Fast Catadioptric Optics with Large Field of View

N. Blanchard, M. Doucet, N. Desnoyers, L. Le Noc, A. Bergeron
INO, 2740 Einstein, Sainte-Foy, Quebec, G1P 4S4, Canada

ABSTRACT

High resolution is in demand for the new applications based on the use of infrared technology. For observation task, high resolution provides more information either under the form of better resolving power or larger field-of-view. Various solutions can be envisioned to achieve high resolution imaging. In this paper, a combination of high resolution detector and microscanning system is proposed. This strategy results in higher resolution and reduced aliasing. A catadioptric configuration is preferred when a microscan is required to increase the spatial sampling frequency. Among the catadioptric configurations, the Schmidt-Cassegrain has wide angle capability due to its aspherical entrance window. However, when the system is used in harsh environment, this compensator window may have to be replaced often. In this case, a flat window would be preferred because it can be removed or easily replaced at reasonable cost. The reduction of the aberrations to an acceptable level without compensator window requires that the mirrors of the telescope be aspherized.

In this paper, we present a modified Cassegrain telescope with two aspherical mirrors and one field lens. Due to the large obscuration of the secondary mirror, the effective F/1.05 necessitates a larger working F-number of 0.75. The spectral band ranges from 7.0 to 14.0 microns and the focal length is 50mm. The system is designed for the ULIS UL04171 microbolometer detector with 640 x 480 pixels and 25 microns pixel pitch. With this sensor, the total field of view of the system is 22.6 degrees, which is very large for a catadioptric system. A microscan increases the system maximal spatial sampling frequency from 20 to 40 cycles per millimeter. Despite of the compactness, there is enough room between the field lens and the detector to insert a shutter. A baffle extending ahead of the device is needed in this large field of view design to avoid undesired rays reaching the detector.

Keywords: infrared lens design, thermal imaging, telescope, microscan, fast focal-ratio, wide field of view

1. INTRODUCTION

Robust catadioptric system with microscan capability have been reported in previous papers for the thermal spectral band [1][2][3]. These designs use an IRM160A 160x120 pixels INO uncooled microbolometers and a F/1.0 Schmidt-Cassegrain catadioptric optics.

A modified Cassegrain configuration with a very large field of view and a very high resolution is reported in this paper. A large field of view enables more effective target detection while high resolution enables more effective target recognition. This paper presents several aspects considered to achieve the modified Cassegrain telescope, including tolerances analysis.

2. SYSTEM DESIGN

The 50-mm-focal-length system with a 22.6 degrees full field of view is corrected for the 7 -14 microns waveband. Due to the obscuration of the secondary mirror, working F-number of 0.75 is required for the achievement of an effective F/1.05 design. Furthermore, a microscan increases the system maximal spatial sampling frequency reducing also the aliasing effects. The design provides enough room to insert a shutter for calibration purpose. A baffle is added to avoid undesired rays reaching the detector.

System requirements and specifications are described in Table 1. Main parameters are discussed in the following subsections.

Thermal imaging optics in the 7 to 14 microns region often requires large field of view in a fast and compact lens design. To maintain high spatial resolution imaging performances within a compact system with large field of view, a 50mm focal length has been chosen with the ULIS UL04171 detector. This uncooled microbolometer detector has 640 x 480

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pixels and 25 microns pixel pitch. A large field of view of 22.6 degrees is obtained with the ULIS detector and 50 mm focal length lens. The ULIS UL04171 has one of the largest sensing areas (16 millimeters by 12 millimeters); therefore this optics could also be used with most of the available microbolometer detector. The focal length choice was influenced by the applications usually encountered for this type of optics.

Table 1. System description.

