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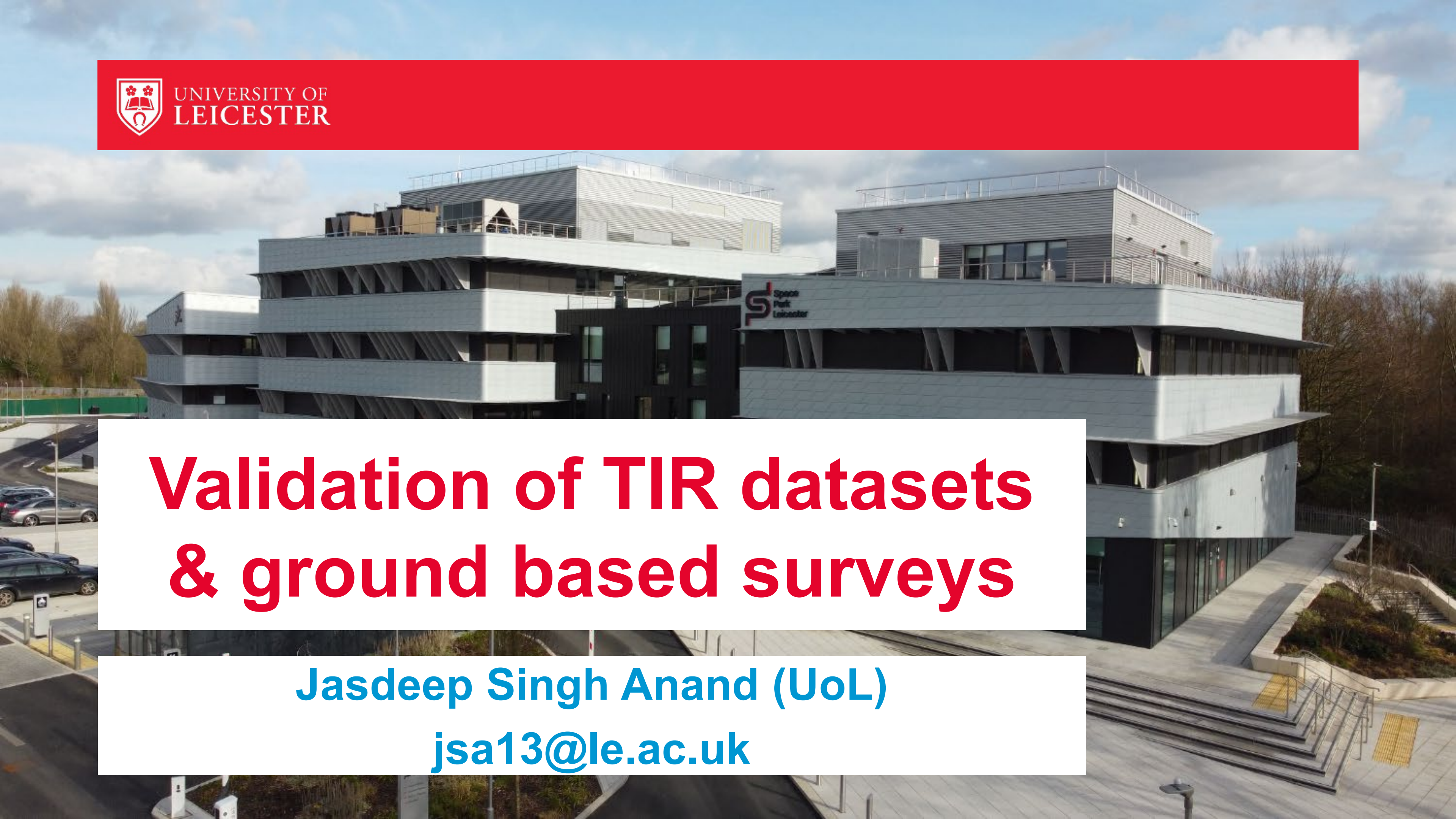


Validation of TIR datasets & ground based surveys

Jasdeep Singh Anand (UoL)
jsa13@le.ac.uk

The need for validation

GCOS Implementation Plan (2016)

Property	Threshold	Goal
Accuracy/Precision	< 1 K	< 1 K
Stability	0.3 K decade^{-1}	0.1 K decade^{-1}

Satellite LST retrieval uncertainty sources

Instrumental	• Detector noise • ISRF • Geolocation
Atmospheric	• H_2O • Other trace gases • Atmospheric temperature
Scene	• Surface emissivity • Shadows • Cloud cover

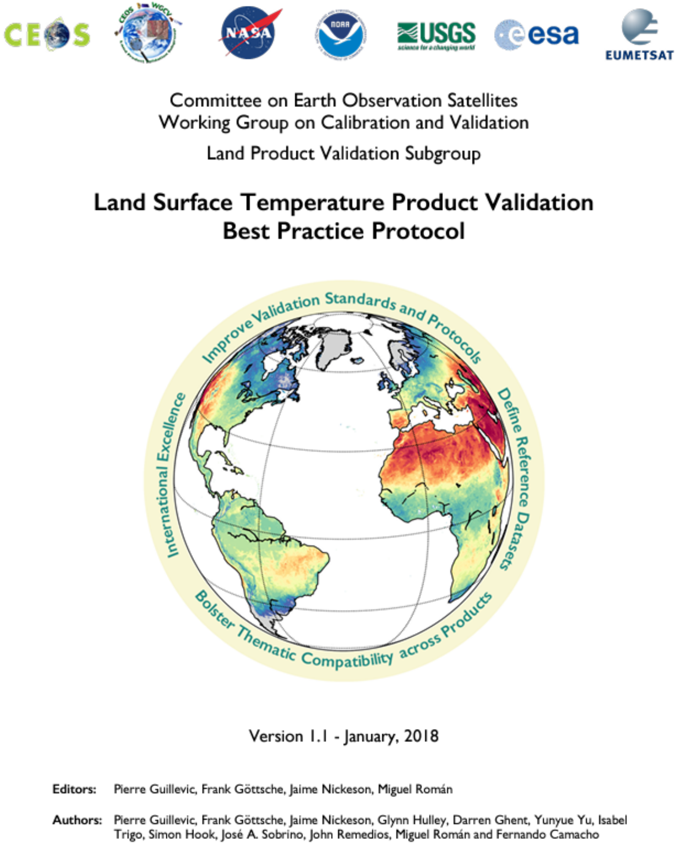
Definitions

- **Accuracy:** closeness of the agreement between the measured LST and the truth
- **Precision:** closeness of the agreement between the results of successive LST measurements
- **Stability:** Long-term drift due to degradation in instrument accuracy

Why in situ LST?

- Need for validation over different biomes/climates
- Direct comparison of measured LST possible
- Both upwelling and downwelling radiances can be measured directly – no RTM required to retrieve LST

The CEOS LST Validation Protocol



Committee on Earth Observation Satellites
Working Group on Calibration and Validation

Land Product Validation Subgroup

Land Surface Temperature Product Validation
Best Practice Protocol

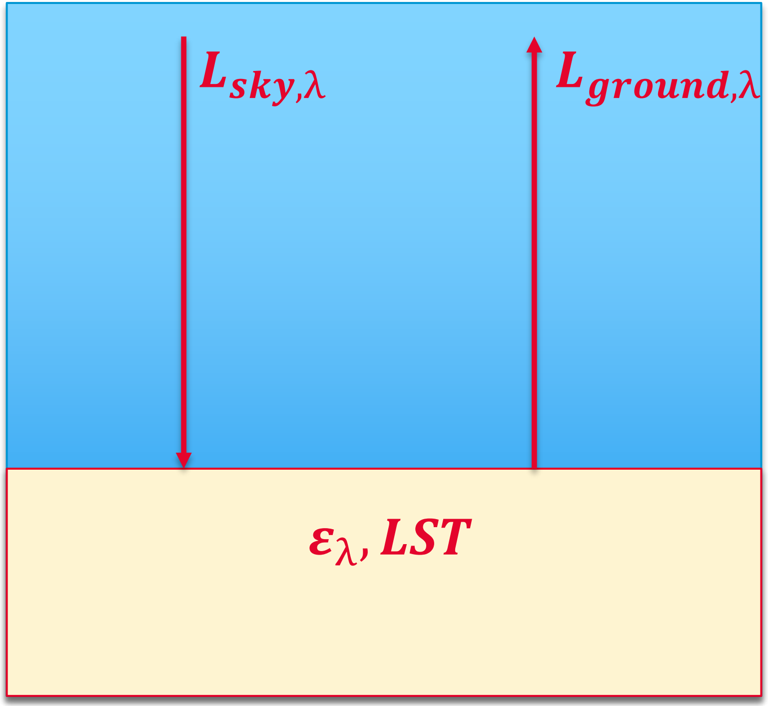
Version 1.1 - January, 2018

Editors: Pierre Guillevic, Frank Göttsche, Jaime Nickeson, Miguel Román

Authors: Pierre Guillevic, Frank Göttsche, Jaime Nickeson, Glynn Hulley, Darren Ghent, Yunyue Yu, Isabel Trigo, Simon Hook, José A. Sobrino, John Remedios, Miguel Román and Fernando Camacho

https://lpvs.gsfc.nasa.gov/PDF/CEOS_LST_PROTOCOL_Feb2018_v1.1.0_light.pdf

In situ LST retrievals



- Land surface radiance (***B***):

$$B = \frac{L_{ground,\lambda} - (1 - \varepsilon_\lambda) \cdot L_{sky,\lambda}}{\varepsilon_\lambda}$$

