Optical Short Course International

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What's "In The Box"?

Optics of Digital Projectors Weekly Newsletter

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Telecentric Projection Lenses in Digital Projectors

By Michael Pate, President, OSCI

Telecentric projection lenses have some additional special properties that make them desirable for use in certain kinds of digital projector light engines. The projection lens assembly or projection lens must create a high fidelity image of the object or modulator on the screen for the viewer. This sounds easy until we add on all of the performance constraints and opto-mechanical limitations under which the projection lens must operate. Projection lenses fall primarily into two categories, telecentric and non-telecentric and in this version of In The Box we are going to discuss telecentric projection lenses as last week we discussed regular projection lenses which are non-telecentric.

Function of Projection Lens

We learned about these functions last week, but it might be good to review them again and to notice that we added the telecentricity specification. In digital projectors the job of the projection lens is to create a high fidelity image of the modulator surface or object on the screen or image plane. This function is similar to a projection lens in a slide projector, film projector, overhead projector, and microfilm reader on the object to be projected is different.

In a slide, film, overhead and microfilm projectors the object is transparent just like LCD panels. In DMD and LCoS projectors the object is opaque and reflective. Being opaque and reflective means that the panel must be illuminated and projected from the same side of the panel or object. This often makes the opto-mechanical space in front of a panel very valuable because both the illumination system and the imaging system want to share that space.

The projection lens must capture the light that reflects or is transmitted from the panels and get it to the screen, with high transmission, while magnifying the size of the panel by about 120 to 150 times. The projection lens must be able to get the image into focus when the projector is placed at different distances from the screen. Some projection lenses must also be able to zoom the size of the image because of different distances from the screen and also once resized to focus the image as well.

Typical Projection Lens Design Parameters

Effective Focal Length: 28mm
Back Focal Distance: 42 mm
Throw Distance: 2 – 10 meters
Zoom Ratio: 1.4:1
Field of View: 58 Degrees
Lens Speed or Aperture Ratio: f/2.4
Projection Lens Offset: 150%
Transmission: > 85%
Distortion: < 1%
Polychromatic MTF: > 60% center, > 40% corner at 72 lp/mm
Lateral Color: < 0.5 pixel full field
Telecentric: < +/- 0.2 degrees across the field of view

See Volume 1 Number 29 for a discussion of each of these design parameters above. We will discuss the telecentricity attribute in this weeks e-newsletter.

Telecentricy

There are several ways to describe the property of telecentricity in an optical system and we will try to describe each of the different definitions and show some illustrations to help make things clear. In an imaging system like a projection lens there is an object and an image. There is a physical aperture stop in an imaging system. This physical aperture stop is the aperture that limits the cone of light from the axial object point. This is often a metal aperture or the diameter of a lens seat or the edge of an optical element. Something limits the cone of light on axis.

An imaging lens can be telecentric on the object side or on the image side or both sides. In metrology and optical gauging or vision system the lenses are often object side telecentric or telecentric in object space where the object is being image onto the CCD detector. In lithography system the projection lens is typically telecentric in image space where the image of a lithography mask is being imaged onto a silicon wafer. In digital projectors the projection lenses are telecentric in object space.

In a projection lens assembly we can say in general (weasel words for this is not always true) that the aperture stop is somewhere in the center of the lens assembly. This means that there are a few lenses between the object and the aperture stop and that there are a few lenses between the aperture stop and the image plane.

