A Multiformat HDTV Camera Head

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This paper describes the development of a compact and configurable HDTV camera system for various studio and in-field applications, including flexible dockable configurations. A novel way to capture native 1080P, 1080I, and 720P at 16:9 aspect ratio and a CinemaScope aspect ratio in 1080P of 2.37:1 is presented. The architecture of the multiformat HDTV camera head is based on a newly designed frame transfer CCD imager, which enables the availability of the HD-SDI (SMPTE 292M) output at the camera head itself. It utilizes three frame transfer CCDs (2/3 in.) with 9.2 Mpixels each (including overscan). Using a 12-phase system, all the vertical resolutions of the SMPTE 274M and SMPTE 296M standards are possible. These pixels are prearranged into image cells at the CCD by Dynamic Pixel Management software. The image diagonal (11 mm) is independent of spatial resolution and therefore the same for all scanning formats.

The electronics industry has always supported the imaging community's search for improved image quality and HDTV standards, starting with the development, in the early 1990s, of an HDTV-FT imager for the European standard[1,2] and the LDK9000 camera system,[3] which was used as a vehicle for many spatiotemporal formats. The next step was the development of an LDK9000-720P camera and FT imager.[4] With regard to dynamic pixel management (DPM) technology[5,6] for FT imagers, the LDK2000[7] at 480P30 (paired field output) and 480I60 was first developed. The temporal spectrum is extended with the LDK23 high-speed camera[8] at 150 Hz and 180 Hz.

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Extensive experience with imagers (FT, DPM) and camera technology was put to the test in the development of the third-generation multiformat HDTV cameras. An enabling technology is needed to merge 1080P, 1080I, and 720P into a single camera head that can switch from one scanning format to another without a loss in image diagonal or viewing angle. A newly developed CCD imager, based on the DPM frame transfer principle, allows scanning of all the imaging formats natively. The fully digital video processing chain consists of three 12-bit A/D converters and two newly developed ASICs that take care of the digital video processing. The 12-bit architectural concept[9] of the SDTV camera was used as a basis for the HDTV camera head design.

Common to all the presently known HDTV spatiotemporal standards is the clock frequency, which is 74.25 MHz, or 74.25 MHz/1.001 (for noninteger frame rates such as 59.94). Key to a multiformat camera head is the HD-SDI output at the multipurpose adapter. Another aspect is the design of a HD-Triax system based on the use of standard Triax cables. The Triax connects to a slim base station with simultaneous HDTV and high-quality SDTV outputs, both in analog and digital formats.

Multiformat FT Imager with 9.2 Mpixels

The design goal for the frame transfer imager was to enable imaging in the 1080P, 1080I, 720P, 480P, and 480I scanning formats, constrained by an aspect ratio of 16:9, without prohibiting other aspect ratios, and to achieve an image diagonal 2/3 in. for all modes. Prime decomposition and the log-prime notation[10] of the above numbers are shown in Table 1.

The minimum number of pixels per column needed to make a switchable imager possible is determined by the least common multiple. This is a mathematical approach to find the smallest positive integer that is a multiple of all elements contained within

Table 1—Prime Decomposition of Vertical Scanning Formats (Resolutions)

Scanning Format	Prime Decomposition	Log-Prime Notation
1080P	$2^3.3^3.5$	[3,3,1,0,0,0]LP6
1080I	$2^2.3^3.5$	[2,3,1,0,0,0]LP6
720P	$2^4.3^2.5$	[4,2,1,0,0,0]LP6
480P	$2^5.3.5$	[5,1,1,0,0,0]LP6
480I	$2^4.3.5$	[4,1,1,0,0,0]LP6

Table 2—Vertical Resolution as a Number of Pixels per Image Cell

Scanning Format	Divisor	Pixels per Image Cell	Combining Super Pixels
1080P	4320/4	4	1 group of 4 pixels
1080I	4320/8	8	2 groups of 4 pixels
720P	4320/6	6	2 groups of 3 pixels
480P	4320/9	9	3 groups of 3 pixels
480I	4320/18	18	3 groups of 6 pixels

