytes of EEPROM for storage. This technology makes it possible to accurately retain camera settings for recall days or months later.

Preprogrammed "Film Emulsion" Set-up Cards

A series of experiments have been successfully completed in preprogramming set-up cards so that the DVW-700 will record a 4:2:2 video that approximately emulates a specific 35mm stock transferred to an equivalent 4:2:2 video component set. High, medium, and slow-speed 35mm film stocks were selected to photograph a range of video test charts and selected scenes, and the uncorrected telecine transfers were carefully measured. Data on tonal reproduction, color reproduction, picture sharpness, exposure index, and exposure latitude were collected on each of the 35mm stocks and used to appropriately preprogram a set-up card to emulate each. These set-up cards facilitate a rapid, convenient methodology to ensure imaging equivalence between specific telecine transferred film stocks and the DVW-700 from the viewpoint of primary imaging capture characteristics.

Some cinematographers might wish to take the film emulation a step further and achieve a closer approximation to

what some describe as the “grittiness” of the film look (a function of sharpness and film grain). To achieve this, some of the secondary imaging characteristics were also approximated. Measurements were made on the total video noise level — a combination of film grain and telecine noise — on the telecine transferred video for each film stock. The set-up cards in each case were preprogrammed to select a master gain setting in the DVW-700 that produced a level of video noise equivalent to the average transferred luminance gray level noise. Simultaneously, an appropriate neutral density optical filter (the DVW-700 has a four-position ND filter wheel) and an electronic shutter setting were selected that configured the DVW-700 to an operational exposure index (sensitivity) approximately equal to that of the chosen film stock’s speed. These cards are available to those who seek a film-like look and operating mode akin to these various films. It must be emphasized that this is only an emulation of motion-picture film transferred to video, and it still produces imagery somewhat distinct from the true and traditional film look.

The VTR Section of the DVW-700

A specific goal in the design of the VTR section was to reduce acoustic noise of the recording system — a much-sought desire of producers and cinematographers. Because a camcorder does not need the high-speed

