Compact Dual Field-of-View Telescope for Small Satellite Payloads

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ABSTRACT

Small satellite payloads commonly involve missions with multiple field-of-view (FOV) capability. For these missions, it is often desirable that the payload instrument contain optical sensors with both a wide FOV for searching or scanning a scene and a narrow FOV to interrogate and identify the object of interest. This generally requires multiple sensors or a zoom lens with multiple moving lenses. For infrared sensors, these approaches are generally not compact enough for use on small space platforms, unmanned air vehicles, or small satellite payloads. This paper describes a compact dual field-of-view telescope with a 6x field ratio. The selection of the field involves changing optical filters, which transmit different spectral wavebands. Each spectral waveband is associated with separate optical paths with differing focal lengths, thus fields-of-view. This concept has been proven through the design, build, and alignment of a long-wave infrared (LWIR) catadioptric telescope.

INTRODUCTION

There is growing interest in the small-satellite community to include multiple FOV optical payloads to meet its various mission objectives. Wide and narrow FOVs are desirable for such missions in order to a) search or scan a scene and b) zoom in to interrogate and identify the object of interest. In such a sensor, the wide, lower resolution FOV is analogous to peripheral vision; and the narrow, high resolution FOV is analogous to foveated vision. A sensor system capable of both peripheral vision and foveated vision generally requires multiple sensors or a large zoom lens with multiple moving lenses. The large mass and volume associated with zoom lenses or multiple sensors can increase payload volume beyond the capacity of a small satellite. Due to the restricted space available on small satellites, small-sat sensors typically contain a single FOV that offers a compromise between peripheral and foveated vision capabilities.

A compact, dual-FOV, catadioptric telescope has been developed using novel optical design. It is so compact that its length is nearly as short as the diameter. This telescope, originally designed, built, and tested for Unmanned Aerial Vehicle (UAV) applications, operates in the long-wave infrared (LWIR) with a 6x field ratio capability. The patent-pending design concept involves selecting the field by changing optical filters, which transmit differing spectral wavebands. Each spectral waveband is associated with a separate optical path with differing focal length, thus field-of-view.

This concept has been proven through the design, build, alignment, and testing of the first-generation compact LWIR telescope. In addition to dual-FOV capability, the design provides optical athermal performance, allowing temperature-independent performance over a wide operating temperature range. The lens requires no alignment except focus adjustment. For this LWIR case, a second-generation telescope has been designed with improved sensitivity and dynamic range.

This concept and design may be applied to small-sat missions requiring a compact, dual-FOV sensor. It can be modified to work in any spectral waveband (visible, near infrared (NIR), short-wave infrared, etc.) with an appropriate adjustment in the optical prescription of the telescope and selection of the focal plane array. Field ratios greater than 6x are possible.

The remainder of this paper presents the design of an existing compact LWIR dual-FOV telescope and its possible modification to fit within small satellite payload volumes. It also presents the analysis of test data collected in a laboratory and one field-test environment. This paper also discusses the related optical trade studies: a) zoom lens and dual-FOV sensor volumes, b) FOV comparison of all-reflective, all-refractive, and catadioptric telescopes, c) athermal design considerations and d) spectral waveband selection considerations.

COMPACT LWIR DUAL-FOV TELESCOPE

Figure 1 shows a photograph of the compact dual-FOV telescope designed and built for a small, light-weight, UAV application in the LWIR spectrum.

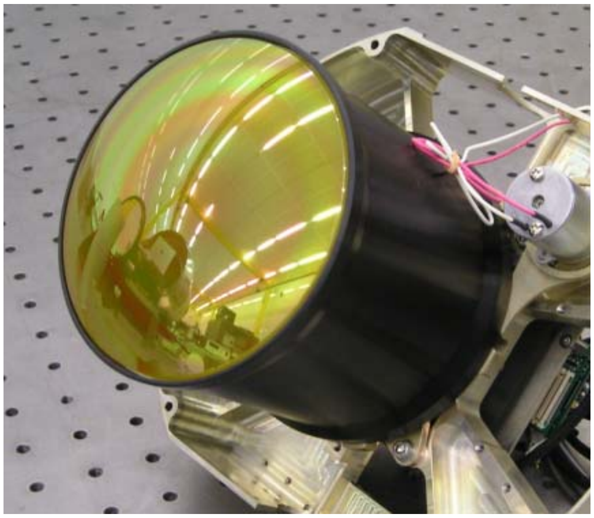


Figure 1: Photograph of the compact, LWIR dual-FOV telescope. The compact nature of this design may be applied to any spectral band and application of interest.

