HD-DPM IMAGERS KEY TO A MULTI-FORMAT HDTV CAMERA

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ABSTRACT

A novel way for capturing native 1080P, 1080I and 720P at 16:9 aspect ratio and a near CineScope aspect ratio in 1080P of 2.37:1 will be presented. It is based on a newly developed 2/3” HD-DPM Imager with 9.2 Mpixels (including overscan). The image diagonal (11-mm) is independent of spatial resolution and therefore the same for all scanning formats. In this paper a comparison between CCD-Imagers and Film from an image capture point of view is given.

The HD-DPM Imager enables the design of a 3-CCD camera that has multiple scanning formats available at the HD-SDI (SMPTE 292M) output of the camera head itself. Combinations of temporal speeds in the range of 60Hz, 50Hz, 30Hz, 25Hz and 24Hz are possible.

The video processing chain consists of three 12-bit ADCs followed by two newly designed ASICs that allow multi-format HDTV video processing.

A dockable concept is exploited in full in the design of a multi-purpose adapter for ‘stand alone’ operation with battery power input, gen-lock input and HD-SDI output (1.5 Gbps) and a wide band analogue TRIAX adapter (Y = 30 MHz, Cr/Cb = 15 MHz) for transmission up to 3000 ft of cable.

INTRODUCTION

In the field of HDTV the professional camera division of Philips Digital Video Systems has always supported the imaging community’s search for an improved image quality and definition of HDTV standards. In the early 90’s a CCD-Imager was developed for the European HDTV standard, Theuwissen et al [1], and used in the LDK9000 camera system, Blankevoort et al [2]. This camera was used as a vehicle for many spatio-temporal formats: 1152I50, 1080I60, 1035I60, 970I60, 576P50, 480P60, 480P30. Next was the development of an LDK9000-720P60 camera and CCD-Imager, Spitzer et al [3]. The latter was extended up to 72 Hz and down to 24 Hz for the cinematography community.

With the Dynamic Pixel Management technology (DPM), Centen et al [4,5], for Frame Transfer CCD-Imagers as a platform the LDK2000 at 480P30 and 480I60 was developed, van Rooy [6]. The temporal spectrum is extended with the LDK23 highspeed camera, Moelands and Centen and Voet [7], at 150 Hz and 180 Hz.

An enabling technology

The massive experience in imagers (FT, DPM) and camera technology was put to a test in the development of the third generation multi-format HDTV camera. An enabling technology was needed to merge 1080P, 1080I and 720P into one camera head that can be switched from one scanning format to the other without loss in image diagonal or viewing angle. This is found in the newly developed HDTV Frame Transfer CCD-Imager based on the Dynamic Pixel Management principle: HD-DPM. Such an imager allows scanning of all the imaging formats natively, including 480P and 480I. 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, van Rooy and Voet [8], of the SDTV camera was used as a basis for the HDTV camera head design.

Common to all the present known HDTV spatial/temporal standards is the clock frequency, which is 74.25 MHz or 74.25 MHz/1.001 (for noninteger frame rates like 59.94). This is also key to a multi-format camera head: the HD-SDI output at the Multi-purpose adapter. Another aspect is the design of a HD-TRIAX system based on the use of standard Triax cables. The Triax connects to a newly designed slim basestation with simultaneous HDTV and high quality SDTV outputs both in analogue and digital format.

In summary this paper describes the design considerations and operation of the HD-DPM Imager including some cinematography items. It reports about the related development of a compact and configurable HDTV camera system to allow for various studio and in-field applications.

HD-DPM IMAGER WITH 9.2 MPIXELS

The design goal for the HD-DPM Imager was to enable imaging in the following scanning formats: 1080P, 1080I, 720P, 480P and 480I, constrained by an aspect ratio of 16:9, without prohibiting other aspect ratios, and an image diagonal which is 2/3" for all modes.

4320 pixels per column

The minimum number of pixels per column one needs, to make a switchable imager possible, is determined by what is known the least common multiple (LCM). 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. In Table 1 the scanning formats are decomposed in primes. Applying the rules for finding the LCM of Table 1 one gets: 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 therefore: $4320 = 2^5.3^3.5$ = [5,3,1,0,0,0]LP6.

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**-Decomposition of the scanning format numbers in primes and using the log-prime notation Poimboeuf [9]. The least common multiple is 4320.*

Hence, an imager designed to handle all the above vertical standards in a native scanning format has to have 4320 pixels per column. The number of pixels per line is defined at 1920. This amounts to a total of 8.3 Mpixels. In practice the number will be larger since one needs additional active pixels 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 having reduced aliasing artefacts and enhanced horizontal resolution.

