

Innovative test method for validating image quality performance of automotive lenses over operating temperature range

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ABSTRACT

The use of electronic imaging systems in the automotive industry has increased dramatically as a result of the wide spread implementation of optical-based safety systems and driver assistance features in new vehicles. The challenging environmental requirements for automotive cameras have given rise to the need for image quality testing of these cameras over a wide range of operating temperatures. Functional and survivability testing of camera assemblies is relatively straightforward and may be carried out in conventional environmental chambers, but assessing the imaging performance of the lens over temperature is critical in evaluating whether hardware performance meets design intent and presents a much more challenging metrology problem. The lens must be contained within a chamber, but the chamber itself must not adversely contribute to the image quality being assessed. Measures must also be taken to prevent condensation in the optical path when operating below the ambient dew point. Additionally, careful consideration must go into the measurement of defocus over temperature – which is the critical metric in temperature testing – to ensure that the chamber is not contributing to the measured focus shift. In this paper, we describe an innovative system that takes these challenges into account and enables users to measure lens image quality metrics over a temperature range of -25°C to 105°C. This system has evolved over the past few years from a strictly in-house laboratory setup to a recently released commercial product, and we will present results from our extensive testing that show good correlation of measurements to modeled behavior.

Keywords: Image quality, automotive, Modulation Transfer Function, metrology

1. INTRODUCTION

Any vehicle that was built in the last ten years probably includes at least one camera, and cars that are being built today are likely to include several such devices. The use of cameras in automobiles may have started out as a novelty, but the prevalence and steadily dropping costs of high resolution camera assemblies has quickly resulted in cameras being integrated into critical automotive safety features. Many governmental bodies now require new cars to have a backup camera, and newer safety features like Pedestrian Automatic Emergency Braking, Blind Spot Detection, and Lane Keeping/Departure Warnings are heavily dependent on the use of cameras. More recently, they have become a key technology in the development of self-driving cars, and it has been widely agreed that the highest levels of autonomous driving cannot be achieved without the use of cameras to replace human vision.

As more cameras are integrated into consumer vehicles in general, and into critical vehicle safety features in particular, the need arises to carefully consider image quality and how it pertains to the automotive industry. Not only must automotive cameras resolve enough detail across the entire field of view to distinguish between a pedestrian and a fire hydrant, but they must also maintain a sufficiently high level of image quality under the most challenging environmental conditions – particularly over the operating temperature range for a vehicle. The cameras typically used in cars are fixed focus, so the operation of the camera is heavily dependent on the camera passively maintaining focus over its lifetime and under all conditions. This is challenging to achieve when the camera is exposed to a wide temperature range, because thermal expansion of mechanical and optical materials and thermal variations of refractive indices can easily result in a defocus becoming the principal aberration if not properly accounted for in the system design. This behavior can be modeled for the camera system – particularly for the lens, which can have very complex thermal behavior depending on the design – but theoretical models necessarily make simplifying assumptions and may not accurately account for hysteresis or non-linear behavior. It is the need to carry out design validation that has resulted in a demand from camera manufacturers and system integrators to test image quality over temperature for both camera assemblies and their components.

Due of the complexity of the thermal behavior of a complete camera assembly, the ability to test only the lens over temperature is critical in understanding whether or not a camera design meets the design intent. In cases where a camera does not perform as expected over temperature, testing at the lens level is also the most informative way to determine the cause of the performance difference. While commercially available thermal chambers with a window can be used for testing a camera over temperature, testing a lens over temperature is a considerably more complicated metrology problem. Until recently, there was no good way to measure the image quality of a lens over temperature and have confidence in the measured results. Through several years of in-house testing and working with customers in the automotive industry, the product development team at Optikos Corporation has developed a thermal module system that addresses the particular challenges of making these measurements.

2. BACKGROUND INFORMATION

2.1 Lens image quality assessment overview

Before delving into the details for testing lenses over temperature, a general understanding of the types of measurements used for assessing the image quality of lens assemblies is required. There are many types of measurements that can be used for this purpose, but the most common measurement is the evaluation of the Modulation Transfer Function (MTF) of the system. MTF measurements provide information about how well the imaging system can reproduce features of varying size in the object, and is frequently referred to as a measure of the resolution of the imaging system.

There are several ways to measure MTF, but the most efficient and widely adopted method is to present the lens under test with a geometric object of known size and essentially perfect contrast, and use Fourier analysis to evaluate the contrast in the resulting image as a function of spatial frequency. By placing the geometric object at various points within the field of view of the system under test, MTF measurements can be made on and off-axis to determine how the image quality changes from the center to the edge of the image. MTF measurements can also be made in various planes along the optical axis (“through focus”) and then plotted as a defocus curve for a specific spatial frequency, as shown in Figure 1. A collection of on and off-axis defocus curves can be used to determine the image plane location that produces the highest MTF values and therefore the best image quality.