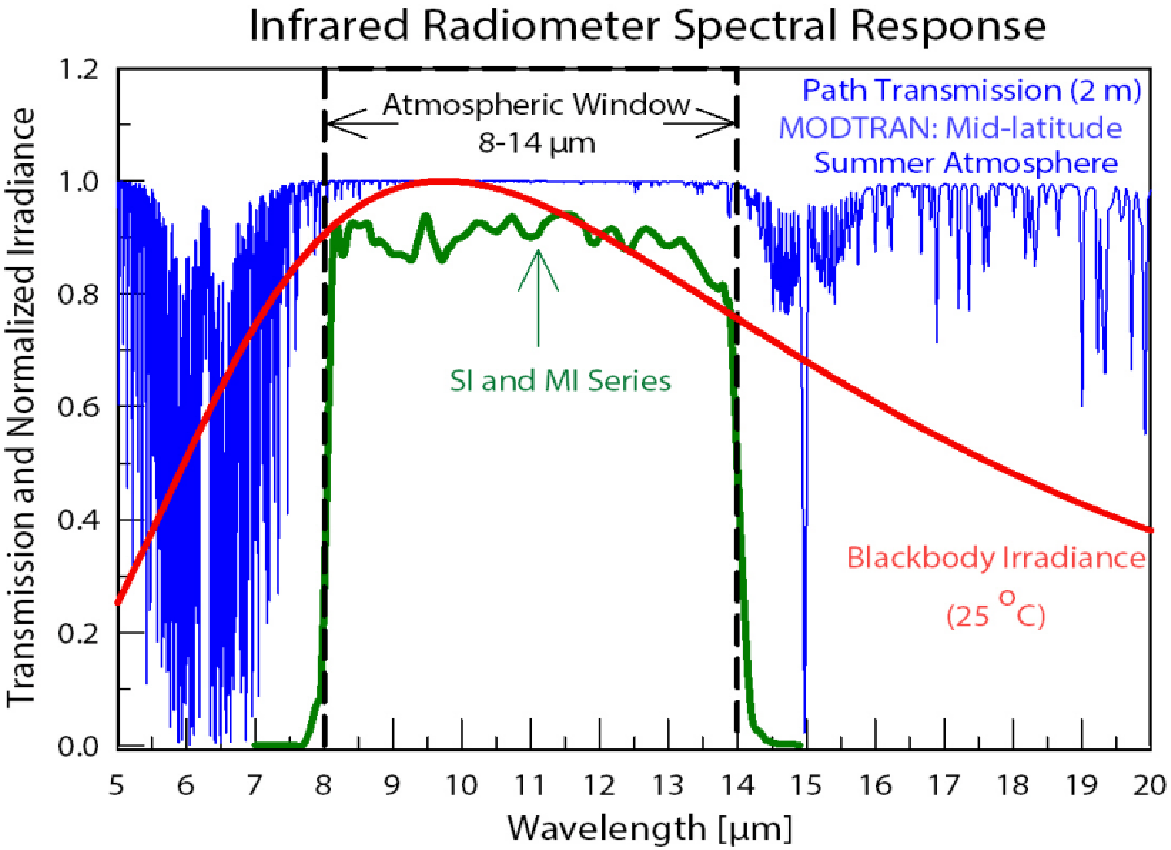
- For **narrow-band** instruments:

$$LST = \frac{2 \cdot h \cdot c^2}{\lambda \cdot \ln\left(\frac{h \cdot c}{B \cdot k \cdot \lambda^5} + 1\right)}$$

- For **broadband** instruments:

$$LST = \sqrt[4]{\frac{B}{\sigma}}$$

The 8 – 14 µm atmospheric window



https://www.apogeeinstruments.com/content/SI-100-400-spec-sheet.pdf

Radiometers II: Heitronics KT15.85 IIP

- **Chopped pyrometer** (measures both target and internal radiance for greater accuracy)
- **FOV**: 16°/29°/66° (interchangeable lenses)
- **Spectral band**: 9.6 – 11.5 μm
- **Accuracy**: 0.5 K (+ 0.7% of target-to-sensor temperature difference)
- **Stability**: < 0.1% year^{-1}
- **Cost**: ~£6500
- **Power**: 3.5 W (10.5 – 30 V DC), or 24 V AC

https://www.heitronics.com/en/product/radiation-thermometer/versatile-specialists/kt15-iip/

Radiometers I: Apogee Instruments SI-121-SS

- **Thermopile** radiation detector + reference thermistor for sensor temperature measurement
- **FOV**: 18°
- **Spectral band**: 8 – 14 μm
- **Accuracy**: 0.2 - 0.5 K (target – detector temperature bias dependent)
- **Precision**: 0.05 K
- **Stability**: < 2% yr^{-1}
- **Cost**: ~£400
- **Power**: 2.5 V DC (excitation only)

https://www.apogeeinstruments.com/si-121-ss-research-grade-narrow-field-of-view-infrared-radiometer-sensor

Radiometers I: Apogee Instruments SI-121-SS

- BT measured by this instrument (T_T) is a function of both **sensor temperature** (T_D) and **thermopile voltage** (V_D):

$$T_T = \sqrt[4]{\left({T_D}^4 + m \cdot V_D + b\right)}$$

- Where:
  - $m = mC2 \cdot {T_D}^2 + mC1 \cdot T_D + mC0$
  - $b = bC2 \cdot {T_D}^2 + bC1 \cdot T_D + bC0$
- mC0, mC1, etc. obtained from varying blackbody *and* ambient temperature – **difficult to recalibrate alone!**
- Due to drift, it's recommended to return instrument for recalibration every 2 years.

https://www.apogeeinstruments.com/si-121-ss-research-grade-narrow-field-of-view-infrared-radiometer-sensor

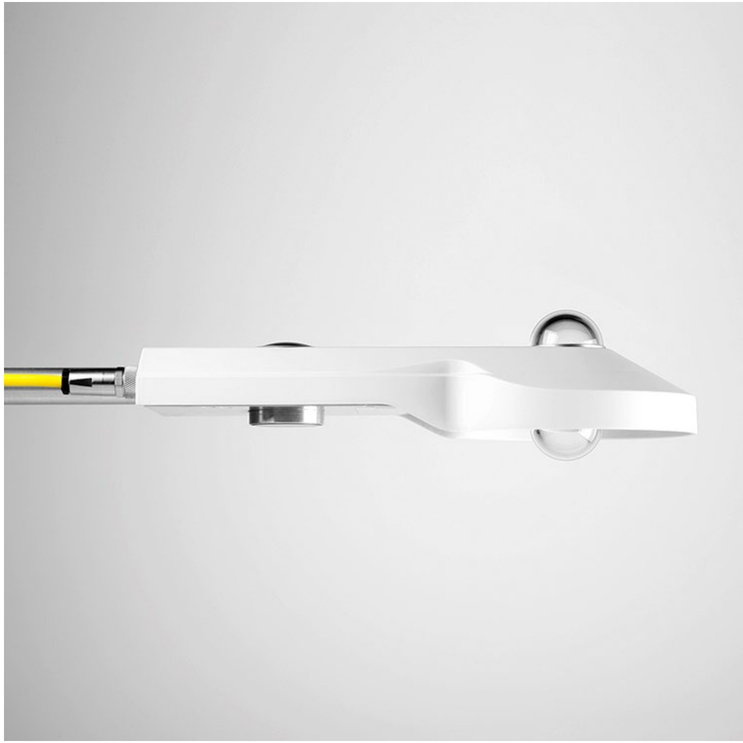
Radiometers III: Cimel CE312

- **Multi-channel radiometer** (filter wheel)
- **FOV**: 10°
- **Spectral bands**: 8 – 14, 8.2 – 9.2, 10.3 – 11.3, 11.5 – 12.5 μm (ASTER and other bands possible on request)
- **Accuracy**: 0.1 K
- **Cost**: ~£30,000
- **Power**: mains electricity (AC, charges battery for short-term campaigns)
- Must be connected to Windows PC at all times

https://www.cimel.fr/ce312/

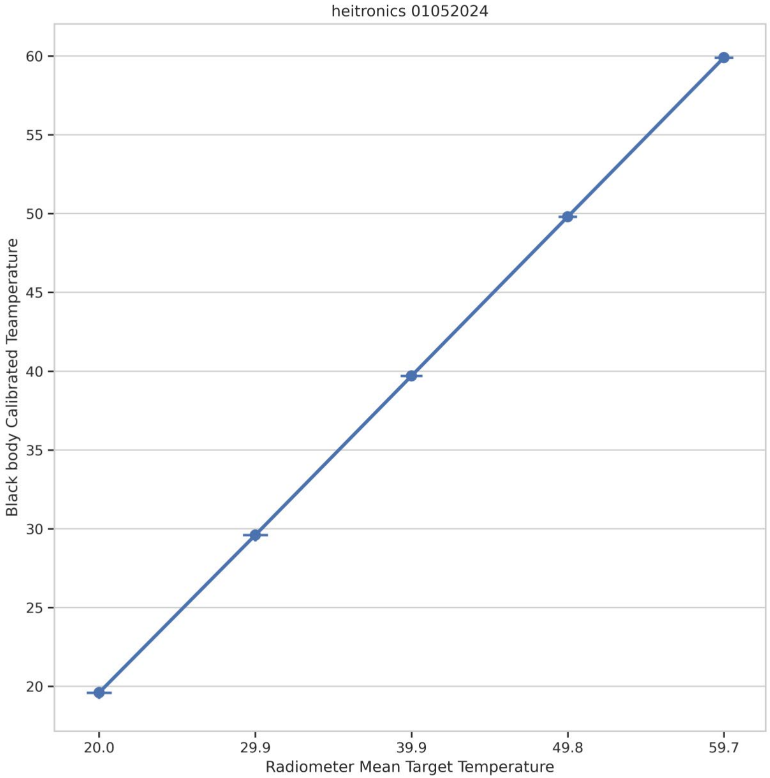
Radiometers IV: Kipp & Zonen CNR4

- **Net radiometer** (hemispherical pyrgeometer), which simultaneously measures L_{ground} and L_{sky} using 2 thermopiles
- **FOV**: 180°
- **Spectral band**: 4.5 – 42 μm (broadband)
- **Stability**: < 1% year^{-1}
- **Power**: 15 W (ventilator & heater)
- **Cost**: ~£6000



