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Counter Unmanned Aerial Systems Testing: Evaluation of VIS, SWIR, MWIR, and LWIR passive imagers

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Abstract

This report contains analysis of unmanned aerial systems as imaged by visible, short-wave infrared, mid-wave infrared, and long-wave infrared passive devices. Testing was conducted at the Nevada National Security Site (NNSS) during the week of August 15, 2016. Target images in all spectral bands are shown and contrast versus background is reported. Calculations are performed to determine estimated pixels-on-target for detection and assessment levels, and the number of pixels needed to cover a hemisphere for detection or assessment at defined distances. Background clutter challenges are qualitatively discussed for different spectral bands, and low contrast scenarios are highlighted for long-wave infrared imagers.

Contents

Executive Summary	7
1 Introduction and test goals	9
2 Imaging background	11
3 Imaging systems information	13
4 Unmanned aerial system information	15
5 Results	18
5.1 Comparison of spectral bands	18
5.2 Target contrast against background	19
5.3 Pixels on target evaluation	20
5.4 Background clutter evaluation	23
6 Discussion and conclusion	27

Figures

1 Spectral atmospheric transmittance versus wavelength. The VIS, SWIR, MWIR, and LWIR spectral bands are shown as defined in table 1. The spectral sensitivity of the cameras used within this test are shown.	12
2 Examples of commercially available UAS utilized in these tests. (a) shows the DJI Phantom 4 quad-copter, (b) shows the Cinestar 8 octo-copter, and (c) shows the Finwing Sabre 9000.	15
3 Visual comparison of the quad-copter, octo-copter, and fixed wing UAS morphologies in the VIS, SWIR, MWIR, and LWIR spectral bands.	18
4 Contrast percent of targets in figure 3 compared to background contrast. The Michelson definition of contrast is used in this analysis.	19
5 Images of the quad-copter UAS at different pixels-on-target values for the VIS, SWIR, MWIR, and LWIR imagers.	21
6 (a) bird in the SWIR, and (b) bird in the LWIR.	24
7 Insects as imaged by the SWIR camera. Targets averaged less than ten pixels in size, and moved quickly through the camera field of view.	24
8 Fixed wing UAS in the LWIR during landing. Target contrast against background decreases as the UAS moves into an atmospheric region of similar temperature compared to the UAS. Contrast returns after target is below thermal equivalence zone and is imaged as cooler than the background.	25
9 UAS angle above horizon versus contrast for the fixed wing Sabre UAS measured with the LWIR camera. Positive contrast indicates the target is brighter (and therefore hotter) than the background, while negative contrast indicates the target is darker (and therefore cooler) than the background. Zero contrast indicates that the UAS target is the same temperature as the background.	26

Tables

1	Definitions used in this report when describing different spectral bands.	11
2	Information regarding imaging devices utilized during tests.	13
3	Total size of data collected across all spectral bands during the week of August 15, 2016.	14
4	Information regarding UAS utilized during tests.	15
5	Estimated pixels on UAS target necessary for detection or assessment.	22
6	Using the data from table 5, and setting a target size of 0.5 meters and pixel size of 15 μm , distances at which detection or assessment should occur were set and focal lengths necessary to achieve this pixel-on-target value were calculated. Additionally, using the instantaneous field of view of each pixel, the total number of pixels on a hemisphere required to meet the detection or assessment distance were calculated.	23

Executive Summary

Testing of visible (VIS), short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR) imagers was conducted using a quad-copter, octo-copter, and fixed wing unmanned aerial systems (UAS) targets during the week of August 15, 2016, at the Nevada National Security Site. The goal of this test was to determine the positive and negative attributes of commercial off the shelf (COTS) imagers at different spectral bands.

We determined that LWIR imaging provided the best contrast of targets against background, followed second by VIS imagers. MWIR showed some promise to reject nuisance targets like birds, but needs additional testing to confirm. SWIR imaging performed poorly for the three UAS tested, and does not appear a likely candidate for a counter UAS (CUAS) imaging element.

Using pixels-on-target estimates enabling detection or assessment, fixed distances were set and imager parameters enabling detection or assessment at those distances were reported. Our analysis estimates that a 1 gigapixel imager could enable hemispherical detection and assessment of a 0.5 meter UAS at approximately 1750 meters for detection and 750 meters for assessment.

Nuisance targets such as birds or insects were captured during the testing phase. All spectral bands contain nuisance targets that could cause false alarms, especially using simple assessment algorithms that only search for objects greater than a few pixels moving across the background. Background clutter and nuisance targets appear minimized in the LWIR and MWIR, but further testing is needed to validate.

A LWIR effect causing low contrast or zero contrast of UAS at certain angles above the horizon was observed and discussed. An example of a UAS target briefly disappearing in the LWIR is provided, and the thermal equivalence angle is reported.

We recommend the further investigation of LWIR and MWIR imagers to understand their behavior when imaging non-UAS targets such as birds, dust storms, or vegetation. Additionally, we recommend the evaluation of these systems during night operation. We also recommend the evaluation of other optical sensing systems to assist with positive UAS assessment, such as LWIR polarimetric imaging. These evaluations may not require a flying UAS, and therefore could take place at Sandia National Laboratories.

