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INFRARED IMAGING-PASSIVE THERMAL COMPENSATION *VIA* A SIMPLE PHASE MASK

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Abstract. Infra-Red (IR) imaging systems are now in wide use, due to new technologies that enable manufacturing of low cost systems. Most of the IR optical materials (Germanium in particular) are very sensitive to temperature variations. This sensitivity is reflected in a temperature dependent refractive index, which in turn affects the focal length and results in strong deterioration of the image quality with temperature variations. The thermal sensitivity can be compensated using a passive all-optical phase mask. IR imaging system incorporating such simple phase mask is hereby proposed and analyzed, followed by simulation results.

Key words: infrared imaging, infrared optical materials.

1. INTRODUCTION

Infra-Red (IR) imaging, widely used for military applications for decades, recently became popular also for civilian applications. Until the beginning of the 21st century, only very expensive IR imaging systems were fabricated, mainly for military applications. However in recent years, primarily because of improvements in the IR detectors industry, IR imaging systems became wide spread for industrial and civilian applications. Due to such growing market, the requirement for inexpensive IR imaging systems gets special attention. In order to produce a low-cost IR imaging system, common optical materials should be used. A short review considering common IR optical materials, the thermal focal shift problem, and known solutions to combat it are presented in this section. In Section 2 the thermal focal shift is formulated as a Depth of Field (DOF) problem. A way to compensate for the thermal focal shift using a simple passive phase mask is proposed in Section 3, along with simulation results. A short summary and conclusions are presented in Section 4.

1.1. IR OPTICAL MATERIALS AND THE THERMAL FOCAL SHIFT (TFS) PROBLEM

Not many IR optical materials are available for use in IR imaging systems, and almost all of them have a unique drawback- high sensitivity of their refractive index with the temperature. The most prominent material among all is Germanium (Ge). Its main attributes are high refractive index, very low dispersion, high transparency (mainly for LWIR), widespread availability and low cost. Due to all of these advantages, Ge is almost the 'perfect' optical material one can desire. Utilizing it as the main material in an IR imaging system can result in a small, lightweight and efficient optical design. Nevertheless, the sensitivity of Germanium's index of refraction with the temperature is a few times higher than that of any other IR material (and 100 times higher than that of visible optics glass, for comparison). The change in refractive index due to thermal variations results in a temperature-dependent focal length. Many approaches have been developed to solve the thermal focal shift problem (coined 'IR Lens Athermalization') so that the use of Ge as an IR optical material would be viable. The presently known approaches are summarized below. (One should note that all of the known methods and also the new methods proposed in this paper are also viable for other IR optical materials, but most of the discussion is concentrated on Ge due to the reasons mentioned above.)

1.2. ACTIVE SOLUTIONS

The active solution approach treats the defocus due to temperature variations as a simple focusing problem; using mechanical shift of the lens by motors or piezo-electric sensors compensates for it [1]. Advanced solutions of this kind rely on having a temperature sensor on the lens, along with image data information. This approach requires advanced opto-mechanical design and complicated manufacturing process, thus making it attractive only for the more expensive high-end systems.

1.3. PASSIVE ATHERMALIZATION USING MECHANICAL THERMAL EXPANSION

Passive solution for athermalization can be achieved *via* proper choice of mechanical materials for the lens housing [2]. By correct selection of mechanical materials that expand with temperature variations in appropriate way, the TFS is compensated and will not be sensed in the image plane. This kind of design relies on exotic mechanical materials, and also on complex opto-mechanical design.

1.4. ATHERMALIZATION USING MIXTURE OF OPTICAL MATERIALS

Another passive approach to solve the thermal focal shift is by using a mixture of optical materials [3]. This method can be also coined 'athermal doublet'- it uses a mixture of IR optical materials, formed as positive and negative lenses, so that the effective focal length remains constant with temperature. This kind of solution usually requires many lenses (not just a simple doublet) and also relies on exotic optical materials.

