Variable Cold Stop for Matching IR Cameras to Multiple f-number Optics **

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ABSTRACT

Cameras operating in the thermal infrared (mid-wave and long-wave IR) use a cold stop that is designed to match the exit pupil of the optics and thus avoid parasitic radiation or vignetting. For years, range operators have been using reflective telescopes, usually with photo-documentation film cameras. Along with the need to shift operation into the infrared comes a problem that (i) these telescopes do not have an exit pupil located at the IR camera cold stop, and (ii) most IR cameras have f/2 or f/4 stop, while the telescope is typically f/7 or greater. These mismatches cause a significant deterioration of the system performance and picture quality. A similar need arises when using zoom optics with IR cameras where, as the field of view changes, so does the optics f/#, creating a mismatch with the camera that has a fixed aperture. The OKSI/WSMR team has demonstrated two implementations of a patented continuous variable aperture / cold stop (CVA/CS or VariAp®) for operating IR cameras with different f/# optics. Two systems were built: (1) an optical relay assembly with an external CVA/CS, and (2) a custom 1024×1024 pixel MWIR camera with a built in CVA/CS and the proper relay optics to match the telescope optics to the camera. The first optical relay with the VariAp® is a retrofit for legacy IR cameras for operations with reflective telescopes. The camera with the built-in VariAp® can function with both reflective (using an additional external relay) and refractive (with no additional relay) telescopes. The paper describes the two systems that open new possibilities in IR imaging for various ranges.

Keywords: Infrared cameras, refractive telescopes, reflective telescopes, variable aperture, cold stop, f-number matching, range operations, IR zoom, multiple FOV, 3rd Gen FLIR, targeting & navigation FLIR.

1. INTRODUCTION

An f-number matched optical system and IR camera are required in order to produce an optimal image quality in the thermal IR (mid-wave or long-wave IR), Fig. 1. When the optics' f/# is larger (i.e., slower) than the camera's, parasitic radiation (extraneous rays arriving not from the imaged scene but from the worm structure) reaches the image plane. This radiation increases the signal count and therefore reduces the camera's dynamic range (by filling the pixel well), and it adds to the FPA shot noise. When the optics f/# is smaller (i.e., faster) than the camera's, the aperture in the camera "stops down" the radiance level that reaches the image plane, and thus cuts down useful signal. As a rule, anything that the FPA can "see" other than the optical surfaces must be cold.

For these reasons IR lenses are designed with an exit pupil located outside the lens, inside the vacuum enclosure (behind the camera window), that matches the position of the camera cold stop that is located on the cold radiation shield. An f/# matched system does not waste signal, nor suffers from parasitic signal.

IR lenses do not use an iris built into the lens in order to control the f/# (as in conventional photography visible light lenses) since a warm iris would be a source of parasitic radiation. Moreover, it would be quite expensive to build IR lenses with internal iris, where the entire assembly is cooled to eliminate the parasitic signal. Hence the solution in use by industry is a camera that has an effective cold iris (a fixed size cold stop) to which the lens pupil is matched. In order

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to reduce the number of camera models, most cameras are built with a cold stop of about f/2 or f/4. Lenses are thus designed and built with a pupil behind the mounting flange of the lens, with matching f/#. It is not possible to change the effective f/# of such conventional IR cameras.

The situation is not as simple with reflective telescopes that are in wide use throughout the range optics community. Telescopes are not designed, nor built with an exit pupil behind the mount. Moreover, most long focal length telescopes exhibit an f/# much larger than that built in cameras. Thus mounting a reflective telescope in front of an IR camera suffers from the two problems discussed above: a mismatch in pupil position, and a mismatch in the f/#.

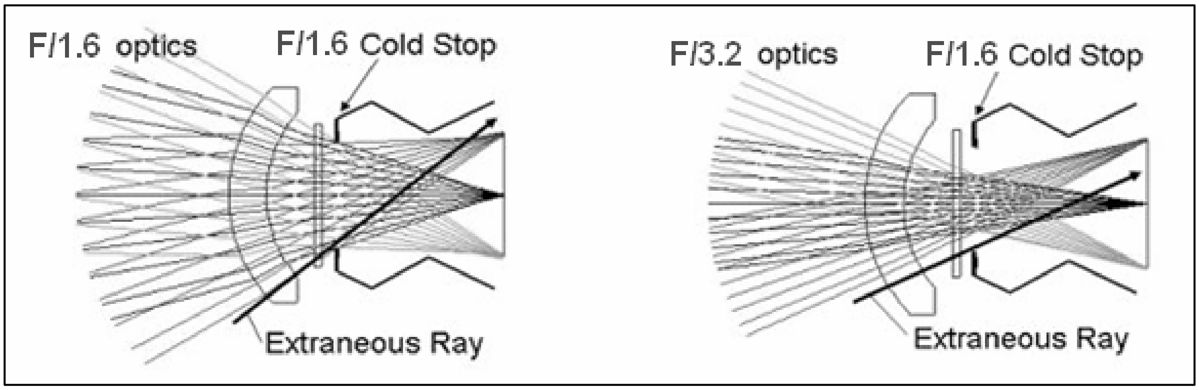

Figure 1. F-number matched (left) and unmatched (right) optical systems.

