An overview of thermal infrared and visible-to-shortwave infrared instrument calibration activities for SnowEx Grand Mesa

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Presentation Overview

(1) SnowEx ground and airborne thermal infrared (TIR) instrument calibration
(2) Visible-to-shortwave infrared (VSWIR) ground instrument calibration
(3) Why SnowEx calibration/validation (Cal/Val) matters
(4) TIR/VSWIR snow measurement / science requirements

Presentation Objectives

(1) Briefly describe SnowEx TIR instrument calibration techniques and communicate initial results on laboratory, P-3 airborne and ground meteorological station cross-calibration.

(2) Briefly describe VSWIR ground instrument calibration techniques and communicate results on the VSWIR spectrometer cross-calibration efforts.

(3) Offer the SnowEx project some recommendations on calibration & planning for future campaign years.

Hall et al. The Infrared Sensor Suite for SnowEx 2017. IGARS Proceedings, 2017

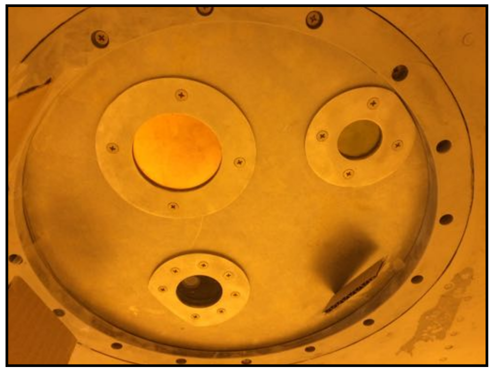
SnowEx TIR Instruments

Contact Thermometer

(1) Everest Interscience EnviroTherm TIR sensor (*transfer standard*)
- (1) FOV = 10^{o}
- (2) 8-14 micron temperature response in C
- (3) Temperature range = -30 C to 80 C
- (4) +/- 0.3 C accuracy

(2) Contact TIR Thermometer (*cross-calibration verification*)
- (1) Contact probe
- (2) +/- 0.2 C accuracy

P-3 Germanium Window



P-3 Cross-Calibration

(3) KT-15 82D Remote Thermometer (*airborne P-3*)
- (1) FOV = 2 degree (100 m at 10,000 ft AGL)
- (2) 8-14 micron temperature response in C
- (3) Temperature range = -50 C to 50 C

(4) Quantum Well Infrared Photodetector (QWIP) (*airborne P-3*)
- (1) FOV = 11 x 9 degrees (~1.8 meters at 10,000 AGL)
- (2) 7-10 micron response function in digital counts
- (3) ~0.02 C accuracy

Met Tower Cross-Calibration

(5) Apogee MI-210 (*Grand Mesa meteorological towers*)
- (1) FOV = 22^{o} half angle
- (2) 8-14 micron temperature response in C
- (3) +/- 0.2 C accuracy

SnowEx TIR Blackbody Sources

(1) NASA/GSFC Code 618 Laboratory Blackbody (stable source)
- (1) Emissivity > 0.98
- (2) Temperature range -10 C to 79 C
- (3) Precision <0.001 C
- (4) Accuracy +/- 0.2 C

(2) Everest Interscience Portable Blackbody (NIST traceable field source)
- (1) Emissivity > 0.98
- (2) Temperature range 0 C to 120 C
- (3) Accuracy +/- 0.1 C

(3) Portable Contact Blackbody (cross-calibration verification)
- (1) Emissivity = > 0.98
- (2) Temperature range: fluctuations with ambient

**SnowEx At-Sensor Target TIR Requirement was within 1°C*

Lab Blackbody

Field Blackbody

Contact Blackbody

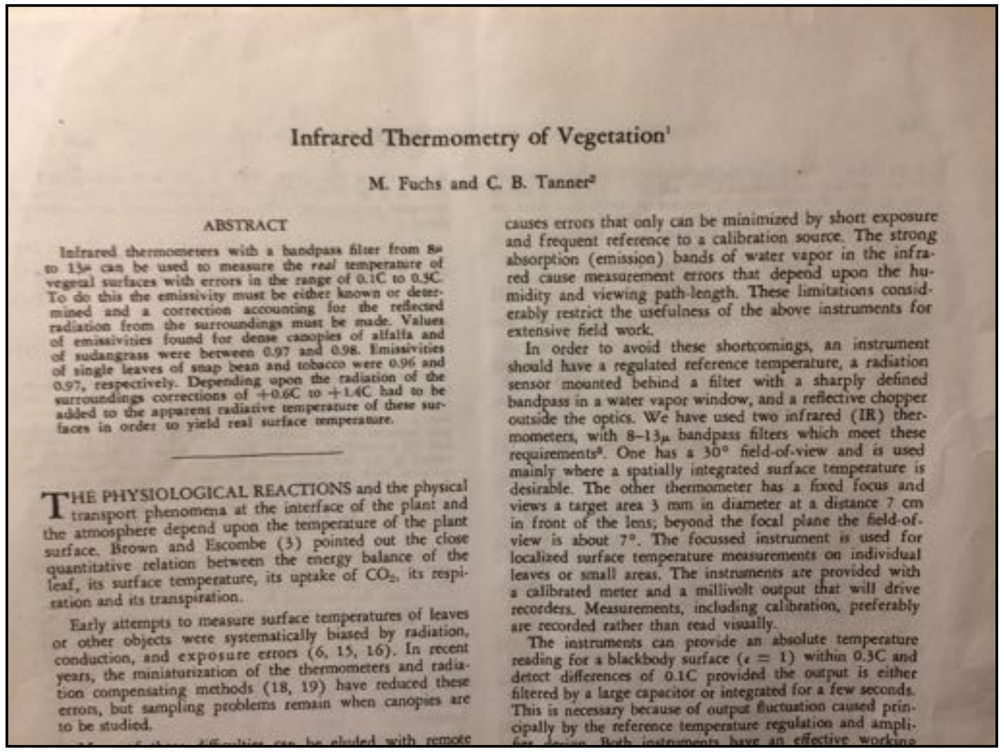
Surface Temperature from TIR Measurements: the basics

Equation 1 (Fuchs and Tanner 1966)

$$R = e\sigma T^4$$

where:

R is the energy flux of electromagnetic radiation
e is the emissivity of any surface
σ is Stefan-Boltzmann constant
T is temperature in degrees Kelvin



Infrared Thermometry of Vegetation[1]

M. Fuchs and C. B. Tanner[2]

ABSTRACT

Infrared thermometers with a bandpass filter from 8μ to 13μ can be used to measure the *real* temperature of vegetal surfaces with errors in the range of 0.1C to 0.3C. To do this the emissivity must be either known or determined and a correction accounting for the reflected radiation from the surroundings must be made. Values of emissivities found for dense canopies of alfalfa and of sudangrass were between 0.97 and 0.98. Emissivities of single leaves of snap bean and tobacco were 0.96 and 0.97, respectively. Depending upon the radiation of the surroundings corrections of +0.6C to +1.4C had to be added to the apparent radiative temperature of these surfaces in order to yield real surface temperature.

THE PHYSIOLOGICAL REACTIONS and the physical transport phenomena at the interface of the plant and the atmosphere depend upon the temperature of the plant surface. Brown and Escombe (3) pointed out the close quantitative relation between the energy balance of the leaf, its surface temperature, its uptake of CO_2, its respiration and its transpiration.

Early attempts to measure surface temperatures of leaves or other objects were systematically biased by radiation, conduction, and exposure errors (6, 15, 16). In recent years, the miniaturization of the thermometers and radiation compensating methods (18, 19) have reduced these errors, but sampling problems remain when canopies are to be studied.

causes errors that only can be minimized by short exposure and frequent reference to a calibration source. The strong absorption (emission) bands of water vapor in the infrared cause measurement errors that depend upon the humidity and viewing path-length. These limitations considerably restrict the usefulness of the above instruments for extensive field work.

In order to avoid these shortcomings, an instrument should have a regulated reference temperature, a radiation sensor mounted behind a filter with a sharply defined bandpass in a water vapor window, and a reflective chopper outside the optics. We have used two infrared (IR) thermometers, with 8–13μ bandpass filters which meet these requirements[3]. One has a 30° field-of-view and is used mainly where a spatially integrated surface temperature is desirable. The other thermometer has a fixed focus and views a target area 3 mm in diameter at a distance 7 cm in front of the lens; beyond the focal plane the field-of-view is about 7°. The focussed instrument is used for localized surface temperature measurements on individual leaves or small areas. The instruments are provided with a calibrated meter and a millivolt output that will drive recorders. Measurements, including calibration, preferably are recorded rather than read visually.