1.5. ATHERMALIZATION USING WAVEFRONT CODING

The most modern approach to IR lens athermalization is by using wavefront coding. A phase mask added along the optical path, results in an imaging optical system that exhibits a constant Point Spread Function (PSF) through the entire thermal focal shift range [4, 5]. After the acquisition of an optical image, image restoration is necessary *via* a digital post-processing stage based on a de-convolution algorithm that requires knowledge of the constant PSF. In this approach the pre-processed image quality is quite poor and therefore post-processing is unavoidable. Moreover, the mask is not circularly symmetric, thus providing resolution preference to two orthogonal directions. Any de-convolution algorithm has two drawbacks: heavy computational power and inherent noise amplification effect. Since IR detectors have quite high noise level to begin with, this method does not provide sufficiently good results.

2. THERMAL FOCAL SHIFT TREATED AS A DEPTH OF FIELD PROBLEM

Another approach for treating the TFS problem is to consider it as a Depth of Field (DOF) problem. In the classical DOF formulation, the defocus is evaluated using the ψ defocus parameter, defined as [6]:

$$\psi = \frac{\pi R^2}{\lambda}\left(\frac{1}{z_{img}} + \frac{1}{z_{obj}} - \frac{1}{f}\right), \tag{1}$$

where λ is the wavelength, R is the pupil radius, z_{img}, z_{obj} are the image and object distances, and f is the imaging system focal length. In classical systems, f is constant, while z_{img}, z_{obj} are changing, thus creating a defocus effect. In a typical IR scenario, the imaging system is (almost always) focused to infinity, thereby $z_{obj} \to \infty$, $\frac{1}{z_{obj}} \to 0$. Since the focal length of an IR imaging system varies with the temperature - $f = f(T)$; the system is designed with respect to an operating central temperature - T_{ctr}, and therefore $z_{img} = f(T_{ctr})$. The updated ψ defocus parameter for IR TFS scenario will now be:

$$\psi = \frac{\pi R^2}{\lambda}\left(\frac{1}{f(T_{ctr})} - \frac{1}{f(T)}\right). \tag{2}$$

The dependence of the focal length on temperature is given by [5]:

$$f(T) = f(T_{ctr})\left[1 - \left(\frac{1}{n(T)-1}\frac{\partial n}{\partial T} - \alpha_L\right)\cdot(T - T_{ctr})\right], \tag{3}$$

where T is the current temperature, $n(T)$ is the temperature dependent refractive index and α_L is the thermal expansion coefficient of the lens material. Assuming a high quality Ge aberration-free lens as a test case, with $f(T = 20^o) = 25mm, F_\# = 1.2$ and operated over a temperature range of $[-20^o, 60^o]C$, the thermal defocus region of interest becomes $-6 \le \psi \le 6$. Examples of the resultant Modulation Transfer Function (MTF) curves are presented in Fig. 1. At the nominal temperature ($T = 20^o$ or $\psi = 0$), the well known diffraction-limited MTF curve is achieved. At higher temperature ($T = 40^o$

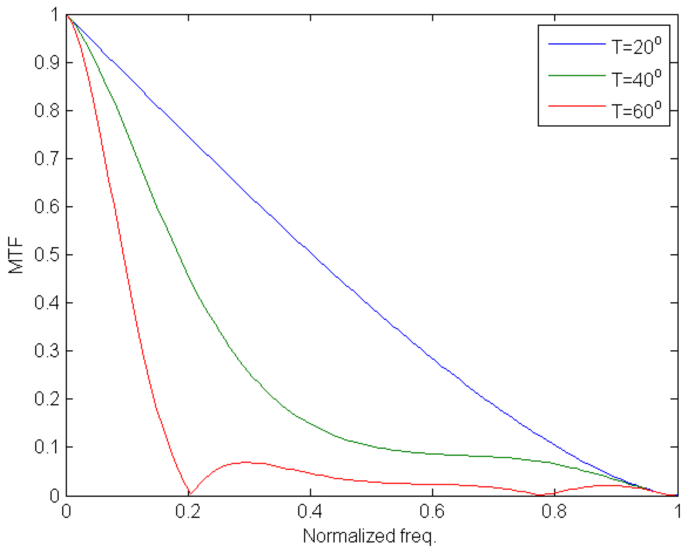

Fig. 1 – MTF curves of IR imaging system with temperature variations, no compensation applied.

or $\psi = -3$), the performance is poorer, and at the edge of the temperature range under consideration ($T = 60^o$ or $\psi = -6$), the MTF curve exhibits two contrast reversals. Contrast reversals significantly reduce the resolution to below the value of the first contrast reversal. One should note that the behavior around the nominal temperature is almost symmetric, therefore the performance for $T = 0^o$ is quite similar to that for $T = 40^o$, and the performance at $T = -20^o$ is similar to that at $T = 60^o$.

