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A Multi-Format HDTV Camera Head



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Abstract

A novel way for capturing native 1080P, 1080I and 720P at 16:9 aspect ratio and a CineScope aspect ratio in 1080P of 2.37:1 will be presented. The architecture of the multi-format HDTV camera head is based on a newly designed Frame Transfer CCD-imager. It enables the design of a camera head that has multiple formats available at the HD-SDI (SMPTE 292M) output of the camera head itself.

The camera head utilizes three Frame Transfer (2/3 inch) CCDs with 9.2 Mpixels each (including overscan). Through the use of a 12-phase system all the vertical resolutions of the SMPTE 274M and SMPTE 296M standards are possible. Under software control (Dynamic Pixel Management™) these pixels are pre-arranged, at the CCD, into image cells. The image diagonal (11 mm) is independent of spatial resolution and therefore the same for all scanning formats.

The video processing chain consists of three 12-bit ADCs followed by two newly designed ASICs that allow multi-format video processing. Amongst many other outputs, the ASICs have an SMPTE 292M-compatible 20-bit parallel output can be serialized to obtain a HD-SDI output at the camera head. The above video chain offers full digital processing capability.

A dockable concept is exploited in full to enable:

- *A multi-purpose adapter for "stand-alone" operation with battery power input, genlock input and HD-SDI output (1.5 Gb/s)*
- *A wide-band analog Triax adapter (Y = 30 MHz, Cr, Cb = 15 MHz) for transmission up to 3000 ft. of cable.*
- *Future adapters to offer the possibility of optical fiber transmission with longer cable lengths or a (DVCPRO HD) camcorder*

Authors


Peter Centen


Ton Moelands


Jan van Rooy


Mike Stekelenburg

1.0 Introduction

Thomson 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 spatio-temporal formats: 1152I50, 1080I60, 1035I60, 970I60, 576P50, 480P60, and 480P30. The next step was the development of an LDK9000-720P camera and FT imager [4]. The first version was a 60 Hz one, soon to be extended to 72 Hz and 24 Hz.

Starting with the Dynamic Pixel Management (DPM) technology [5,6] for FT imagers the LDK2000 [7] at 480P30[1] and 480I60 was developed. The temporal spectrum is extended with the LDK23 high-speed camera [8] at 150 Hz and 180 Hz.

Extensive experience in imagers (FT, DPM) and camera technology was put to a test in the development of the third generation multi-format 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 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 spatio-temporal standards is the clock frequency, which is 74.25 MHz or 74.25 MHz/1.001 (for non-integer frame rates like 59.94). Key to a multi-format camera head is the HD-SDI output at the multi-purpose adapter. Another aspect is the design of an HD-Triax system based on the use of standard Triax cables. The Triax connects to a newly designed slim base station with simultaneous HDTV and high-quality SDTV outputs, both in analog and digital format.

In summary this paper describes the development of a compact and configurable HDTV camera system to allow for various studio and in-field applications, including flexible dockable configurations.

1.1 The Multi-format 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" for all modes. Prime decomposition and the log-prime notation [10] of the above numbers are show in Table 1:

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 1: Prime decomposition of vertical scanning formats (resolutions).

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 a set of elements. It is the same as taking 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 is 3^3, and for prime 5 it is 5. The least common multiple of the numbers of Table 1 is $4320 = 2^5.3^3.5$ = [5,3,1,0,0,0]LP6.

An imager designed to handle all the above 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 (1280x720) the 1920 pixels per line offer a comfortable oversampled signal with 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 3, 4 or 6 pixels. An image cell is created through the addition of super pixels, shown in the fourth column of Table 2. The addition of the super pixels, to create an "image cell," is done in the storage area and the horizontal register of the CCD.

Scanning Format	Divisor	Pixels per image cell[2]	Combining super pixels[2]
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

Table 2: The vertical resolution as a number of pixels per image cell.

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 Section 1.2).

[1] *Paired Field Output.*

[2] *A pixel is one discrete light-sensitive element, a super pixel is a sum of a number of pixels, and an image cell is a special kind of super pixel of which the pixels contained equals one TV-line.*

In Figure 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 [11]. The focus of this paper is on 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 image area and/or the manner in which the super pixels are combined together in storage or horizontal-shift register. Defined in this way, the number of image cells is the number of TV-lines.