The instruments can provide an absolute temperature reading for a blackbody surface ($\epsilon = 1$) within 0.3C and detect differences of 0.1C provided the output is either filtered by a large capacitor or integrated for a few seconds. This is necessary because of output fluctuation caused principally by the reference temperature regulation and ampli-

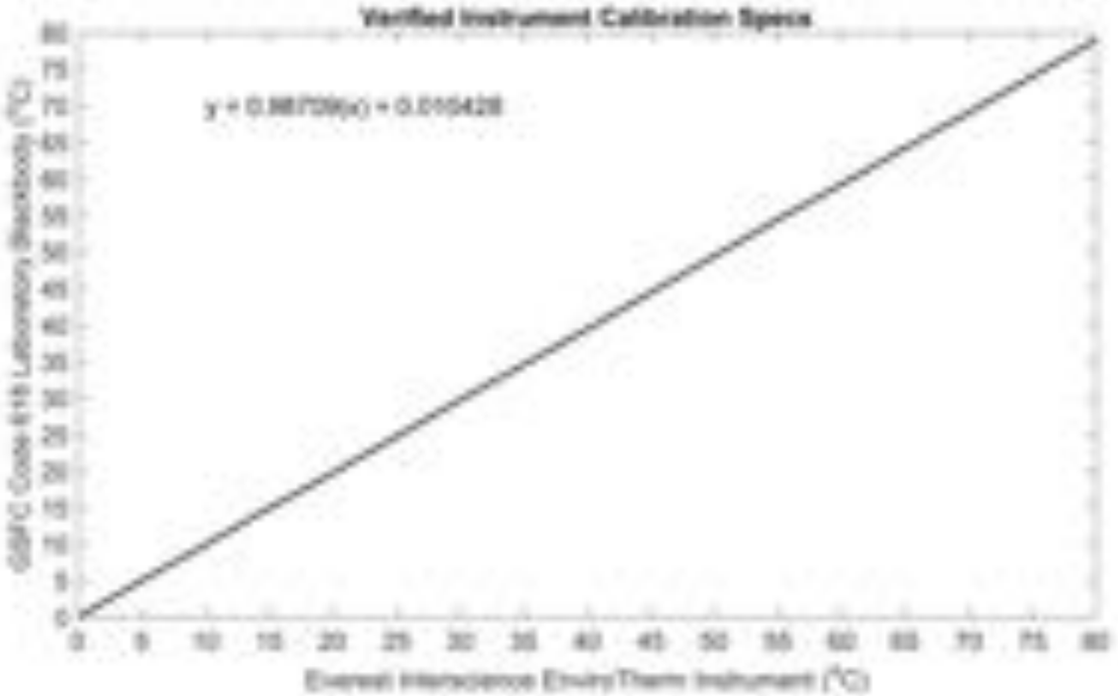
Equation 2 (Fuchs and Tanner 1966)

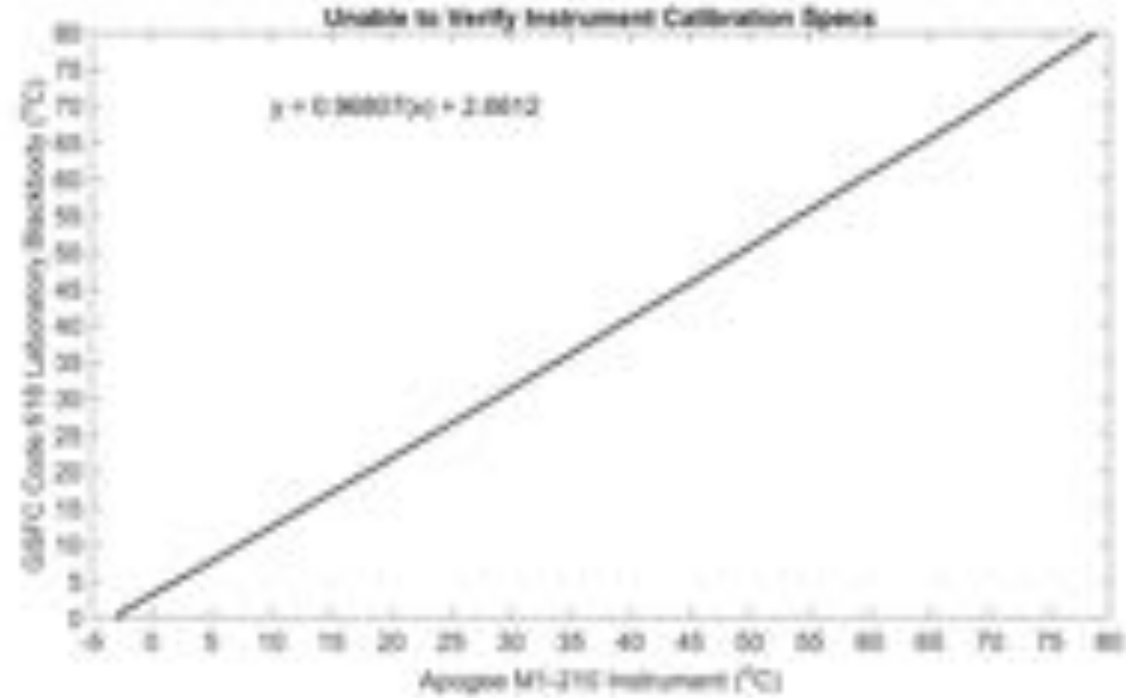
$$W(\lambda)d\lambda = e_\lambda\ E(\lambda,T)d\lambda + (1-e_\lambda)B(\lambda,T_\delta)d\lambda$$

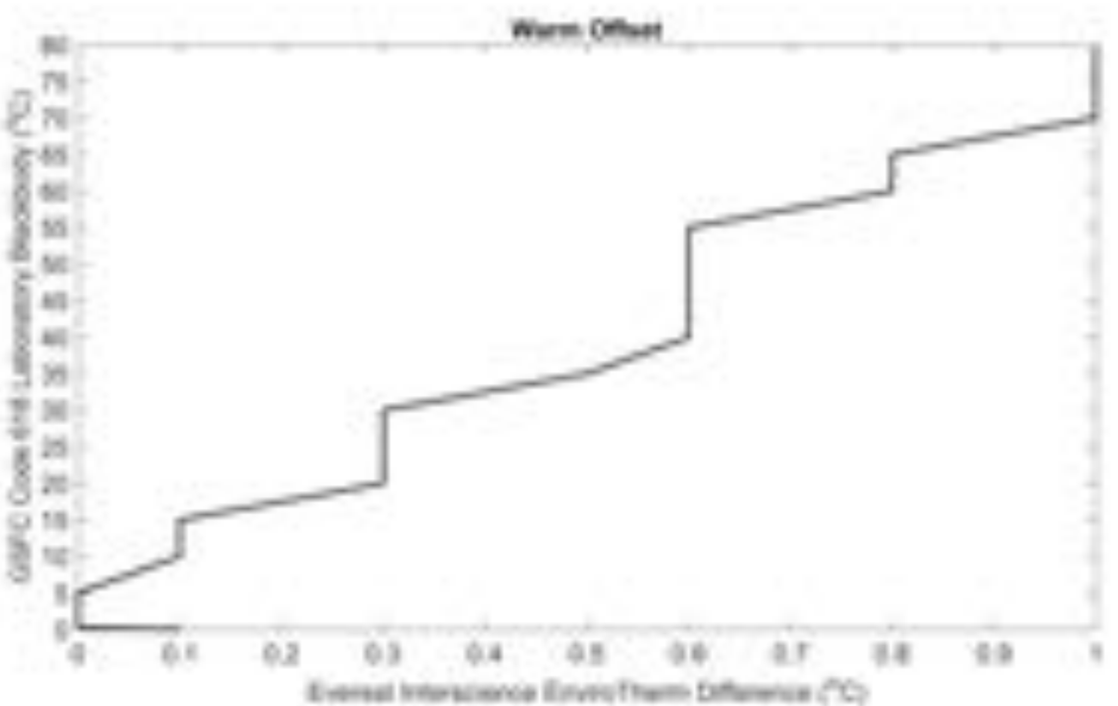
where:

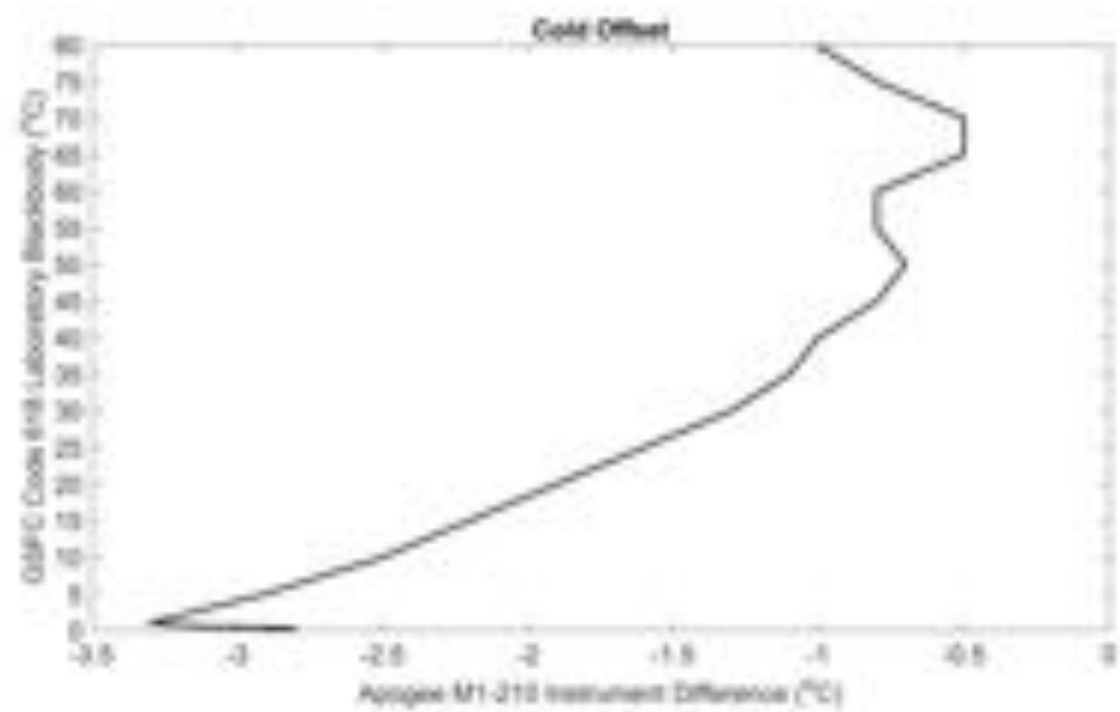
$W(\lambda)d\lambda$ outward flux of thermal energy λ
e_λ is emissivity of surface at wavelength
$E(\lambda,T)$ is value of Planck's energy distribution law and surface temperature
$B(\lambda,T_\delta)$ is the radiant energy flux incident on the surface from the surrounding integrated radiative temperature

