Image Resolution of the One-CCD Palomar Motion Picture Camera

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Abstract

The developmental Palomar motion picture camera employs a single 4k x 2k CCD image sensor with RGB filters arranged in a mosaic pattern. A one-CCD camera architecture has several advantages over 2- and 3-CCD cameras including optical compatibility with existing 35mm cinematography lenses, elimination of optical aberrations resulting from optical alignment and thermal stability issues, and simplicity in overall design. These advantages must be weighed against a reduction in image resolution relative to the native photosite count and overall optical sensitivity. This paper analyzes image resolution and shows the available resolution of this architecture to be 1600 L/PH (lines per picture height), approximately 60% greater than a high end 3-CCD digital HD camera employing 2M photosite count 2/3" CCDs.

Introduction

The one-CCD Palomar motion picture camera employs a 4046H x 2048V frame transfer CCD image sensor with a 1.5" image diagonal in a 2:1 aspect ratio. Table I compares Palomar to various motion picture film aperture formats and to 2/3" CCD format. Figure 1 is a pictorial comparison and shows the focal plane height is comparable to exposed Academy aperture and considerably exceeds projected widescreen academy.

Table I – Comparison to Standard 35mm Film Formats

	X	Y
Palomar, 1.98:1	34.0mm (1.338")	17.2mm (0.677")
Academy Aperture, 1.37:1 (exposed)	22.0mm (0.827")	16.0mm (0.600")
Widescreen Academy, 1:85 (projected)	21.0mm (0.825")	11.3mm (0.446")
Super 35 1.33:1 (exposed)	24.92mm (0.981")	18.67mm (0.735")
Cinemascope 2.39:1 (exposed)	20.95mm (0.827")	17.53mm (0.689")
2/3" CCD, 1.78:1	9.6mm (0.378")	5.4mm (0.213")

The overall camera resolution is also affected by photosite composition. Each 8.4μm square photosite of the Palomar sensor is covered by either a red, blue or green color filter deposited directly onto the surface of the silicon. The standard Bayer pattern filter is employed wherein any 2x2 photosite group consists of 2 green, 1 red and 1 blue photosite as illustrated in Figure 2. The greater number of green photosites improves effective resolution as green dominates luminance and the human visual system has much higher spatial acuity for luminance that for color. The 1.6μm opaque photosite border limits color crosstalk between photosites. The border cannot be resolved with most lenses and does not contribute significantly to aliasing.

A representation of the optical path is illustrated in Figure 3. It consists of two optical elements between the lens and the focal plane, a 3mm thick optical lowpass prefilter and the CCD cover glass. Chromatic and spherical aberration are undetectable with an f2.0 lens. The camera incorporates a rotating shutter and reflex viewing system, these have been omitted from the drawing.

Resolution Analysis

As in any imaging system, be it digital or film based, effective resolution depends not only on the optical elements but a combination of a number of system elements that are used to produce the final image. In a digital camera these consist of a number of optical, electronics, and digital processing elements illustrated in the simplified block diagram of Figure 4. The elements impacting resolution are each analyzed separately in the following sections.

1. Lens

An ideal (diffraction-limited) lens has a modulation transfer function described by the following relationship:

$$MTF(v) = \frac{2}{\pi}\left[\cos^{-1}(v\lambda N) - (v\lambda N)\sqrt{1-(v\lambda N)^2}\right],$$

where N is the lens f number, λ the light wavelength, and v the spatial frequency.

Lens performance, especially for fast lens, may be degraded by optical aberrations. The theoretical results presented in this paper assume an ideal f5.6 lens.

2. Optical PreFilter

The optical prefilter reduces the aliasing created by the periodic arrangement of CCD photosites at 8.4μm pitch. It is a layered birefringent crystal that splits each light ray into four rays, each offset 8.4μm vertically and horizontally on the focal plane. The modulation transfer function is described by the following relationship:

$$MTF(v) = \cos(\pi d v),$$

where d is the 8.4μm ray separation and v is the spatial frequency.

3. CCD Focal Plane

The CCD focal plane consists rectangular array 4k x 2k photosites on a 8.4μm square grid with a 1.6μm opaque border between photosites. The MTF is described by the sampling aperture expression:

$$MTF(v) = \frac{\sin(\pi a v)}{\pi a v},$$

where a is the 6.8μm photosite clear aperture and v is the spatial frequency.

