Technical Aspects of the New World of Multiformat DTV Embodying Progressive, Interlaced, and Segmented Frame Video Format

By Laurence J. Thorpe

In the past year, an unprecedented flurry of industry activity on the product and system development (and standardization) of a 24 frame progressive scan HDTV production system (now generally known as the 24P-system), has been driven by two marketplace imperatives: DTV multiformat production and a digital adjunct to motion picture film for movie production. Issues of acquisition, transport, and post-production relating to this format must all be encompassed in their respective overall system designs. 24P offers novel solutions to managing post-production in our new world of multiformat DTV, which encompasses both progressive and interlaced scanning. Suddenly, the old established world of analog 50/60-Hz interlaced video is about to be replaced by mixed progressive, interlaced, and segmented frame digital video—all operating at a variety of frame and field rates. Understanding this new world, and the options available to sensibly implement flexible systems, will be helped by a better understanding of the essential differences between interlaced, progressive, and segmented frames video structures. This paper will attempt to outline the basic technical characteristics of each.

On June 3, 1999, the International Telecommunication Union (ITU) issued a press release reporting on the achievement of a major milestone in the history of television with its adoption of a new electronic production standard for television program origination. The addition of the 24-frame capture rate to the family of other rates surrounding the novel concept of a common image format for HD production could, as stated in the press release, "revolutionize the film and television industries." The new ITU standard reached out to encompass the 50 and 60-Hz systems (in both their progressive and interlace embodiments) as well as adding 24, 25, and 30-frame progressive scanning formats. The ITU further recognized the merits of the segmented frame transport mechanism and have included it in the recommendation.

Now a new DTV world is emerging where traditional picture sources such as the camera and the telecine will no longer solely provide 525-line red, green, and blue (RGB) and analog composite NTSC outputs. The HDTV cameras and telecines that are rapidly replacing them are now anticipated to be multiformat, and definition of the latter is evolving as rapidly as the marketplace. Two years ago multiformat meant an HD output signal accompanied by a downconverted 525-line SDTV signal (otherwise known as 480i). Recently this was expanded to include a downconverted 480P output. The U.S. marketplace has now spurred manufacturers to extend the downconversion flexibility to further include a digital conversion from both 1080i and 720P.

There are also new choices emerging in how the contemporary HD video formats are originated and transported:

- HDTV pictures can be originated by progressive capture (P) or 2:1 interlace capture (i).
- Progressive captured video can be transported by progressive transport and segmented frame transport.
- Interlace captured video will be transported with interlace transport.

Something New—24P High Definition and Segmented Frames

The concept of 24P has been discussed since the original proposal for the 1920 x 1080 standard in 1993. Sony originally defined their version of this standard as a segmented frame signal, 48 sF, in the mistaken belief that it would best convey that this somewhat strange signal was a 48-Hz video signal (comprised of 48 segmented frames/sec). Early in the SMPTE process, this was changed to 24 sF, as the nomenclature should always carefully preserve the numeral that describes the initial capture rate. Later, detailed deliberations within the ITU committee on this topic went one better: determining the signal structure to be 24 PsF, because this more definitively stipulated that the original capture is 24 frames progressive, but also that the video has subsequently been restructured into the segmented frame transport format. This 24 PsF nomenclature is now firmly embedded in the new ITU international HDTV standard.

Perhaps the biggest challenge to system implementation is integrating the new 24P operation into an existing, hugely entrenched 60/50-Hz interlaced infrastructure. The goal of

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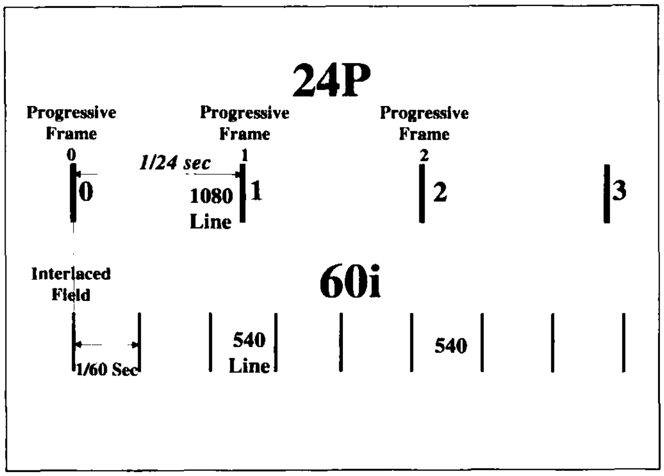

Figure 1. Illustrating the significant temporal difference between the traditional 60-Hz interlaced and the new 24-Hz progressive video formats.

