AN001: Calibrated lenses benefits and overview

Table of Contents

1. Benefits

Theia’s calibrated lenses are individually characterized and calibrated at the factory to provide a rich array of data sets. This calibrated data makes the lenses easier to use by allowing accurate conversion from intuitive units to lens settings. The calibrated data is also provided to allow image resolution optimization for fast and accurate machine vision applications.

Many of Theia's calibrated lenses are motorized varifocal lenses allowing flexibility of setting the focal length and focus distance remotely and automatically. Motorized adjustable lenses have many applications including image optimization for barcode reading in mobile robots, variable image field of view for improved navigation, quick set up for non-fixed cameras, and many more. These benefits are enabled with calibration data frames which may include MTF resolution performance, focal length, F/#, geometrical distortion, relative illumination, and more. This calibrated data is provided so the user can optimize image quality in real time and possibly without the requirement to use difficult or costly field calibration fixtures.

Calibrated data is a combination of data unique to one lens and design data that is common across lenses in the same family. This data is available for download from Theia’s cloud database along with application notes providing some options for using the data and motor control firmware and software for quick integration into a custom program.

Theia calibrated lenses

Theia offers many different calibrated lens models with varying feature sets. Benefits include:

User benefit	Calibrated lens features
Simplifies camera setup in applications that don't have a fixed camera position or object distance.	Most of Theia's calibrated lenses have internally adjustable lens groups for focal length and focus position. In applications where the field of view and object distance must change because the camera is not in a fixed position, this focal length and focus adjustability allows the image to be optimized without moving the camera position.
Allows intuitive and understandable control of image parameters.	Many users want to set a field of view, depth of field, or object distance. These engineering units are transparently converted using Theia's available lens control library or GUI so the lens can be controlled without the need for complicated external calculations, curve fitting, and interpolation.
Enhances object resolution for applications such as mobile robots and fixed box scanners which have variable distance to the object of interest.	In applications where the object is a variable size or variable distance such as barcodes on boxes or number plates on vehicles, the field of view of Theia's calibrated lenses can be automatically changed so the object is captured at the optimum size in the image, allowing the best chance for automated reading.
Enables remote and automated image optimization for difficult-to-access cameras due to the surrounding environment or level of camera integration.	Many applications include a highly integrated vision system that may be difficult or undesirable to allow physical access to the lens. Theia's calibrated lenses allow remote control of focal length, focus, aperture, and bandpass filter so the image optimization can be completed after full camera integration.
Improves object recognition accuracy in uncontrolled outdoor lighting applications such as ITS, ANPR, and aerial crop monitoring.	Outdoor applications often have no control over lighting but Theia's calibrated lenses allow precise and adjustable aperture size using a p-iris. Many lenses can also be switched between transmitting visible light for accurate color rendition during daylight and transmitting IR light for improved sensitivity at night (with or without additional IR illumination).
Facilitates easy integration of a lens' increased ability into existing machine vision systems	Theia's calibrated lenses follow the extended Gen-I-Cam standard for communication with machine vision components allowing the user to easily access and control the features of the lens such as motorized focus, focal length, and iris.

Feature	Benefits
• Motorized zoom and focus	Lenses often need to be controlled remotely or automatically. For lenses that are difficult to physically access or those that need adjustment periodically (due to object distance, desired image resolution, or temperature change for example) there is no need for physical access to the lens. Many of Theia’s calibrated lenses have focus and zoom motors. In these cases, Theia provides a focus/zoom tracking curve so the user can program the lens focus motor position to maintain good focus as focal length is changed.
• Adjustable motorized p-iris	For many of Theia’s calibrated lenses, the lens aperture is controlled by a precision iris (p-iris) which can be digitally controlled for varying lighting

