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Inter-comparison of thermal measurements using ground-based sensors, UAV thermal cameras, and eddy covariance radiometers

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ABSTRACT

With the increasing availability of thermal proximity sensors, UAV-borne cameras, and eddy covariance radiometers there may be an assumption that information produced by these sensors is interchangeable or compatible. This assumption is often held for estimation of agricultural parameters such as canopy and soil temperature, energy balance components, and evapotranspiration. Nevertheless, environmental conditions, calibration, and ground settings may affect the relationship between measurements from each of these thermal sensors. This work presents a comparison between proximity infrared radiometer (IRT) sensors, microbolometer thermal cameras used in UAVs, and thermal radiometers used in eddy covariance towers in an agricultural setting. The information was collected in the 2015 and 2016 irrigation seasons at a commercial vineyard located in California for the USDA Agricultural Research Service Grape Remote Sensing Atmospheric Profile and Evapotranspiration Experiment (GRAPEX) Program. Information was captured at different times during diurnal cycles, and IRT and radiometer footprint areas were calculated for comparison with UAV thermal raster information. Issues such as sensor accuracy, the location of IRT sensors, diurnal temperature changes, and surface characterizations are presented.

Keywords: sensor comparison, thermal sensors, surface temperature, high-resolution, UAV, proximity sensors.

1. INTRODUCTION

Estimation of thermal information for agricultural purposes is paramount for several agronomic activities, vegetation management and water applications such as canopy temperature [1] soil moisture [2], water stress [3,4] energy balance [5,6], canopy turbulence formulations [7], and canopy stomatal conductance [1], among others. Major satellite platforms used in agriculture (MODIS Terra and Landsat) have intensive efforts in place to enhance and calibrate thermal information [8].

At field and subfield levels, thermal proximity sensors are used increasingly to monitor carefully selected locations that can provide an understanding of conditions across the farm. These sensors, known as infrared radiometers or IRT, can be placed at any elevation, distance, or angle, depending on the crop or soil feature to be monitored or tracked [9]. These sensors have low energy requirements and are robust against environmental conditions in tracking continuously the selected feature within its field of view (FOV). In addition, a custom configuration can be applied to IRTs to adjust for emissivity conditions (~0.98 for vegetation, ~0.99 for water); and the most typical IRT configuration, emissivity is set to 1.00. These sensors provide excellent accuracy (+/- 0.5 Celsius), as described by the manufacturer.

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Similar to the IRT sensors, radiometer sensors are used in experimental setups designed to measure energy fluxes and micrometeorological processes such as in eddy covariance towers [10–14]. These radiometer sensors measure short- and long-wave upwelling and down-welling radiance for calculation of energy balance fluxes. The longwave upwelling radiance measurement is of interest because it is based on measurements of infrared temperature to quantify radiance emitted from the surface using the Stefan-Boltzmann equation and an assumed emissivity.[15,16].

Complementary to these proximity sensors are microbolometer thermal cameras for UAVs [17,18]. These sensors provide temperature imaging at relatively coarser resolution compared with similar-sized optical cameras. These thermal cameras are the only available imaging sensor solution for UAVs due to weight. The manufacturer's radiometric calibration plays a major role in data quality, with reported laboratory accuracies of +/-5 Celsius [19] and +/-1 Celsius [20] depending on the manufacturer.

2. AREA OF STUDY

Study Site

The area of study is a commercial vineyard field operated by E&J Gallo and located on the outskirts of the City of Galt, Sacramento County, California. The field center is located at 38°17'7.40"N, 121° 6'58.11"W). This field is part of the USDA Agricultural Research Service Grape Remote Sensing Atmospheric Profile and Evapotranspiration Experiment (GRAPEX) Project [21]. Fig. 1 shows the location of the site in California and details of the commercial vineyard part of this study.