1 Introduction and test goals

Three primary steps are required by counter unmanned aerial system (CUAS). They are defined as:

1. **Detection** – The collection of some phenomenological information captured by a sensor. This step does not necessarily denote assessment (that is, differentiation of nuisance alarm versus target).
2. **Assessment** – Analysis of data received in the detection phase, with the goal being to separate real targets from highly cluttered, noisy background data.
3. **Denial of mission/neutralization** – Once a target is positively assessed in the previous step, additional action must be taken to deny mission success, including the potential for target neutralization.

This study evaluates passive commercial off the shelf (COTS) imaging systems within the visible (VIS), short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR) wavebands for the purpose of detection and assessment of UAS. The tests discussed in this document took place at the Nevada National Security Site (NNSS), from August 15, 2016, to August 18, 2016.

Three UAS morphologies were investigated: a quad-copter, octo-copter, and fixed wing system. All devices were composed of plastics, Styrofoam, and some metallic components. Targets ranged from tens of meters to greater than five kilometers from the imaging systems.

Tests were conducted to answer the following questions:

- Is there a clear best performer amongst the VIS, SWIR, MWIR, and LWIR imaging spectral bands?
- What notional pixels-on-target are required to detect and assess the presence of a UAS, and at what distance is this achievable?
- What is the contrast of background clutter such as birds or insects within the VIS, SWIR, MWIR, and LWIR imaging bands?
- Do any spectral bands fail to enable the detection of a UAS under nominal conditions?

2 Imaging background

The purpose of this test was to evaluate the capability of commercial off the shelf (COTS) passive imaging systems of different spectral sensitivities to image unmanned aerial systems (UAS). Four distinct spectral bands were evaluated in this study; visible (VIS), short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR). The wavelengths covered by these regions are shown in table 1.

Spectral Band Name	Shorthand	Wavelength region	Sensor types
Visible	VIS	0.4 μm to 0.7 μm	Si
Short-wave infrared	SWIR	1.0 μm to 3.0 μm	InGaAs
Mid-wave infrared	MWIR	3.0 μm to 5.0 μm	InSb, HgCdTe
Long-wave infrared	LWIR	8.0 μm to 12.0 μm	HgCdTe, microbolometers

Table 1. Definitions used in this report when describing different spectral bands.

It is important to differentiate between reflected photons and self-emitted photons, and clarify these two concepts within the context of commercially available imaging systems.

Reflected photons consists of light emitted from a source, reflected off the UAS, and captured by the passive imaging device. The VIS and SWIR imaging systems rely upon reflected photons, either from the sun or a terrestrial light. Objects that appear highly reflective in the VIS bands may not appear so in the SWIR, especially if the target contains dyes designed for the VIS spectrum. Thus, a comparison between VIS and SWIR imaging systems is useful to determine if one spectral band is more sensitive to the materials composing a UAS, and if one band enables earlier detection or assessment in the presence of environmental clutter like insects, birds, and vegetation.

Self-emitted photons originate from all objects with a temperature above absolute zero. The spectral location at which the majority of self-emitted photons are located can be calculated using Wien's law.

$$\lambda_{max} = \frac{\sim 2900[\mu\text{m K}]}{T_{obj}[K]} \quad (1)$$

Using this equation, and assuming we have an object at 100 °F (311 K), we can calculate the wavelength of the peak self-emitted photons as 9.3 μm , well within the LWIR spectral band. Both the MWIR and LWIR bands rely primarily upon self-emitted photons from objects in the scene, and therefore can be used without the presence of solar illumination or terrestrial lights.

¹The precise numerator coefficient is $2.8977729 * 10^3$ m K, but this coefficient is useful for quick caluclations.

The spectral band definitions used in table 1, as well as the spectral sensitivity ranges of the SWIR, MWIR, and LWIR cameras are plotted in figure 1