The compact optical design includes a catadioptric Cassegrain telescope combined with an all- refractive lens system, both focused onto a focal plane array (FPA). The two optical paths comprise 2-degree and 12-degree FOVs. Cassegrain telescopes are known for their compact optical designs but are generally limited in FOV. Because the wide-FOV, all-refractive telescope is included within the same package, the dual-FOV telescope is compact.

This dual-FOV sensor FPA can either be single-color or two-color. In the case of a single-color FPA, it is important that the FPA only see one FOV at a time. This is accomplished by assigning separate spectral bands to each optical path.

For this telescope, the spectral waveband is split such that the wide-FOV optical path allows passage of longer wavelengths than the narrow-FOV optical path. This LWIR telescope achieved a field ratio of 6 ((Wide FOV)/ (Narrow FOV) = 12 degrees/2 degrees). Figure 2 is a photograph of the actual LWIR telescope assembled into the ball gimbal UAV instrument.

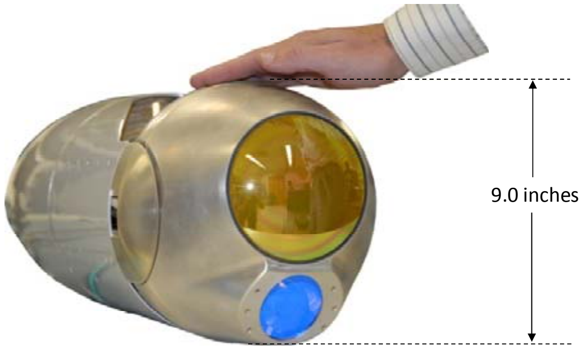


Figure 2: Photograph of UAV instrument with LWIR dual-FOV telescope behind the yellow dome

COMPARISON TO AVAILABLE ZOOM LENS AND DUAL-FOV SENSORS

Comparison of the compact LWIR dual-FOV telescope developed for small UAV applications with other zoom or step zoom systems available for sale or described in literature demonstrate the value of this approach. Figure 3 shows the physical length of several LWIR dual-FOV or zoom lenses plotted versus their longest focal length. The LWIR dual-FOV telescope described in this paper is represented by the red square. Greater magnification and reduced size are realized toward the upper left corner where the lenses or telescopes have the longest focal length with the shortest physical length. The blue diamonds represent various refractive lenses. These lenses fit well to the graphed linear line, as making a refractive lens compact is difficult. Utilizing mirrors in a catadioptric configuration allows for longer focal lengths with reduced telescope length. The green triangle represents the most compact alternate approach discovered in the market and literature survey. This lens is still more than 50mm longer than the described dual-FOV telescope (red square) with a similar focal length.

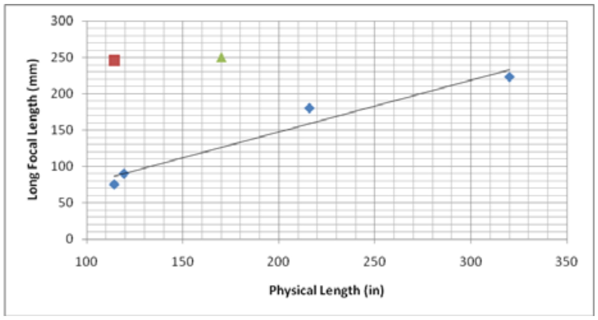


Figure 3: Focal length versus physical length comparison of various LWIR dual-FOV and zoom lenses

Comparisons of focal length and physical length for lenses of other wavelength regions will show similar trends with the refractive lenses longer. However, shorter wavelengths allow additional size reduction or increased compactness with high magnification.

Figure 4 shows lens weight versus zoom ratio or FOV step ratio. In general, the larger the FOV step ratio, the more complex and heavy the optic will be. The red square represents the LWIR dual-FOV telescope described in this paper. It doubles the step ratio of the lightest lenses of equivalent mass. The blue diamonds represent a survey of dual-FOV and zoom lenses available for sale or described in literature.