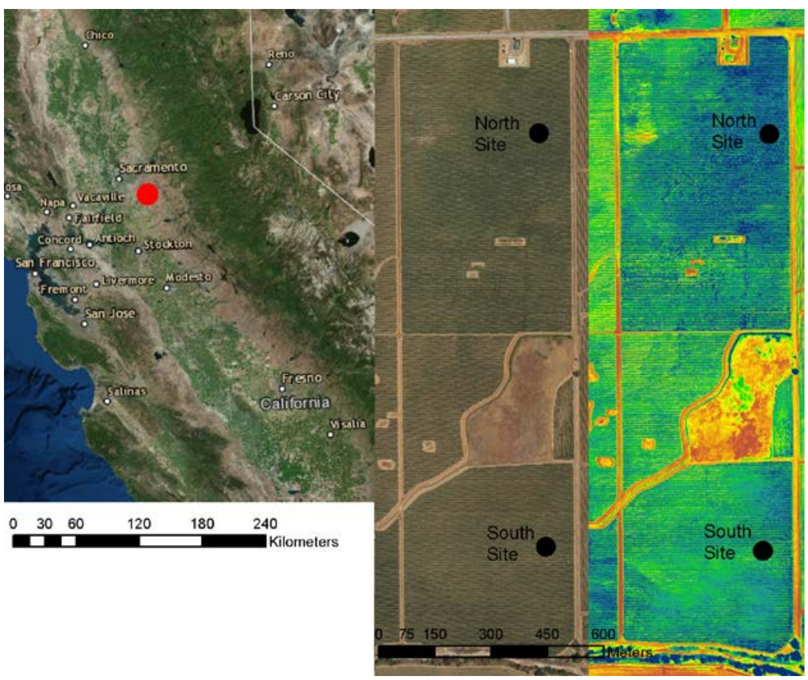

Figure 1. Location of the study area: Location in California (left) and AggieAir sUAS coverage area for all flights in RGB mosaic (center) and thermal (right)

AggieAir UAV

The AggieAir UAV is an unmanned platform developed for research applications at Utah State University. AggieAir has been used widely for remote sensing assignments in support of research in environmental settings, water resources, and agricultural applications [22–28]. The system incorporates a custom payload integration compatible with multiple platforms and an interchangeable sensor package that includes optical and thermal sensors. The AggieAir platforms have incorporated continuous improvements (flight times extended to 3.0 hrs. on a single battery charge, up to 3,500 m. MSL, weather sensors, etc.). To achieve scientific accuracy, intensive ground data collection efforts have been conducted to produce reflectance estimation protocols, address camera vignetting, assure accurate image orthorectification, etc. In addition, the optical and thermal cameras are located within a payload frame to minimize atmospheric effects (chilling) on the sensor due to flight elevations (up to 1,000 m above ground) and speeds (~50 mph). Figure 2 shows details of the AggieAir "Minion" UAV and payloads used in this study.

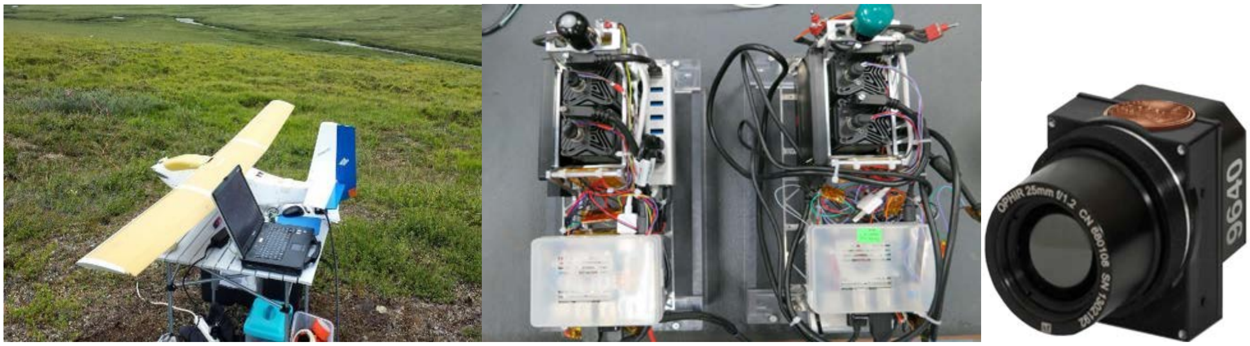

Fig. 2 Details of the AggieAir UAV. (left) Aircraft, (Center) Payload, (Left) UAV Thermal camera

IRT and Eddy Covariance Sensors

IRT sensors for this study were obtained from Apogee Inc. [29] and were set up in the field as presented in the Fig. 3. The upwelling radiometer was acquired from Campbell Scientific [30].