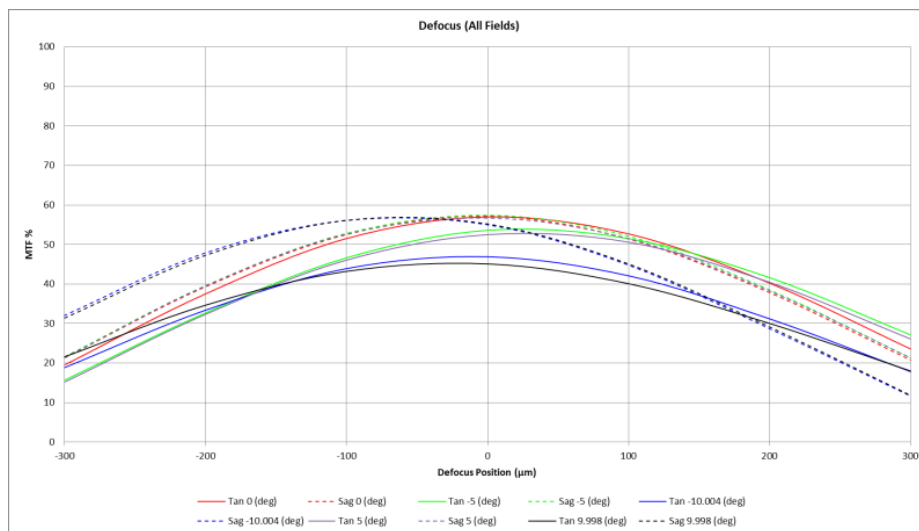


Figure 1 Through focus MTF measurements made over the field of view of an imaging system can be used to produce the defocus curves for a specific spatial frequency.

MTF is often used to assess the image quality of an imaging system because it can be accurately predicted by optical modelling and included as an operand in tolerancing the design, which means that measured values can be directly compared to the design predictions. MTF is not the only measurement that can be used to compare the hardware performance to the design intent. The most basic set of measurements includes first order parameters that are inherent to a lens design and which can readily be tested to confirm that an assembled lens matches the theoretical model. These

parameters include entrance and exit pupil sizes and locations and f-number. Measuring these parameters is a good starting point when assessing the as-built performance of a lens.

The next level of testing usually includes MTF and MTF-based measurements like field curvature, field tilt, astigmatism, axial color, and the physical distance between the vertex of the last lens element and the image plane (Back Focal Length, BFL) and between a mechanical datum or mounting flange on the lens barrel and the image plane (Flange Focal Length, FFL). MTF is employed in these measurements as the metric by which the best focus location is determined. Additional categories of testing that are not directly based on MTF but which may still have a bearing on the image quality are image location based measurements such as Effective Focal Length (EFL), distortion, Chief Ray Angle (CRA) and lateral color, and measurements like relative illumination and stray light that are based on comparing signal levels across the image plane.

The choice of which measurements should be performed for a given lens depends on the application and the way the lens was designed, and with an appropriately configured lens testing bench one setup can often measure multiple lens parameters. For lens testing over temperature, the primary measurement of interest is the variation in flange focal length, but the thermal module design described in this paper does allow for other parameters to be evaluated using the same apparatus. This is because the thermal module is designed as an accessory to standard Optikos lens testing benches, so a general understanding of how a lens testing bench works is helpful.

2.2 Lens assembly test bench for image quality measurements

The majority of lenses are designed to work with an object at infinity, so a typical lens test bench will place the geometric object at the focus of a collimating lens or an off-axis parabolic mirror to make the object appear at an infinite distance from the lens under test. The object is back illuminated by a broadband source that can be filtered to the desired test spectrum, and there are multiple standard objects (pinholes or slit targets) of varying sizes that can be selected depending on the lens under test. The lens under test is mounted on a rotary platform that presents the collimated object to the lens at selectable field angles in order to test both on and off axis. When testing in the visible spectrum, the image formed by the lens is magnified by the image analyzer assembly and relayed onto a high resolution sensor for capturing before being transmitted to a computer for analysis. The image analyzer assembly is mounted on a 3-axis stage assembly that can locate the image analyzer within the image plane and along the optical axis of the lens under test for off-axis and through focus testing. The images in Figure 2 show two different lens test bench configurations and identify the main components of each.

The need for the image analyzer assembly to relay and magnify the image formed by the lens is one reason why testing lenses over temperature is so challenging. The lens must be enclosed within the thermal module to ensure that the lens temperature is stable while the image analyzer must be able to access the image plane while remaining outside of this envelope so that its own imaging performance is not adversely affected. This problem does not arise when testing complete camera assemblies over temperature because the image is captured directly by the integrated sensor and relayed out of the thermal chamber to over a cable to the computer for analysis. However, the analysis that can be done at the camera level is far more limited because measurements can only be made in the sensor plane and are limited in resolution by the fixed sampling frequency of the sensor. Testing at the lens level offers the opportunity to separate lens contributions from those of the entire assembly, and to make measurements at higher spatial frequencies.