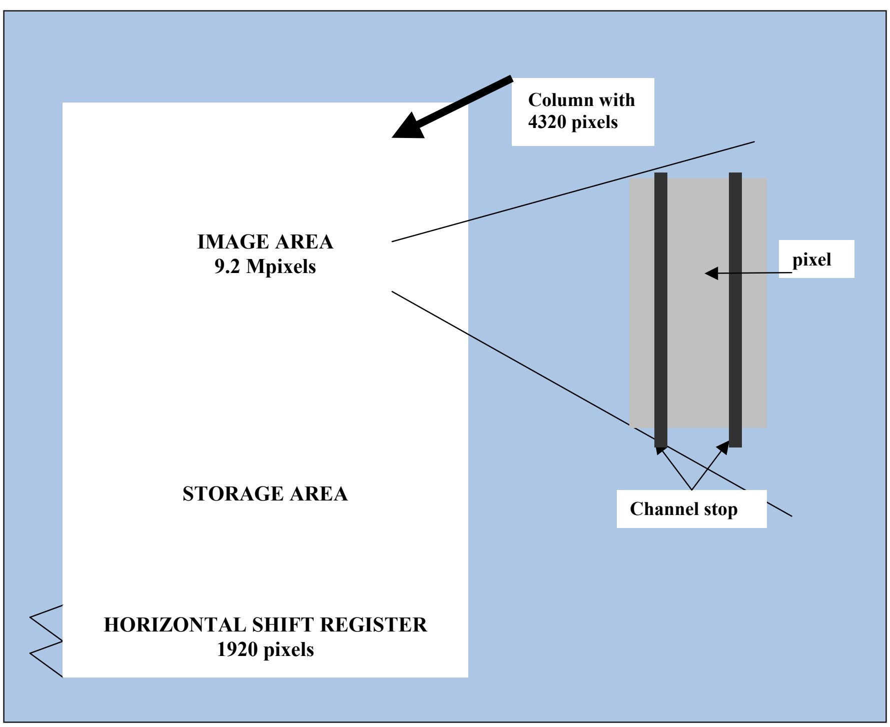

Figure 1. The HD-DPM frame transfer imager.

a set of elements. It is the same as determining the maximum of all individual prime numbers in which the elements in a set are decomposed. Applied to Table 1, the maximum of prime 2 is 2^5, for prime 3 it is 3^3, and for prime 5 it is 5. The least common multiple of the numbers in Table 1 is

$4320 = 2^5.3^3.5$ = [5,3,1,0,0,0]LP6.

An imager designed to handle all the vertical standards in a native scanning format must have 4320 pixels per column; the number of pixels per line is defined at 1920. In practice the number will be larger, since additional active pixels are required for proper generation of the horizontal and vertical contour signal and run-in of the filters. Hence the number of pixels is 9.2 Mpixels. In the 720P mode (1280 x 720), 1920 pixels per line offer a comfortable oversampled signal, having reduced aliasing artifacts and enhanced horizontal resolution.

Next, how to read out/combine this massive number of pixels must be decided. An image cell consists of the combination (summation) of several pixels, and the number depends on the required scanning format, or TV lines. This entails interconnection to the image area. The question is: by going backwards from 4320 pixels per column, how can one realize all scanning formats with minimum interconnection (driving electronics)?

Looking at the prime decomposition of the line numbers (Table 1), the conclusion is that all can be derived by making combinations of three or four pixels. Such a combination of pixels is called a super pixel. The readout mechanism combines the super pixels into image cells, which are equivalent to TV lines.

In other words, a pixel is one discrete light-sensitive element, a super pixel is the combination of a number of pixels, and an image cell is a special kind of super pixel in which the pixels equal one TV line. Therefore, by grouping pixels in numbers of 4 (4320/4), 1080 vertical image cells are generated; by combining them into two groups of four pixels (4320/8), 540 image cells are generated; and by shifting four pixels each field, 1080I is generated. Combining six pixels (4320/6) results in 720P, and three at a time (4320/3) results in 1440P.

With a 12-phase addressing system one could make super pixels of three, four, or six pixels. An image cell is created through the addition of super pixels, as shown in the fourth column of Table 2. The addition of super pixels, the creation of an image cell, is done in the storage area and the horizontal register of the CCD.