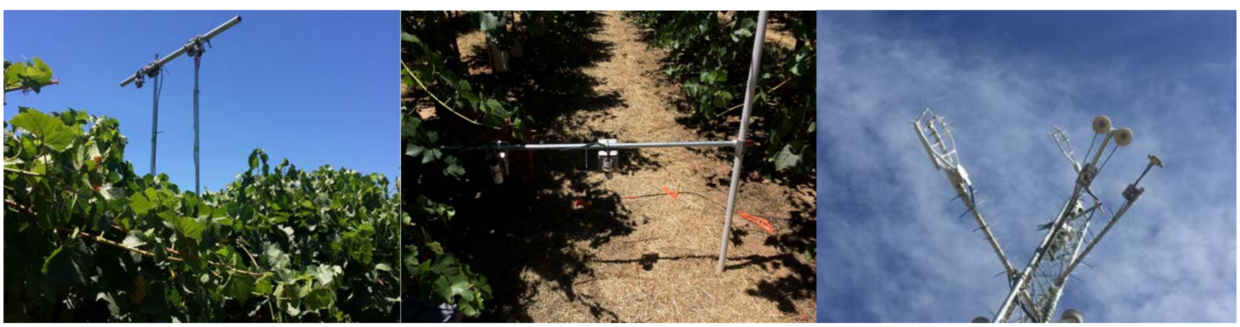

Fig 3. Details of IRT and eddy covariance radiometer setups in the study area

3. METHODOLOGY

The AggieAir UAV was employed to fly over the area of study and collect thermal imagery during a 2-year campaign (2015–2016). The flight altitude was 450 m above ground level (AGL) and was constant for all flights. Measurements (and flights) were made at early morning (approximately a half-hour after sunrise), Landsat 8 overpass time (close to solar noon), and mid-afternoon. Exact times are presented in Table 1. Based on the study performed by Torres[17], any microbolometer-based thermal imagery requires compensation due to atmospheric conditions and elevation. A version of the general atmospheric correction, along with a vicarious calibration procedure for radiometric surface temperature, was applied to the thermal imagery in Table 1. Details of the atmospheric correction are presented at Torres [17], and an example of the correction is presented in Fig. 4.

Table 1 AggieAir UAV flight times over the area of study. Times are Pacific Standard format

Date	Flight 1	Flight 2	Flight 3
June 02, 2015	5:53-6:06	10:23-10:41	13:57-14:17
July 11, 2015	5:39-5:51	10:29-10:42	14:00-14:13
May 02, 2016	6:15-6:23	10:55-11:04	13:55-14:02
May 03, 2016	6:45-6:54	11:39-11:47	

