Advanced Optics for Vision

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Schneider Optics, Inc.
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Machine Vision

Machine Vision (MV) ≡ Interpretation of an image of an object or scene through the use of optical non-contact sensing mechanisms for the purpose of obtaining information and / or controlling machines or processes.
• Modulation Transfer Function (MTF)
  – What is it
  – Aberration effects
  – f/number effects
  – Manufacturing effects
  – How should you use it
The MTF (Modulation Transfer Function) describes the quality of an imaging system with respect to sharpness and contrast.

**Brightness Distribution:** 1 = white  0 = black

Modulation (MTF) = "Difference in Brightness" Modulation as a function of the fineness of lines (No. of line pairs/mm)

\[
\text{Modulation} = \frac{I(\text{MAX}) - I(\text{MIN})}{I(\text{MAX}) + I(\text{MIN})}
\]

**Intensity / Brightness**

\[
\text{MTF} = \frac{\text{Modulation In Image}}{\text{Modulation In Object}}
\]
The MTF depends on the orientation of the object structures. Therefore the MTF is typically stated for test grids orientated in tangential and radial direction to the optical axis.

Figure 2
Radial and tangential orientation of object patterns.
Classic MTF Plot

POLYCHROMATIC DIFFRACTION MTF

DOUBLE GAUSS
THU JUL 14 2005
DATA FOR 0.4861 TO 0.6563 μm.
SURFACE: IMAGE

SCHNEIDER OPTICS, INC.
STUART W. SINGER
DOUBLE GAUSS 28 DEGREE FIELD.ZMX
CONFIGURATION 1 OF 1
How are Contrast and Resolution Linked

• Resolution and contrast are closely linked.

• Resolution is defined at a specific contrast.

• Contrast describes the separation in intensity between blacks and whites.

• For an image to appear well defined black details need to appear black, and the white details need to appear white.

• The greater the difference in intensity between a black and white line, the better the contrast.

• The typical limiting contrast of 10-20% is often used to define resolution of an CCD imaging system (we will come back to this).

• For the human eye a contrast of 1-2% is often used to define resolution.
Final Lens System MTF is comprised of numerous factors:

- Actual lens Design
- f/number being used
- Lens Performance with respect to actual Working Distance (Magnification)
- Manufacturing Tolerances / errors
- Focus position
- Pixel Size……….. To be Discussed
- Object contrast
- Lighting
- Actual Blur Circle
- Anti-Reflection Coatings / Veiling Glare

A reputable optical company should be able to provide you with MTF tolerances from Theoretical vs. what you actual purchase. Also other parameters (such as focal length tolerances, etc.....) should be provided.
What MTF do I need in my “Lens”?

Typical criteria for a lens selection process:
- 30% contrast at 0.67*Nyquist frequency
- 30% at Nyquist frequency (but risk of Moiré-effects)

Note:
The total system’s MTF is the product of the lens’s MTF, filter’s MTF, camera MTF and the MTF of the electronics.
Resolution Conversion

Lp/mm or Cy/mm $\rightarrow$ Cy/mrad

$Lp/mm = \frac{1}{(f') \tan[(1000)(Cy/mrad)]^{-1}}$

$Cy/mrad = \frac{1}{(1000) \tan^{-1} [(Lp/mm)(f')]^{-1}}$

NOTE: Have Calculator in Radian Mode....! Most Optical Design Programs can do this conversion
Diffraction vs. Geometrical MTF

**Diffraction MTF Polychromatic**

**Geometrical MTF Polychromatic**

*Note: Geometrical MTF is approx. 20% >*
Basics Optical Aberrations
Spherical Aberration = can be defined as the variation of focus with aperture.

**Paraxial Focus** = Where light infinitely close to the optical axis will come to focus

**Transverse Spherical**

**Longitudinal Spherical**
Spherical Aberration

No Spherical Aberration

With Spherical Aberration
An Astigmatic Image Results When Light In One Plane (YZ) is Focused Differently From Light In Another Plane (XZ)

Astigmatism = Essentially A Cylindrical Departure of The Wavefront From Its Ideal Spherical Shape
Astigmatism

<table>
<thead>
<tr>
<th>Original</th>
<th>Compromise</th>
</tr>
</thead>
<tbody>
<tr>
<td>aio</td>
<td>aio</td>
</tr>
<tr>
<td>Horizontal Focus</td>
<td>Vertical Focus</td>
</tr>
</tbody>
</table>

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**Coma**

**Coma:** can be defined as the variation of magnification with aperture.

- The Central or Chief Ray usually defines the image height
- A Comatic Image occurs when the outer periphery of the lens produces a higher or lower magnification than dictated by the Chief Ray
- Coma can be controlled by shifting the aperture stop and selectively adding elements
Coma

No Coma

With Coma
In the absence of Astigmatism, the image is formed on a curved surface called the “Petzval” Surface.

For a single element as shown above, the Petzval Radius is approximately 1.5 times the focal length.

This is for glass of 1.5 refractive index.
Field Curvature

No Field Curvature

With Field Curvature
Geometric Distortion

Distortion is a change in magnification as a function of field of view.

\[ y' = f' \tan \theta \]

Real Chief Ray

Paraxial Chief Ray

Distortion (Positive)

Height

Warning – TV Distortion ≠ Geometric Distortion
Geometric Distortion

\[ GD\% = \left( \frac{h' - h}{h} \right) \times 100 \]

* Note * GD (Positive = Pin & Negative = Barrel)
In projection note the effect = reversal

**EXAMPLE**

GD\% = Percent Geometric Distortion

h' = Actual Image Height (includes distortion)

h = Image Height (without distortion effect)

\[ h' = 4.95\text{mm (actual Image Height)} \]

* Note * Must Use Common Units
Geometric Distortion Pictures

No Geometric Distortion

- 40% Geometric Distortion
Keystone Distortion

Introduced because of the geometry between the Image Plane and Object Plane. Scheimpflug condition...great focus (longitudinal magnification), change in magnification with field...

See SMPT paper for projection distortion for equations
Axial Chromatic (Longitudinal)

Primary Axial Color

Residual of Secondary Axial Color
Aperture / f-stops
f/number & Depth of Focus/Field

Low f/number (fast) = steep angle rays

Small Depth of Focus & Depth of Field

Optical Axis

High f/number (slow) = small angle rays

Large Depth of Focus & Depth of Field

\[ f/\# = \text{Focal Length} / \text{Entrance Pupil Diameter} \]

As your f/number is set lower = faster = larger aperture = more light =
Smaller Depth of Focus & Smaller Depth of Field

As your f/number is set higher = slower = smaller aperture = less light =
Larger Depth of Focus & Depth of Field
f-Numbers cont.

- Increasing the aperture one full stop doubles the amount of light transmitted by the lens.
- Reducing the aperture one full stop halves the amount of light transmitted by the lens.

- **Lowering the f/number = More Light**
- **Increasing the f/number = Less Light**

<table>
<thead>
<tr>
<th>Half Stops</th>
<th>1.2</th>
<th>1.7</th>
<th>2.4</th>
<th>3.4</th>
<th>4.8</th>
<th>6.7</th>
<th>9.5</th>
<th>13.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4</td>
<td>2</td>
<td>2.8</td>
<td>4</td>
<td>5.6</td>
<td>8</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

**Full Stops (cont.):** 16, 22, 32, 45, 64, 90

One Full Optical Stop = Factor 2x or 1/2x (Amount of Light)
Effective f/number (Finite Systems)

\[ ef = (f/#) (\beta' + 1) \]

\[ ef^* = f/# \left[ (\beta' / \beta'p) + 1 \right] \]

**EXAMPLE**

\[
\begin{align*}
\text{f/4.0} \\
\beta' = 1 \\
\text{ef} = 8.0
\end{align*}
\]

Finite Systems - Employ Your EF Value For The f/#

Effective f/number should be used when calculating Depth of Field & Depth of Focus when imaging “Close-up” Objects and/or low magnifications (1:4 to 4:1) and needs to be used for any lighting calculation

* = Use when the pupil magnification of the lens is known
Optical Parameters
Diffraction limited imaging: the Airy disc

For a point-like source the wave fronts on the object side are spherical waves and limited in their extent by the EP. On the image side these wavefronts are limited by the EXP. For a diffraction limited system these wavefronts are again spherical with their center in the image point O'.

**Note:** A diffraction limited (or perfect) optical system is given if the wavefront in the EXP deviates less than $\lambda/4$ from a sphere (Rayleigh-criterium)

Because of the limitation of the spherical wavefronts the image point is no more a point without extension but a blurred disc, the diffraction disc.

The extent of this disc depends (besides the wavelength $\lambda$) only on the form and extent of the limiting opening. For circular symmetric limitations (as usual in optics) the relative illumination distribution in the image plane is the so called Airy disc. For image points on optical axis this disc is rotationally symmetric.

$$\Theta = 2.44 \lambda f/#$$

$$\Theta \approx 84\% \ Total \ Energy$$
Airy Disk Diameter

The Airy disk is the smallest point a beam of light can be focused. The disk comprises rings of light decreasing in intensity and appears similar to the rings on a bulls-eye target. The center bright spot contains approximately 84% of the total spot image energy, 91% within the outside diameter of the first ring and 94% of the energy within the outside diameter of the second ring and so on.

