ARL-TR-8475 ● AUG 2018

US Army Research Laboratory

Calibrated Long-Wave Infrared (LWIR) Thermal and Polarimetric Imagery of Small Unmanned Aerial Vehicles (UAVs) and Birds

by Kristan P Gurton

NOTICES

Disclaimers

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
August 2018	Technical Report	1 July 2018–1 August 2018

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Calibrated Long-Wave Infrared (LWIR) Thermal and Polarimetric Imagery of Small Unmanned Aerial Vehicles (UAVs) and Birds	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Kristan P Gurton	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
US Army Research Laboratory ATTN: RDRL-CIE-S 2800 Powder Mill Road Adelphi, MD 20783-1138	ARL-TR-8475
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We report a series of both radiometric and polarimetric calibrated long-wave infrared (LWIR) imagery of a variety of small/micro-sized unmanned aerial vehicles (UAVs) and birds recorded at Ft. Sill, OK, during the April 5–6 2017 time period. The goal of this report is to produce a set of well-calibrated imagery, both conventional LWIR thermal (watts/cm2-sr) and its corresponding polarimetric imagery (percent radiance polarized), in order to evaluate the ability for distinguishing between small UAVs and birds of similar size and dimensions. Thermal and calibrated Stokes images (S0, S1, and S2) and the degree-of-linear-polarization were recorded using a research grade LWIR polarimetric camera system, which is based on a spinning-achromatic-retarder optical design. Target imagery was recorded at various distances ranging from 0.5–4.0 km during various periods of the diurnal cycle. Regions of interest (ROI) for each image were generated that encompassed either the target region only or the corresponding background (i.e., target ROI and background ROI), respectively.

15. SUBJECT TERMS

Polarimetric, LWIR, UAV signature, bird, radiance, imagery, longwave infrared, thermal imaging

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Kristan P Gurton
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER (Include area code)**
Unclassified	Unclassified	Unclassified	UU	28	301-394-2093

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

Currently, agencies within the Department of Defense (DOD) and the private sector are trying to develop techniques capable of detecting the presence of small unmanned aerial vehicles (UAVs) at ranges on the order of 1–5 km.[1] Often complicating this effort is the presence of small birds of similar dimensions that are frequently mistaken to be small UAVs when imaged using various methodologies, such as visible, short-wave infrared (SWIR) and thermal imaging.

Our initial study was limited to long-wave infrared (LWIR) thermal imaging that in theory should be effective for both day and night time operation. The goal was to record a preliminary set of calibrated radiometric and polarimetric images in which both small UAVs and birds were present in the scene. Targets (i.e., UAV and/or birds) within each image were segmented and regions of interest (ROI) were generated by tracing a circumference around the object. Pixel values were then averaged to yield both a radiometric value (watts/cm^2-sr) and a corresponding polarimetric value (percentage linearly polarized) in order to quantify similarities and differences between "generic" bird and UAV signatures. Although LWIR radiometric thermal signature capture and analysis techniques are very mature and well understood, thermal polarimetric methods and analysis are less developed. For the polarimetric analysis presented here, we will use the well-accepted Stokes image methodology that effectively yields the percentage of the overall radiance emitted/reflected from the object that is linearly polarized.

2. Stokes Image

The most common approach for measuring the polarization state for emitted or reflected light is to measure the Stokes parameters: S0, S1, S2, and S3. For imaging applications these Stokes parameters are determined on a pixel-by-pixel basis in order to reconstruct a 2-D image. The Stokes parameters are determined by measuring the intensity of radiance that is projected through a polarizer/wave-plate pair that are oriented at various angles in order to measure the intensity of a particular state.

The Stokes images S0, S1, S2, and S3 are defined by Eqs. 1–4:

$$S1 = I(0) - I(90) \ (\text{w/sr-cm}^2), \quad (1)$$

$$S2 = I(+45) - I(-45) \ (\text{w/sr-cm}^2), \quad (2)$$

$$S3 = I(R) - I(L) \ (\text{w/sr-cm}^2), \quad (3)$$

where I(0), I(90), I(+45), and I(–45) represent the measured radiant intensity of the linear states (measured relative to the vertical), at angles 0°, 90°, +45°, and –45°, respectively, and I(R) and I(L) represent right- and left-handed circularly polarized radiant states. The total radiance, S0, image (often thought of as just the intensity image) is defined as,

$$S0 = \sqrt{S1^2 + S2^2 + S3^2} \ \text{(w/sr-cm}^2\text{)}, \quad (4)$$

and the degree-of-total-polarization parameter/image is defined as,

$$DoP = \frac{\sqrt{S1^2 + S2^2 + S3^2}}{S0},$$

$$\text{where} \quad 0 \leq DoP \leq 1. \quad (5)$$

However, for most applications that involve remote passive polarimetric imaging in the thermal IR, S3 is very small and rarely measurable and thus taken to be approximately zero. As a result, Eq. 5 is reduced to the more common degree-of-linear-polarization (DoLP) parameter/image and is defined as,

$$DoLP = \frac{\sqrt{S1^2 + S2^2}}{S0}. \quad (6)$$

There are a variety of optical approaches/methods implemented in various polarimetric camera designs appropriate for polarization state filtering and analysis in the thermal IR.[2] Examples include division-of-time approach, which uses a spinning-achromatic-retarder (SAR) arrangement, a division-of-amplitude (DoA) in which a polarized beam-splitting-plate is used to project different polarization states of the same scene onto one, two, or more focal-plane-arrays (FPA), and the division-of-focal-plane (DoFP) design in which micro-polarizers oriented at different angles are attached to individual pixels that make up the FPA. An example of an LWIR thermal image (left) and its corresponding polarimetric DoLP image (right) are shown in Fig. 1.