The fourth column has been chosen for the implementation. This has to do with the optical filtering properties of such grouped pixels. An optical FIR filter forms in which the points of zero MTF are exactly located at the vertical frame and/or vertical field sample frequency (see the section on optical filtering).

In Fig. 1 the FT imager is depicted with its image area, its storage area, and the horizontal shift register. A detailed description of the operation of CCD imagers can be found in Ref. 11. The focus of this paper is the derivation of the several native scanning formats on a pixel level. One pixel is the smallest fixed light-sensitive element. In an FT imager this equals one gate, and in an IT/FIT imager this equals one photo diode. In an FT imager the number of pixels an image cell can contain is defined by the voltages applied to the image area and/or the manner in which the super pixels are combined in storage or in the horizontal-shift register. As such, the number of image cells is the number of TV lines.

In Fig. 1, a portion of one column is enlarged to show a number of pixels in a column. The channel stoppers define a pixel horizontally and are formed by a shallow p^{++} implant. The imager has two output registers as a result of variations in speed. In 1080I mode the net pixel output frequency is 74.25 MHz, and at 720P the output frequency is 111.375 MHz. With the double register these reduce to 37.175 MHz and 55.69 MHz, respectively.

Figures 2 and 3 depict the driving of the image area. By applying appropriate driving voltages through the 12-phase interconnect, super pixels can be made of three, four, and six pixels. Super pixels that are smaller than the image cells are combined at the storage/image transfer region or in the storage/horizontal-shift register region.

All the spatiotemporal formats previously outlined are possible with an imager as described above.

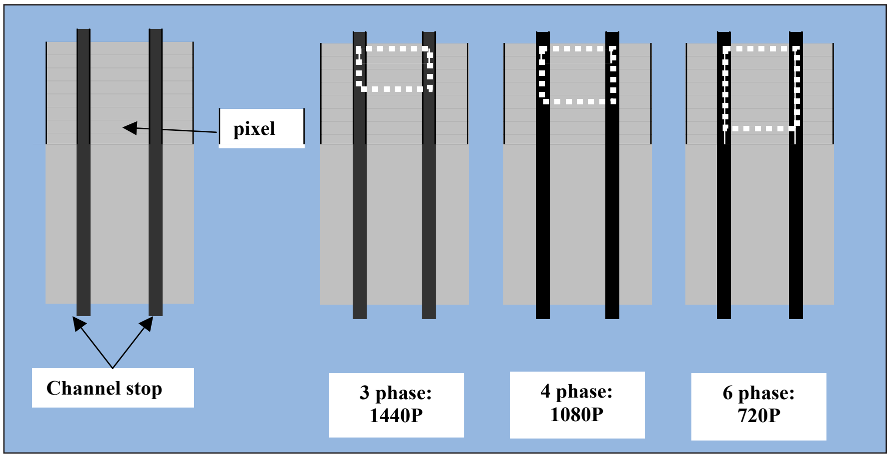

Figure 2. The combination of pixels to arrive at the scanning formats. This image cell is depicted by the white dotted line, the super pixel by the white solid line, and the pixel by the gray bar.