Note: must use all common units – Wavelength need to be in “mm”

\[
\lambda = 632.8\text{nm (Red = HeNe)} = 0.0006328\text{mm}
\]

<table>
<thead>
<tr>
<th>f/#</th>
<th>Diameter of Airy Disk</th>
<th>Diameter of Airy Disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>f/1.0</td>
<td>0.00154mm</td>
<td>1.54\mu m</td>
</tr>
<tr>
<td>f/1.4</td>
<td>0.00216mm</td>
<td>2.16\mu m</td>
</tr>
<tr>
<td>f/2.0</td>
<td>0.00309mm</td>
<td>3.09\mu m</td>
</tr>
<tr>
<td>f/2.8</td>
<td>0.00432mm</td>
<td>4.32\mu m</td>
</tr>
<tr>
<td>f/4.0</td>
<td>0.00618mm</td>
<td>6.18\mu m</td>
</tr>
<tr>
<td>f/5.6</td>
<td>0.00865mm</td>
<td>8.65\mu m</td>
</tr>
<tr>
<td>f/8.0</td>
<td>0.01235mm</td>
<td>12.35\mu m</td>
</tr>
<tr>
<td>f/11</td>
<td>0.01698mm</td>
<td>16.98\mu m</td>
</tr>
<tr>
<td>f/16</td>
<td>0.02470mm</td>
<td>24.70\mu m</td>
</tr>
</tbody>
</table>

ADD = (2.44)(f/#)(wavelength)

Spot Size vs. Pixel Size related to diffraction effects
Optical Definitions

**Airy Disk** = The central peak (including everything interior to the first zero or dark ring) of the focal diffraction pattern of a uniformly irradiated, aberration-free circular optical system (Lens)

**Circle of Confusion** = The image of a point source that appears as a circle of finite diameter because of defocusing or the aberrations inherent in the lens design or manufacturing quality

**Blur Circle** = The image formed by a lens on its focal surface (image plane) of a point source object. The size of the blur circle will be dictated by the precision of the lens and the state of focus. The blur can be caused by aberrations in the lens, defocusing and manufacturing defects.

**f/number (f/#)** = The expression denoting the ratio of the equivalent focal length of a lens to the diameter of its entrance pupil. Lower f/# on a well corrected lens = small spot size in the image plane – Larger f/# = larger spot size in the image plane.
MAGNIFICATION ($\beta'$)

$$\beta' = \frac{y'}{y}$$

* Note *  Must Use Common Units

**EXAMPLE**

$\beta' = \text{Magnification}$

$y' = \frac{1}{2} \text{ Image Height (CCD Length)}$

$y = \frac{1}{2} \text{ Object Height (1/2 FOV)}$

$y' = 4.4 \text{mm (1/2 CCD Length)}$

$y = 50 \text{mm (1/2 FOV)}$

$\beta' = 0.088$

$1/\beta' = 11.36x$

Reduction of the Object

When $\beta' < 1.0 = \text{(Reduction of Object Size)}$

When $\beta' > 1.0 = \text{(Enlargement of Object Size)}$
Magnification (PSS)

- **Pixel Sampled Size (PSS)** = Footprint of one Pixel in Object Space.

\[ \text{Pixel Size (PS)} \]

**Magnification** = \( \beta' = \frac{\text{PS}}{\text{PSS}} \)

\[ \text{Object Distance} \]

\[ \text{Focal Length} \]

\[ \text{Pixel Size} \]

\[ \text{Focal Length} \quad = \quad \text{Object Distance} \]

Note: Can be use also for - CCD Size / Focal Length = FOV / Object Distance

* Note * Must Use Common Units
Magnification/Resolution DPI

Typical Document Scanning Specification

Dots Per Inch (dpi)

256 dpi

1 inch

Dots Per Inch (dpi) = 256

1(dpi) = 1/256 = 0.003906 inch = 1 dot

0.003906" / 0.03937 = 0.099229

1 dot = 0.09922mm

Sensor (example)

Pixel Size (PS) = 13 microns

PS = 0.013mm

Pixel Sampled Size (PSS) = 0.09922mm

Footprint of the pixel in Object Space

Magnification

β' = PS / PSS

β' = 0.013 / 0.09922

β' = 0.13102

1/β' = 7.63x reduction

1 Pixel will Sample 1 Dot
Resolution (Object / Image)

Minimum Defect Size

How Many Pixels do I need to Cover (sample) The Smallest Defect I am Trying to Resolve?

Pixel Sampled Size (in object space) = PSS

Object Resolved Distance (ORD) = 2(PSS)

PSS = Pixel Sampled Size in Object Space (footprint)

CONSIDER
1) What is the size of the smallest defect/object I am trying to resolve?
2) What is the size of my Pixel?
3) How many pixels do I need to resolve my smallest defect?
4) Items 1,2,3 from above define my Optical Magnification!

Example: Why can’t I count sheets of stacked paper?

Typical Minimum = 2 Pixels to sample
On/Off needed to find Edge
A typical lens for Document Scanning:
- Focal Length = 50mm
- f/# = 2.8
- Pixel Size = 0.013mm
- Magnification = 0.14286 (7x reduction)

\[ D_{\text{focus}} = (\beta')^2 \times D_{\text{field}} \]

\[ D_{\text{focus}} = 0.08\text{mm} \]
\[ D_{\text{field}} = 4.04\text{mm} \]
Hyperfocal Distance

The object distance at which a camera must be focused so that the Far Depth of Field just extends to infinity.

\[ H = \frac{(f')^2}{(f/\#)(c)} \]

**EXAMPLE**

Focal Length \((f') = 50\text{mm}\)
F-Number \((f/\#) = 5.9\)
Circle of Confusion \((c) = 0.010\text{mm}\)
i.e. Pixel Size or any Value

\[ H = 42,373\text{mm} \]

*Note* Must Use Common Units
DEPTH OF FIELD (Far)

Depth of Field = The amount by which the object may be shifted before the acceptable blur is produced.

\[
\text{Depth of Field (Far)} = \frac{(H) \times (a)}{H - (a - f')} \]

- \(H\) = Hyperfocal Distance
- \(f'\) = Focal Length
- \(a\) = Focus Distance

(distance from lens front nodal point to the principal plane of focus at the object)

EXAMPLE

- \(f' = 50\text{mm}\)
- \(a = 1000\text{mm}\)
- \(H = 42,373\text{mm}\)
- \(\text{FAR} = 1,023\text{mm}\)

FYI – Depth-of-Field (Far & Near) Equations should be used for objects that lie between (300mm to 2,500mm) from the lens/camera

* Note * Must Use Common Units
DEPTH OF FIELD (Near)

Depth of Field = The amount by which the object may be shifted before the acceptable blur is produced.

Depth of Field (Near) = \( \frac{(H) \times (a)}{H + (a - f')} \)

<table>
<thead>
<tr>
<th>H = Hyperfocal Distance</th>
<th>f' = Focal Length</th>
<th>a = Focus Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(distance from lens front nodal point to the principal plane of focus at the object)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EXAMPLE

f' = 50mm
a = 1000mm
H = 42,373mm

NEAR = 977mm

* Note * Must Use Common Units
Total Depth of Field = FAR - NEAR

EXAMPLE

\[ f' = 50\text{mm} \]
\[ f/\# = 5.9 \]
\[ C = 0.010\text{mm} \]
\[ a = 1,000\text{mm} \]
\[ H = 42,373\text{mm} \]
\[ \text{NEAR} = 977\text{mm} \]
\[ \text{FAR} = 1,023\text{mm} \]
\[ \text{TOTAL} = 46\text{mm} \]
DEPTH OF FIELD (cont.)

To be used for close-up object distances & when your magnification is known.

Depth of Field (Total) = \( \frac{2C(\text{EF})}{(\beta')^2} \)

**EXAMPLE**

\[
\begin{align*}
\text{EF} &= 8.0 \\
\beta' &= 0.5 \\
C &= 0.010 \text{mm} \\
\text{Depth of Field} &= 0.64 \text{mm}
\end{align*}
\]

Slowing a lens up (Larger f/#) increases Depth of Field (too slow = diffraction effects)

* Note *  Must Use Common Units
How Can Apertures Be Used To Improve Depth Of Field?

- If we express our resolution as an angularly allowable blur ($\omega$) we can define depth of field geometrically.

- Below we see how two lenses with different f/#s have very different DOF values.

Note: Increasing the f/# vs. spot size


Edmund Optics
More Points To Remember

- **DOF** is often calculated using diffraction limit, however this is often flawed if the lens is not working at the diffraction limit.

  - Increasing the f/# to increase the depth of field may limit the overall resolution of the imaging system. Therefore, the application constraints must be considered.

  - An alternative to calculating DOF is to test it for the specific resolution and contrast for an application.

  - Changing the f/# can also have effects on the relative illumination and overall system resolution illumination of the image obtained.

- **General rule of thumb** – I use (2 x Pixel size) for my blur circle
Depth of Focus

Depth of Focus = is the amount by which the image may be shifted longitudinally with respect to some reference plane and introduce no more than the acceptable blur.

\[
\text{Depth of Focus} \, (1/4\lambda \, \text{OPD}) = \pm \frac{\lambda}{2N \sin^2 U_m}
\]

* Note * Must Use Common Units

\( \lambda = \text{Wavelength of Light} \)

\( N = \text{Index of Final Medium} \)

Air = 1.0

\( U_m = \text{Final Slope of Marginal Ray} \)

\( U = \arcsine \, (\text{NA}) \)

\( \text{OPD} = \text{Optical Path Difference} \)

Depth of Focus = \( \pm \, (f/#) \, (\text{Pixel Size}) \)

IFF \( \lambda = \text{Visible Light} \)

Please keep in mind \( f/# \) vs. EF/f#
Lens Design Types and Form Selection

How Lens Forms change with Working Distance & Magnification
LENS DESIGN TYPES

f/# =

Parabola
Achromatic Doublet
Cassegrain
Ritchey-Chretien
Unobscured 3-Mirror
Schmidt-Cassegr.
Schmidt
Petzval
Split Triplet
Triplet
Tessar
Land-Scape
Angulon
Fisheye
Optical Disk Objective
Microscope Objective
Full Field Angle (degrees)
Machine Vision (Possible) Lens Types

- Telecentric
- Macro
- Macro Zooms
- Zooms
- Large Format Taking
- Fish-eye
- Telephoto
- Inverse Telephoto
- Retrofocus
- Mirror / Catadioptric
- Micro
- Afocal
- Very Wide Angle
- Relay
- Double Gauss
- Petzval
- F-Theta
- Projection
- Enlarging
- Cylinder Anamorphic
- Doublets
- Triplets
- ETC...
Issues That Factor Into A Lens Design / Performance
**Vignetting**

In an optical system, the gradual reduction of illumination as the off-axis angle increases, resulting from limitations of the clear aperture of the elements (or mechanical constraints) within the lens system.