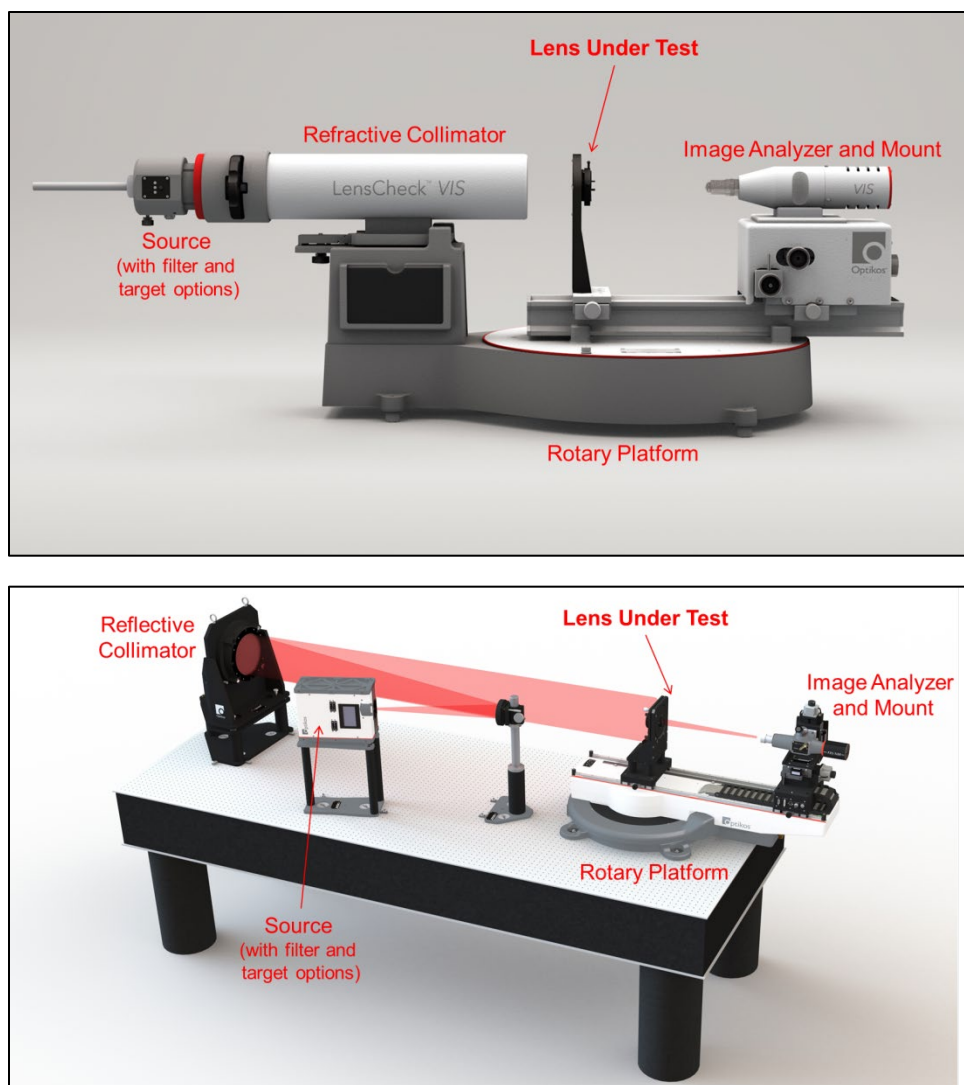


Figure 2 Standard components for a lens test bench. Different bench configurations may be required for different types of lenses. The *LensCheck™* system (top) is suitable for small lenses with large fields of view, while the *OpTest®* bench (below) can test larger lenses over a broader spectrum.

3. THERMAL CHAMBER MODULE

3.1 Optikos thermal module system overview

In order to take full advantage of the image quality measurement capability offered by standard Optikos lens testing benches, the TM-1000 Thermal Module product line was designed as an optional accessory to the standard lens testing benches shown in Figure 3. The thermal module is used in place of the usual lens mount.

The thermal module operates on the principle of thermal conduction, and circulates heated or cooled fluid through a heat exchanger to set the temperature of the lens under test. Unlike other methods of testing over temperature, this approach does not require pulling a vacuum to get the lenses to the coldest temperatures, which makes this testing more suitable for lenses of all types and for all applications. The Optikos thermal module can achieve lens temperatures between -25°C and 105°C with standard hardware (additional options are available to extend that temperature range further if needed).



Figure 3 The TM-1150 thermal chamber (top left) is intended for large lens assemblies and can be mounted on an *OpTest*® bench rotary platform as shown in the top right. The TM-1050 thermal chamber (bottom right) is intended for smaller lens assemblies that would typically be tested on a *LensCheck*™ *VIS* test bench (bottom left)

3.2 System components

There are three main components to the thermal module system: the recirculating chiller/heater, the dry air manifold and control unit, and the thermal chamber in which the lens is mounted. Insulated hoses are provided to connect the three subsystems. The thermal chamber provides the mounting interface for the lens under test, and has a double pane removable window assembly on the front to allow the light from the collimated source to enter the chamber. The chamber also has an insulated shutter assembly behind the lens (on the image side) that is used to seal the chamber during thermal soak times and which opens to allow the image analyzer to access the image once the lens temperature has stabilized. The main components of the chamber are shown in Figure 4.