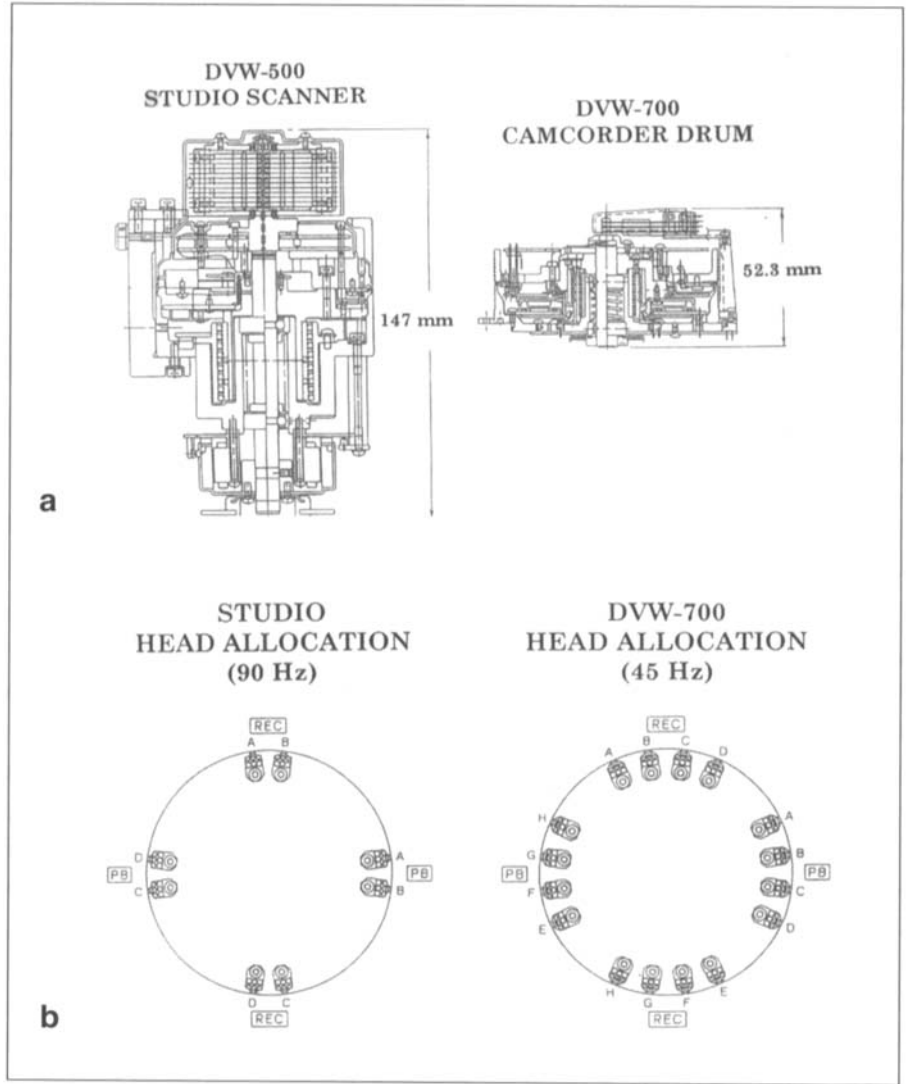


Figure 17. (a) Relative size of digital Betacam studio scanner and portable DVW-700 head drum; (b) relative head allocation (and rotational speed) for studio and DVW-700 heads.

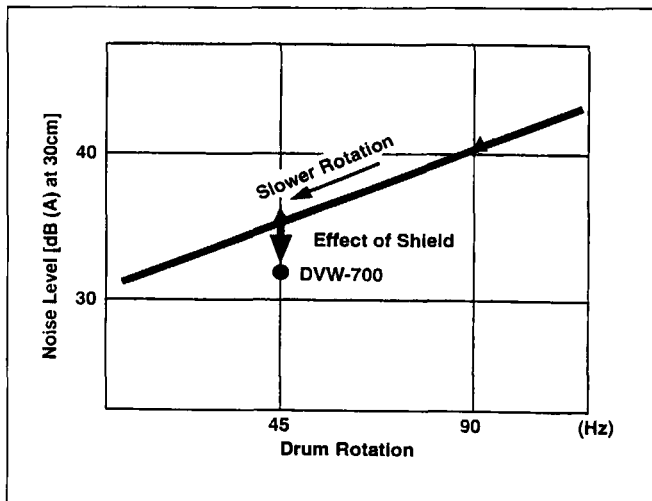


Figure 18. The acoustic noise target specification for a DVW-700 operating in the recorder mode.

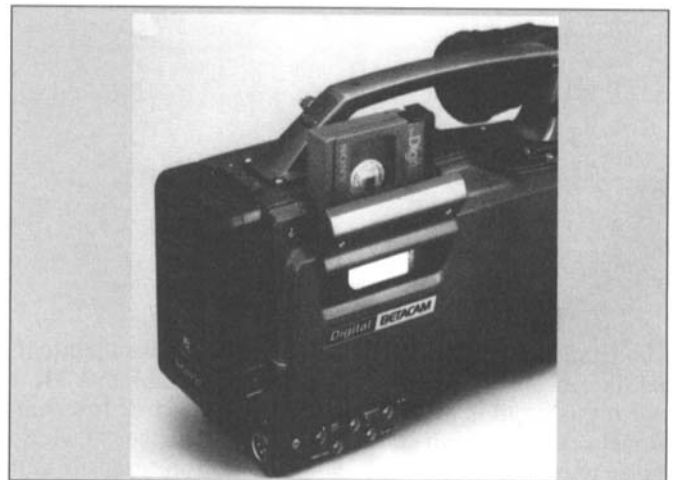


Figure 19. Showing the digital Betacam 1/2-in. cassette (40-min recording duration) access in the DVW-700. Note also new BP-L60 battery attached.

