High Performance Optics for a New 70mm Digital Format

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Introduction

• Sensor MTF: 35mm film < 70mm film < 70mm digital
• New lens technology combined with new 70mm digital sensor gives unprecedented image quality
• Designing lenses and camera together permitted a systems approach to maximize overall quality and usability
• Camera filter pack designed by Panavision specifically to accommodate gigapixel-class lens technology requiring a short working distance
Optical Specifications

• Format: 20.25 x 48mm (52.1mm diagonal)
• Pixel Size: 6.25 microns (80 lp/mm Nyquist)
• EFL = 27, 35, 40, 50, 65, 80, 100, 125, 150, 200, 250, and 300mm
• Aperture: f/2.5 (T/2.8), except for 300mm
• Waveband: 400 – 680nm, extended to NIR
• Color Correction: Apochromatic for 27-40mm; Superachromatic for 50-300mm
Why f/2.5?

• High speed for such a large format
• DOF equivalent to f/1.25 lens used on 35mm
• Size and weight similar or less than conventional f/1.4 – f/1.7 optics used on 35mm
Optical Design Principles

- Short working distance & strategic field-flattening element(s) largely eliminate the need for high index glass
- Permits extraordinary apochromatic (3-color) or superachromatic (4-color) color correction
- Aspherics used as necessary
- Resulting designs are nearly diffraction-limited at f/2.5 over a broad waveband and over a large 52.1mm diameter image circle
Optical Design: Layout

- Protective Dome
- Dense Flint, Concave Front
- Asphere
- Camera Filter Pack
- Special Effects Filter
- Aperture Stop
- Concave Toward Image
- Short Working Distance
- Fluor Crown Glass
Optical Design: Focusing
Performance: MTF

![Graph showing MTF performance for 65mm film with different line pairs per millimeter and image height (mm).](image-url)
Comparison to Leica S2

• Leica S2 optics use same aperture and image size as new 70mm lenses

• Leica lens has worse contrast at 20 lp/mm than new 70mm lens does at 40 lp/mm

• New 70mm lens provides >4x improvement in image quality
Performance: MTF

![Graph showing MTF performance for different image heights and line pairs per millimeter (lp/mm). The graph includes lines for 35mm film with markers for different line pair densities (10, 20, 40, 80 lp/mm) and different imaging techniques (S, T).]
Performance: MTF

![Graph showing MTF performance with different image heights and line pairs per millimeter]

- Relative Contrast vs. Image Height (mm)
- 125mm
- 10 lp/mm
- 20 lp/mm
- 40 lp/mm
- 80 lp/mm
- S and T curves for each line pair rate
Performance: MTF

![Graph showing MTF performance with different image heights and line pairs per millimeter.](image)

- 200mm
- 10 lp/mm
- 20 lp/mm
- 40 lp/mm
- 80 lp/mm

Relative Contrast vs. Image Height (mm)
Future-Proof Optics

• Rule of thumb for high quality cine imaging: 80% contrast at \( \frac{1}{2} \) Nyquist frequency
• Current Panavision 70mm sensor uses 6.25 micron pixels (7680 across 48mm), so Nyquist freq. = 80 lp/mm
• 70mm lenses achieve ~90% contrast at 40 lp/mm, corresponding to ~8k sensor resolution
• ~80% contrast at 80 lp/mm, corresponding to ~16k

Initially, the camera will use super-sampled 4k output, and lenses achieve ~95% contrast at 20 lp/mm
Performance: Chromatic Aberration
Filter Pack Effect: 70mm Digital Lens

![Graph showing relative contrast vs. image height with and without filter pack for a 50mm lens at 40 lp/mm.]
Filter Pack Effect: 35mm Film Lens

35mm Lens for 35mm Cine Film Format
40 lp/mm

Relative Contrast

Image Height (mm)

Without Filter Pack
With Filter Pack
Ghosting

125mm Lens, No Front Filter

125mm Lens, With Front Filter
Mechanical/Electrical Specifications

• Outer barrel diameter: 126.5 mm
• Length (front of barrel to image plane): 200mm for focal lengths from 27mm to 100mm; gradually increases for longer focal lengths
• Focus/Iris Control: Outer mechanical gears plus internal motorized electronic control
• Metadata: Focus distance, aperture, temperature, lens ID, transmitted via 12-pin connector on lens mount
Mechanics: Layout
Mechanics: Ultra-Round Iris

T/2.8  
T/5.6  
T/22
Mechanics: Weight Reduction
Electronics: 70mm Mount
Summary

• New 70mm lenses designed from the ground up to work with the new Panavision 70mm digital camera
• The new lenses provide dramatically better image quality than any previous cine or photographic optics, and are fully suitable for 8k and beyond
• Electronic focus/iris control combined with external geared controls offers excellent user-friendliness
• Metadata includes focus distance, aperture, temperature, and lens ID
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Abstract. This paper details technical features of the first series of high-speed prime lenses designed for a new 70mm digital format developed by Panavision. These new lenses offer full aperture (f/2.5) performance at or near the diffraction limit from near-UV to near-IR over a 48x20.25mm image area. These lenses are also designed to work properly with optical filters inserted between the lens and sensor.