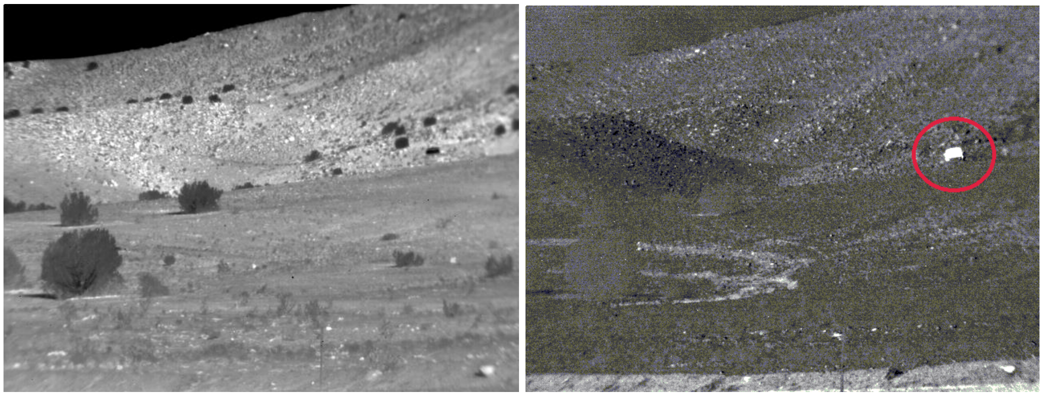

Fig. 1 Example conventional LWIR thermal image (left) and resultant LWIR polarimetric image (right) in which a vehicle at ambient temperature is parked on a hillside. Shown is a key aspect for using thermal polarimetric imaging for low-observable targets in which the vehicle is difficult to discern from the background in the conventional thermal image (left) while the polarimetric image clearly shows the "man-made" object (right).

3. LWIR Polarimetric Camera

Imagery and video presented for this study were recorded using an LWIR polarimetric camera that was based on a division-of-time, SAR approach.[3–5] The polarimetric camera consisted of a Stirling-cooled, 640 × 480 array-size, Mercury Cadmium Telluride (MCT) FPA with a spectral response range of 7.5–11.1 µm. The camera was fitted with an Ophir SupIR duel field-of-view (FOV) LWIR objective.

The polarimetric filtering system uses a rapidly spinning phase-retarder that is mounted in series with a linear polarizer. A sequence of images are recorded at 120-Hz frame rate where each image represents a particular polarization state. A Fourier modulation technique is applied to the pixel readout in which a Fourier series expansion is calculated for each channel. Finally, the expansion is inverted to yield the Stokes-image parameters in terms of Fourier coefficients, which are used to generate the desired Stokes image as described in Eqs. 1–6. Figure 2 highlights key features and specifications for the LWIR polarimetric camera.

Parameter	Value
FPA Format	640 x 480
Narrow FOV	3.3° x 2.5°
Wide FOV	10.6° x 7.9°
Pixel Size	15 x 15 µm
IFOV at 1 km	4” (Narrow FOV) 12” (Wide FOV)
Sensor Dimensions (mm)	10”L x 6”W x 7.5”H
Sensor weight	31 lbs
Power	24V; 1.5 A

Fig. 2 Photograph and specifications for the LWIR thermal/polarimetric SAR camera system

4. Calibrated LWIR and Polarimetric Imagery

The majority of the LWIR and polarimetric image/video was recorded at Ft. Sill, OK, during a two-day period on April 5–6, 2017. During the test period, a variety of small UAVs were flown randomly so that all field-test participants, positioned at different locations and working on different schedules, could record target imagery at will throughout the day. As a result, recording desired image sets was somewhat “hit-or-miss” depending on whether the sensor was operational during a particular flight. This problem was exacerbated when it came to recording imagery of birds, since they flew on an unpredictable schedule and at random locations. Nevertheless, we were able to generate a reasonably good set of LWIR thermal and polarimetric images of both birds and similarly sized UAVs for a variety of target locations at different orientations. During the two-day study we focused on two UAV platforms that were made readily available: a small handheld quadcopter termed InstantEye, and a larger prototype UAV termed Joint Tactical Aerial Resupply vehicle (JTARV), both shown in Fig. 3.

Fig. 3 Photographs of the two UAVs imaged during the test. The UAV on the left is a prototype OEM vehicle (often termed a JTARV), which is approximately 1 m in length. The smaller UAV on the right is a commercially available drone called InstantEye, which measures approximately 12 inches in length.

During the two-day field test temperatures ranged from a low of 45 °F to a high of 73 °F with average relative humidity of 52%. Clear skies prevailed throughout the two-day period with the exception of an early morning test period on April 5 in which a ridge of Stratocumulus clouds appeared for approximately a 3-h period. Average sun rise for the two-day period was 7:14 AM.

Presented in the following figures are various examples of paired greyscale image sets of registered LWIR thermal and polarimetric images in calibrated units (watts/cm^2-sr) and DoLP (%), respectively. Included in each image set is a full FOV image accompanied by a magnified ROI for each particular target (i.e., bird or small UAV). ROIs were judiciously chosen to include only pixels that encompassed the body of the target region.

Figures 4–7 show example thermal/polarimetric image pairs of birds recorded during the two-day period. It should be noted that Figs. 6 and 7 were recorded at 7:14 AM (sunrise) on April 6 in order to evaluate low-detection periods of the diurnal cycle.[6]