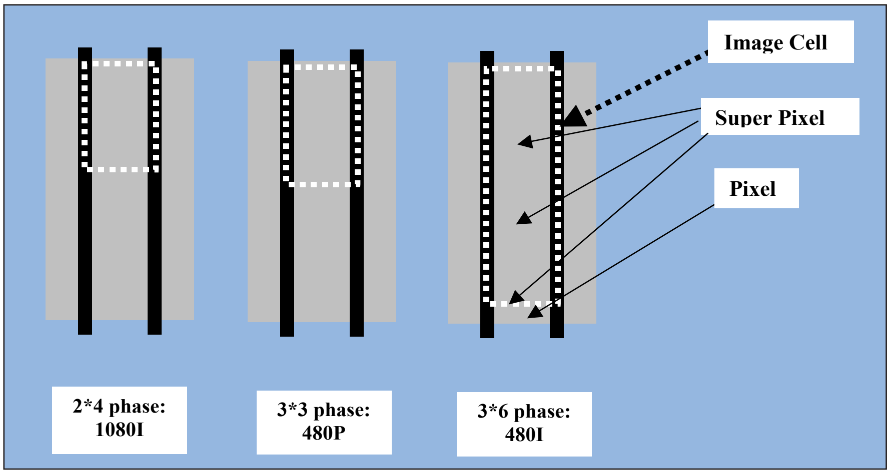

Figure 3. The combination of pixels to arrive at the scanning formats. The pixel (gray bar). Super pixel (white solid line), and image cell (white dotted line) definitions are shown for the 4801 image cell, which is made up of a total of 18 pixels arranged in 3 super pixels of 6 pixels each.

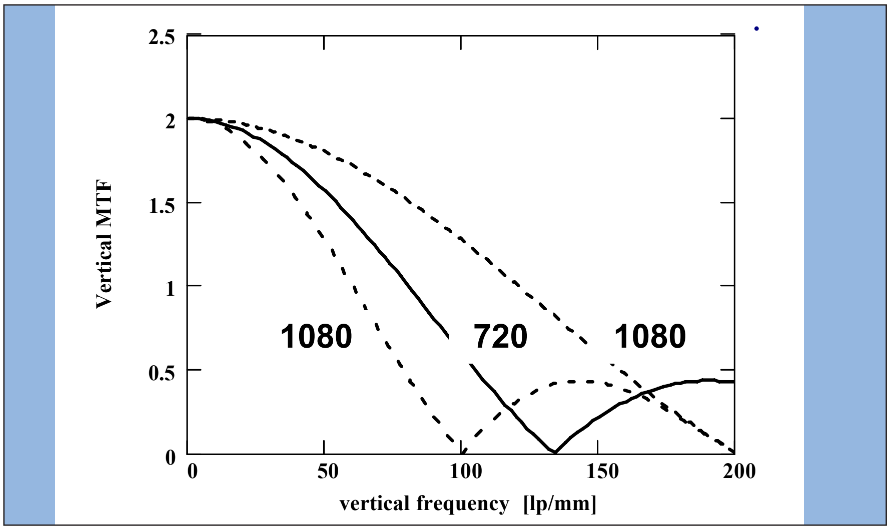

Figure 4. Vertical shaping of the MTF, using HD-DPM, to obtain anti-aliasing properties matched to the scanning format. The optical transfer function is shown for the 1080I mode (solid line), 1080P, and 720P (dashed line).

Table 3—Spatial Frequencies at which the MTF = 0 through the Use of DPM FIR Filtering as a Function of the Chosen Vertical Scanning Format

Scanning Format	Optically Zero Transfer	Zero Transfer Frequency (lp/mm)	Zero Transfer Frequency (cpph)
1080P	F_{frame}	200 lp/mm	1080 cpph
1080I	F_{field} F_{frame}	100 lp/mm, 200 lp/mm	540 cpph, 1080 cpph
720P	F_{frame}	133 lp/mm	720 cpph
480P	F_{frame}	88.8 lp/mm	480 cpph
480I	F_{field} F_{frame}	44.4 lp/mm, 88.8 lp/mm	240 cpph, 480 cpph

Table 4—ASIC Parameters

Parameter	ASIC B	ASIC A
Process	0.35 µm	0.35 µm
Gate count	185455	425000
Die size	59 mm^2	74 mm^2
RAMs	540 kbit (delay lines + control)	132 kbit
Input word length	12 bit	14 bit
Internal representation	20 bit	20 bit
Package	QFP160	QFP208