The recirculating chiller/heater contains a reservoir of thermal fluid that is used to set the lens temperature. The temperature of the chamber and the lens under test is monitored continuously through the control unit by the system computer, which in turn communicates with the recirculating chiller/heater to adjust the fluid temperature as needed to achieve a desired lens temperature. The control unit also regulates the flow of dry air into the chamber to eliminate condensation and controls the insulated shutter on the chamber during the measurement routine. An automated measurement routine can be run via the *OpTest*® 7 software application, which is provided with each Optikos lens test bench.

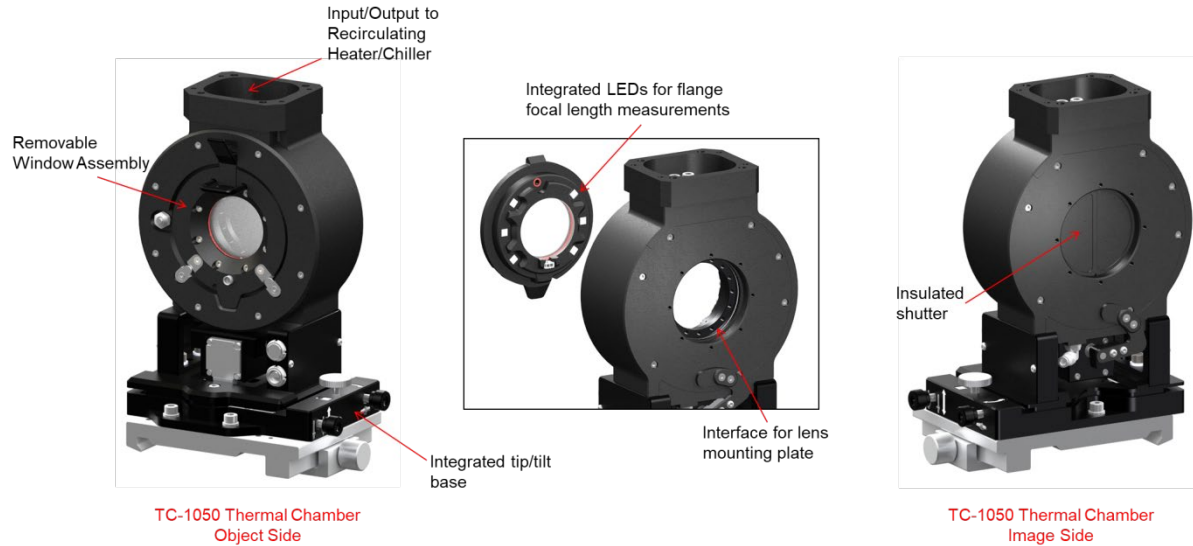


Figure 4 Main Components of the TC-1050 Thermal Chamber assembly, shown without hoses.

3.3 Thermal module design considerations

All of the thermal chamber designs offered by Optikos share similar design characteristics that seek to solve the same physical design challenges. In each case, the chamber is based on the concept of a cylindrical heat exchanger through which the externally heated or cooled thermal fluid is circulated. Each lens under test is mounted to an interface plate which is then mounted to the end of the heat exchanger. The principal heat transfer mechanism for the lens under test is conduction through this interface plate, although convection and conduction through the air in the chamber play a role that becomes increasingly significant for longer lenses. The temperature of the lens is measured using small Platinum Resistance Thermometer (PRT) probes that are affixed directly to the lens barrel or, in the case of very small lenses, to the interface plate immediately adjacent to the lens.

The most significant challenge is the most obvious – to hold a lens at a temperature that is different from the ambient laboratory conditions without introducing variables that might affect the imaging performance of that lens. Light must be allowed to enter and exit the chamber, but the thermal chamber must be sufficiently sealed to be able to maintain its temperature and the temperature of the lens under test. In the Optikos thermal chamber design, the wavefront of the incident collimated beam is preserved through the use of high quality windows. In all cases (with the exception of the chamber designed for use with very wide field lenses) the entrance window arrangement comprises two plano parallel fused silica windows separated by a small dry air gap. This air spaced double-pane arrangement provides some measure of reduced heat flow through the windows without incurring the distortions that will necessarily result from a vacuum break between them. In the wide field of view chamber, the two pane entrance window is replaced with a double dome arrangement.