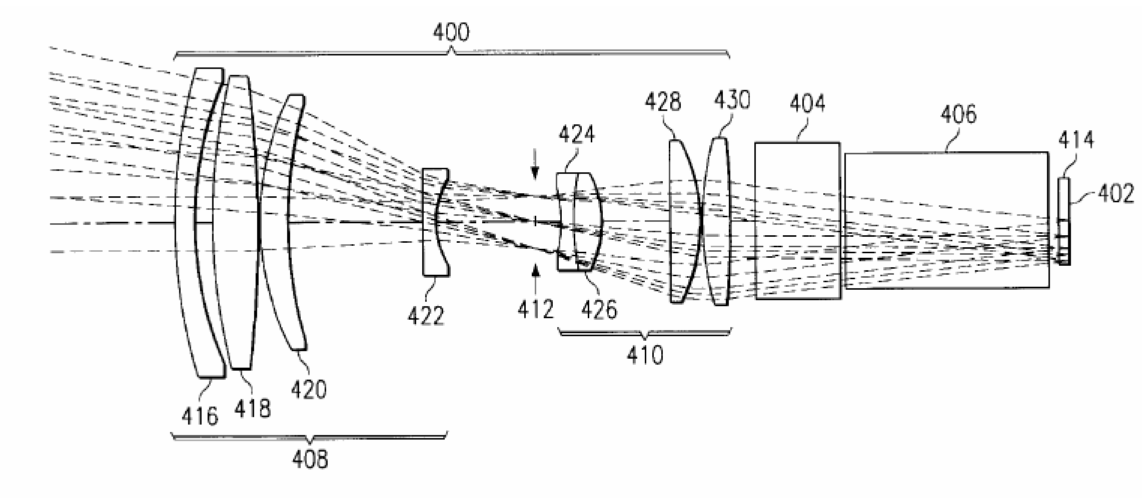

Figure 1. Telecentric Projection lens
Graphic Courtesy of US Patent US 5,914,818

For example lets look at the four optical elements in Figure 1 that are between the image plane on the left and the aperture stop labeled 412. These four optical elements 416, 418, 420, and 422 together have a focal length and a principle plane. These four optical elements with power and a focal length will form an image of the aperture stop in image space. This image of the aperture stop in image space is called the exit pupil. It may be real or virtual and it has a location and a diameter. If we were to physically look into the front of this projection lens assembly through element 416 we would see the exit pupil – ie. The image of the physical aperture stop 412 in image space.

If we look at the optical elements between the aperture stop and the object plane in Figure 1 we will see that there are four lenses and three windows. These four powered optical elements labeled 424, 426, 428, and 430 and the windows labeled 404, 406, and 414 all combine to a certain focal length. These elements together will form an image of the aperture stop in object space. This image of the aperture stop in object space is called the entrance pupil of the projection lens. If this group of lenses in object space is located with its principle plane at one focal length away from the aperture stop then the image of the aperture stop is located at infinity, see Figure 2 below.

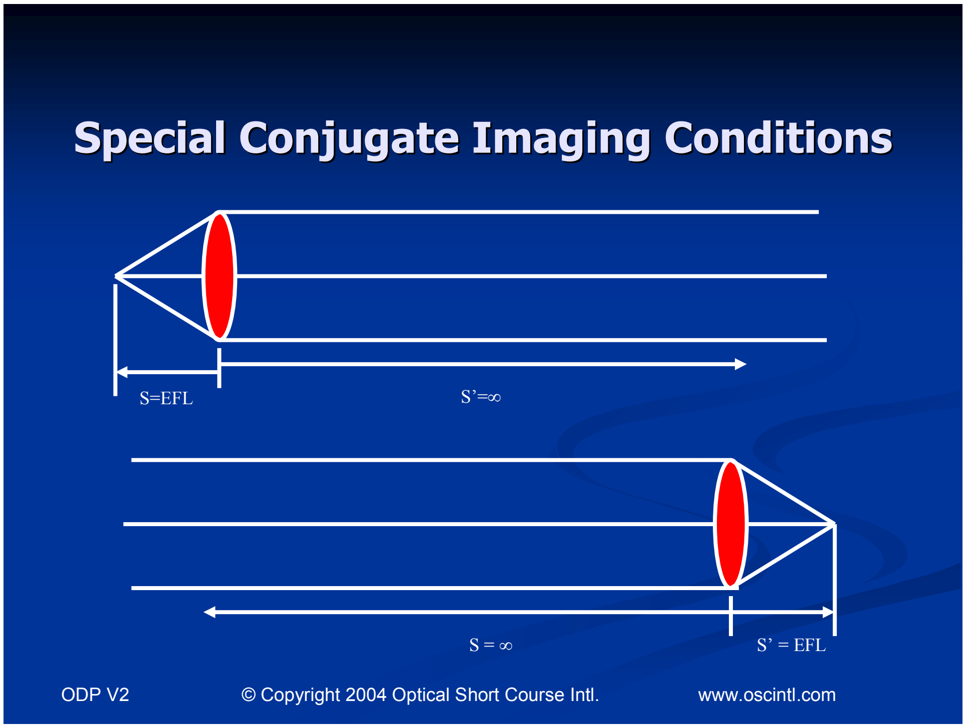

Figure 2. Aperture Stop Located at EFL Away From Lens
From OSCI's Optics of Digital Projectors DVD Course
http://www.oscintl.com/prod01.htm

This is the aperture stop definition of telecentricity: The image of the aperture stop is located at infinity. If the image of the aperture stop in object space is located at infinity then the lens is said to be object side telecentric. If the image of the aperture stop in image space is located at infinity then the lens is said to be image side telecentric.