System criteria	**Specifications and Requirements**	**Designed Lens**
Waveband	7 to 14 microns	Corrected from 7 um to 14 um
Focal Length	50.0 mm	50.0 mm
Effective F/#	Faster than F/1.05	F/1.05
Working F/#	Depends on obscuration	F/0.75
Detector	640 x 480 pixels 25 micron pitch & microscan	640 x 480 pixels 25 microns pitch & microscan
Entrance Pupil Dia.	Depends on FOV, F/# and secondary obscuration	67.5 mm
Elements	Front window Primary mirror Secondary mirror Field Lens	Flat (Zinc Selenide) Aspherical (Aluminum) Aspherical (Aluminum) Aspherical/Conical (Germanium)
Relative illumination	85% at 6 degrees	87 % at 6 degrees 69 % at 9.09 degrees
Microscan response time (from one position to the other)	< 2 milliseconds	<1.5 milliseconds
Manual focus range	10 meters to infinity	10 meters to infinity
Optical dimensions	75 mm diameter 100 mm length	72 mm diameter (78mm with flange) 114 mm length including baffle
Optics mass	Lowest possible	131 grams without front window
Athermal range	-30^0 C to $+60^0$ C with focus	+/-50 microns focus range required

2.1 Modified-Cassegrain Telescope

Refractive optics is usually preferred for fast optics with a large field of view [4]. Nevertheless, several reasons make a Cassegrain telescope a more interesting configuration for this application. Cassegrain telescope based designs are generally more compact, are easy to athermalize and can be made light weight.

The design presented in this paper has a flat entrance window. An aspheric window of a Schmidt-Cassegrain telescope helps reducing aberrations, but a flat front window is less expensive and easier to replace. Further more, in harsh environment, a system still operable even if the front flat window breaks.

This design consists of three optical components (see Figure 1) i.e. a primary mirror, a secondary mirror and a field lens. Each optical component is aspheric to reduce the aberrations to a reasonable level. Because detector size is large in comparison to the lens focal length, the secondary mirror makes an obscuration of 50%. This obscuration has to be controlled during optimization process because it reduces the modulation transfer function diffraction limit [5]. Furthermore, the larger is the obscuration the larger should be the aperture stop to keep the required effective focal ratio of F/1.05. For this system, the required working F/# is F/0.75. Furthermore, the faster is the optics the more sensitive is the system to manufacturing and assembly errors.

For system calibration, a compact shutter mechanism has been inserted between the field lens and the microbolometer. Achieving acceptable optical performances with the constraint of keeping enough space for the shutter has been a challenge for the optical design. Reducing the effective thickness of the shutter has also been a challenge for the mechanical design.

The system is equipped with a manual focusing mechanism for object distances ranging from 10 meters up to the infinity. Note that the optical performances are optimal for an infinite object distance and are still quite good down to 25 meters. The focus mechanism has been designed to withstand harsh environment and is designed to keep its desired position even under severe shocks or high vibration events. The mechanism resolution is smaller than 5 microns over the full 2.5mm displacement range.

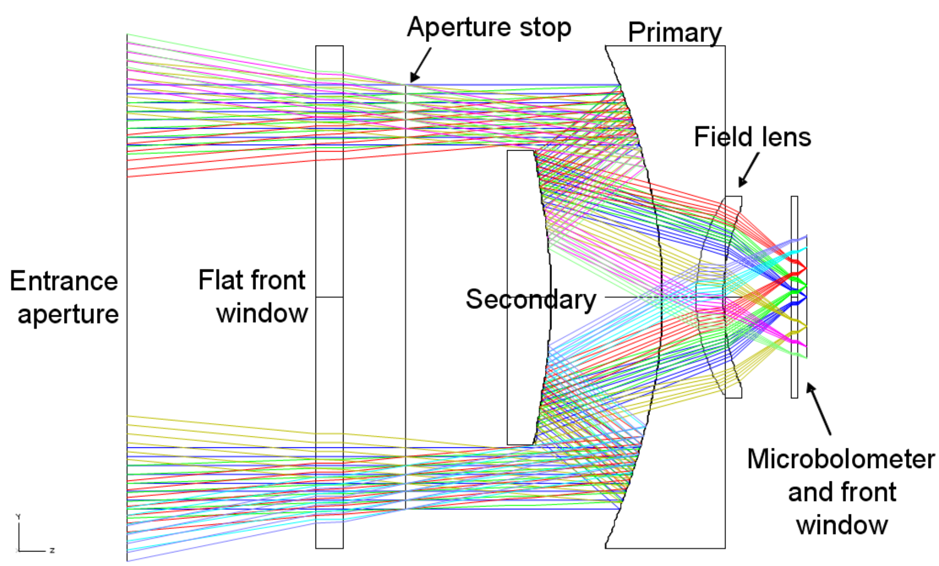

Figure 1. Optical layout.