Since the example presented is a test case for a high quality lens, for higher $F_\#$ values the defocus range will be smaller. It is thus safe to refer to $-6 \le \psi \le 6$ as the defocus range in consideration. Of course, any proposed solution can be easily modified to handle a smaller temperature/defocus range, if desired.

3. SOLVING TFS USING DOF PHASE MASK

In a recent publication [6], the DOF of an imaging system was extended by using a simple phase mask consisting of concentric rings that provide a π-phase shift (for a central wavelength), as sketched in Fig. 2. The phase shift is achieved by etching into a substrate made of an adequate optical material; the etching depth is set according to the following relation:

$$\varphi_{mask} = \frac{2\pi}{\lambda} h(n-1), \tag{4}$$

where λ is the wavelength, h is the ring's depth, n is the mask substrate refractive index, and φ_{mask} is the resulting phase shift. In order to determine the mask's ring radii, one should define the extent of the defocus range (ψ range) that the mask should handle, as well the acceptable minimum contrast value. The next step is to choose the number of phase rings to implement in the mask; thereafter the rings' radii are determined by solving the following optimization problem:

$$\max_{r} \min_{\psi \in DOF} \lfloor \nu : MTF(\nu, r, \psi) = C_d \rfloor, \tag{5}$$

where r is the mask radii vector, ψ is the defocus measure, ν is the spatial frequency, and C_d is the desired acceptable minimum contrast value. The solution to the optimization problem expressed in Eq. (5) provides the ring radii that will maximize the minimum (worst) cut-off frequency along the entire DOF under consideration (one should note that the cut-off frequency is determined by the chosen acceptable minimum contrast value). Solutions for several practical cases have been calculated in [6]. Utilizing the appropriate solution for the test case presented in Section 2 ($-6 \le \psi \le 6$), the TFS case could be accommodated using a one-ring (1R) mask with radii of $r_1 = 0.82, r_2 = 0.94$. The use of such a mask improves the imaging system response with respect to the clear aperture for large ψ values, as shown in the MTF curves presented in Fig. 3 (all the curves presented are in normalized spatial frequency scale, where the normalization factor is the cut-off frequency of the aberration-free system). One should note that according to this solution, by improving the performance for large ψ values, the performance at the original in-focus position ($\psi = 0$) is significantly reduced in comparison to that obtainable with a clear aperture system, as readily observed in the curves of Fig. 3. One should also notice that because the mask provides π-phase shift, the response is symmetric around the nominal temperature, since $\pm\pi$ phase shifts are indistinguishable.

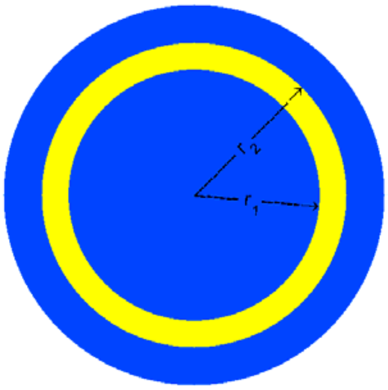

Fig. 2 – DOF phase mask outline. The phase ring (yellow) provides π-phase shift.