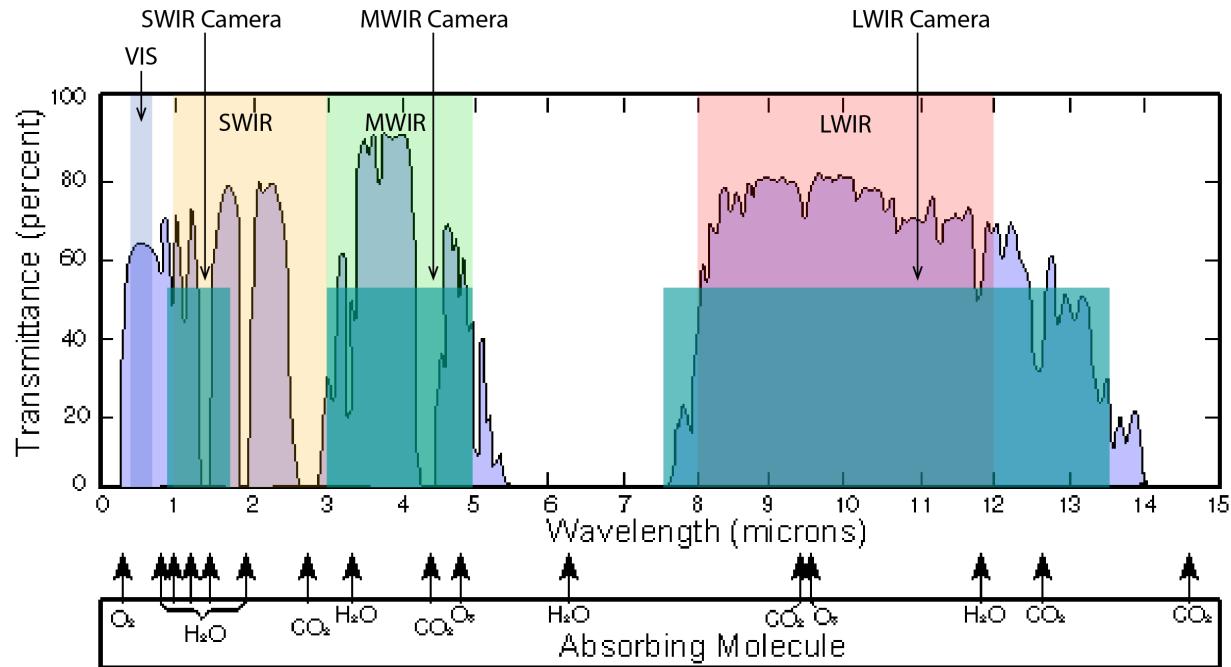


Figure 1. Spectral atmospheric transmittance versus wavelength. The VIS, SWIR, MWIR, and LWIR spectral bands are shown as defined in table 1. The spectral sensitivity of the cameras used within this test are shown.

Figure 1 shows that this is not an exhaustive study of the best spectral band from 0.4 μm to 12.0 μm . Rather, this study is intended to examine the COTS offerings for different spectrally sensitive imaging systems and determine how these systems apply to detection and assessment of UAS.

3 Imaging systems information

The UAS imaging test was comprised of five visible imaging systems, one cooled SWIR device, one cooled MWIR device, and one uncooled LWIR device. Detailed information regarding the focal lengths, sensor sizes, and lens models are included in table 2.

Spectral region	Sensor size [pixels]	Focal length
VIS	1920 x 1200	12 mm
VIS	1944 x 1104	23 mm
VIS	2992 x 1680	50 mm
VIS	1376 x 1032	50 mm
VIS	1280 x 1024	35 mm
SWIR	640 x 512	50 mm
MWIR	640 x 512	50 mm
LWIR	640 x 480	35 mm

Table 2. Information regarding imaging devices utilized during tests.

The five visible imaging systems tested included previous generation security cameras as well as newer systems with higher resolution and larger dynamic range than past imagers. A variety of focal lengths were chosen for the visible imagers to simultaneously capture different pixel on target values.

The LWIR imaging device utilizes a microbolometer detector. These cameras represent a less expensive, security-oriented LWIR product. They come embedded in environmental housings with a single 35 mm focal length lens. Since this is a microbolometer based imager, the sensor is uncooled and can operate in the large temperature differentials expected at the test location. However, the sensor noise present in a microbolometer imager is typically larger than that present in a cooled LWIR imager.

The SWIR camera and MWIR camera are often used in scientific and engineering settings for low-noise imaging. These cameras used fixed lenses of 50 mm focal length. Both cameras utilized cooled detector arrays. For practical reasons, these cameras remained inside the testing facility and were positioned such that a window could be opened or closed to enable recording of the UAS targets.

Spectral band	Total Data
VIS	700.0 GB
SWIR	73.5 GB
MWIR	149.5 GB
LWIR	7.2 GB
Total	930.2 GB

Table 3. Total size of data collected across all spectral bands during the week of August 15, 2016.

A significant quantity of data was collected during the testing period, as shown in table 3. Data from the visible cameras was recorded using the Milestone video management software. Data from the SWIR and MWIR imagers was recorded using vendor-supplied software. Data from the LWIR camera was recorded using the ffmpeg software to convert an RTSP connection to file.

In regards to future testing, we strongly recommend the separation of any SWIR and MWIR cameras to independent computer systems, as there appeared to be networking conflicts between these cameras and the Milestone video management software used to record visible camera data.

We also recommend the inclusion of pan-tilt-zoom (PTZ) cameras placed above the testing facility. Performing tests exclusively with fixed imagers increases test time and requires more precise flying of UAS such that the target is captured in all fields-of-view. PTZ systems may offer functional benefits and flexibility that could increase usable test data.

4 Unmanned aerial system information

Three UAS were flown during the test period; a DJI Phantom 4 quad-copter, FreeFly Systems Cinestar 8 octo-copter, and Finwing Sabre 1900. Information regarding these systems is shown in table 4. Images of the UAS are shown in figure 2.

UAS Name	Dimensions	Approximate Flight Duration
DJI Phantom 4	170 x 144 x 193 mm	28 minutes
Cinestar 8 octo-copter	1000 x 900 x 350 mm	30 minutes
Finwing Sabre 1900	Wing Span: 1900 mm Length: 1320 mm	60-120 minutes

Table 4. Information regarding UAS utilized during tests.

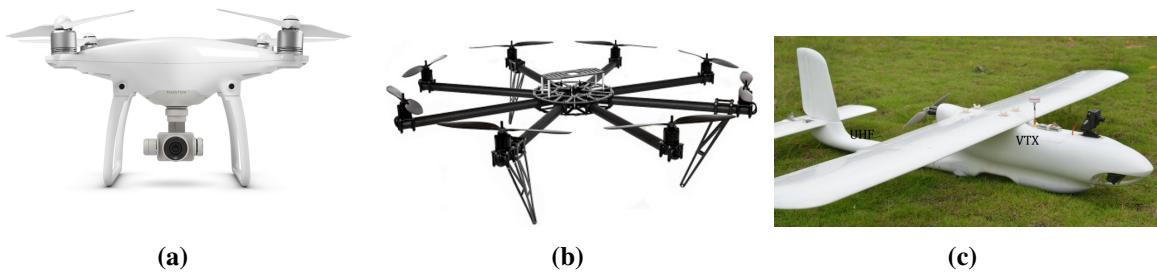


Figure 2. Examples of commercially available UAS utilized in these tests. (a) shows the DJI Phantom 4 quad-copter, (b) shows the Cinestar 8 octo-copter, and (c) shows the Finwing Sabre 9000.