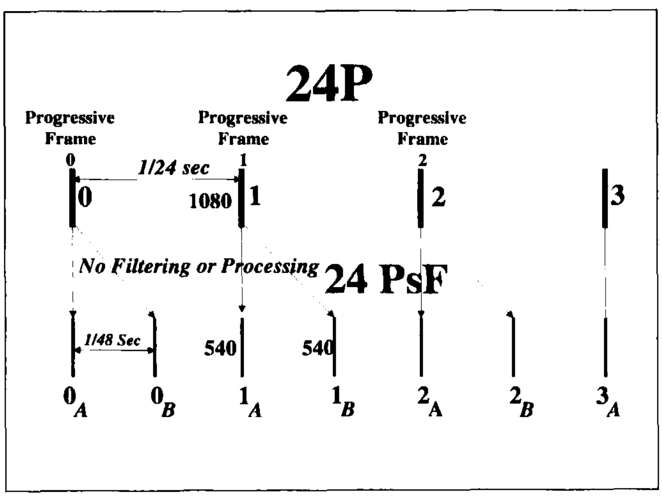

Figure 2. The ploy of reformatting the 24-Hz progressive video into that of a 48-Hz segmented frame format renders the progressive video closer in temporal structure to that of 50/60 Hz. The progressive characteristics are fully preserved.

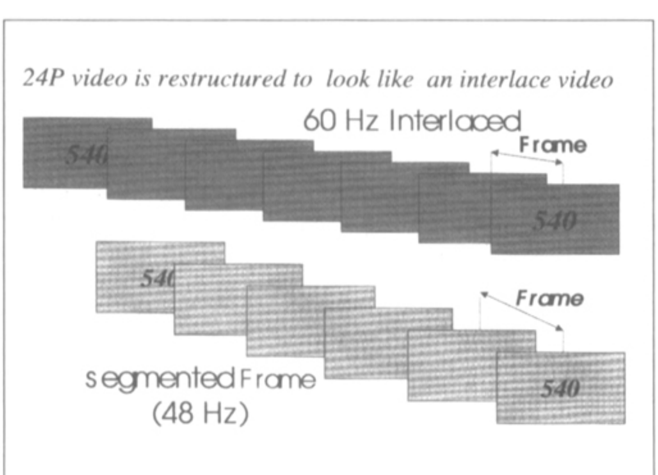

Figure 3. A pictorial representation of 24 PsF and 60i.

creating a hybrid HD post-production operation—one that can switch operation between 24P and/or 50 and 60-Hz interlaced—was urged by many in the industry during formative discussions on the 24-frame HD system throughout 1998 and 1999. The challenge to cost-effectively do so lies in the significant temporal disparity between traditional 60i and 24P (Fig. 1).

Practical implementation of such a hybrid system is facilitated by the restructuring of the 24P original image capture into a new video format, called segmented frames (Fig. 2). The digital video signal then becomes structurally close to that of traditional 50/60-Hz interlaced video (yet still retains all of the superior characteristics of the original progressive scan capture). In addition, 25P and 30P are also highly interesting to many: 25P is a useful alternative to 24P within the 50-Hz countries; and 30P offers the electronic emulation of 30 frames/sec film capture (useful for many television program and television commercial productions within the 60-Hz countries). Both of these progressive formats can capitalize on the use of segmented frame transport.

The 30 PsF video signal is structurally identical to a 60i video signal and can therefore be directly accommodated within any SDI-based 4:2:2 "601" digital production and post-production system (some software changes are required in switchers and DMEs to accommodate the time coherent nature of the adjacent segments). On the other hand, if it is desirable for the 24 PsF video signal to be handled by the same 60i circuits, switching of digital clock frequencies to lower the sampling frequency appropriate to this slower video signal will be required (Fig. 3). However, because it is now a 48-Hz video signal, it is still easily handled by the same circuits that deal with the 60i video signal (once this clock frequency switch is made). The need for field and frame delays (that would be needed to switch some circuits between 24P and 60i operation) has been obviated.

Larger Progressive Scan Agenda

Perhaps the most significant new stimulant to further flexibility in HD picture sources was the breakthrough consensus forged by the ITU during 1992 through 1999. Following many years of work, the international community finally converged on a singular digital sampling structure of 1920 x 1080 (and a singular total number of lines of 1125) for HDTV program origination and international program exchange (Table 1). However, they cleverly folded this into a wide choice of picture capture rates, both progressive and interlace, with progressive being decisively the dominant scanning mode. It is useful to look a little more closely at this ITU work.