	conditions. For high dynamic range (HDR) images, the iris can be set to allow different exposures for the same scene brightness. In addition, the iris can be used along with exposure time to control for depth of field of the image.
• Internal dual optical filters	Some applications require capturing a color image of a scene for visual documentation and then switching to an IR only filter for enhanced OCR, food and crop condition, or improve SNR for IR illuminated scenes. Theia's calibrated lenses may include an internal switchable filter system. The lens can switch optical transmission passbands with an internal dual "filter wheel". Depending on the lens specifications, the lens can switch between transmitting visible light and IR light or from visible only to visible and IR together.
• Intuitive unit conversion for zoom, iris, and focus	Setting the lens to a desired focal length by specifying millimeters or setting focus to a specific distance by specifying meters is a typical application. Theia's calibrated lenses provide curves to convert from intuitive unis to motor steps and vice versa.
• Calibrated distortion and optical axis position	Mapping applications and 3D imaging applications requiring known object positions can be set up and calibrated by the end user without complicated distortion mapping illumination grid jigs. Each lens is individually calibrated and positional corrections due to lens distortion are available at multiple focal lengths.
• Calibrated resolution	The user can maximize image sharpness and light gathering ability while minimizing image blurring in low light by intelligently setting the lens aperture, focal length, and focus position. Lens MTF resolution (optical sharpness) is measured and calibrated for each lens.
• Calibrated relative illumination	Bin picking and quality control applications are made easier with a uniformly exposed scene. Each Theia calibrated lens is individually calibrated for relative illumination (vignetting) so that corner to corner image brightness can be adjusted for uniformity at different focal lengths and F/# settings.
• Zoom/Focus tracking curve	Many of Theia's calibrated lenses include motorized zoom and focus. For these models the user can program the focus motor position to maintain a continually sharp image as the field of view is changed.
• Calibrated lateral color and chief ray angle	De-Bayering algorithms depend on knowing the color balance as a function of pixel position to calculate uniform image color. Color can be affected by both CRA-to-microlens array mismatch and lateral color performance. Each lens is calibrated for lateral color and designed CRA to allow the fine tuning of the color balance of pixels in the image.
• IR correction	Maintaining a single image focal plane for visible through near IR light allows broad spectrum and multi-spectral applications to use a single lens without requiring frequent focus adjustments. For many applications the designed-in IR correction is sufficient, but Theia's calibrated lenses also provide a focus shift calibration curve at different wavelengths that may be used to improve the image resolution further.

2. Calibration data files

Theia's calibrated lens data files are available from our cloud database and are linked to individual lenses by the lens serial number. The data files include both individually calibrated measured data and design data for each lens. See application note AN002 for more information about reading data files.

3. Lens setting accuracy

Even though the lenses are calibrated, the tolerance of the sensor position or mount size must be calibrated for each camera. The back focal length calibration procedure is described in application note AN004. Lenses have very tight tolerances that affect how accurately they can be setup without any lens-to-lens calibration. For example a tolerance of 0.1mm between the sensor active area and the lens mounting plane can result in a focus motor position error of >100 steps. This is greater than the depth of focus range of ±20 steps (depending on focal length and F/#) so there could be a noticeable lack of focus if the initial BFL calibration is not done.