Next, one has to decide on how to readout/combine this massive amount of pixels. An image cell will consist of the combination (summation) of several pixels. The number depending on the required scanning format, TV-lines. This section is about how to interconnect to the image area. The question is: how can one by going backwards from 4320 pixels per column realise all scanning formats with minimum interconnection (driving electronics)? Looking at the prime decomposition (Table 1) of the line numbers one can conclude that all can be derived by making combinations of 3 or 4 pixels (Table 2). Such a combination of pixels is called a super pixel. The readout mechanism combines the super pixels into image cells, which are equivalent with TV-lines. For example, creating an image cell by grouping pixels in numbers of 4, 4320/4=1080 vertical image cells are generated. Combing them into 2 groups of 4 pixels, 4320/8=540 and by shifting 4 pixels each field 1080I is generated. Combining 6 pixels results in 4320/6=720P and 3 at a time 4320/3=1440P.

12 Phase addressing system

With a 12 phase addressing system one can make super pixels of 3, 4 or 6 pixels. An image cell (or TV line) is created through the addition of super pixels. As 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-Imager.

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

Scanning Format	Devisor	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

***Table 2**- The vertical scanning format expressed as a number of pixels per image cell (third column). The fourth column describes the image cell as a combination of super pixels.*

In Figure 1 the HD-DPM Imager is depicted with its image area, its storage area and the double horizontal shift register. A thorough treatment on the operation of CCD-Imagers can be found in Theuwissen [10]. In this paper focus is on the derivation of the several native scanning formats on a pixel level. One pixel is the smallest (fixed) light sensitive element. In a FT-imager it equals one photo-gate and in an IT/FIT imager this equals one photo-diode. In a FT-imager the number of pixels an image cell contains is controlled by the voltages applied to image area and/or the way the super pixels are combined together in storage or horizontal shift register. Such a definition of an image cell makes it equivalent to a TV-lines. In Figure 1 a portion of one column is zoomed in 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 HD-DPM Imager has two output registers for reasons of speed. In 1080I mode the (net) pixel output frequency is 74.25 MHz and at 720P, 111.375 MHz. With the double register these reduce to 37.175 MHz and 55.69 MHz.

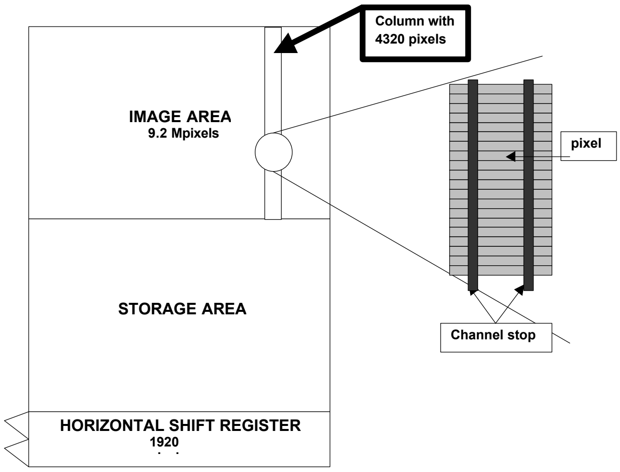

***Figure 1**-Blockdiagram of the HD-DPM imager*

In the Figures 2 and 3 the driving of the image area is depicted. By applying appropriate driving voltages through the 12-phase interconnect one can make super pixels of 3,4, and 6 pixels.