ITU Common Image Format

The common image format defines common picture parameter values for production that are independent of the picture capture rate. This ingenious approach to achieving maximum unanimity among the international community pragmatically recognized some old and some new global realities:

- Virtual impossibility of the entrenched 60-Hz and 50-Hz regions of the world moving away from those picture rates in the near future.

Table 1 — The Common Image Format

Parameters	System: 1125/60		1125/50	
	1080 60(59)/2:1	1080 60(59)/1:1	1080 50/2:1	1080 50/1:1
Aspect Ratio	16:9			
Samples per active line	1920			
Active lines per picture	1080			
Sampling lattice	Orthogonal			
Pixel aspect ratio	1:1 (Square Pixels)			
Total number of lines	1125		1125	
Field/frame freq. (Hz)	60 (60/1.001)		50	
Interlace ratio	2:1	1:1		2:1
Sampling frequency (MHz)	74.25 (74.25/1.001)	148.5 (148.5/1.001)	148.5	74.25

Table 2 — Transport Mechanisms

Image Capture Rate	Transport	System Nomenclature
60 Hz Progressive	Progressive	60/P
50 Hz Progressive	Progressive	50/P
30 Hz Progressive	Progressive	30/P
30 Hz Progressive	Segmented Frame	30/PsF
25 Hz Progressive	Progressive	25/P
25 Hz Progressive	Segmented Frame	25/PsF
24 Hz Progressive	Progressive	24/P
24 Hz Progressive	Segmented Frame	24/PsF
60 Hz Interlace	Interlace	60/i
50 Hz Interlace	Interlace	50/i

- Desirability of migrating to progressive scan while also protecting the pragmatic continuation of the use of interlace scan.
- The huge defacto reality of 24-frame motion picture film constituting a source of television programming all over the world being a model of a world standard for production.
- Consequent desirability of encouraging deployment of the digital emulation of 24-frame picture origination.

Accordingly, the ITU Study Group 11 and its Working Party 11A finally forged an international consensus in 1999 that is reflected in the new ITU Rec. BT 709-3. Table 1 summarizes the primary convergence that spurred the broader consensus forged in Geneva in June 1999. This recommendation achieved unanimity on all parameters that define the still picture (or the single picture frame) including:

- Aspect ratio
- Horizontal digital samples for the active picture
- Vertical samples for the active picture
- Total number of lines/frame
- Total number of samples/line
- Colorimetry
- Optoelectronic nonlinear transfer characteristic of the picture source
- Derivation of luminance signal components
- Derivation of color-difference signal components

The final version developed in 1999 included agreement on the total number of lines per frame and total number of samples per line, prior to the completion of the work achieved by the ITU Task Group 11/3 p in 1997. All of the singular set of parameter values detailed above would now completely describe a picture that can be operated at any of the capture rates and can use any of the transport mechanisms listed in Table 2.

Figure 4 illustrates the ingenuity of the ITU consensus. It shows the regional field and frame rates pertinent to the 50 and 60-Hz countries. It also shows the singularity of the 24-frame rate being a universal frame rate that can potentially be used by all, as is 24-frame motion picture film today. This is a standard that takes a giant step beyond that achieved by the ITU (then known as the International Radio Consultative Committee (CCIR)) back in the early 1980s when they forged the "best" compromise of the digital 4:2:2 CCIR Rec. 601 standard. Now, by achieving unanimity on all still frame parameters, the door has been opened for manufacturers to develop switchable equipment capable of operating at all of these picture capture rates.

A Closer Look at Progressive, Interlace, and Segmented Frame

To better grasp some of the essential differences between progressive, interlace, and segmented frames video structures, it is useful to look more closely at the contemporary techniques used to originate each of these video formats. While the progressive scan capture can be preserved as a 24P (or 30P, or 60P) video signal throughout a total production and post-production system, Sony concluded two years ago that there were distinct system merits in transforming this coherent progressive video structure into segmented frames as early in the production system as possible.

Just as the analog-to-digital (A/D) converter, which precedes contemporary digital signal processing (DSP) in today's cameras and telecine picture sources, can be located immediately following the analog imager that accomplishes the optoelectronic transformation or be moved further downstream, so too, can the decision on where to convert 24P into 24 PsF be made. Sony decided to handle all elements of their 24P system on the basis of a segmented frame transport and concluded that creating the segmented frame structure right within the optoelectronic imager's readout would be most efficient.

The charge-coupled device (CCD) device is the almost universal imager presently employed in modern SDTV and HDTV cameras. The CCD imager, by appropriate manipulation of its digital readout mechanisms (Fig. 5) can be operated in a variety of modes to support creation of video scanning structures that are either progressive, interlaced, or segmented frame.