4. Available calibration data

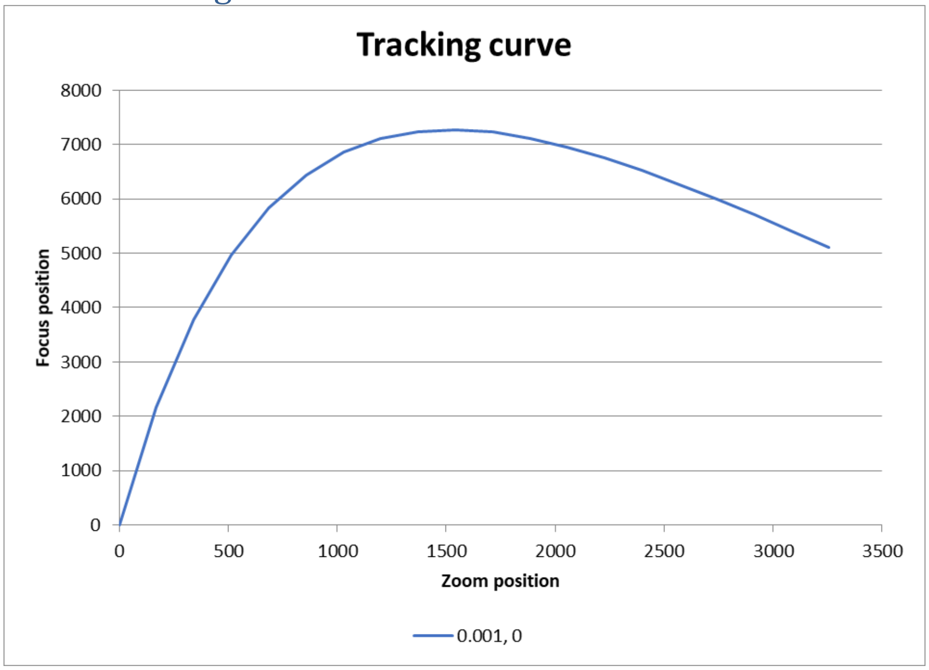
Theia's calibrated lenses offer calibration curves for many data frames. Some of these data frames are available on a per-lens calibrated basis. Where the lens to lens variation is small the calibration data is provided as design data.

Depending on the lens capabilities, the available calibration data will be different. Not all data frames have been developed yet but the table shows which data frames are possible for each lens family.

				Calibration data available for lenses			
Function	**Y axis**	**X axis**	**Source**	**TL1250**	**MY23F**		
Focus/zoom tracking	Focus motor step	Zoom motor step	Calibrated	yes	no		
Distortion	Object angle [deg]	Image height [mm]	Design	yes	yes		
Focal length conversion	Zoom motor step	Focal length [mm]	Calibrated	yes	no		
Relative illumination	Illumination [%]	Image height [mm]	Design	yes	yes		
Aperture	Aperture [1/(2*F/#)]	Iris motor step	Design	yes	no		
Iris diameter	Iris short diameter	Iris motor step	Design	yes	no		
Image sharpness	MTF modulation	Aperture [1/(2*F/#)]	Calibrated	yes	yes		
Focus shift due to temperature	Focus motor step	Temperature [°C]	Design	yes	no		
Focus shift due to wavelength	Focus motor step	Focal length [mm]	Design	yes	no		
Back focus distance	BFL [mm]	Glass thickness [mm]	Design	yes	no		
Chief ray angle	CRA	Image height [mm]	Design	yes	yes		

Since the MY23F lens is not motorized for example, several of the data frames are not available because they are specific to motor control. Other lenses will have another suite of data frames depending on their capabilities.

4.1. Focus/zoom tracking calibration curve



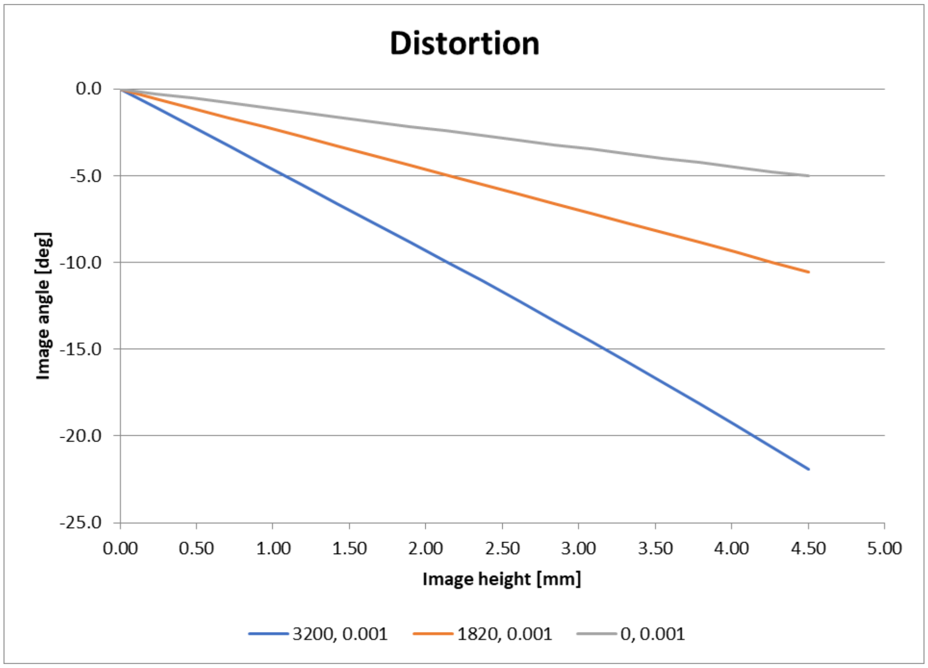
Applicable to: motorized lenses
Calibration type: individually calibrated for each lens