https://www.kippzonen.com/Product/85/CNR4-Net-Radiometer

Laboratory calibration



Deploying radiometers in the field

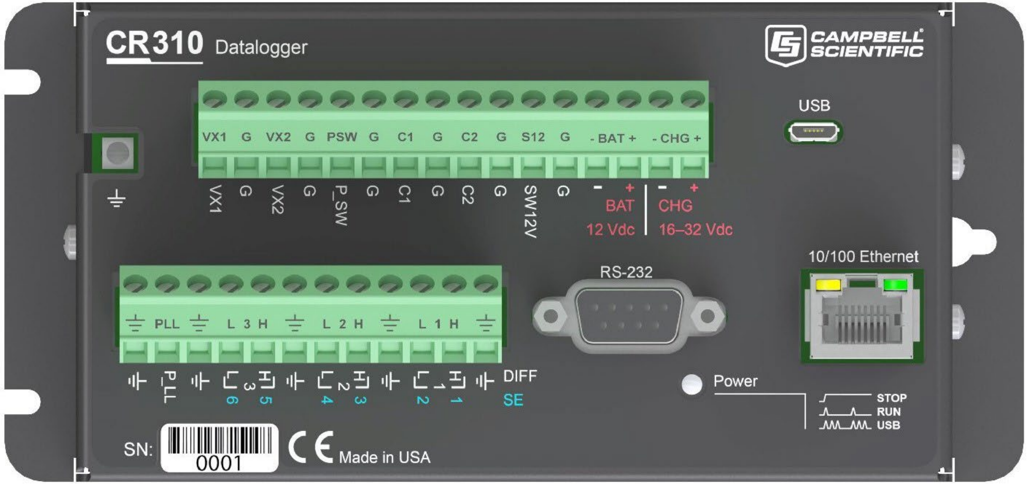
Heitronics KT15.85 IIP

$L_{ground,\lambda}$

Apogee SI-121-SS

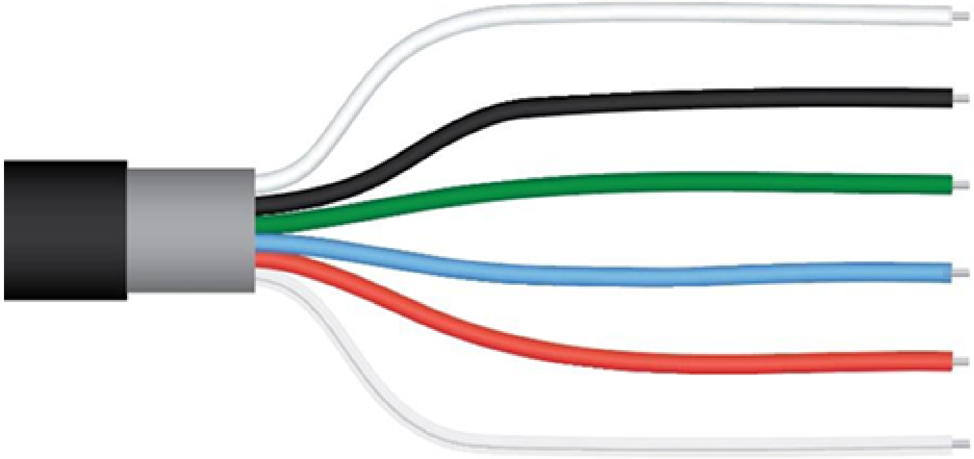
$L_{sky,\lambda}$

The Campbell Scientific CR310 data logger



- **Cost**: ~£1200
- **Storage**: 30 MB flash memory (+1 year)
- Measures both **analogue voltage** (-0.1 – 2.5 V, DIFF 1 - 3) and **current** (0 – 20 mA, SE1 and SE2) signals
- **Switched 12 V DC** terminal (SW12V) for powering sensors
- **2 sensor excitation** (0.15 – 5 V) terminals (VX1 & VX2)
- Programmable using proprietary **CRBasic** language (incl. thermistor voltage to temperature functions)
- **Ethernet** and **RS232** ports (variants with cellular modem also available)
- Can transmit data either via **USB**, or internet protocols (**FTP, HTTP**)

Wiring the SI-121-SS



White: High side of differential channel (positive thermopile lead)

SE3

Black: Low side of differential channel (negative thermopile lead)

SE4

Green: Single-ended channel (positive thermistor lead)

SE5

Blue: Analog ground (negative thermistor lead)

Ground

Red: Excitation channel (excitation for thermistor)

VX1

Clear: Shield/Ground

Ground

https://www.apogeeinstruments.com/content/SI-100-manual.pdf

Programming the SI-121-SS

```
'Declare public variables (Apogee)
Public SBTempC, SBTempK, TargmV, m, b, TargTempK, TargTempC

'Declare original calibration constants for the Apogee
Const mC2 = 158421.0
Const mC1 = 17997500.0
Const mC0 = 2998800000.0
Const bC2 = 9639.19
Const bC1 = -257712.0
Const bC0 = -11914800.0
```

Programming the SI-121-SS

```
'Define data table (Table_op will contain the mean data recorded every 60 seconds)

DataTable (Table_op,1,-1)

  DataInterval (0,60,Sec,0)

  Average (1,TargTempK,FP2,False)

EndTable


'Main program (program is making a measurement every 2 seconds)

BeginProg

Scan (2,Sec,0,0)


'Instruction to measure sensor body temperature in C (green to SE5, red wire to VX1, blue wire to ground)

Therm109 (SBTempC,1,5,VX1,0,_60Hz,1.0,0)
```

Programming the SI-121-SS

```
'Instruction to measure mV (-2.2 – 2.2 mV) output of thermopile detector (white wire to 2H, black wire to 2L, clear wire to ground)

VoltDiff (TargmV,1,mV34,2,True ,0,60,1.0,0)


'Calculation of m (slope) and b (intercept) coefficients for target temperature calculation

m = mC2 * SBTempC^2 + mC1 * SBTempC + mC0

b = bC2 * SBTempC^2 + bC1 * SBTempC + bC0


'Calculation of target temperature

SBTempK = SBTempC + 273.15

TargTempK = ((SBTempK^4) + m * TargmV + b)^0.25
```

Programming the SI-121-SS

```
'Call output tables and proceed to next scan

CallTable Table_op

NextScan

EndProg
```

Wiring the KT15.85 IIP

Role	Heitronics wire	CR310 terminal
Analogue power input	Brown (+)	SW12V
	White (-)	Ground
Analogue current output	Yellow (+)	SE1
	Green (-)	Ground

Programming the KT15.85 IIP

```
'Declare public variables (Heitronics)
Public Heitronics


'Define data table (table is outputting data every 60 seconds; taking the mean of every 10 sec of observations)
DataTable (Table_op,1,-1)
  DataInterval (0,60,Sec,10)
  Average (1,Heitronics,FP2,False)
EndTable
```

Programming the KT15.85 IIP

```
'Main program
BeginProg


‘Activate 12 V DC current to Heitronics
  SW12 (2)


‘Take measurement every 2 seconds
  Scan (2,Sec,0,0)
```

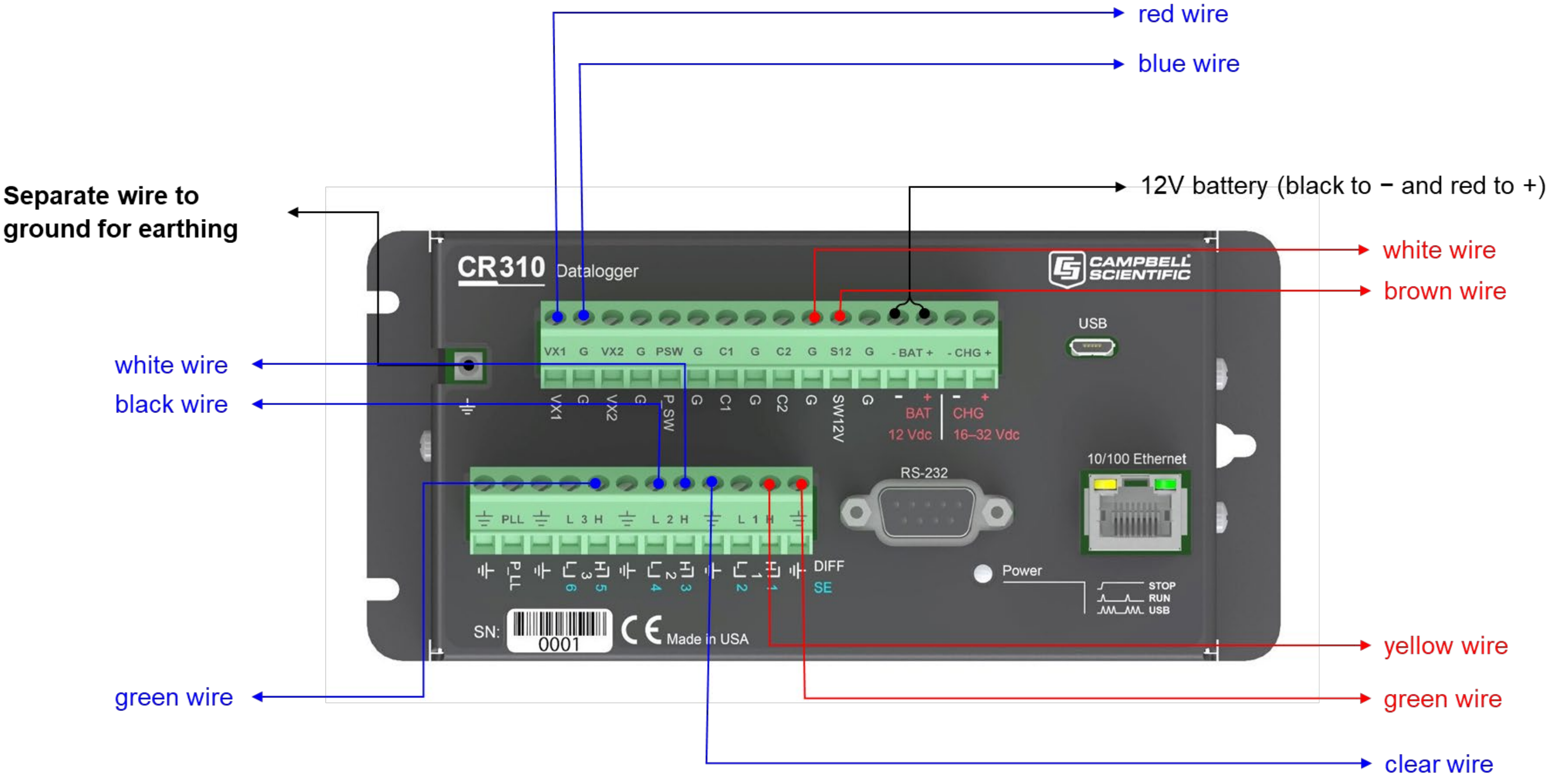
Programming the KT15.85 IIP

```
'Main program
BeginProg

‘Activate 12 V DC current to Heitronics
  SW12 (2)

‘Take measurement every 2 seconds
  Scan (2,Sec,0,0)
```