TIR Laboratory Calibration

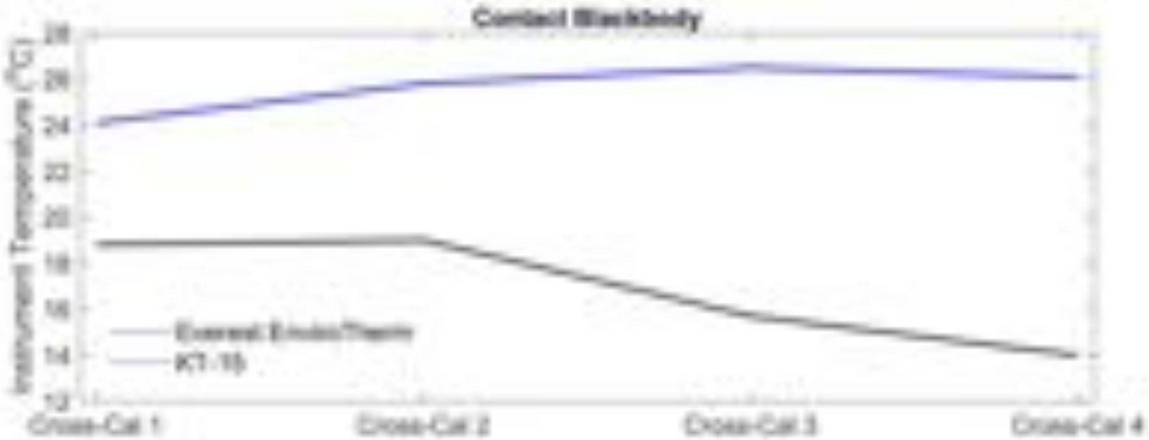


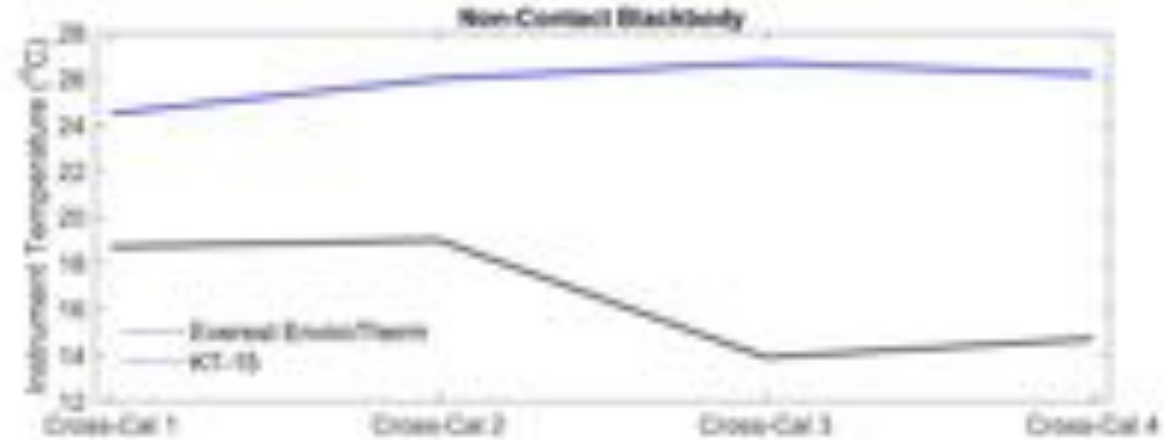


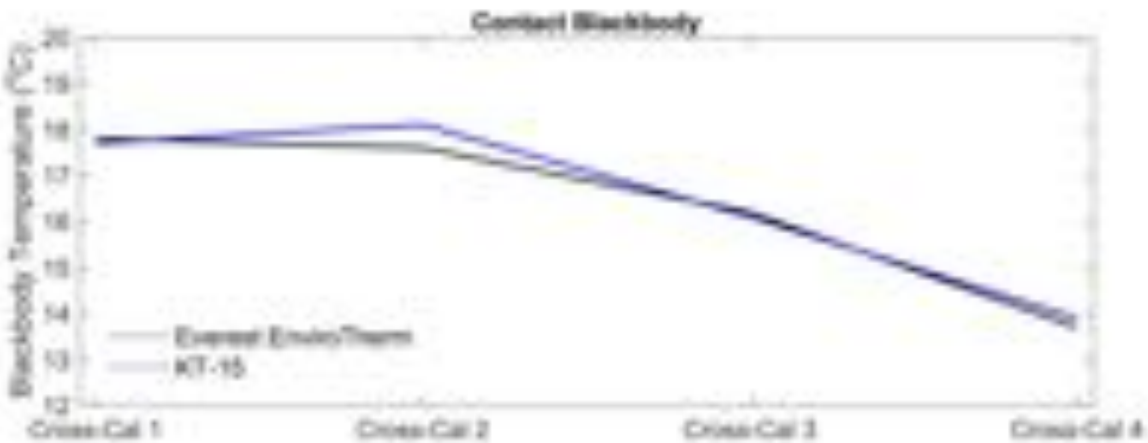


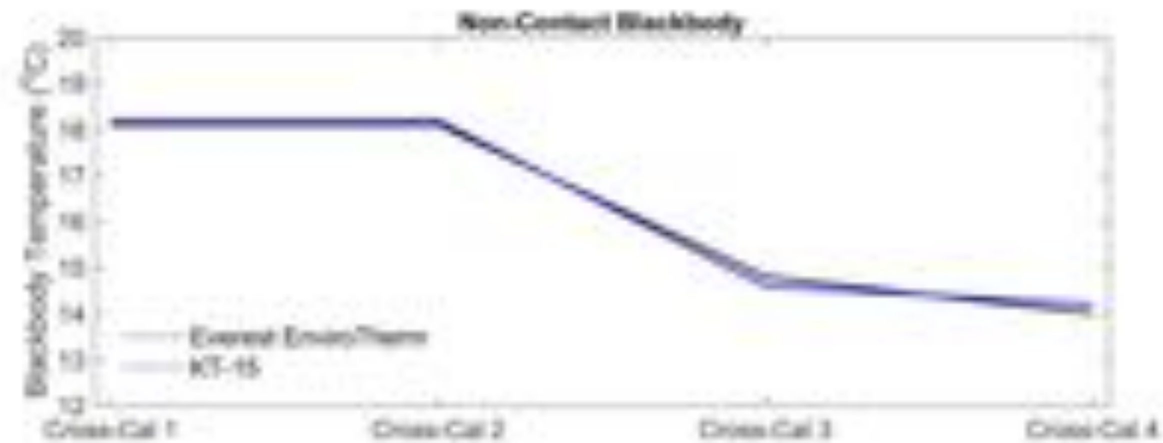


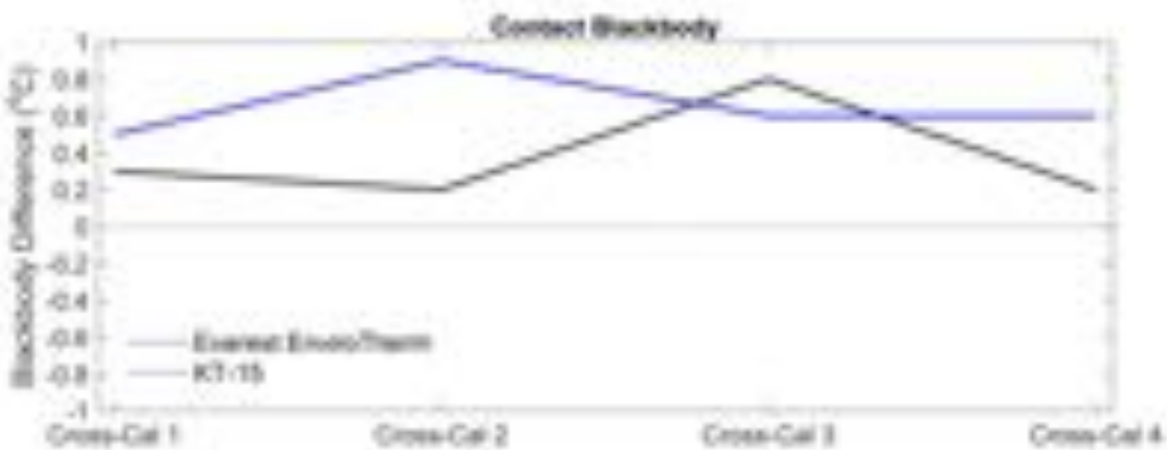
TIR P-3 Airborne Cross-Calibration

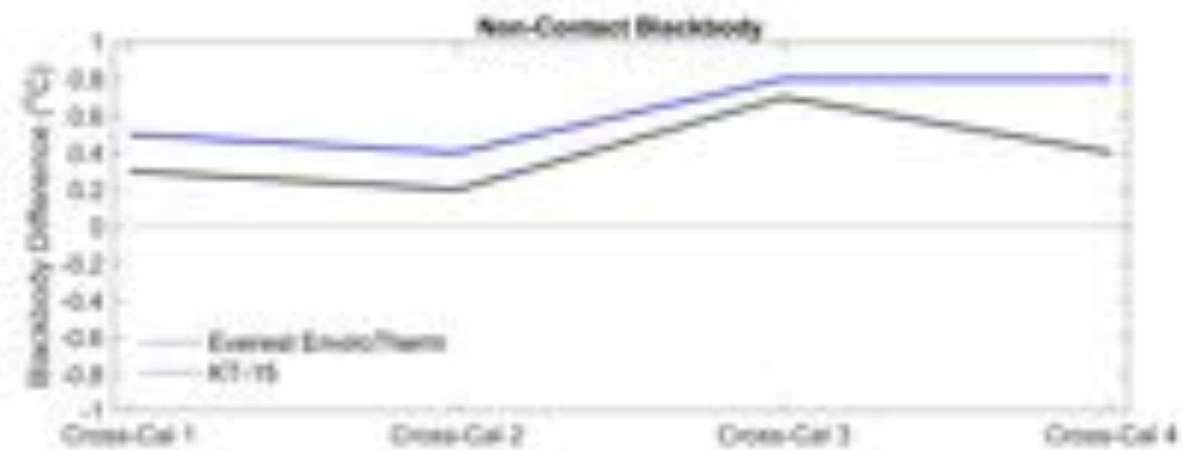




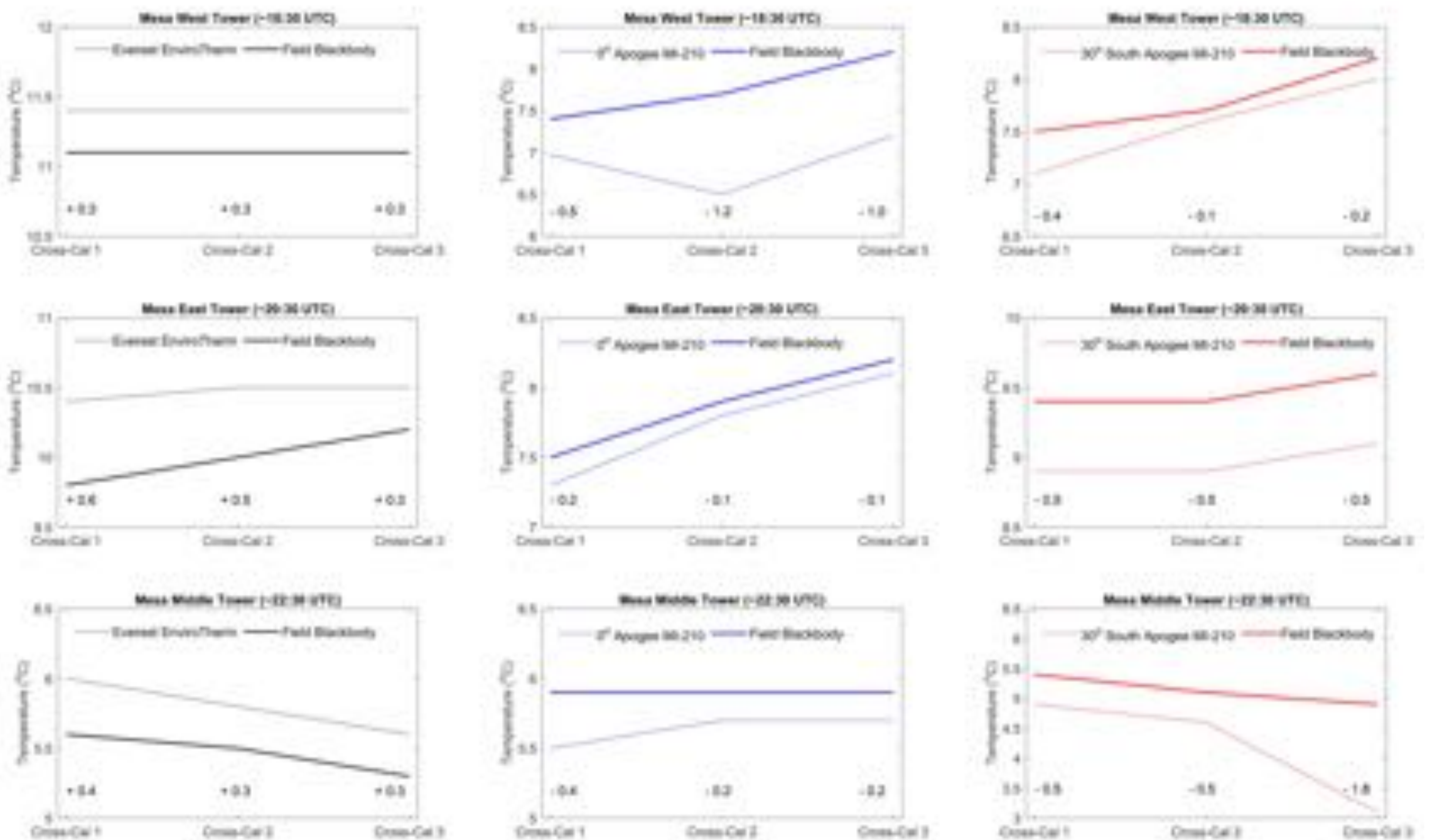




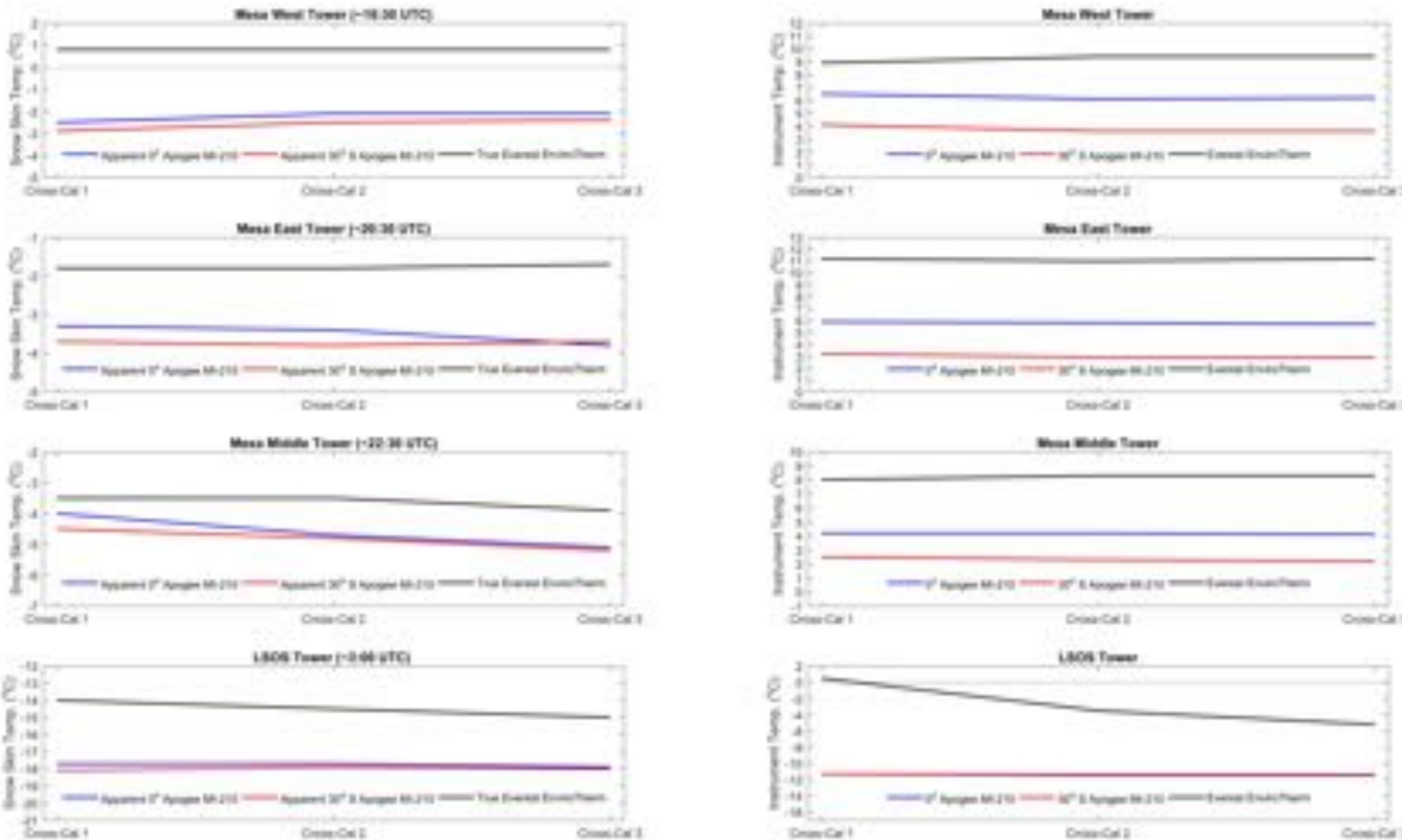




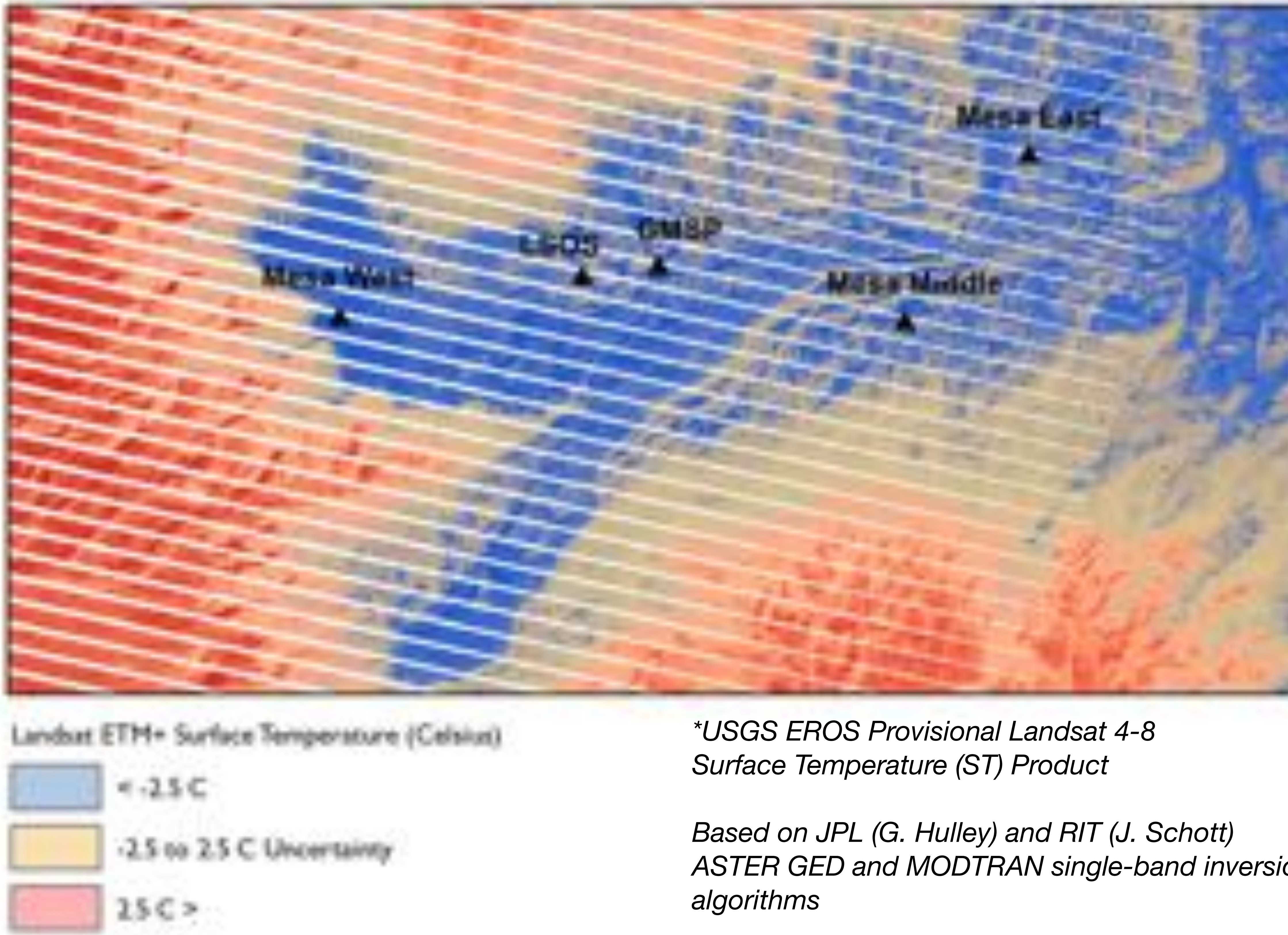
TIR Ground Meteorological Tower Cross-Calibration



TIR Meteorological Tower Snow Surface Temperature



Benchmarking Against On-Orbit Landsat-7 ETM+ TIR (Feb. 15, 2017)