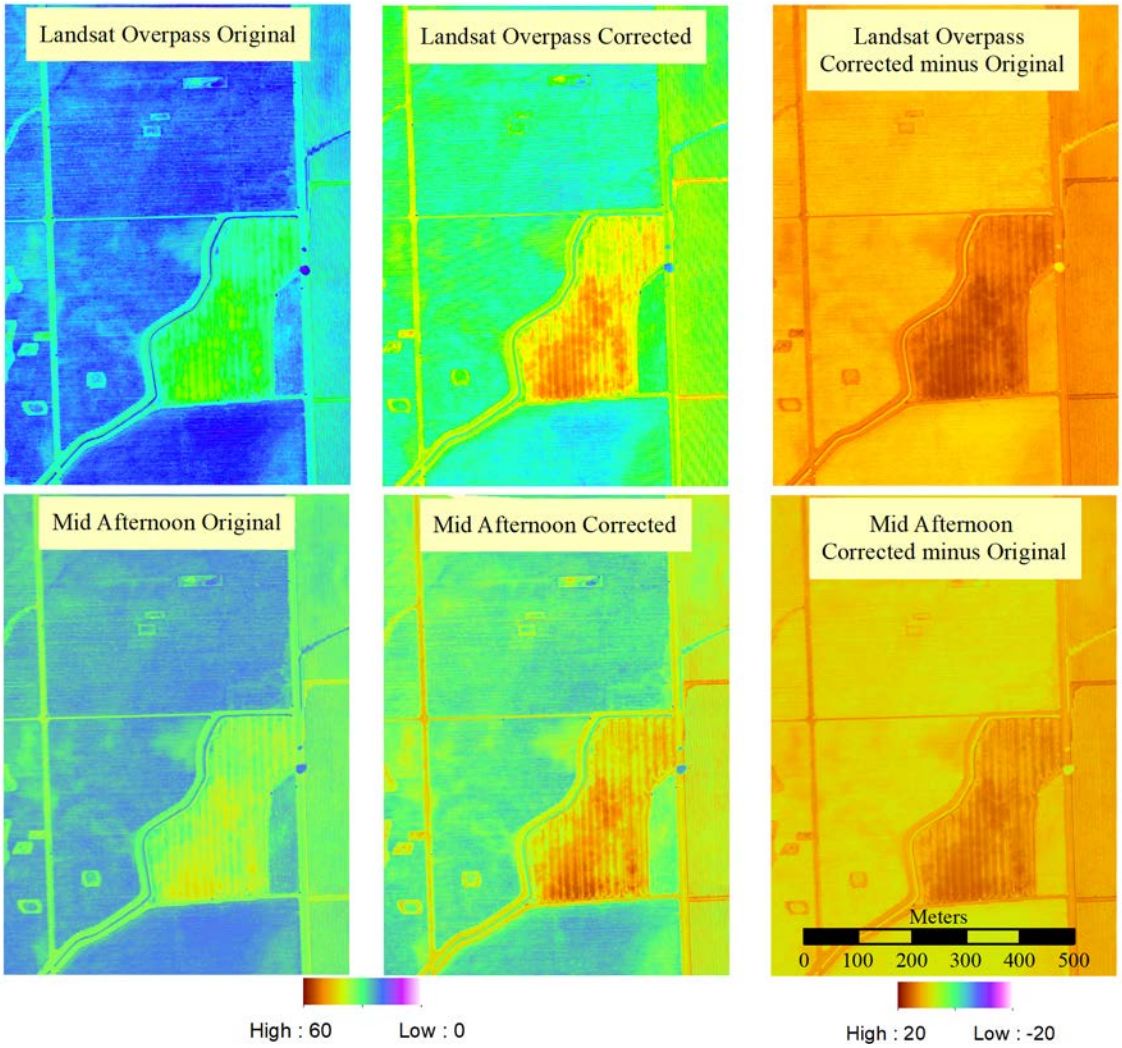

Figure 4. Example of temperature image correction at 0.6 m resolution for May 2, 2016, using the vicarious calibration as described by Torres (2014). Information is presented for Landsat Overpass (top row) and Mid-Afternoon times (bottom row). Units are in Celsius. The left column is the UAV original temperature image, the center column is the original sUAS image after the atmospheric correction, and the right column is the difference between the corrected minus the original sUAS imagery.

To perform the multi-sensor comparison, technical details of each of the sensors were collected along with expected FOV for the proximity sensors. Table 2 presents the collected information. The IRT sensors had a typical configuration for vines (Fig. 5). For the upwelling longwave radiometer, elevation above ground was considered. Figure 6 and 7 show details of the proximity sensors footprint within the vineyard field.

Table 2. Instruments used to collect temperature information in this study.