Programming the KT15.85 IIP

```
'Measures current output from Heitronics, and converts to temperature (yellow - 1H, green - ground)

‘The current signal varies between 0 – 20 mA, linearly scaling to a temperature range between -25 – 200 °C, so we use a multiplier: 225 / 20 = 11.25, and offset: -25.0 to convert directly to temperature

CurrentSe (Heitronics,1,mV2500,1,0,500,50,11.25,-25.0)

Heitronics = Heitronics + 273.15


'Call output tables and proceed to next scan

CallTable Table_op

NextScan

EndProg
```

Combined wiring diagram



red wire

blue wire

12V battery (black to − and red to +)

Separate wire to ground for earthing

white wire

brown wire

white wire

black wire

yellow wire

green wire

green wire

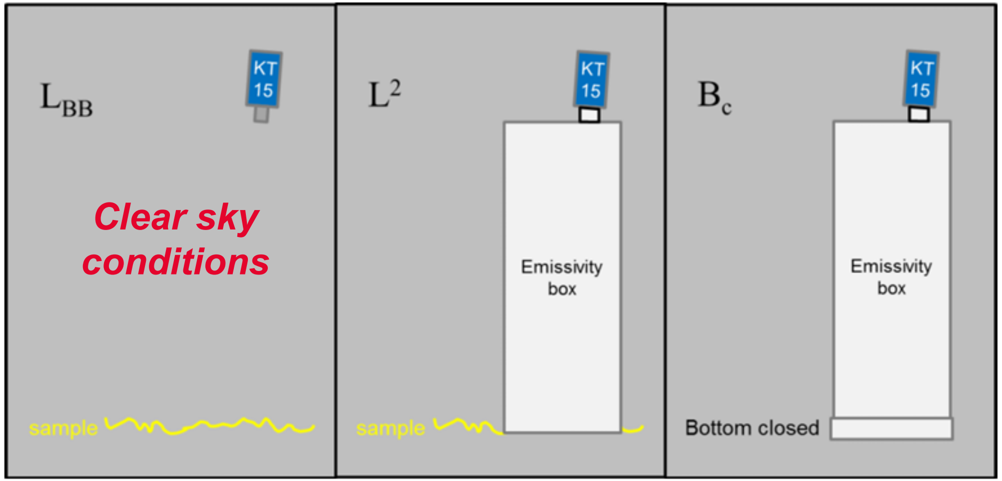
clear wire

Note: **Apogee = Sky View**

Heitronics = Ground View

Live demonstration

Field estimation of ε – “The one lid box”



- Highly polished aluminium box lid (ε = 0.03)
- Dimensions: 30 × 30 × 80 cm
- Radiometer viewing angle: 5° to avoid viewing own reflection

- Uncorrected emissivity (ε_0):

$$\varepsilon_0 = \frac{L_{BB} - L_{sky}}{L^2 - L_{sky}}$$

- Need to add correction term (**δε**) to correct for influence of the box on radiance measurements (R = 0.265):

$$\delta\varepsilon = (1 - \varepsilon_0)\left\{1 - \frac{L^2 - L_{sky}}{L^2 - L_{sky} - R(L^2 - B_C)}\right\}$$

The Combined ASTER and MODIS Emissivity over Land (CAMEL) dataset

- In the absence of available in situ measurements, or in the case of heterogeneous land cover, consider using satellite-derived values for ε.
- The NASA-JPL/University of Wisconsin-Madison CAMEL dataset merges MODIS + ASTER ε data to produce a **global monthly 5 km dataset**
- Data is provided over 13 hinge points based on MODIS + ASTER spectral bands: 3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 8.6, 9.1, 10.6, 10.8, 11.3, 12.1, and 14.3 μm
- Temporal range: **March 2000 – December 2023**
- Broadband emissivity (**BBE**) from CAMEL is available between **2000 – 2015**
- If LST (T_s) is known, the BBE can be calculated from CAMEL data using:

$$\varepsilon_{BBE} = \frac{\int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda B_\lambda(T_s)\,d\lambda}{\int_{\lambda_1}^{\lambda_2} B_\lambda(T_s)\,d\lambda}$$

Deployment notes: L_{sky}

- Measuring L_{sky} can be done in 3 ways:

1. **Zenith-sky measurement**:
    - Empirical conversion from sky BT to L_{sky}

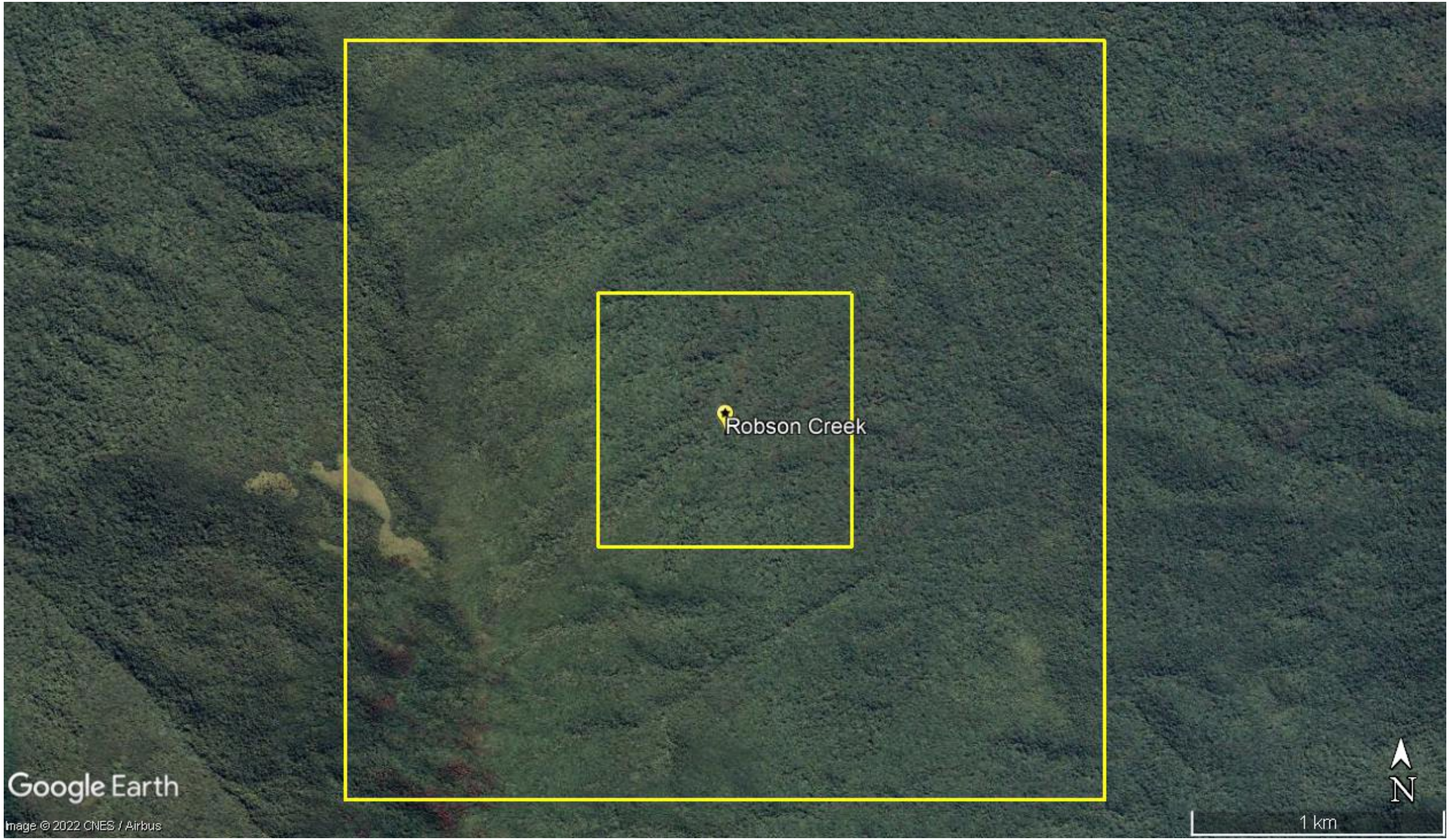
$$L_{sky} = 1.3 \cdot B[T(0°)]$$

2. **Representative viewing angle:**
    - Measure sky BT at a viewing zenith angle of ~53°
    - **AVOID THE SUN** – point the SI-121-SS away from the equator!
3. **Ground measurement of a diffuse gold plate or crinkled aluminium foil**
    - High reflectivity; negligible contamination of the measured BT