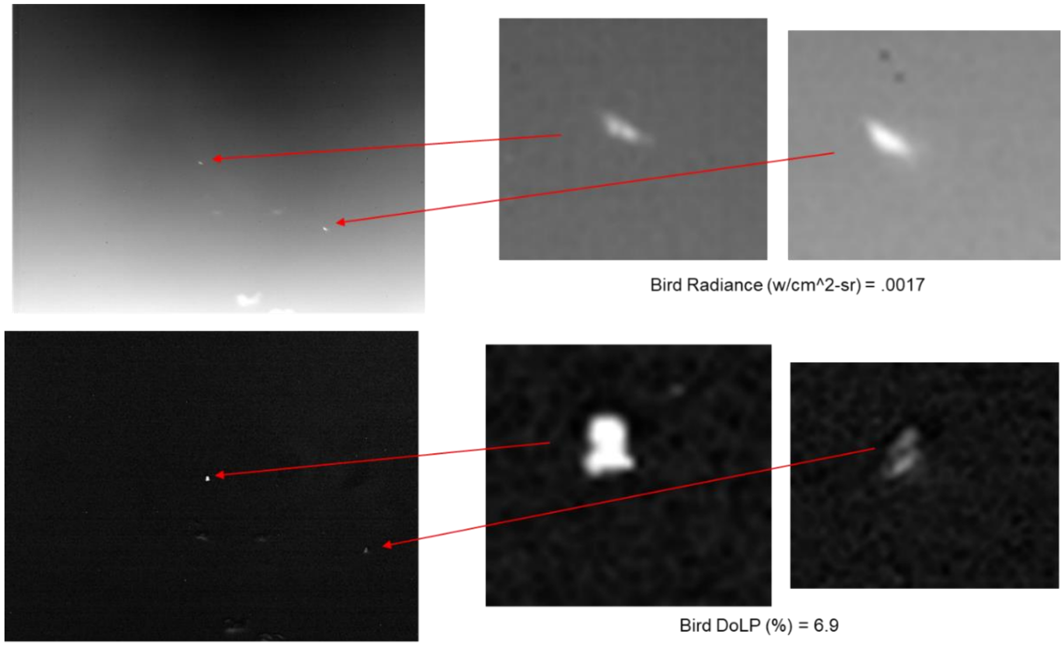

Fig. 4 Top (left) full FOV thermal and corresponding magnified image (right) of bird(s) against a cold sky with recorded radiance of 0.0017 w/cm2-sr. Bottom (left) shows the resultant full FOV LWIR polarimetric DoLP image and corresponding magnified image (right) of the same bird(s) displaying a DoLP value of 6.9%. Approximate range is 3.5 km.

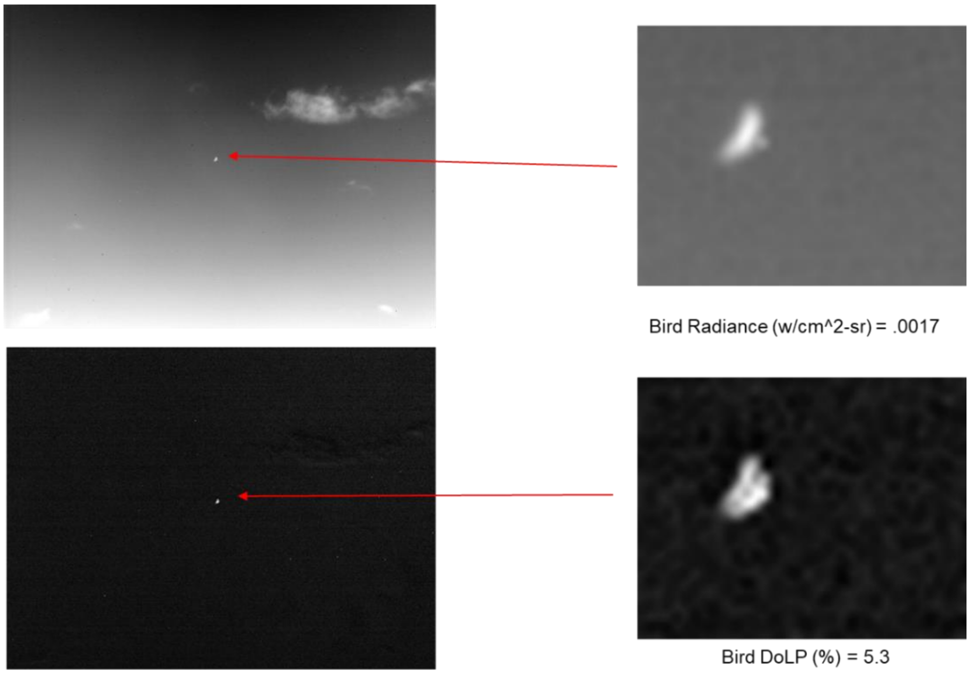

Fig. 5 Top (left) full FOV thermal and corresponding magnified image (right) of a bird against a cold sky with recorded radiance of 0.0017 w/cm2-sr. Bottom (left) shows the resultant full FOV LWIR polarimetric DoLP image and corresponding magnified image (right) of the same bird displaying a DoLP value of 5.3%. Approximate range is 3.5 km.