Operation of the CCD Imager

On a simplistic basis, the operation of the CCD can be separated into three sequential events:

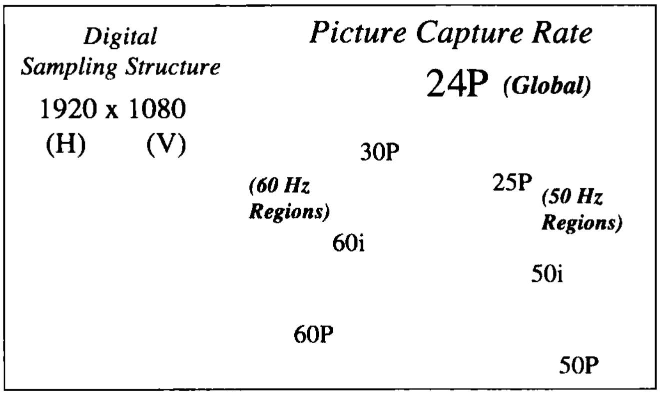

Figure 4. Another way of looking at the new ITU standard, showing the hierarchy of regional field/frame rates and the unique singularity of the international 24-Hz frame rate.

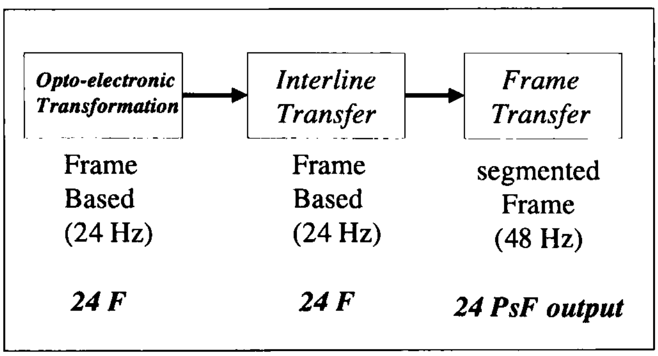

Figure 5. The CCD imager operates in a sequence of processes, and a variety of options are available for video read out.

- Optoelectronic transformation within the CCD sensors
- Structuring of the output video format the role of the readout registers
- Serial readout and analog output filtering

Optoelectronic Transformation

The basis of this initial task of the CCD imager is to transform the scene that is optically imaged onto the two-dimensional area-array CCD into an electronic spatial and temporal replication of that moving image. In a 1920 x 1080 area-array CCD, each of those 2.2 million sensors samples an element of that spatial image. It does so for 1/60 of a second in the case of the 60-frame progressive CCD and for the same precise 1/60 of a sec for the 60-field interlaced CCD. This is a very essential point that is sometimes misunderstood: The optoelectronic transformation is identical for a "progressive" imager and its "interlaced" counterpart. Both use full-frame 1080-line capture of the optical image. The fundamental spatial and temporal "samplings" are the same for both. Effective imager "scanning" has yet to take place and that becomes the role of the CCD's subsequent readout system. This is very significant, because it was not the case for the photoconductive pickup tube, where the optoelectronic transformation and the scanning were inextricably entwined. For those CCD imagers designed to directly output the third variant, namely, the segmented frame video structure, the optoelectronic sampling process is also identical to that described for both progressive and interlace.

Role of the Readout Registers—Defining Progressive Frames, Interlaced Fields, or Segmented Frames

In the earlier pickup tube, the beam scanning mechanism was electronically prescribed to be either progressive or interlaced. In the CCD imager, the scanning mechanism is synthesized—as a separate and distinct operation that follows the previously described optoelectronic transformation. Within that synthesis, some interesting processes can be performed on the sampled three-dimensional video signal.

Progressive Scan CCD

The case of the 1920 x 1080 60-frame progressive CCD will be considered. The process begins as earlier described, with all sensors simultaneously charging during the picture exposure period. Subsequently, the electronic charges are read out as 60 full 1080-line frames every sec. The bandwidth required to sustain this high-speed video format is inordinately high, approximately 60 MHz each for the three RGB video component signals. When later digitized within the camera's DSP processing circuits, this translates into a total baseband digital data rate of about 3.0 Gbits/sec (for 10-bit sampling), and some 4.0 Gbits/sec for the far more desirable 12-bit sampling (considered necessary for high-performance RGB nonlinear processing).

Vertical sampling produces the classic vertical aperture shown in Fig. 6 (based upon contiguous vertical sensors) with a precisely defined Nyquist limit, in addition to the fixed alias that is the inevitable artifact of any sampling system. In the case of both progressive and interlace scanning this alias is centered about the carrier frequency Fs (1080 cycles/ph or 2160 TVL/ph) as shown.