For varifocal lenses, changing the focal length will cause the image to lose focus. Setting best focus for a desired field of view (focal length) is an iterative process. Theia calibrated lens data sets include this focus/zoom tracking curve which can be used to keep the lens in focus while changing zoom position (depending on minimum motor speeds) or at least to set the focus at a known zoom position.

After commanding the zoom motor to a known position (see the focal length calibration curve for converting focal length to zoom motor steps) the focus motor can be commanded to the expected position that would provide best focus at infinity or some other object distance. From this position a fine focus adjustment may be required to compensate for small tolerance differences in the lens and lens mount positions.

See application note AN012 for more information about how to use this tracking curve.

4.2. Distortion calibration



Applicable to: all calibrated lenses
Calibration type: design data common to all lenses of the same model.

Distortion is the measured object angle at different sensor image heights compared to the simple paraxial angle. The basic paraxial calculation uses similar geometric triangles to calculate the angle of the object. For example, at image height 3.0mm (radial from sensor center) in a lens with focal length 12mm the calculated object angle is

$$\tan(\theta) = \frac{3.0}{12.0}$$

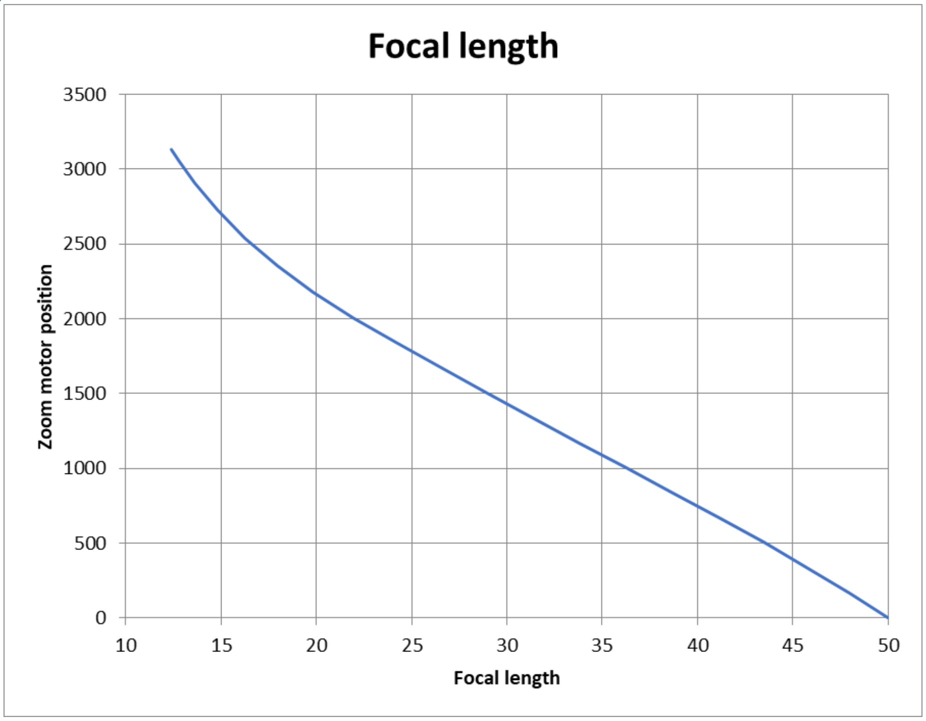
$$\theta = 14°$$

However due to distortion in the real lens, this angle is in-exact. The distortion equation can be used to find the real angle of $\theta = 14.5°$ as an example using Theia's 12-50mm lens (TL1250P N6-CAL). Although the difference seems small, it is equivalent to approximately 43 pixels on a 4K sensor. For mapping applications such as 3D or navigation this correction can greatly improve the prediction of the object position in the real world and allow the robot to avoid or contact the object as appropriate for the application.