Many organizations have made a large investment over the years in long-range optics; telescopes that were designed and used with film cameras and later with CCD or CMOS cameras. In the visible portion of the spectrum, or the near and short wave IR, the primary source of signal, is reflected solar radiation or emitted radiation by bright targets. Hence, the (VIS, NIR or SWIR) camera does not have a built-in aperture stop, and the signal level is determined by the f/# of the collecting optics. The thermal radiance produced by the optics and the mounts, is negligible in the VNIR and SWIR, and the film or CCD detectors are insensitive to that spectral range anyway.

Although a telescope can be recoated for the thermal IR service, as explained above, it cannot produce a proper match with an IR camera, and the system will produce non-optimal imagery

There is another case where matching f/# is critical, when IR zoom lenses are used. Either continuous zoom, or fixed step zoom lenses are in service. For example, targeting and navigation pods use the IR camera with optics that may have several preset fields of views (FOV) and thus several f/#s. Since the IR camera has a fixed cold stop, such targeting /navigation FLIR systems do not function in an optimal manner at all settings.

The solution addressing these issues is a variable aperture / cold stop assembly that is built into the camera and replaces the fixed aperture cold stop. For cameras that are already in use, and that use a hermetically sealed dewar and cannot be upgraded, an external CVA/CS assembly can be built. The technology was first developed by OKSI for GEN-III FLIR systems[1,2] and is now patented[3] with other patents pending.

2. THE VARIABLE APERTURE MECHANISM

In principle the mechanism making the VariAp® is similar to an iris in a regular lens. The difference is that the blades are (i) custom made using materials that are compatible with vacuum requirements for long life time hermetically sealed dewars, (ii) are coated with IR "black" coatings, i.e., exhibiting low reflectivity in the spectral range of interest, (iii) the black coatings are non-particulating so that the repeated opening and closing the aperture does not cause the shedding of small particles that may settle on the FPA, and (iv) the coatings are vacuum compatible, see Fig. 2. The actuation, opening and closing of the CVA/CS, is implemented in various ways, depending on the specific camera. Some cameras

[1] Garman, J., and Gat, N. "Variable Aperture Cold Stop for Dual F/# IR Optical Systems." 2004 Meeting of the Military Sensing Symposia (MSS) on Passive Sensors, Raytheon Missile Systems, Tucson, AZ, 22-26 March, 2004.

[2] Garman, J., Gat, N., Vizgaitis, J., "Dual F/Number Tactical Dewar Development." 2006 Meeting of the Military Sensing Symposia (MSS) on Passive Sensors, Orlando, FL, 13-17 February 2006.

[3] Gat, N., *et-al*, "Cryogenically cooled adjustable apertures for infrared cameras," US Patent # 7,157,706.

use a manual feedthrough micrometer to operate the aperture. In other cameras this is motorized and computer controlled (the software can be used to automatically adjust the aperture to match the optics and also as a pseudo auto-gain control, AGC). In hermetically sealed dewars the operation is via vacuum compatible piezo motors placed inside the vacuum enclosure (for details see references 1 thru 3). This type of CVA/CS mechanism is used in the systems described in the following sections, and have been tested for hundreds of thousands actuations over long period of time, and were also shock and vibrations tested to SADA-II specs.

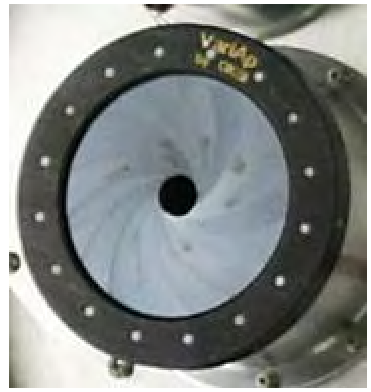

Figure 2. CVA/CS for IR cameras mounted on a cold radiation sheild.

3. EXTERNAL VARIABLE APERTURE

In the system described in this section the following parameters were of interest. The telescope is a Cassegrain f/10.5 with a 25.4 mm diagonal image size. The camera (Indigo, Phoenix) is a fixed f/4.1 with a 20.16 mm FPA diagonal. The problem thus is to design an external relay system that will effectively cold stop the telescope (and other similar telescopes) and provide the needed 1.25:1 demagnification.