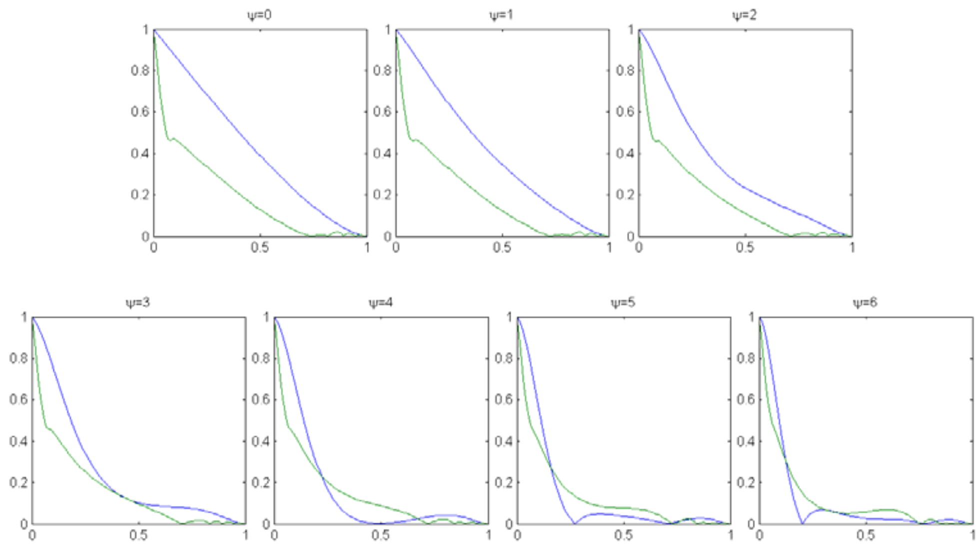

Fig. 3 – MTF curves for clear aperture (blue) and with DOF mask (green) for various defocus conditions (color online).

3.1. IMAGING PERFORMANCE OF THE IR DOF MASK – SIMULATION RESULTS

The MTF curves derived above (Fig. 3) were used to simulate the imaging performance. As a first test case, a template consisting of the USAF resolution target [7] has been imaged, followed by a typical IR surveillance scene. Imaging simulation results for various ψ conditions are presented in Fig. 4 (USAF target) and Fig. 5 (IR scene[1]) for clear aperture, as well as when the DOF phase mask is incorporated in the optical train. One should note that for large values of ψ the images representing results obtainable with the mask are superior to those of the clear aperture. The MTF curves (Fig. 3) show just a small improvement, but in actual imagery the differences in the displayed images are readily observable by inspection. It can be clearly seen that at the nominal temperature/in-focus position, the mask deteriorates the image quality, but the objects in the scene are still resolved (especially the people). This is due to the fact that the mask is designed to provide a high cut off-frequency (the payoff being the reduced contrast). In IR surveillance scenes the cut-off frequency is (generally) more important than the contrast, since the user is more interested in details, like the separation of objects, rather than in their identification or gray-level appearance. This fact is clearly seen at images obtained for $\psi = -6, T = 60^o$: without the mask close figures are not resolved, while with the mask they are still separated. At 'mid-way' values ($\psi = -3, T = 40^o$), the images are quite similar for the two cases, and this state can be considered as the 'break-even' point; from this point on, the DOF mask starts providing better images of higher quality. In all the cases the resulting images were presented without any attempt to restore image quality using image post-processing. A simple example outlining the benefits of even elementary image processing techniques is presented in Fig. 6. In this example the raw images generated in the imaging simulation (displayed in Fig. 5) are processed for simple contrast enhancement. For this application, 1% of the extreme (high and low) gray-level values have been eliminated, and then the image limits have been 'stretched' over the entire dynamic range. One can notice that objects that are just resolved before the post-processing stage are resolved with better contrast thereafter. One also notices that the image obtained with the phase mask at the nominal condition case (ψ=0) is much improved. However objects that are not resolved in the 'raw' imaging stage, are not improved by this simple processing algorithm and thus cannot be resolved 'a-posteriori'. The benefit of the DOF mask is that is allows the system cut-off frequency to be extended to include higher frequencies, thus resolving finer features. As already mentioned, the 'payoff' for achieving that feat is in the reduction of contrast; the simple post processing used, enabled the improvement of the image acuity.

[1] IR scene image taken from 'IEEE OTCBVS WS Series Bench' database, in courtesy of J. Davis and M. Keck.

