Wavefront Coding: jointly optimized optical and digital imaging systems

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ABSTRACT

Many of the limitations of traditional optical-only imaging systems can be eliminated with jointly optimized optical and digital imaging systems. Jointly optimized optical and digital imaging systems exploit the complementary aspects of optics and digital signal processing to form systems with characteristics not possible with traditional optics-only systems. For example, in traditional imaging systems light gathering and large depth of field are competing goals and are inversely related. On the other hand, in optimized optical/digital imaging systems light gathering and large depth of field can be independent parameters. Instead of requiring a small aperture to produce a large depth of field, a large aperture and a large depth of field are both possible and practical. We call jointly optimized optical and digital imaging systems Wavefront Coded imaging systems. Concepts of Wavefront Coding are illustrated below through an athermalized, refractive, silicon/germanium IR imaging system with aluminum optical mounts subject to an ambient temperature range of –20^{o}C to +70^{o}C.

Keywords: Wavefront Coding, IR imaging, athermalization, optical/digital imaging

1. INTRODUCTION

Traditional optical imaging systems suffer from a variety of well-known limitations that often are mitigated by increasing the size, weight, and cost of the system. Some of these limitations include light gathering/depth of field tradeoffs, aberration correction vs. number of lens elements, and the difficulty of controlling thermally induced defocus. Traditional optics offers few solutions to these fundamental limitations. By considering the use of the complementary aspects of optics and digital signal processing together, solutions to many of these limitations can be found. We call these optimized optical and digital imaging systems Wavefront Coded imaging systems. The optical portion of the system "codes" the optical wavefronts through general aspheric optics. The digital signal processing portion "decodes" the captured images and produces sharp clear imagery with characteristics not possible with traditional optics. Wavefront Coding can be used to break the traditional tradeoffs between light gathering and depth of field, can enable aberration correction with a limited number of lens elements, and can control thermally induced aberrations. This paper specifically describes the benefits of Wavefront Coding in a passive silicon/germanium IR imaging system with aluminum optical mounts subject to ambient temperature changes between -20^{o}C and +70^{o}C.

IR imaging systems have been important in military imaging applications for many years. Recent advances in materials and fabrication are leading to increased commercial applications in areas from law enforcement to automobile-based night vision. IR imaging systems by their very nature are almost always fast (low F/#) systems. This fact, together with the large index of refraction change with temperature that is common in IR optical materials, makes it difficult to design and fabricate a simple system that works reliably over even a relatively small temperature range[1]. For example, the value of dn/dT for germanium is over 100 times larger then for common optical glasses. Many schemes have been developed to reduce the effect of temperature changes on IR optical system. These include using different optical materials with refractive optics[2,3], using optical mounting materials that change with temperature in such a way to counteract the changes in optical properties[1], or the use of diffractive optics[4]. Wavefront Coding can be used in combination with these traditional athermalization techniques to reduce the amount of traditional athermalization required. Or, with a fixed amount of athermalization, Wavefront Coding can be used to extend the usable temperature range of the system. The following system uses a traditional refractive

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athermalization design with silicon and germanium optics and aluminum optical mounts with Wavefront Coding to greatly extend the usable temperature range. The next section describes the traditional IR system being used and illustrates the limitations of this system with changes in temperature. Section three describes the Wavefront Coding modifications made to the traditional IR system in order to extend the usable temperature range.

2. EXAMPLE TRADITIONAL IMAGING SYSTEM

The traditional IR imaging system used here is a refractive three element, silicon/germanium/silicon, imaging system. The layout of this lens is given in figure 1. The F/# is 2 and the focal length is 100mm. The half field of view (HFOV) is three degrees. The wavelength is 10 microns and the pixel size is 20 microns with 100% fill factor. The optical mounting material is aluminum. The total track length is about 120mm. The design goal for usable temperature range is –20°C to +70°C. The ambient temperature of the optics is not controlled, but the detector itself can be assumed to be temperature stabilized, as is common with microbolometers. The selection of optical materials, curvatures, and thicknesses were chosen in order to traditionally athermalize the system at a 10 micron wavelength[2].