Returning to the all-important nomenclature that describes this image creation process and the final video output interface from the camera:

Camera Picture Capture Rate	**Picture Frame Structure**	**Transport**	**System Nomenclature**
(Exposures/sec)	(Full-frame Pictures/sec)		
60 Hz	60 Hz	Progressive	1080/60P

This nomenclature describes an HDTV picture source where the camera system (or telecine) originates a 1920 (H) x 1080 (V) progressive digital video format at 60 full frames/sec (with system transport, or camera output interface signal format, by means of that same progressive structure).

The Interlaced CCD

The case of the 1920 x 1080 60-field interlaced CCD will now be considered.

Here, the actual optoelectronic transformation is accomplished in a manner precisely identical to that described above for the 60-frame progressive camera; thus, the camera picture capture rates are identical. In this case, however, the CCD readout is an entirely different mechanism. Each full 1080-line original picture frame that is created by the sensors is, in the subsequent readout process, downconverted and filtered (by a vertical finite impulse response [FIR] filter) to construct a 540-line field (Fig. 7).

The CCD readout is then timed so that every consecutive two of these synthesized fields are spatially interlaced with each other as shown in Fig. 8. Each of the two fields are still separated in time by 1/60 of a sec, and the interlaced combination makes the final output full-frame 1080-line pictures at a 30-Hz rate. The penalty for this synthesis of an interlaced signal is the creation of an additional alias (not present in the case of the progressive CCD imaging system) as depicted in Fig. 9. This alias is centered about the 1080 television line (TVL) carrier Fs/2 frequency. It alternates in polarity from field to field and is accordingly dubbed the "flickering" alias, the source of the infamous interline flicker of interlaced scanning (Fig. 10). Operation of the interlaced camera system is described according to:

Camera Picture Capture Rate (Exposures/sec)	Picture Frame Structure (Full-Frame Pictures/sec)	Transport	System Nomenclature
60 Hz	30 Hz	Interlace	1080/60i

Synthesis of the interlaced video structure reduces the required camera system bandwidth as well as that of the subsequent video system; this, of course, being the whole point of interlaced scanning. It allows, for example, more than twice spatial sampling of the 1080-line format to be accommodated within a system bandwidth essentially the same as that required to sustain the 1280 x 720/60P video, that is, about 30 MHz for each of the RGB component video signals. The associated digital data rate is approximately 1.5 Gbits/sec (for 10-bit sampling).

It is important to note that the temporal resolution of this interlaced format is identical to that of 60-frame progressive origination—for most frequencies. On fast-moving subjects, however, the vertical-temporal filter can break down producing, for example, the familiar serrated edges on a vertical transition that is moving horizontally (a well-known artifact of the interlaced signal).

Segmented Frame CCD

Considering the 24-frame progressive HD camera, the camera engages all CCD sensors to simultaneously charge

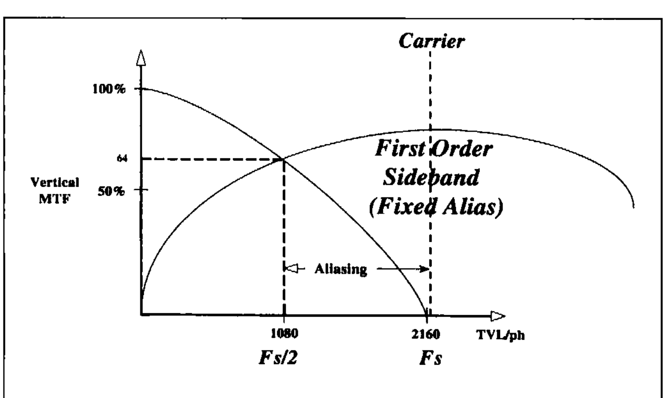

Figure 6. Depicts the vertical aperture of the 1080-line CCD in progressive scan mode together with the alias (often called the "fixed" alias) arising from the sampling process.

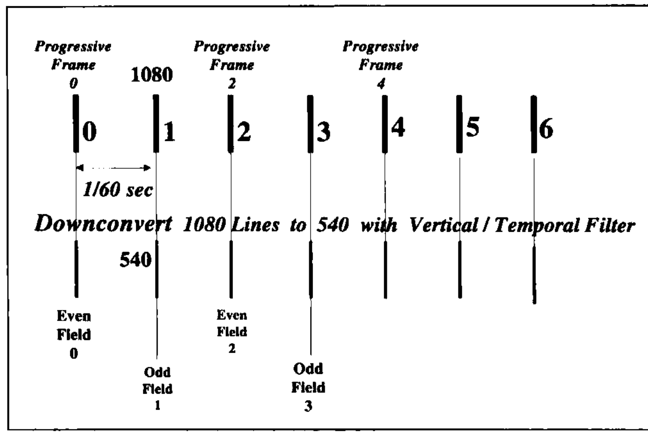

Figure 7. Illustrates the synthesis of the interlaced 60-field video. Every 1080-line full frame capture is subsequently downconverted and filtered to produce a corresponding 540-line field.