2.2 Microscan and spatial resolution

A microscan mechanism enables higher spatial resolution with a smaller and lower cost detector, resulting in reduced size of the optical system. With microscan, the detector line-of-sight is moved half the instantaneous field of view of a pixel. The microscan tilts the beam by 50 arc seconds according to X and according to Y. Tilt angle has to be smaller than the permitted optical tolerance angle. The superimposition of these images increases the spatial resolution, and the 640 x 480 pixels detector produces images similar to a 1280 x 960 pixels detector. To achieve the same resolution with this detector but without microscan, the system focal length would have to be 100mm instead of 50mm increasing by a large factor the weight and size of the optics. This would also require larger optics and the full field of view would have been reduced by a factor of two (11.3 degrees instead of 22.6 degrees). It could also be possible to achieve the same resolution with the same full field of view without microscan, but it requires a 1280 x 960 pixels detector. In this case, system focal length would depend on the detector pixel pitch.

Figure 2 compares an image and its simulated microscanned version. Image is smoother and less noisy, which reduces eye fatigue of the human observer.

The microscan mechanism, designed at INO, has been optimized to be intrinsically athermal. Aluminum was the preferred material for its compatibility with optical and barrel material. The 35 gram microscan mechanism has its first natural frequency around 1000 Hz. Microscan actuators are small and allow a very compact design, which is highly desirable for this application. Its power consumption, when activated, is around 1 W. In order to reduce the power consumption, the microscan can be disabled when high spatial resolution is not required. The microscan mechanism minimum response time is lower than 1.5 milliseconds from one position to the other with minimal damping movement when it is driven with appropriate electrical signal.

The use of a microscan mechanism in such system requires that the first natural frequencies of the optomechanical cells and barrels as well as those of the optical components be sufficiently high (high stiffness to weight ratio) to avoid undesired dynamic effects. In addition, the high sensitivity to manufacturing tolerances makes necessary the implementation of adjustable cells allowing the alignment of each optical component. Special lock features on the alignment mechanisms have been included to avoid unwanted dynamic effects.

Figure 2. Images comparison: without microscan (left) and with microscan (right).

2.3 System performances

Image Simulation tool from Zemax Software is used to simulate the image produced by the system with its microscan (Figure 3). The 1280 by 960 pixels scene has been chosen for its spatial frequency content characterized by a lot of high frequencies.

Figure 4 shows the modulation transfer function calculated by Zemax. The 25 microns pixel pitch corresponds to a 20 cycles per millimeters, but microscan increases the spatial resolution up to 40 cycles per millimeters. System has been optimized to have the highest resolution at the center of the image, but keeping relative illumination and performances acceptable over the entire detector effective area.

It can be seen in the RMS wavefront curves in Figure 5 that the system is almost diffraction limited over the 160 x 120 pixels central window. This corresponds to a 2.86 degrees half field of view. Figure 5 also shows the RMS spot radius over the field of view.

Vignetting due to the system obscuration leads to decreasing illumination towards the edges of the detector (Figure 6). Calibrating the microbolometers camera can correct for this effect at the expense of a degradation of the signal-to-noise-ratio.

System shows weak distortion over the full detector area. The impact on image quality is negligible. For the central part of the field corresponding to a 160 x 120 pixels sub-aperture, distortion is less than -0.2%. The maximum distortion is about -1.9% at the corners of the sensor area.

Figure 3. Image simulation for 8.5 microns, 10 microns and 11.5 microns wavelengths.

