Universität Zürich[UZH]

Department of Geography

Conducting TIR UAV surveys: Best practices and recommendations

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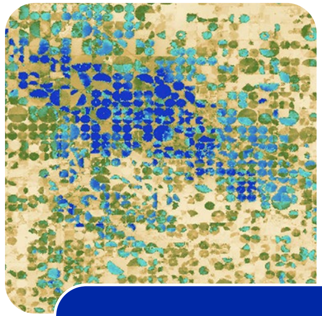
3rd December 2024

Demonstration overview

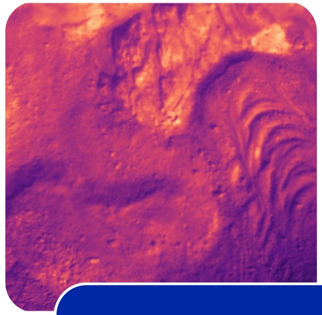


Deciding if TIR UAV is appropriate for your needs

Before the survey

Ancillary data for the survey

During the survey



After the survey

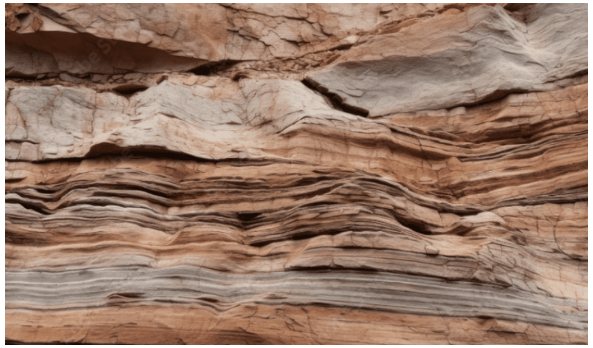
Cascading set of best practices and recommendations