The image side of the lens offers the greater challenge since the placement of any type of window in the converging beam would introduce spherical aberration into the image (the exception to this rule is those cases in which a thin piece of glass must be inserted in place of a sensor cover glass). It is also quite often the case with small lenses that the back focal length is too short and the requirement to also be able to measure flange focal length is too constraining for a window arrangement to be practical. Instead, we have taken the approach of employing a mechanical shutter to isolate the lens under test in the chamber during thermal soaking and then opening the shutter only as much as is necessary and only for the shortest possible time when making a measurement. Since any ambient air in the chamber will result in condensation or frosting at temperatures below the ambient dew point, it is necessary to maintain a positive pressure within the chamber when the shutter is opened. This is achieved by maintaining a steady flow of dry air through the chamber, the rate of which is controlled remotely according to the state of the shutter. It is inevitable that the temperature of the lens under test will change after opening the shutter, but the automation of the measurement ensures that these changes are kept to a minimum by opening the shutter for only as long as is necessary.

The heat exchanger components through which the thermal fluid is circulated and to which the lens mounting plate is attached are enclosed within a shell of machined glass fiber composite. This rigid layer of insulation provides a low thermal conductivity structure for mounting the chamber to a two-axis tip-tilt alignment mount, but also serves an important safety function by ensuring that the outermost surface never reaches a dangerously high or low temperature. Outside of the rigid insulation shell is a removable layer of soft thermal insulation that provides most of the thermal insulation for the chamber.

In order to maximize the testable field of view of a lens the distance between the entrance pupil of the lens and the entrance window of the chamber should be minimized. In the case of our largest chamber, the TC-1150, the axial length of the chamber may be altered to match the lens under test by the addition or removal of chamber segments. These segments comprise an inner heat exchanger ring attached to an outer ring of rigid insulation. The thermal fluid circulates through each segment in the wall structure in a patented double helix manner; spiraling from the lens mounting end to the window end and then back again, thereby ensuring uniform heating along the entire length of the chamber. The smaller thermal chamber models currently offered have fixed lengths that suit the majority of typical automotive lenses.

3.4 Measuring flange focal length over temperature

A typical flange focal length measurement involves focusing the image analyzer assembly on the on-axis image by optimizing MTF, and then moving the image analyzer assembly along the optical axis until it is focused on the rear surface of the mounting flange and recording the axial displacement of the image analyzer stage assembly between those two focus positions. When testing over temperature this measurement becomes a fair bit more complicated. In order to ensure that the entire lens assembly is at thermal equilibrium, the entire lens assembly (including the mounting flange) is typically enclosed within the chamber. The mounting flange of the lens is also the primary thermal conduction path and so it will usually be completely obscured by the plate used to hold the lens under test in the thermal chamber.

To address this, our thermal module system uses a special lens mounting plate design. With this design, the reference surface on the lens mounting flange is transferred outside of the chamber by using Invar (an iron alloy with a very small thermal expansion coefficient) as the material for the mounting plate. Because the change in thickness of the Invar plate is negligible over the typical measurement temperature range, relative flange focal length measurements can be made using the external surface of the plate as a surrogate for the mounting flange. The data output from a flange focal length measurement is then a set of flange focal length shift values as a function of temperature.

A recent addition to the lens mounting plate design is the integration of two back illuminated, chrome on glass reticles into the external surface of the mount, as shown in the figure below. This feature allows the user to make automated FFL variation measurements over temperature through the *OpTest® 7* software application. To ensure that the chrome reticle surfaces are kept co-planar with the outer surface of the mounting plate over the full temperature range, they are spring loaded against two lapped transfer plates. Illumination of the targets is provided by LEDs installed in the thermal chamber window assembly that are turned on only when needed for making FFL variation measurements. An example of a lens mounting plate is shown in Figure 5.

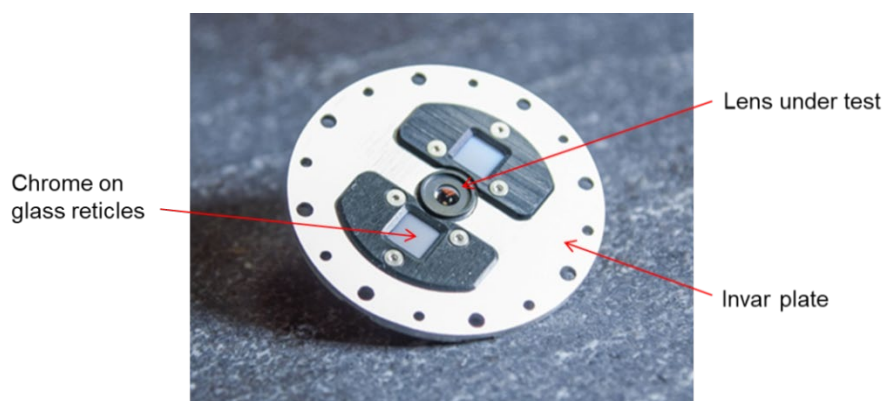


Figure 5 Lens mounting plate for the TC-1050 thermal chamber.

By its very definition, the measurement of flange focal length depends on the location of the mounting flange on the lens. When measuring the variation in the flange focal length, it is critical that that lens be mounted to the interface plate using the same mounting features as are used when mating it to the sensor housing in the camera assembly. It is important to note that the flange focal length may not be expected to be invariant with temperature, since the lens designer will have accounted for the expansion and contraction of the sensor housing in the design process. Measured alone, an athermalized lens design would be expected to exhibit a variation in flange focal length equal to the change in the length of the sensor housing.