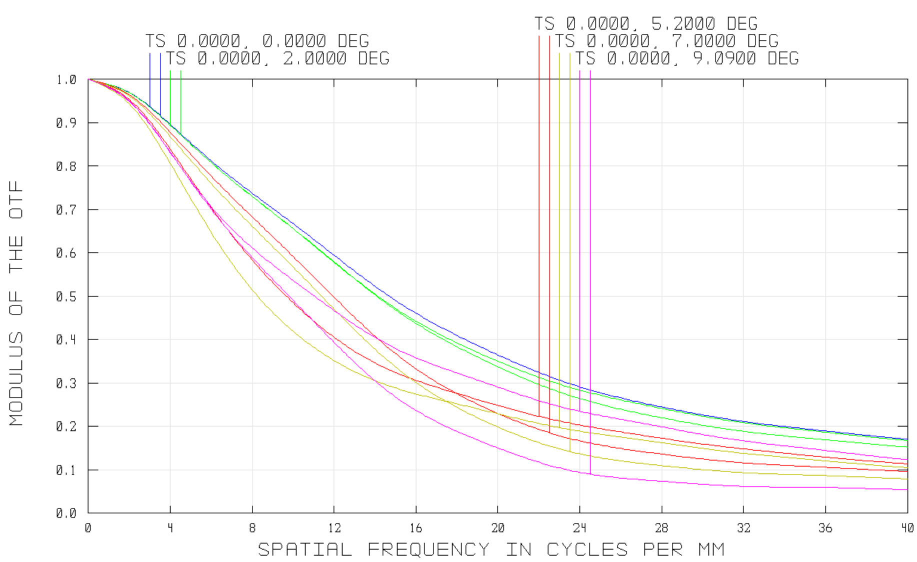

Figure 4. Calculated polychromatic modulation transfer function. System corrected for the 7 -14 microns waveband.

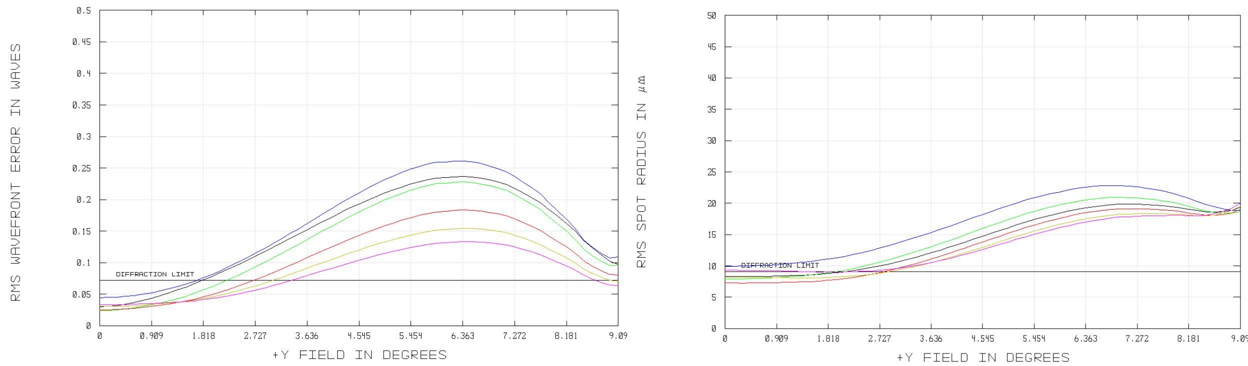

Figure 5. Calculated RMS wavefront error in waves (at 10 microns) and RMS spot radius in microns.

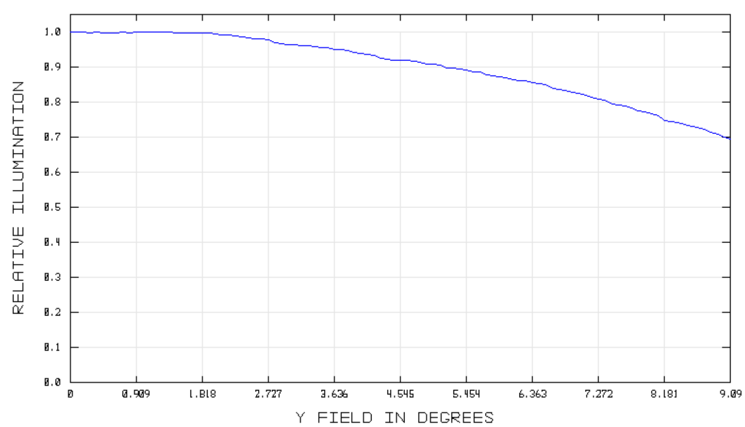

Figure 6. Calculated relative illumination at 10 microns.