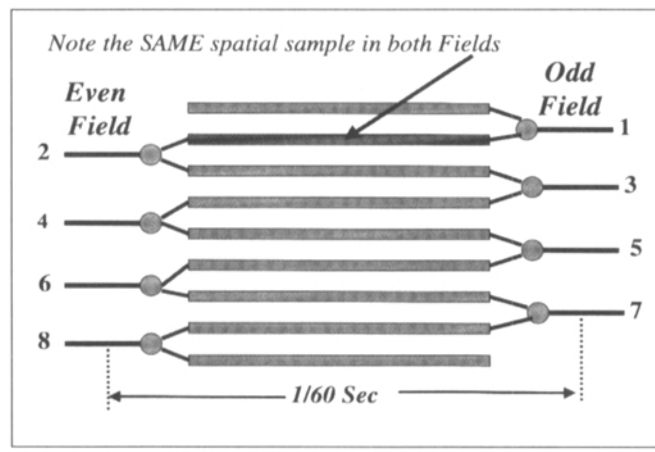

Figure 8. Showing the vertical cosine FIR filter that is structured by "overlapping" the vertical readout.

for 1/24 of a sec, after which they are transferred to the readout registers. This exposure creates a full-frame 1080-line picture. The CCD can itself subsequently transform this 24-Hz acquisition format into the 48-Hz segmented frame transport format, or alternatively, this could be digitally accomplished further down within the video system.

If done within the CCD (which will be the more common practice), the readout of that coherent 24-Hz exposure is accomplished in two steps: The odd lines are sequentially read out to form the first 540-line segment of that frame, followed by the reading out of the even lines 1/48 of a sec later (to form the second 540-line segment of that same frame) in Fig. 11. No downconversion or filtering process is employed in this readout mechanism and that is what decisively differentiates this readout from that of the interlaced CCD. The readout mechanism thus creates a segmented frame video structure that is similar to that of the 60i video, but having none of the characteristics of that interlaced signal (Fig. 12).

Segmented frames should be viewed as a simple means to transport the 24P video signal in a multiplexed manner, that is, multiplexing two separate segments that have been carefully structured so that they do not in any way contaminate the time-coherent nature of the original full-frame

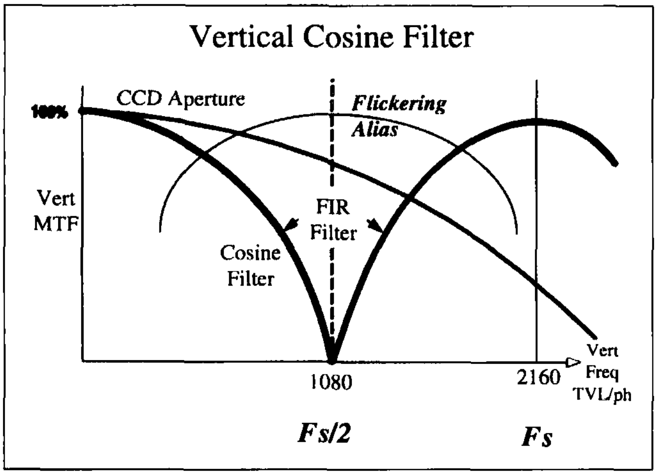

Figure 9. The effective cosine FIR filter created in the readout mechanism is superimposed onto the original aperture of the CCD capture, the resultant output vertical aperture being the product of the two. Also shown is the infamous interlace alias (sometimes called the "flickering" alias).

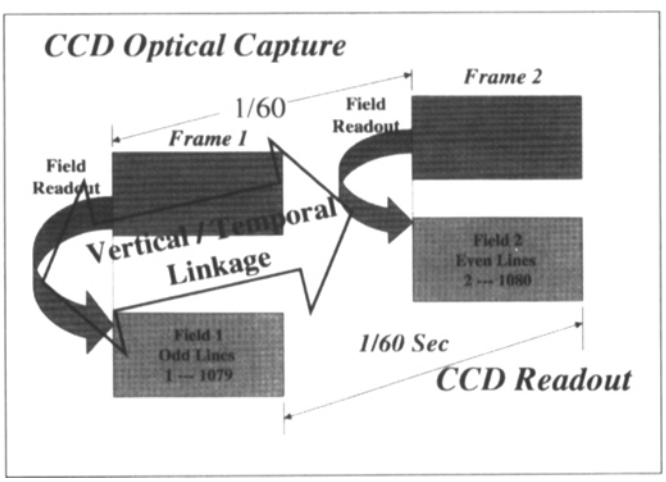

Figure 10. The complex interlace readout mechanism inherently creates a direct linkage between the vertical and the temporal domain; hence the attenuated vertical resolution and the enhanced temporal performance.