Twelve focal lengths are under development, ranging from a 27mm ultrawide to a 300mm telephoto. In addition to traditional externally-gearred controls, all lenses have internal motors for focus and aperture. High resolution metadata is transmitted continuously to the camera. Metadata includes focus distance, aperture, temperature, and individual lens identification. A replaceable internal filter near the aperture stop permits a variety of creative effects, including soft-focus.
Keywords. Lenses, lens design, cine, cinematography, 70mm, large format, digital, superachromat, superachromatic, apochromat, apochromatic, UV, IR, Panavision, metadata, gigapixel, Caldwell Photographic, iris, bokeh

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Introduction

For much of the history of cinematography, the industry has preferred the image quality inherent in the 70mm cine format over smaller formats. Lenses that are considered mediocre on 35mm can deliver excellent results on 70mm because the resolution and MTF requirements are significantly reduced. The same advantages that accrue to larger film formats also apply to digital sensors.

Two years ago, a team with optical, mechanical, electronic and sensor design expertise began discussions as to how to develop a series of premiere lenses for Panavision’s new 70mm digital camera. The goals were to: improve performance dramatically, keep the lenses light and compact, and take advantage of the newest technologies, including the use of electronics.

The advantages of a systems approach soon became obvious. In particular, the filter pack and lens mount of the new 70mm digital camera needed to be designed to accommodate the relatively short working distance required by a series of gigapixel class lens designs developed by Caldwell Photographic. By designing everything from the ground up, and also taking full advantage of recent advances in aspheric manufacturing and optical glass technology it became possible to make significant advances in system performance.

This paper will present some of the technical features and performance characteristics of the new series of 70mm digital lenses.

Lens Specifications

Below is a brief listing of the lens specifications:

• Focal Lengths (mm): 27, 35, 40, 50, 65, 80, 100, 125, 150, 200, 250, 300
• Maximum Aperture: f/2.5, T/2.8 (f/2.8 for 300mm lens)
• Format: 20.25mm x 48mm (52.1mm diagonal)
• Pixel Size: 6.25 microns (80 lp/mm Nyquist frequency)
• Waveband: 400nm – 680nm
• Color Correction: Apochromatic (3-color) for 27mm, 35mm and 40mm focal lengths; Superachromatic (4-color) for 50mm and greater focal lengths
• Focusing: Internal focusing to maintain image quality at all object distances
• Outer Barrel Diameter (front): 126.5mm for all focal lengths
• Length (front of barrel to image plane): 200mm for focal lengths from 27mm to 100mm; gradually increases for longer focal lengths
• Focus Control: Outer mechanical gear plus motorized electronic control
• Iris Control: Outer mechanical gear plus motorized electronic control
• Metadata: Focus distance, aperture, temperature, lens ID

Optical Design and Performance

Design Technology

All of the designs incorporate patented design technology originally developed for gigapixel class image sensors\textsuperscript{1,2}. Several important features of this technology are illustrated below in Figure 1. Note that the lenses take full advantage of the short working distance allowed by non-reflex style digital cameras. This is important because it permits correction of field curvature.
and astigmatism by placing negative-powered elements near the image plane. In particular, the designs utilize a strong concave surface facing the image in which the marginal ray height is small compared to the entrance pupil radius. The designs also include a negative-powered group in front of the aperture stop which also serves to flatten the field.

These field flattening measures eliminate the need for positive elements to be made from high index crown glass, which is a common characteristic of virtually all other high-performance large aperture lenses. As a result, the new designs make maximum use of low-index fluor crown glass to eliminate secondary spectrum. Most of the designs also use at least one positive element made from dense flint glass in order to also eliminate the tertiary spectrum, thus resulting in broadband superachromatic color correction.