2.4 Athermalized design

Primary and secondary mirrors as well as the mechanical parts are all made of aluminum. Being of the same material, the mechanical barrel and the mirrors will undergo proportional dimensional changes upon temperature variations. Temperature changes correspond to a scale factor applied to both mechanical barrel and mirrors, making the catadioptric system nearly intrinsically athermalized. The system is not perfectly athermalized due to the temperature dependent refractive index of the field lens optical material. The focal distance changes slightly (+/-50 microns) over the entire operation temperature range, which is from -30 degrees Celsius to +60 degrees Celsius. The manual focus is adjusted to compensate this 50 microns offset. Figure 7 illustrates the calculated polychromatic modulation transfer function over the operation temperature range.

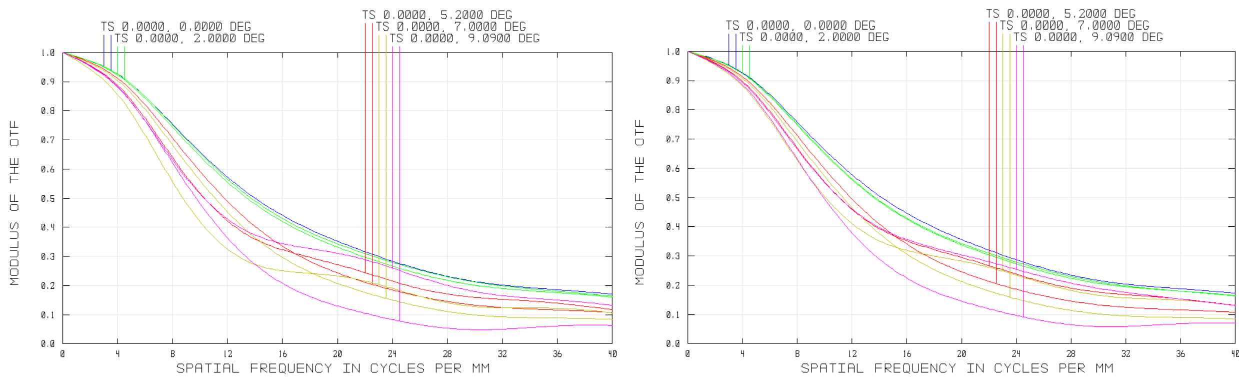

Figure 7. Calculated polychromatic modulation transfer function at – 30 degrees Celsius and +60 degrees Celsius.

2.5 Stray light considerations

As mentioned earlier in this paper, 22.6 degrees is a large field of view for a Cassegrain catadioptric design. Such a large field of view requires large opening along the optical path. The barrel has to be extended to include a baffle to avoid rays from the scene going straight to the detector, without going through the optical path. Figure 8 shows baffle design and how the light that would normally go straight to the detector is blocked. The 64-mm-length optical device has to be extended by nearly a factor of 2 for a total length of 114-mm.

Some steps have to be considered during the optimization process to limit the baffle length:

- the aperture stop has been moved away from the mirror
- the secondary mirror has been brought closer to the primary mirror
- a baffle has been put in the hole of the primary mirror.