Silicon and Germanium were chosen due to their high index of refraction at 10 microns. This allowed a much higher HFOV, while using only spherical surfaces, than ZnSe or other lower index materials would have allowed, and still maintain a high level of aberration correction. The effect of an increase in ambient temperature, for both silicon and germanium, is an inward movement of the ideal focal plane[2]. However, a typical aluminum mount will expand with an increase in temperature and push the detector farther away from the optics, thus aggravating the thermally induced defocus. Silicon has both a smaller dn/dT and a smaller coefficient of thermal expansion than germanium[2]. Since silicon pulls the focus inward at a lesser rate than germanium, the silicon was used for the positive lenses and the germanium was used for the negative center lens.

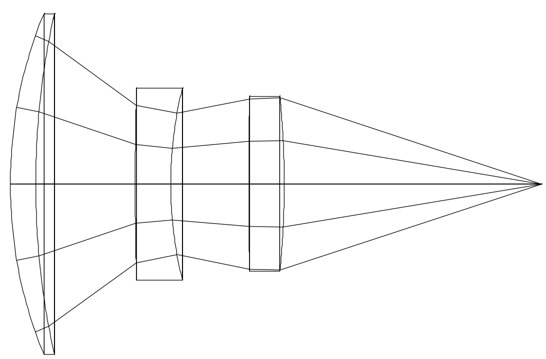


Figure 1: Layout of traditional IR imaging system. Three refractive elements, silicon/germanium/silicon. The F/# is 2, focal length is 100mm. Wavelength is 10 microns. Half field of view is 3 degrees. Total track is about 120 mm. Aperture stop is at the rear of the right most lens. Optical mounting material is aluminum. This design is diffraction limited at +20°C.

Although diffraction limited at +20°C, this system cannot meet the wide temperature range design goal. Figure 2 shows the MTFs of this system as a function of temperature. From the MTFs of figure 2, the usable range of this system is about 0°C to +45°C. At temperatures of -20°C to +70°C the MTFs are severely depressed. For 20 micron pixels (with a Nyquist frequency of 25 lp/mm) this loss of MTF at the -20°C and +70°C temperatures translates to less then half the potential spatial resolution. Figure 3 shows sampled PSFs of this system for temperatures of +20°C and +70°C. At +20°C the sampled PSF is very compact, but at +70°C the sampled PSF is severely blurred. From figures 2 and 3 it is obvious that this particular system requires additional temperature stabilization in order to image well over the -20°C to +70°C temperature range.

The major optical aberration induced by large temperature change in this system is misfocus. The use of Wavefront Coding in this IR imaging system can increase the usable temperature range of the imaging system without any special materials or sensors. The next section describes modifications made to this system in order to control the changes in system performance as a function of temperature.

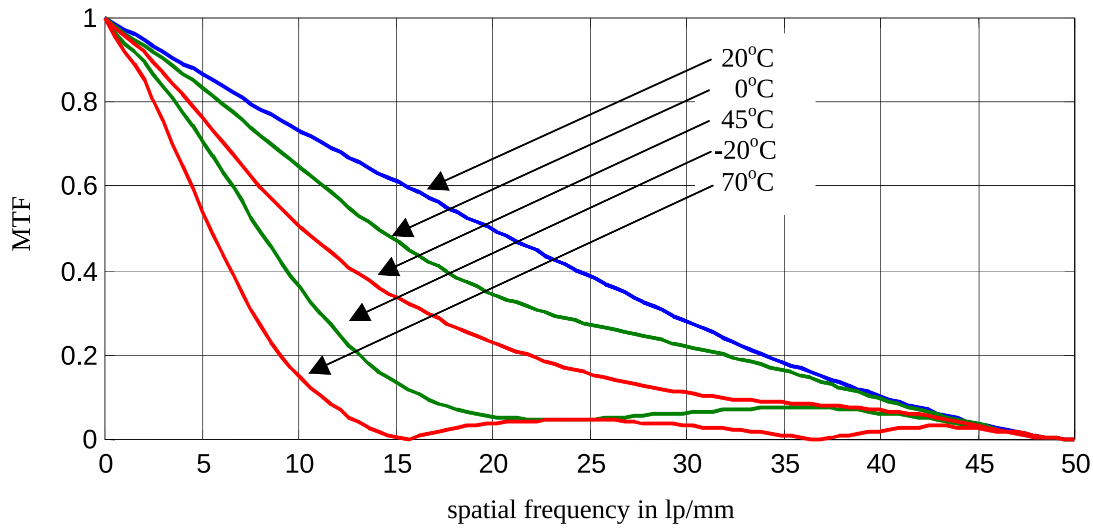


Figure 2: MTFs of the traditional imaging system of figure 1 as a function of temperature. This system is diffraction limited at 20°C. The usable temperature range for this system is about 0°C to +45°C. This system cannot meet the temperature range design goal of -20°C to +70°C.