In Figure 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 it is 111.375 MHz. With the double register these reduce to 37.175 MHz and 55.69 MHz, respectively.

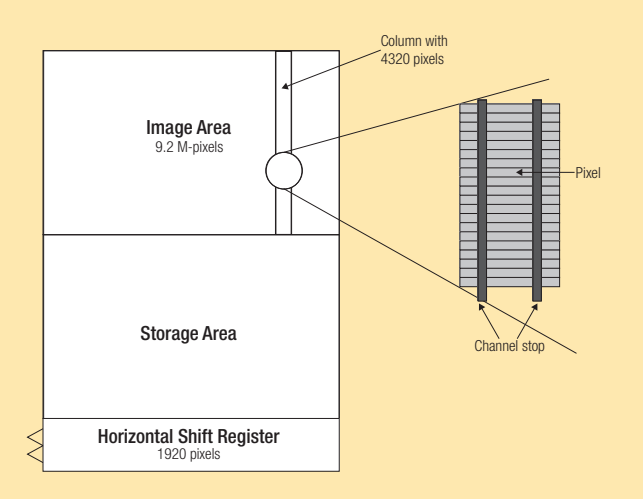


Figure 1: The HD DPM frame transfer imager.

Figures 2a and 2b depict the driving of the image area. By applying appropriate driving voltages through the 12-phase interconnect, super pixels can be made of 3, 4, and 6 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.

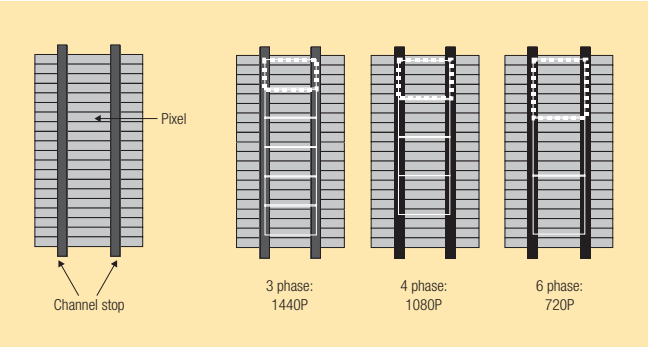


Figure 2a: The combination of pixels to arrive at the scanning formats. The image cell is depicted with the white dotted line, the super pixel with the white solid line and the pixel with the small gray bar.

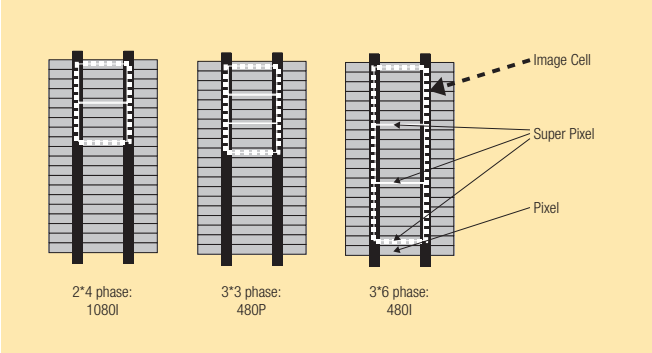


Figure 2b: The combination of pixels to arrive at the scanning formats. Also the pixel (gray bar), super pixel (white solid line) and image cell (white dotted line) definitions are depicted for the 480I image cell, which is made up of 18 pixels in total, arranged in 3 super pixels of 6 pixels each.

All the spatio-temporal formats previously outlined are possible with an imager as described above. This imager is implemented in the recently introduced Philips LDK6000 HDTV camera system.

1.2 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 filter 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 the formats (5 µm) the OLP only has to have a zero MTF=0 at 200 lp/mm. Vertically, the optical filter must have MTF=0 at the optical sample frequency, which is known as vertical field and vertical frame sample frequency.