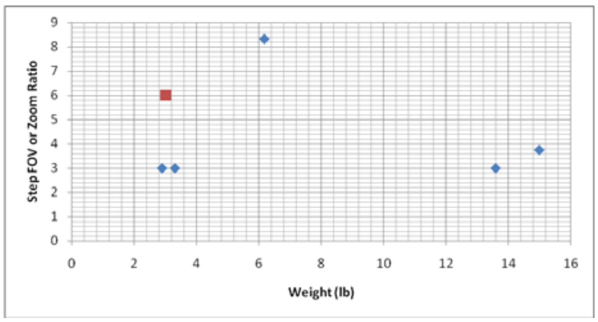


Figure 4: Zoom ratio or FOV step ratio versus lens weight of various LWIR dual-FOV and zoom lenses

OTHER DESIGN CONFIGURATIONS

The discovery and design of this compact dual-FOV approach has opened several design options. One configuration maximizes the independence of the two optical paths, utilizing multiple mirrors for an all-reflective narrow FOV that replaces the catadioptric Cassegrain telescope.

Another variation replaces the single-color FPA with a two-color FPA. Such a change eliminates all moving parts within the instrument. The key challenge, in this case, would be to find an available, feasible two-color FPA that matches the wavebands of interest.

The filter wheel mechanism can also be eliminated by adding a dichroic beam splitter between the secondary mirror of the Cassegrain telescope and the FPA. The purpose of the dichroic beam splitter would be to separate the two optical paths/FOVs to two separate FPAs. A challenge in this case would be the avoidance of vignetting and/or mechanical interference between camera assemblies and the primary mirror. This approach requires two cameras, resulting in a necessary increase in instrument volume, mass, and power requirement.

ATHERMAL DESIGN CONSIDERATIONS

The LWIR dual-FOV telescope was designed for use on UAV platforms. UAVs see global usage and fly at various altitudes, experiencing wide operational temperatures. To meet this application, the telescope design enables athermal optical performance from -25^o C to 40^o C without active focus adjustment.

The athermal design was achieved through strategic selection of refractive element materials in a particular sequence, such that the cumulative unit change in refractive index per unit of change in temperature (dn/dT) balanced with the dL/dT of the aluminum housing, thus maintaining focus on the FPA over the specified temperature range.

Though the constructed unit has not been tested over this temperature range to date, detailed modeling of the optical assembly predicts only small variations of image quality, well within optical performance requirements.

However, the athermal requirement over such a wide temperature range heavily constrained the LWIR telescope optical design. For small satellite applications, a reduction in this requirement would result in greater design flexibility and potentially improved performance. Operational temperature range could be reduced by the use of heaters, or passive athermal requirements could be reduced by active focus adjustment.

SPECTRAL WAVEBAND SELECTION CONSIDERATIONS

The UAV dual-FOV telescope discussed above was designed, built, and tested for use in the LWIR spectrum. However, this concept may be applied to any spectral band of interest where small satellite volumes require compact designs. Small satellite applications may employ spectral wavebands from the ultraviolet (UV) through the LWIR.

Utilizing any spectral waveband other than the LWIR will require redesign of the telescope. Design considerations include a) refractive element substrate materials, b) selection of an appropriate focal plane array, and c) spectral radiometric parameters for the mission of interest.

Compared to the infrared, many more substrate material options exist for applications in the UV and visible spectra. Appropriate selection of refractive element substrate materials plays heavily in optical image performance. The selection of appropriate substrate materials can balance chromatic aberration and reduce total system aberration, resulting in good image quality.

Spectral waveband selection also dictates the type and range of focal plane array options. Many choices are available in the visible and near-infrared wavelengths relative to the mid- and long-wave infrared. If cryogenic cooling of the focal plane array is not feasible for an infrared small satellite mission, there are relatively few focal plane arrays available. For example, in LWIR applications where cryogenic cooling is not feasible, focal plane array selection is limited to microbolometer and ferroelectric arrays. In the short-wave infrared (SWIR), thermal-electric cooled focal plane arrays are available, but the number of choices is still relatively small.

Finally, the spectral radiometric parameters for the mission of interest will necessarily play into the design. The selection of the waveband will determine whether the detected energy is reflection- or emission-dominant. The proper radiometric modeling of the system, calculating system signal-to-noise ratio (SNR), will drive the selection of optical parameters of the design, including focal length, f-number, aperture size, and spectral waveband for each optical/FOV path.

FABRICATION AND ALIGNMENT OF DUAL-FOV TELESCOPE FOR UAV APPLICATION

The dual-FOV telescope was built and tested with funding at SDL in 2007. Fabrication utilized proprietary SDL techniques to produce a compact, rugged lens in a relatively short time. The assembly process only spanned two weeks, but optical component procurement and fabrication for LWIR optics required 12 weeks. Thorough tolerance allocation and analysis allowed cost-effective assembly and optical alignment that produced a precise optical assembly. Early design work reduced alignment compensators to focus compensation for the narrow- and wide-FOV optical paths. The assembled telescope mounted to the ball gimbal bulkhead is shown in Figure 6.