In the case these super pixels are smaller than the

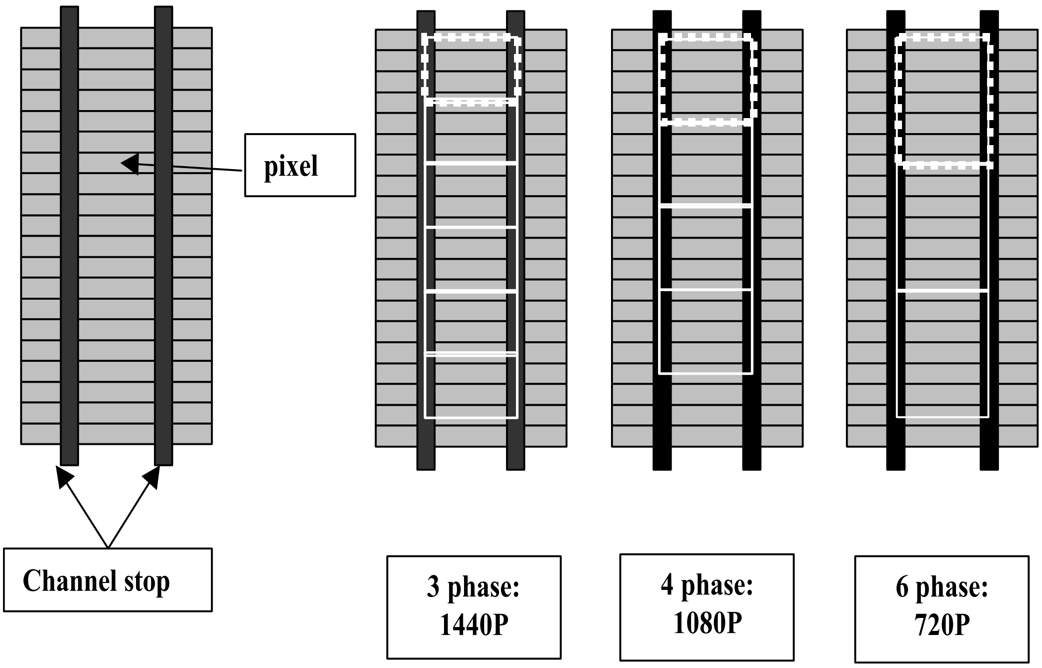

***Figure 2**-A Pixel (left) is depicted with the small gray bar. The image cell (right) with the white dotted line and the Super Pixel (right) with the white solid line. (See also Figure 3). Shown are 1440P, 1080P and 720P. In the modes shown the super pixel and image cell are the same.*

image cells, Figure 3, they are combined at the storage/image transfer region or in the storage/horizontal-shift register region.

Basically all the spatio temporal formats, as given in Table 1, are possible with an imager as described above. This imager is implemented in the recently introduced Philips LDK6000/LDK7000 HDTV camera system.

HD-DPM TO REDUCE ALIASING

The imager is usually of the 2-dimensional spatial sampler kind. Based on classical sampling theory a 2-dimensional low pass filter at Nyquist is needed for pre-filtering. The 2-dimensional optical low pass filter is the equivalent for an imager. Optical filtering is needed for proper aliasing behaviour. The reason lays in the fact that scene frequencies near the sample frequency are most visible since they fold back as low frequencies and the human eye is much more sensitive for low frequency patterns than for high frequency patterns. Therefore all video cameras are equipped with some form of a horizontal and a vertical optical low pass filter. An optical low pass filter (OLP) has zero transfer (MTF=0) at the optical sampling frequency. Through this choice the aliasing is adequately suppressed.

Horizontally

Since the pixels in the HD-DPM Imager have horizontally the same width in all the scanning formats (5 um) the horizontal OLP only has to have a zero (MTF=0) at 200 lp/mm.

Vertically

In a camera equipped with (HD) DPM-imagers one only needs a horizontal optical low pass filter. Dynamic Pixel Management (DPM [4,5]) is used to create a many taps optical FIR-filter for the vertical axis. In the case of the multi-format imager the vertical notch frequency is automatically adjusted to the correct sample frequency, Figure 4.

The simplest optical FIR-filter, and widely used in IT and FIT too, is the addition of two pixels to create an image cell. Charge adding of two contiguous pixels gives rise to an additional cosine filtering. This cosine has zero MTF at the spatial field sample frequency. (Compare 1080I and 1080P in Figure 4). In HD-DPM super pixels are used which function optically in the same way. Due to this choice the optical filtering is always matched to the chosen scanning format.

As pointed out before the point spread function determining the optical transfer function can be shaped using DPM. Its effect can be viewed as a FIR-filter with taps at 1/4 of the image cell height in 1080P, 1/8 at 1080I, 1/6 at 720P, 1/9 at 480P and