**Lens Design Tool or Trick** = Sometimes a lens designer induces Vignetting to intentionally block some of the off-axis rays in order to produce greater off-axis performance. This does not effect ray near the optical axis. Less light falls on the off-axis spot/image area creating a large spot size (higher f/#) but creating a better image at the penalty of loosing light.
**Cosine Fourth Law** = A formula indicating that, for an imaging lens system, the image brightness for off axis points will fall off at a rate proportional to the \( \cos^4 \) of the off axis angle.

**Example** = \( \theta = 20\, \text{deg} \) – the relative illumination = \( \cos^4 (20) = 80\% \)

20% less light off axis with respect to on axis
Relative illumination = takes into account $\cos^4$ loss and vignetting and is typically plotted and part of your lens performance package/data.

TFOV = 40 deg = +/- 20 deg.

Relative Illumination slightly below 80% due to small vignetting factors in the lens design.
Fall-off of illumination in % from the optical axis to the maximum image height - also called vignetting. One differentiates the natural vignetting, which depends on the $\cos^4$ of the angle of field (can not be prevented) and those, which is intentionally implemented by the optics designer, in particular for lenses with high relative apertures.
Stray Light:
Also known as the expression scattered light. Stray Light is caused by reflections within the optical system.

By thorough matting (Blacking) the lens edges and grooving or matting of the internal mechanical parts, the stray light can be further reduced.

Quality of antireflection coatings

Good lens systems have a stray light ratio of less than 3%.
Lens Performance Changes with (Working Distance/Magnification)

CINECON 1.8/16

\[ f = 18.4 \text{ mm}, \quad \theta_f = 2.59\% \]

\[ w_p = 114 \text{ mm}, \quad w_s = 17.4 \text{ mm} \]

\[ \theta_p = 18.5 \text{ \(^\circ\)}, \quad \theta_s = 4.1 \text{ \(^\circ\)} \]

\[ HIF = 15.9 \text{ mm}, \quad \phi = 37.5 \text{ \(^\circ\)} \]

RELATIVE ILLUMINATION

The relative illumination is shown for the given focal distances or magnifications.

\[ f/1.6, \quad f/4.0, \quad f/6.0 \]

\[ \theta = 0.0000, \quad \alpha = 6.0, \quad \theta = 0.0000, \quad \alpha = 6.0, \quad \theta = 0.0000, \quad \alpha = 6.0 \]

DISTORTION

Distortion is shown for the given focal distances or magnifications. Positive values indicate pincushion distortion and negative values barrel distortion.

\[ \theta = 0.0000, \quad \gamma = 3.0, \quad \theta = 0.0000, \quad \gamma = 3.0, \quad \theta = 0.0000, \quad \gamma = 3.0 \]

TRANSMITTANCE

Relative spectral transmittance is shown with reference to wavelength.

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Ringstrasse 162 55549 Bed Krefeld Germany
Basic Lens Data

f' = focal length
u = total object size
u' = total image size
s' = image/object size ( = u'/u )
s = object/image size ( = u/u' )
OO' = object-to-image distance
s'F' = back focal distance for infinity
x' = shift from infinity
sEP = entrance pupil position
s'AP = exit pupil position
β'P = exit/entrance pupil diameter
(entr.p.d. = f'/f# = 41.5/2.8 = 14.8mm)
Our common presentation of three line pair values for tangential and radial test grid orientation over the image height (from the image center to the image corner).
Relative Illumination

Fall-off of illumination in % from the optical axis to the maximum image height - also called vignetting. One differentiates the natural vignetting, which depends on the $\cos^4$ of the angle of field (can not be prevented) and those, which is intentionally implemented by the optics designer, in particular for lenses with high relative apertures.
Mega Pixels – Sensors & Lenses
A possible definition:

A lens which is able to image an object onto a sensor with about a million pixels in a quality where the image quality is not limited by the performance of the lens.

... and more general:

A "X" megapixel lens is a lens which is able to image an object onto a sensor with about "X" million pixels in a quality where the image quality is not limited by the performance of the lens.

A simple conclusion might be:

I have a "X" megapixel sensor. I can choose any "X" megapixel lens and I will get a good performance match of the sensor and lens for my application.

... but is this the truth?
The Key Sensor Characteristics for a Lens

**Pixel size:** Defines the required resolution of the lens.

The lens resolution must be high enough to image structures onto the sensor as small as the pixels are.

Irregular structures are not well suited to describe resolution. Therefore line pairs (a dark and a bright line) are used as description. The sensor’s maximum resolution is reached when a line pair is imaged on two rows of pixels.
The limit is reached when a dark and a bright line fill 2 rows of pixels.

**Nyquist Frequency (line pairs/mm)** = \( \frac{1000}{2 \times \text{pixel size (µm)}} \)

**Example:**

Pixel size = 3.4µm  
Nyquist Frequency = \( \frac{1000}{(2 \times 3.4)} \) = **147 lp/mm**
Is the Limit the Limit?

When object structures close to the Nyquist frequency are imaged, the sensor information might not properly represent the object:

The same object can cause totally different information on the sensor when structures close or over the Nyquist frequency are resolved (e.g., **Moiré-effects**).
# Examples of MegaPixel Sensors

<table>
<thead>
<tr>
<th>Sensor Model</th>
<th>Resolution (Mpix)</th>
<th>Pixels:</th>
<th>Pixel Size:</th>
<th>Sensor Diagonal:</th>
<th>Nyquist Frequency:</th>
<th>2/3 of Nyquist:</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAI 16000</td>
<td>16</td>
<td>4872 x 3248</td>
<td>7.4µ x 7.4µ</td>
<td>43.2mm</td>
<td>68lp/mm</td>
<td>45lp/mm</td>
</tr>
<tr>
<td>KAI 8050</td>
<td>8</td>
<td>3296 x 2472</td>
<td>5.5µ x 5.5µ</td>
<td>22.7mm</td>
<td>91lp/mm</td>
<td>61lp/mm</td>
</tr>
<tr>
<td>Sony ICX 625</td>
<td>5</td>
<td>2456 x 2058</td>
<td>3.45µ x 3.45µ</td>
<td>11.0mm</td>
<td>145lp/mm</td>
<td>97lp/mm</td>
</tr>
<tr>
<td>Aptina MT9J003</td>
<td>10</td>
<td>3856 x 2764</td>
<td>1.67µ x 1.67µ</td>
<td>7.9mm</td>
<td>299lp/mm</td>
<td>200lp/mm</td>
</tr>
</tbody>
</table>

Megapixel sensors are very different => There is not "The Megapixel Lens"
Example: Lens for 10 Mpix Sensor

(10 Mpix)
Pixels: 3856 x 2764
Pixel Size: 1.67µm x 1.67µm
Sensor Diagonal: 7.9mm
Nyquist Frequency: 299 lp/mm
2/3 of Nyquist: 200lp/mm

It is extremely difficult to design and produce a lens which resolves 200 lp/mm for a practical range of working distances and iris settings. Moving towards a custom design solution.
A X-Megapixel lens can not be combined with every X-Megapixel sensor.

Even if the correct lens for the sensor is choosen, a X-Megapixel lens does typically not fulfill the requirements for a X-Megapixel sensor under all circumstances.

A lens not intended for a certain sensor resolution can also be well suited for specific application.

The smaller the pixel size, the more difficult it is to design and manufacture a suitable lens.
You should never choose a lens only because of its description.

You should know from your application, which image size, resolution, working distance and iris setting is required.

You should verify at least by the data sheets, if the chosen lens fulfills these requirements. (Data sheets need to be available!)

You should not choose Ultra small pixels, otherwise it will be hard (or impossible) to find a suitable lens.

Knowing the requirements and lens data, you may choose also a lens from a lower level series for your application.

Remember to take into consideration the airy disk / circle of confusion of a lens at a particular f/stop and realize that you are not availing yourself of all the pixels on a megapixel sensors.
• Choosing the correct lens / Type for your Application
Best Type/Form Machine Vision Lens

Magnification ($\beta'$) Calculation

Define Working Distance (max/min) WD

Focal Length ($f'$) Calculation

Determine which lenses (Required $f'$) can properly image (Required $\beta'$)

Which lens/lenses can cover Required $2y'$

Is the Lens Performance (MTF / Resolution) Commensurate with Sensor Pixel Size (Image resolution) or Object Space Require Resolution

Which lens/lenses can interface/mount to the (Require Camera Mount)
(i.e., F-Mount, C-Mount, M72, etc...)

Final Lens Selection & Associated Hardware
Best Type/Form Machine Vision Lens

**MAGNIFICATION**

- $1/\beta' \rightarrow \infty$
  - Infinity Corrected Lenses

- $\beta' \approx 0.04$ to $0.33$
  - 25x to 3x Reduction of The Object

- $\beta' \approx 0.5$ to $2.0$
  - 2x Reduction To 2x Enlargement of The Object

- $\beta' \approx 3.0$ to $5.0$
  - 3x to 5x Enlargement of The Object

- $\beta' \geq 6x$
  - Microscope Objectives 2y' Limitations

*Does Not Include Telecentric Lenses*
Best Type/Form Machine Vision Lens

$\beta' \approx 0.04 \text{ to } 0.33$

25x to 3x
Reduction of The Object

$2y' > 22\text{mm}$
- 12k/16k
- 8k
- 6k
- 4k
- 2k
- Linear
- Area

$2y' \approx 22\text{mm}$
- 1.3” (=22mm)
- 1k
- 2k
- Linear
- Area

$2y' < 22\text{mm}$
- 1” (=16mm)
- 2/3” (=11mm)
- 1/2” (=8mm)

Common Mounts:
- C-Mount
- F-Mount
- Threaded (T2, etc.)