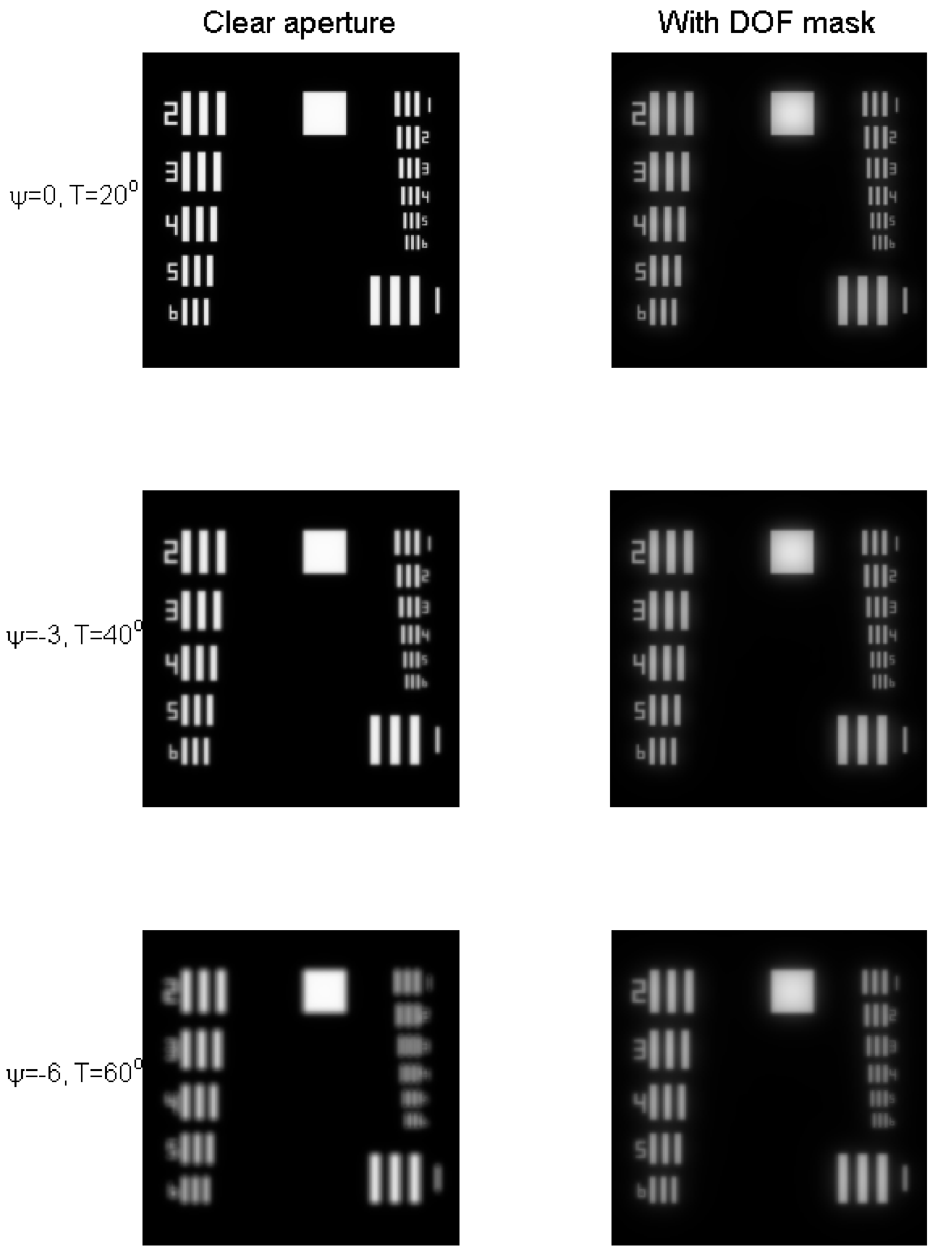

Fig. 4 – Imaging simulation of a USAF resolution target for clear aperture (left) and with DOF mask (right) for various temperature/defocus conditions.

