



AN004: BFL compensation

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1. Back focus length (BFL)

Lenses are tested during manufacturing based on industry standards. C-mount is a threaded mount with mounting flange 17.526mm from the image sensor plane¹. CS-mount has the same threads but the mounting plane is either 12.526mm or 12.500mm from the image sensor plane. There does not seem to be a consensus on this exact distance. However, in a real camera, this 26µm difference is overshadowed by tolerances in the mount plane height, image sensor height, and other stacked tolerances that make the image plane different than the ideal location.

For lenses that have an internal focusing group like Theia's motorized lenses, this tolerance stack must be compensated for in the focus/zoom relationship. The focus/zoom curve for Theia's calibrated lenses is based on an ideal back focus length position for each lens individually. For Theia's IQ series lenses, the curve is based on a recent average of lenses but it doesn't change much from lot to lot.

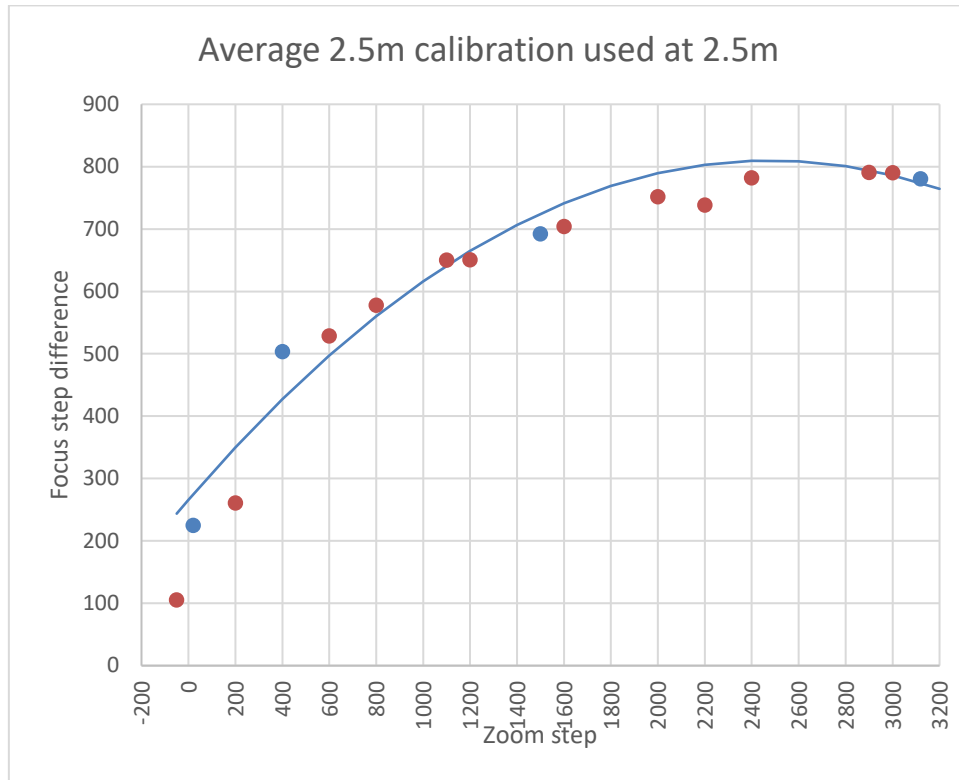
Using this procedure to calibrate BFL should allow good prediction² of the focus step for any zoom step and object distance.

In this graph below, the blue points are the 5 measured data points from the calibration procedure. These points are used to create the quadratic curve used for BFL correction (difference between predicted and measured best focus step position). The graph shows the BFL correction at different zoom step positions. The abundance of red points are verification data points showing that the curve is predictive but due to variations some fine tuning may still be required.