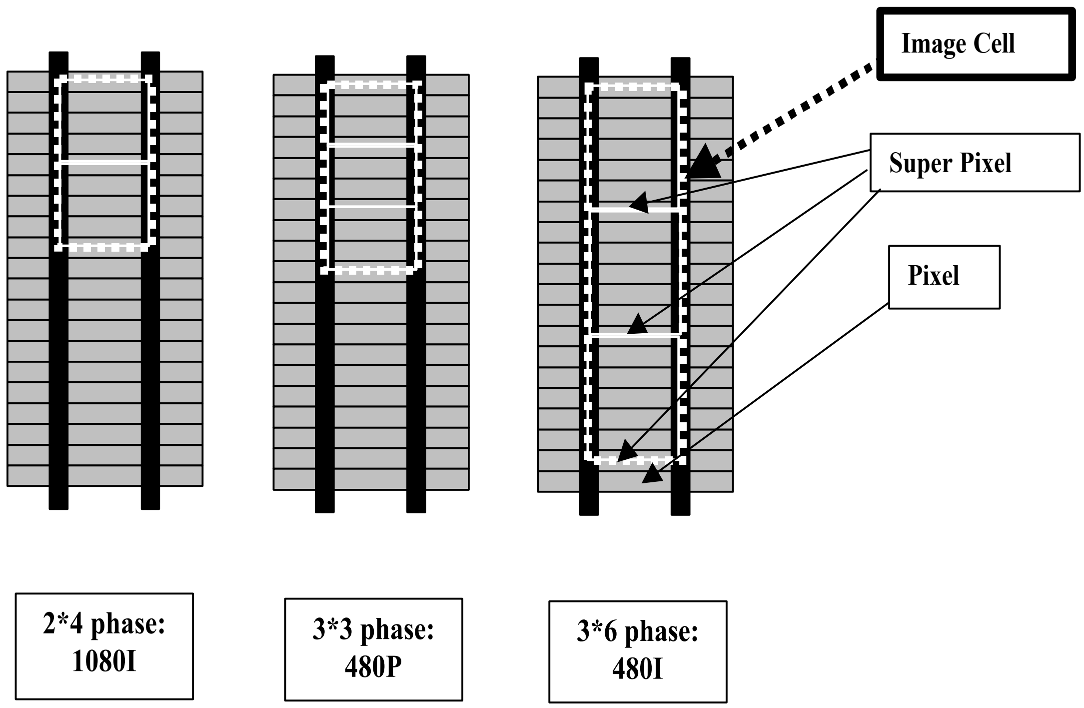

Figure 3*-The Pixel (right) is depicted with the small gray bar. The image cell with the white dotted line and the Super Pixel with the white solid line. (See also Figure 2). Shown are 1080I, 480P and 480I. Now an Image Cell is made up of several Super Pixels*

1/18 at 480I. Through the use of super pixels (Table 2 and Figure 2 and 3) and the addition of those one shapes the filtering properties needed for proper aliasing behaviour.

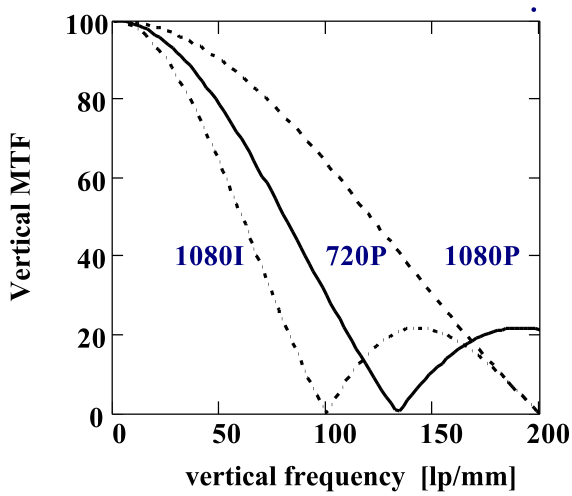

Figure 4*-Vertical shaping of the MTF, using HD-DPM, to obtain anti-aliasing properties matched to the scanning format*

For those more acquainted with TV-parameters Table 3 shows the main 'anti-aliasing' parameters in cpph.

Scanning Format	Optically zero transfer at
1080P	1080 cpph
1080I	540 cpph, 1080 cpph
720P	720 cpph
480P	480 cpph
480I	240 cpph 480 cpph

Table 3*- Spatial frequencies at which the MTF=0 through the use of HD-DPM FIR filtering*

HD-DPM AND CINEMATOGRAPHY

A few topics that relate Film and Imagers will be addressed in this section. First the super wide aspect ratio of 2.37:1 is discussed next a comparison of the MTF (resolution) between Film and a CCD-Imager in general to end with a more detailed comparison between Film and CCD-Imager. Elaborations on equivalent and additional thema's can be found in Centen et al [11], Thorpe [12].

A Super Wide Aspect Ratio

The imager and its camera are designed in the first place for the 16:9 broadcast video aspect ratio. With the DPM principle [4,5] some other aspect ratios are possible. The image area of the HD-DPM Imager can be addressed in 1440P-imaging mode, Figure 2. Now one has an overkill of scanning lines. Through the application of a DPM cut a 1080P image is generated out off these 1440P. The effect is a super wide aspect ratio of 2.37:1, Figure 5.