In the case of the multi-format imager the vertical field and vertical frame sample frequency (lp/mm) change. This also applies to the optical transfer function. The point spread function determining the optical transfer function can be shaped using DPM. Its effect can be viewed as an FIR filter with taps at 1/4 of the image cell height at 1080P, 1/8 at 1080I, 1/6 at 720P, 1/9 at 480P, and 1/18 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:

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

Adding two contiguous pixels together results in

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

Which reduces to the well-known

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

This filter has zero optical transfer at the vertical field and at the vertical frame is two times the vertical field sample frequency, which reduces aliasing most effectively (see Figure 3).

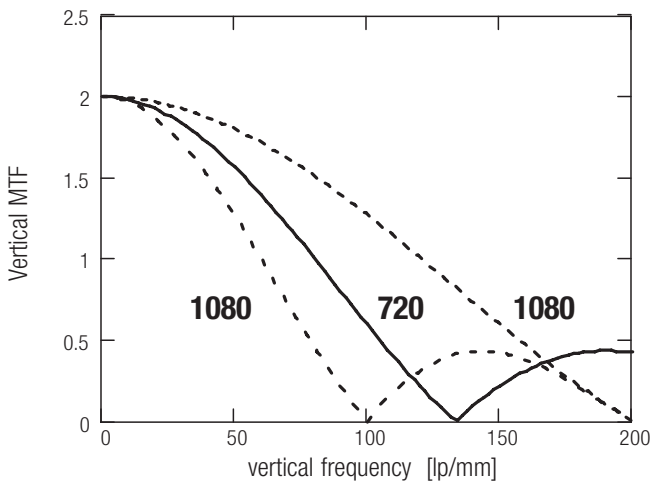


Figure 3: Vertical shaping of the optical transfer function to obtain an optical low pass filter. The horizontal axis is relative to the frame sampling frequency. The vertical transfer function is depicted for the 1080I mode (solid), and 1080P and 720P modes (dashed).

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 (see Table 3).

Scanning Format	Optically zero transfer at	Zero transfer frequency	Zero transfer frequency
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 3: The spatial frequencies at which the MTF=0 through the use of DPM FIR filtering as a function of the chosen vertical scanning format.

2.0 Digital Video Processing

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

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*
- *A 20-bit parallel output, formatted according SMPTE 292M*

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

Table 4: ASIC parameters.

3.0 The Dockable Camera Concept

The LDK6000 is a dockable HDTV camera head, with a magnesium diecast housing, for broadcast studio and EFP applications.

The camera is dockable with a number of special designed HDTV adapters:

- *Wide-band Triax adapter*
- *Multi-purpose adapter*

In the near future following adapters will complete this range:

- *Long distance fiber optic adapter*
- *HD recorder adapter*

The camera will be applicable together with the existing SuperXpander (Large Lens Adapter) to carry box type studio lenses and a 7-inch HDTV viewfinder.

The camera head consists of following major sub-assemblies:

- *The camera front with three 2/3 inch HDTV Frame Transfer CCDs and Pulse Pattern Generator PC-board*
- *An optical shutter to cover the image part of the sensor during vertical transport*
- *Two 4-position filterwheels with ND and effect filters*
- *Full digital video processing with 12-bit A to D conversion and specially designed video processing ASICs*
- *A 160-pin docking connector to the adapter containing parallel digital Y/C (2x10-bits) video according to the SMPTE 274M/296M standards*

Dimensions: camera head with Triax adapter (l x w x h): 349 (260) x 117 x 197 mm

Weight: camera head with Triax adapter: 5.0 kg (4.4 kg)

(Values in parentheses apply to the multi-purpose version of the camera)

3.1 Multi-purpose Adapter

The multi-purpose adapter is a small dockable unit mainly intended to allow stand-alone operation of the camera with HD SDI output at the camera.

The following BNC output signals are available on the multi-purpose adapter:

- *HDTV SDI output (1.5 Gb/s) with switchable video formats (1080I/1080P/720P)*
- *VF output (HDTV)*
- *Down-converted CVBS viewing output (NTSC)*
- *HDTV Genlock reference input*

In this stand-alone mode, the camera can be controlled by a Local Control Panel (LCP 100), a PC through RS-232 interface or a VF-menu accessible by the camera rotary control.