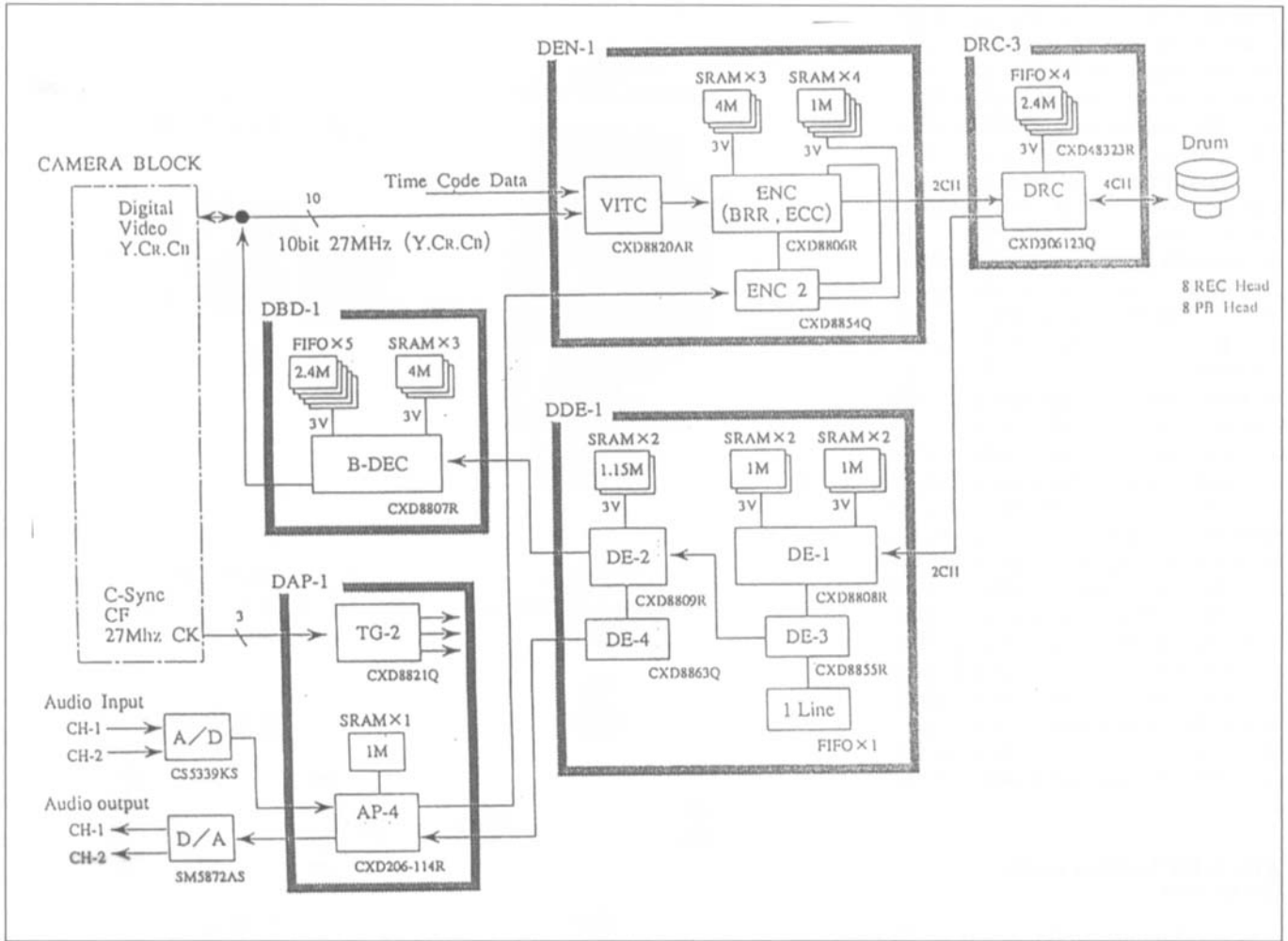


Figure 20. Simplified block schematic of the DVW-700 recorder section, which shows the PC board partitioning and identifies the digital LSI employed.