Figure 6: UAV dual-FOV telescope mounted to the ball gimbal bulkhead

Active alignment of focus was accomplished in the lab. The telescope focus was optimized for targets at infinity for both the wide and narrow fields of view. Active alignment utilized a black body illuminated pinhole aligned to the focal point of an off-axis parabola. The telescope is placed in collimated space viewing the pinhole, as shown in Figure 7. The focus compensators were adjusted to minimize the imaged pinhole size for both the wide and narrow FOV optical paths. The narrow and wide FOV pinhole images are shown in Figures 8 and 9, respectively.

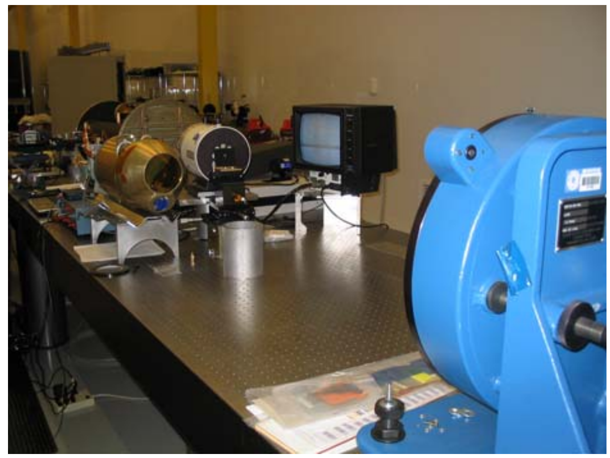


Figure 7: Active focus alignment test setup

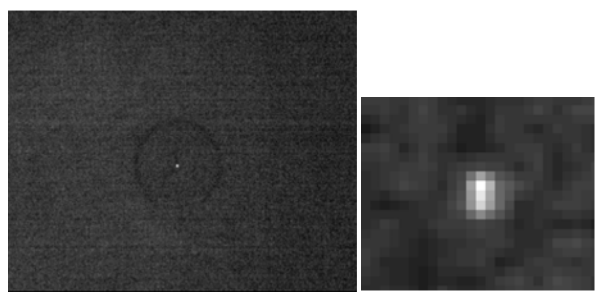


Figure 8: Imaged pinhole in the narrow FOV path

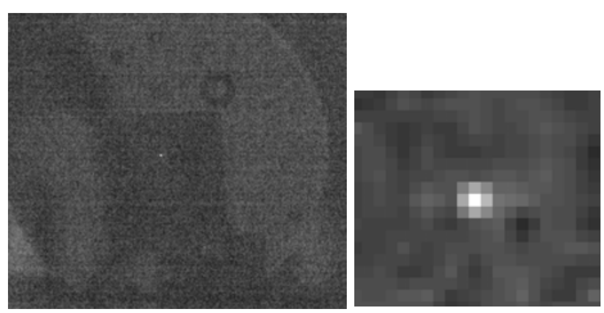
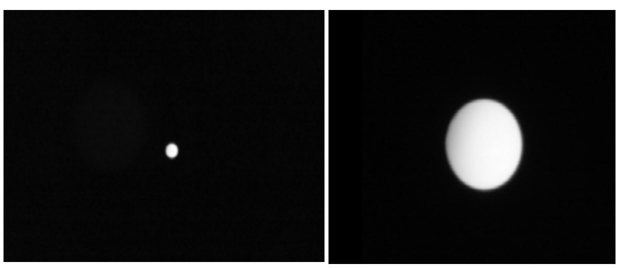


Figure 9: Imaged pinhole in the wide FOV path

PERFORMANCE TESTING

Lab testing quickly showed that the detector was not receiving sufficient photons to yield high contrast, fine-grained images. The grainy image caused by the low SNR can be easily seen in the pinhole image in Figures 8 and 9. Roof testing also showed the SNR deficiency, producing a grainy image shown in Figure 11At first it was thought that this could be an optical element nonconformance. SNR tests were completed in the lab with extended target sources as shown in the LWIR image in Figure 10 a) for the narrow FOV and Figure 10 b) for the wide FOV. SNR measurements showed results very similar to the SNR predicted by analysis. It was determined that the issue was with the micro-bolometer camera. We found that the allowed control of gain and integration time in the FPA readout was limited, restricting our ability to achieve good contrast of the temperatures of interest. It is recommended that a camera with more dynamic range control and sensitivity be utilized with future LWIR telescopes of this type. The radiometric throughput deficiency of the telescope was further addressed through redesign, discussed later. Consequent analysis and camera testing predict good dynamic range of the redesign telescope.



a **b**

Figure 10: Extended source images for the narrow FOV (a) and the wide FOV (b)

Image quality testing showed the lens performs as predicted, showing good edge definition and low aberration. Pinhole imaging showed that most of the energy was focused within a 4 pixel cross. Roof testing confirmed good optical performance with sharp edge definition. Quantitative MTF or CTF image data analysis has not been completed at this time.