Figure 3: Sampled point spread functions as a function of temperature for the traditional imaging system of figure 1. Sampling is with 20 micron square pixels with 100% fill factor. Left graph represents the sampled PSF of the system at +20°C. The right graph represents the sampled PSF when the temperature is +70°C. The PSF at -20°C is similar to that at +70°C. This system cannot maintain spatial resolution over the temperature range design goal of -20°C to +70°C.

3. WAVEFRONT CODED IMAGING SYSTEM

The traditional IR imaging system of figure 1 is diffraction limited at +20°C but cannot maintain performance with a large change in temperature. Wavefront Coding can be used as an additional method of athermalization to extend the usable temperature range. Wavefront Coding could also be used as the sole means of athermalization, if for example only one type of optical material could be used.

The general block diagram of Wavefront Coding imaging systems is shown in figure 4. Wavefront Coding is an optical/digital solution where complementary aspects of optics and digital processing are used together to achieve system performance not possible with all-optical methods[5]. The optical components of figure 4 can be thought to "code" the image wavefronts to make the sampled image insensitive to a number of traditional aberrations. These aberrations can include misfocus[5], spherical aberration[6], astigmatism, chromatic aberration[7], petzval curvature, and temperature related misfocus as used in this application. The sampled or "coded" imagery is blurred and requires digital processing to restore image clarity and sharpness. The digital processing component performs the removal of the image blur from the sampled image through linear and non-linear processing. Any type of digital processing to remove an image blur will amplify some spatial frequency information of the image as well as any additive noise. This noise amplification can affect the final image quality if the final noise value becomes too large. Non-linear processing can be used to remove the effect of some of this amplified additive noise. Algorithms such as block-Wiener filtering, median filtering, and similar can be applied to greatly reduce the effects of additive noise while maintaining the non-random spatial frequency details.

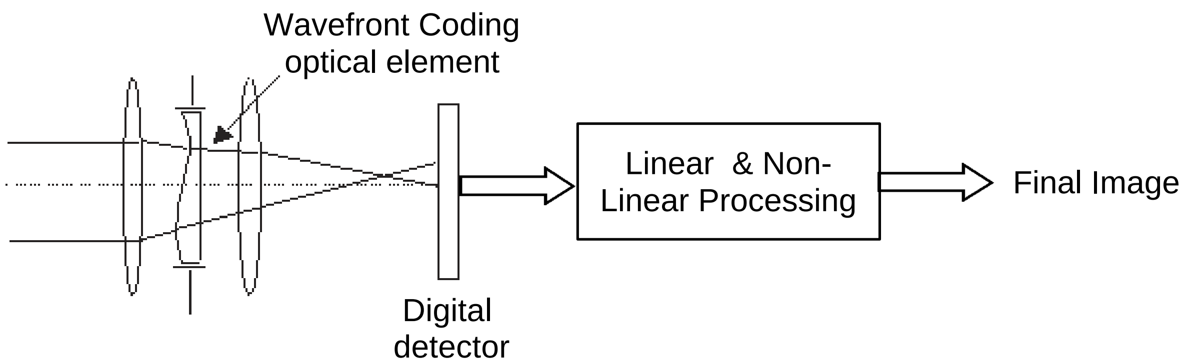


Figure 4: Block diagram of general Wavefront Coded imaging system. An aspheric Wavefront Coded optical element is included at or near the aperture stop of the imaging system. After detection, images are processed with linear and non-linear processing to remove the image blur and produce the final image.

There are two broad types of Wavefront Coding optical elements and related processing. These are rectangularly separable and non-separable optical elements. When the optical Wavefront Coding element can be mathematically described by the product of a function of one dimension and another function of the other dimension, the resulting Wavefront Coding element is rectangularly separable. One of the most important reasons to use rectangularly separable forms is that the resulting digital processing can then take advantage of very computationally efficient separable filters. Separable filters require approximately N/2 times less processing then general non-separable filters where N is the order or length of the filters. For real-time operation this factor of N/2 can translate to dramatically faster processing. The processing performed with separable filters is to 1) filter each row separately with the digital filter for rows and form an intermediate image, then 2) filter each column of the intermediate image with the column filter to form the final image. Length N separable filters require 2*N multiplications and additions per image pixel. Square 2D filters of side length N in contrast require N*N multiplies and additions per image pixel.