Eliminating positive elements made of high index crown glass permits unprecedented levels of color correction. However, the resulting reliance on low-index fluor crown glass also increases the difficulty of correcting spherical aberration. In most of the lenses from the new series this problem is solved by the use of an aspheric surface as shown below in Figure 1. The resulting lens design is almost perfectly corrected for all aberrations over a waveband ranging from the near-UV through the near-IR.

In practical terms, this means that the new lenses can be used to create a truly immersive viewing experience without any disturbing visual artifacts due to the lens.

Figure 1. Layout of 125mm lens showing design features used throughout the series.

Gigapixel-class designs optimized for infinity form the basis of this new lens series. In order to extend this level of performance over a large focusing range it was necessary to adopt various internal focusing strategies. For short focal length lenses the main focusing issues are variation of astigmatism and lateral color with object distance. For medium and long focal lengths the primary issue is variation of coma with object distance. Figure 2 illustrates how the 125mm design uses two independent focusing groups to eliminate aberration variation with focus. Other focal lengths in the series use a similar technique.
Performance: MTF

All of the lenses in the 70mm series have unusually high MTF. This is due in part to an extremely low level of chromatic aberration (both axial and lateral), and in part to a nearly perfect correction of all monochromatic aberrations. Notably absent is any oblique spherical aberration, which is a major limiting aberration of nearly all large aperture photographic lenses.

Extensive experience with digital cine cameras and lenses at Panavision has indicated that in order to achieve excellent cinematographic image quality the lenses must have a contrast of 80% or higher in the center of the image field at half the Nyquist frequency of the sensor. A gradual falloff in off-axis performance is acceptable, especially for wide angle lenses.

In the present case with 6.25 micron pixels the Nyquist frequency is 80 lp/mm, so the key spatial frequency of interest is 40 lp/mm. All of the 70mm series lenses exceed the 80% requirement at 40 lp/mm. Several exceed 90% in the center of the field. Off-axis performance is also uniformly high throughout the series, with sagittal and tangential curves staying very close together in all cases. Note that the 80 lp/mm Nyquist frequency corresponds to a sensor resolution of nearly 8k (7.68k to be exact).

In the case where output from the sensor is super-sampled to provide true 4k footage the demands on lens performance is significantly reduced. Here the lenses are perfect for all intents and purposes, and produce no visible aberrations. There is every reason to believe that the 70mm lenses will remain state-of-the-art for many years to come because they provide sufficient image quality for sensor resolutions of 8k, 16k, and beyond.

Performance of these new lenses is in fact so good that they approach the diffraction limit even when used wide open. This is particularly true for the 50mm, 65mm, 80mm, 100mm and 125mm focal lengths. For apertures of f/2.5 and smaller the laws of physics don’t permit...
significantly better image quality. In principle it would be possible to improve the image quality by using a larger aperture, but this would bring penalties of size and weight that are not generally desirable. Also, it is worth bearing in mind that f/2.5 on 70mm format has similar depth of field to f/1.25 on 35mm cine format when the focal length of the lenses is scaled to maintain an equal angle of view on both formats. So, increasing the aperture is only useful when extremely shallow depth of field effects are desired.

Figure 3. MTF vs Image Height at 10, 20, 40 and 80 lp/mm for four different focal lengths (35mm, 65mm, 125mm and 200mm) in the 70mm digital series. Note that lower spatial frequencies have higher contrast.
**Performance: Chromatic Aberration**

Virtually all large aperture photographic lenses exhibit noticeable artifacts due to chromatic aberrations when used on digital sensors. These artifacts include purple fringing or haloing due to poor chromatic correction in the deep violet, as well as purple and green false colors in defocused areas due to secondary spectrum. Purple fringing is particularly harmful in cinematography, especially in green screen applications where mercury illumination is present. Because of the strong mercury output peaks at 404nm and 435nm it was decided to fully correct all of the 70mm series lenses for an unusually broad 400nm – 680nm waveband. By contrast, nearly all other cine lenses to-date have been corrected for a much narrower waveband starting at 435nm or more typically 450nm.

It was clear from nearly the beginning of the project that ordinary achromatic (two-color) correction was completely inadequate for covering the 400nm – 680nm waveband. In fact, for longer focal lengths it was decided that even apochromatic (three-color) correction did not provide sufficient freedom from chromatic artifacts. As a result, focal lengths 50mm and longer have superachromatic (four-color) correction, while focal lengths 40mm and shorter are apochromatic.