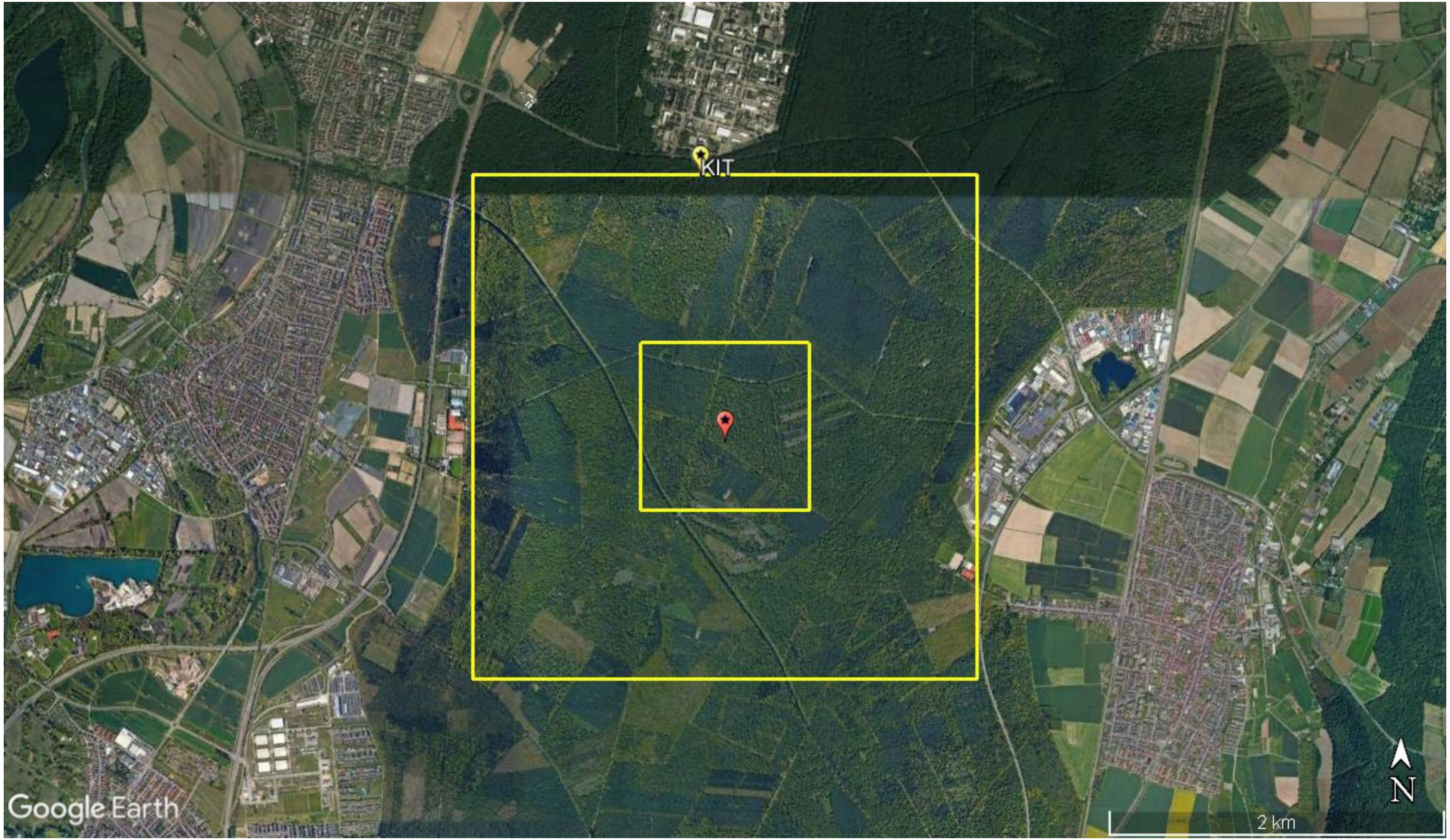
Deployment notes: L_{ground}

- Radiometers should be traceably calibrated to within ±0.3 K against a reference blackbody before deployment
- Nadir viewing angle should be 0 – 30° to minimise angular variation of L_{ground}
- **Avoid obstructions** (trees, buildings, etc.)
- If the focus is validating LEO satellite missions, ensure that the instrument FoV is **clear of shadows** from the measurement tower, trees, etc. during the satellite daytime overpasses (10:30 AM – 1:30 PM)
- : L_{ground} and L_{sky} should be measured simultaneously at the same site
- **Measure BTs every 1 minute** to minimise temporal matchup uncertainties with the satellite overpass
- Observed FoV must be representative of the satellite ground pixel area
  - Homogeneous land cover within 3 × 3 ground pixel grid preferable

Example siting: Robson Creek (Australia)



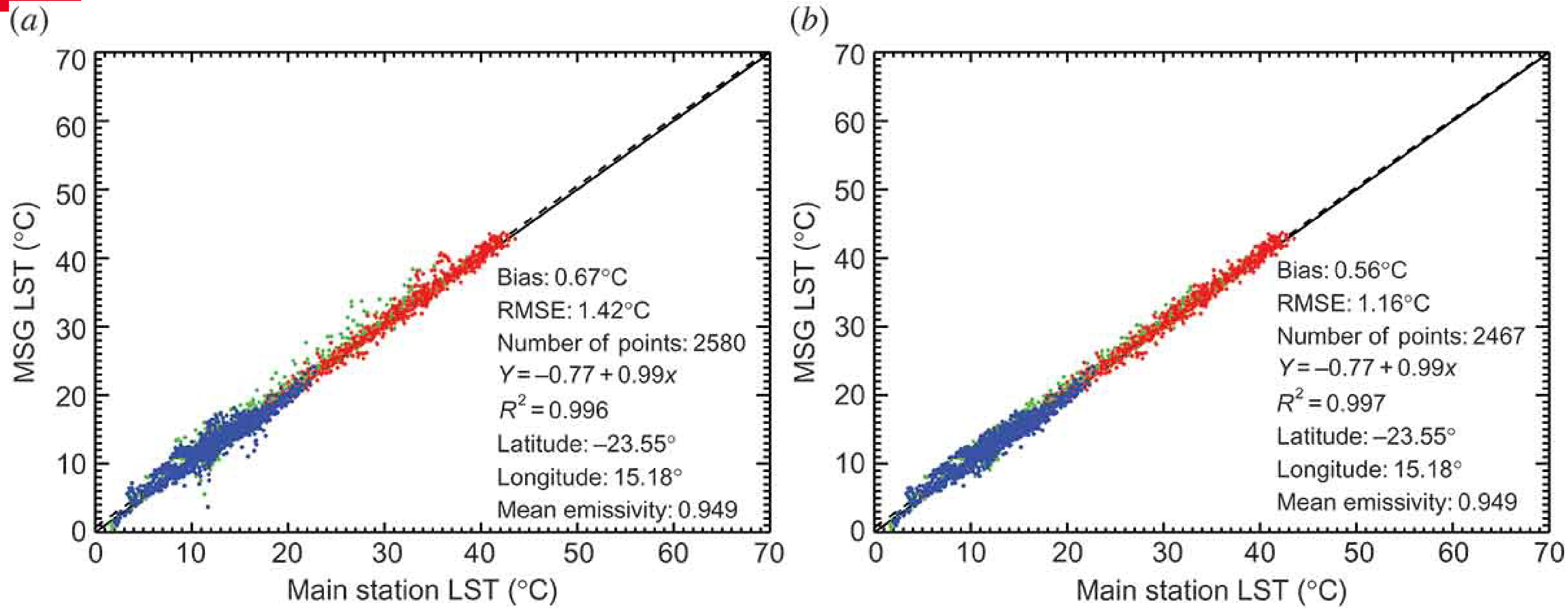
Example siting: KIT (Germany)



Validation & Hampel filtering

- Validation is performed via direct comparison between in situ LST with satellite LST data from a **suitably representative ground pixel.**
- Temporal interpolation from in situ to satellite overpass time (UTC) necessary before comparison
- **Unflagged cloudy pixels** will introduce **large outliers** to any comparison. Before comparing data, filter these out using a **Hampel filter**:
  1. Compute median of satellite – in situ LST bias for all matchups
  2. Calculate standard deviation ($\boldsymbol{\sigma}$) of the median bias
  3. Filter out points where: $|\boldsymbol{LST_{Sat}} - \boldsymbol{LST_{IS}}| < \boldsymbol{2\sigma}$