Common Mounts:
- C-Mount
- CS Mount

$2y' = \text{Maximum Image Plane Length}$

Double Gauss
Telephoto
Inverse Telephoto
Large Format
Zoom.....
Best Type/Form Machine Vision Lens

\[ \beta' \approx 0.5 \text{ to } 2.0 \]

2x Reduction
To
2x Enlargement
of The Object

\[ 2y' > 16\text{mm} \]

- 12k/16
- 8k
- 6k
- 4k
- 2k
- 1.3" (= 22mm)
- Linear
- TDI
- Area

Common Mounts:
- C-Mount
- CS-Mount
- (2y'\leq 22mm)

\[ 2y' < 16\text{mm} \]

- 1" (=16mm)
- 2/3" (=11mm)
- 1/2" (= 8mm)

Common Mounts:
- C-Mount
- CS Mount

\[ 2y' = \text{Maximum Image Plane Length} \]
Best Type/Form Machine Vision Lens

$\beta' \approx 3.3 \text{ to } 5.0$

3x to 5x
Enlargement of
The Object

$2y' < 86\text{mm}$

- $12k/16k$
- $8k$
- $6k$
- $4k$
- $2k$
- $1.3'' (= 22\text{mm})$
- $1'' (= 16\text{mm})$
- $2/3'' (= 11\text{mm})$
- $1/2'' (= 8\text{mm})$
- Linear
- TDI
- Area

Macro
Reverse Double Gauss ($\beta' \geq 1.0$)
Long WD Objectives ($2y'' < 11\text{mm}$)

Common Mounts:
(2y' $\leq 22\text{mm}$)
C-Mount
CS-Mount
(2y'' $\geq 24\text{mm}$
F-Mount
Threaded Mounts (M95, M72, M58, Etc..)

$2y' = \text{Maximum Image Plane Length}$
• Classic Examples - Solved
1) **Supplied Parameters:**
- Camera: 16K Line Scan
- Pixel Count: PC = 16,384
- Pixel Size: PS = 0.0035mm sq.
- Sensor Length: 2y' = 57.344mm
- Lens/Camera Interface: M72 Threads
- Distance from Interface to Sensor: Internal Depth = 12mm
- FOV = 2y = 15" = 381.001mm
- Working Distance: 16" = 406mm (a bit flexible)

Magnification: \( B'/B = 2y'/2y = \frac{57.344}{381.001} = 0.15051 \)
\( 1/B' = 6.644x \) reduction of the object

2) **Set-Up Dimensions:**
- Total Track (Object to Sensor): 00' = 525.30mm
- Master Set-Up (Object to Front M72 Camera Face): MS = 513.30mm
- Working Distance (Object to Front Lens Housing Face): WD = 434.39mm (17.1 inch)

3) **Items Required in Sequential Order of Assembly:**
- **MAKRO-APO-CPN 4.0/60mm**
  - P/N 25-014802
  - Qty Needed = 1
- **10mm Makro Extension Tube**
  - P/N 25-020178
  - Qty Needed = 1
- **Makro to Leica Adapter**
  - P/N 25-020054
  - Qty Needed = 1
- **Unifoc-76 Focusing Mount**
  - P/N 21-013048
  - Qty Needed = 1
- **M58 to M72 Adapter**
  - P/N 21-013052
  - Qty Needed = 1
Example 1 Cont.

UNIFOC 58/76 SYSTEM With Macro Lenses in FORWARD Position

This spreadsheet is to aid in selecting the proper lens, focus mount, extension tubes and camera interface adapters for the Macro lenses in forward position (reduction) only. After entering the "Camera Lens Mounting Flange - to - CCD" distance and the "Camera Adapter Thickness" you need to enter your required magnification = (β) which is defined as either:
(Image Height / Object Height) or (Active Array Length / FOV) or [(image size) / (Object Resolution in DPI)] x (25.4). NOTE: KEEP COMMON UNITS
Choose your required "Extension Tube Length" from Table 1 and then enter your chosen value(s) into the grey box(es) as required in Table 2 to calculate your chosen optical systems flexibility.

I. Enter The Values Into The 2 Gray Cells:
- Camera Flange to CCD Distance (Camera Depth) (mm)
- Adapter Thickness (mm)

II. Enter Magnification in the Grey Cell or Enter the Values into the 2 orange Cells - then Grey Magnification Cell must contain a "0" Magnification (β) (Image size / object size)

Table 1:

<table>
<thead>
<tr>
<th>Lens</th>
<th>Required Extension</th>
<th>Object to Image distance (mm)</th>
<th>Working Distance</th>
<th>Flange Focal Distance @ β</th>
<th>Object to Camera (Macro Setup)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mk-CPN 2.8/28</td>
<td>P/N 25-014794</td>
<td>35 (10)</td>
<td>254.65</td>
<td>196.52</td>
<td>29.54</td>
</tr>
<tr>
<td>Mk-CPN 2.8/35</td>
<td>P/N 25-014792</td>
<td>29 (9)</td>
<td>304.09</td>
<td>239.48</td>
<td>36.01</td>
</tr>
<tr>
<td>Mk-APO-CPN 2.8/40</td>
<td>P/N 25-014796</td>
<td>21 (9)</td>
<td>362.96</td>
<td>299.00</td>
<td>44.36</td>
</tr>
<tr>
<td>Mk-APO-CPN 4.0/45</td>
<td>P/N 25-014783</td>
<td>10 (10)</td>
<td>407.41</td>
<td>329.46</td>
<td>49.35</td>
</tr>
<tr>
<td>Mk-CPN 3 2.8/50</td>
<td>P/N 25-014780</td>
<td>15 (10)</td>
<td>438.08</td>
<td>359.93</td>
<td>49.55</td>
</tr>
<tr>
<td>Mk-APO-CPN 4.0/60</td>
<td>P/N 25-014802</td>
<td>3 (23)</td>
<td>552.30</td>
<td>434.99</td>
<td>62.31</td>
</tr>
<tr>
<td>Mk-CPN 4 4.0/80</td>
<td>P/N 25-014780</td>
<td>25 (50)</td>
<td>704.75</td>
<td>586.56</td>
<td>89.59</td>
</tr>
</tbody>
</table>

Table 2: Enter Amount of Extension Tubes To Be Used

<table>
<thead>
<tr>
<th>Extension Tube Length</th>
<th>Magnification (1/β)</th>
<th>Object-to-Image Distance</th>
<th>Working Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.93</td>
<td>0.72</td>
<td>127.36</td>
</tr>
<tr>
<td>1</td>
<td>3.66</td>
<td>0.99</td>
<td>204.10</td>
</tr>
<tr>
<td>0</td>
<td>34.89</td>
<td>1.54</td>
<td>1530.70</td>
</tr>
<tr>
<td>5</td>
<td>23.86</td>
<td>1.68</td>
<td>1203.49</td>
</tr>
<tr>
<td>0</td>
<td>Infinity</td>
<td>2.18</td>
<td>Infinity</td>
</tr>
<tr>
<td>10</td>
<td>Infinity</td>
<td>2.76</td>
<td>Infinity</td>
</tr>
<tr>
<td>25</td>
<td>Infinity</td>
<td>6.43</td>
<td>Infinity</td>
</tr>
</tbody>
</table>

Camera Depths / Face Plate Mount

- C-Mount: 17.52mm / 1x32tpi
- CS-Mount: 12.52mm / 1x32tpi
- Sony NF: 12mm / M17 x 0.75
- Nikon-F: 46.5mm / Bayonet
- Cannon AF: 44.0mm / Bayonet
- Cannon FT: 42.1mm / Breech-Bayonet
- Pentax K: 45.5mm / Bayonet
Example 1 Cont.

### NOTES:
- All lenses must be mounted in the "Forward Position" for reduction of the object.
- All Lenses must contain the "Macro - To - Leica" Adapter PIN 25-020654 (all calculations take this into account).
- The calculations account for 6.5mm of thickness for the Leica adapter for the required Extention Tubes.
- **Max** = Macro-Symmar 80mm & 120mm only use when \( \beta < 0.25 \) is between (0.25 - 4.0).
- Only use the lenses in this "Forward" configuration for \( \beta < 1 \).

### Maximum Total Image Plane (CCD Length) Height Useable:
- CPN 2.8/28 & CPN 2.8/35 = 30mm Max
- APO-CPN 2.8/40 & APO-CPN 4.0/45 & CPN-S 2.8/50 = 42mm Max
- APO-CPN 4.0/60 & CPN-S 4.0/90 = 78mm Max
- Macro MSR 5.6/80 = 151mm Max
- APO-CPN 4.6/90 = 89mm Max
- CPN-S 5.6/100 = 97mm Max

### Adapters / Thickness:

<table>
<thead>
<tr>
<th>Adapter / Thickness</th>
<th>PIN 21-041629</th>
<th>PIN 21-080100</th>
<th>PIN 21-080101</th>
<th>PIN 21-080105</th>
<th>PIN 21-080107</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2-to-C Mount</td>
<td>5.5mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2-to-Nikon F</td>
<td>10mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>T2-to-M42x1.0</td>
<td>9.5mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2-to-C-Mount</td>
<td>2mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2-to-Leica</td>
<td>8.0mm</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Leica-to-T2</td>
<td>2.0mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Makro to Leica</td>
<td>6.5mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APO-CPN 2.8/40</td>
<td>5mm</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>APO-CPN 4.0/45</td>
<td>7.5mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APO-CPN 4.0/60</td>
<td>9mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APO-CPN 4.6/90</td>
<td>11mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPN-S 5.6/100</td>
<td>13mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPN-S 5.6/100</td>
<td>15mm</td>
<td></td>
<td></td>
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<tr>
<td>CPN-S 5.6/100</td>
<td>17mm</td>
<td></td>
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### Extension Tubes:

<table>
<thead>
<tr>
<th>Extension Tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIN 21-060400</td>
</tr>
<tr>
<td>PIN 21-039315</td>
</tr>
<tr>
<td>PIN 21-039312</td>
</tr>
<tr>
<td>PIN 21-060100</td>
</tr>
<tr>
<td>PIN 21-080005</td>
</tr>
<tr>
<td>PIN 21-080010</td>
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<tr>
<td>PIN 21-080015</td>
</tr>
<tr>
<td>PIN 21-0800105</td>
</tr>
<tr>
<td>PIN 21-016431</td>
</tr>
<tr>
<td>PIN 21-016431</td>
</tr>
<tr>
<td>PIN 21-016431</td>
</tr>
<tr>
<td>PIN 21-0800042</td>
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<td>PIN 21-080045</td>
</tr>
<tr>
<td>PIN 21-080045</td>
</tr>
<tr>
<td>PIN 21-080045</td>
</tr>
</tbody>
</table>