INSTRUMENT	IRT	LW Radiometer	THERMAL CAMERA
Brand/Model	Apogee Ins/SI-111	Campbell Sci/NR01-L	ICI/9640-P
Weight (gr)	190	1300	141
Image Size (pixel)	NA	NA	640 by 480
Spectral Range (µm)	8 to 14	4.5 to 50	7 to 14
Spectral Band Centre (µm)	10.5	27.25	10.35
Operating Range	-55 to 80^{0}C	-40 to 80^{0}C	-40 to 140^{0}C
Reported Accuracy	+/- 0.5^{0}C	+/- 1.0^{0}C	+/- 1.0^{0}C
Reported Emissivity	1.0	1.0	1.0
NIST Traceable?	NOT REPORTED	Int'l temp standard	NOT REPORTED

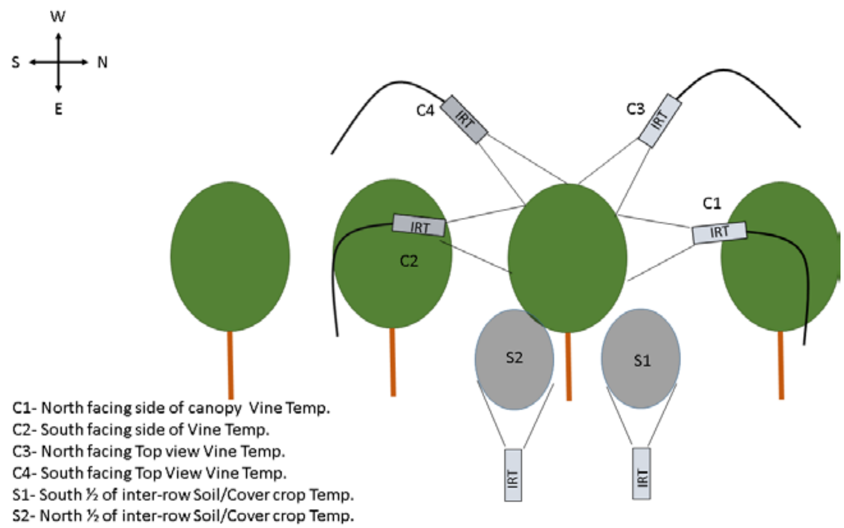

Figure 5. IRT set up for this study. Note that semi-horizontal IRTs were not considered in the analysis.

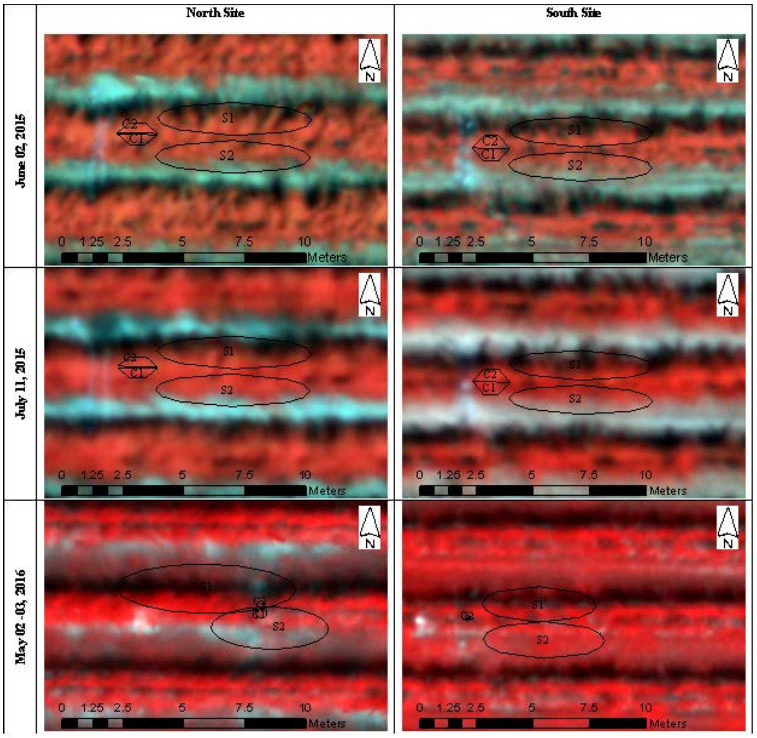

Fig. 6. IRT footprint over false color AggieAir image for the north and south monitoring locations.