The ability to accurately measure flange focal length changes is not actually dependent on the ability to make an accurate flange focal length measurement. We have seen that the approach discussed here uses one side of the Invar mounting plate as a surrogate for the flange that is mounted against the opposite side. What matters in this case is the repeatability of the measurement, and this is found to be primarily dependent on the repeatability of the through focus measurement used to determine both the best focus image position and the location of the chrome on glass reticles used as the mechanical reference surface. A repeatable through focus measurement requires a defocus curve with a definitive peak MTF value, and the shape of the defocus curve is dependent on the depth of focus of the lens being tested. Therefore, faster lenses with lower f-number values will have more repeatable flange focal length measurement results than a slower lens with a larger f-number (but slower lenses are also less sensitive to focus shifts for the same reason). The shape of the defocus curve is also dependent on the overall MTF performance of the lens – in general, a lens with poor image quality and low MTF values will not produce good defocus curves and repeatable flange focal length results. By comparing multiple flange focal length shift results of lenses with various f-numbers measured at room temperature, Optikos has been able to determine that the typical uncertainty in a flange focal length shift measurement is on the order of $\pm 2\mu\text{m}$.

4. SAMPLE RESULTS

The figure below shows a flange focal length shift measurement that was performed at Optikos using the thermal module system. The typical measurement procedure is to start at room temperature (somewhere between 20°C and 25°C) and proceed down to the coldest temperature point required. Measurements are made as the lens is brought from the coldest temperature point to the warmest temperature point, with another data point being collected at room temperature on the way back up. The measurement concludes with a final measurement taken at room temperature to compare the initial and final flange focal length values. The three room temperature measurements are represented by the cluster of data points at 20°C in the figures below.

The initial room temperature flange focal length measurement is subtracted from the set of flange focal length measurements to produce the flange focal length shift plot in Figure 6. The measured flange focal length shift values are plotted with the typical uncertainty of $\pm 2\mu\text{m}$. In the case of this lens, the theoretical flange focal length shift values were known and could be compared directly to the measured values (the theoretical thermal shift is plotted as a black line in the figure below).

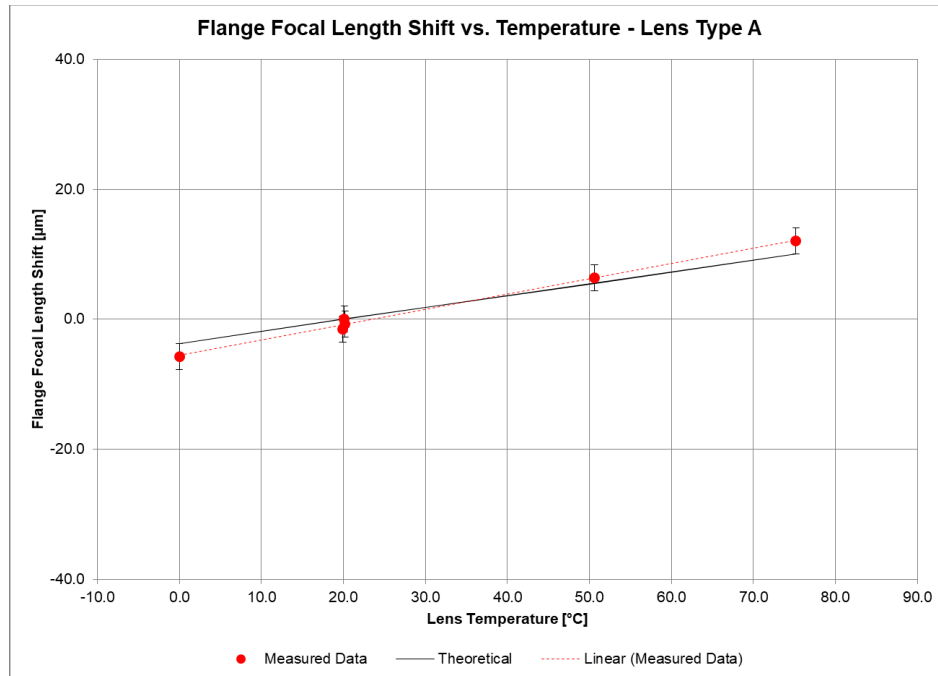


Figure 6 Measured flange focal length shift values compared to the theoretical model

The measured values agree with the theoretical model within the typical uncertainty of the flange focal length measurement. However, the scatter is not random and it appears that the measured values are following a linear trend (the red dotted line on the plot above) with a slightly different slope than the theoretical model predicts, so rather than the mismatch between the two plots arising from measurement uncertainty, it is possible that the thermal performance of the lens is actually slightly differently from the theoretical model. This emphasizes the importance of making this measurement for a lens that is required to perform over a significant temperature range - even if the thermal behavior can be modeled - because the lens may not perform exactly as the model predicts.