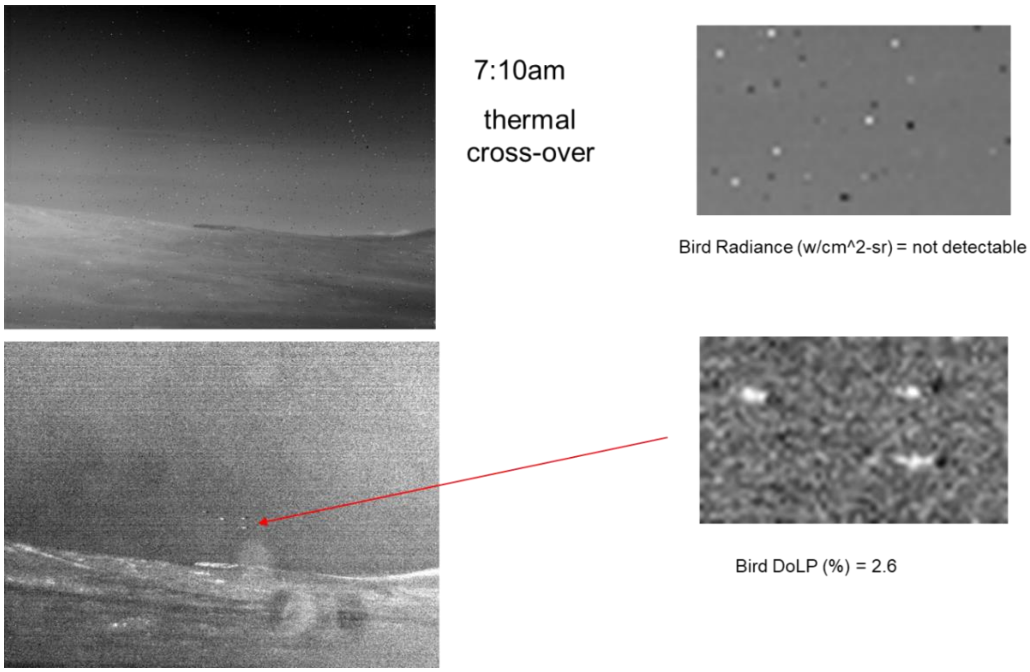

Fig. 6 Early morning April 6, 2017, 7:10 AM (sunrise 7:14 AM) during thermal cross-over period. Conventional thermal LWIR (top left) flying birds not visible. Resultant LWIR polarimetric image (bottom) showing three flying birds with DoLP value 2.6%. Approximate range is 3.75 km.

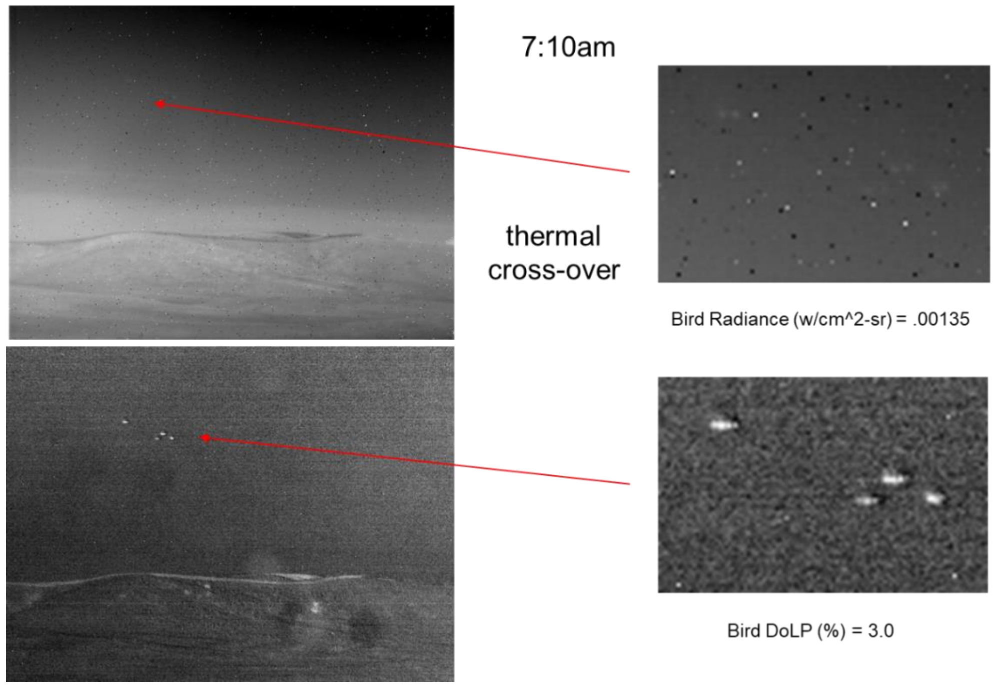

Fig. 7 Early morning April 6, 2017, 7:10 AM (sunrise 7:14 AM) during thermal cross-over period. Conventional thermal LWIR (top left) flying birds near minimum detection limit of 0.00135 w/cm^2-sr. Resultant LWIR polarimetric image (bottom) clearly showing four flying birds with DoLP value 3.0%. Approximate range is 3.75 km.

Figures 8–10 show the thermal/polarimetric image sets for the small InstantEye UAV. Again, note that images shown in Figs. 9 and 10 were recorded during the morning of April 6 during the dawn inversion period in which thermal contrast is low.

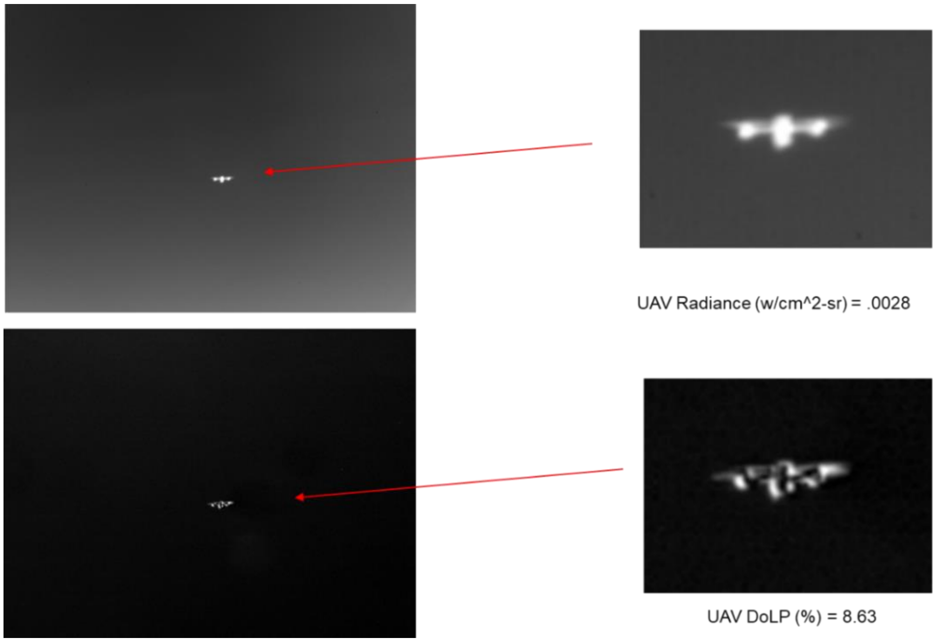

Fig. 8 **Mini-drone InstantEye flown April 6, 2017, imaged against cool sky. Conventional LWIR thermal image (top) with measured radiance value 0.0028 (w/cm^2-sr). Corresponding LWIR polarimetric image (bottom) with measure DoLP value 8.63%. Approximate range is 1.5 km.**