The external CVA/CS is built into a relay optical assembly that established a match between a telescope and the camera with a fixed cold stop, Fig. 3. The relay is designed to work with a telescope that forms an image on the left side of the relay in the figure. Lenses in groups 1 and 2 straddle the cold stop and form a 1:1 relay, with a pupil located at the CVA/CS position (stop assembly), and a secondary image is formed after lens 6. Lenses in group 3 form a 1.25:1 relay that reimages the secondary image onto the FPA to the right of lens 11, via the vacuum window, camera fixed cold stop and a cold filter. The demagnification is designed to match the image plane of the telescope with the size of the FPA. The lenses in groups 2 and 3 reimage the CVA/CS onto the camera's fixed stop.

The CVA/CS is housed in a vacuum enclosure between lenses 3 and 4. The enclosure does not have windows; it uses the lenses on both sides to provide the vacuum seal. The shape of the lenses was designed specifically to provide adequate flat area to cover an O-ring seal. The cold stop is cooled with a 1W Stirling engine, Fig. 4. A manual feedthrough can be seen on the top left side of the vacuum enclosure. A worm gear calibrated with a digital dial indicator is used for operating and setting the CVA/CS to any desired and known stop size. The 11 lenses in the relay, were manufactured by and assembled at Janos Technologies, and the assembly tested for performance at Optikos.

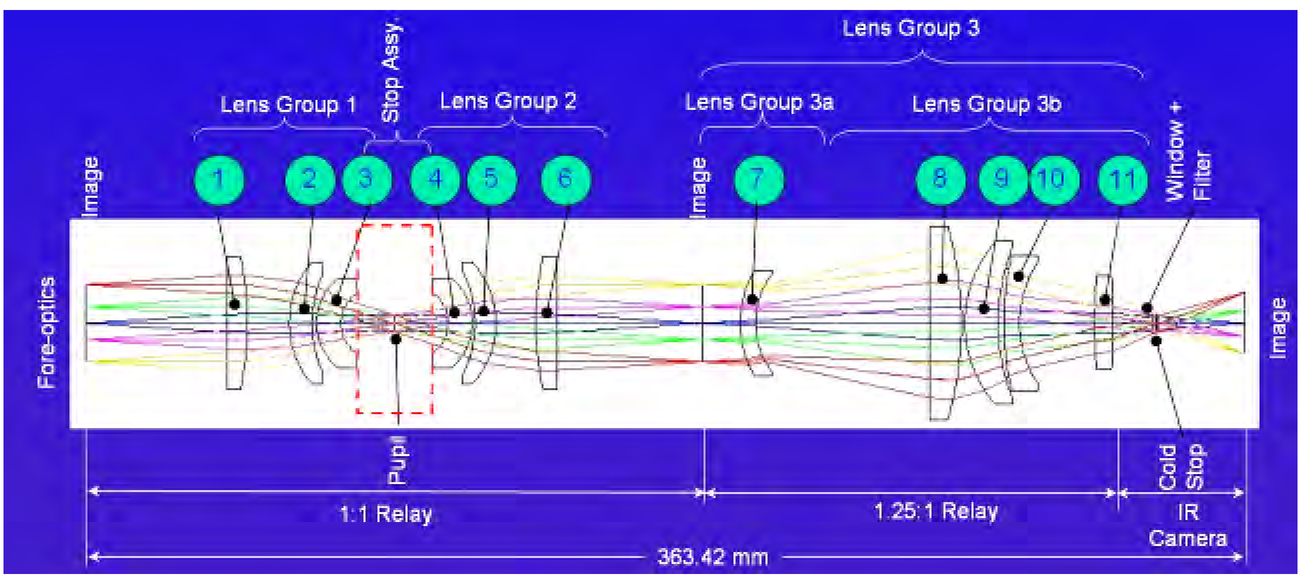

Figure 3. Optical relay with an external cold CVA/CS assembly.

The relay assembly with the external CVA/CS was tested after assembly and the MTF across the FOV was found to meet the design criteria. Further tests verified that the dial indicator readout (i.e., the aperture stop) produces the expected changes in radiance. Image quality at this point was tested only with targets placed at the image plane of the relay (in front of lens 1). Results are shown in Fig. 5.