**USGS EROS Provisional Landsat 4-8 Surface Temperature (ST) Product*

Based on JPL (G. Hulley) and RIT (J. Schott) ASTER GED and MODTRAN single-band inversion algorithms

Summary of TIR Challenges & The Way Forward

1. Ground and airborne TIR instrument calibration is challenging due to changing physical (i.e., local winds, radiative heating) and logistical factors

2. Involvement of multiple TIR instruments with different spectral response functions, manufacturer calibration procedures, & variation in blackbody sources introduces additional complexity

3. Limited access to stable and traceable cold blackbody sources to support low temperature studies

4. Local radiative environment, sky radiation and temperature effects, & variations in the emissivity coefficient cannot be overlooked

5. If SnowEx wants to pursue a TIR measurement design, then calibration must be central to this effort to clearly define snow measurement and science needs & requirements

Grand Mesa VSWIR Instrument Calibration / Ground Measurements

GSFC NIST Traceable Source

Snow Transect Measurements (*L*)

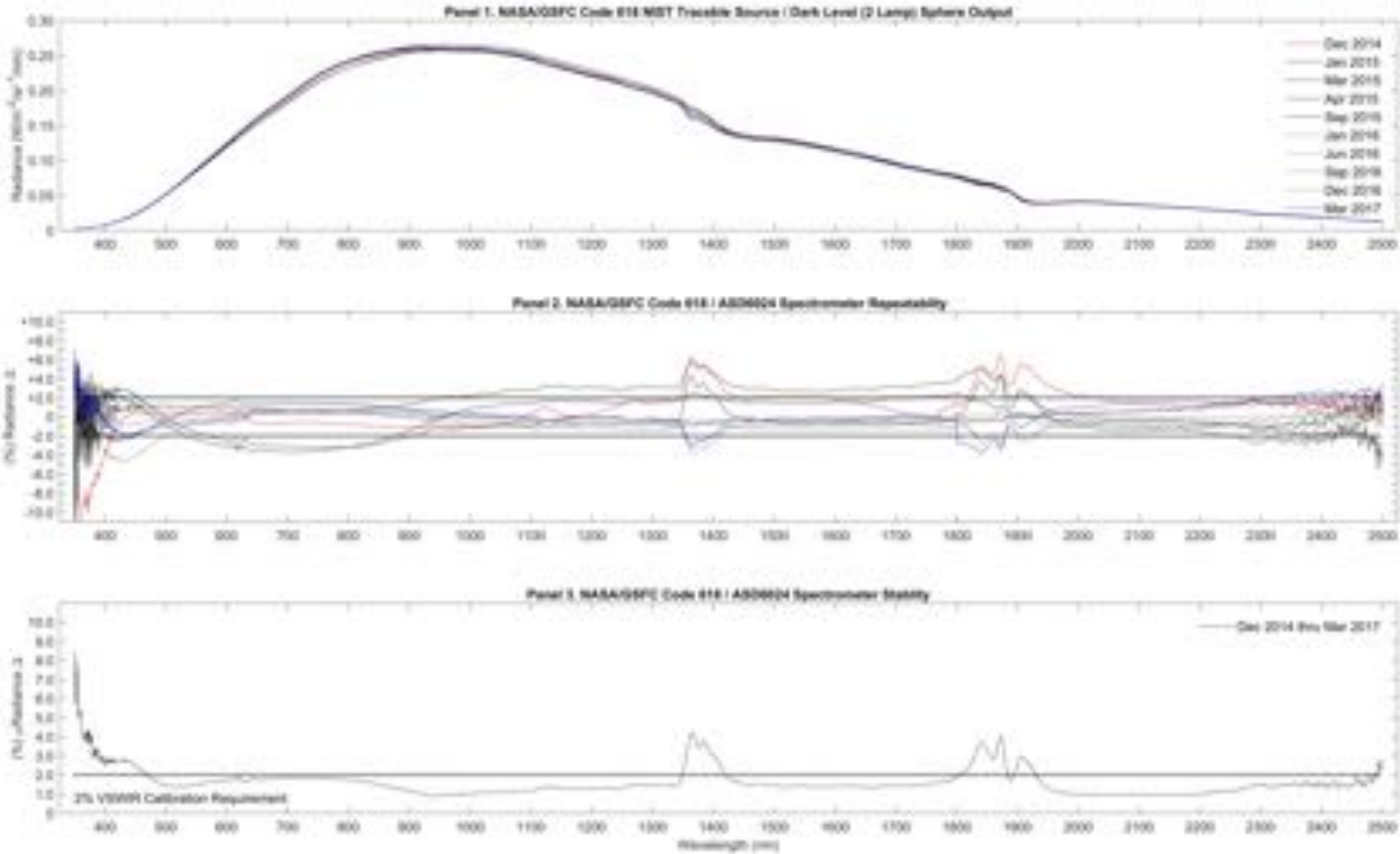
Snow Pit Upwelling (*E*)

Spectrometer Cross-Calibration

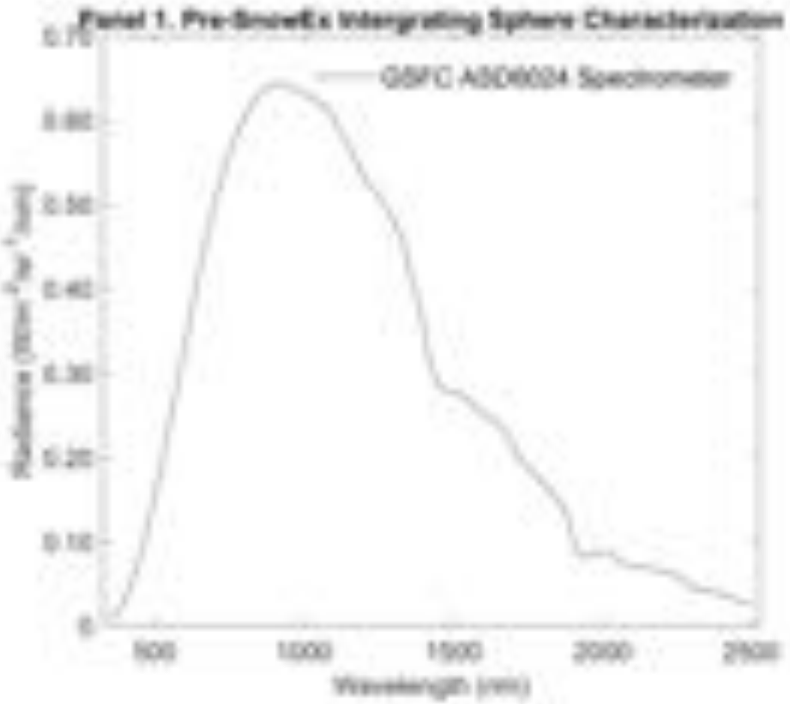
Feb. 13th: SnowEx training
Feb. 14th: VSWIR logistics & protocols
Feb. 15th: TIR ground met tower cross-cal
Feb. 16th: VSWIR science data / ASO flight
Feb. 17th: VSWIR science data
Feb. 18th: VSWIR spectrometer cross-cal