Distortion increases with wider angle lenses like Theia's TL410 (4-10mm) and wide angle lenses not using Theia's Linear Optical Technology®. Depending on how well corrected they are, rectilinear lenses like those using Linear Optical Technology (Theia's MY23F (2.3mm) for example) can rely on the simpler paraxial calculation for object angle.

See application note AN010 for more information about distortion correction.

4.1. Focal length calibration curve



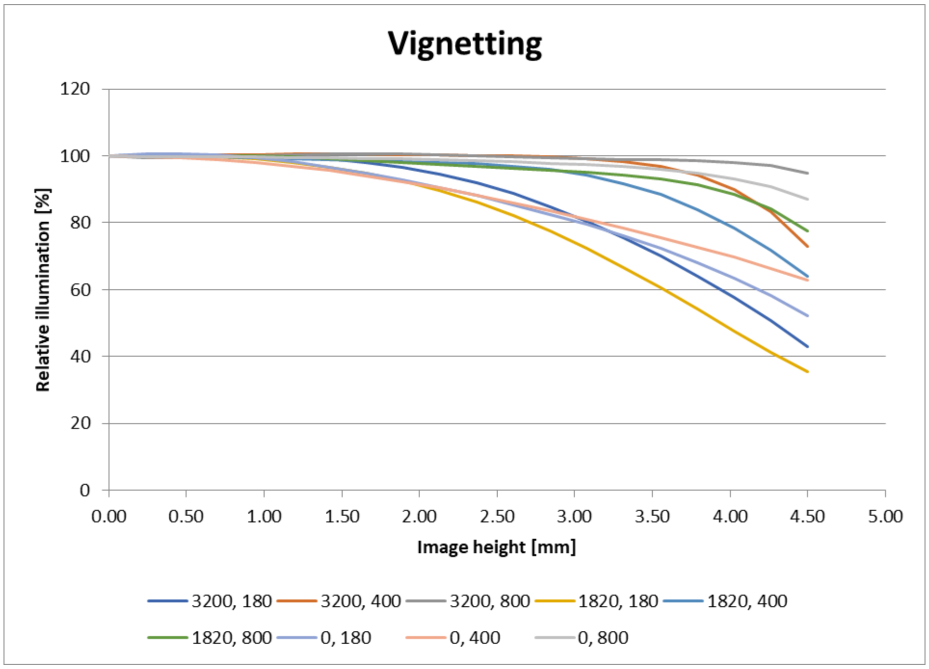
Applicable to: lenses with motorized zoom and focus.
Calibration type: individually calibrated for each lens.

For calibrated lenses that include motorized zoom and focus, this function relates the zoom motor step position to the actual focal length allowing the user to set the lens zoom position correctly. In most applications the field of view is known. Using the distortion correction curve (along with the known image sensor size) will allow conversion from field of view to focal length. Follow this with the conversion shown above to convert focal length to zoom motor step position. This will allow the user to set the lens to the desired focal length.

For example if the field of view requires a focal length of 25mm in Theia's 12-50mm lens (TL1250P R6-CAL), this is converted to zoom step number 1784. Commanding the zoom motor to this step (in Theia's MCR600 motor control board or customer written software) will move the zoom and give the desired field of view.

See application note AN015 for more information about aperture and F/# calibration.