4. CCD Non-ideality

A CCD introduces some distortion and noise in converting the optical image into an electrical signal. Table II lists the distortions and Table III lists the noise. Excepting veiling glare from photosite crosstalk, the distortions are digitally corrected and do not

impact resolution. The noise is temporally and spatially uncorrelated and cannot be removed from the image without sacrificing resolution. Noise does not impact resolution in motion picture applications except at significant underexposure.

Table II – CCD Distortions

Distortion Source	Effect	Digitally corrected
Photosite Sensitivity	2% variation photosite-to-photosite (fixed grain)	Yes, in camera
Photosite Dark Offset	1% variation (fixed grain in dark)	Yes, in camera
Photosite Crosstalk	Scene dependent photosite sensivitity variation in alternating green photosites	Yes, in camera
Photosite Saturation	Color shift and detail loss in highlights	Partially, in camera
Photosite Flare	0.1% (est.) veiling glare	Not implemented
Image data transfer	10% color and luminance shading	Yes, in camera
Amplifier Gain	2% non-linearity	Yes, in camera

Table III – CCD Noise Sources

Noise Source	Resolution impact
Amplifier Noise	Reduces resolution at low light levels (>8 stops below sat)
Photon shot noise	Essentially no impact – reduces resolution for very low contrast (<1% MTF) images
Charge transfer shot noise	No impact (negligible compared to photo shot noise)
Dark current shot noise	Negligible compared to Amplifier noise

5. Digital Processing

Digital processing corrects CCD non-idealities with photosite gain/offset correction, amplifier non-linear gain correction, photosite crosstalk correction, and charge transfer correction. Taken together, CCD non-linearity and digital correction do not affect MTF or resolution.

Digital processing may be used to add film-like qualities. Film is superior to existing HDTV digital systems in that it exhibits the highly desirable S-shaped transfer function that simultaneously preserves details in both shadow and highlight areas of an image. Combining the inherent Palomar photosite response with novel patent pending processing electronics in the camera results in a digital transfer function that is similar to film. This work is in its early stages and it is not discussed in this paper.

6. Color Interpolation

Color interpolation is a digital processing algorithm to calculate the three color components for each pixel. The Palomar camera employs a novel patent-pending non-linear algorithm that calculates the color values for any given pixel based on the color information in a kernel of adjacent pixels. The impact on resolution and cannot be modeled analytically and is excluded in the theoretical camera MTF study that follows. It is included in the simulations and these simulations demonstrate that it maintains unity MTF at spatial frequencies below half-Nyquist (1000 L/PH) and may slightly reduce MTF at higher spatial frequencies. Final analysis will be conducted using empirical data from the camera prototype.

7. Compression / Storage

The camera architecture allows for real-time mathematically lossless compression to reduce transmission and storage bandwidth requirements. Decompression will restore the exact image bit-for-bit resulting in no loss of resolution; however the compression ratio is image dependent. The Palomar camera will also have options for visually lossless compression at a future time and as such the impact on resolution is indeterminate at the time of writing of this paper.

Overall Camera Resolution

Figure 5 illustrates the MTF of the individual system elements as well as the combined MTF of the Palomar camera, excluding color interpolation. The camera resolution is 1600 L/PH, corresponding to the point where the modulation level dips below 20%. The optical prefilter limits modulation to less than 20% for all frequencies greater than the 2048 L/PH Nyquist frequency. This high frequency modulation would only produce false detail or aliasing.

A computer analysis of resolution was employed to model the entire signal chain, including the color interpolation algorithm. The simulated sinusoidal resolution has 60% modulation at spatial frequency from 300 L/PH to 2400 L/PH (exceeding the 2048 L/PH Nyquist limit of the camera). The simulated output image is illustrated in Figure 7 and has the following properties:

0-1000 L/PH	Resolution and modulation level well preserved
1200 L/PH	Resolution preserved at reduced modulation
1600 L/PH	Resolution preserved, modulation reduced and some false color
2000 L/PH	No modulation
2400 L/PH	Low level modulation causing reduced aliasing

A second simulation was made of a star burst pattern as illustrated in Figure 8. Again the modulation is 60% with sinusoidal bars. Some false color is visible at high resolutions but good resolution is achieved to 1600 L/PH.

Comparison with Film and Other CCD Cameras

As illustrated in Figure 6, the Palomar camera has a distinctly different MTF curve than negative color 200T film [2]. At low spatial frequencies, film MTF exceeds 100% due to the presence of chemical inhibitors. If desired this effect could be reproduced through

digital processing. At mid-range frequencies the MTF of film and the Palomar camera are comparable. At the high frequencies, the negative film can resolve extremely fine details. However this fine detail is ordinarily lost during the film transfer process. The measured MTF curve of internegative film included in this plot may be more indicative of actual performance. Palomar camera MTF at midrange and high frequencies exceeds internegative film as it does not suffer from generational loss.