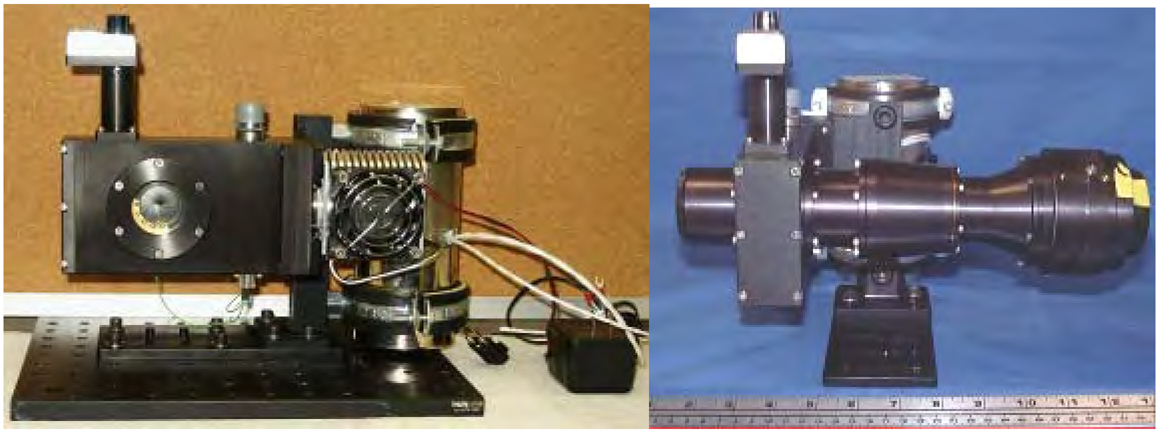

Figure 4. The vacuum enclosure with the VariAp® inside (the windows in this image are used for testing the vacuum on the unit before mounting the relay lens assemblies) (left), and the complete assembled system (right).

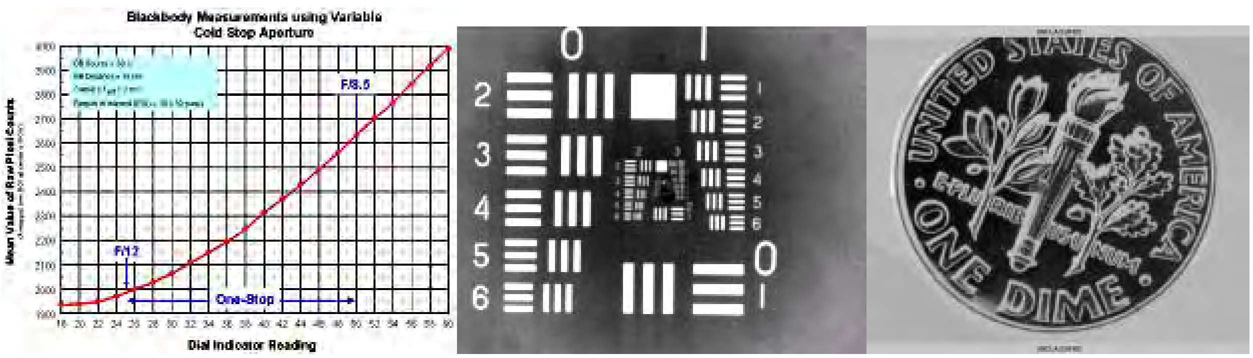

Figure 5. Performance quality tests with the external VariAp® relay showing stop effect of the VariAp: as the aperture is closed, the radiance level at the FPA decreases (left), a resolution target (center), and a coin (right) placed at the image plane of the relay (telescope image location). The images were captures with a f/4.1 InSb camera from Indigo[4] (FLIR Systems).

4. CAMERA WITH A BUILT-IN VARIABLE APERTURE

A MWIR camera, 1,024×1,024, 19.5 µm pixels, InSb FPA (model SB184, Santa Barbara Focalplane), 114 fps via 16 output taps, was built with an internal VariAp® and a four-positions cold filter wheel. The system was designed to work both with refractive and reflective optics. In order to work with refractive optics (specifically with a 500 mm, f/1.67 DiOP lens) the camera's internal cold stop and back working distance were designed to match those of the lens. In order to work with reflective telescopes (specifically with Richie-Chretien family of telescopes made by RCOS) a custom correction lens and a relay assembly were designed and built, Figs. 6a and 6b.

[4] Data courtesy of Kevin Norwood, NewTec, WSMR.

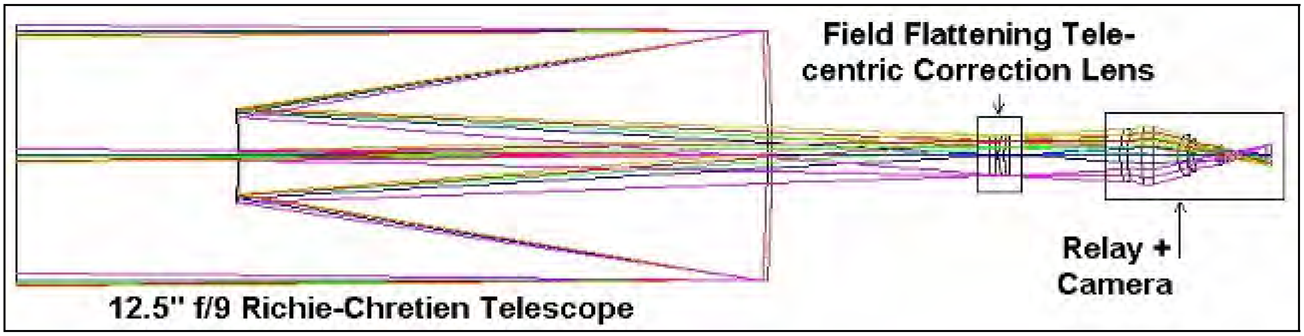

Figure 6a. A correcting lens + relay assembly designed to match the f/# of a Richie-Chretien telescope with the InSb camera with the internal CVA/CS.