3.2 Triax Transmission

Since there is a large installed base of Triax cable, the worldwide standard for camera signal transmission, a wide-band Triax adapter with full studio/EFP functionality has been included in the LDK6000 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.

All presently available Triax connectors will remain optional for the HDTV Triax adapter. 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.

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

Table 5: Carrier frequencies and bandwidths of the analog HDTV-Triax.

The maximum cable length for full specification of video signals is designed to be 1000 meters.

A teleprompter channel with 5 MHz bandwidth will be implemented at a carrier frequency of 135 MHz for use at limited cable lengths (< 200 meters).

3.3 Base Station

The LDK6000 HDTV camera with wide-band analog Triax adapter can be connected to a new modular HDTV base station. This 19" rack-mounted base station is only 2 units high (2 HE) and therefore very well suited for OB-van applications.

Following functionality is implemented in this HDTV base station:

- *Camera power supply*
- *Triax transmission interconnection*
- *Audio/intercom*
- *Signaling and data*
- *Video inputs/outputs*
- *SDTV output (high-end scaler)*
- *Video monitoring*

Inside the base station a high-quality down-converter is implemented to provide standard NTSC or PAL output signals. In case of interlaced acquisition (1080I) a high performance de-interlacer will be part of the down-conversion.

Video outputs available at the base station:

- *HDTV main output: 3x SDI (1.5 Gb/s)*
- *Analog HDTV outputs on VGA type connector (RGBHV on 15-pole D-connector)*
- *Main SDTV output: 3x SDI (270 Mb/s)*
- *Analog SDTV outputs switchable RGB/YCrCb/CVBS*
- *NTSC viewing output*

The SDTV outputs are standard in 4:3 aspect ratio and will be switchable between 4:3 and 16:9.

Luminance coding will be according to the “709 standard” for HDTV and according to the “601 standard” for SDTV video signals.

4.0 Digital Cinematography with the Multi-Format 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 be varied between e.a -6 dB (-1 f-stop) up to e.a. 18 dB (+3 f-stop). 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 for artistic freedom.

4.1 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 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 as possible. Although the output signal of an imager/camera is positive, its response, such as gamma (0.45) and latitude (see Figure 4), is closer to film negative. In view of this, the curve in Figure 4 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.

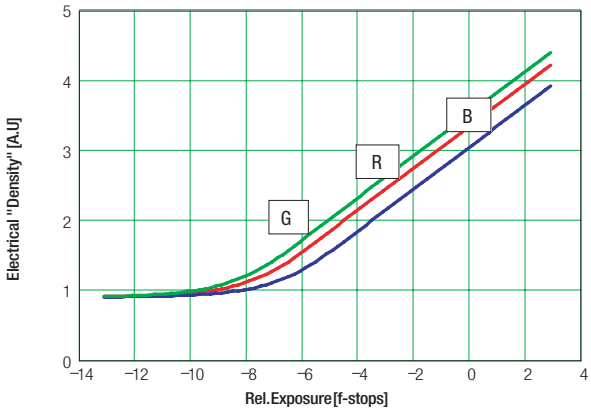


Figure 4: The estimated sensitometric response of the imagers in 1080P, at 3200K, for R, G, and B.

4.2 Super Wide Aspect Ratio

The imager and its camera are principally designed for the 16:9 broadcast video aspect ratio. With the DPM principle [5,6] some other aspect ratios are possible. The image area of the HD-DPM CCD can be put in a 1440P imaging mode (Figure 2a), 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.

In the 1440P imaging mode an image cell is 3 pixels high. Its height is 3x1.25 µm = 3.75 µm. The width of the image cell is 5 µm. The total width of the 1920 horizontal image cells is: 1920*5 µm= 9.6 mm and the total height of the 1080 image cells: 1080*3.75 µm = 4.05 mm. Therefore, the aspect ratio is 2.37:1 (9.6/4.05).