Figure 4a below (left plot) shows focus shift as a function of wavelength for the 65mm focal length lens. The curve crosses the zero focus shift axis four times, corresponding to longitudinal color correction at four widely-spaced wavelengths. These wavelengths include two in the visible band (blue and red) plus one each in the near-UV and near-IR. Figure 4b (right plot) shows lateral color at five different wavelengths as a function of relative image height. Here, the lateral color from 400nm to 680nm is much less than a pixel in extent (6.25 microns), and even when the waveband is extended from 375nm to 1000nm the lateral color only barely exceeds a pixel. Thus, the lens substantially exceeds chromatic correction requirements, and can be used in the invisible near-UV and near-IR portions of the spectrum for special applications. Other lenses in the 70mm series have similarly excellent chromatic correction.

![Figure 4. Axial (4a, left) and lateral (4b, right) chromatic aberration for the 65mm lens.](image-url)
In practical terms, the benefit of this exceptional color correction is that images are rendered with better clarity, and appear much more lifelike than those taken with conventional lenses. In particular, areas that are out of focus appear much more true-to-life because no false colors appear.

**Filter Pack**

Up to now, cine lenses have been designed to work with film cameras without any plane parallel glass elements between the lens and the image plane. Digital cameras, however, necessarily incorporate several such elements, including a protective coverglass very close to the actual sensor surface, an anti-aliasing filter, and an IR/UV blocking filter. Recent cameras also include additional plano elements such as neutral density filters.

In the case of the Panavision 70mm digital camera the total filter pack is optically equivalent to a 7.0mm thick plane parallel plate of BK7 glass. Figure 5 below shows the MTF at 40 lp/mm for the 65mm lens with and without the filter pack. Note that for this calculation the lens was re-focused for best possible performance when the filter was removed. The result: performance is drastically reduced when the filter is not present. This clearly illustrates the need for lenses to be designed properly in order to accommodate any filters that are present in the camera system. The new 70mm lenses are the first cine lenses designed specifically to work properly with a digital camera having a filter pack.

![Figure 5. MTF for the 65mm focal length lens at 40 lp/mm with and without the filter pack.](image-url)
Figure 5 shows how a high performance lens designed for use with a digital filter pack is severely degraded when the filter pack is removed and the lens is re-focused. A similar situation occurs when a lens designed for film without any filter pack is used on a digital sensor with a filter pack. In this case the performance of the lens is degraded because of the presence of the filters. Figure 6 shows how the performance of a 35mm cine lens designed for film is degraded when it is used on a digital camera having a filter pack identical to that used in the new Panavision 70mm camera.

![Figure 6. MTF for the 35mm focal length cine lens at 40 lp/mm with and without filter pack.](image)

**Special Effects Filter**

The performance data presented above demonstrates that the new 70mm series lenses are effectively “perfect” in terms of aberration correction. Still, flawless lenses are not universally desired in cinematography. A significant amount of spherical aberration is often desired to achieve flattering soft-focus effects. In order to meet this and other stylistic needs, all of the new lenses have been designed with a technician-replaceable special effects filter close to the aperture stop. By replacing the default plain filter with a special aspheric filter it is now possible to introduce any desired amount of spherical aberration for visual look. By locating the effects filter near the aperture stop, the amount of filter-induced aberration is uniform throughout the image field, even for wide angle lenses.

Other special effects are also possible. Examples include: 1) apodization to alter the bokeh by using a filter with radially variable neutral density and 2) special highlight effects by using a holographic filter.

**Ghosting**

In addition to using high-performance anti-reflective coatings, all of the lenses are designed to have minimal ghosting problems. All of the lenses necessarily comprise a large number of lens
elements. There are literally hundreds of pairs of reflections from the various lens surfaces (including the sensor surface). Each of these creates a distinctive ghost image at the image plane. Since it is impossible to eliminate all ghost images the most effective approach involves reducing the visibility of the ghost images by ensuring that they are either very large and dim, or else very de-focused. These ghost images must be carefully controlled during the design process.

The de-ghosting phase of the design is often more difficult than the initial aberration-correction phase, but the quality results are well worth the effort. In most cases it is possible to reduce ghosting to a far lower level than is commonly encountered when a flat filter is added to the front of the lens. Figure 7 below shows a ghosting pattern for the 125mm lens when the lens is used alone (top) and when the lens is used with a high-performance front filter with 99.5% efficient anti-reflective coatings (bottom). The brightness of the patterns has been enhanced to make them visible. In both cases all lens surfaces are given 99.5% efficient coatings. Note that the 125mm lens, used alone, includes the slightly curved protective front element shown in Figures 1 and 2. The bright ghost image in the lower left of the pattern is due to reflection/scattering from the sensor followed by reflection from the two surfaces of the front mounted filter. By comparison, the ghosting produced by the 125mm lens alone is dim and spread out. In practice this is essentially invisible. The inherent ghosting problems presented by front mounted flat filters is the reason that the fixed front protective element in the 125mm lens has a a quasi dome shape.