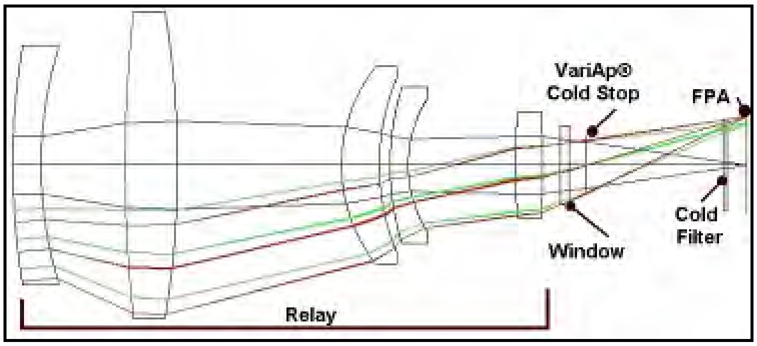

Figure 6b. The optical relay assembly.

The RC telescope is f/9 with image plane size of 50.12 mm diagonal. The FPA has a diagonal dimension of 28.23 mm, and thus a 1.77:1 demagnification is desired. By introducing a demagnification, the effective focal length of the telescope changes, but this was a tradeoff between the FOV and the overall magnification.

Some of the interior components of the camera, i.e., the cold filter wheel, the radiation shield and the CVA/CS can be seen in Figs. 7a and 7b. The vacuum enclosure, and the feedthrough for the CVA/CS and for the filter wheel, as well as the 5W Stirling cryocooler are shown in Fig. 7c.

Figure 7a. 3D CAD model of the cold assembly showing the radiation shield, the cold filter wheel, cold stop, and getter (left), and the as-built parts (right).

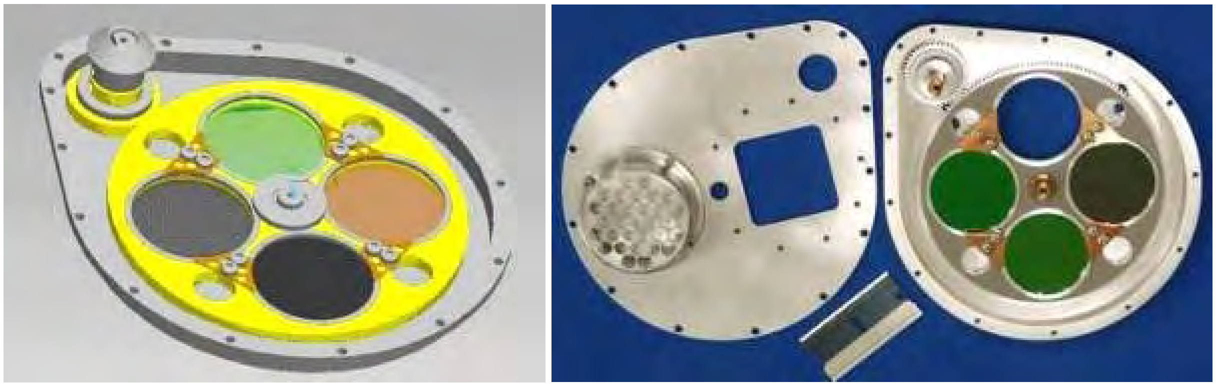

Figure 7b. 3D CAD model of the cold filter wheel (left), and the as-built parts with radiation shield (right).

The new camera with the built-in CVA/CS was tested both with the refractive and reflective telescopes (Figs. 8a and 8b). In Fig. 8a, the DiOP lens is mounted directly in front of the camera and the back working distance and pupil position are matched. In Fig. 8b, the RCOS telescope is seen with the field flattening / telecentric optics mounted behind it. The relay assembly is mounted onto the camera. The focusing is achieved by adjusting the distance between the camera/relay and the RC/correcting lens. The system is shown mounted on a KTM at WSMR in Fig. 8b. The performance of the complete optical system is shown in ray tracing analysis results, to be diffraction limited over the 3 to 5 µm range, Fig. 9. User's interface for manual and automated control of the VariAp® was developed and the main screen shown in Fig. 10.