Table 8 — Comparison of Recording Performance Specifications

	Betacam-SP Analog	DVW-700 Digital
Luminance bandwidth (MHz)	4.5	5.75
Color difference bandwidth (MHz)	1.5	2.75
Luminance signal-to-noise ratio (dB)	51	62
Transient response (%) K-factor	2	1
Luminance/chrominance delay (nsec)	25	15

shuttling requirements of the studio editing machine, an upper drum was used; this drum is lighter than a traditional scanner, which caused acoustic noise to be lowered.

The height of this drum assembly is quite a bit less than in the studio VTR (Fig. 17a). The head drum diameter,

while identical to the studio digital Betacam VTR, only rotates at half its speed, lowering acoustic noise even further. Twice as many video heads are used to faithfully conform to the recording format (Fig. 17b). Finally, a special acoustic screen is incorporated into the VTR deck assembly.

The design target set for the overall acoustic noise level of the actively recording camcorder is shown in Fig. 18. An improvement of a full 6 dB (A) at 30 cm over the earlier BVW-400 generation of camcorder was sought because this number was felt to be adequate for meeting the demands of production personnel experienced in high-end EFP work. Using the techniques described, the DVW-700 fully meets this design goal. For high-end EFP or EC, this is expected to be an important attribute of an acquisition system capable of direct high-quality digital audio recording.

VTR Cassette Loading

To minimize the risk of entry of moisture and dust via the tape loading slot, the DVW-700 utilizes a specially redesigned tape-loading system.

Table 9 — Primary Imaging Specifications

	Electronic Cinematography 1994	Film Cinematography 1994	High-speed 35mm film	Electronic Cinematography 1978
Primary Imaging Specifications	DVW-700 (CCD + DSP Technology)	Slow-speed 35mm film	High-speed 35mm film	Pick-up tube camera
Sensitivity (exposure index)				
EI studio	580	12	500	280
EI daylight	650	50	320	320
Exposure latitude (dynamic range)				
f-stops	11	9 1/2	9	6 1/2
Picture sharpness (resolution)				
Horizontal:				
MTF @ 400 TVL/ph	70	60	50	40

The access slot, located well away from the video head drum, is made smaller by using the endloading of the cassette eject mechanism, thus furnishing a simple manual eject system activated by a single screw. Figure 19 shows the new vertical cassette loading method with the much smaller entry port.

DVW-700 Digital Betacam VTR LSI Circuits

The VTR section is partitioned into the five basic PC boards shown in Fig. 20. A total of 14 different LSIs were developed to reduce the complex digital audio/video recording and playback system to the miniature VTR package shown in Fig. 1.

New High-Capacity Battery Technology

The development of new battery technology was integral to the overall goal to enhance camcorder performance and extend both recording duration and operating time while simultaneously lowering total operating weight. Lithium-ion technology has been harnessed to achieve a significant improvement in capacity-to-weight ratio over that of nickel-cadmium batteries. Capacity versus