In this next data example, five lenses of the same design (Lens Type B) were tested over the same temperature range, and the flange focal length shift values for the five lenses are summarized in Figure 7. Note that the vertical axes in Figure 6 and Figure 7 have different scales – Lens Type B has significantly more thermal shift than Lens Type A. The slope of the thermal shift for Lens Type B is also the opposite sign from Lens Type A. For Lens Type A, the image plane moves away from the lens at warmer temperatures and closer to the lens for cooler temperature, while Lens Type B exhibits the opposite behavior. The thermal shift for each lens sample is first plotted separately, with the final plot showing the thermal shifts for all five lenses (the error bars have been left off in that plot for ease of viewing). For this lens design, the theoretical thermal shift values were not known, so the lines included on the individual plots below are a linear fit to the measured thermal shift data. The significant variation seen here between samples of the same lens design suggests that process variation is a factor and highlights another important reason for making measurements of this type.

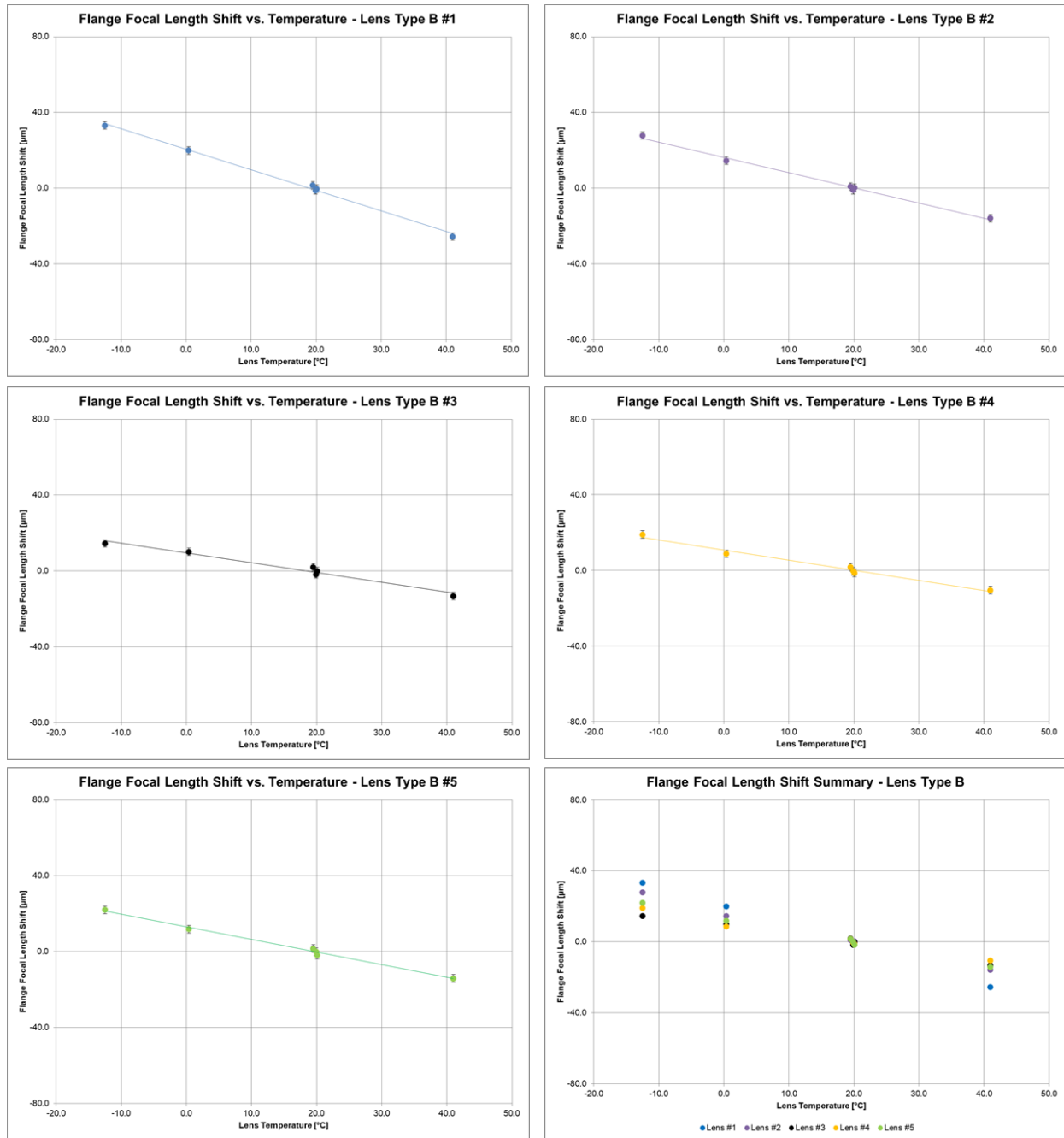


Figure 7 Lens Type B thermal shift comparison between five lens assemblies of the same design.