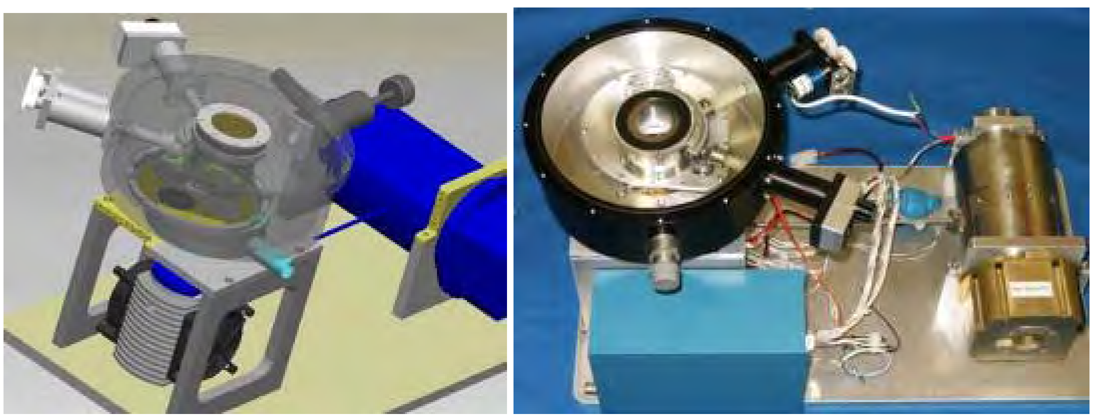

Figure 7c. 3D CAD model of the camera assembly with a 5 W Stirling cooler (left) and the actual parts without the lid on the vacuum enclosure (right).

Figure 8a. The InSb VariAp® camera with a 500 mm, f/1.67 refractive lens, and an image captures with the system.

Figure 8b. The InSb VariAp® camera with the relay optics, correcting lens and a Ritchie-Chretien 12.5” telescope (left), and the system on a tracker mount at WSMR (right).

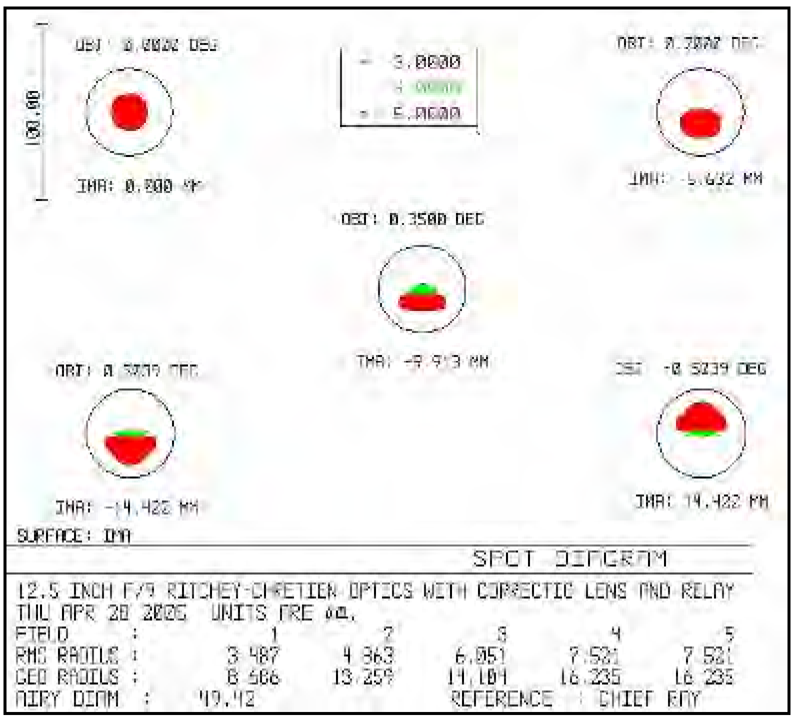

Figure 9. Performance of the entire RC telescope with correcting lens, relay, camera window, and filter is diffraction limited.