Validation & Hampel filtering

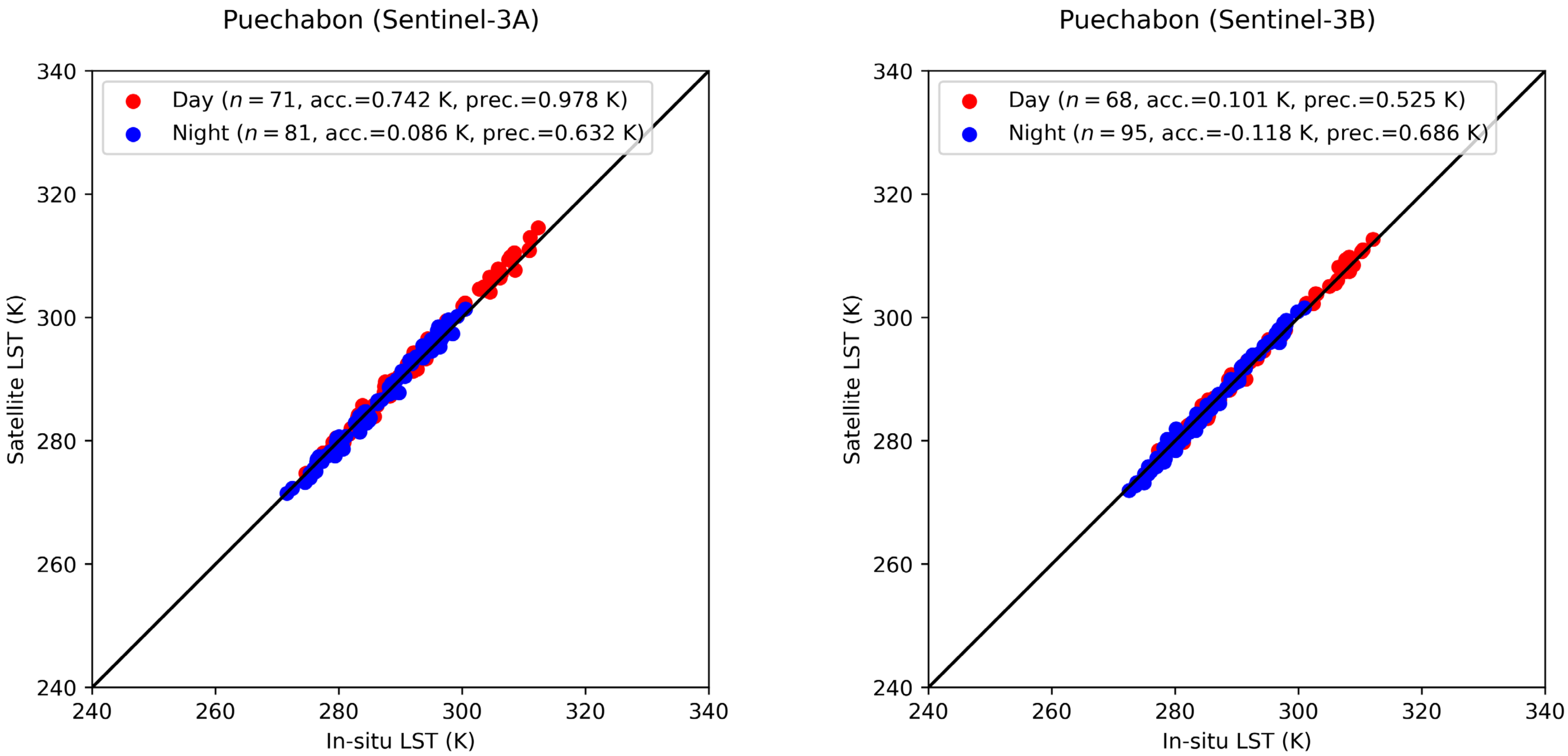


Effect of the 3σ-Hampel filter on time series of matched-up LSA SAF LST and in situ LST (Gobabeb main station): (a) linear regression of unfiltered LST for July 2010 and (b) linear regression of 3σ-Hampel filtered LST for July 2010. From Gottsche et al, 2013

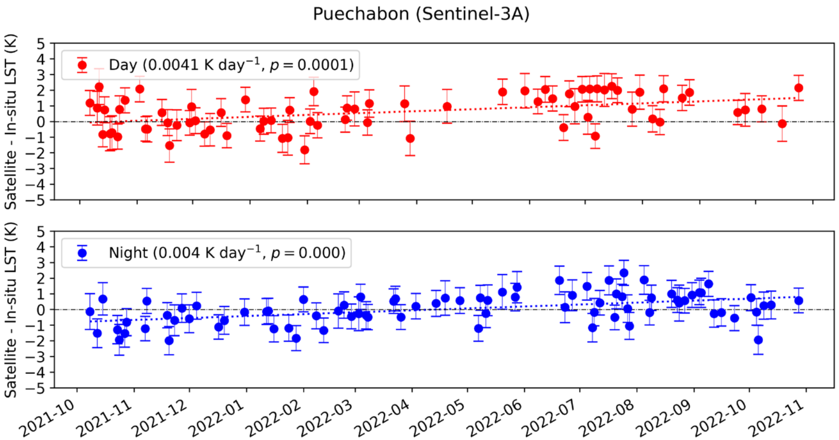
Useful validation statistics

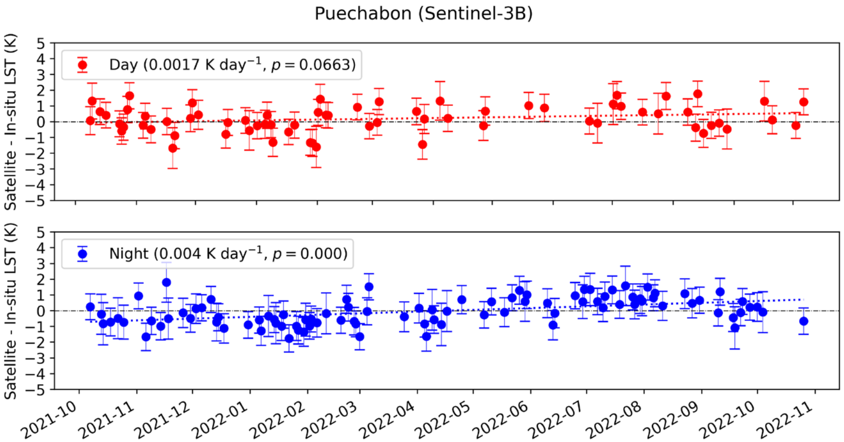
- **Accuracy**: $\mu = \mathrm{Mdn}(\boldsymbol{LST_{Sat}} - \boldsymbol{LST_{IS}})$
- **Precision**: $\sigma = \mathrm{Mdn}(|(\boldsymbol{LST_{Sat}} - \boldsymbol{LST_{IS}}) - \mu|)$
- Gradient and intercept using **Orthogonal Distance Regression**
- Number of matchups removed using Hampel filter
- Time series analysis of bias over time
- RMSE of $\boldsymbol{LST_{Sat}} - \boldsymbol{LST_{IS}}$
- Separate analyses for daytime and night-time overpasses

