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Introduction
Small Unmanned Aerial Systems (sUAS) have become an accessible technology for collection of spatially distributed temperature data in fine resolution. Nevertheless, lack of standard procedures for atmospheric temperature correction can have an adverse impact on the conclusions and replicability of studies using this technology. This work presents a vicarious calibration methodology for sUAS thermal imagery traceable back to NIST standards. For this methodology, a 3-yr. data collection campaign with a sUAS technology, called AggieAir, developed at the Utah Water Research Laboratory, was performed under different daytime conditions. A comparison between original and vicarious calibration for the sUAS thermal imagery is provided, along with a set of recommendations for scientific thermal sUAS applications.

Thermal Sensors for sUAS
In terms of weight limitations, sUAS (under 25 Kg) have one available radiometric thermal solution: microbolometer sensors (below 150 gr) with a spectral response from ~7um to ~14um (using Vanadium Oxide VOx/Amorphous Silicon A-Si). Cryogenic thermal sensors are still too heavy (over 1000 gr). Manufacturers’ radiometric calibration plays a major role in data quality, with reported laboratory accuracies of +/-5 °C (FLIR) and +/-1 °C (ICI).

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Materials & Methods
A 3-year campaign (2014-2016) in agricultural lands (vineyards) in California was conducted to collect temperature information at ground level and sUAS elevation. The flight altitude was 450m AGL. Measurements (and flights) were made at sunrise, mid-morning, and afternoon times.

Thermal Sides for sUAS
AggieAir is a collection of sUAS remote sensing equipment, including multiple platforms and interchangeable sensor packages, developed by Utah State University for scientific applications in natural resources, environmental applications, and agriculture. It has a customizable payload for short, medium, and long wavelengths sensors, with continuous improvements for extended flight time (3 hrs.), on a single battery capacity, up to 12,000 ft. MSL, water vapor, etc.). To achieve scientific accuracy, intense ground data collection and research has been conducted to produce radiance correction protocols, address camera vignetting, assure accurate image orthorectification, etc.

As for any thermal sensor, microbolometer sensors are affected by external conditions (flight elevation, water vapor, air temperature) which will impact their accuracy. In scientific applications in natural resources, environmental applications, and agriculture. These factors can be addressed by using a radiative transfer model (Barsi et al. 2003):

\[ L_u = \frac{c}{\lambda T^4} + \tau \varepsilon L_u + (1 - \tau)(1 - \varepsilon)L_d \]

where \( t \) is the emissivity of the surface, \( L_u \) is the radiance of a blackbody target of kinetic temperature \( T \) at ground level, \( L_d \) is the downwelling or sky radiance, and \( L_u + (1 - \varepsilon)L_d \) is the radiance measured by the thermal camera on board the sUAS. Radiance is in units of W/m²um.K. \( \lambda \) is the mean wavelength (m) and \( T \) is temperature (K).

The Proposed Methodology

\[ T(\lambda, T) = \frac{c}{\lambda^4} + \tau \varepsilon T + (1 - \tau)(1 - \varepsilon)T_d \]

where \( c = 3.74x10^8 \) W/m²um²K, and \( c = 1.44x10^8 \) W/m²um²K, \( \lambda \) is the mean wavelength (m), and \( T \) is temperature (K).

Conclusions
Vicarious calibration is necessary for scientific applications that require accurate radiometric data, such as evapotranspiration, soil moisture, nitrogen estimation, etc. The proposal procedure is for brightness temperature estimation (without accounting for emissivity). This methodology is applicable to any environment (natural, urban, agriculture, open water, tall canopy, etc.). This methodology can benefit from simultaneously flying two sUAS (a VTOL at a higher altitude with a fixed-wing at a lower AGL).

References
ICI Cameras http://www.infraredcameras.com/
Palmer-Wild http://www.palmerwild.com/
Utah State University - AggieAir http://aggieair.usu.edu/