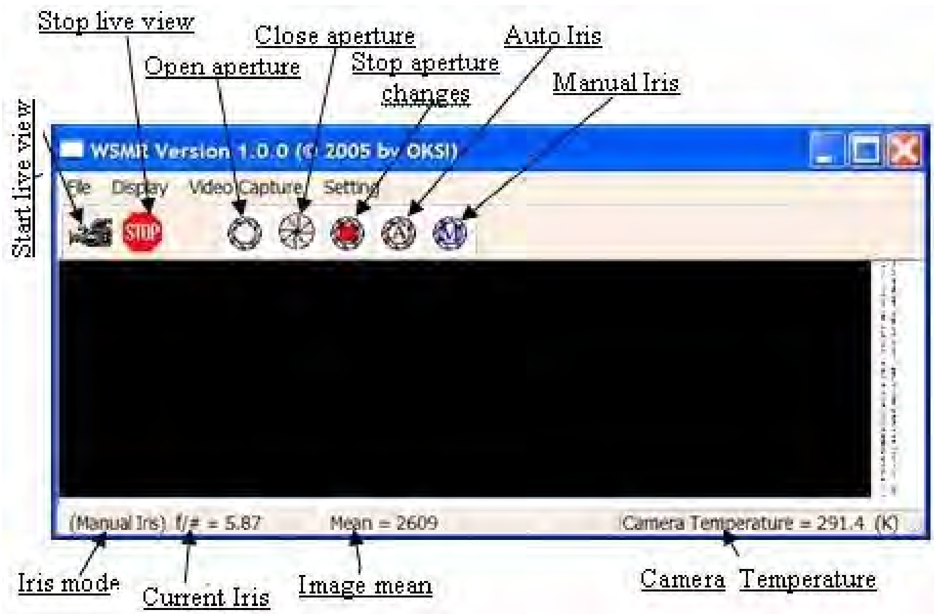

Figure 10. User interface and VariAp control functions.

5. HERMETICALLY SEALED DEWAR IR CAMERAS

The VariAp® has also been implemented in hermetically sealed FLIR cameras.[1,2] One specific implementation is shown in Fig. 11. In this case the CVA/CS is mounted over the radiation shield at the position of the fixed cold stop. The actuation mechanism is the "cage" structure that is designed to reduce heat conduction. Piezo motors are used to apply rotation force to the ring at the bottom of the actuation mechanism. The piezo motors are vacuum compatible and are kept at ambient temperature since conduction through the actuator was proven to be negligible.

Figure 11. CVA/CS design that was implemented for FLIR systems.

6. PARASITIC RADIATION ANALYSIS

A simple analysis can show the effect of parasitic radiation due to mismatched f/# between optics and camera. The signal collected by a pixel in an imaging camera, and the shot noise (for a BLIP system this is the dominant source) associated with the signal can be expressed, in electron count as:

$$S = \frac{K \cdot \Omega \cdot \Delta t}{\exp\left(\frac{C_2}{\lambda \cdot T}\right) - 1}, \text{ e}^- \qquad \Delta S = \sqrt{\frac{K \cdot \Omega \cdot \Delta t}{\exp\left(\frac{C_2}{\lambda \cdot T}\right) - 1}}, \text{ e}^-$$

where the K parameter contains the emissivity, band pass, detector quantum efficiency, optics transmission, etc., and the solid angle is defined by the f/#. All other terms are used in their traditional representation.

$$K = A \cdot C_1 \cdot \Delta\lambda \cdot \varepsilon / (\pi \cdot \lambda^5) \cdot (QE) \cdot \eta_O \cdot (h \cdot c/\lambda) \quad \text{and} \quad \Omega = \pi/[4 \cdot (f)^2]$$

The change in signal ΔS, due a small change in temperature, ΔT is:

$$\Delta S = K \cdot \Omega \cdot \Delta t \cdot \left[\frac{1}{\exp\left(\frac{C_2}{\lambda \cdot [T + \Delta T]}\right) - 1} - \frac{1}{\exp\left(\frac{C_2}{\lambda \cdot T}\right) - 1} \right], \text{ e}^-$$

Equating the change in signal due to a small ΔT to the shot noise gives the NEΔT = ΔT, as:

$$\Delta T = T \cdot \frac{\frac{1}{\beta} \cdot \ln\left[1 + \left(\frac{e\beta}{\alpha}\right)^{0.5}\right]}{1 - \frac{1}{\beta} \cdot \ln\left[1 + \left(\frac{e\beta}{\alpha}\right)^{0.5}\right]} \qquad \text{Where} \qquad \alpha = K \cdot \Omega \cdot \Delta t, \text{ and } \beta = C/\lambda T.$$

The signal collected by a pixel, from the scene and from the parasitic radiation is expressed as the sum of signals from the scene at temperature, T_1, and the emitting mechanical structure temperature, T_2, and the solid angles for the camera and the optics Ωc and Ωo., as: (the difference between these two angles defined how much of the structure the pixel can "see").

$$S \approx \frac{K \cdot \Omega_O \cdot \Delta t}{\exp\left(\frac{C_2}{\lambda \cdot T_1}\right)} + \frac{K \cdot (\Omega_C - \Omega_O) \cdot \Delta t}{\exp\left(\frac{C_2}{\lambda \cdot T_2}\right)}$$

The noise expressed as NEΔT, can thus be shown to be:

$$\Delta T = \frac{\lambda \cdot T_1^2}{C_2} \sqrt{\frac{\exp\left(\frac{C_2}{\lambda \cdot T_1}\right)}{K \cdot \Omega_o \cdot \Delta t}} \left\{ 1 + \exp\left[\frac{C_2}{\lambda} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \right] \cdot \left[\left(\frac{f_o}{f_c} \right)^2 - 1 \right] \right\}^{0.5}$$

The term in the brackets represents the mismatch in f/# and parasitic radiation. This final expression has the f/# of the optics, f_0, and the f/# of the camera, f_c. When those match, the expression in the brackets goes to zero, and we get the conventional definition of NEΔT due to shot noise only. When $f_0/f_c < 1$, we get stopping down (i.e., overall reduction in signal and correspondingly reduction in shot noise), and when $f_0/f_c > 1$, we get contribution from the parasitic radiation term to the signal and the associated shot noise. Of course, even if the optics and scene are at the same temperature ($T_1 = T_2$), there still is an undesired parasitic radiation.