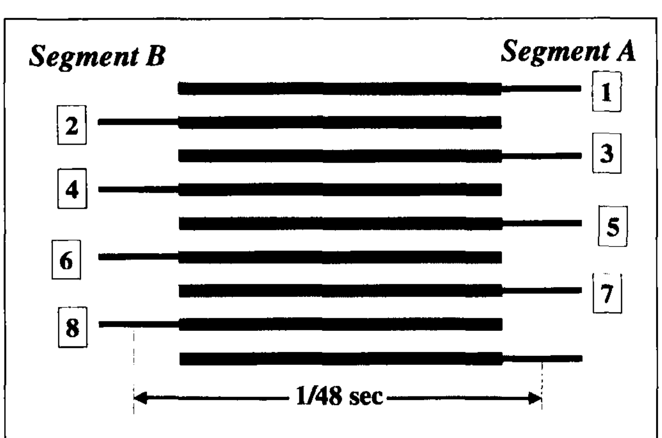

Figure 11. In the case of the segmented frame imager, the readout is far simpler than that of the interlaced CCD.

progressive capture. The segmented frame camera system accordingly is described as follows:

Camera Picture Capture Rate	**Picture Frame Structure**	**Transport**	**System Nomenclature**
(Exposures/sec)	(Full-Frame Pictures/sec)		
24 Hz	24-Hz Progressive	Segmented Frame	1080/24PsF

The nomenclature describes a camera system where the camera originates a 1920 (H) x 1080 (V) digital video format that is progressively scanned at 24 frames/sec, but this format is then converted for transportation as a 48-Hz segmented frame structure. Note that the system nomenclature carefully identifies the 24-Hz capture, the progressive scan nature of that capture, the 1080-line format, and the fact that the camera video output uses the segmented frame format as an interface (or transport) signal.

On the other hand, if any manufacturer elects to produce an HD camera or telecine that does not employ a segmented frame video transport format (but rather delivers the full-frame 24 progressive frames as the output signal), then their camera system would be described as:

Camera Picture Capture Rate	**Picture Frame Structure**	**Transport**	**System Nomenclature**
(Exposures/sec)	(Full-Frame Pictures/sec)		
24 Hz	24-Hz Progressive	Progressive	1080/24P

Thus, a system where the camera originates a 1920 (H) x 1080 (V) digital video format progressively scanned at 24 frames/sec that is also then transported as 24 full frames/sec.

Here, the CCD optoelectronic action is identical to that of the 1080/24 PsF camera, except that the CCD readout is purely progressive, such that it outputs the video as full-frame 1080-line pictures every 1/24 of a sec. This is also the video format delivered at the camera output interface.

As a final illustration, the SDTV picture source captures imagery at 30 frames/sec progressive and outputs a segmented frame interface video signal:

Camera Picture Capture Rate	**Picture Frame Structure**	**Transport**	**System Nomenclature**
(Exposures/sec)	(Full-Frame Pictures/sec)		
30 Hz	30-Hz Progressive	Segmented Frame	480/30 PsF

A system where the camera originates a 720 (H) x 480 (V) digital video format progressively scanned at 30 frames/sec, which is then converted for transportation as a 60-Hz segmented frame structure. Note that the system nomenclature clearly identifies that it is a 480-line video format captured at 30-frame progressive scan, and that the format is subsequently structured as a 60-Hz segmented frame video output.

In this example, the camera engages all CCD sensors to simultaneously charge for 1/30 of a second, following which they are transferred to the readout registers. Each separate exposure creates a full-frame 480-line picture. The readout