Flange focal length shift which manifests as defocus is often the primary aberration affecting image quality over temperature. Since performing a through focus MTF measurement is part of the flange focal length shift measurement process, that data is readily available and provides useful information illustrating how the MTF is impacted by temperature.

The upper plot in Figure 8 shows a series of defocus curves for Lens Type C, in which each pair of defocus curves (a pair contains tangential and sagittal MTF data) represents a through focus measurement at the same spatial frequency for a different lens temperature. The solid black line at $0\mu\text{m}$ of defocus represents where the sensor would be located in the camera assembly – the distance between the sensor and the lens mounting flange remains fixed over temperature in this system. Below room temperature, the MTF value at the sensor plane is relatively consistent, but the MTF begins to degrade

significantly at elevated temperatures. The lower plot shows the average MTF value for the selected spatial frequency at the sensor plane as a function of temperature to further illustrate this point. It is noteworthy that there is relatively little variation in the peak MTF or the shape of the curves in the upper graph – the MTF drop that is seen by the sensor is entirely attributable to defocus.

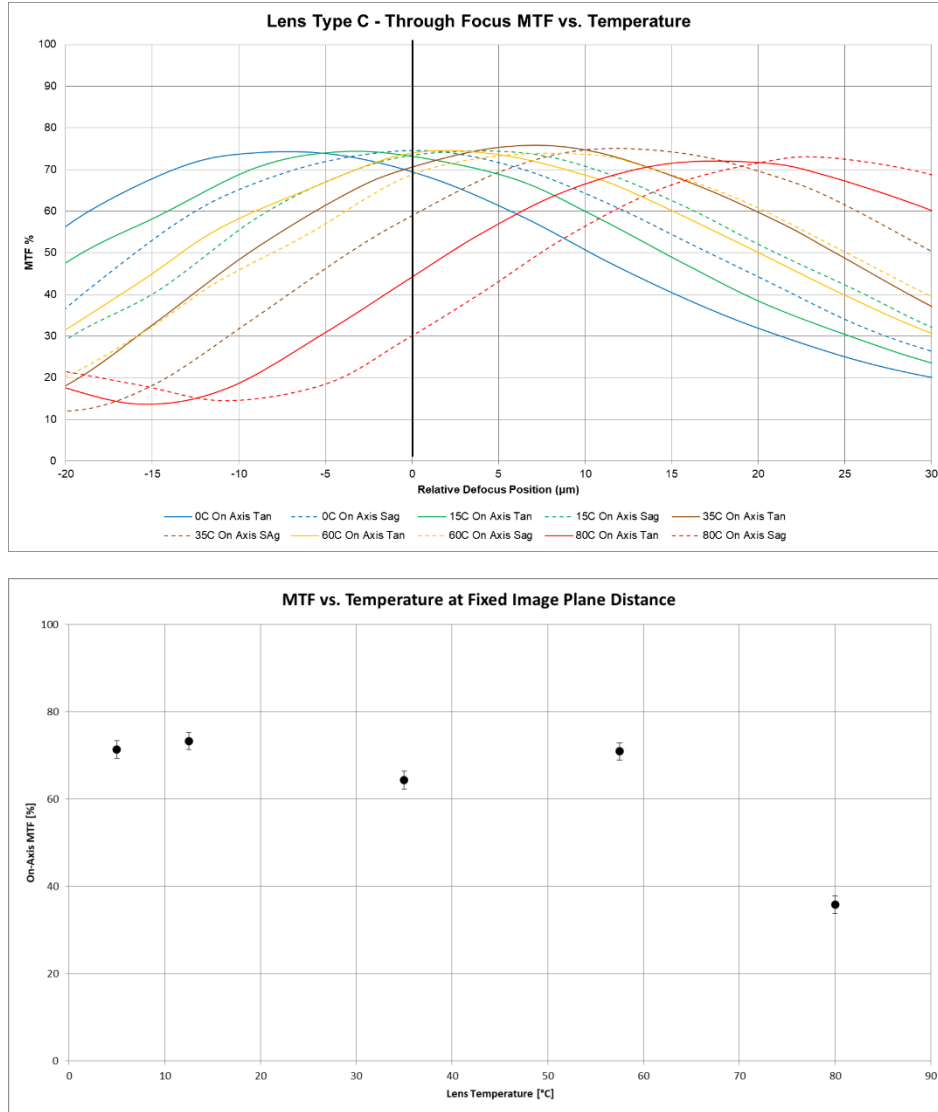


Figure 8 Through focus MTF measurements as a function of temperature show significant performance degradation when evaluated in the same plane. The lower chart shows the average of sagittal and tangential MTF graphs in the upper chart, evaluated at the 0μm position.

5. CONCLUSION

The commercialization of sophisticated apparatus designed to aid in measuring the performance of lenses over their specified operating temperature range is a recent development that has been spurred on by the demands of the automotive camera industry. While the measurement itself is typically more challenging to perform than measurements made at room temperature, it is becoming increasingly important as a means of design and process verification and troubleshooting for high-performance camera lenses, and especially for those that find application in automotive safety systems.