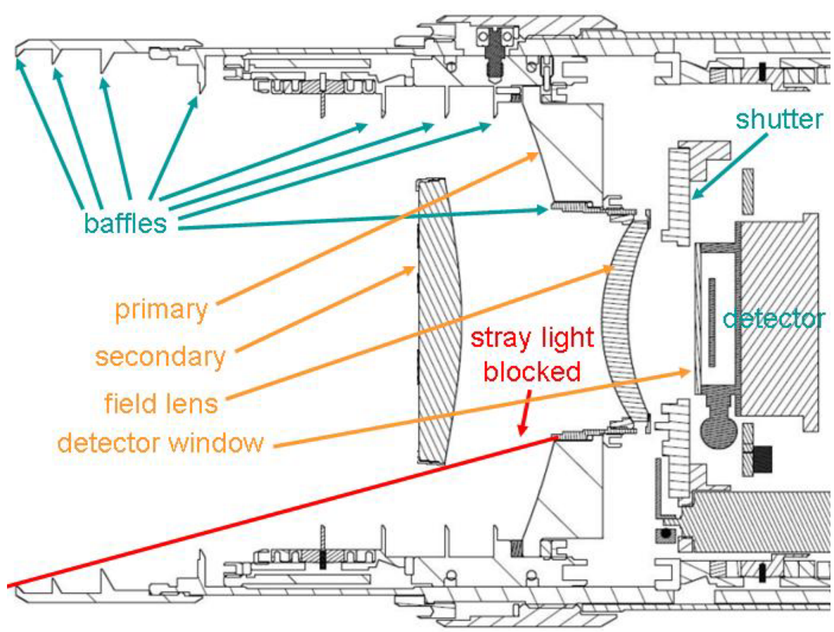

Figure 8. Mechanical view with baffles.

3. TOLERANCES ANALYSIS

An F/0.75 working F/# involves very tight tolerances. Tolerances analysis was done considering a simple and accurate alignment technique. The planed assembling process involves the characterization of each optical component and the manufacturing of customized mechanical supports in order to compensate for the manufacturing errors and uncertainties.

Manufacturing and alignment tolerances analysis has been conducted by conventional Monte Carlo simulations over 1000 random optical layouts. Criterion considered is root-mean-square (RMS) spot radius with normal statistic distributions. Analysis results are shown in Table 2. Compared to the nominal RMS spot radius of 27.8 microns averaged over the entire spectral band and the entire field of view, 90% of the chances are that the performance will be better than 29.8 microns. Figure 9 shows a typical calculated modulation transfer function with mean RMS spot radius of 29.9 microns, which is close to the worst results for 90% of the cases. Figure 10 shows the RMS spot radius for the same random layout with the 29.9 microns mean RMS spot radius. Figure 11 and Figure 12 show image simulations at the center of the field of view and on the detector edges.

Table 2. Tolerancing results.

	RMS spot radius [microns]
Nominal	27.8
Mean	28.5
Standard Deviation	1.0
98% cases are lower than	31.1
90% cases are lower than	29.8
80% cases are lower than	29.2

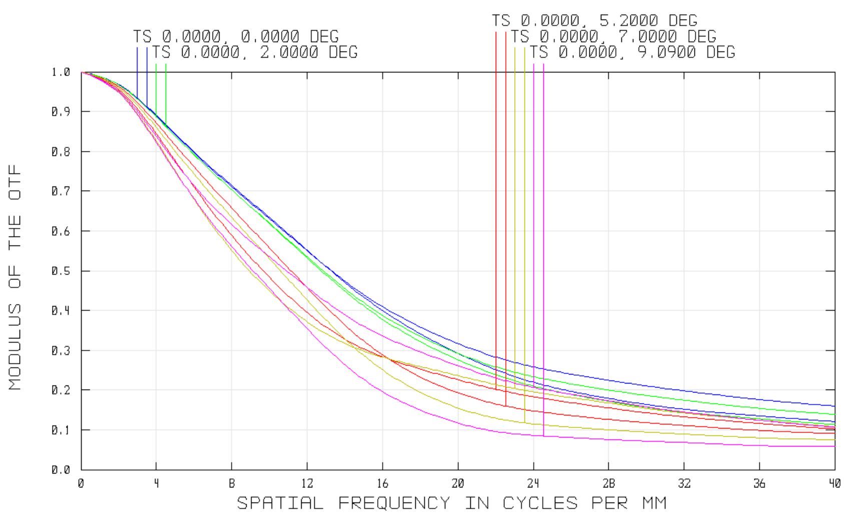

Figure 9. Calculated polychromatic modulation transfer function for a typical Monte Carlo case representing a worst result in 90% of the cases. The mean RMS spot-radius of this case is 29.9 microns.