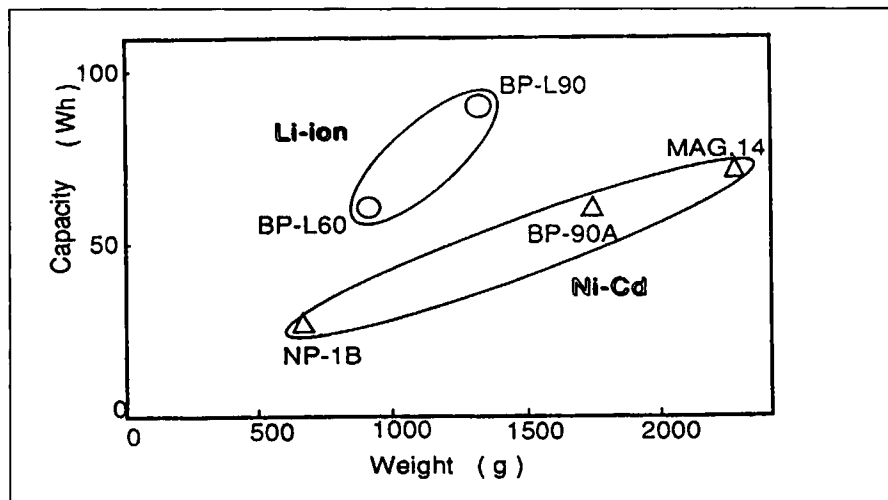


Figure 21. The charge capacity vs. weight figure for the new lithium-ion batteries (BP-L60/90) compared to traditional nickel-cadmium batteries.

weight figures for the new BP-L60 (60-W) and the BP-L90 (90-W) batteries as compared to traditional batteries used on other camcorders are shown in Fig. 21. This new technology has a further advantage in that the conventional battery "memory effect" is eliminated, as is the need for full discharge prior to recharging.

The BP-L60/90 batteries can be directly attached to the camcorder via a V-shoe attachment and a direct power connection interface. The BP-

L60 provides continuous camcorder operation for approximately 120 min.

The battery capacity is monitored by an LED readout in five steps (full, 75%, 50%, 25%, and 0%).

The Significance of Digital Component Video Recording

The DVW-700 fulfills a decade-long quest to realize EFP according to the international standard for digital studio quality origination (CCIR 601). First-generation picture material

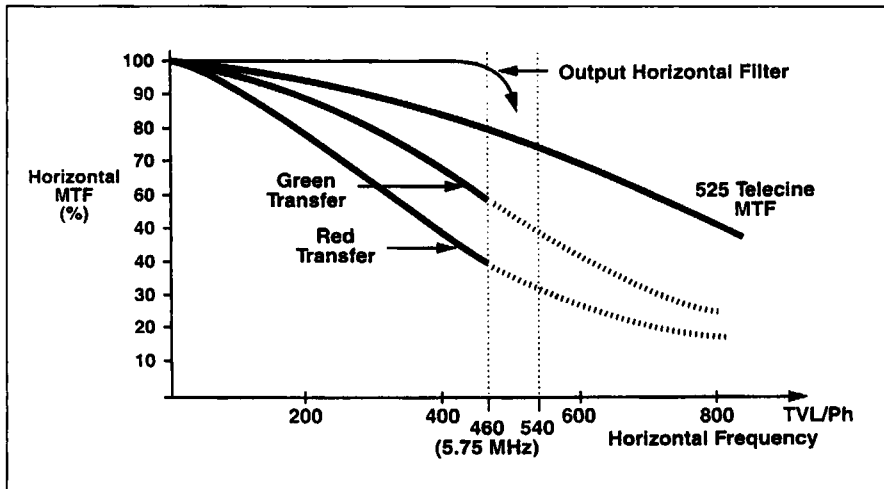


Figure 22. Red and green horizontal MTF at telecine digital 4:2:2 output (with no image enhancement).