Macro Extension Tubes Inside Diameter = 33mm
Example 2

1) Supplied Parameters:
Camera: 4k Line scan
Lens to Camera interface: F-Mount
Interface to sensor distance: Depth = 46.5mm
Pixel Size: $PS = 0.0053$mm sq.
Sensor Length: $2y' = 41$mm
FOV (Object Length): $2y = 406$mm
Working Distance: $WD$ around 25” (635mm)

Magnification: $B' = 2y'/2y = 41/406 = 0.1010$
$1B' = 9.902x$ reduction of the object
Sensor Resolution Limit: Nyquist = 94 Lp/mm

2) Set-Up Dimensions:
Total Track (Object to Sensor): $O0' = 603.72$mm
Master Set-Up (Object to F-Mount Camera Face): $MS = 557.22$mm
Working Distance (Object to Front Lens Housing): $WD = 526.96$mm

3) Item(s) Required:
Xenon-Emerald 2.2/50mm F-Mount
P/N: 21-1062672
Delivery: In Stock in New York
**Example 2 Cont.**

**XENON-EMERALD Lenses in (Forward Normal Position)**

This spreadsheet is to aid in selecting the proper F-Mount Lens - Lens in Forward Position Only (reduction of the object size).

After entering the "Camera Lens Mounting Flange - to - CCD" distance and the "Camera Adapter Thickness" you need to enter your required Magnification = (β) which is defined as either:

\[ \text{Image Height / Object Height} \text{ or } \text{Active Array Length / FOV} \text{ or } \text{[pixel size] / [Object Resolution in DPI]} \times 25.4 \]

**NOTE:** KEEP COMMON UNITS

---

### I. Enter the Values into the 2 Gray Cells:

- **Camera Flange to CCD Distance (Camera Depth) (mm)**
  - **46.5**
  - **0**

- **Adapter Thickness (mm)** (F F-Mount or Canon use "0"

---

### II. Enter Magnification in the Grey Cell or Enter the Values into the 2 orange Cells - then Grey Magnification Cell must contain a "0".

- **Magnification (image size / object size):**
  - \( \frac{1}{\beta} = 9.001 \)
  - \( \beta = 0.101 \)

---

<table>
<thead>
<tr>
<th>Lens</th>
<th>Shift From Infinity Focus ( X' ) (mm)</th>
<th>Object to Image distance ( D' ) (mm)</th>
<th>Working Distance ( WD ) (mm)</th>
<th>Back Focal Distance ( \beta ) (mm)</th>
<th>Object to Camera Face (Master Set-Up)</th>
<th>Iris range (f/8)</th>
<th>Weight (grams)</th>
<th>Recommended Working Distance Range (mm)</th>
<th>Maximum Working Distance Range (mm)</th>
<th>Recommended Magnification Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Image Circle = 43.3mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emerald F-Mount 2.8/28-S</td>
<td>2.90</td>
<td>401.76</td>
<td>281.98</td>
<td>40.88</td>
<td>365.26</td>
<td>2.8 - 22</td>
<td>517</td>
<td>833 - 233</td>
<td>∞ - 0.0</td>
<td>0.03 - 0.08</td>
</tr>
<tr>
<td>Emerald F-Mount 2.8/28-L</td>
<td>3.16</td>
<td>400.88</td>
<td>281.24</td>
<td>41.13</td>
<td>364.38</td>
<td>2.8 - 22</td>
<td>516</td>
<td>1306 - 446</td>
<td>∞ - 0.0</td>
<td>0.02 - 0.06</td>
</tr>
<tr>
<td>Emerald F-Mount 2.8/50mm</td>
<td>6.17</td>
<td>603.72</td>
<td>528.96</td>
<td>37.37</td>
<td>557.22</td>
<td>2.2 - 16</td>
<td>200</td>
<td>∞ - 276</td>
<td>∞ - 1.66</td>
<td>0.0 - 0.20</td>
</tr>
<tr>
<td>Emerald F-Mount 2.8/100-S</td>
<td>10.11</td>
<td>1185.27</td>
<td>1034.97</td>
<td>86.92</td>
<td>1138.77</td>
<td>2.8 - 22</td>
<td>463</td>
<td>2046 - 544</td>
<td>∞ - 421</td>
<td>0.05 - 0.167</td>
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<tr>
<td>Emerald Canon Mount</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 2:

<table>
<thead>
<tr>
<th>Lens</th>
<th>Required Extension</th>
<th>Object to Image Distance (f0')</th>
<th>Working Distance</th>
<th>Flange Focal Distance @ P°</th>
<th>Object to Camera Face (Mount Set-Up)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Max.</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>Image Circle = 43.3mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emerald V-Mount 2.8/26-S</td>
<td>P/N 21-1071611</td>
<td>0</td>
<td>19</td>
<td>401.76</td>
<td>261.58</td>
</tr>
<tr>
<td>Emerald V-Mount 2.8/26-L</td>
<td>P/N 21-1071610</td>
<td>0</td>
<td>20</td>
<td>400.08</td>
<td>261.24</td>
</tr>
<tr>
<td>Emerald V-Mount 2.1/50mm</td>
<td>P/N 21-1070074</td>
<td>(7)</td>
<td>$</td>
<td>603.72</td>
<td>526.95</td>
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<td>Emerald V-Mount 2.6/100-S</td>
<td>P/N 21-1070119</td>
<td>41</td>
<td>63</td>
<td>1185.27</td>
<td>1034.57</td>
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<tr>
<td>Emerald V-Mount 2.5/100-L</td>
<td>P/N 21-1073834</td>
<td>44</td>
<td>65</td>
<td>1194.06</td>
<td>1040.80</td>
</tr>
</tbody>
</table>

Note: You have two options for using extension tubes (listed below):
A) Use V48 Extension tubes to clear the focusing threads and then terminate with your required adapter.
B) Use the V48 to M58 Adapter first and then use M58 Extension Tubes to clear the focusing threads on the lens - then terminate with an adapter.
Example 3

1) Supplied Parameters:
   Camera: 2K Line Scan
   Lens/Camera Interface = C-Mount
   Pixel Count: PC = 2048
   Pixel Size: PS = 0.00704mm
   Sensor Length: 2y' = 14.418mm
   Working Distance = 75mm
   Object Length (FOV): 2y = 35mm
   Viewing surface of a glass plate 1.1mm thick
   Needs little Depth of Field so 2nd surface is not imaged.
   Magnification: 2y'/2y = 14.418/35 = 0.41194
   1/B' = 2.43x Reduction of the Object

2) Set-Up Dimensions:
   Total Track (Object to Sensor): 00' = 138.87mm
   Master Set-Up (Object to Camera Front C-Mount Face): MS = 121.35mm
   Working Distance (Object to Front Lens Housing): WD = 75.05mm

3) Required Items:
   Xenoplan 2.0/28mm Compact Style C-Mount Lens
   P/N 21-1001972
   8mm C-Mount Extension Tube
   P/N 21-039315

4) Depth of Field (Using two pixels for my Blur Circle):
   f/2.0 = 0.47mm f/2.8 = 0.70mm f/4.0 = 1.0mm (best performance at this f/#)
Compact Style C-Mount Lenses in **Forward (Normal Position)**

This spreadsheet is to aid in selecting the proper Compact C-Mount Lens in Forward Position Only.

After entering the "Camera Lens Mounting Flange - to - CCD distance" and the "Camera Adapter Thickness" you need to enter your required Magnification \( \frac{p'}{p} \) which is defined as either:

\[ \frac{\text{Image Height}}{\text{Object Height}} \text{ or } \frac{\text{Active Array Length (FOV)}}{\text{Object Resolution in Dots by} \times \text{25.4}} \]

**NOTE:** KEEP COMMON UNITS

### I. Enter The Values Into The 2 Gray Cells:

<table>
<thead>
<tr>
<th>Camera Flange to CCD Distance (Camera Depth) (mm)</th>
<th>Adapter Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.62</td>
<td>0</td>
</tr>
</tbody>
</table>

### II. Enter Magnification in the Grey Cell or Enter the Values into the 2 orange Cells - then Grey Magnification Cell must contain a "0".

<table>
<thead>
<tr>
<th>Lens</th>
<th>Image Circle = 11mm</th>
<th>Shift From Infinity Focus [(p')]</th>
<th>Object to Image Distance [(\delta')]</th>
<th>Working Distance [WD]</th>
<th>Back Focal Distance @ [(\beta)] [(\delta')]</th>
<th>Object to Camera Face (Master [(\beta)] Set Up)</th>
<th>Iris range [H]</th>
<th>Weight [grams]</th>
<th>Working Distance Range (No Ext Tube) [mm]</th>
<th>Working Distance Range (7mm Ext Tube) [mm]</th>
<th>Working Distance Range (10mm Ext Tube) [mm]</th>
<th>Working Distance Range (10mm Ext Tube) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cinegon 1.8/4.8-0902</td>
<td>P/N 21-1001955</td>
<td>2.05</td>
<td>59.46</td>
<td>1.70</td>
<td>15.23</td>
<td>41.94</td>
<td>1.8 - 11</td>
<td>90</td>
<td>-0.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cinegon 2.1/6-0901</td>
<td>P/N 21-1055691</td>
<td>2.57</td>
<td>64.84</td>
<td>0.10</td>
<td>17.86</td>
<td>47.32</td>
<td>2.1 - 16</td>
<td>118</td>
<td>-0.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cinegon 1.4/8-0902</td>
<td>P/N 21-1001919</td>
<td>3.40</td>
<td>60.77</td>
<td>7.45</td>
<td>16.97</td>
<td>43.25</td>
<td>1.4 - 11</td>
<td>90</td>
<td>-0.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cinegon 1.4/12-0906</td>
<td>P/N 21-1001951</td>
<td>5.22</td>
<td>74.82</td>
<td>9.46</td>
<td>17.91</td>
<td>67.30</td>
<td>1.4 - 11</td>
<td>99</td>
<td>-0.12</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Xenoplan 1.4/17-0903</td>
<td>P/N 21-1001957</td>
<td>7.24</td>
<td>81.87</td>
<td>24.14</td>
<td>20.40</td>
<td>64.35</td>
<td>1.4 - 11</td>
<td>86</td>
<td>-0.42</td>
<td>42 - 11</td>
<td>19 - 4</td>
<td>N/A</td>
</tr>
<tr>
<td>Xenoplan 1.4/23-0902</td>
<td>P/N 21-1001917</td>
<td>9.27</td>
<td>99.99</td>
<td>36.59</td>
<td>24.26</td>
<td>82.47</td>
<td>1.4 - 11</td>
<td>94</td>
<td>-0.82</td>
<td>82 - 31</td>
<td>44 - 19</td>
<td>N/A</td>
</tr>
<tr>
<td>Apo-Xenoplan 1.4/23-0903 (5 mp)</td>
<td>P/N 21-1012344</td>
<td>9.44</td>
<td>103.21</td>
<td>37.35</td>
<td>24.90</td>
<td>85.69</td>
<td>1.4 - 11</td>
<td>106</td>
<td>-0.86</td>
<td>86 - 33</td>
<td>33 - 22</td>
<td>N/A</td>
</tr>
</tbody>
</table>
### Example 3 Cont.