5 Results

5.1 Comparison of spectral bands

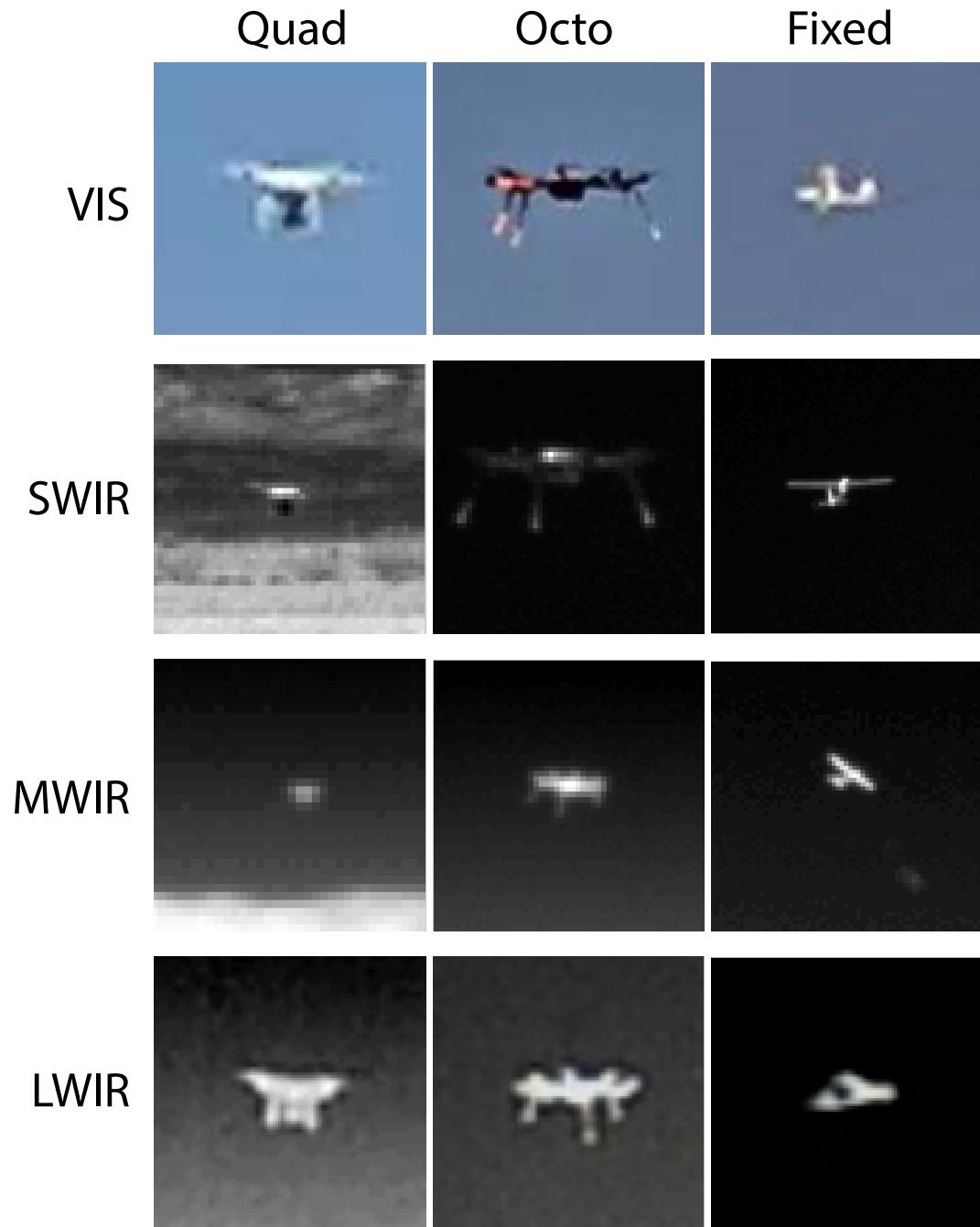


Figure 3. Visual comparison of the quad-copter, octo-copter, and fixed wing UAS morphologies in the VIS, SWIR, MWIR, and LWIR spectral bands.

Figure 3 shows the VIS, SWIR, MWIR, and LWIR images of the octo-copter, quad-copter, and fixed wing UAS. Visible imagery tended to capture the target well when against the sky background, but performs poorly when the target is against highly cluttered backgrounds near the horizon. SWIR imagery captured the quad-copter and fixed wing UAS well, but failed to capture the struts of the octo-copter. This is likely due to the carbon fiber material composing the body of the octo-copter. SWIR imagery is primarily relying upon reflected photons from the sun, and likely suffers in low-light conditions. MWIR imagery performs well, but the particular camera used in this test had fewer pixels on target than other devices tested. LWIR captures the quad, octo, and fixed wing morphologies well, but suffers when targets are flown near the horizon or against background objects of the same temperature, such as mountains or hills.