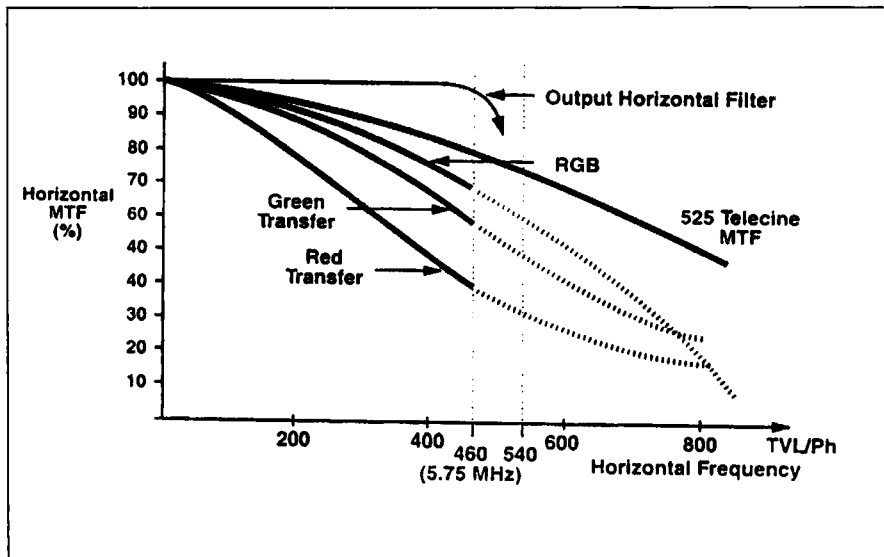


Figure 23. The DVW-700 horizontal MTF for each of the RGB signals (and luminance Y) compared to the telecine transfer.

can now be acquired on remote location with a compact, lightweight, and battery-operated camcorder. The technical quality of this first-generation recording is a substantial improvement over contemporary analog-field acquisition systems. Table 8 compares the video recording specifications of the DVW-700 with those of its analog component video recording counterpart. In all respects, performance is notably improved.

Of special note are the much wider video component bandwidths (fully conforming to CCIR Rec. 601) and the very significant improvement in signal-to-noise performance. This

produces a sharp and very clean first-generation picture that will be important in a future era where MPEG-based digital compression schemes will be used for program contribution feeds and final distribution (satellite, cable, terrestrial broadcasting, and digital packaged media) to the home.

The wide-bandwidth color difference video recordings, with high signal-to-noise performance, also brings a new dimension to off-tape chroma key and Ultimate bluescreen compositing, which should extend creative flexibility in both program production and television commercial production.

The DVW-700 as Electronic Cinematography Acquisition

The EC Camera "Shoot and Capture" Performance

Table 9 summarizes the primary imaging specifications of sensitivity, dynamic range, and resolution of the DVW-700 and compares these with both the early attempts at electronic cinematography (circa 1978) and the contemporary high- and low-speed 35mm films transferred via a 525 telecine to 4:2:2 digital component video.

Exposure Index or EI (Sensitivity)

Typical high-speed 35mm film emulsions today have an EI of 500 in 5600°K daylight lighting, which falls to approximately EI = 320 in 3200°K tungsten lighting. The DVW-700 camcorder's operating sensitivity, on the other hand, actually rises to EI = 650 in 5600°K lighting. This is because of the substantial increase in blue light under the daylight conditions that CCD imagers favor.

A choice of high-speed (EI = 500) motion-picture film or a low-speed (perhaps EI = 50) is typically made based upon scene lighting conditions and the commensurate desire for the "graininess" of the sought-for imagery. With this in mind, the direct comparison between the DVW-700 and the film stock becomes more difficult. While the camera, operating at nominal video grain (0 dB), is inherently more sensitive than present-day 35mm film, the attendant noise level of the video is quite a bit less than the rms granularity of a 500 ASA 35mm film and even 50 ASA 35mm film. The 62-dB SNR essentially means invisible "grain." Indeed, the only way any form of electronic emulation of the film grain of a given film stock can be achieved is by deliberately increasing the video gain, which increases the effective sensitivity of the camcorder even further. In the hands of a skilled film cinematographer, a wide range of choices of sensitivity, depth of field, and noise (or "grain") can be readily set up by adroit manipulation of lens aperture, ND filters, video master gain, and variable exposure electronic

shuttering. The use of appropriately preprogrammed BSC-1 set-up cards greatly simplifies such camcorder alignment.