The system layout of a Wavefront Coded version of figure 1 is given in figure 5. Only the optical surface at the aperture stop has been changed from that shown in figure 1. Notice that the traced rays do not meet at the image plane. Blurred imagery is formed. There is no “focused” image anywhere behind the lens in a Wavefront Coded imaging system. Digital processing is required to transform the blurred image into a sharp and clear image. The exit pupil of this Wavefront Coded system is also shown in figure 5. The peak-to-valley OPD of this exit pupil is approximately 4 wavelengths. This surface is rectangularly separable and is similar to a cubic phase surface. This particular surface was found through optical/digital design optimization[8].

The MTFs of this Wavefront Coded imaging system, both before and after digital processing, as a function of temperature are given in figure 6. The central curve in this figure represents the sampled diffraction-limited MTF from the system of figure 1 for comparison. The effect of sampling is included in the MTF via the pixel MTF. Each of the MTFs in this figure include the pixel MTFs of the 20 micron 100% fill factor detector. The lower set of MTF curves represent the Wavefront Coded system before processing at temperatures of -20^{o}C, $+20^{o}$C, and $+70^{o}$C. Notice that each of these curves is very similar to each other, and that these MTFs do not have zero values, in contrast to the traditional system MTFs in figure 2. After applying a single digital filter to each of the MTFs, the highest set of MTF curves is formed. Note that the filter applied is identical for all MTFs; this is not an adaptive filtering operation. Each of the optical/digital MTFs are again very similar to each other and very similar to the sampled diffraction-limited MTF. The optical/digital MTFs only extend out to the Nyquist frequency of the pixels being used – in this case 25 lp/mm.

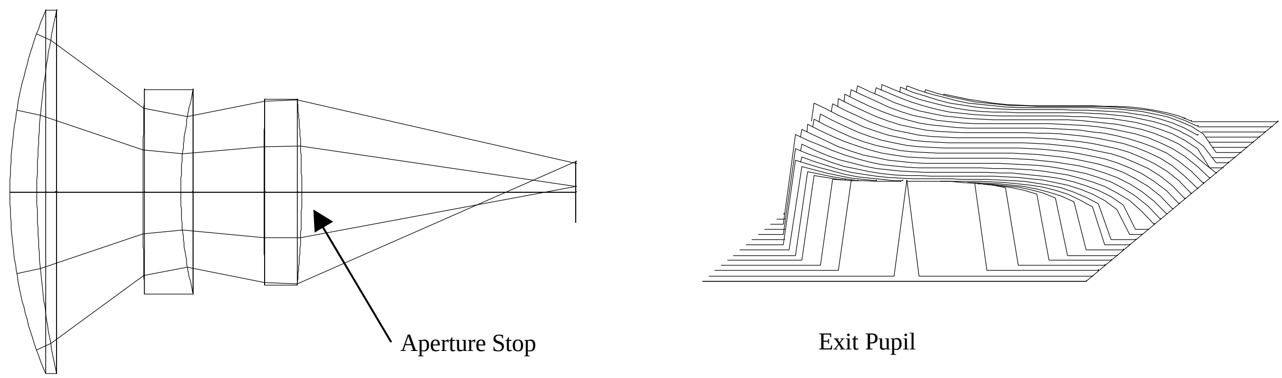


Figure 5: System layout of Wavefront Coded IR system. This design is identical to the system of figure 1 with the exception of the surface at the aperture stop. Notice that the traced rays do not meet at the image plane. A clear focused image is not directly formed by the optical portion of a Wavefront Coded system. Digital processing of the resulting image is needed to produce the final sharp and clear image. A representation of the exit pupil is given on the right. The peak-to-valley OPD is about 4 wavelengths. This surface was found via optical/digital software design optimization.