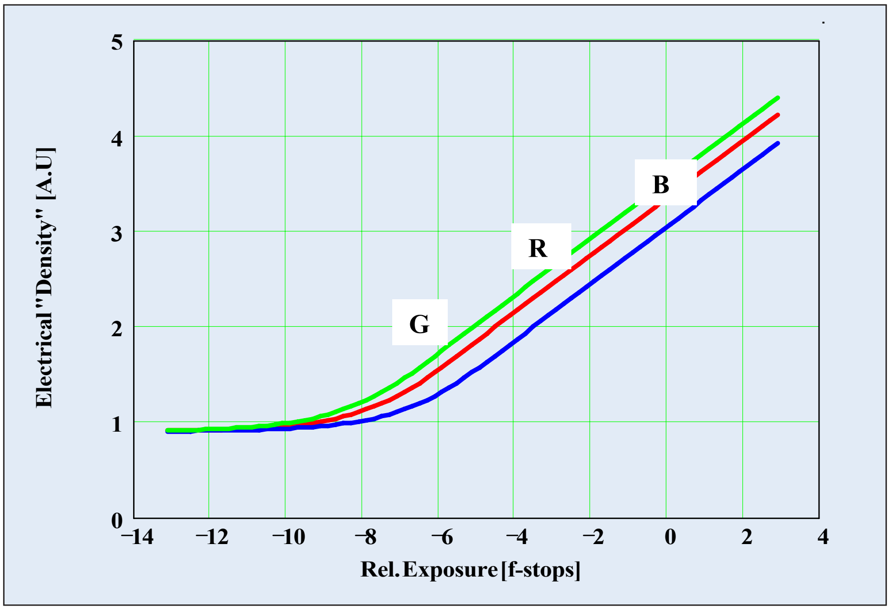

Figure 5. The estimated sensitometric response of the imager in 1080P, at 3200K, for R, G, and B.

Optical Filtering

Optical filtering is needed for proper aliasing behavior. Scene frequencies near the sample frequency are most visible since they fold back as low frequencies; the human eye is more sensitive to low-frequency patterns than to high-frequency patterns. All video cameras are equipped with an optical low-pass (OLP) filter. This OLP has zero transfer (MTF = 0) at the optical sampling frequency. As a result, the aliasing is adequately suppressed. In a camera equipped with FT imagers, only a horizontal OLP is required; vertically, DPM[6] is used as an optical FIR filter. Because pixels have the same horizontal width in all formats (5 µm) the OLP only has to be zero (MTF = 0) at 200 lp/mm. Vertically, the optical filter must be MTF = 0 at the optical sample frequency, which is known as vertical field and vertical frame sample frequency.

In the case of the multiformat imager, the vertical field and vertical frame sample frequency (lp/mm) change. This also applies to the optical transfer function. The point spread function that determines the optical transfer function can be shaped using DPM. Its effect can be viewed as an FIR filter with taps at one-quarter of the image cell height at 1080P, one-eighth at 1080I, one-sixth at 720P, one-ninth at 480P, and one-eighteenth at 480I. The filtering properties needed for proper aliasing behavior are shaped through the use of super pixels (Table 2) and the addition of the FIR filter.

The simplest optical FIR filter, also widely used in IT and FIT, is the addition of two pixels to create an image cell. Assuming an aperture for the pixel of 100%, the response of one pixel will be:

$$\mathrm{pixel}(f_y) := \left|\mathrm{sinc}\left(\frac{f_y}{F_{frame}}\right)\right|$$

Adding two contiguous pixels together results in

$$\mathrm{ImageCell}(f_y) := 2\left|\mathrm{sinc}\left(\frac{f_y}{F_{frame}}\right)\right| \cdot \left|\cos\left(\frac{\pi}{2}\cdot\frac{f_y}{F_{field}}\right)\right|$$

which reduces to the well-known

$$\mathrm{ImageCell}(f_y) := 2\left|\mathrm{sinc}\left(\frac{f_y}{F_{field}}\right)\right|$$

This filter has zero optical transfer at the vertical field, and the vertical frame is two times the vertical field sample frequency, which reduces aliasing most effectively (Fig. 4).

Super pixels function optically the same as one pixel. If super pixels are used, the optical filtering is always optimally suited for the chosen scanning format (Table 3).

Digital Video Processing

The design of digital video processing follows the ideas outlined in Ref. 9. Processing consists of signal preconditioning for three 12-bit AD converters and two custom-designed ASICs for HDTV video processing. A number of video processing functions are embedded, as outlined in the following lists and Table 4.