Exposure Latitude (Dynamic Range)

It is in this realm of imaging characteristics that EC has bounded forward most dramatically. The effective dynamic range of pickup tube cameras hovered in the neighborhood of 46 to 50 dB, and that of the Hyper-HAD CCD imagers in the DVW-700 is in excess of 70 dB. The superb blooming characteristic of this imager on the most severe highlight and the total absence of lag and highlight image retention (or comet-tailing) provides almost 3 *f*-stops of overexposure that, like the 35mm film counterpart, can be very effectively employed to enhance the creativity of the cinematographer. At the lower end, when imaging in deep shadowed scenes, the CCD imagers truly exhibit their extended dynamic range capabilities. The 62-dB SNR translates into almost 9 *f*-stops of exposure latitude below reference white exposure. And, unlike film, which exhibits a limiting "toe" characteristic at typically 6 *f*-stops below reference white, the CCD maintains a linear capture characteristic all the way down to true black, or more accurately down to where the incremental SNR becomes 0 dB, at which point further imaging becomes irrelevant.

Overall Transfer Characteristic

Modern 35mm film can exhibit a total exposure latitude of about 9 1/2 *f*-stops (Fig. 8) with a predetermined nonlinear transfer characteristic (the well-known S-curve with a linear range of 6 to 7 *f*-stops and graceful limiting at both extremities). The DVW-700 has considerably more capture capability, with more than 11 *f*-stops of total dynamic range (or exposure latitude). Moreover, the total transfer characteristics is quite variable with approximately three degrees of adjustments:

- The traditional "gamma" nonlinear precorrection, operating from black to nominal white exposure
- A variable "knee" to compress

overexposed portions of the scene.

- An optional "black stretch" (or compression) to afford nonlinear adjustment at the lower shadowed regions.

Videographers are accustomed to manipulating all of these controls (generally in real time, during actual shooting by appropriate video monitoring on a high-quality monitor) to achieve a desired total exposure characteristic. Such in-the-field manipulation would probably be alien to many film cinematographers, who instinctively control exposure and scene lighting against fixed and known film-stock S-curve transfer characteristics. This is where the preprogrammed plug-in set-up card described earlier can play a major role.

Picture Sharpness (Resolution)

An examination of the published MTF curves for motion-picture film emulsion reveals a very high MTF over the typical video passband (5 to 6 MHz or perhaps 460 TVL/ph). But the three emulsions have, in fact, quite different MTF curves; in most cases, blue has the highest resolution, with green somewhat lower, and red considerably lower than both. What is actually recorded on the film negative is, moreover, a function of the film and lens MTFs (the latter being very much dependent upon the aperture setting). The negative is subsequently processed in the film lab, where another lowering of MTF takes place. Finally, the first-generation negative is transferred down to 525 digital 4:2:2 component video in the telecine. The effective MTF of the telecine is a function of both its optics and the imager technology employed (the flying spot CRT system and line array CCD are the most popular techniques). Figure 22 shows the horizontal MTF of a modern high-performance telecine and the output MTFs of the red and green video (up to the band-edge of the final filters on the matrixed Y/R-Y/B-Y component outputs).

These MTFs, which are shown without any image enhancement, are very respectable and contribute to the sharp imagery generally evident on such film transfers. The matrixed luminance resolution will be largely determined by the green and red

video and can thus be expected to be somewhat lower than the green video — somewhere in the neighborhood of 55% at 400 TVL/ph. Vertically, the MTF is limited by the 525-line sampling of the telecine and is thus lower than the horizontal MTF.

The DVW-700 EC system is, on the other hand, a simpler system from the viewpoint of concatenation of the MTF. The lens and the CCD imaging system, including its optical low-pass filter, determine the horizontal MTF. The 980 horizontal active elements combined with the carefully designed optical low-pass filter and the output electrical filtering produce a 74% horizontal MTF at 400 TVL/ph. A high-quality 2/3-in. production lens, at an aperture setting of about *f*5.6, will lower this to about 70% and a horizontal limiting resolution of 850 TVL/ph.

Figure 23 compares this MTF, which is essentially equal for each of the RGB video components, to the 525-line telecine output of the 35mm film transfer. The DVW-700 has a luminance (Y) depth of modulation of 70% (without image enhancement), as compared to the approximately 55% of the 35mm film transfer.