<table>
<thead>
<tr>
<th>Adapter / Thickness</th>
<th>Part Number</th>
<th>Extension Tubes</th>
<th>PIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-Mount to Sony EF</td>
<td>21-090000</td>
<td>C-Mount 5mm</td>
<td>21-080310</td>
</tr>
<tr>
<td>C-Mount to CS-Mount</td>
<td>21-050000</td>
<td>C-Mount 5.5mm</td>
<td>21-070309</td>
</tr>
<tr>
<td>C-Mount to T2 - 15mm</td>
<td>21-020000</td>
<td>C-Mount 6mm</td>
<td>21-060308</td>
</tr>
<tr>
<td>C-Mount Range - 5.6mm</td>
<td>21-010000</td>
<td>C-Mount X1 X2</td>
<td>21-050000</td>
</tr>
</tbody>
</table>

**Example Data**

<table>
<thead>
<tr>
<th>Model</th>
<th>P/N</th>
<th>Image Circle</th>
<th>F2.8</th>
<th>F4</th>
<th>F5.6</th>
<th>F8</th>
<th>F11</th>
<th>F16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenoplan 1.9/35-0901</td>
<td>21-1001960</td>
<td>14.39</td>
<td>155.63</td>
<td>89.02</td>
<td>31.42</td>
<td>138.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apo-Xenoplan 1.8/35-0901 (5 mp)</td>
<td>21-1057664</td>
<td>14.49</td>
<td>154.80</td>
<td>62.97</td>
<td>39.70</td>
<td>137.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tele-Xenar 2.2/70-0902</td>
<td>21-1014593</td>
<td>29.05</td>
<td>315.73</td>
<td>195.17</td>
<td>57.52</td>
<td>298.21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Image Circle

- **16mm**
  - Cinegon 1.9/10-0901 | P/N 21-101978 | 4.27 | 78.86 | 10.93 | 20.41 | 61.34 |
  - Cinegon 1.8/16-0901 | P/N 21-1001482 | 6.77 | 91.49 | 26.29 | 25.22 | 73.97 |

- **22/24mm**
  - Apo-Xenoplan 2/20 Anti-Shading | P/N 21-1056472 | 8.45 | 122.47 | 37.36 | 32.63 | 104.95 |
  - Apo-Xenoplan 2/24 Anti-Shading | P/N 21-1071371 | 14.39 | 112.28 | 43.34 | 32.12 | 96.36 |
  - Xenoplan 2.0/25-0901 | P/N 21-1001972 | 12.97 | 186.97 | 75.05 | 32.90 | 121.35 |
  - Apo-Xenoplan 2.035 Anti-Shading | P/N 21-1006219 | 14.45 | 161.36 | 77.62 | 39.63 | 143.84 |
  - Xenoplan 2.8/60-0902 Anti-Shading | P/N 21-1001976 | 20.67 | 239.71 | 152.66 | 62.36 | 222.19 |

*Available Upon Request Only*
Example 4

1) Supplied Parameters:
   - Camera: 12K Line Scan
   - Lens/Camera Interface = M72 x 0.75 Thread
   - Pixel Count: PC = 12288
   - Pixel Size: PS = 0.005mm
   - Sensor Length: 2y' = 61.440mm
   - Camera Threads to Sensor: Camera Depth = 6.56mm
   - Working Distance = TBD (> 125mm)
   - Magnification: Specified B' = 2.0 Enlargement of the object
   - Object Length (FOV): 2y'/B' = 61.440/2 = 30.72mm
   - Pixel Sampled Size (PSS): PSS = PS/B' = 0.005/2 = 0.0025mm = 200 Lp/mm Object Space

2) Set-Up Dimensions:
   - Total Track (Object to Sensor): 00' = 538.60mm
   - Master Set-Up (Object to Camera Front C-Mount Face): MS = 532.04mm
   - Working Distance (Object to Front Lens Housing): WD = 153.80mm

3) Required Items in Sequential Order of Assembly:
   - Makro-Sympmar 5.6/120-0060 P/N 25-1002650 Qty Needed = 1
   - 25mm Makro Extension Tube P/N 25-020179 Qty Needed = 1
   - Makro To Leica Adapter P/N 25-020054 Qty Needed = 1
   - Unifoc-76 Focusing Mount P/N 21-013048 Qty Needed = 1
   - M58 to M72 Adapter P/N 21-013052 Qty Needed = 1
   - [320-295 = <308> – 25 = 283] of M72 tubes are required
   - 200mm M72 Extension Tube P/N 21-1079484 Qty Needed = 1
   - 50mm M72 Extension Tube P/N 21-1054733 Qty Needed = 1
   - 25mm M72 Extension Tube P/N 21-026406 Qty Needed = 1
   - 10mm M72 Extension Tube P/N 21-1072421 Qty Needed = 1
12K MAKRO-SYMMAR-SYSTEM with lenses in Reverse Position

This spread sheet is to aid in selecting the proper lens, focus mounts (Unifoc 100/95, 100/77 & 78), extension tubes and camera interface adaptors for the 12K lenses in Reverse Positions Only.

After entering the "Camera Lens Mounting Flange - to - CCD" distance and the "Camera Adapter Thickness" you need to enter your required Magnification * (β) which is defined as either (Image Height / Object Height) or (Active Array Length / FOV) or (line pixel size / (Object Resolution in DPI) * x (25.4)). NOTE: KEEP COMMON UNITS

### 12K Camera Types / Mounts

<table>
<thead>
<tr>
<th>Camera</th>
<th>Model</th>
<th>Camera Depth</th>
<th>Adapter Thickness</th>
<th>Focus Mount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalsa</td>
<td>P2-12K</td>
<td>4.00mm</td>
<td>30.00mm</td>
<td>Unifoc 100/95</td>
</tr>
<tr>
<td>Dalsa</td>
<td>P3-12K</td>
<td>6.56mm</td>
<td>30.00mm</td>
<td>Unifoc 100/77</td>
</tr>
<tr>
<td>Dalsa</td>
<td>P3-12K</td>
<td>6.56mm</td>
<td>2.00mm</td>
<td>Unifoc 78</td>
</tr>
<tr>
<td>Atmel</td>
<td>UMB 12K</td>
<td>9.40mm</td>
<td>2.00mm</td>
<td>Unifoc 76</td>
</tr>
</tbody>
</table>

### I. Enter The Values into The 2 Gray Cells:

| Camera Flange to CCD Distance (Camera Depth) (mm) | 6.56 |
| Adapter Thickness (mm)                            | 0    |

### II. Enter Magnification in the Grey Cell or Enter the Values into the 2 orange Cells - then Grey Magnification Cell must contain a "0".

<table>
<thead>
<tr>
<th>Magnification β' (image size / object size)</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Size</td>
<td>1/β' 0.500</td>
</tr>
<tr>
<td>Object Size</td>
<td>β' = 2</td>
</tr>
</tbody>
</table>

### Table 1:

<table>
<thead>
<tr>
<th>Lens</th>
<th>Required Extension</th>
<th>Object to Image Distance [β'] (mm)</th>
<th>Working Distance (mm)</th>
<th>Flange Focal Distance @ β' (mm)</th>
<th>Object to Camera Face (Master Set-Up) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNIFOC 100/95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Makro-Symmar 5.5/120-0058</td>
<td>346</td>
<td>541.35</td>
<td>155.85</td>
<td>352.90</td>
<td>534.79</td>
</tr>
<tr>
<td>Makro-Symmar 5.5/120-0068</td>
<td>346</td>
<td>639.70</td>
<td>155.00</td>
<td>352.10</td>
<td>533.14</td>
</tr>
<tr>
<td>Makro-Symmar 5.5/120-0080</td>
<td>346</td>
<td>538.60</td>
<td>153.80</td>
<td>352.20</td>
<td>532.04</td>
</tr>
<tr>
<td>Makro-Symmar 5.5/120-0061</td>
<td>343</td>
<td>538.65</td>
<td>153.05</td>
<td>350.00</td>
<td>529.09</td>
</tr>
<tr>
<td>Makro-APO-CPN 4.5/90-0015</td>
<td>254</td>
<td>468.04</td>
<td>111.92</td>
<td>260.82</td>
<td>358.48</td>
</tr>
<tr>
<td>UNIFOC 100/77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Makro-Symmar 5.5/120-0058</td>
<td>346</td>
<td>541.35</td>
<td>155.85</td>
<td>352.90</td>
<td>534.79</td>
</tr>
<tr>
<td>Makro-Symmar 5.5/120-0059</td>
<td>346</td>
<td>539.70</td>
<td>155.00</td>
<td>352.10</td>
<td>533.14</td>
</tr>
<tr>
<td>Makro-Symmar 5.5/120-0060</td>
<td>346</td>
<td>538.60</td>
<td>153.80</td>
<td>352.20</td>
<td>532.04</td>
</tr>
</tbody>
</table>