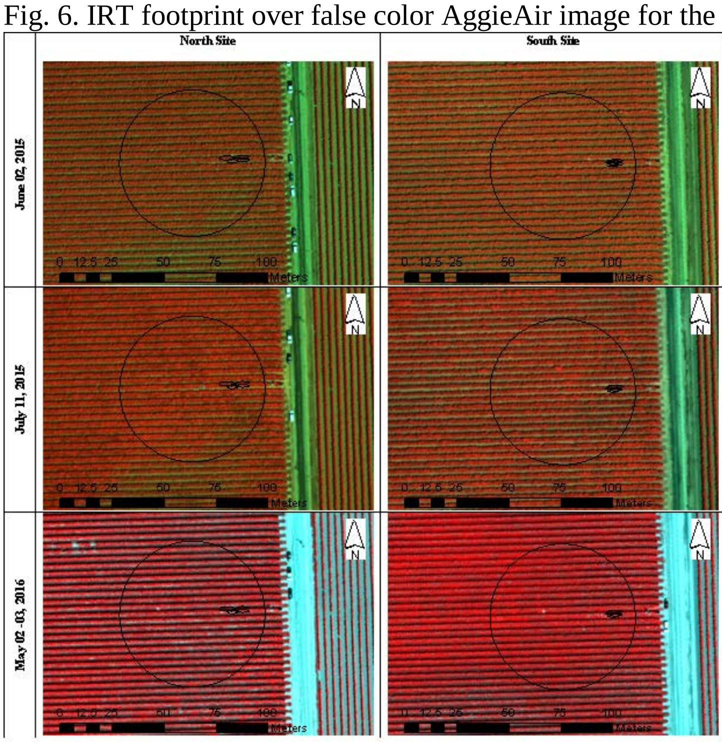

Fig. 7. Longwave radiometer footprint over false color AggieAir image for the north and south monitoring locations.

4. RESULTS AND DISCUSSION

From Figs 6 and 7, it is evident that IRT and AggieAir thermal cameras will provide different temperature measurements. Effects in IRT sensors can be listed as incorporating measurements under canopy and having a strong influence from soil conditions when the canopy is partially present in the FOV. The UAV thermal camera shows manufacturer and environmental effects on the measurements during flight, image processing protocols, and point spread function. Factors that influence the upwelling radiometer measurements are emissivity assumptions due to soil and vegetation conditions, FOV, effects of the installation components (tower frame within FOV), and the weighing influence of locations closer to the center of the FOV. Having these potential effects in mind, a direct comparison of the IRT, upwelling radiometers, and AggieAir imagery is presented in Figs. 8 and 9.

As presented in Fig. 8, the relationship between IRT and Thermal Camera is not direct/linear. This is more evident in the soil IRT and AggieAir estimates. This is because, while the IRT sensor is looking under the vine canopy (Figs 5 and 6), AggieAir thermal pixels are combining canopy and soil temperatures. Canopy temperatures are closer in magnitude between IRT and AggieAir despite the IRT view angle as shown in Fig 5. Comparing AggieAir before and after vicarious calibration and with IRT data, the vicarious calibration indicates a positive influence on the thermal image data, reducing the difference between the uncorrected AggieAir camera and the IRT values. Because of the small IRT FOV dimensions, it is expected that AggieAir data is affected by its Point Spread Function, which causes a smoothing of the temperature image information. Additional efforts can be put into thermal sharpening based on existing methodologies.

Similar results can be seen in Fig. 9 for the comparison between the upwelling radiometer and the AggieAir data before and after vicarious calibration. Because of the radiometer footprint (~70m diameter), Point Spread Function influence is minimized. Fig. 9 shows that AggieAir and the Upwelling Radiance Sensor have a direct relationship, less convoluted than with IRT measurements. The impact of the AggieAir vicarious calibration can be seen clearly in the bottom row of Fig. 9, where AggieAir vicarious calibration reduced the difference between the Upwelling Radiance Sensor and AggieAir average temperature. Still, additional efforts are required to determine the nature of the differences between these two sensors.