The system NEΔT improves (becomes smaller) as the K term (see above), and the integration time, Δt, become larger.

Typical theoretical results are shown in Fig. 12 for an opto-mechanical structure that is slightly wormer than the scene. In this case the NEΔT increases (becomes worst) as the optics f/# becomes larger (i.e., slower than the camera's). This is shown by the solid lines. The lines also indicate improvements with longer integration time. As one would expect, the situation is more severe, with the f/2.3 camera than with the f/4. For the f/4 camera, as the optics become faster than f/4, the cold stop does not allow any further reduction (improvement) in NEΔT, and the curve is flat.

The graph also shows what would happen if the camera equipped with a CVA/CS constantly matches the f/# of the optics, dashed lines. The NEΔT in such case is significantly better (lower).

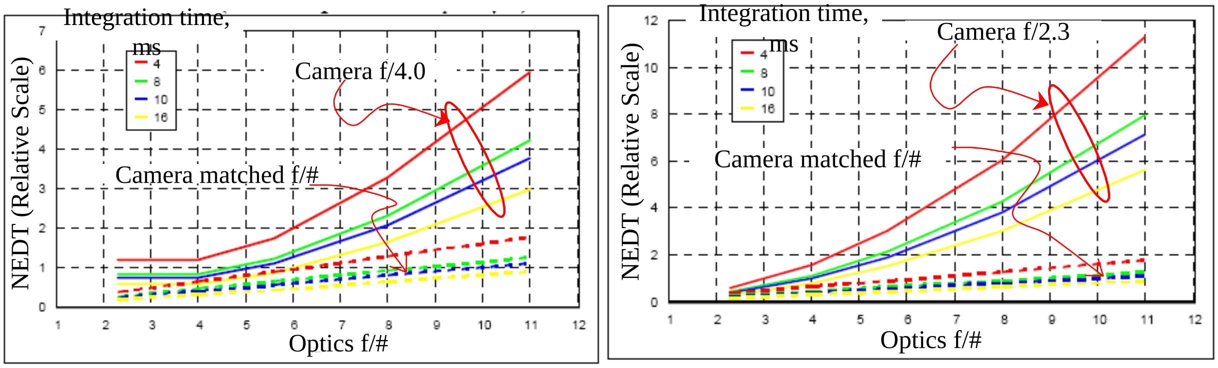

Figure 12. NEΔT for a f/4 camera (left), and f/2.3 camera (right): scene = 290K, optics 300K, @3µm (several T_{intg}); solid lines show camera fixed f/#; dashed lines show camera with CVA/CS, constantly matched to optics f/# (NEΔT is better if it is a smaller number).

7. SUMMARY

In order to optimally operate thermal IR cameras with long-range telescopes, provisions must be made to (a) match the f/# of the telescope and camera, and (b) match the optics' exit pupil to the position of the camera cold stop. When an IR zoom lens is used with a camera, similar needs exist for matching the zoom changing f/# with that of the camera. Without such matching arrangements, image quality suffers from parasitic radiation emitted by the worm opto-mechanical components that are "seen" by the IRFPA, or vignetting may be suffered. The concept has been demonstrated from first principles of radiometric analysis.

The paper describes work under which a camera with an internal, built-in, continuous variable aperture / cold stop was developed. The camera can match the f/# of a zoom lens at any zoom position.

With the addition of an external relay optical assembly, the camera can also work with reflective telescopes. The relay assembly re-images the image plane of the telescope onto the IRFPA, and also the telescope exit pupil is re-imaged onto the camera CVA/CS.

In cases of legacy cameras (those with a fixed cold stop), it is still possible to operate the cameras with reflective telescopes by providing an external CVA/CS that is built into an optical relay assembly. The relay re-images the telescope image plane onto the IRFPA, and also re-images the telescope exit pupil onto the external CVA/CS, and then onto the fixed camera cold stop. This special relay extends the usefulness of legacy IR cameras for service with multiple long-range telescopes.

Finally, the same technology was also adapted for hermetically sealed IR cameras. The CVA/CS is computer controlled, can be matched to changes in the FOV of the optics (such as in dual or triple FOV systems), and can also be used as an aperture stop for preventing FPA saturation when signal brightness increases momentarily.

In addition to range optics, the technology has direct applications to GEN-III FLIR systems, and to targeting and navigation pods with multiple fields of view.