In the 1440P-imaging mode an image cell is 3 pixels heigh, 3x1.25 um = 3.75 um. The width of the image cell is 5 um. The total width of the 1920 horizontal image cells is 1920*5 um= 9.6 mm and the total height of the 1080 image cells: 1080*3.75um=4.05 mm. The aspect ratio now being 9.6/4.05= 2.37:1.

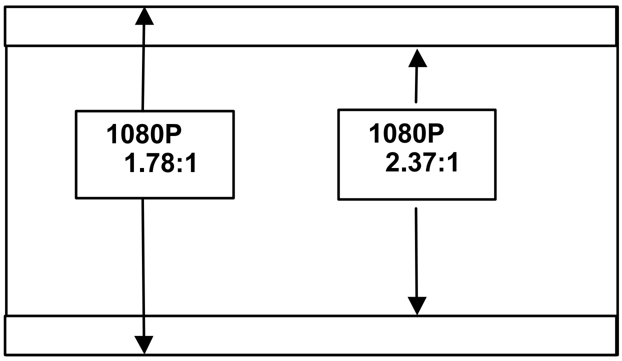

Figure 5*-Cinematographer aspect ratio of 2.37:1 in 1080P through the use of HD-DPM*

Temporal speeds

When staying within the SMPTE standards the only difference between 60Hz and 50Hz is the width of the horizontal blanking. The same holds for 30Hz and 25Hz and even 24Hz. Even intermediate frame rates are envisaged. Present state of the art Imagers can do all that. There is no hard limit to the lowest frame rates one can get with an imager and therefore compares favourably with Film.

Perceived MTF for Film and CCD-Imager

The perceived MTF is as best described through the area below the MTF curve squared, Schade [13]. The area represents an equivalent 'optical bandwidth' which is a measure for the resolution (MTF). Focusing on the horizontal resolution and application to a CCD-Imager result, without surprise, in an equivalent 'optical bandwidth' of 100 lp/mm, being the Nyquist frequency for a 2/3" CCD-Imager. Converted into an equivalent number of pixels per line it results, again without surprise, in 1920. For comparison purpose the KODAK film 5279/7279 was taken. It has with 76 lp/mm the highest equivalent 'optical bandwidth' in Blue; in Green an intermediate number of 65 lp/mm and in Red the lowest of 26 lp/mm. These equivalent 'optical bandwidths' can be converted into an equivalent number of pixels, Table 4. From a perception point of view the Green 'channel' mainly determines the resolution (MTF). Therefore Table 4 shows that the imaging format of 1920x1080P is somewhere between 16-mm and 35-mm film.

As an after thought the following remark can be made: Since the size of the tagged grain depends on exposure level the MTF of Film should depend on exposure too!

	R	**G**	**B**
5279/7279 Kodak Film	**26 lp/mm**	**65 lp/mm**	**76 lp/mm**
16 mm	590	1470	1720
35 mm	1290	3220	3760
65 mm	2400	5980	6990
2/3" Imager	**100 lp/mm**	**100 lp/mm**	**100 lp/mm**
11 mm	1920	1920	1920

Table 4*- MTF based comparison between CCD-Imager and Film where the equivalent 'optical bandwidth' in lp/mm is converted into an equivalent number of pixels per 'line'. The numbers are calculated for the horizontal axis only.*

Comparison of Film and CCD-Imager

A comparison of a few important parameters that define the 'imaging' behaviour of a CCD-Imager and Film-negative is given in Table 5. The remark about the random and fixed sample grid is rather trivial. But it is the cause of the invisible spatial aliasing for film. The number of photons to tag or to generate electrons is to show the sensitivity, quantum efficiency, of media. They compare more or less the same. Film-negative has a powerlaw transfer characteristic with a gamma of about 0.55. Imagers have intrinsic a linear transfer characteristic its the camera with a gamma=0.45 that can give it a powerlaw. On one hand Film saturates slowly when overexposed, an Imager saturates abruptly above a given maximum exposure. On the otherhand both media have about equal Latitude or dynamic range. The MTF is discussed in the prior section. Graininess versus Noise is difficult to compare since the dependence on exposure is quit different for both media. Both imaging media have variable frame rate possibilities over a large range of frames-per-second. Finally Film has a fixed speed whereas in a camera the gainswitch could be interpreted as a speed switch.