Figure 11: Wide FOV imaging of rooftop platform, neighboring building, and mountains with dual-FOV UAV telescope

The potential for spectral and spatial mixing based on leakage is addressed in laboratory tests. Minor leakage was observed in the SNR testing when viewing a very bright source. Figure 10 a) shows a very dim, almost unobservable circle to the left of the sharp white dot. This large circle is leakage from the wide-FOV path mixing with the narrow-FOV path. This magnitude of leakage is insignificant for the purpose of this UAV sensor, but a similar magnitude may be undesirable for some imaging applications. Careful filter coating design can further reduce this leakage.

MODIFIED COMPACT DUAL-FOV LWIR TELESCOPE

Because of the low contrast and grainy images described earlier, the original LWIR dual-FOV telescope was redesigned to improve SNR by factors of 3.8 and 2.2 for the wide and narrow FOV paths, respectively. Broadening the total spectral bandpass contributed to this improved second-generation design SNR. Further improvement arose by changing the refractive element substrates to materials with higher transmissions in the LWIR. Thus, we expect the redesigned dual-FOV telescope to deliver significantly better imagery compared to that shown above.

In increasing the SNR, we allowed a significant reduction in the athermal range, requiring a heater in the ball sensor. This was necessitated by the elimination of a key band-limited refractive element material that allowed for the wide athermal range in the original design. Such a tradeoff increases complexity with the addition of heaters, but improves performance with increased contrast and SNR.

SNR can be further improved by changing to a cryogenically cooled mercury-cadmium-telluride (HgCdTe) focal plane array. However, such a change would significantly increase instrument cost, weight, required power, and volume. An increase in these areas is undesirable for both small UAV and small-satellite applications. Compact, low-cost LWIR sensors are generally constrained to the use of microbolometer (or possibly ferroelectric) arrays.

COMPACT DUAL-FOV CONCEPT FOR SMALL SATELLITES

This paper has described a compact dual-FOV telescope design concept developed for small UAV applications. The design may be extended to other applications where volume and weight are limited, such as small satellites, especially those requiring both search and interrogation modes.

With careful consideration of FOV, f-number, and FPA selection, the optics and mechanical housing may be scaled to fit very small volumes. Radiometric modeling for the selected wavebands will be necessary to ensure that the final design results in adequate SNR and dynamic range performance of the sensor. Mechanical heaters may be necessary to maintain good focus over the temperature extremes anticipated for such missions.

Figures 12 a) and b) below simulates and compares 6X field-ratio images of a space object at approximately 300 meters in search (wide FOV) mode and interrogation (narrow FOV) mode, respectively.

a) Wide FOV (analogous to peripheral vision) b) Narrow FOV (analogous to foveated vision)

Figure 12: Simulation showing how two visible space images of the same object with a 6x field ratio may compare.

SUMMARY/CONCLUSION

Many small satellite applications would benefit from the capability to perform search (wide FOV), identification (narrow FOV), and interrogation of objects. Such dual-FOV capability is challenging to accomplish in small satellites due to their limited payload volumes. Often, multiple sensors or zoom-lens systems are used to gain such capability, but quickly overfill the allotted volume. This challenge is particularly severe for sensors operating in the infrared wavebands.

The described, novel, compact dual-FOV telescope design concept overcomes the volume constraints of small-satellite payloads. The design concept was developed and tested for a small UAV application. This compact LWIR dual-FOV UAV system was successfully designed and tested at Space Dynamics Laboratory in 2007. Though initial tests of the first-generation LWIR system produced low contrast, grainy images, the design met image quality requirements while maintaining its availability to UAVs and other small platforms through its low cost. Furthermore, an improved, more sensitive second-generation LWIR design was completed with analysis and camera testing predicting good dynamic range.

Our investigation recognizes that this compact design concept may be extended to small satellite applications where weight and volume are limited, but dual-FOV capability is desired. This investigation also recognizes that this concept may be applied to any waveband of interest.