5.2 Target contrast against background

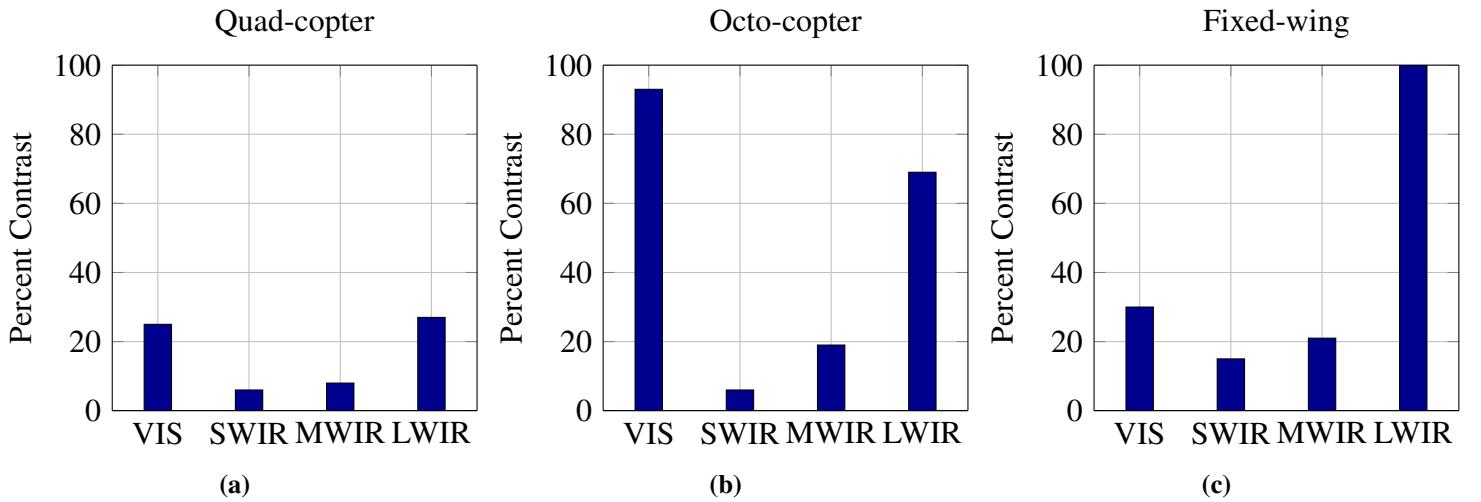


Figure 4. Contrast percent of targets in figure 3 compared to background contrast. The Michelson definition of contrast is used in this analysis.

Figure 4 shows the percentage contrast of the targets from figure 3 against the background. This data attempts to determine which spectral band enables the greatest contrast difference between targets and background.

The quad-copter reflects well in the VIS, but the background sky also highly reflects scattered sunlight, which yields a moderate contrast value. The SWIR signal is lower contrast than the MWIR, which itself has lower contrast than the LWIR, the best spectral band to differentiate the quad-copter from the background sky.

The octo-copter shows a similar trend as the quad-copter, with the exception of a larger VIS

contrast. This is due to the black, highly absorbing material composing the majority of the octo-copter. The very dark target against the sky background yields a high contrast difference.

The fixed wing shows similar trends, with SWIR, MWIR, and LWIR increasing in contrast. The high contrast value in the LWIR is due to the target flying against the cold sky, and moderate image processing on the LWIR camera that reduces noise of the background.

This analysis would indicate best to worst spectral bands for the detection of UAS targets is LWIR, VIS, MWIR, and SWIR. However, this may not be the case in a practical CUAS system. Clutter, such as birds, debris, and dust, appears different in each spectral band and environmental specific conditions may guide a system towards a certain spectral band even if the contrast of the target against the background is lower than other spectral regions.

5.3 Pixels on target evaluation

Figure 5 shows the quad-copter imaged by the VIS, SWIR, MWIR, and LWIR systems at different pixel-on-target values.