Film (negative)	**CCD-Imager**
Random spatial sample grid that also changes temporally. Fixed temporal sample grid	Fixed spatial sample grid Fixed temporal sample grid
No visible spatial aliasing	Sometimes visible spatial aliasing
4 photons to tag one grain	2-4 photons to generate one electron
Powerlaw response	Linear response
Shoulder Degrades gradually when overexposed	Qmax Clips when overexposed more than 2 F-stops
Large latitude 10 F-stop	Large dynamic range 10-13 F-stop
Different MTF for R,G,B	Equal MTF for R,G,B
MTF depends on Exposure	MTF independent of Exposure
Graininess: Random in nature and changes from frame to frame and depends on exposure.	Noise: Random in nature and changes from frame to frame. Its partly indepen-dent (readout noise) from exposure and in part proportional with the root of exposure (shotnoise).
Variable frame rate	Variable frame rate
Fixed speed (ASA)	Gainswitch as a speed (ASA) control

Table 5*- Comparison between Film-negative and a CCD-Imager as capture media.*

THE HD-DPM DIGITAL CAMERA

This section describes the design considerations that lead to the LDK6000 and LDK7000 HD-DPM multi-format camera.

Digital Video Processing

The design of the digital video processing is according to the ideas outlined in [8]. Basically the RAW data from the 3 HD-DPM imagers is pre-conditioned to allow for a proper mapping of the signals onto the range of the 12 bit AD-converters. The ADCs are followed by two custom designed ASICs (A and B) for HDTV video processing. The first set of SDTV ASICs was developed in close co-operation with Thomson Broadcast Systems, Botte and van Rooy [14] and Lacoste and Botte [15], just as the second set of (HDTV) ASICs. Some parameters of the latter are given in Table 6, more can be found in [11].

Parameter	ASIC-A	ASIC-B
Process	0.35 um	0.35 um
Gate Count	425000	185455
Die-size	74 mm^2	59 mm^2
RAMs	132 kbit	540 kbit
Input word length	14 bit	12 bit
Variable gain stage representation	Float	
Internal representation integer	20 bit	20 bit
Package	QFP208	QFP160

***Table 6**-Parameters of the customer defined HDTV digital signal processing: ASIC A and ASIC B.*

A Dockable Camera Concept

The Philips LDK6000/LDK7000 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 HD-DPM Imagers and Pulse Pattern Generator 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 special designed video processing ASICs
- A 160-pin docking connector to the adapter containing parallel digital Y/C (2x10 bits) video acc. to the SMPTE 274M/296M standards

Dimensions Camerahead with Triax adapter (l x w x h): 349 (260) x 117 x 197 mm Weight camerahead with Triax adapter: 5.0 kg (4.4 kg) (Values in-between brackets apply to the Multi-purpose adapter version of the camera)

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.

Following BNC output signals are available on the Multi-Purpose adapter:

- HDTV SDI output (1.5 Gbps) with switchable video formats (LDK6000:1080I/720P, LDK7000: 1080P, 720P)
- VF output (HDTV)
- Downconverted CVBS viewing output (NTSC)
- HDTV Gen-lock 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.

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/LDK7000 camera system. Based on the experience with the High-Speed Camera [7] the analogue HD Triax system was developed with 30 MHz bandwidth for luminance and 15 MHz for both colour difference signals; Cr and Cb.

All present 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 done by means of component signals with carriers swapped w.r.t. the high speed camera to enhance bandwidth and cable length.

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).

Base Station
The LDK6000/LDK7000 HDTV camera with wide band analogue 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
- Signalling and data
- Video inputs/outputs
- SDTV output (high-end scalar)
- Video monitoring

Inside the Base Station a high quality down converter is implemented to provide standard NTSC or PAL output signals. Video outputs available at the Base Station:

- HDTV main output: 3x SDI (1.5 Gbps)
- Analogue HDTV outputs on VGA type connector (RGBHV on 15-pole D-connector)
- Main SDTV output: 3x SDI (270 Mbps)
- Analogue 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 acc. to “709 standard” for HDTV and acc. to “601 standard” for SDTV video signals.

CONCLUSION

HD-DPM as 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 matched properties for the optical filtering in suppressing aliasing is shown. A comparison between Film and CCD-Imagers is given. In conjunction with the new HD-DPM imagers also a new set of Asics is developed with enhanced functionality. Finally the design of an analogue Triax adapter, as part of the dockable camera concept, is discussed. The discussed items lead to the design of the LDK6000 and LDK7000 multi-format HDTV camera series.

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