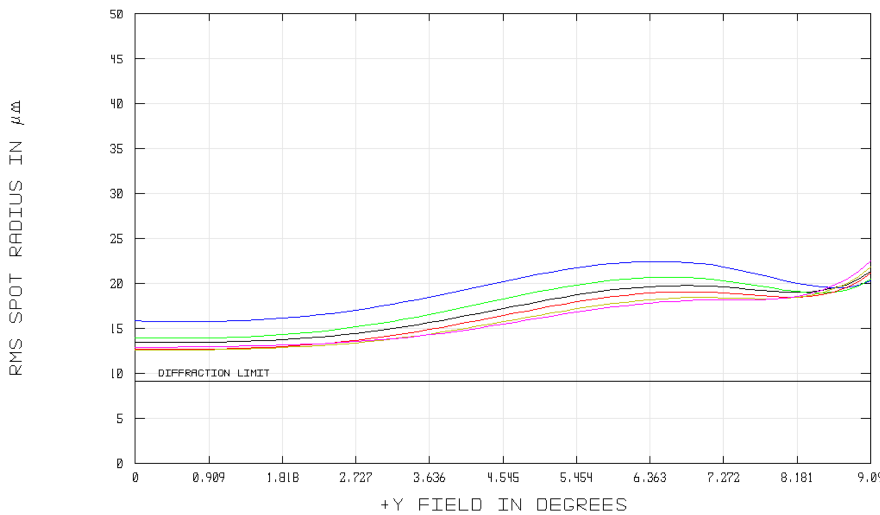

Figure 10. Calculated RMS spot radius according to field of view for a typical Monte Carlo case representing a worst result in 90% of the cases. The mean RMS spot-radius of this case is 29.9 microns.

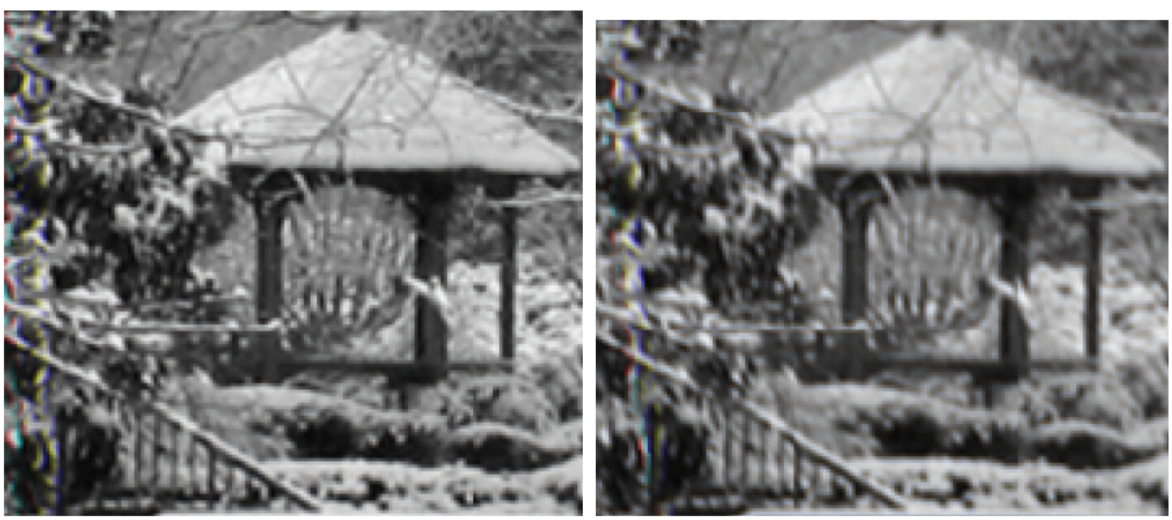

Figure 11. Image simulation comparison at the center of the detector: nominal design (left) and typical results with a 29.9 microns mean RMS spot-radius (right).