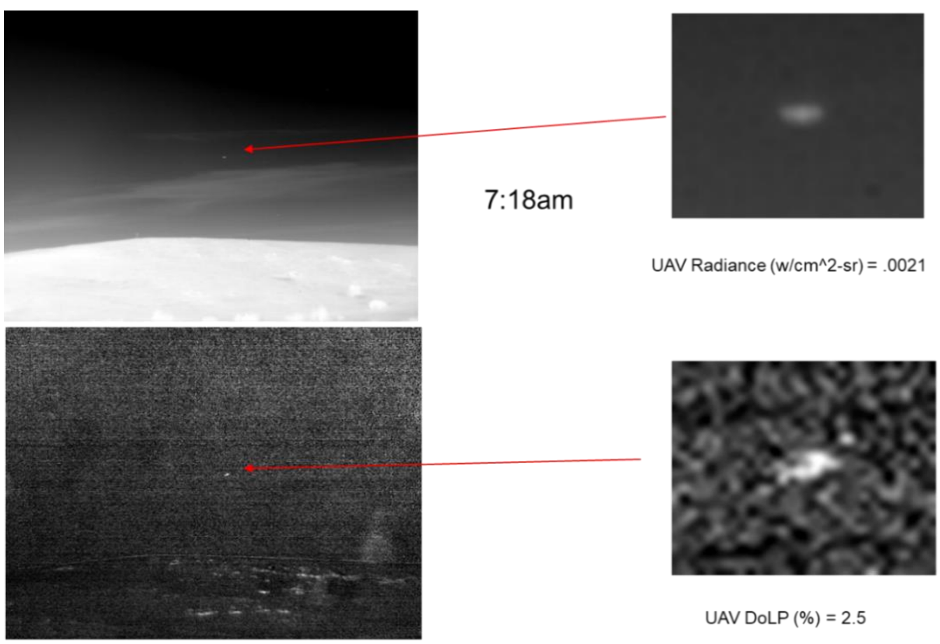

Fig. 9 **Early morning April 6, 2017, 7:18 AM (sunrise 7:14 AM) during thermal cross-over period. Conventional thermal LWIR (top-left) of InstantEye mini-drone with value 0.0021 w/cm2-sr. Resultant LWIR polarimetric image (bottom) with DoLP value 2.5%. Approximate range is 3.0 km.**

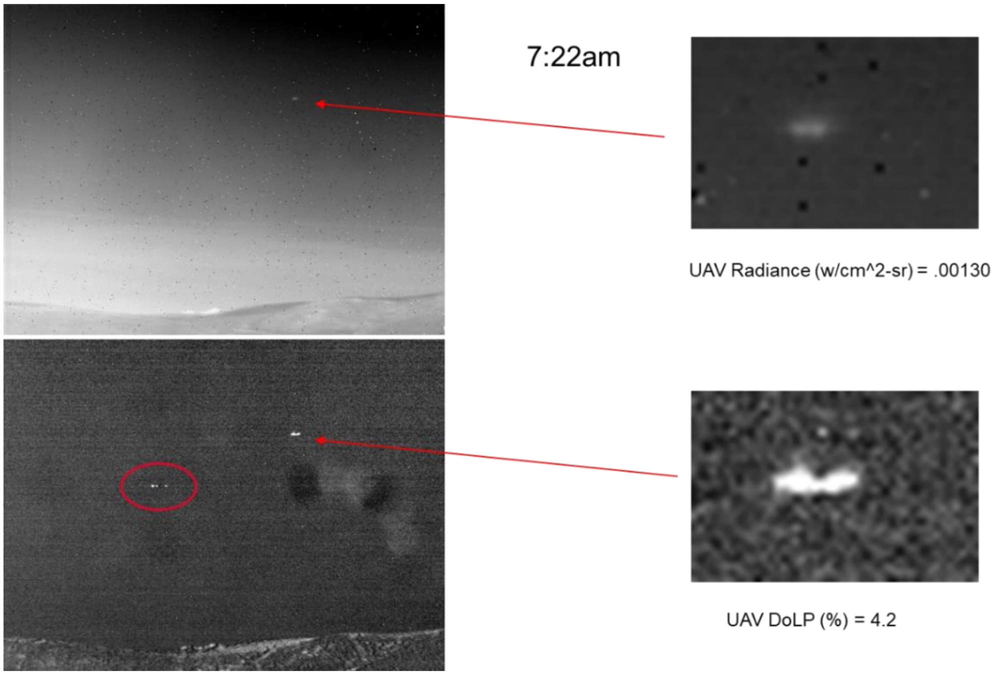

Fig. 10 Early morning April 6, 2017, 7:22 AM (sunrise 7:14 AM) during thermal cross-over period. Conventional thermal LWIR (top left) of InstantEye mini-drone with value 0.0013 w/cm^2-sr. Resultant LWIR polarimetric image (bottom) with DoLP value 4.2%. Approximate range is 3.0 km. Unidentified objects believed to be a flock of birds are apparent only in the LWIR polarimetric image (circled).

Figures 11–14 show a similar set of thermal/polarimetric images for the larger JTARV UAV shown in Fig. 3 (left).