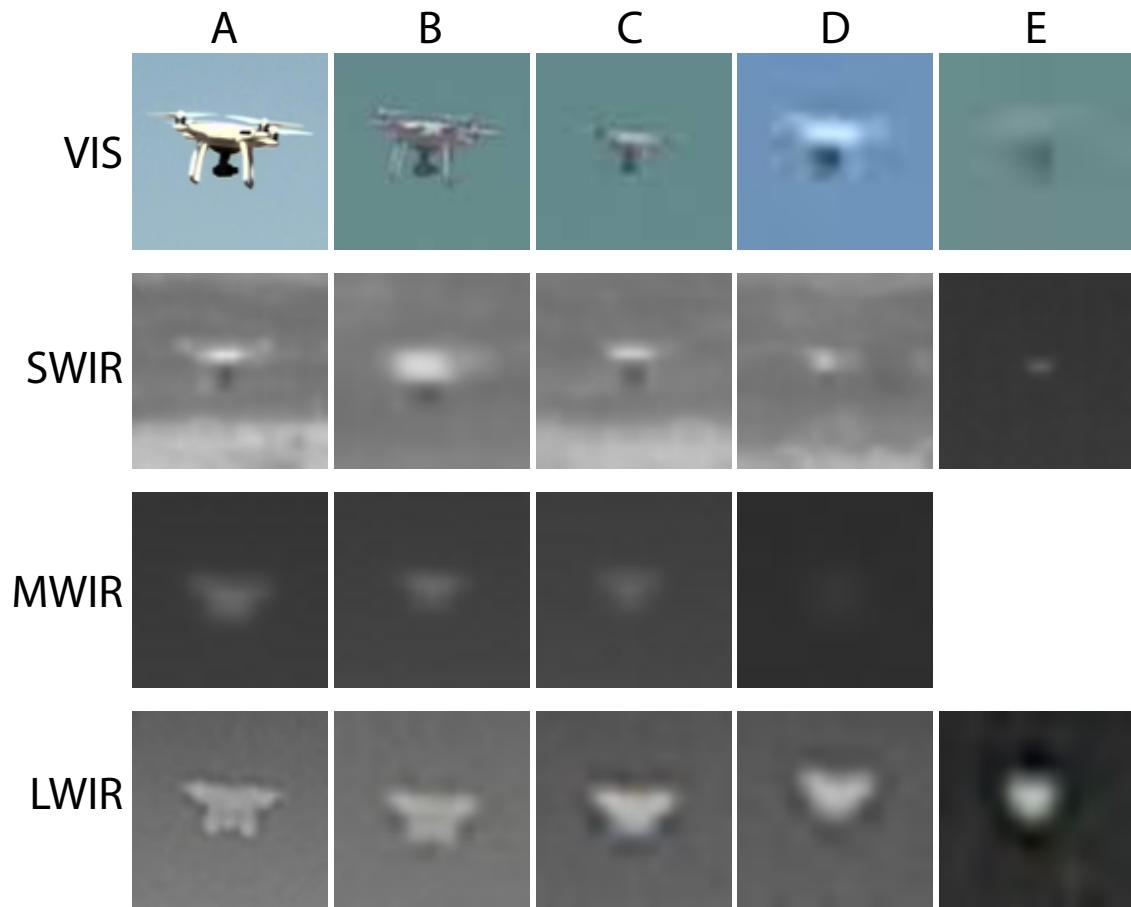


Figure 5. Images of the quad-copter UAS at different pixels-on-target values for the VIS, SWIR, MWIR, and LWIR imagers.

Based upon the data shown in figure 5, estimated detection and assessment pixels on target are calculated for the different spectral bands in table 5. These values should be taken as approximations, and further testing under varying conditions is needed before a more precise pixels on target number can be found.

Spectral band	Detection Pixels On Target	Assessment Pixels On Target
VIS	6 pixels (Fig. 5 Image E)	17 pixels (Fig. 5 Image D)
SWIR	8 pixels (Fig. 5 Image B)	13 (Fig. 5 Image A)
MWIR	8 pixels (Fig. 5 Image B)	15 pixels ^a
LWIR	5 pixels (Fig. 5 Image D)	14 pixels (Fig. 5 Image A)
Mean	7 pixels	15 pixels

^aNote that figure 5 MWIR Image A has 11 pixels on target. We believe this too low a number for assessment, but due to the large field of view of the MWIR camera tested we did not capture DJI Phantom 4 targets with greater pixel on target values.

Table 5. Estimated pixels on UAS target necessary for detection or assessment.

Using an average detection pixels on target of 7 pixels, and an average assessment pixels on target of 15 pixels, it is possible to evaluate an arbitrary distance at which the system must detect or assess a target of a given size. The focal length needed to project the necessary number of pixels onto a target at the desired distance can also be calculated.² Additionally, the individual pixel solid angle subtended upon a sphere can be determined, and the total number of pixels needed to observe a hemisphere can be found. These calculations are presented in table 6.

²Note that a target size and detector pixel size must be chosen to perform this calculation. A 0.5 meter target and 15 μm pixel size were utilized in our calculations.

Distance [m]	Camera focal length for detection [mm]	Camera focal length for assessment [mm]	Gigapixels for hemispherical detection	Gigapixels for hemispherical assessment
100	21	45	0.004	0.018
250	52.5	112.5	0.024	0.1125
500	105	225	0.100	0.45
750	157.5	337.5	0.220	1.0125
1000	210	450	0.400	1.8
1500	315	675	0.880	4.05
2000	420	900	1.5	7.2
5000	1050	2250	9.8	45.0

Table 6. Using the data from table 5, and setting a target size of 0.5 meters and pixel size of 15 μm , distances at which detection or assessment should occur were set and focal lengths necessary to achieve this pixel-on-target value were calculated. Additionally, using the instantaneous field of view of each pixel, the total number of pixels on a hemisphere required to meet the detection or assessment distance were calculated.

The focal lengths estimated for detection and assessment are reasonable, though focal lengths of over 500 mm can be difficult and expensive to acquire for certain spectral bands. An important point to note is the 1 gigapixel threshold, which represents a just-achievable capability using current technology. These calculations estimate that detection is achievable for a system out to approximately 1750 meters if long focal length lenses and large detectors are utilized in a gigapixel sensor. Assessment appears achievable using 1 gigapixel at approximately 750 meters. Recent investment in multi-sensor gigapixel imagers may be a reasonable path of investigation for UAS detection via passive sensors.

5.4 Background clutter evaluation

Birds

Several birds were observed throughout the course of testing. Images from the SWIR and LWIR are shown in figure 6.



Figure 6. (a) bird in the SWIR, and (b) bird in the LWIR.

Bird targets represent a particularly challenging nuisance type. As evident from figure 6 (a), birds can appear similar to fixed wing UAS. Birds were observed on the VIS, SWIR, and LWIR, and to a much lesser extent, the MWIR.