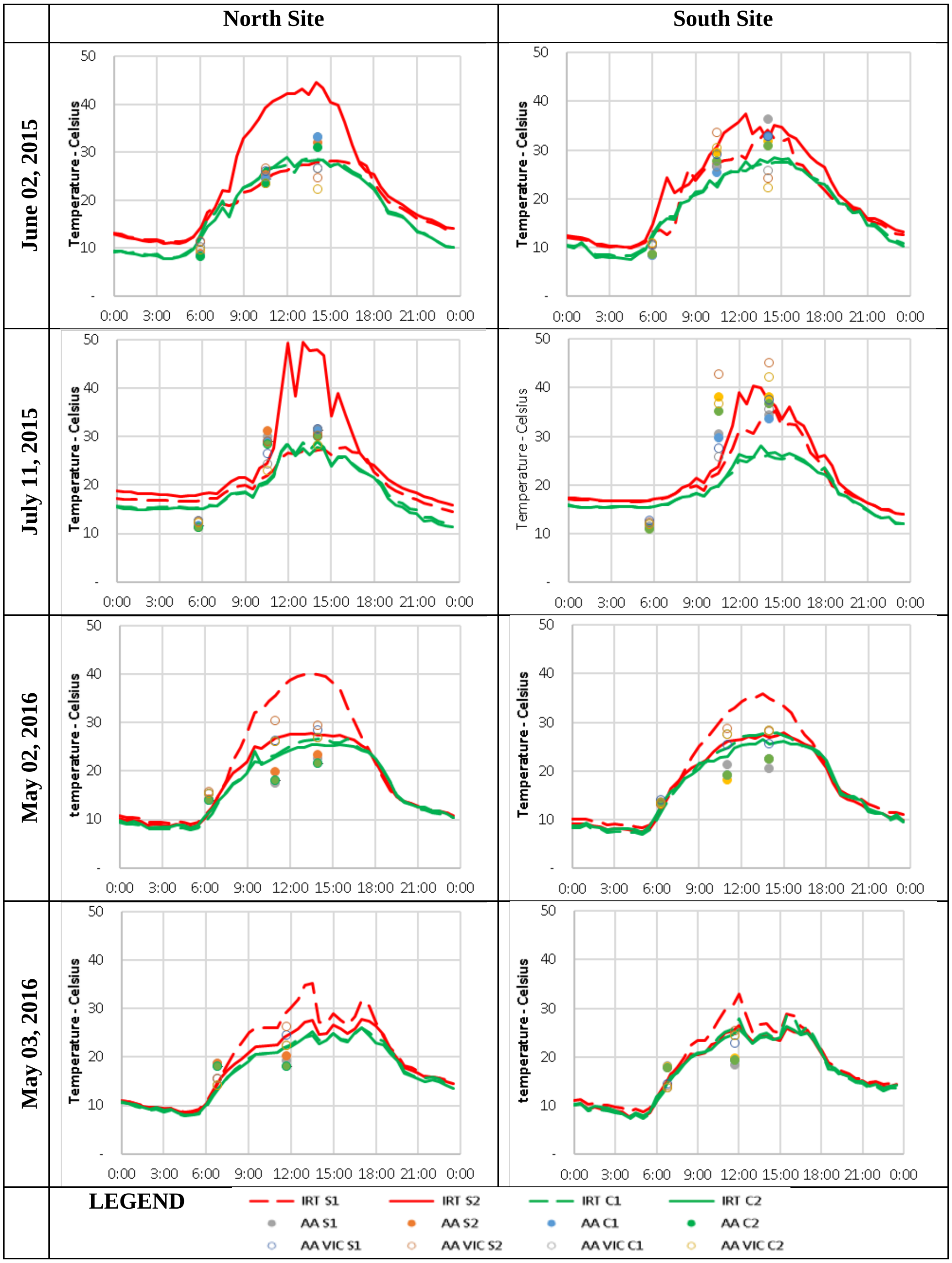

Fig 8. IRT and AggieAir before and after vicarious atmospheric calibration for each of the UAV flights in California (lines represent IRT temperature diurnal fluxes, solid dots are AggieAir before calibration, hollow dots are AggieAir thermal data after vicarious calibration). Time is Pacific Standard