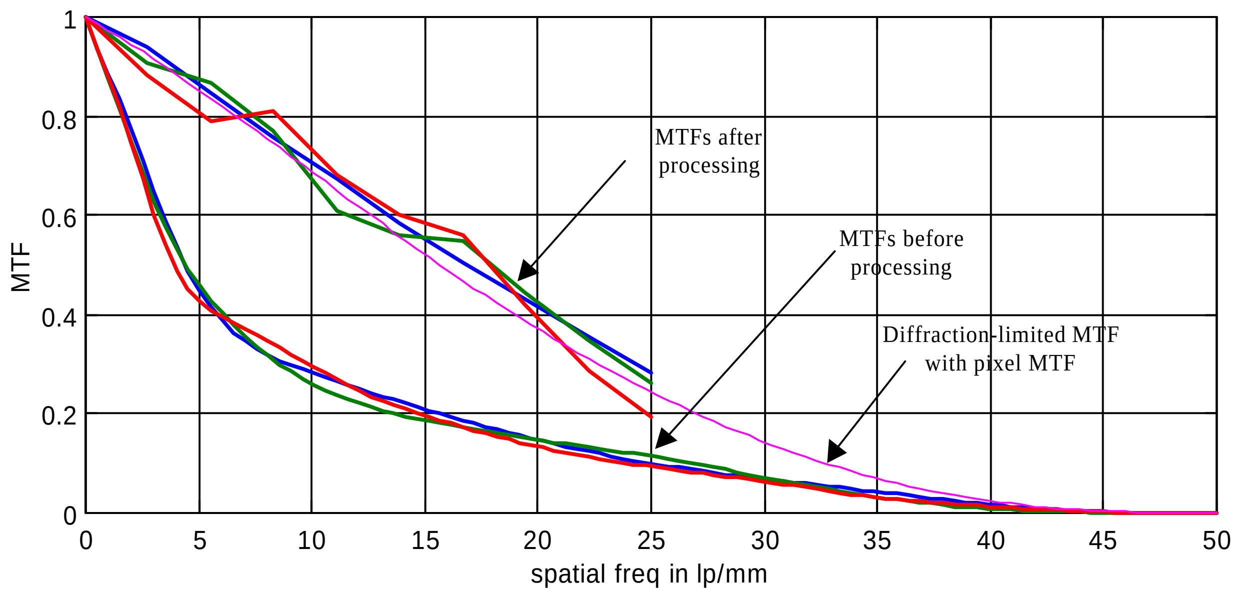


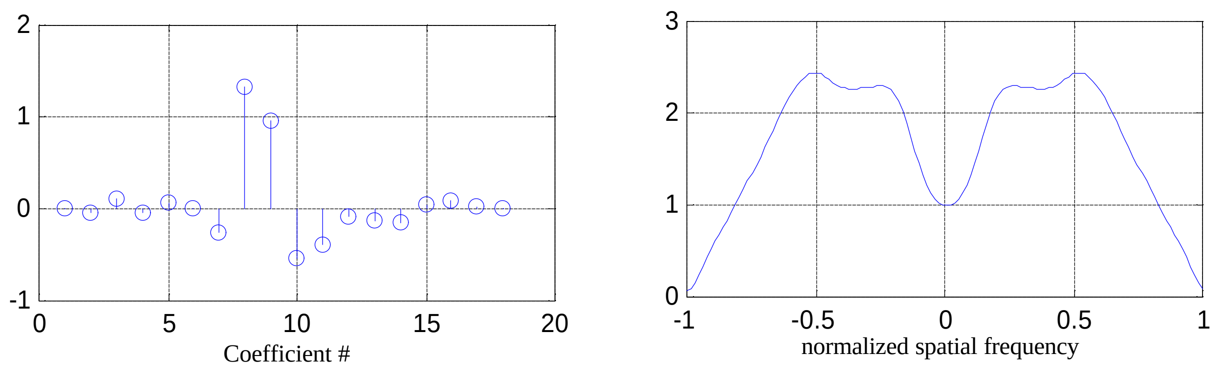
Figure 6: MTFs of Wavefront Coded imaging system as a function of temperature. Each MTF includes the pixel MTF. The lower set of MTFs represent the MTF of the optical system before processing at temperatures of –20^{o}C, +20^{o}C, and +70^{o}C. The upper set of MTFs represent the MTFs of the system after applying a single digital filter. These later MTFs are shown only out to the Nyquist limit of the detector, or 25 lp/mm. The central MTF is the diffraction limited MTF of figure 2, with pixel MTF, for comparison.