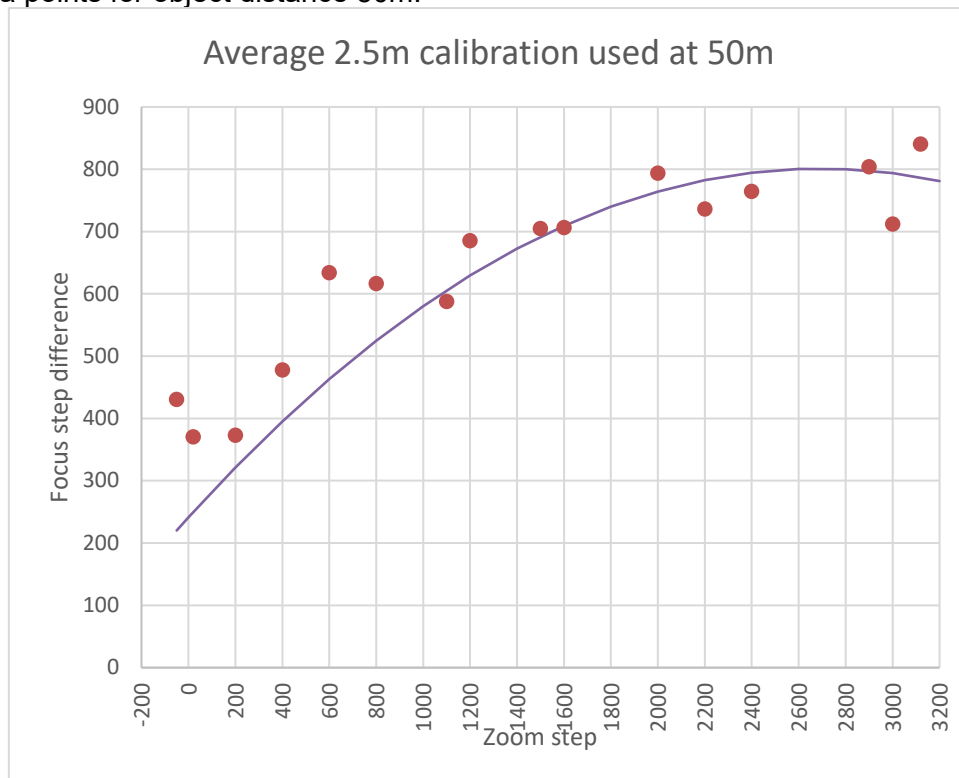
¹ https://en.wikipedia.org/wiki/C_mount

² Depending on the application, a fine focus adjustment may need to be done to achieve best focus position. Because of lens tolerances and necessary looseness, results of this procedure cannot be relied on for best focus every time.

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This data above is for calibration done at 2.5m object distance and verified at 2.5m object distance. Without redoing the calibration, the same curve (adjusted for object distance per the focus/zoom prediction curve) can be used at different object distances with similar accuracy. The chart below shows verification data points for object distance 50m.



2. BFL calibration procedure

This procedure must be done with each lens/camera combination because it is accounting for very small tolerances (<20 μ m). The lens focus step must be controllable using Theia's MCR controller³ or an alternative driver and an image must be available to the user (alternately an automatic focus function could be used but this must be developed by the integrator).

1. Measure the distance to a target object. The distance should be >3m but ideally between 5m and infinity.
2. Initialize the lens motors by homing the motors to the limit switches. The focus and zoom motor step count should be set to the respective limit switch step positions as specified in the lens specification.
3. Choose a minimum of 5 focal lengths (for the TL1250 series lenses use 12.5mm, 23mm, 32mm, 38mm, and 47mm).
 - a. Move the zoom motor to the first focal length. Store the zoom motor step number or focal length as the x-value.
 - b. Calculate the expected focus motor step position for that focal length (see the following sections for the procedure).
 - c. Visually focus the lens.
 - d. Calculate and save the difference between the calculated best focus step (from the focus/zoom curve) and the measured best focus step set visually. This difference is the BFL offset at this focal length and should be stored as the y-value.
 - e. Repeat this for the other focal lengths.
4. Fit a quadratic curve to these 5 or more data points. A quadratic curve has enough flexibility to fit the points without too much unreal fluctuation between the measured points.
5. This curve can be used to predict the focus step offset required as a function of focal length. Add this offset to the predicted value from the focus/zoom curve at any lens focal length.

Two alternate methods for calculating the focus/zoom curve are described below.

3. Use Theia's Lens IQ™ software

The easiest option for back focal length calibration is to use Theia's Lens IQ™ software⁴. This is a Python module developed by Theia that allows intuitive engineering value inputs (meters, degrees, etc) and calculates the corresponding motor step values. This Python module can be used with your own program. Alternately, Theia has also developed a graphical user interface (GUI) for Windows based on this Python module.

The software includes functions for storing the calibration points and calculating the BFL focus step offset. After storing data points, the software will calculate a quadratic curve of focus step offset versus focal length. This curve can be accessed to calculate an offset from the calibration curve at any focal length.

4. Focus/zoom curve calculations

The calibration data is at the top level of the JSON formatted data file (either the per-lens calibration file or the -IQ averaged data file). The focus/zoom curve polynomial coefficients can be found under the "tracking" key. This abridged sample of the calibration data file shows focus-zoom tracking curve. This case shows that there are 4 curves to choose from ("count": 4) based on the object distance control point ("cp1Type": "1000/obj dist"). It may be required to read the coefficients for a couple curves and

³ <https://www.theiatech.com/lenses/accessories/mcr/>

⁴ Contact Theia for information about licensing the Theia Lens IQ™ software.