Insects

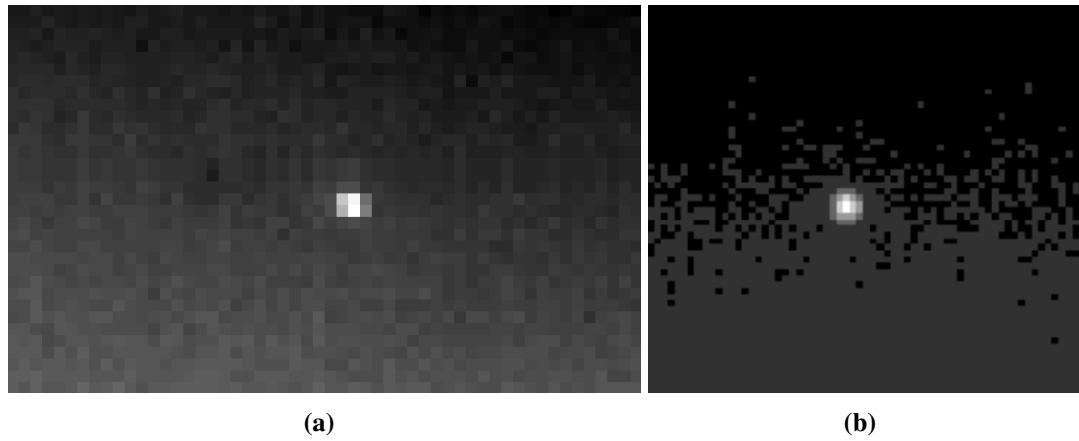


Figure 7. Insects as imaged by the SWIR camera. Targets averaged less than ten pixels in size, and moved quickly through the camera field of view.

The SWIR camera captured numerous small, bright, and fast moving targets. We theorize these are flying insects near the camera that strongly reflect in the SWIR. The fast motion, small size, and high reflectivity will likely cause alarms for automated systems using SWIR imagery.

Temperature equivalence angle

Targets of different temperatures will image at different digital values in a LWIR imager. Therefore, LWIR imager are only effective if the target being imaged is at a different temperature than the background. UAS targets are typically higher temperature than that of the sky, but as the UAS flies closer to the horizon the thermal background increases in temperature. Practically, this results in an angular position above the horizon at which UAS appear invisible to a LWIR camera. Figure 8 shows a series of sequential images taken of the fixed wing Sabre UAS descending in altitude to land. Targets well above the horizon are imaged with high contrast (figures 8 (a) through (c)), but as the UAS descends it moves into higher temperature backgrounds and contrast is reduced (figures 8 (d) and (e)). At a certain position, contrast is entirely lost, and the UAS cannot be detected against the background (figures 8 (f)). As the UAS continues to descend, contrast inverts and the target becomes cooler than the background (figures 8 (g) and (h)).

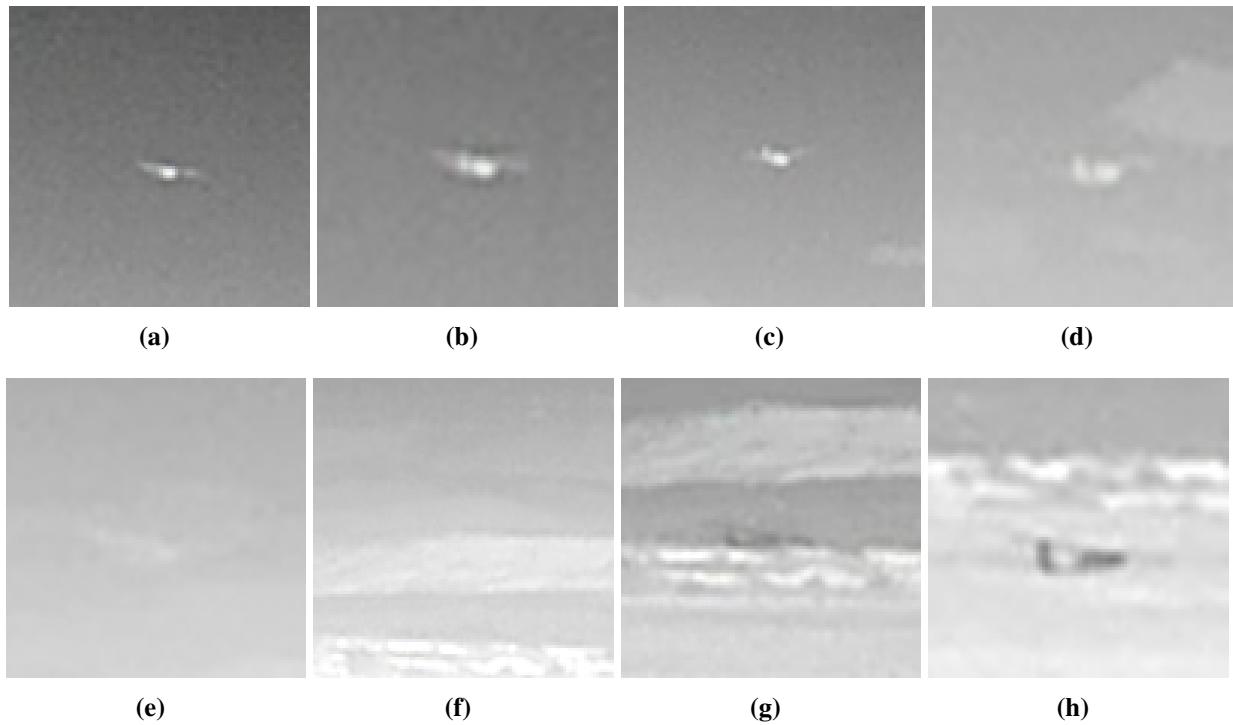


Figure 8. Fixed wing UAS in the LWIR during landing. Target contrast against background decreases as the UAS moves into an atmospheric region of similar temperature compared to the UAS. Contrast returns after target is below thermal equivalence zone and is imaged as cooler than the background.