An experimental camera with three 4k x 2k sensors has been reported [3]. This camera achieves the theoretical limit of 2000 L/PH Nyquist resolution limit of the green channel sensor. Commerical high end 3-CCD cameras based on 2/3" 1920H x 1080V image sensors cannot exceed the 1080 L/PH. All 3-CCD camera systems employ a prism beam splitter which restricts lens selection.

Conclusions

The Palomar camera provides a focal plane height comparable to Academy aperture but an extended width for a 2:1 aspect ratio. Both theoretical MTF analysis and computer simulated imagery predict a 1600 L/PH resolution, slightly less than the 2000 L/PH limit of a 3-CCD 4k x 2k camera and approximately 60% greater than high end 3-CCD 2/3" 1920H x 1080V based cameras.

References

[1] "35mm Cinema Film Resolution Test Report", Document 6/149-E, International Telecommunications Union, 20 September 2001.

[2] "Kodak Vision 200T Color Negative Film / 5274 / 7274", Kodak Publication No. H-1-5274, minor revision 7/2001, 2001.

[3] Kohji Mitani *et. al.*, "Experimental Ultrahigh-Definition Color Camera System with three 8M-pixel CCDs", *SMPTE 143rd Technical Conference and Exhibition*, New York City, November 2001.
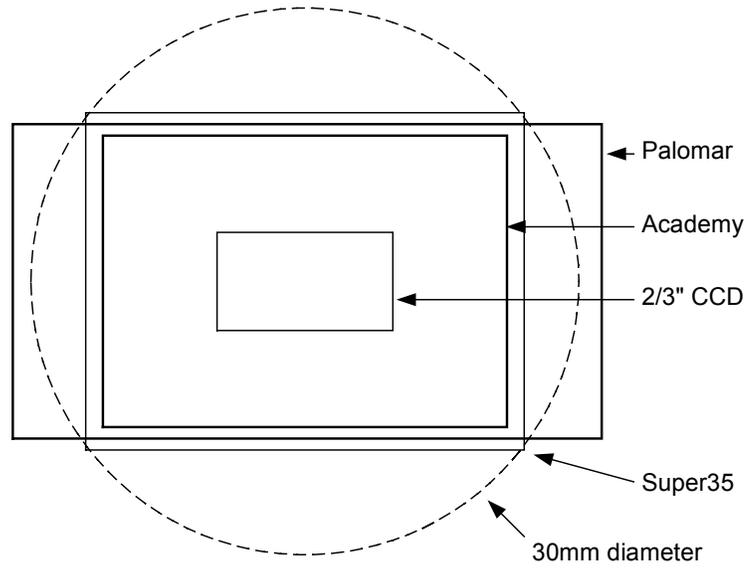
Figure 1: Palomar focal plane compared with standard formats. The Palomar focal plane is 4046 photosites horizontal and 2048 photosites vertical. The image diagonal spans 1.500".
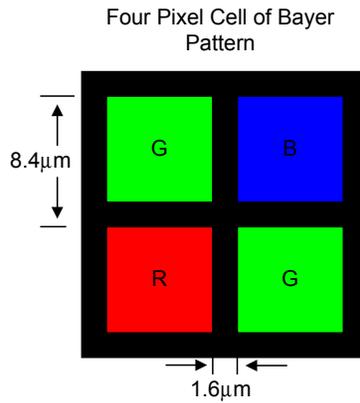
Figure 2: A pictorial view of 4 photosite block in the focal plane. The photosites are arranged in a RGB Bayer pattern. The 8.4μm photosite pitch includes a 1.6μm opaque border.
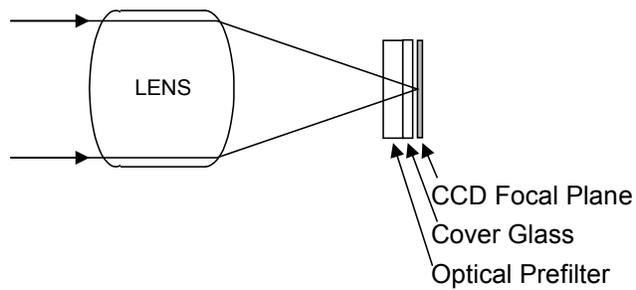
Figure 3: Simplified model of optical path showing the optical prefilter, cover class and CCD focal plane.
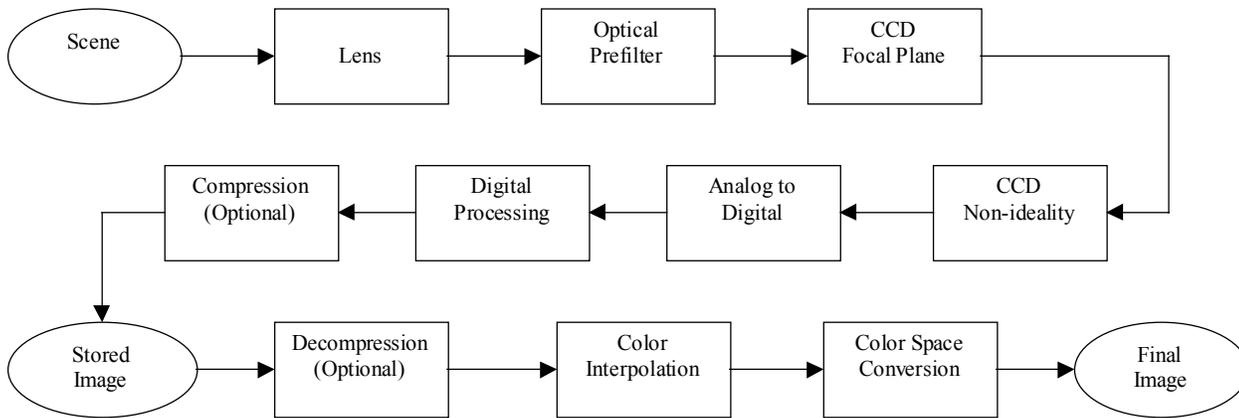
Figure 4: The optical, electronic, and primary signal processing elements in the camera.
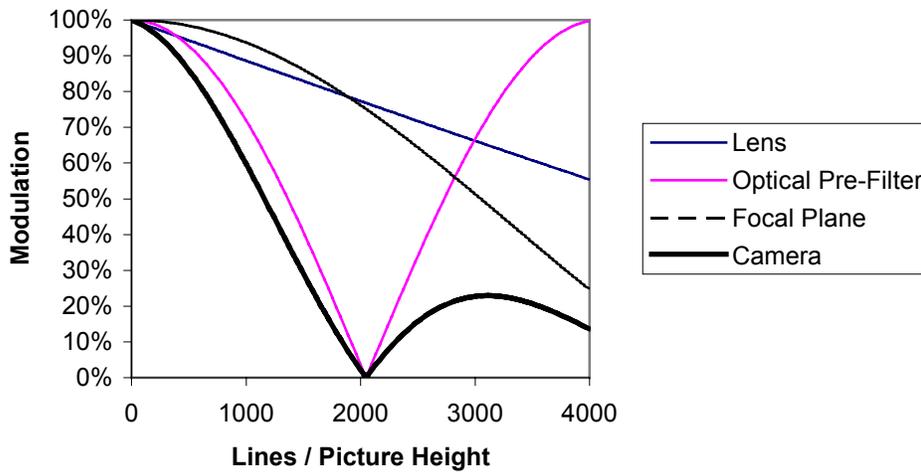
Figure 5: The theoretical MTF prior to color interpolation, and the individual MTF components. To convert to line pairs per mm (lpmm), multiply by 0.029.