ASIC A
- Black level clamp/black level control
- Gain switch/gain control
- Knee
- Matrix
- Gamma
- Flare correction
- White shading

ASIC B
- Leaking pixel correction
- Video noise reducer (optional)
- Contour processing
- Black stretch
- Black and white limiters
- Viewfinder signal generation
- Viewfinder contours and zebra processing
- Test signal generator
- 20-bit parallel output, formatted according to SMPTE 292M

Dockable Camera Concept

The Philips LDK6000 is a dockable HDTV camera head with a specially designed wideband Triax and multipurpose HDTV adapters.

Multipurpose Adapter

The multipurpose adapter is a small dockable unit mainly intended to allow standalone operation of the camera with HD-SDI output/ 1080P/720P). In standalone mode, the camera can be controlled by a local control panel, a PC through RS-232 interface, or a VF menu accessed by the camera rotary control.

Triax Transmission

Because there is a large installed base of Triax cable, a wideband Triax adapter with full studio/EFP functionality has been included in the camera system. Based on experience with the high-speed camera,[8] the analog HD-Triax system was developed with 30-MHz bandwidth for luminance and 15 MHz for both color difference signals Cr and Cb. The transmission between camera and base station covers power, FM channels (audio, intercom, data, HV lock), and the VF return channel. In the HDTV-Triax system, video transmission from camera to base station is achieved by swapping component signals with carriers to enhance bandwidth and cable length (Table 5). The maximum cable length for full specification of video signals is designed to be 1000 m. A teleprompter channel with 5-MHz bandwidth is implemented at a carrier frequency of 135 MHz for use at limited cable lengths (< 200 m).

Base Station

The camera with a wideband analog adapter can be connected to a new modular HDTV base station. Inside the base station a high-quality downconverter is implemented to provide standard NTSC or PAL output signals. In case of interlaced acquisition (1080I) a high-performance deinterlacer will be part of the downconversion.

Digital Cinematography with the Multiformat HDTV Camera

The nominal operating point of a video camera is usually referenced as 0 dB. With respect to this setting, the gain of the camera can vary between e.a. -6 dB (*f*-1) and e.a. 18 dB (*f*+3). Increasing the gain gives the captured image a more "grainy" appearance; however, less exposure is required for an equal output level. Therefore, the gain switch of the camera allows artistic freedom.

Sensitometric Curves

The interpretation of the speed of a video camera depends on whether one sees it as a film-positive or a film-negative type. The film-positive approach requires measurement of the exposure needed for midtone.[12] The film-negative approach is signal-to-noise based,[13,14] or saturation based.[13] In the film-positive interpretation, the speed and graininess of a video camera's output depend on the gain; the film-negative approach results in a range of speeds.

It would be ideal to describe the sensitometric response of an imager/camera as closely to the film

Table 5-Bandwidths of the Analog HDTV-Triax

Channel	Bandwidth
Return video	5 MHz
Luminance (Y)	30 MHz
Color difference (Cr/Cb)	15 MHz

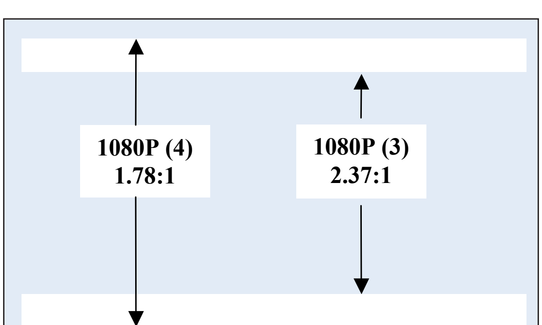

Figure 6. Super wide screen in 1080P generated with three pixels per image cell and normal wide screen with four pixels per image cell.