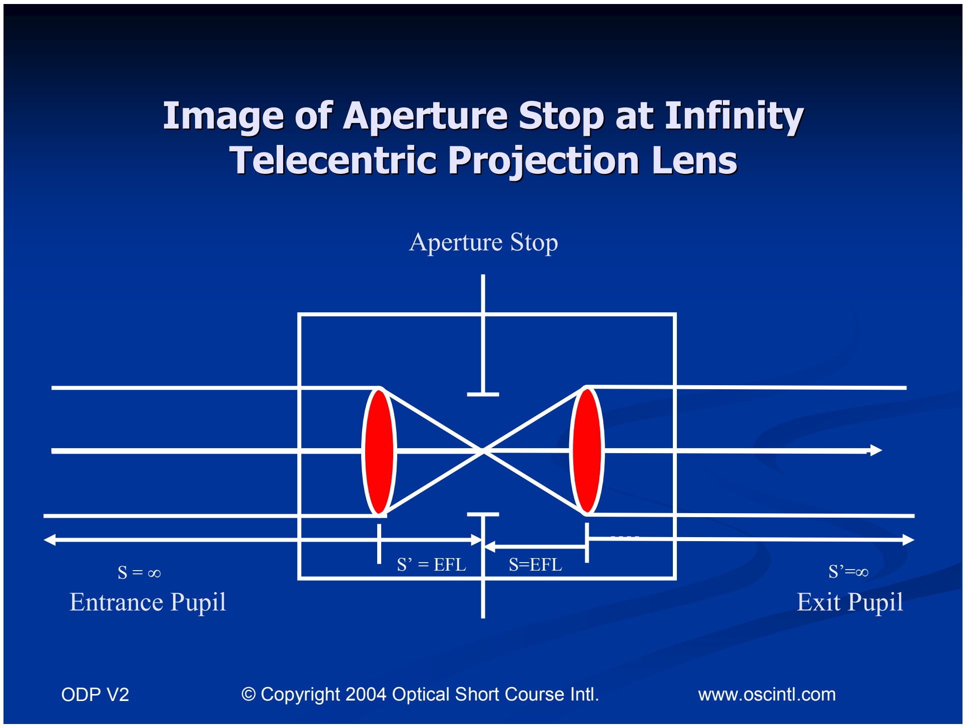

Figure 3. EFL and F/# of a Projection Lens
From OSCI's Optics of Digital Projectors DVD Course
http://www.oscintl.com/prod01.htm

If you don't like the aperture stop definition of a telecentric lens then lets try the chief ray definition. If we consider a non-telecentric camera lens for example in Figure 4 on the left we will see that the three cones of light corresponding to the top edge, axial and bottom edge field points are shown in blue, white, and green respectively. You will notice that the chief ray of each of these fields crosses the optical axis in the center of the lens or at the aperture stop. The chief ray of each of these field cones intersects the image plane (white plane) at an angle.

If we consider that the image plane may be slightly out of focus on the short side (green plane) of the true image plane (white) or on the long side of focus (red plane). If we are long or short in focus it is clear that the spots at these out of focus locations would be larger in diameter as shown. The center of these larger spots can still be found and are denoted by the distance between the green lines for the short focus shown as a green vertical arrow, or the distance between the red lines for long focus shown as a red vertical arrow.

If this non-telecentric camera lens was being used in a metrology application we can see that if we were slightly out of focus short or long we would measure a different part size as shown with the green and red vertical arrows. Now look at the image side telecentric lens on the right of Figure 4. We can see that the chief ray of each field cone is perpendicular to the image plane. Now if we are slightly short or long in focus the centroids of the spots will still be the same distance apart vertically.