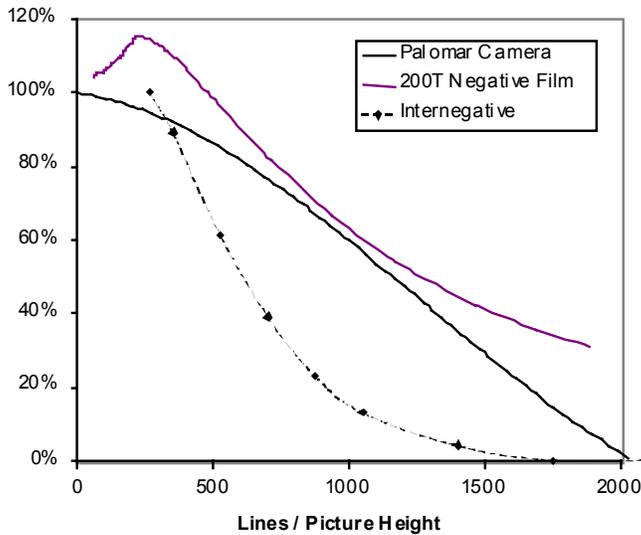
Figure 6: Theoretical MTF curves for Palomar camera (prior to color interpolation) and 200T color negative film [2], with ideal f5.6 lens. Measured MTF for internegative film included for comparison [1].
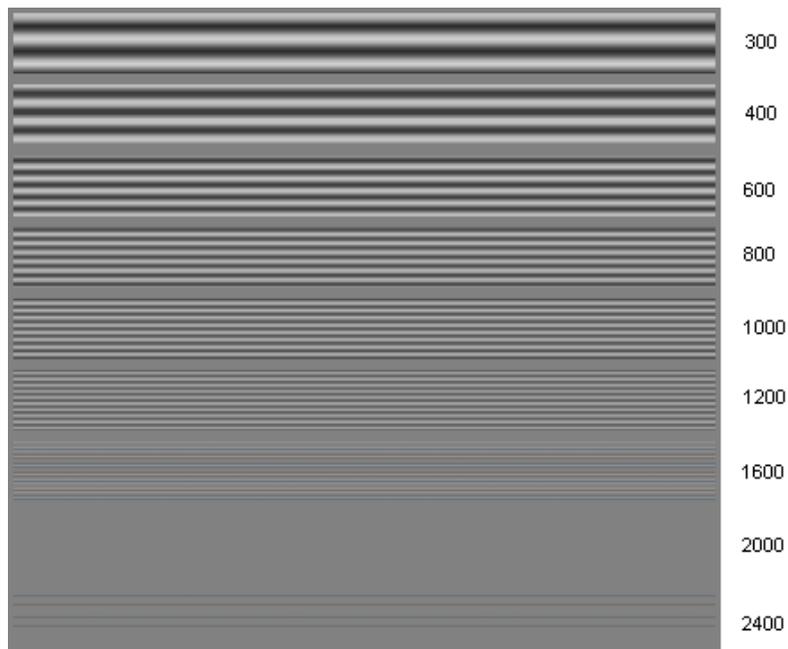
Figure 7: Model of camera output for a sinusoidal resolution target with 300, 400, 600, 800, 1000, 1200, 1600, 2000, and 2400 lines/picture height test bars. The test chart modulation is 60% with 50% gray borders. Model includes an ideal 5.6 lens. Test bars up to 1200 L/PH are clearly resolved. Some false color is present at 1600 L/PH. Faint aliasing is visible at 2400 L/PH.
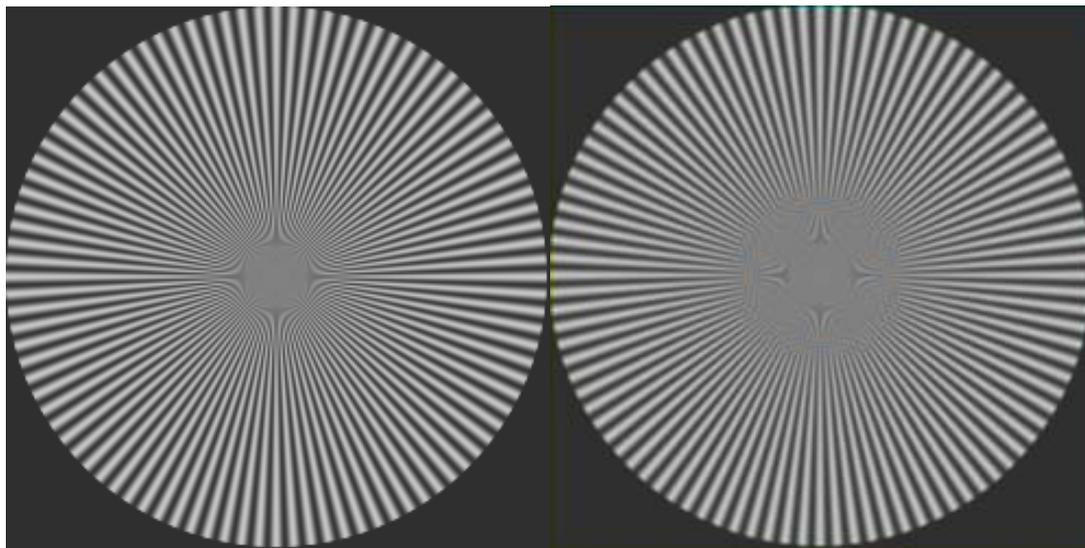
(a) Ideal   (b) Simulated Image

Figure 8: Simulated image of sinusoidal star burst pattern with 60% modulation on a 250x250 segment of the focal plane. Figure 8(a) is the original image assuming an ideal f5.6 lens. Figure 8(b) is the image from the camera after the color interpolation. The starburst circumference corresponds to 500 L/PH, yielding a camera resolution of 1600 L/PH.