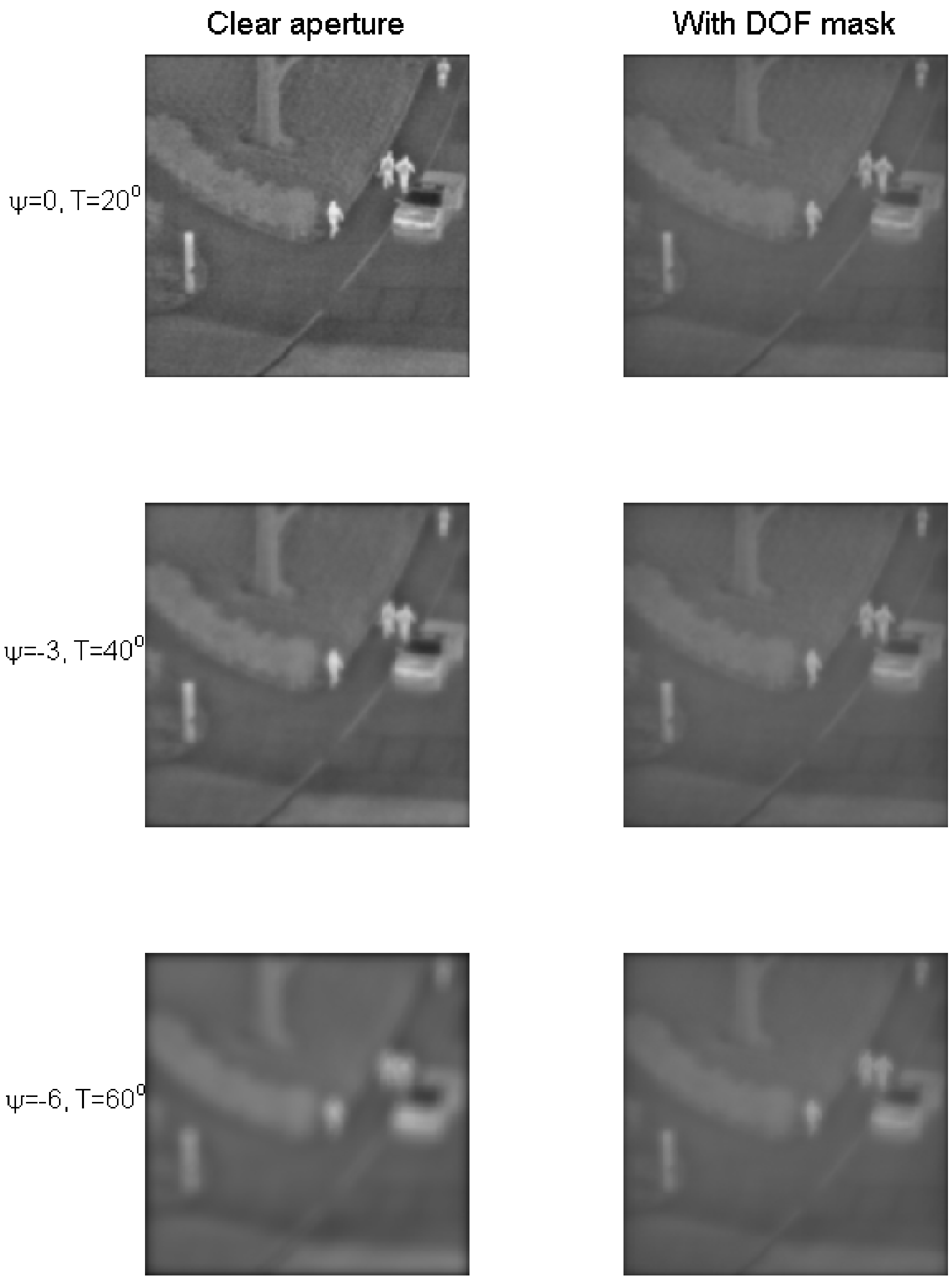

Fig. 5 – Imaging simulation of a typical IR scene for clear aperture (left) and with DOF mask (right) for various temperature/defocus conditions.