Example: Puechabon (France), Oct 2021 – Oct 2022

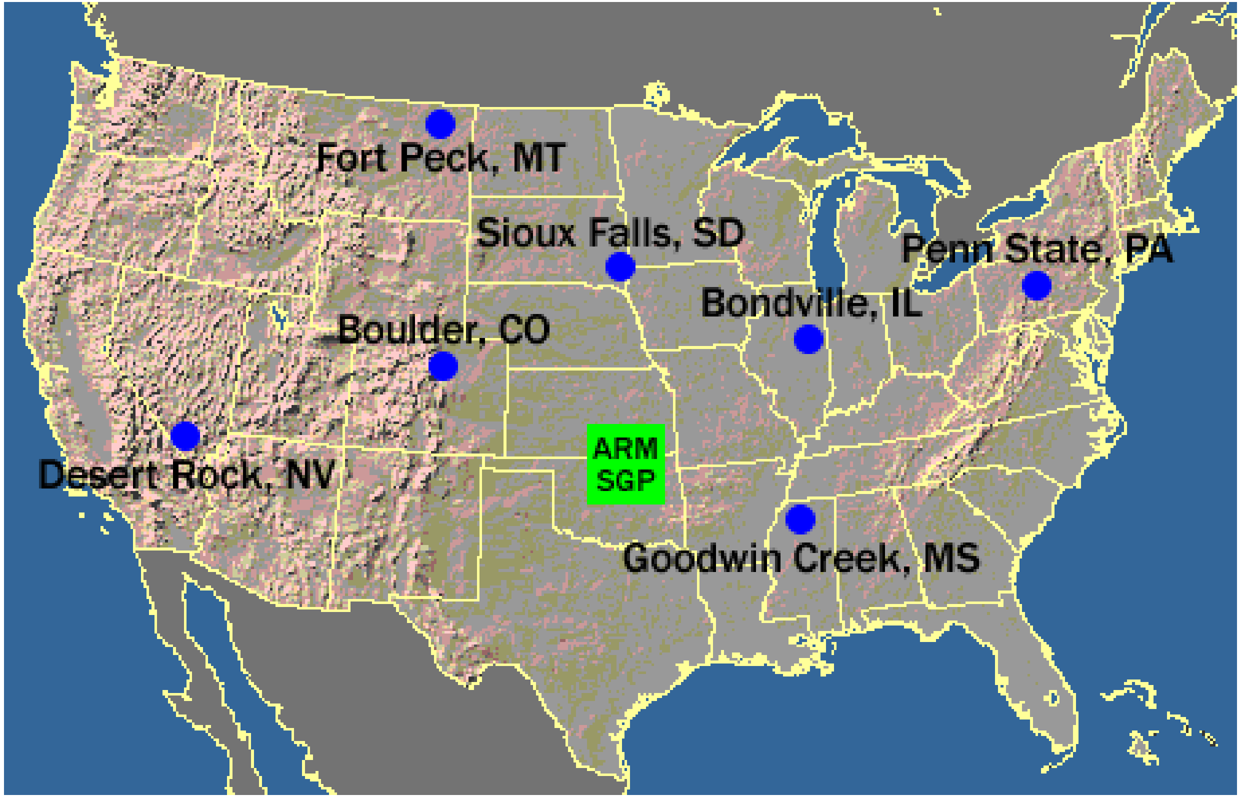


Example: Puechabon (France), Oct 2021 – Oct 2022



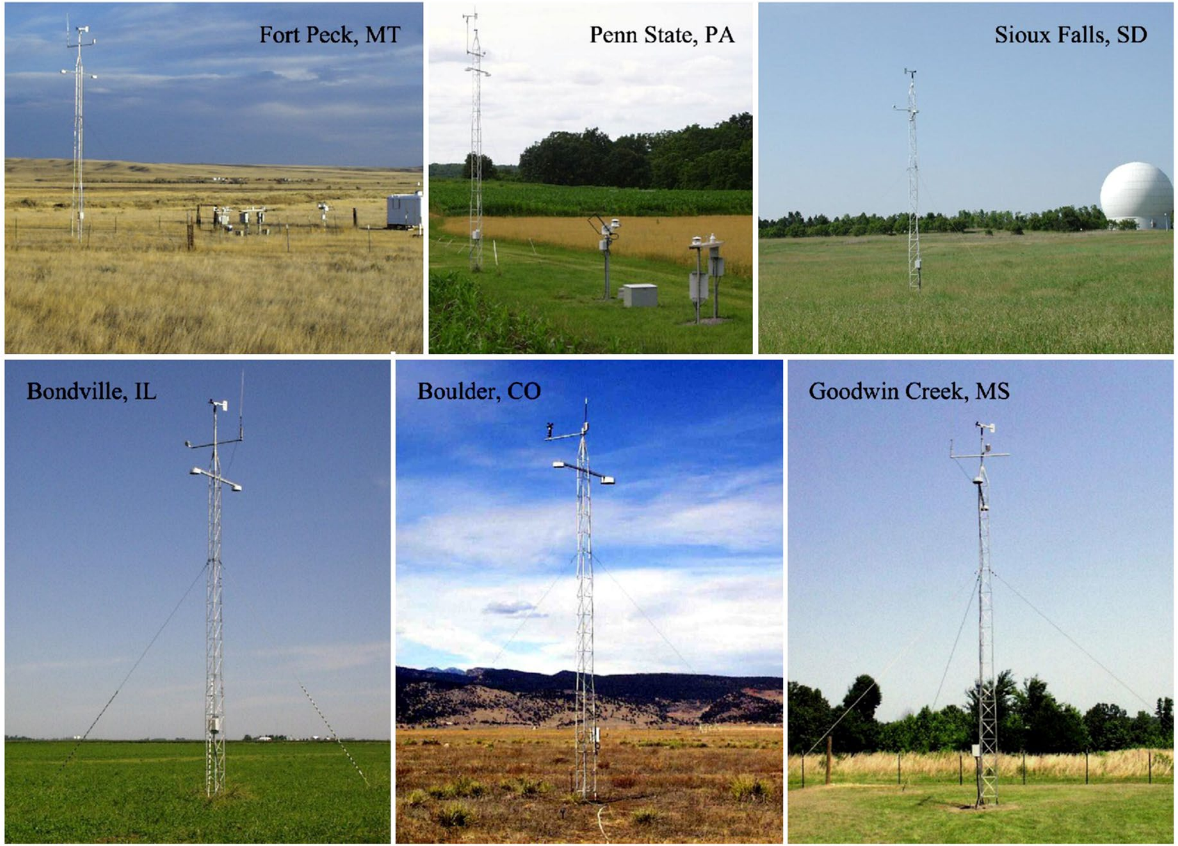


Existing validation networks – SURFRAD and ARM



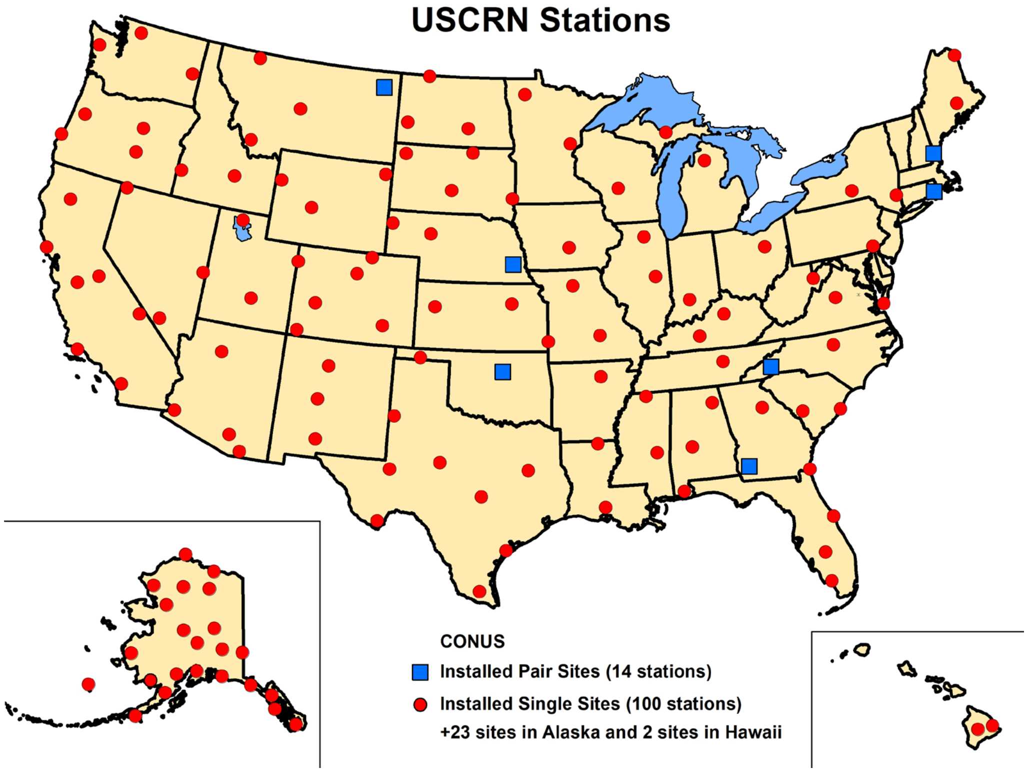
https://gml.noaa.gov/grad/surfrad/overview.html

Existing validation sites – SURFRAD and ARM



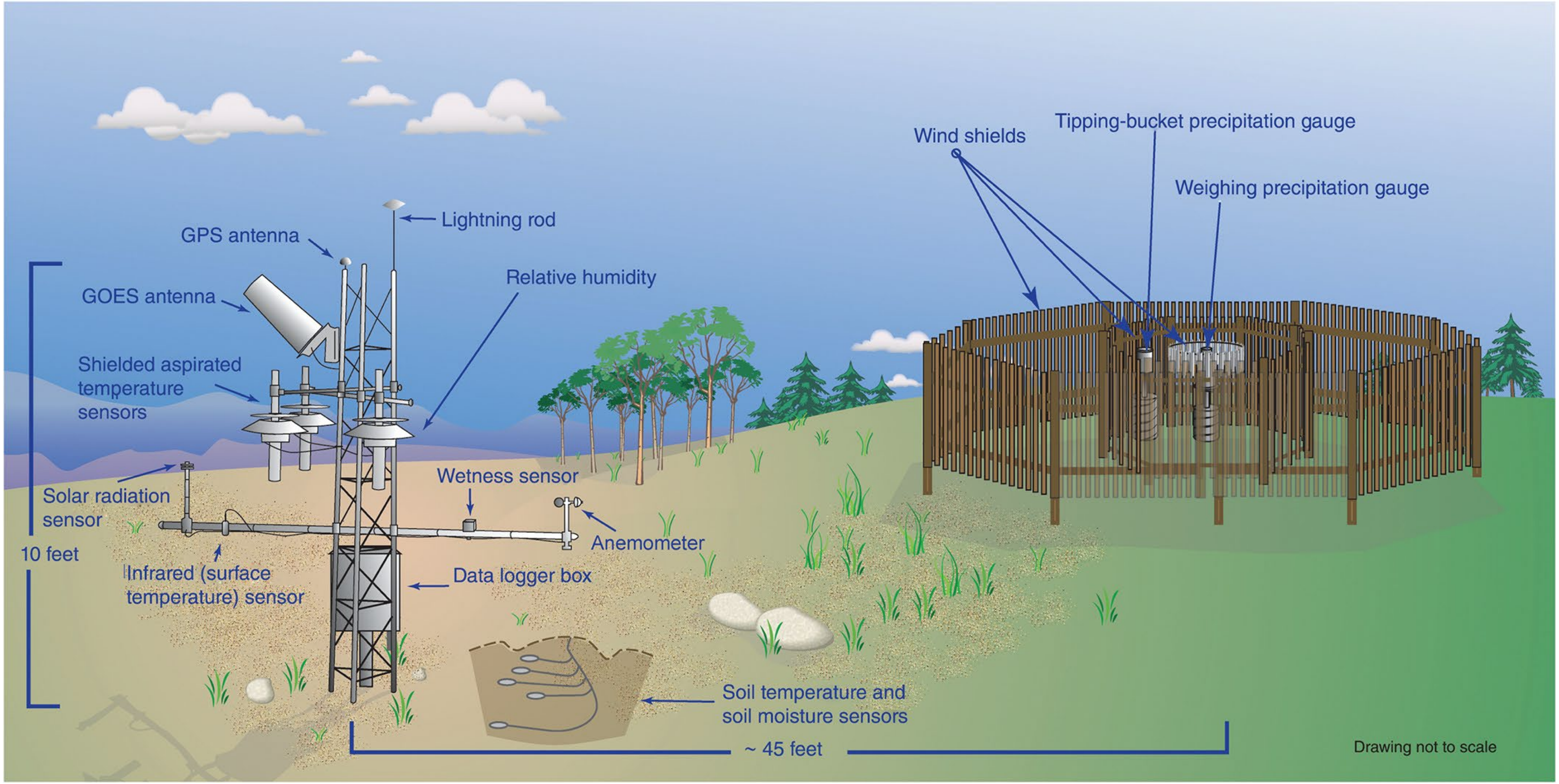
Wang and Liang, Remote Sensing of Environment, 2009