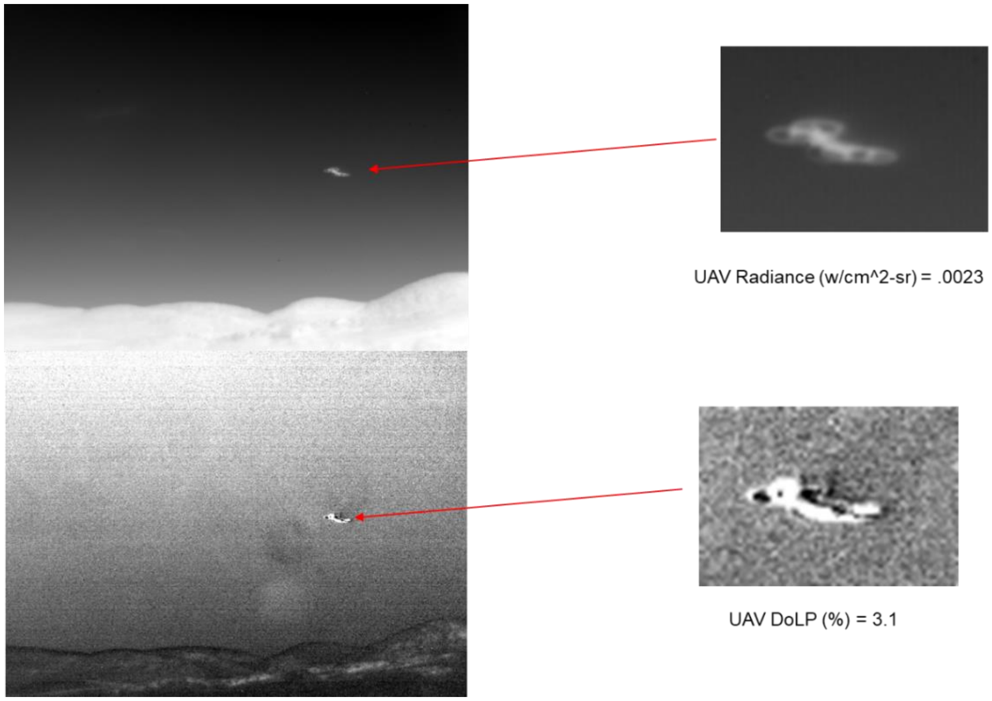

Fig. 11 Conventional thermal LWIR (top left) of the larger JTARV with radiance value 0.0023 w/cm^2-sr. Resultant LWIR polarimetric image (bottom) with DoLP value 3.1%. Approximate range is 0.70 km.

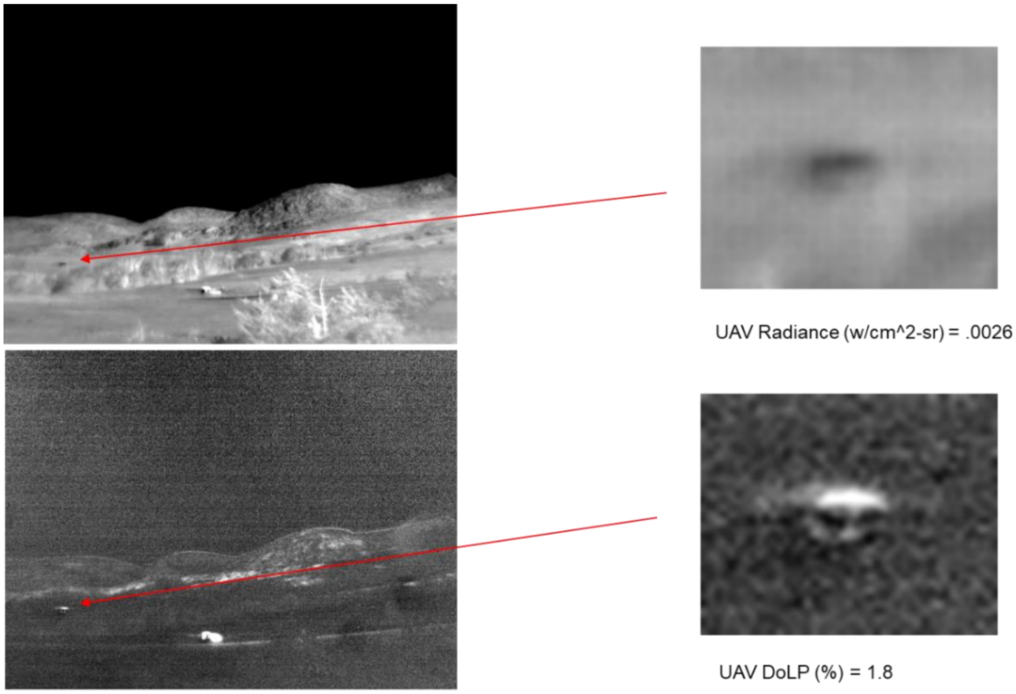

Fig. 12 Conventional thermal LWIR (top left) of the larger JTARV imaged against warm terrain with radiance value 0.0026 w/cm^2-sr. Resultant LWIR polarimetric image (bottom) with DoLP value 1.8%. Approximate range is 0.80 km.