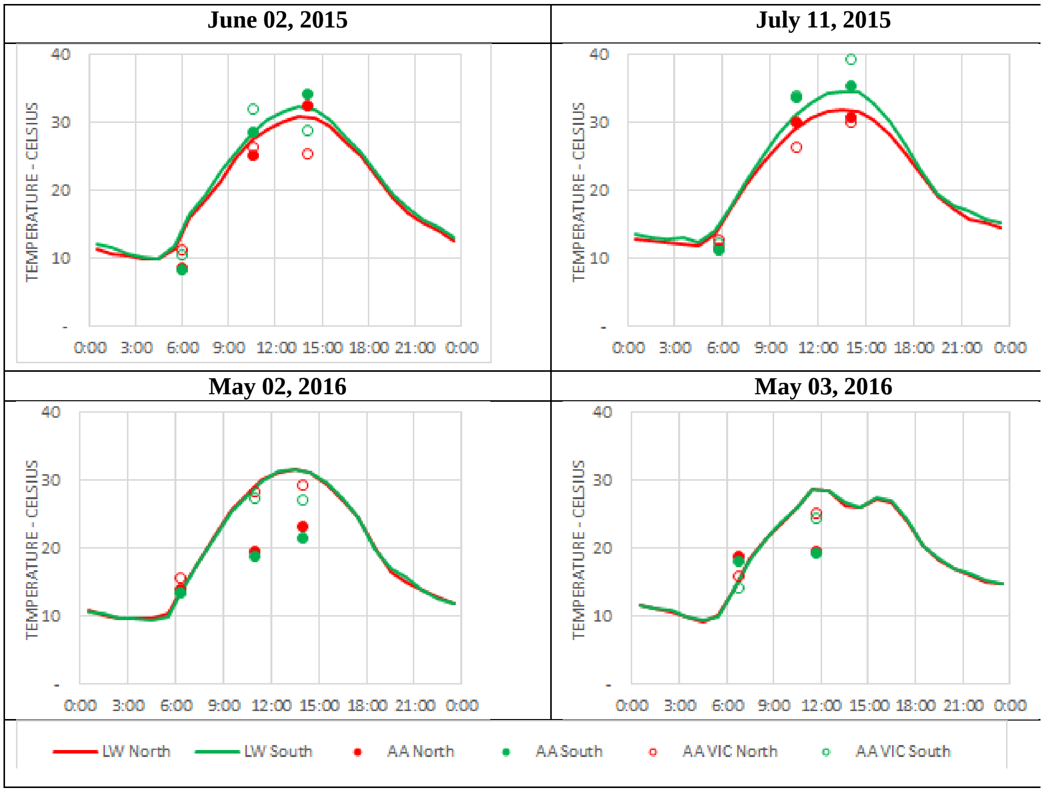

Fig 9. Eddy Covariance Tower Upwelling Radiance vs. AggieAir Temperatures. Red color indicates measurements in the north side of the field and green color at the south.

5. CONCLUSIONS

Scientific applications of thermal sensors, regardless of their nature, require intercomparing and validation of temperature information. This study presents a comparison of infrared temperature IRT sensors, upwelling radiance sensors, and microbolometer UAV cameras such as the ones carried by AggieAir. The results indicate that field sensor settings (over/under canopy), environmental conditions (e.g. elevation of UAV), and sensor FOV have a significant impact on the comparison of thermal information. The IRT FOV makes it necessary to improve the imaging thermal information by using sharpening techniques, thus minimizing the thermal camera point spread function influence. In eddy covariance upwelling, the effects of the vicarious calibration are more visible, showing its positive impact to the thermal imagery. Future work will evaluate sharpening thermal imagery information against IRT sensors and the suitability of eddy covariance upwelling radiance to improve vicarious calibration of UAV thermal information.

6. ACKNOWLEDGMENTS

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