DVW-700 Cinematography Lenses

Perhaps the most central operational tool for the cinematographer is the lens. Imaging functionality and creative craftsmanship merge in this lens. Historic imperatives have led to divergent developments in motion-picture film lenses and their video counterparts. Electronic cinematography seeks a film-style lens, and for this reason dialogue was initiated with major lens manufacturers to consider development of such a lens for the DVW-700.

The first lens has recently been introduced by Canon. It is a 9:1 zoom lens (5.2 to 47 mm) with a high optical speed of T1:2.0 and is based upon their high-performance Super 16mm film lens. Engineered to tight technical standards, the lens has, in the 16:9 widescreen format, an 85.4° x 54.8° angular field of view and a minimum object distance of 0.6 m. The iris aperture control is calibrated in traditional "film" T-stops. Mechanically, it has the same smooth precision feel

of the traditional film lens when manually adjusting iris, zoom, and focus.

Because the 2/3-in. image format of the DVW-700 is smaller than the 35mm film format, the operating optical depth of field at equivalent aperture settings will be longer than that of the film camera. To a degree, this difference can be narrowed by appropriate use of scene lighting, neutral density optical filters, setting of video gain, and adjustment of the lens aperture.

Conclusion

Following a convoluted and fitful 20-year history, the question might still be asked: what is electronic cinematography and what does it mean to traditional film cinematography? Perhaps the only sensible answer to the first part of the question is that EC is an electronic acquisition system that might be readily embraced by a film production crew, provided it meets basic criteria to which they are accus-

tomed. EC allows capture of a look different from the film look, but a look of special value to certain projects nevertheless. The EC system should produce a first-generation digital 4:2:2 recording having an overall quality at least as good as that from the output of a 525-line telecine transferring a high-quality 35mm film origination, at least in terms of the primary imaging capture characteristics.

As to what EC means to film cinematography, the answer is surely that it should be sufficiently different in the imagery it produces to warrant its consideration as a creative alternative to film. The decision of which form of cinematography is applicable to a given project, whether it be entertainment program production, documentary, wildlife and natural history, or television commercial production, should be determined solely by issues of script/storyboard, desired imagery, special effects, and the creative

aspirations of the program director and cinematographer.

The arrival of the all-digital, component, one-piece camcorder is the culmination of a long quest to achieve a versatile production tool that might indeed attract the attention of program producers, directors, directors of photography, and cinematographers. It is believed that the many projects now being performed by the DVW-700 will demonstrate a significant fulfillment of expectations. The unique image capture capabilities described in this paper, when combined with the wonderful creativity of the experienced film cinematographer, should reveal a powerful new tool for expanding creative versatility.

What is unquestionable is the role played by a long history of 35mm film imaging in establishing the high-performance goals and specific design criteria for the world's first all-digital component video camcorder.

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Laurence J. Thorpe is vice-president of Broadcast Camera/HDVS at Sony Corp., Montvale, N.J., where he is responsible for product planning and marketing of Sony's studio and portable camera products. Thorpe began his engineering career in 1961, at the BBC Designs Department in London. Five years later, he joined the Broadcast Division of RCA, Camden, N.J., where he held a number of executive positions until he left in 1982. Among his accomplishments there were the development of studio switchers, distribution equipment, telecines, and studio color cameras. He was responsible for a number of new developments in studio cameras, for which he currently holds ten patents. In 1982, he was appointed director of studio project management at the new Sony Broadcast Co., responsible for market development of the Sony HDVS system.



Laurence J. Thorpe



Akio Takeuchi

In 1994 he was elevated to his current position.

Thorpe has presented many papers at SMPTE conferences, many of which have been published in the *SMPTE Journal*. He was the recipient of the Journal Award in 1989 and 1991, and he was presented with a Journal Certificate in 1994. A Fellow of the Society, Thorpe was the featured speaker at the Fellows Luncheon

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Takeuchi has been a member of IEC SC60B (BC VTR WG) in Japan since 1985. In October 1995 he received an Emmy Award for the development of Digital Betacam on behalf of the project group.