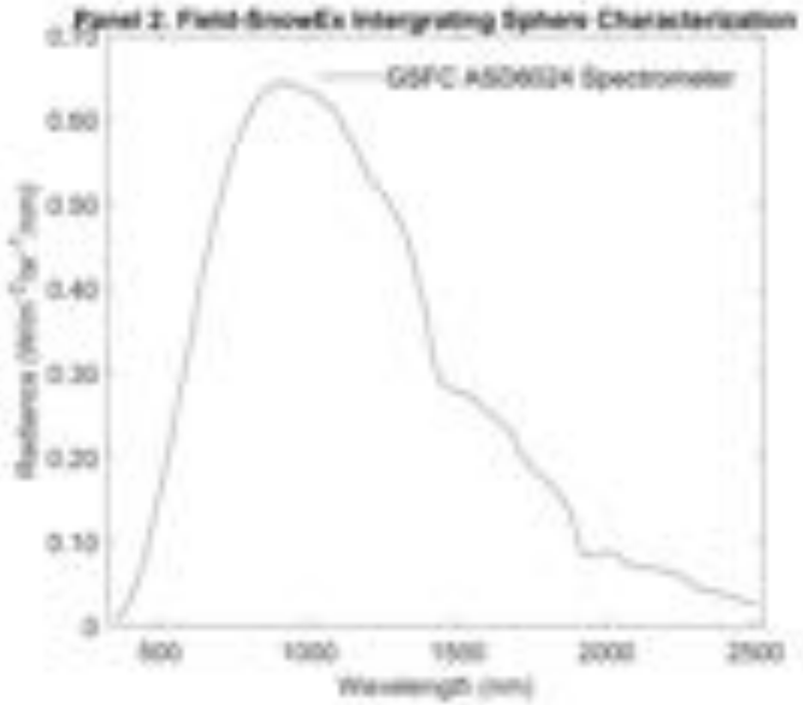
Snow Pit Downwelling (*E*)

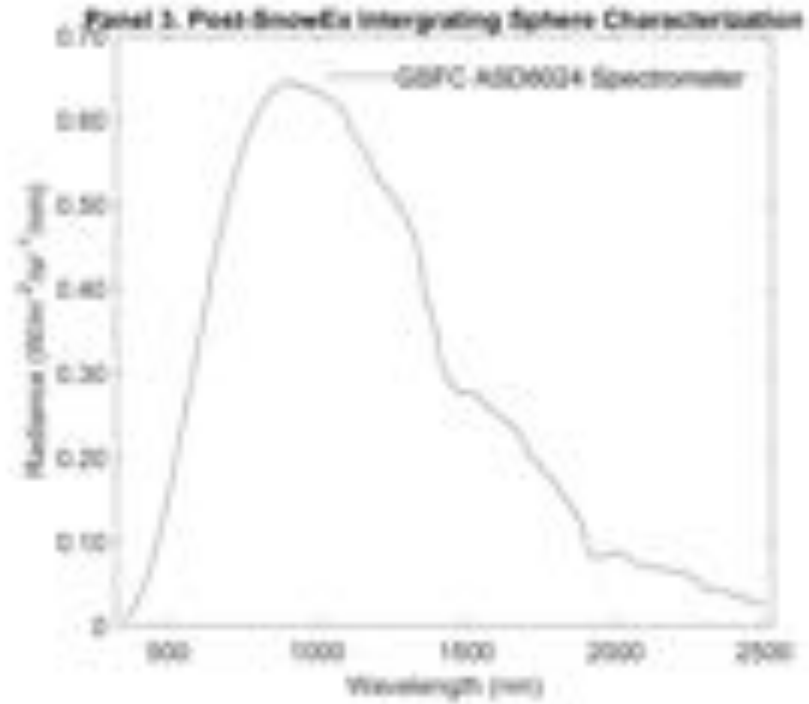
GSFC VSWIR Spectrometer Laboratory Characterization / Calibration