---

91
Example 4 Cont.

<table>
<thead>
<tr>
<th>Makro-Symphar 5.6/120-0061 (β' = 3.84x - 2.63x) P/N 25-1004611</th>
<th>343</th>
<th>535.65</th>
<th>153.05</th>
<th>350.00</th>
<th>528.09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makro-APO-CPN 4.5/90-0018 (β' = 5.0x - 2.5x) P/N 25-1004531</td>
<td>254</td>
<td>405.04</td>
<td>111.92</td>
<td>260.52</td>
<td>398.48</td>
</tr>
<tr>
<td>UNIFOC-76</td>
<td>min.</td>
<td>max.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*Makro-Symphar 5.6/120-0058 (β' = 1.13x - 0.88x) P/N 25-1002647</td>
<td>295</td>
<td>321</td>
<td>541.35</td>
<td>165.85</td>
<td>362.90</td>
</tr>
<tr>
<td>*Makro-Symphar 5.6/120-0059 (β' = 1.59x - 1.13x) P/N 25-1002648</td>
<td>295</td>
<td>320</td>
<td>539.70</td>
<td>155.00</td>
<td>352.10</td>
</tr>
<tr>
<td>*Makro-Symphar 5.6/120-0060 (β' = 2.63x - 1.89x) P/N 25-1002650</td>
<td>296</td>
<td>320</td>
<td>538.60</td>
<td>163.80</td>
<td>362.20</td>
</tr>
<tr>
<td>*Makro-Symphar 5.6/120-0061 (β' = 3.84x - 2.63x) P/N 25-1004611</td>
<td>292</td>
<td>318</td>
<td>535.65</td>
<td>153.05</td>
<td>350.00</td>
</tr>
<tr>
<td>*Makro-APO-CPN 4.5/90-0018 (β' = 5.0x - 2.5x) P/N 25-1004531</td>
<td>203</td>
<td>229</td>
<td>405.04</td>
<td>111.92</td>
<td>260.52</td>
</tr>
</tbody>
</table>

25mm makro extension tube is required at a min. If you need to add tubes between the lens and mount.

* Automatically Includes the Makro-to-Leica Adapter P/N 25-020054 into the calculations

<table>
<thead>
<tr>
<th>Adapter</th>
<th>Thickness</th>
<th>PIN</th>
<th>Focus Mount</th>
<th>PIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>M72 Tilt Adapter = 35mm</td>
<td>25-1071325</td>
<td>UNIFOC 100/95</td>
<td>25-10003231</td>
<td></td>
</tr>
<tr>
<td>V70 to M72 = 10mm</td>
<td>25-1072415</td>
<td>UNIFOC 100/77</td>
<td>25-1004157</td>
<td></td>
</tr>
<tr>
<td>M68 to M72 = 2mm</td>
<td>21-013052</td>
<td>UNIFOC 76</td>
<td>21-013048</td>
<td></td>
</tr>
<tr>
<td>M58 to M95 x 1.0 = 4mm</td>
<td>21-01623891</td>
<td>31.5mm +/- 12.5mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M72 to M95 x 1.0 = 4mm</td>
<td>21-0177013</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Extension Tubes:**

- M72 = 5mm
- M72 = 10mm
- M72 = 25mm
- M72 = 50mm
- M72 = 100mm
- M72 = 200mm
- M95 x 1.0 = 10mm
- M95 x 1.0 = 25mm
- M95 x 1.0 = 50mm
- M95 x 1.0 = 100mm
- M95 x 1.0 = 200mm

Unifoc 100/95 & 100/77 Minimum Ext. Tube Length = (106 - 1.5) = 104.5mm

Unifoc 100/95 & 100/77 Maximum Ext. Tube Length = (208 + 9) = 217mm

Fine Focus Travel = +9.0mm / -1.5mm

All lenses must be mounted in the "Reverse Position" for enlargement of the object.
Example 4 Cont.

* = Lens to be “Flipped” into its reverse orientation for enlargement Mode

Note the large amount of extensions tubes – Consider extra support around the extension tubes to avoid vibration
Example 5

1) Supplied Parameters:  
- Camera: Dalsa 16K Line Scan  
- Lens/Camera Interface = M95 x 0.75 Thread  
- Pixel Count: PC = 16,384  
- Pixel Size: PS = 0.0035mm  
- Sensor Length: \(2y' = 57.344\)mm  
- Camera Threads to Sensor: Camera Depth = 12mm  
- Working Distance = TBD  
- Magnification: Specified \(B' = 3.5\) Enlargement of the object  
- Object Length (FOV): \(2y'/B' = \frac{57.344}{3.5} = 16.384\)mm  
- Pixel Sampled Size (PSS): \(PSS = \frac{PS}{B'} = \frac{0.0035}{2} = 0.001\)mm = 500 Lp/mm Object Space  
- Requires Highest Performing lenses (Sapphire & Diamond)

2) Set-Up Dimensions:  
- Total Track (Object to Sensor): \(00' = 404.9\)mm  
- Master Set-Up (Object to Camera Front C-Mount Face): \(MS = 446.05\)mm  
- Working Distance (Object to Front Lens Housing): \(WD = 73.2\)mm

3) Required Items in Sequential Order of Assembly:  
- Xenon-Diamond 2.2/117mm P/N 25-1002650 Qty Needed = 1  
- V-90 to M95 x 1.0 Adapter P/N 25-1077293 Qty Needed = 1  
- [405-443 = <424>] of M95 tubes are required  
- 200mm M95 Extension Tube P/N 21-1077291 Qty Needed = 2  
- 25mm M95 Extension Tube P/N 21-1062892 Qty Needed = 1

Note the large amount of extensions tubes – Consider extra support around the extension tubes to avoid vibration
12K / 16K Xenon Diamond Line Scan Lenses

Please Note: These lenses can also be used on either 12K or 16K Cameras (Image Circle Max. 82mm).

This spread sheet is to aid in selecting the proper 16K Lens in Forward Position Only.

After entering the “Camera Lens Mounting Flange - to - CCD” distance and the “Camera Adapter Thickness” you need to enter your required Magnification = (β') which is defined as either

(Image Height / Object Height) or (Active Array Length / FOV) or [(one pixel size) / (Object Resolution in DPI)] x (25.4)]

NOTE: KEEP COMMON UNITS

16K Camera Types / Mounts

<table>
<thead>
<tr>
<th>Camera</th>
<th>Model</th>
<th>Camera Depth</th>
<th>Mount Type</th>
<th>Pixel Size</th>
<th>2y'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalsa</td>
<td>P3-SO-16K</td>
<td>12.00mm</td>
<td>M72 or M72 Tilt Adapter</td>
<td>0.0035mm</td>
<td>57.344mm</td>
</tr>
<tr>
<td>Dalsa</td>
<td>P3-80-16K</td>
<td>12.00mm</td>
<td>M72 or M72 Tilt Adapter</td>
<td>0.0035mm</td>
<td>57.344mm</td>
</tr>
<tr>
<td>e2v</td>
<td>ELiiXA+CL</td>
<td>9.40mm</td>
<td>M95 x 1.0</td>
<td>0.0050mm</td>
<td>81.920mm</td>
</tr>
<tr>
<td>e2v</td>
<td>ELiiXA+CXP</td>
<td>9.40mm</td>
<td>M95 x 1.0</td>
<td>0.0050mm</td>
<td>81.920mm</td>
</tr>
<tr>
<td>Takex</td>
<td>TL-16000CL</td>
<td>19.55mm</td>
<td>M72 Thread</td>
<td>0.0053mm</td>
<td>57.344mm</td>
</tr>
<tr>
<td>Chromasens</td>
<td>allPIXAx7300K</td>
<td>17.52mm</td>
<td>M72 Thread</td>
<td>0.0100mm</td>
<td>73.000mm</td>
</tr>
</tbody>
</table>

Choose your required "Extension Tube Length" from Table 1

I. Enter The Values into The 2 Gray Cells:

| Camera Flange to CCD Distance (Camera Depth) (mm) | 12 |
| TOTAL Adapter(s) Thickness (mm) | 10 |

II. Enter Magnification in the Grey Cell or Enter the Values into the 2 orange Cells - then Grey Magnification Cell must contain a "0".

Table 1:

<table>
<thead>
<tr>
<th>Lens</th>
<th>Required Extension</th>
<th>Object to Image distance (f')</th>
<th>Working Distance</th>
<th>Flange Focal Distance @ β'</th>
<th>Object to Camera Face (Master Set-Up)</th>
<th>Magnification Range (β')</th>
<th>Mount Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon-Diamond 2.7/111mm (β' = -2.6)</td>
<td>P/N 21-1078039</td>
<td>413.4</td>
<td>636.57</td>
<td>73.2</td>
<td>455.37</td>
<td>624.57</td>
<td>-2.45 to -2.75</td>
</tr>
<tr>
<td>Xenon-Diamond 2.9/106mm with BS (β' = -2.6)</td>
<td>P/N 21-1078949</td>
<td>580.3</td>
<td>622.34</td>
<td>52.2</td>
<td>436.99</td>
<td>610.34</td>
<td>-2.45 to -2.75</td>
</tr>
</tbody>
</table>
# Example 5 Cont.