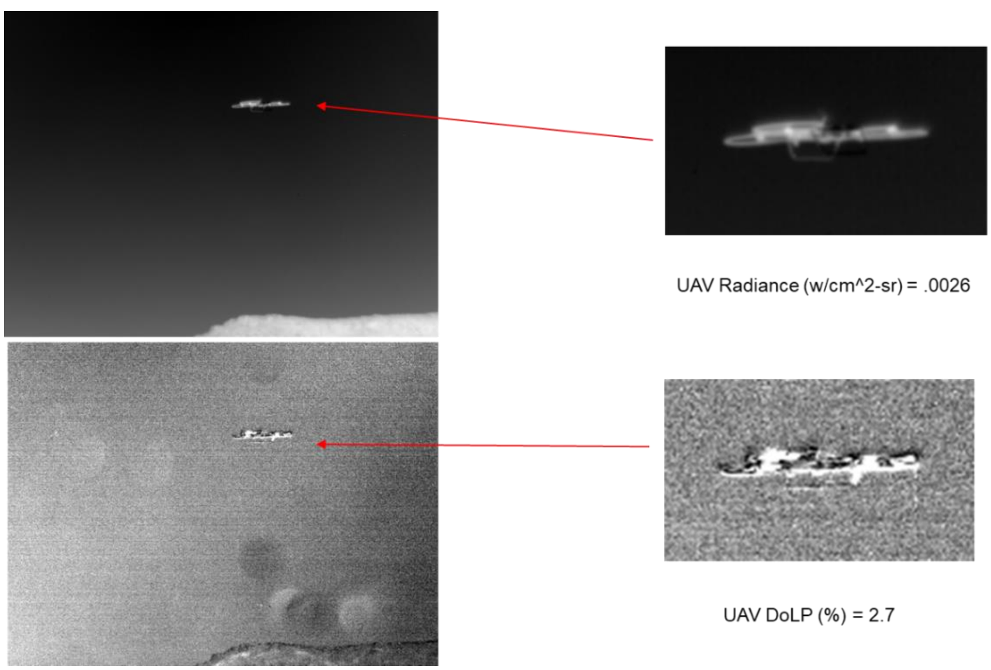

Fig. 13 Conventional thermal LWIR (top left) of the larger JTARV imaged against the cold sky with radiance value 0.0026 w/cm^2-sr. Resultant LWIR polarimetric image (bottom) with DoLP value 2.7%. Approximate range is 0.50 km.

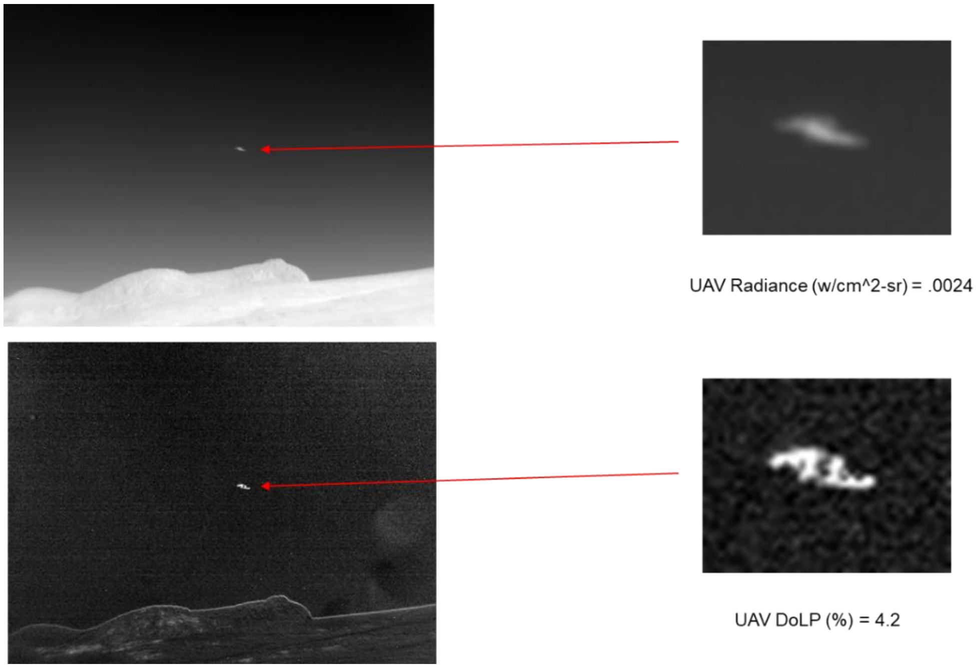

Fig. 14 Conventional thermal LWIR (top left) of the larger JTARV imaged against the cold sky with radiance value 0.0024 w/cm^2-sr. Resultant LWIR polarimetric image (bottom) with DoLP value 4.2%. Approximate range is 1.25 km.

5. Results

All results for the two-day study are tabulated and shown in Tables 1–4, in which thermal and polarimetric parameters are grouped into two generic categories (i.e., birds Tables 1 and 3; UAVs Tables 2 and 4). Each table includes either the calibrated LWIR thermal radiant or polarimetric DoLP values for birds or UAVs.

Table 1 **Calibrated LWIR thermal radiance values for birds and their corresponding background. A radiant contrast parameter is also included, which is a measure of the ability to distinguish target from background. Imagery recorded during the inversion period (early morning) of April 6, 2017.**

File name	BIRD radiance (w/cm^2-sr)	Bird background radiance (w/cm^2-sr)	Radiance contrast (target-BG)/BG
4_5_17_Bird_frame363	0.002	0.0015	0.333
4_5_17_Bird_frame883	0.0017	0.0013	0.308
4_5_17_Bird_frame131	0.0017	0.0014	0.214
4_5_17_Bird_frame898	0.0018	0.0016	0.125
4_5_17_Bird_frame1785	0.0017	0.0016	0.062
4_5_17_Bird_frame2880	0.0017	0.00159	0.069
4_5_17_Bird_frame2880a	0.00185	0.00159	0.164
4_5_17_Bird_frame5	0.0021	0.0019	0.105
4_6_17_Bird_frame1530	0.00135†	0.0013†	0.038†
4_6_17_Bird_frame1997	0.00138†	0.00133†	0.038†
Average	**0.0017**	**0.0015**	**0.1456**

Table 2 **Calibrated LWIR thermal radiance values for both the InstantEye and JTARV UAVs and their corresponding backgrounds. A radiant contrast parameter is also included, which is a measure of the ability to distinguish target from background. Imagery recorded during the inversion period (early morning) of April 6, 2017.**

File name	UAV radiance (w/cm^2-sr)	UAV background radiance (w/cm^2-sr)	UAV radiance contrast (target-BG/BG)
4_6_17_IE5	0.0028	0.002	0.4000
4_6_17_IE6	0.0027	0.0022	0.2273
4_6_17_IE2	0.0021†	0.001†	1.1000
4_6_17_IE9	0.0013†	0.0012†	0.0833
4_6_17_JTARV	0.0023	0.0017	0.2353
4_6_17_JTARV_2	0.0026	0.0026	0.0000
4_6_17_JTARV_5	0.0026	0.0028	0.0714
4_6_17_JTARV_4	0.0024	0.0018	0.3333
4_6_17_JTARV_3	0.0026	0.0021	0.2381
Average	**0.0023**	**0.0019**	**0.298**

Table 3 Calibrated LWIR polarimetric DoLP values for birds and their corresponding background. A polarimetric contrast parameter is also included, which is a measure of the ability to distinguish target from background. Imagery recorded during the inversion period (early morning) of April 6, 2017.