The contrast of the targets shown in figure 8 are plotted versus angle above horizon in figure 9.

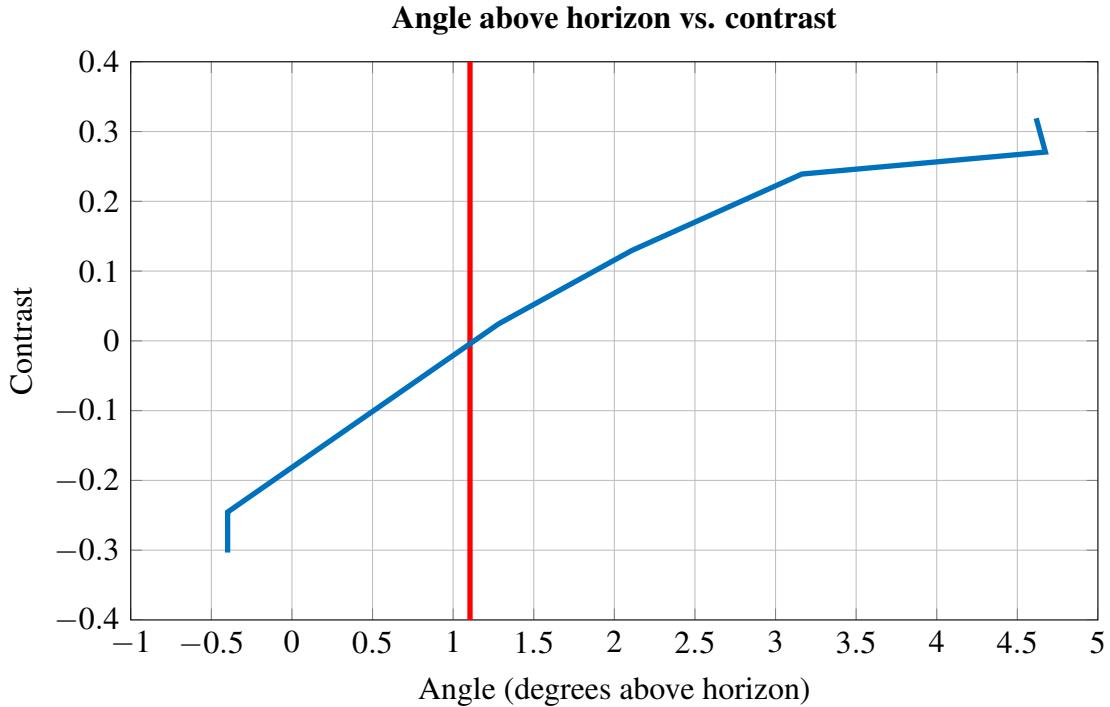


Figure 9. UAS angle above horizon versus contrast for the fixed wing Sabre UAS measured with the LWIR camera. Positive contrast indicates the target is brighter (and therefore hotter) than the background, while negative contrast indicates the target is darker (and therefore cooler) than the background. Zero contrast indicates that the UAS target is the same temperature as the background.

We define the angle above the horizon at which target contrast reaches zero as the temperature equivalence angle (TEA). The TEA value will vary based on the temperature of the target, and the background environment temperature. In our particular test, the fixed wing Sabre TEA was measured as approximately 1.1° above the horizon. Therefore, targets at 1000 meters distance from the LWIR camera will be measured with zero contrast at approximately 19 meters above the horizon.

If thermal imaging systems are used as a primary component to detect or assess the presence of a UAS, the system TEA must be evaluated for different targets and at different environmental background temperatures to establish ingress angles that may present challenges to a CUAS system.

6 Discussion and conclusion

VIS imagers work best with targets located against a uniform background, and require external light sources. Because of this, we believe VIS imagers will be less useful for detection and assessment of UAS unless required by a human for assessment after detection by an additional sensor.

SWIR imagers do not appear to be good candidates for UAS detection due to their reliance of external light sources, sensitivity to SWIR absorbing materials used on UAS, and frequent capture of fast and bright insects.

LWIR imaging may be best suited for detection and assessment of UAS. However, nuisance sources such as birds will also be captured in the LWIR, and certain angles above the horizon may present challenges due to temperature equivalence of the target and background. MWIR may offer better clutter rejection, while still relying upon self-emitted photons from targets.

We estimate that 7 pixels on target are needed for detection, and 15 pixels on target are needed for UAS assessment. Over 1000 meter detection and assessment may be achievable with 1 to 2 gigapixel imagers, but this represents a significant engineering challenge, especially in the LWIR.

We recommend the following:

- Further investigation between the MWIR and LWIR to evaluate nuisance targets and performance in highly cluttered environments
- Evaluation of these systems under night conditions
- Investigation of other optical sensing systems such as LWIR polarimetric imagers to determine detection and assessment capabilities

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