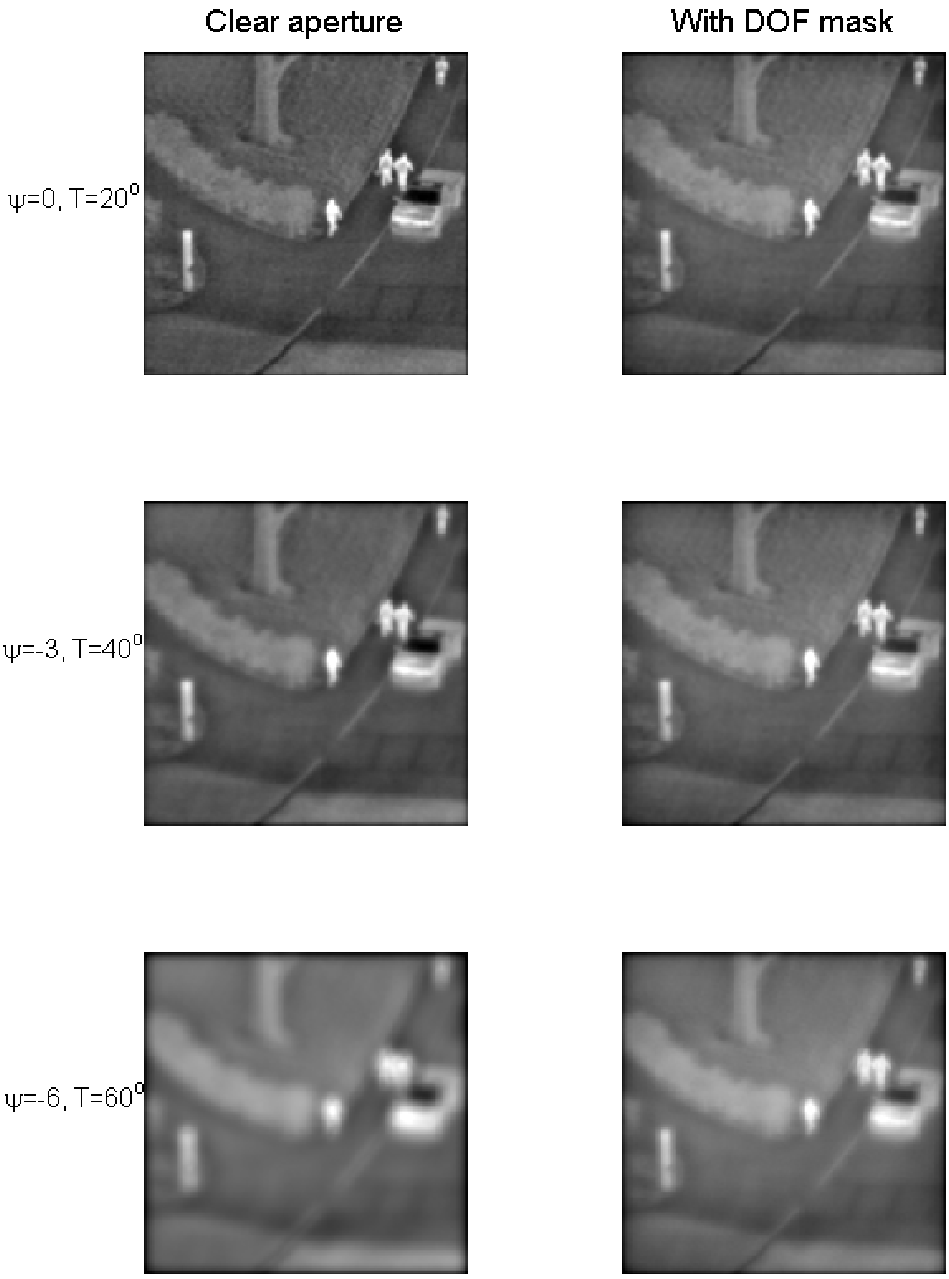

Fig. 6 – Imaging simulation of a typical IR scene with post processing for contrast enhancement. Clear aperture (left), with DOF mask (right) for various temperature/defocus conditions.

4. CONCLUSION

It has been shown that Thermal Focal Shift (TFS) in Ge limits its usage as a viable optical material for IR lenses. Many methods to solve the TFS problem have been proposed in the past, but it seems that a simple all-optical solution had not been proposed and implemented yet. In this work, the TFS problem is formulated as a Depth of Field (DOF) problem. Using a simple all-optical phase mask, the DOF of the imaging system is extended; thus changes in the focal length due to temperature variations are compensated. In particular for autonomous systems relying on machine vision interpretation, the use of passive phase masks like the one presented in this work should be attractive.

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