File name	Bird DoLP (%)	Bird DoLP background (%)	DoLP contrast (target-BG)/BG
4_5_17_Bird_frame363	5.5	0.5	10.0
4_5_17_Bird_frame883	6	0.6	9.0
4_5_17_Bird_frame131	5.5	0.71	6.7
4_5_17_Bird_frame898	6.2	0.7	7.9
4_5_17_Bird_frame1785	5.3	0.59	8.0
4_5_17_Bird_frame2880	7.5	0.51	13.7
4_5_17_Bird_frame2880a	3.3	0.51	5.5
4_5_17_Bird_frame5	8	0.7	10.4
4_6_17_Bird_frame1530	3†	0.7†	3.3
4_6_17_Bird_frame1997	3.2†	0.7†	3.6
Average	**5.35**	**0.62**	**7.80**

Table 4 Calibrated LWIR polarimetric DoLP values for the InstantEye and JTARV UAVs and their corresponding backgrounds. A polarimetric contrast parameter is also included, which is a measure of the ability to distinguish target from background.

File name	UAV DoLP (%)	UAV DoLP background (%)	UAV DOLP contrast (target-BG/BG)
4_6_17_IE5	8.63	0.55	14.69
4_6_17_IE6	6.3	0.41	14.37
4_6_17_IE2	2.5	0.82	2.05
4_6_17_IE9	4.22	0.81	4.21
4_6_17_JTARV	3.1	1.31	1.37
4_6_17_JTARV_2	1.8	0.33	4.45
4_6_17_JTARV_5	4.5	0.5	8.00
4_6_17_JTARV_4	4.2	0.28	14.00
Average	**4.4**	**0.626**	**7.89**

Also included in each table is a contrast parameter, which is the fractional difference between target and background pixel values. In general, the ability for either a human operator or computer algorithm to discern and/or detect the presence of on object within a scene is closely related to the relative difference in signal values between the object in question and its associated background (i.e., contrast).

6. Analysis

The primary goal for conducting this initial study was to discern whether or not there are meaningful differences in either the thermal or polarimetric response between a generic bird and a typical small UAV that can be used as a distinguishing metric. Although the sample size and time frames involved were small, there appear to be relevant/meaningful differences.

The most obvious result comes from comparing the average thermal radiant values (w/cm^2*sr) for birds and UAVs shown in Tables 1 and 2. As one can see, average bird radiance of 0.0017 (w/cm^2*sr) is 26% lower than the average radiance value of 0.0023 (w/cm^2*sr) for the two UAV platforms considered. We believe the reason for this is two-fold.

First, throughout the two-day field test we noticed that UAV radiant values tracked very well with terrestrial/terrain radiant values, indicating that both UAVs were predominantly "reflecting" the ground-based radiance in the LWIR. However, this coupling of ground radiance to apparent UAV radiance becomes less with increasing altitude as the UAV radiance source transitions from reflection from terrain, to thermal emission synonymous with ambient air temperatures, which are typically much less.

Second, birds appear consistently cooler than the UAVs considered and we believe much of this is a result of the insulating nature of their feathered coating, since typical bird temperatures are on the order of 40 °C, which should be seen as a relatively "hot" target when imaged against a cold sky.[7]

When comparing the average DoLP values for birds and UAVs, as shown in Tables 3 and 4, the differences are not as definitive as seen for the LWIR radiance comparison. As seen in Tables 3 and 4, the average DoLP for birds and UAVs are 5.35% and 4.40%, respectively. From a polarimetric standpoint these two values are statically very similar. However, thermal polarimetric imaging tends to suppress background clutter while highlighting the main target. As a result, the gradation seen in conventional thermal imagery is transformed to a more "binary" type image in which the dynamic range between the target and background is enhanced.[8] This effect is best seen by comparing the relative contrast values between the radiance and polarimetric set of images, which shows that the relative contrast values for conventional LWIR thermal are 0.145 (birds) and 0.298 (UAVs), compared to 7.80 (birds) and 7.85 (UAVs) seen in the polarimetric imagery. It is for this reason that thermal polarimetric images are usually best suited for targeting and tracking rather than for identification purposes.

7. Summary and Conclusion

In summary, we recorded two sets of calibrated LWIR thermal and polarimetric images of birds and similarly sized UAVs in an attempt to find distinguishing differences that could be used to discriminate between a mundane bird and a hazardous UAV. Although our initial data set was relatively small (i.e., two days of testing), preliminary results show that the two UAVs considered were consistently "warmer" in terms of raw radiance in w/cm^2*sr, when compared to bird radiance recorded at the same location and time. Unfortunately, the resultant polarimetric signatures were less conclusive and appeared to be statistically equivalent for the data recorded here. We hope to replicate this study in the near future to expand our data set to include more types of micro-UAVs and species of birds and include a new mid-wave infrared (MidIR) polarimetric sensor that is currently under development.

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List of Symbols, Abbreviations, and Acronyms

2-D	2-dimensional
DoA	division-of-amplitude
DOD	Department of Defense
DoFP	division-of-focal-plane
DoLP	degree-of-linear-polarization
FOV	field-of-view
FPA	focal-plane-arrays
JTARV	Joint Tactical Aerial Resupply vehicle
LWIR	long-wave infrared
MCT	Mercury Cadmium Telluride
MidIR	mid-wave infrared
ROI	regions of interest
SAR	spinning-achromatic-retarder
SWIR	short-wave infrared
UAV	unmanned aerial vehicle

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