<table>
<thead>
<tr>
<th>Xenon-Diamond 2.2/117mm (β' = -3.5)</th>
<th>P/N 21-10769853</th>
<th>404.9</th>
<th>443.3</th>
<th>668.05</th>
<th>73.2</th>
<th>446.05</th>
<th>656.05</th>
<th>-3.35 to -3.65</th>
<th>V90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon-Diamond 2.3/116mm with BS (β' = -3.5)</td>
<td>P/N 21-1079718</td>
<td>397.7</td>
<td>436.1</td>
<td>671.97</td>
<td>53.8</td>
<td>438.90</td>
<td>659.97</td>
<td>-3.35 to -3.65</td>
<td>V90</td>
</tr>
</tbody>
</table>

**NOTES:**

Some Lenses must contain the "V70 - To - M72" Adapter P/N 25-1072419 = 10mm Thick
Some Lenses must contain the "V90 - To - M95" Adapter P/N 21-1077293 = 10mm Thick
You must add the 10mm for the V70-to-M72 or V90-to-M95 Adapters in Cell C16
If using M72 the Tilt Mount add an additional 35mm to Cell C16

<table>
<thead>
<tr>
<th>Adapters / Thickness:</th>
<th>P/N</th>
<th>Focus Mount</th>
<th>P/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>M72 Tilt Adapter = 35mm</td>
<td>25-1071925</td>
<td>Unifoc 100 / 95</td>
<td>25-1001231</td>
</tr>
<tr>
<td>V70 to M72 = 10mm</td>
<td>25-1072419</td>
<td>Unifoc 100 / 77</td>
<td>25-1004157</td>
</tr>
<tr>
<td>M95 to M95 x 1.0 = 4mm</td>
<td>21-105291</td>
<td>Unifoc 76</td>
<td>21-013048</td>
</tr>
<tr>
<td>V90 to M95 x 1.0 = 10mm</td>
<td>21-1077293</td>
<td>31.6mm +/- 12.5mm</td>
<td></td>
</tr>
</tbody>
</table>

**Extension Tubes:**

<table>
<thead>
<tr>
<th>P/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>M72 = 5mm</td>
</tr>
<tr>
<td>M72 = 10mm</td>
</tr>
<tr>
<td>M72 = 25mm</td>
</tr>
<tr>
<td>M72 = 50mm</td>
</tr>
<tr>
<td>M72 = 100mm</td>
</tr>
<tr>
<td>M72 = 200mm</td>
</tr>
<tr>
<td>M95 x 1.0 = 10mm</td>
</tr>
<tr>
<td>M95 x 1.0 = 25mm</td>
</tr>
<tr>
<td>M95 x 1.0 = 50mm</td>
</tr>
<tr>
<td>M95 x 1.0 = 100mm</td>
</tr>
<tr>
<td>M95 x 1.0 = 200mm</td>
</tr>
</tbody>
</table>
Example 5 Cont.

- In Luft (in air)
  - $S_0 = -72.5$
- Linsenscheitel (lens vertex)
  - $4.7$
- Inbusschraube zur Fokusklemmung (Allen screw for focus lock)
  - Schlüsselweite (wrench size) 2mm
- Rändelschraube zur Blendenklemmung (Knurled screw for iris lock)
- Schneider V-Mount 90
- Schutzglas (Cover plate) Nicht enthalten (not included)

Measurements:
- $\phi 95.6$
- $\phi 86$
- $\phi 62$
- $56$
- $52$
- $19.2$

Bildebene / image plane

Filtergewinde (filter thread)

$M 82 \times 1$

- $\phi 90$
- $0.025$
- $0.05$
Basic Optical Calculations
FOCAL LENGTH ($f'$)

\[
f' = \frac{a}{1 + \left(\frac{1}{\beta'}\right)}
\]

* Note *  Must Use Common Units

\[
f' = \frac{a}{1 + \left(\frac{y}{y'}\right)}
\]

\[
f' = \text{Focal Length}
\]
\[
a = \text{Object Distance}
\]
\[
\beta' = \text{Magnification}
\]
\[
y = \frac{1}{2} \text{ Object Height}
\]
\[
y' = \frac{1}{2} \text{ Image Height}
\]

EXAMPLE

\[
a = 1000\text{mm}
\]
\[
\beta' = 0.1 \text{ (10x reduction)}
\]
\[
f' = 91\text{mm}
\]
TOTAL TRACK (OO')

* Note * Sign Condition of HH'

\[ OO' = f'(2 + \beta' + \frac{1}{\beta'}) + HH' \]

* Note * Must Use Common Units

EOO' = Total Track (Object to Image)
    f' = Focal Length
    \beta' = Magnification
    HH' = Nodal Point Separation

**EXAMPLE**

\[ \beta' = 0.10 \]
\[ f' = 100\text{mm} \]
\[ HH' = 5\text{mm} \]

Object to Image (OO') = 1215\text{mm}
**INFINITY FOCUS SHIFT ($X'$)**

The shift from infinity focus ($X'$) is given by the formula:

$$X' = \frac{(f')^2}{a - f'}$$

Where:
- $a$ = Object Distance
- $f'$ = Focal Length
- $X'$ = Shift From Infinity Focus

**EXAMPLE**
- $f' = 50\text{mm}$
- $a = 250\text{mm}$
- $X' = 12.5\text{mm}$

*Note* Must Use Common Units

As an object comes closer to a lens the image moves away (increases) from the lens.
NODAL POINT Locations

C = Front Lens Vertex to Front Nodal Point
C' = Rear Lens Vertex to Rear Nodal Point
f' = Focal Length
S_f = Front Focal length
S'_f' = Back Focal Length

Typically provided by the Lens manufacturer

\[ C = S_f + f' \]
\[ C' = f' - S'_f' \]

EXAMPLE

f' = 102.3mm
S_f = -61.8mm

C = 40.5mm
Distance from EL#1 R1 Vertex into the lens (40.5mm) is the location of the front Nodal Point
\[ \alpha = \frac{1}{2} \text{Angular FOV} \]

\[ y' = \frac{1}{2} \text{Image Height} \]

\[ f' = \text{Focal Length} \]

\[ 2\alpha = \text{Total Angular FOV} \]

**EXAMPLE**

CCD Length = 11mm

\[ y' = \frac{11}{2} = 5.5\text{mm} \]

\[ f' = 50\text{mm} \]

\[ \alpha = 6.28 \text{ degrees} \]

Total Angular FOV = \(2 \alpha = 12.56\) deg.

* Note * Must Use Common Units
Angular Resolution

Ang. Res. = \frac{\text{Pixel Size}}{\text{Focal Length}}

**EXAMPLE**

Focal Length = 100mm
Pixel Size = 0.007mm

Ang. Res. = 0.00007 radians
= 0.00401 degrees
= 14.438 arc seconds

FYI – Human Eye
Normal visual acuity is one minute and this is the value for the resolution of the eye under what may be termed “Normal Conditions”

* Note * Must Use Common Units
Micro Lenses / Lenslets
If the external lens used in a design exceeds the acceptance angle of the microlens used with the sensor, light from objects farther from the center field of view of the lens (green and red) may not reach the sensor.

To overcome the problem associated with microlens-based sensors, lens manufacturers will offer external lenses that are near telecentric in image space. The angle from light farther and farther from the center will remain on-axis and no angular roll-off will occur.
Microlenses increase the fill factor of the sensor by capturing as much light as possible. However, they have an acceptance angle at which they will effectively collect light and focus it onto the active portion of the pixel.
Why Anti-shading Lenses

Sensors are using often micro lenses to improve the sensitivity

Typically there are no problems when the sensor format ≤ 1”

Schematic view of the micro lenses on a single pixel (grey = active pixel surface) (yellow = focused light area)
COTS - Modification – Development

COTS = Commercial Off-The-Shelf

• Modifying Existing Designs and Creating New Ones
  – What it takes
  – What Information needs to be taken into account
  – How to get what you need
  – General time lines
  – Volume requirements across industry
Modifying Existing Designs and Creating New Ones

If a standard design/lens “off-the-shelf” cannot satisfy your requirements then your first approach should be to see if the Lens Manufacturer can make a modification to an existing design. This will save time and “$’s” and gets you a finished / working lens ASAP. Depending on the amount of “Modifications” that might have to be made to a lens (change out an element, air-space, etc.....) this could take ≈ 4 to 8 weeks for a prototype lens and after approval serial production could start to deliver lenses ≈ 6 to 10 weeks from prototype approval. Depends upon the Optical Company....! Do not be afraid to ask.....!

If a new lens design is deemed necessary – you must be prepared for the following:

Quote Lead Time = 4 to 6 weeks.
Quote would include (All Optical & Mechanical NRE), small prototype quantity approx 2 to 6 lenses. Delivery of Prototypes ≈ 12 – 16 weeks ARO.
Once prototypes are tested /evaluated and approved by you – serial production can first start. Delivery of first production lenses ≈ 12 – 16 weeks ARO.
Minimum time starting including quote ≈ 6 months to production lenses could be up to one year.
In order for a custom lens to be made in production – quantities should be > 100 lenses to be somewhat cost effective.
Lens Selection “Up-Front” ?’s

1) Object Size (L W H) {sometimes called “FOV”}?  
2) Image (Area or Linear, L W H, # of Pixels)?  
3) Magnification?  
4) CCD (Color, BW, Pixel Size, IR Block Filter)?  
5) Wavelength Region (mono, visible, Near IR)?  
6) Relative Aperture (f/#, How much light)?  
7) Camera Mount (C-Mount, F-Mount, ......)?  
8) Camera Flange Focus Depth?  
9) Object Distance (Working Distance)?  
10) Black Box Size (Lens: Max Diameter, Length)?  
11) Black Box Size (system, OO)?  
12) System Resolution (Object Space)?  
13) Object Contrast?  
14) Environmental (Temp Range, Vibration, Dust)?  
15) Geometric Distortion?  
16) Optical Filtering ?  
17) Focal Plane (Sensor) Micro Lenslets?  
18) Single sensor or “3 CCD” prism assembly?
Do Not treat the lens/optics as an “After Thought”!

It is somewhat common to 1st look into your lens selection AFTER:

- Camera is Chosen (Mount type, Sensor Format/Size, Lighting, Etc…)
- This can greatly limit your “off-the-shelf” lens choices
- As well as possibly driving you towards a “Custom lens Design/Development”
- Lens parameters needs to be defined concurrently during your initial system layout – specifications!

Classic Case: I have a CCD camera that contains a 60mm CCD length
I want a working Distance of about 1 foot
My magnification needs to be 10x Enlargement
I want to resolve 1 micron defect in object space
My total “Black Box” length = 18 inches
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• SCHNEIDER OPTICS (Jim Sullivan)
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