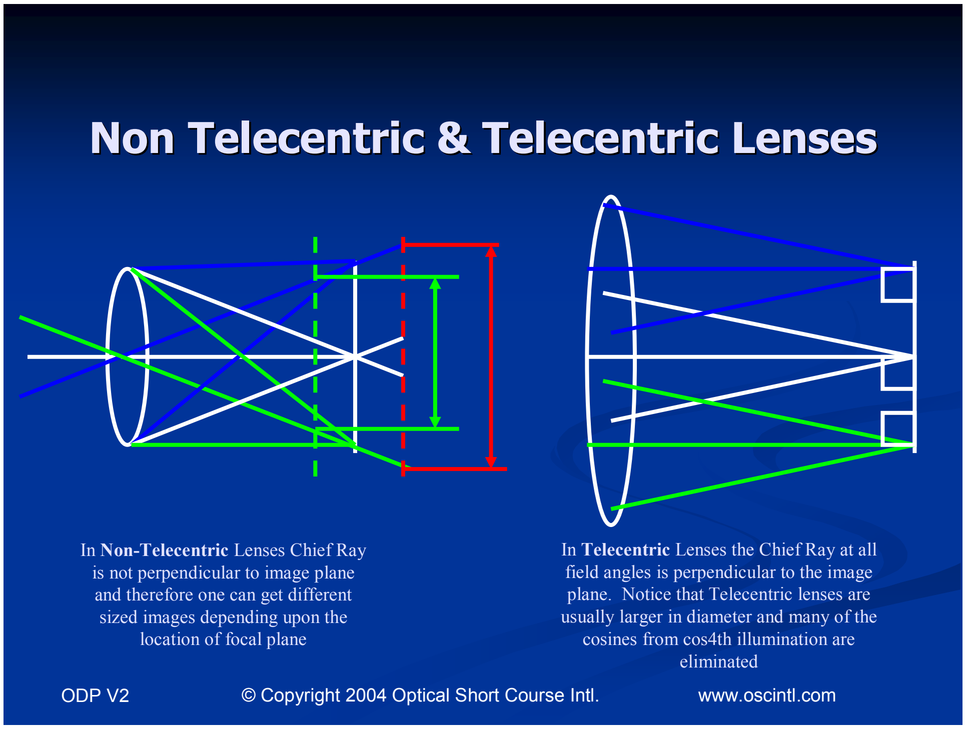

Figure 4. Non-Telecentric and Telecentric Lenses
From OSCI's Optics of Digital Projectors DVD Course
http://www.oscintl.com/prod01.htm

The chief ray definition for the telecentric lens is that the chief ray at each field point is perpendicular to the object plane in object side telecentric lenses and perpendicular to the image plane in image side telecentric lenses.

You will notice another feature of the telecentric lens that the optical elements must be larger in diameter on the telecentric side of the aperture stop so that the full cone at each field point can be imaged or transmitted through the system. There is a benefit for optical coatings as well. If we consider the range of angles that a coated window will see from the telecentric lens in Figure 4 we can see that there is about a +/- 15 degree angle of incidence from the chief ray of each field cone. If we look at the non-telecentric lens we can see that the coatings will need to be designed for the full range of chief ray angles +/- 20 degrees plus the largest marginal rays +/- 15 degrees or about +/- 35 degrees angle of incidence. The coatings with the larger range of angles of incidence will be more complicated and costly and will probably not perform as well.

If we consider the non-telecentric rays propagating through a window or prism (unfolded prism or tunnel diagram) we can see that the optical path through the window or prism will vary with field of view and this complicates the optical design of the projection lens imaging performance and design.

The telecentricity specification is < +/- 0.2 degrees across the full field of view. On axis the telecentricity should be perfect or ninety degrees to the image or object plane. As the field is increased from the axis radially outward to the edge of the field the telecentricity error will often gradually increase in error. The error will be increasing in error toward the edge or it may peak at a positive number at some fraction of the radial field and switch sign for the rest of the way to the edge of the field. The telecentricity specification must be met over the full field of view, at all zoom positions, and wavelength bands.

The telecentric projection lens assembly will also have a much more uniform transmission across the field of view compared to a non-telecentric projection lens assembly. The more uniform optical transmission with field comes from having the chief ray perpendicular to the object or image plane. The optical transmission is a function of the cosine of the field angle to the fourth power and this law or rule of thumb is often called the cosine to the fourth law. We will learn about this law in a future edition of In The Box.

Summary

We have looked at the function and parameters of a telecentric digital projector projection lens assembly in this issue. We now know that a digital projector requires are projection lens from a specific category called an inverse telephoto lens. We looked at two different definitions of telecentricity: the aperture stop definition and the chief ray definition. The coating implications of reduced angle of incidence across the field of view have been described. The optical transmission of the projection lens is more uniform when it is telecentric because a reduction in the chief ray angle. We have also learned about some of the more advanced techniques for improving digital projector performance by projection lens design techniques.

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