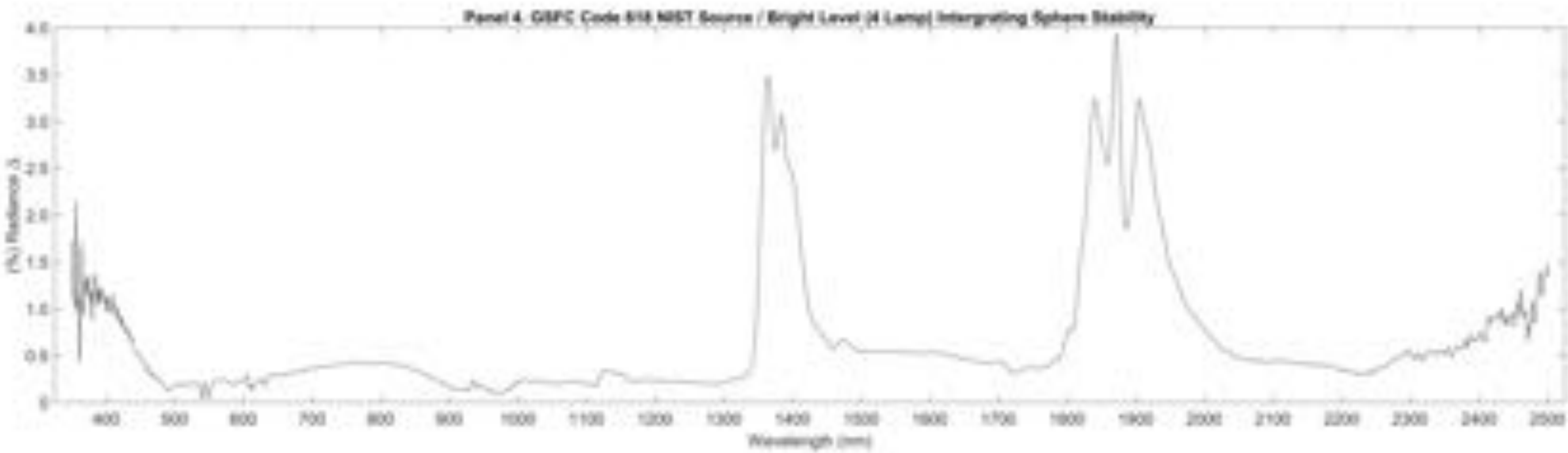


GSFC NIST Traceable Source Characterization

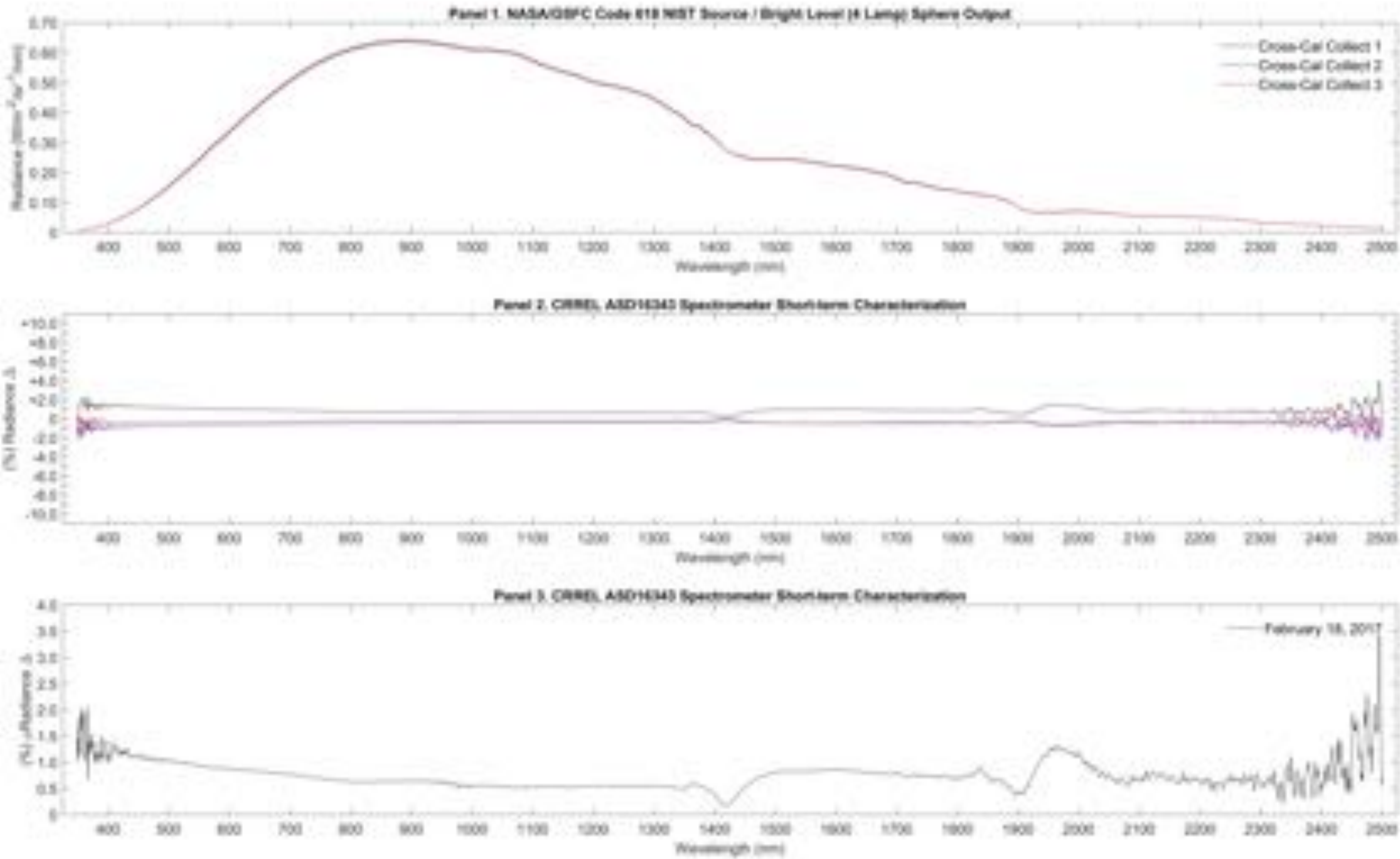




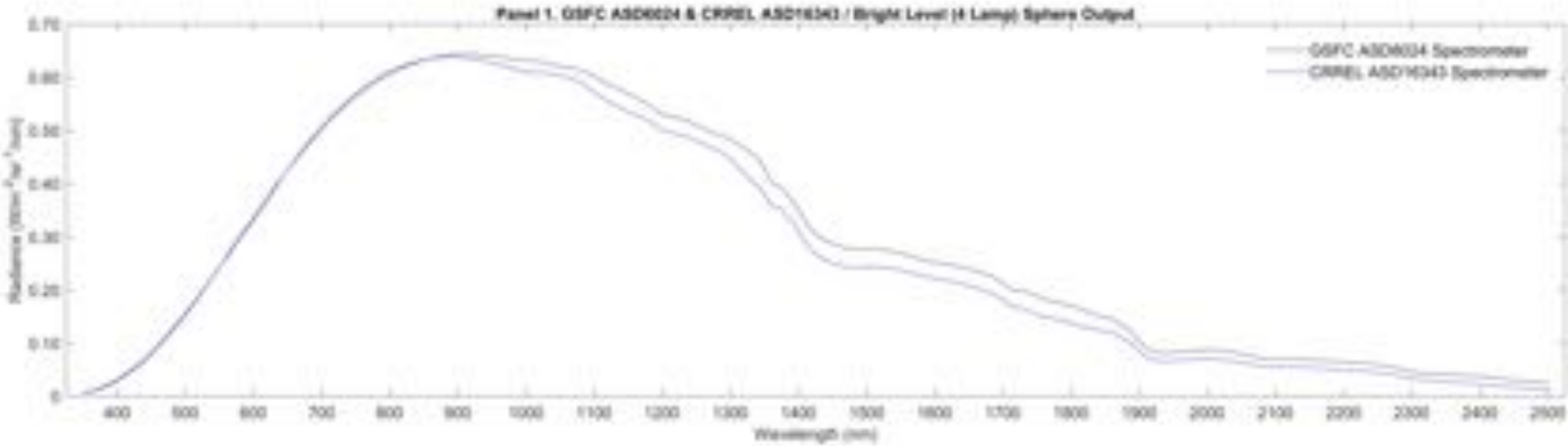


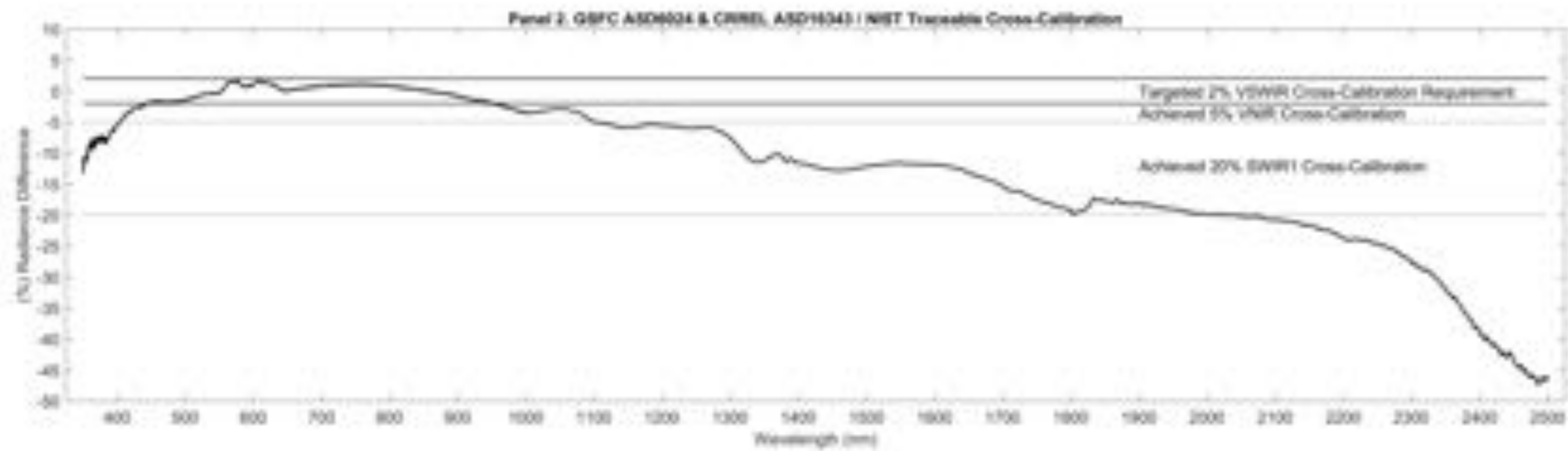


CRREL VSWIR Spectrometer Short-term Characterization

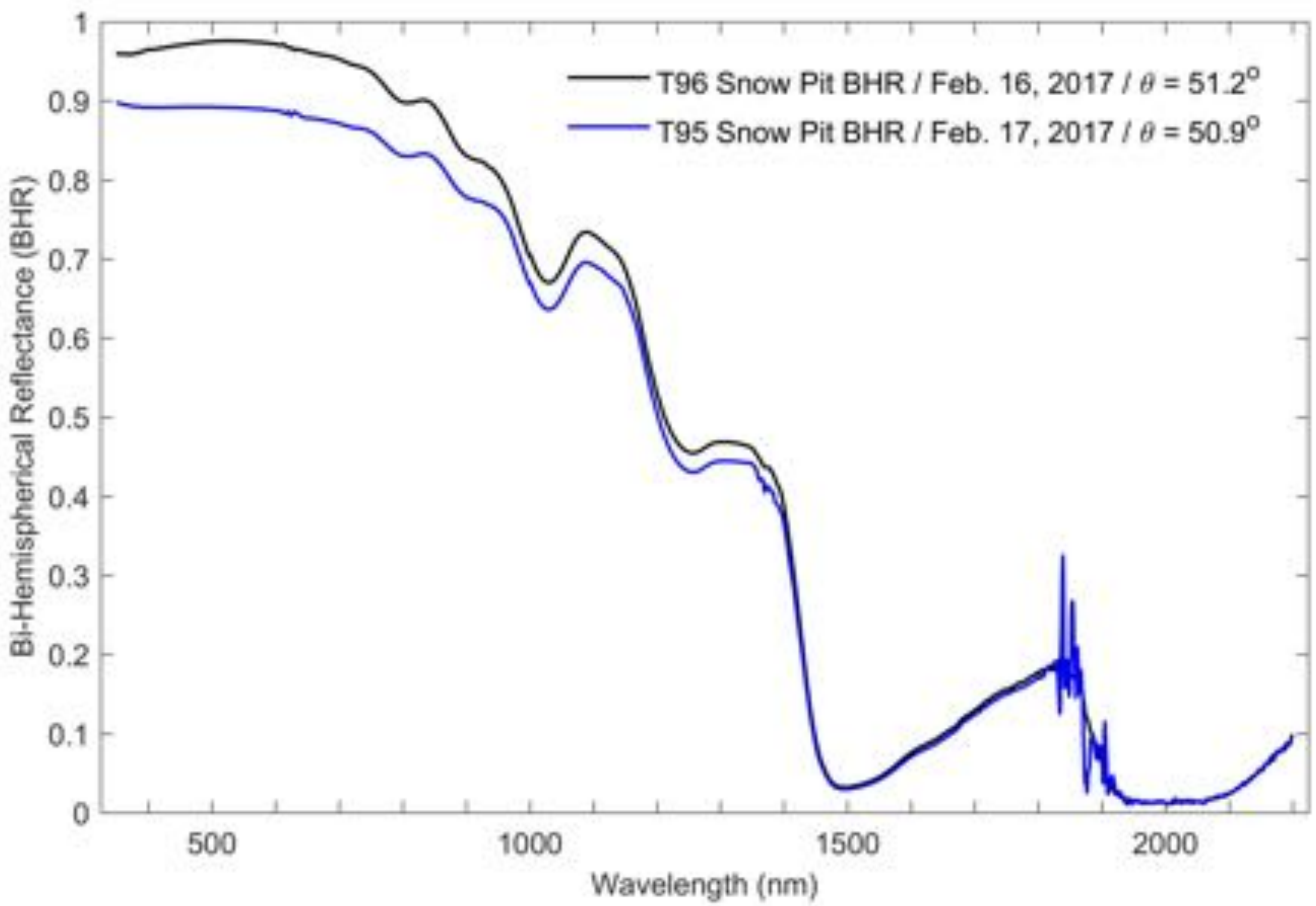


GSFC & CRREL VSWIR Spectrometer Cross-Cal for Grand Mesa

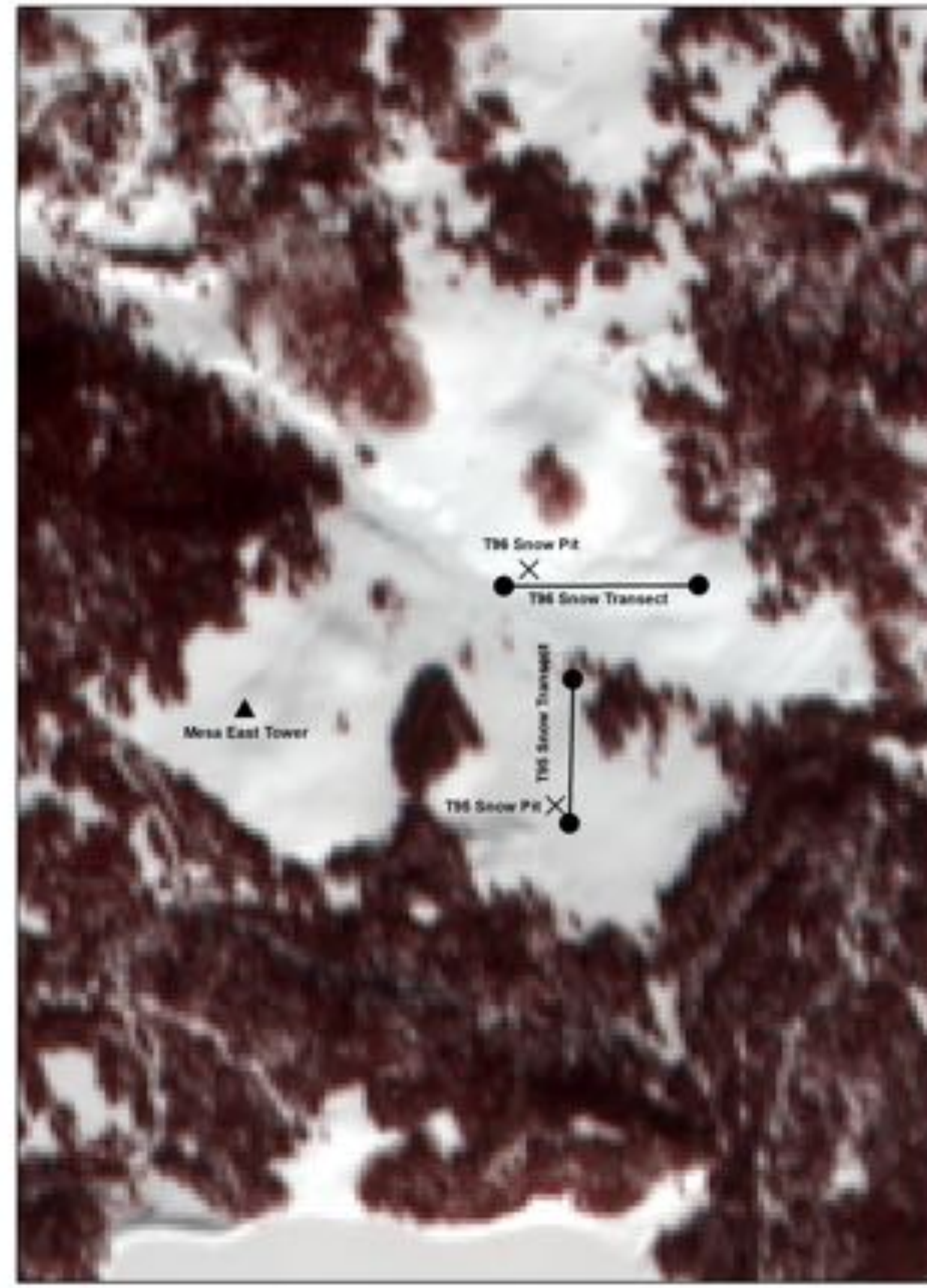




GSFC VSWIR Snow Pit Measurements (Grand Mesa Week 2)



Sentinel-2A MSI: February 14, 2017



$$BHR_{\lambda} = \frac{E_{up,\lambda}(\theta_v, \theta_o, \Phi)}{E_{down,\lambda}(\theta_v, \theta_o, \Phi)}$$

Schaepman-Strub et al (2006)

where:

λ is wavelength
E_{up} is upwelling spectral irradiance

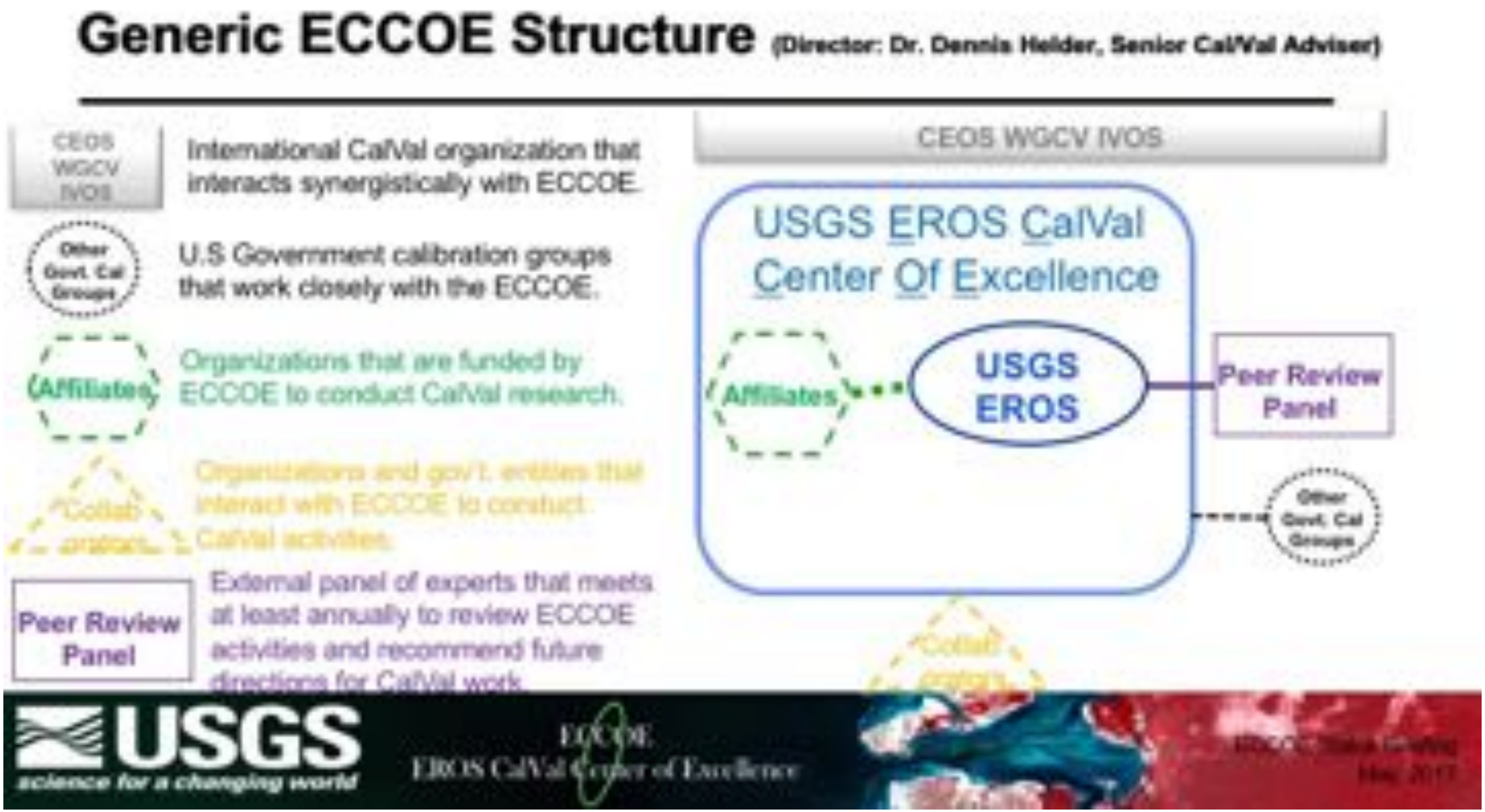
E_{down} is downwelling spectral irradiance

θ_v is viewing angle

θ_o is solar zenith angle

Φ is solar azimuth

Why Cal/Val Matters for SnowEx and its Satellite Mission Design



USGS/NASA Landsat 10 & Sustainable Land Imaging (SLI) Measurements / Snow Science Requirements

(1) NASA currently has solicitations out on technology innovations under the SLI program https://sustainablelandimaging.gsfc.nasa.gov

(2) USGS released RFIs on Landsat 10 and SLI user requirements in 2016 & 2017 https://remotesensing.usgs.gov/rca-eo/

(3) The 2012-2017 USGS Landsat Science Team (LST) has made significant contributions to the requirements process via individual members and within LST working groups https://landsat.usgs.gov/landsat-science-team-meeting-jul-2017

(4) USGS Reston and 2012-2017 USGS LST jointly held a 'Landsat Spectral Band Workshop' in May 2017

(5) The outgoing 2012-2017 USGS LST is drafting a recommendation on Science, Measurements, and Data Product Requirements for Landsat 10 and beyond

Calibration Recommendations for Future SnowEx Campaigns

(1) Instrument calibration and cross-calibration between investigators/institutions reduces measurement uncertainty and enables radiometric continuity

(2) Traceability is foundational for evaluating an instrument's radiometric performance

(4) Adhering to national and international standards fosters a Cal/Val best practices mentality

(5) Cal/Val is often a meticulous and time consuming process that does not always lead to cutting edge science results, but is essential for benchmarking progress

(6) Development of a coordinated SnowEx Cal/Val plan with broad cross-calibration participation is recommended for future campaigns