![125mm Lens, No Front Filter](image1)

![125mm Lens, With Front Filter](image2)

Figure 7. Ghosting pattern for the 125mm lens used alone (top) and with a front filter (bottom).
Mechanical Features

A brief description of some of the mechanical features of the new lens series is given below.

Uniform Dimensions

All focal lengths in the 70mm prime lens series have a common location and size for the focus and iris external control gears as shown in Figure 8 below. All lenses share a common front diameter of 126mm. The manual focus markings are located on this large diameter for ease of use, in order to maximize their legibility and accuracy. All lenses shorter than 125mm EFL are 200mm long, as measured from the front of the outer barrel to the image plane (160mm to the flange surface). For focal lengths of 125mm and longer, the length increases gradually as necessary to accommodate the optics.

![Figure 8. Exterior lens drawing showing features and dimensions common to the 70mm series.](image)

Cammed Focus

In order to reduce the friction, and therefore the load on the focusing motor, all moving groups are mounted on linear ball bearings. Their precise positioning is controlled by cams. All the moving groups are internal. This greatly improves the mechanical robustness, and allows for
reasonable sealing against dust. By using a non-linear cammed focus, the angular spacing of the focus ring markings for larger object distances can be increased.

**Ultra-round Iris**

The iris uses 15 rounded blades for an almost perfectly round shape for all T-stops, as illustrated in Figure 9. This is important for maintaining an ideal shape for the out-of-focus highlights (bokeh) regardless of aperture. In addition, the iris has a special design to linearize opening area as a function of control tab angle. As a result, the engraved stops on the external iris gear are evenly spaced.

![Figure 9. Iris assembly with the shape of the aperture at T2.8, T5.6 and T22](image)

**Lightweight**

Although all of the lenses have a large outer diameter, most of them weigh only about 2kg. This required aggressive weight reduction measures. Wherever possible, the glass elements were chamfered close to the edge rays. The wall thicknesses of the metal parts were kept to a minimum, and all the main barrel parts have machined slots and holes for weight reduction, as illustrated in Figure 10.

![Figure 10. Wherever possible, metal parts have been perforated and slotted to save weight.](image)
Electronic Features

Unlike previous cine lenses, the new 70mm series not only transmits metadata to the camera, but also has precise internal motorized control of focus and aperture. While the lenses retain all of the traditional geared manual controls that cinematographers are accustomed to, they also provide the latest technical innovations. Some of the electronic features are detailed below.

**Encoders and Metadata**

A full set of high resolution metadata is transmitted to the camera, including focus distance, aperture, temperature, and lens identification. Focus is determined via a high-resolution magnetic encoder mounted to the focus cam barrel. The aperture data is determined by an encoder integral to the iris drive motor, plus a magnetic home switch mounted to the iris drive cam barrel. Metadata transmission to the camera is done via a rugged connector located on the flange surface, as shown in Figure 11. The rectangular opening at the rear is a field stop that serves to minimize stray light.

![Figure 11. Lens mount assembly with contact pins](image)

**Motorized Focus and Iris**

The lenses are designed primarily for motorized operation of focus and iris, both controlled by the camera body. Two slim, but powerful micro servo motors with gear head and rotary encoder, are used to drive both functions.

At the same time, it is possible to attach a manual follow focus and iris drive to the external gears. There are no clutches to disengage the motors during manual operation, but a suitable gear ratio is used to allow the motors to spin without damage. By keeping the linkage between external focus gear and internal focus cam permanently engaged, the external distance scale always indicates the correct focus distance, whether in manual or motorized mode.
Conclusion

A series of lenses with unprecedented image quality has been designed for a new 70mm digital format developed by Panavision. Unusually good correction of both chromatic and monochromatic aberrations is made possible by taking advantage of a short working distance. As a result of this excellent optical correction, cinematographers will be able to create a truly immersive viewing experience without any disturbing artifacts caused by lens aberrations.

All of the new lenses are designed for optimal performance with the filter pack used in the new 70mm digital camera system. The lenses share a common outer diameter and geared control locations, and most of the lenses share a common length. In addition to traditional externally geared controls, all lenses have internal motors for focus and aperture. High resolution metadata is continuously transmitted to the camera, including focus distance, aperture, temperature, and individual lens identification. A replaceable internal filter near the aperture stop permits a wide range of creative effects, including soft-focus.

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Patents