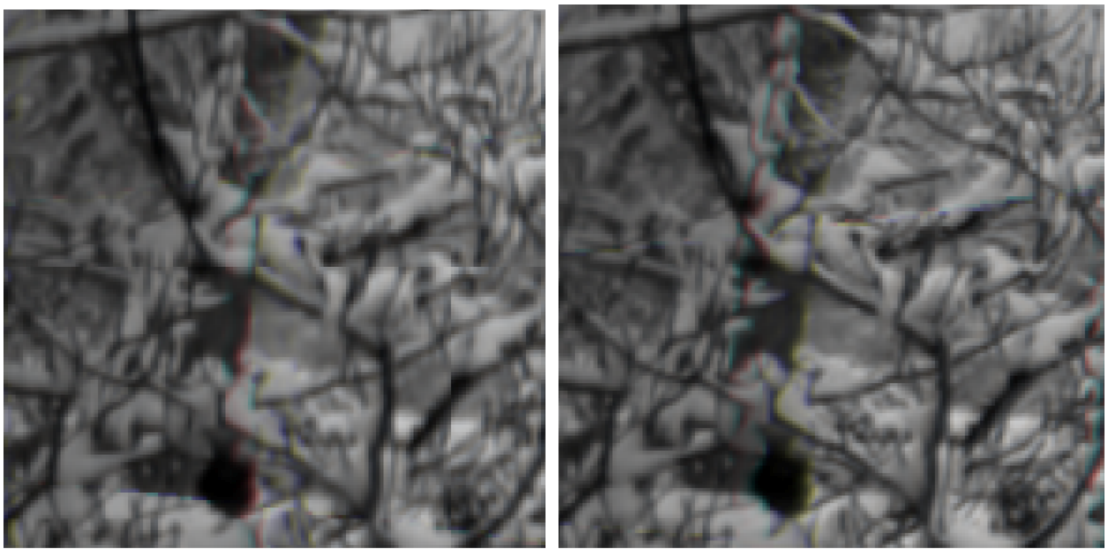

Figure 12. Image simulation comparison on the edge of the detector: nominal and typical results with a 29.9 microns mean RMS spot-radius.

4. CONCLUSION

The modified Cassegrain telescope design for very high resolution imaging presented in this paper offers a large 22.6 total angular field of view while maintaining complete diffraction limited performance over 25% of the field of view at the center of the sensor. The athermalized design is optimized for the 7-14 microns long wave infrared waveband of the uncooled microbolometric 640 x 480 pixels detectors. The optics could eventually be used with lower resolution arrays as well. The use of a microscan increases the system resolution over the entire detector and opens the way to reduce the aliasing effects as well. Manufacturing of the camera is currently ongoing.

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REFERENCES

[1] Bergeron, A., Jerominek, H, Laou, P., Doucet, M., Lagacé, F., Desnoyers, N., Bernier, S., Mercier, L., Boucher, M., Jacob, M., Alain, C, Pope, T.D., "Lightweight uncooled TWS equipped with catadioptric optics and microscan mechanism" (Invited Paper), Proc. SPIE 6206-59, (2006)

[2] Bergeron, A., Jerominek, H., Laou, P., Doucet, M., Lagacé, F., Desnoyers, N., Bernier, S., Mercier, L., Boucher, M., Jacob, M., Alain, C., Pope, T.D., "Dual-band dual field-of-view TWS prototype", Proc. SPIE 6206-60 (2006)

[3] Bergeron, A., Jerominek, H., Laou, P., Lacoursière, J., Desnoyers, N., Alain, C., "Novel lightweight uncooled thermal weapon sight", Proceeding SPIE Orlando [5406-43], 402-411 (2004).

[4] Smith, W.J., [Modern Lens Design], McGraw-Hill Professional Engineering, SPIE Press, 41-45 (2005).

[5] Smith, W.J., [Modern Optical Engineering], McGraw-Hill, SPIE Press, 380-381 (2000).