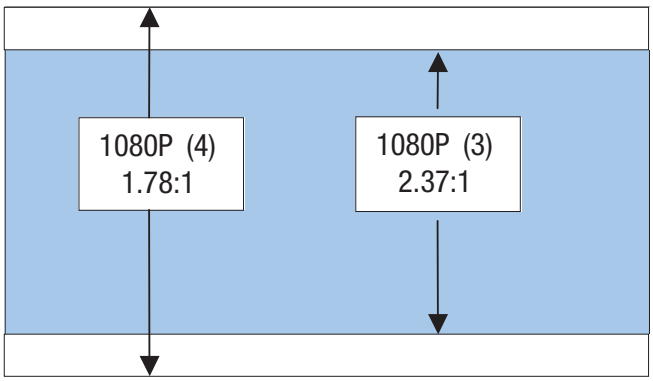


Figure 5: Super wide screen in 1080P generated with 3 pixels per image cell and the normal wide screen with 4 pixels per image cell.

4.3 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 [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 multi-aspect 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 Figures 6a, 6b, and 6c, 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.

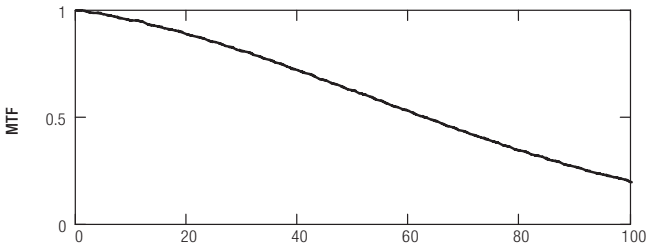


Figure 6a: Horizontal MTF for two aspect ratios, 1.78:1 and 2.34:1 as a function of lp/mm for a 1080P camera.

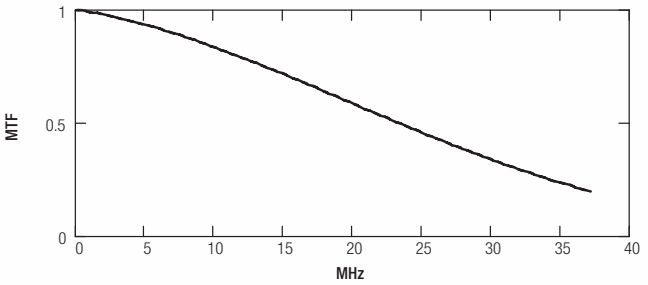


Figure 6b: Horizontal MTF for two aspect ratios, 1.78:1 and 2.34:1 as a function of MHz for a 1080P camera.

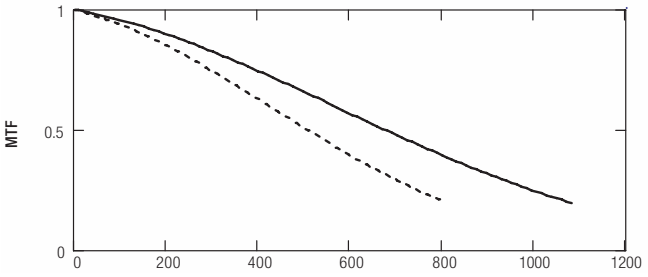


Figure 6c: Horizontal MTF for two aspect ratios, 1.78:1 (solid line) and 2.34:1 (dashed line) as a function of (the vertical metric) TVL for a 1080P camera.

5.0 Conclusion

A novel way for capturing native 1080P, 1080I, and 720P at 16:9 aspect ratio and for 1080P a CineScope aspect ratio of 2.37:1 is described. The successful development and design considerations that led to the LDK6000 multi-format HDTV camera are reported. The camera was first demonstrated at the NAB 2000 exhibition.

6.0 Acknowledgements

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Thomson Worldwide Headquarters
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95801 Cergy Pontoise Cedex
FRANCE

Cameras
Kapittelweg 10
4827 HG Breda
P.O. Box 90159
4800 RP Breda
The Netherlands

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Sales and Technical Support Numbers

North America
Sales/Support +1 800 547 8949
Fax +1 530 478 3347

Pacific
Sales +852 2531 3000
Support +852 2531 3056
Fax +852 2802 2996

Latin America
Sales +1 305 477 5488
Support +1 305 629 1107
Fax +1 305 477 5385

Rest of the World
Sales +33 (0) 1 34 20 70 00
Support +33 (0) 1 34 20 73 60
Fax +33 (0) 1 34 20 70 46

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