4.2. Relative illumination calibration



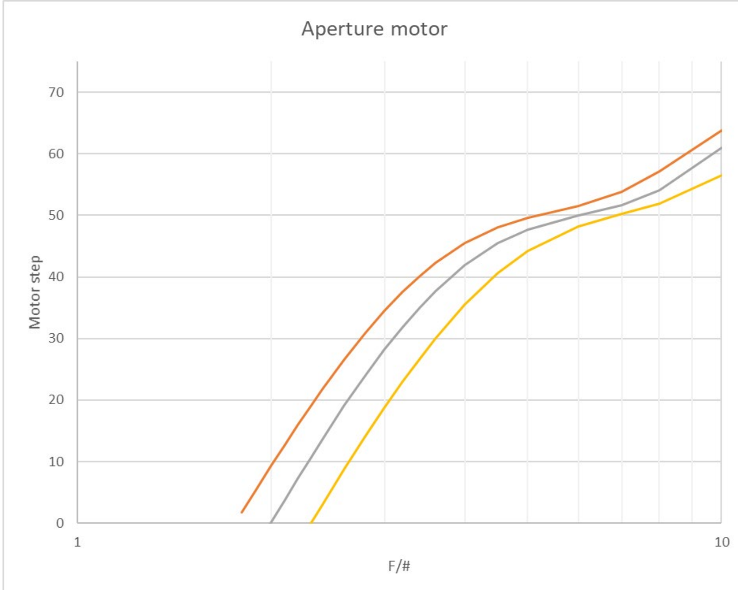
Applicable to: all calibrated lenses
Calibration type: design data common to all lenses of the same model.

Towards the edge of the image for any lens, the brightness starts to drop off. This is not really noticeable to a user visually when the corner relative illumination is above 50% but may affect an automated image processing algorithm that is searching for a gray level contrast to isolate an object of interest. This vignetting calibration data can be used to compensate for the brightness fall off and improve the image analysis.

Vignetting is a function of F/# and focal length. Slower F/# will improve the brightness uniformity at the cost of total brightness throughput.

See application note AN013 for more information about relative illumination.

4.3. Aperture calibration curve

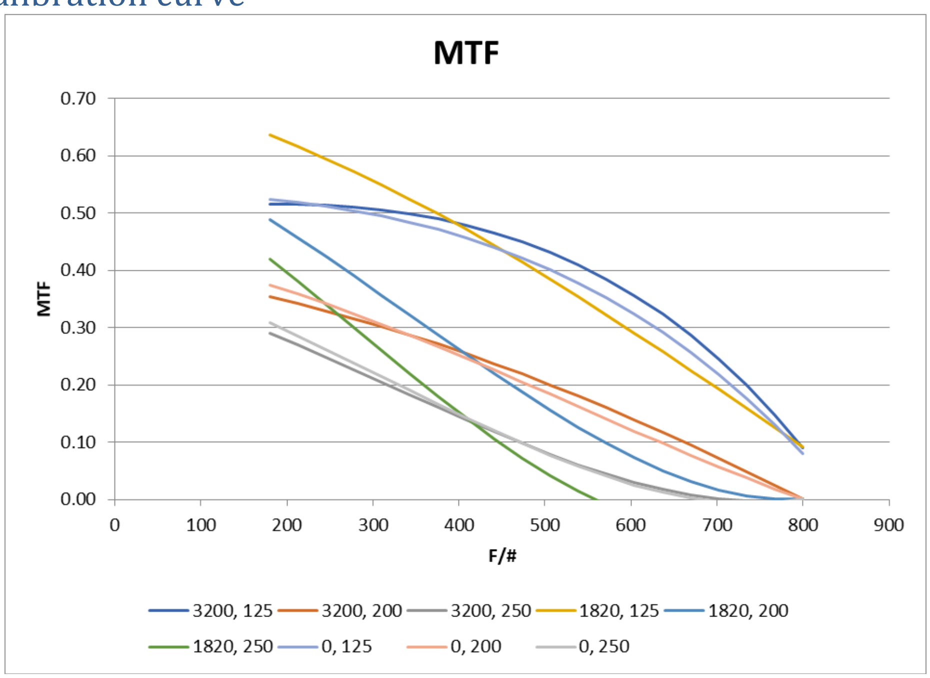


Applicable to: lenses with p-iris.
Calibration type: design data common to all lenses of the same model.