The sampled PSFs of the imaging system before digital filtering are given in figure 7. Figures 7(a) and (b) represent the sampled Wavefront Coded PSFs before digital filtering at +20^{o}C and +70^{o}C respectively. The sampled PSF at -20^{o}C is very similar to that at +70^{o}C. These sampled PSFs are far different then the PSFs of the traditional imaging system of figure 3, but these PSFs are very similar to each other. And from Figure 6, these PSFs are related to MTFs that have no zeros over the desired –20^{o}C to +70^{o}C temperature range. After applying a single digital filter to both PSFs the resulting system PSFs of Figure 8(a) and (b) are formed. These system PSFs are very similar to the PSF from the traditional imaging system at +20^{o}C of figure 3(a). Good quality imaging is thus possible over this temperature range with Wavefront Coding.

Figure 7: Sampled PSFs of Wavefront Coded system. (a) represents the sampled PSF at +20°C while (b) represents the sampled PSF at +70°C. Sampled PSF at -20°C is similar to that at +70°C. Notice that these sampled PSFs are very different from the sampled PSFs of figure 3 from the traditional imaging system, and by design these sampled PSFs are also very similar to each other by design.

Figure 8: Sampled PSFs after digital filtering. A single digital filter was applied to each of the sampled PSFs of figure 7. The filtered PSF at +20°C is represented by (a), while the filtered PSF at +70°C is represented by (b). The filtered PSF at -20°C is very similar to that of (b). These sampled PSFs are very similar to the sampled PSF of the traditional imaging system of figure 3 at +20°C.

The digital filter used to filter the PSFs is given in figure 9. The one-dimensional spatial domain filter is given in 9(a) while the one-dimensional filter transfer function in given in 9(b). This filter is a rectangularly separable finite impulse response (FIR) linear filter. The 1-D length of this filter is 18 taps. The maximum spatial frequency gain of the filter is about 2.4 at about ½ the Nyquist frequency. The two-dimensional RMS value (or gaussian noise gain) of this filter is approximately 3.5. This implies that the RMS value of additive noise after filtering with this filter is approximately 3.5 times larger then the RMS value before filtering. This noise gain, or related parameters, is in practice what places limits on the practical amount of benefit that can be achieved with Wavefront Coding in any particular system.



(a) (b)

Figure 9: Linear digital filter. (a) shows the spatial domain values of the one-dimensional digital filter. (b) shows the transfer function representation of this filter with the horizontal axis being spatial frequency normalized to the pixel sampling nyquist frequency. The RMS value of the two-dimensional version of this filter (or gaussian 2D noise gain) is about 3.5.

For this particular imaging system the design goal of a usable temperature range of –20°C to +70°C was chosen without any design goal for the length or RMS noise gain of the digital filter used to produce the final image. Suppose that either the design goal usable temperature range was decreased or a more thermally stable optical mounting material than aluminum was to be used. In this case the size of the sampled PSF would decrease as would the length and RMS noise gains of the digital filter. Less control of thermal aberrations would be required of the Wavefront Coding part of the system. Suppose again that the usable temperature range design goal was increased by, say, a factor of two without changing the optics or mounting.

Then, to first order, the resulting sampled PSFs would double in size, the digital filters lengths would double, and the RMS noise gains would also increase by a factor of two. As the filter lengths and RMS noise gain values increase there is some point where the system becomes impractical due to the amount of processing required or the amount of noise in the final image. For given optics, amount of computation, and final image noise level, the usable temperature range of the modified traditional IR system is fixed. Increasing the amount of computation, possibly by adding non-linear noise reduction processing, would lead to an increased amount of usable temperature range. As the cost of processing decreases and the quality of detectors improves over time, so can the usable temperature range of Wavefront Coded IR systems as this example demonstrates.

4. CONCLUSION

By designing imaging systems with the complementary power of optics and digital processing, imaging systems with important characteristics that differ greatly from traditional imaging systems can be made. Wavefront Coding is the term we use to describe these complementary optical and digital imaging systems. Wavefront Coding systems can remove the effects of misfocus-like aberrations. Temperature related aberrations in IR imaging systems is one example of misfocus-like aberrations. Traditional means of athermalization can be used to improve the usable temperature range of an IR imaging system. This temperature range can be improved still further by the use of Wavefront Coding. Alternatively, Wavefront Coding can be used as the primary means of athermalization if for example, only one optical material and refractive surfaces must be used.

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