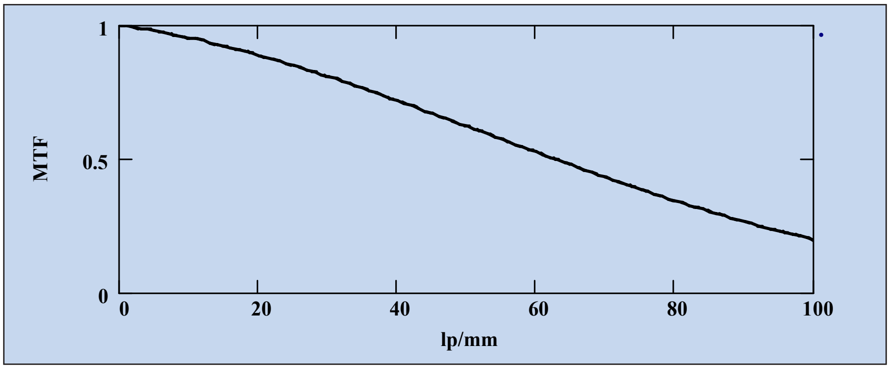

Figure 7. Horizontal MTF for two aspect ratios, 1.78:1 and 2.34:1, as a function of lp/mm for a 1080P camera.

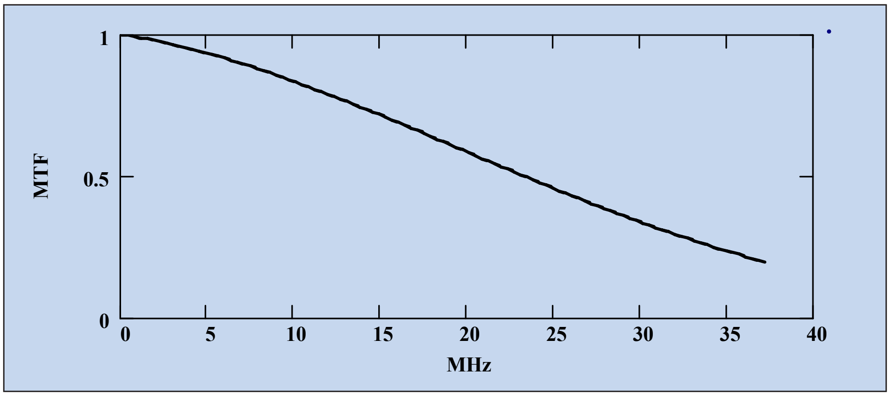

Figure 8. Horizontal MTF for two aspect ratios, 1.78:1 and 2.34:1, as a function of MHz for a 1080P camera.

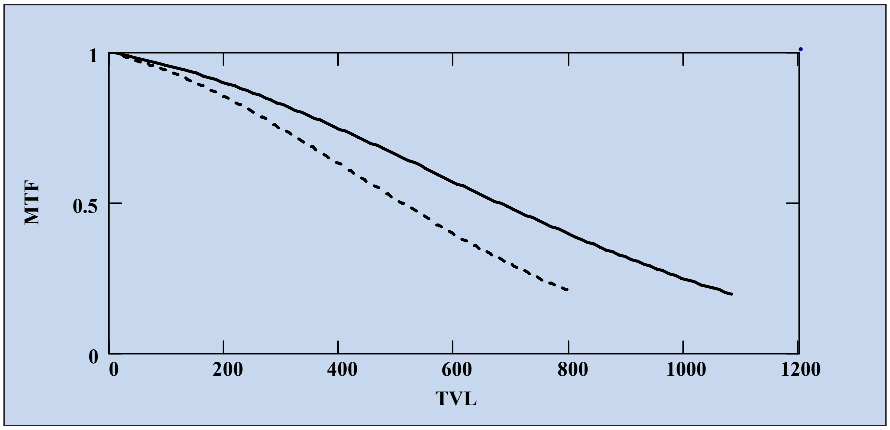

Figure 9. Horizontal MTF for two aspect ratios, 1.78:1 (solid line) and 2.34:1 (dotted line), as a function of the vertical metric TVL for a 1080P camera.

as possible. Although the output signal of an imager/camera is positive, its response, such as gamma (0.45) and latitude (shown in Fig. 5), is closer to film negative. In view of this, the curve in Fig. 5 is incorrect on a pure density basis; however, the curve does correctly represent performance. To determine density, a parameter that resembles it, referred to as electrical "density," is estimated by determining the average output as a function of exposure. This parameter describes the whole range in which the imager can be used.