For calibrated lenses that include a p-iris (regardless of whether they have motorized focus and zoom or not) this curve relates the iris motor step number to the aperture of the lens. The aperture F/# and numeric aperture definitions are described in application note AN015. Pupil diameter can also be a function of focal length but it generally doesn't cancel the effect on F/#. So like most lenses, the F/# is affected by the focal length.

To create a curve with well-fitting data it is plotted as numeric aperture (1/(2*F/#)) instead of directly as F/#.

4.4. MTF calibration curve



Applicable to: all calibrated lenses
Calibration type: individually calibrated for each lens

The user must balance many variables to achieve the best image for the application including aperture (shutter speed and motion blur), field of view (image resolution), and supplemental lighting (power and budget). This calibration curve plots the MTF modulation value against iris aperture for different MTF frequencies. This data can be used to optimize the image resolution at different iris positions giving the user some idea of trade-offs between image sharpness and aperture opening.

In the example plotted here, zoom motor positions range from 50mm telephoto through 12mm wide angle and different MTF frequencies from 150lpm to 250lpm. The x-axis is the aperture size plotted at numerical aperture (1/2*F/#) to provide a smooth well-fitted curve. For this telephoto lens, as the aperture gets slower, the MTF decreases but also notice that the mid-focal range of ~25mm has the highest performance with a wide open aperture (yellow, cyan, and green) at all 3 frequencies plotted.

See application note AN014 for more information about MTF calibration curves.

4.5. Temperature focus shift calibration curve

TBD: Plot focus shift v. focus motor step at different focal lengths
Applicable to: all calibrated lenses
Calibration type: design data common to all lenses of the same model.

All Theia lenses are all thermally compensated to maintain good focus over a wide range to temperatures. There is a small focus shift which can be compensated by a shift of the focus motor. This shift is dependent on the focal length of the lens and may or may not be significant to improving the image quality in the application.

One mechanical requirement to allow accurate temperature compensation is that the mount material between lens and sensor should be aluminum or 30% glass filled polycarbonate (30% GFPC) because the thermal expansion of the lens mount is included in the thermal design of the lens. Other materials have different thermal expansion coefficients which are not included in the lens design.

4.6. Wavelength focus shift calibration curve

TBD: Plot focus shift v. IR wavelength

Applicable to: all calibrated lenses
Calibration type: design data common to all lenses of the same model.

All Theia calibrated lenses are IR corrected to maintain good focus across a broad wavelength spectrum. IR corrected lenses have the advantage that they can simultaneously provide good focus in broadband visible and NIR light. However when illumination changes to IR there could be a slight focus shift to keep optimum focus depending on the application. This curve shows the focus change between best visible focus position and best IR focus position at different zoom focal lengths.

4.7. Back focal length adjustment (BFL)

TBD: Plot focus shift v. BFL

Applicable to: all calibrated lenses with internal focus groups
Calibration type: design data common to all lenses of the same model.

Some of Theia's lenses are focused by moving the entire lens relative to the image plane. In this case there is no calibration data. However many lenses (like TL1250 and TL410 lenses) have internal focus groups so the tolerance in the lens to image sensor spacing can affect the focus motor position for optimum focus.

Both the lens mount tolerance and the amount of glass between the lens and image sensor plane will affect the focus/zoom curve of the lens. Theia recommends an initial back focal length compensation routine for each individual lens and camera. See application note AN0004 for more information.

4.8. Chief ray angle (CRA)

TBD: Plot CRA v. image height

Applicable to: all calibrated lenses
Calibration type: design data common to all lenses of the same model.

Chief ray angle on the sensor varies. This data is available as a maximum number or a graph versus image height on most data sheets but for greater accuracy and programmatic control it is included in the calibration data file as well. This CRA is a design value as it doesn't vary significantly from lens to lens.

5. Revisions

Version	Change	Reason
220311		Preliminary release