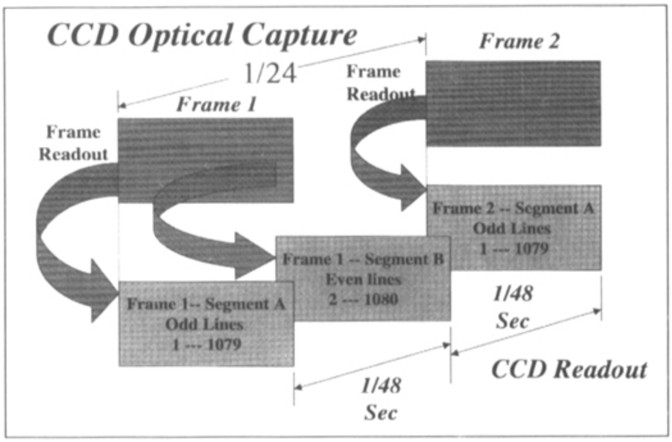

Figure 12. Illustrates the total lack of any temporal-vertical linkage (as in the case of interlaced); thus, the characteristics of the original progressive capture are preserved in this output transport video format.

of that coherent exposure is then accomplished in two steps. The odd lines are sequentially readout to form the first 240-line segment of that frame, followed by the reading out of the even lines 1/60 of a sec later (to form the second 240-line segment of that same frame). No downconversion or filtering process is employed. This readout mechanism thus creates a segmented-frame video structure that is essentially identical to that of the 60i video, but having none of the spatial-temporal characteristics of that interlaced signal. The 30-frame progressive video also has the identical system bandwidth of the 60i video signal.

Conclusion

Progressive scan HDTV is arriving faster than many anticipated. All domestic and international HD standards now have progressive scan formats centrally placed within those standards. The march of the higher resolution 1920 x 1080 progressive digital format is briskly under way. The tremendous boost this year, by the ITU, with their addition of the 24/25/30 frame progressive formats (under the banner of this 1920 x 1080 Common Image Format) has triggered a vigorous thrust by manufacturers to implement HD production and post-production equipment that will be switchable between the three formats and also encompass the traditional 50 and 60-Hz interlaced variants. The stage has been set for a new era in television history—that of new worldwide HD products that can be switched to the picture capture rate of choice as well as addressing the regional needs between the two global camps of 50 and 60 Hz. It is perhaps significant that these will appear in the year 2000.

With such switchable cameras, camcorders, and recorders emerging, it is to be expected that producers will soon learn a new flexibility: shooting certain scenes (stills, and those with relatively modest motion) in 30-frame progressive and then switching the acquisition system to 60 interlace when fast action scenes are encountered. The use of segmented frame video formats will make this dual capture mode virtually transparent to the post-production system. It might be anticipated that overall picture quality should be augmented by this dexterous use of different capture modes.

Progressive scan is, at last, about to make its debut in the real world of HD production. Much will soon be learned of all that was promised by this scanning format, albeit initially at lower picture capture rates. The significant improvement expected in vertical resolution, and the attendant lowering of vertical aliasing artifacts, will add a great deal to overall picture sharpness—although this will probably be more apparent in some pictures than in others. Certainly, it will benefit the transfer of digital progressive HD to motion picture film significantly.

With the definitive arrival of 24P HD, the final convergence between motion picture film and HD video is about to take place. Lingering debate on the differences between tonal reproduction, exposure latitude, and picture sharpness of the two media will invariably continue. Nevertheless, the stunning prowess of contemporary DSP will soon dispel whatever differences might still exist between them. Twelve-bit DSP, in a new generation 24 frame/sec progressive HD camcorder, has already arrived.

This new performance parity between 35mm film and 24P HD is good news for the movie-maker, prime-time television producer, independent film producer, for all will benefit from the new creative flexibility afforded by a choice of media operating on a common 24, 25, or 30-frame platform. Scripts, storyboards, aesthetics, creative aspirations, and, budgets will determine the choice between the two, or, their joint utilization. And, already 60-frame progressive 1920 x 1080 is looming on the horizon as the MPEG-4 Committee rapidly approaches finalization of the "ultra-high" level compression algorithm that will make 4:2:2 profile at such a high resolution and frame rate possible.

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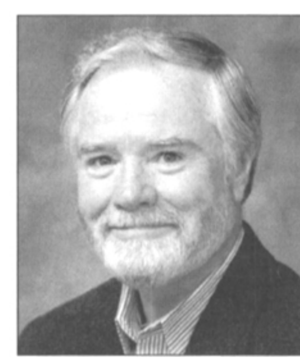

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Thorpe is currently vice-president of acquisition systems for the Broadcast and Professional Co., Sony Electronics Inc., responsibile for all of the broadcast studio and portable cameras (including HDTV) for the Sony Division. In a previous position at Sony Advanced Systems, he represented Sony on ATSC technology groups, as well as various SMPTE working groups involved with high-definition electronic production.

Thorpe is a Fellow of SMPTE. He has published many papers on camera technology and the topic of HDTV imaging. In 1981, he won the David Sarnoff Award for his innovations in automatic studio color cameras.

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