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interpolate to match the actual setup. The parameters for the first 2 curves are shown (1000m object distance and 10m object distance).

```
"tracking": {
  "type": "cal",
  "idx": 1,
  "count": 4,
  "xAxis": "zoom step",
  "xMin": 0,
  "xMax": 3147,
  "yAxis": "focal step",
  "cp1Type": "1000/obj dist",
  "cp2Type": "",
  "cp1": [
    1,
    100,
    200,
    400
  ],
  "cp2": [
    0,
    0,
    0,
    0
  ],
  "coef": [
    [
      6759.133767954516,
      -13.266890381130867,
      0.012903478977987942,
      -7.821620295284879e-06,
      3.1040961493589914e-09,
      -6.794893760069593e-13,
      6.079222365350608e-17
    ],
    [
      6340.913193162877,
      -12.807459523420478,
      0.01366060335123544,
      -9.581190218374742e-06,
      4.314254359301763e-09,
      -1.030045758461539e-12,
      9.764951444254434e-17
    ]
  ],
  ...
}
```

The focal length conversion calibration curve is also required. This is found at the top level using the "FL" key. The polynomial coefficients are used to convert from focal length to zoom motor step number. The inverse conversion, from zoom motor step number to focal length, is also provided using the "coefInv" key. Conversion in both directions is provided because this calibration curve is often used in both directions for many calculations.

```
"FL": {
  "type": "cal",
  "idx": 4,
  "count": 1,
  "xAxis": "focal length",
  "yAxis": "zoom step",
  "cp1Type": "1000/obj dist",
  "cp2Type": "none",
}
```

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```
"cp1": [  
  0.01  
],  
"cp2": [  
  0  
],  
"coefInv": [  
  [  
    46.07560599052303,  
    -0.02530984936782476,  
    1.3629475955340803e-05,  
    -8.725767416579793e-09,  
    3.840083178032434e-12,  
    -8.625672106411288e-16,  
    7.419428745018643e-20  
  ]  
],  
"coef": [  
  [  
    5843.494670020867,  
    -216.94698495829604,  
    -5.132311501752025,  
    0.4951739872094595,  
    -0.011599296350493596,  
    9.103106689613345e-05  
  ]  
],  
...
```

1. Use the conversion polynomial coefficients from the "FL" key to calculate the zoom motor step number from a given focal length so the lens (which operates in steps) can be set to the required focal length.

$$zs = \sum_{k=0}^n P_k * FL^k$$

Where zs is the zoom motor step number, FL is the lens focal length [mm], and P_k is the polynomial coefficient. For $FL = 32.2\text{mm}$, the zoom motor step can be calculated as $zs = 745$.

2. Calculate the ideal focus motor step number from the polynomial coefficients for the "tracking" focus zoom curve in the data file. Interpolation may be necessary if an object distance other than the ones listed in the file is selected.

$$fs = \sum_{k=0}^n P_k * zs^k$$

Where zs is the zoom motor step number and fs is the focus motor step number. For this example, at 10m object distance, the ideal focus motor step $fs = 1277$.

3. Focus the lens and record the best focus motor step position (e.g. 1460). The focus motor step position must be tracked in the motor control program to be able to extract this number. In addition, the zoom motor step and expected (calibrated) focus step will be required.

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Zoom step	Calibrated FL	Calibrated focus step	Predicted focus	Measured focus	Difference from calibration
745	32.2	1277		1460	183

4. Repeat this at 4 or more additional focal lengths. Calculate the zoom step for the focal length and calibrated focus step. Measure the best focus position and calculate the difference from the calibrated focus step. 3 points are shown below (but a minimum of 5 is suggested) can be used to create a quadratic fit for the BFL offset.

Zoom step	Calibrated FL	Calibrated focus step	Predicted focus	Measured focus	Difference from calibration
745	32.2	1277		1460	183
1596	22.2	353	536	866	513
2680	14.5	1642	2575	2340	698

The quadratic fit for BFL offset (focus step difference from calibration) vs. focal length creates these three points is (P2, P1, P0):

quadratic	-0.0001476	0.76096357	-298.424058
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5. The BFL compensation curve can now be used to find the predicted focus step for any focal length⁵. The compensation will be a change in focus motor step position versus focal length. It should be slightly quadratic. Whenever a focus motor step is calculated or used, apply this compensation factor to get close to the ideal focus position. For example, at focal length 27.2mm, the focus step position should be adjusted by +367 steps from the predicted position to find the best focus.

Zoom step	Calibrated FL	Calibrated focus step	Predicted focus	Measured focus	Difference from calibration
1116	27.2	563	930		367

5. Revisions

Version	Change	Reason
230411		Preliminary release
231020	Procedural modification	Simplified BFL compensation procedure
231127	Procedural additions	Added clear examples to step by step procedure
231201	Added telephoto points to compensation calibration	Telephoto points are needed for a good fit at telephoto end
240109	Procedural change, added software description	Software release.

⁵ Depending on the application, a fine focus adjustment may need to be done to achieve best focus position. Because of lens tolerances and necessary looseness, results of this procedure cannot be relied on for best focus every time.