Super Wide Aspect Ratio

The imager and its camera are principally designed for the 16:9 broadcast video aspect ratio. With the DPM principle some other aspect ratios are possible. The image area of the HD-DPM CCD can be put in a 1440P imaging mode (Fig. 2), which results in a surplus of scanning lines. One option is to use only 1080P lines of a possible 1440P through the application of a DPM cut. The effect is a super wide aspect ratio (Fig. 6).

In the 1440P imaging mode the height of the image cell is 3 pixels (3 x 1.25 μm = 3.75 μm), and its width is 5 μm. The total width of the 1920 horizontal image cells is 9.6 mm (1920 x 5 μm), and the total height of the 1080 image cells is 4.05 mm (1080 x 3.75 μm). Therefore, the aspect ratio is 2.37:1 (9.6/4.05).

Resolution: Modulation Transfer Function and Aliasing

Among other functions, the sampling aperture of the image cell determines the MTF. The repetition grid of the image cells determines the aliasing. The amount of maximum frequency that can be resolved depends on both the MTF and aliasing.

Discussion on how to present sharpness information as offered in Ref. 15 requires elaboration. Regardless of the criteria used, the more pixels per line, the better the horizontal MTF. Of course, there is a metric for expressing horizontal MTF that shows the reverse, such as using television lines (TVL) for different aspect ratios. However, this only demonstrates that the horizontal MTF should not be expressed in a vertical metric. This expressly applies to a multiaspect ratio environment. In putting this theory to practice, a line imager, by definition, has a height of 1 TVL. Assuming that the line imager has 5000 pixels/line, when using a vertical metric the horizontal resolution is 1 TVL. For example, in Figs. 7, 8, and 9, the horizontal MTF is depicted in lp/mm, MHz, and TVL for an aspect ratio of 16:9 and a super wide aspect ratio of 2.34:1. The figures require no explanation.

Conclusion

A novel way for capturing native 1080P, 1080I, and 720P at 16:9 aspect ratio and for 1080P a CinemaScope aspect ratio of 2.37:1 is described. The successful development and design considerations that led to the Philips multiformat HDTV camera are reported.

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Peter Centen holds B.S and M.S degrees and a Ph.D. in electrical engineering from Eindhoven University of Technology, The Netherlands.

As a researcher at Philips Research Laboratories, he worked on optimal signal processing for CCD-imagers, noise reduction of CCD-imager output circuitry, and its high-speed operation. Implementation of this work resulted in the LDK-HS series. For many years he has been involved in the development of HDTV cameras and switchable SDTV cameras at the R&D department of Thomson multimedia Broadcast Solutions, formerly known as Philips DVS. At present he is a group leader in the camera R&D department of Thomson, responsible for the implementation of CCDs in professional video cameras and the front-end design of the multiformat HDTV camera head.

As a co-inventor, Centen holds patents for Dynamic Pixel Management (DPM) and HD-DPM, and is founder of the optical filtering method using DPM. He is a member of the IEEE and has published numerous journal and conference articles.

Ton Moelands is senior system architect and leader of the camera system group of the Camera R&D department of Thomson multimedia Broadcast Solutions in Breda, the Netherlands.

In 1980 he joined the R&D department of professional broadcast cameras and is the architect of camera systems for both standard TV and HDTV. Currently he is involved in the definition, design, and implementation of all different HDTV formats worldwide.

Jan van Rooy is technology officer at the camera group of Thomson multimedia Broadcast Solutions in Breda, The Netherlands. His design experience includes the videoprocessing architecture of the LDK9000 HDTV camera, the LDK23 high-speed camera, and digital signal processing ASICs. Currently, he is involved in the development of new technologies in several European projects.

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Mike Stekelenburg began working at Philips Research Laboratories in The Netherlands, in the area of CCD image. After completing his education in electrical engineering he became a project leader for the FT-SR (single register) imager that lead to the LDK-SR series. Later, he was head of R&D cameras, sourcing, and product management. He is now general manager for Thomson multimedia's broadcast cameras business.

Stekelenburg holds many patents in the field of CCD imagers and cameras and invented the super wide screen mode for the LDK7000. His interests include digital cinematography and related fields.