Existing validation networks – USCRN



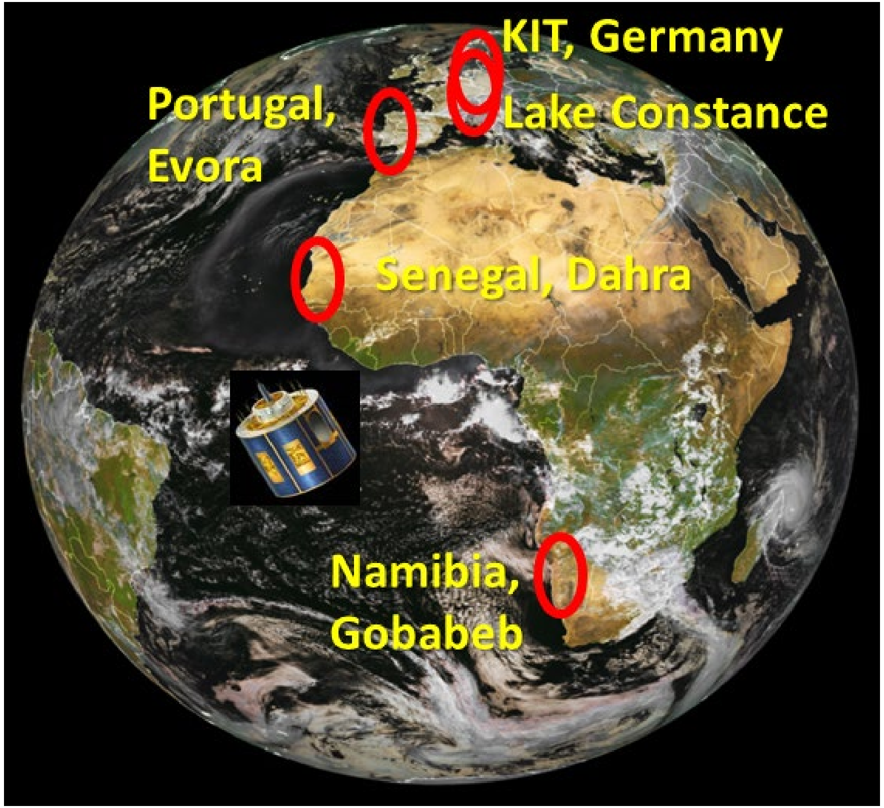
https://www.arl.noaa.gov/news-pubs/arl-news-stories/field-notes-uscrn/

Existing validation networks – USCRN



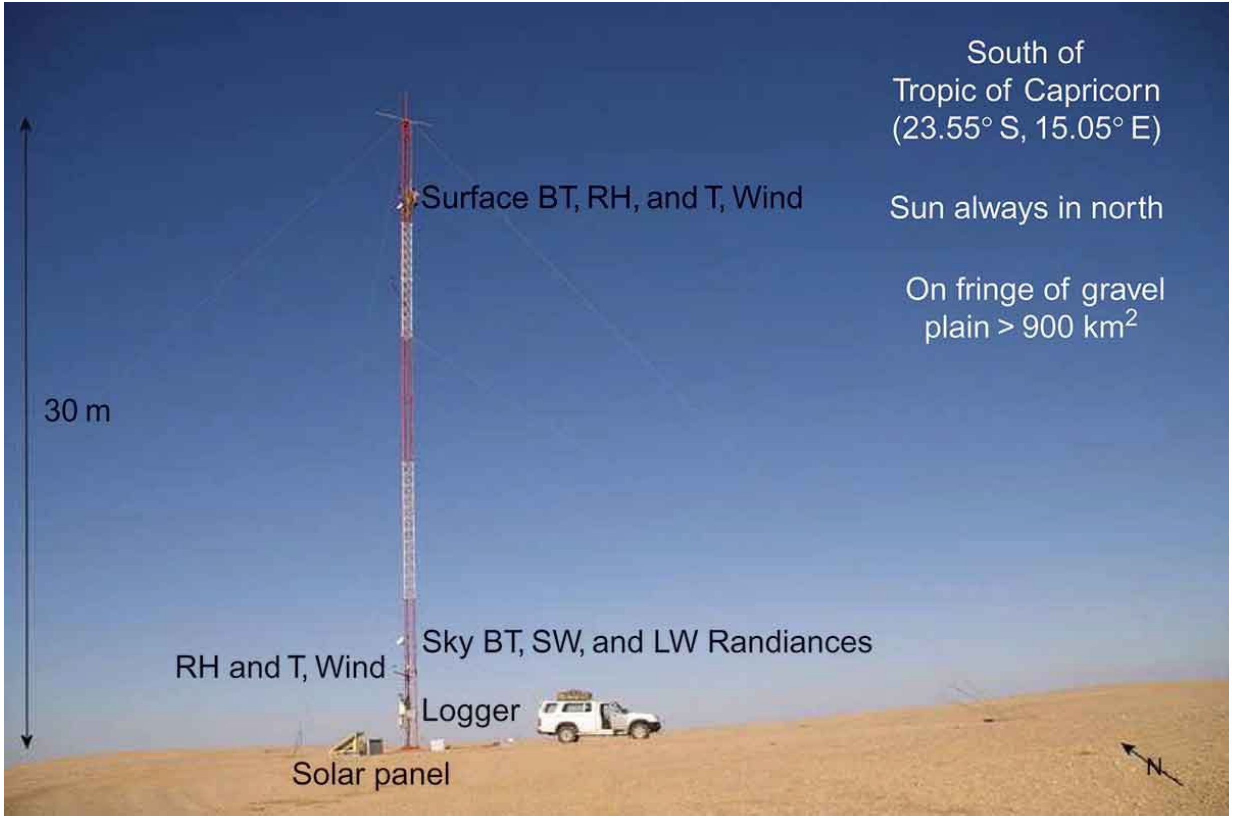
Thorne et al, International Journal of Climatology, 2018

Existing validation networks – KIT



https://www.imk-asf.kit.edu/english/skl_stations.php

Existing validation networks – KIT



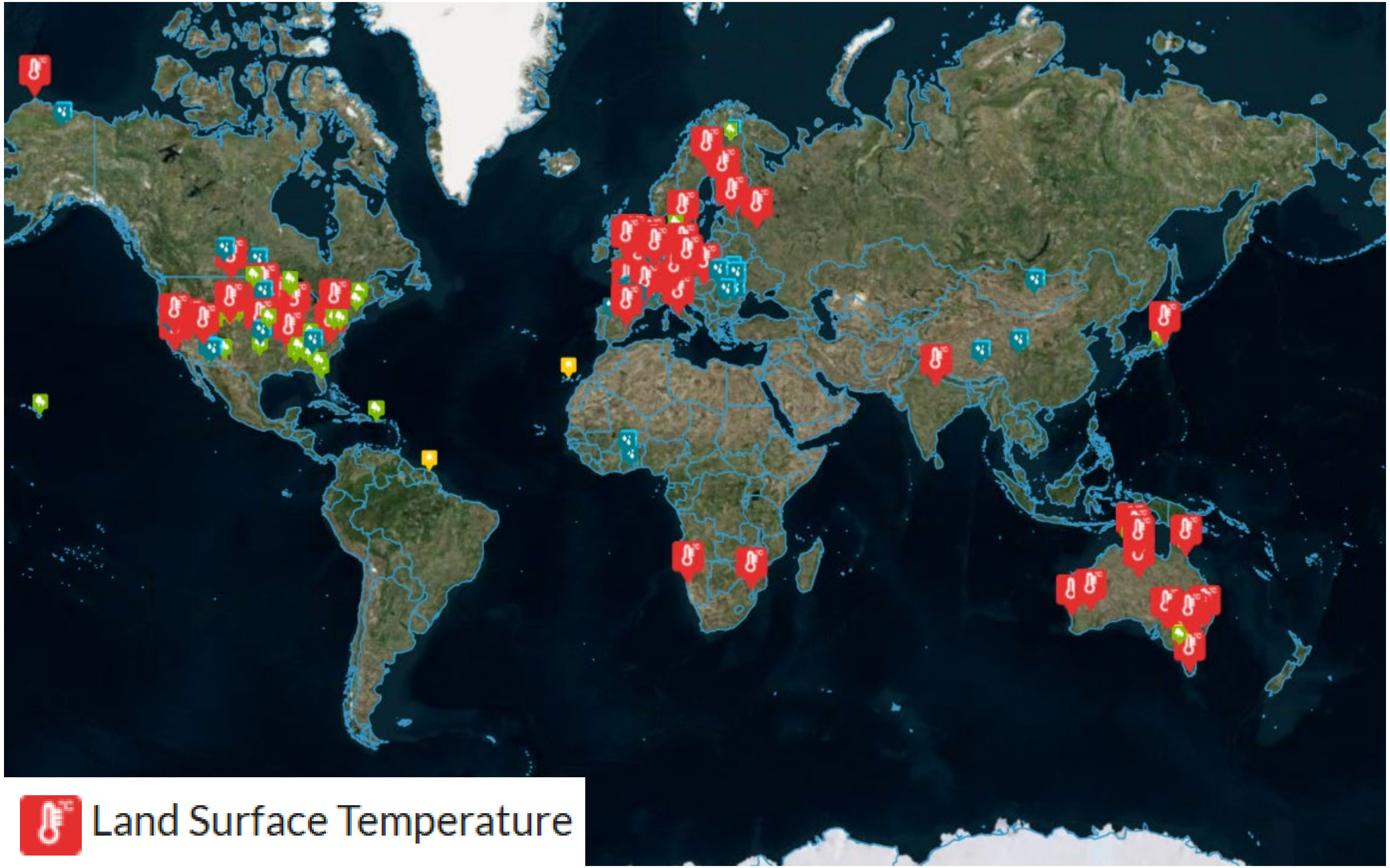
Gobabeb (KIT); Gottsche et al, Intl. Journal of Rem. Sens., 2013

Existing validation networks – LAW

Existing validation networks – LAW

Svartberget (LAW)

Copernicus Ground-Based Observations for Validation (GBOV)



https://gbov.land.copernicus.eu/

Thank you!

Ask me anything at:
jsa13@le.ac.uk