From ideal to minimum realistic

Applications of thermal UAV data informs many decisions on the UAV survey

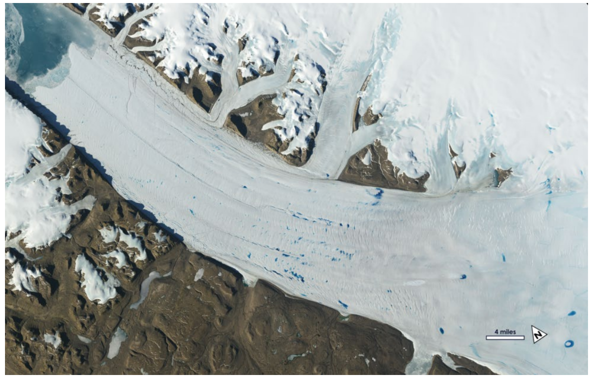
Coastal and inland waters

Surveying / infrastructure

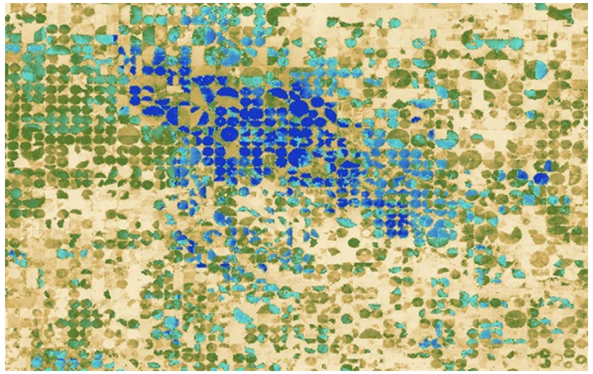


Geology and archaeology

Search & rescue / wildlife monitoring



Cryosphere

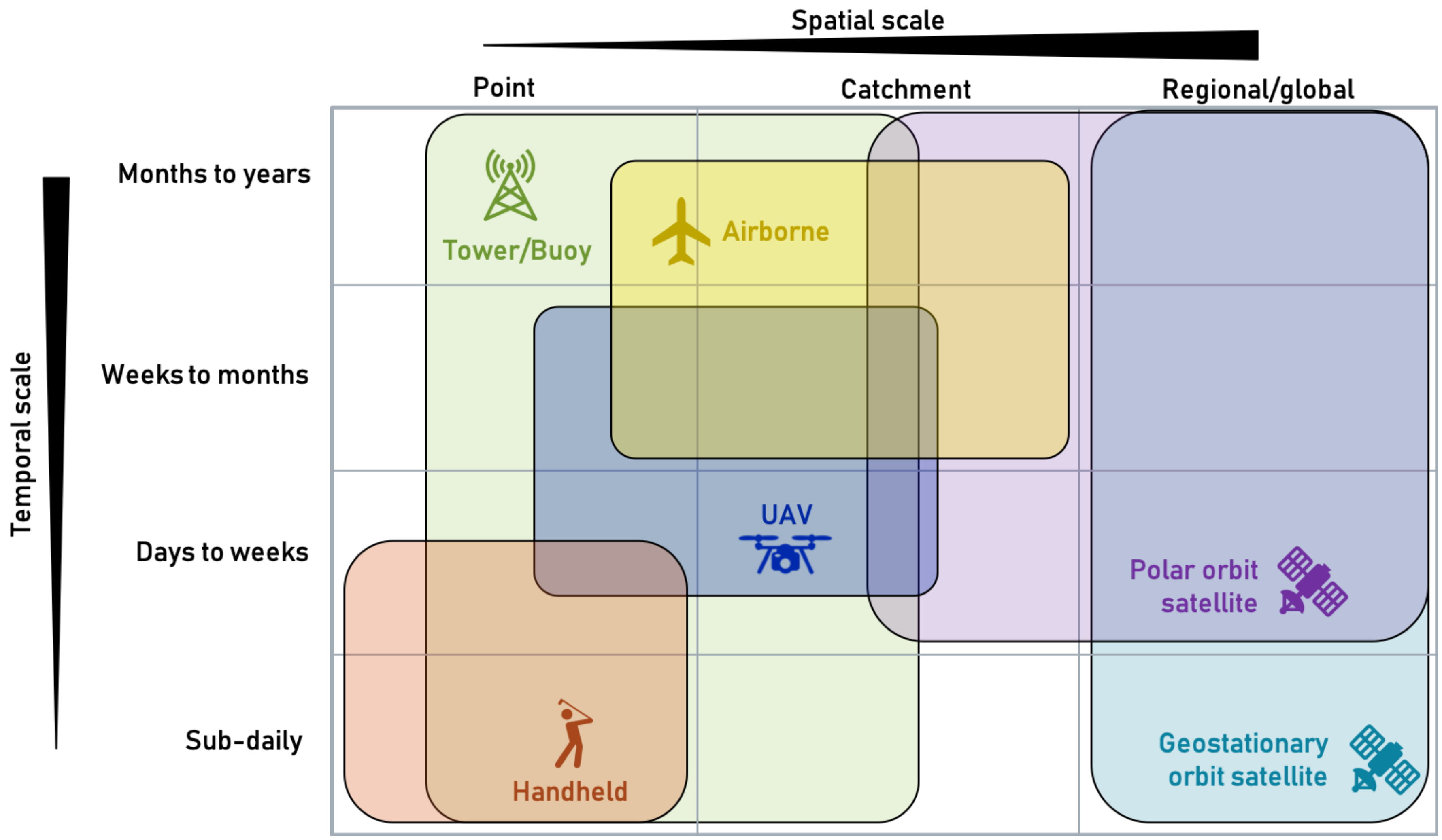


Ecosystem stress / water use

Urban

Solid earth

Where does UAVdata fit in? Example for vegetation



Adapted/inspired by Farella et al (2022)

Areminder on thermal sensors and what they measure

target-emitted radiance

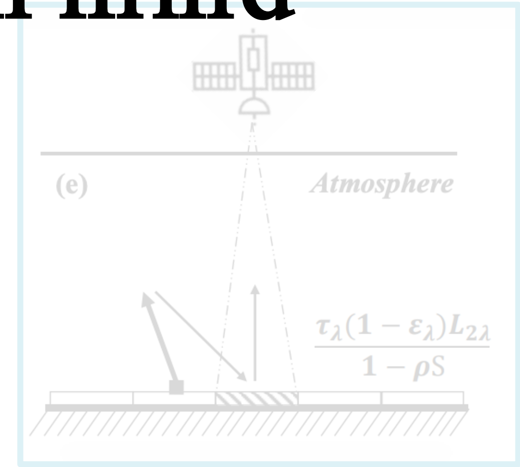
target-reflected atmospheric downwelling radiance

atmospheric upwelling radiance

single scattered adjacent pixel radiance

Which means our UAVsurveys have some considerations, characterisations and ancillary data to keep in mind

+adjacent pixel radiance reflected by atmosphere and then reflected by target pixel.



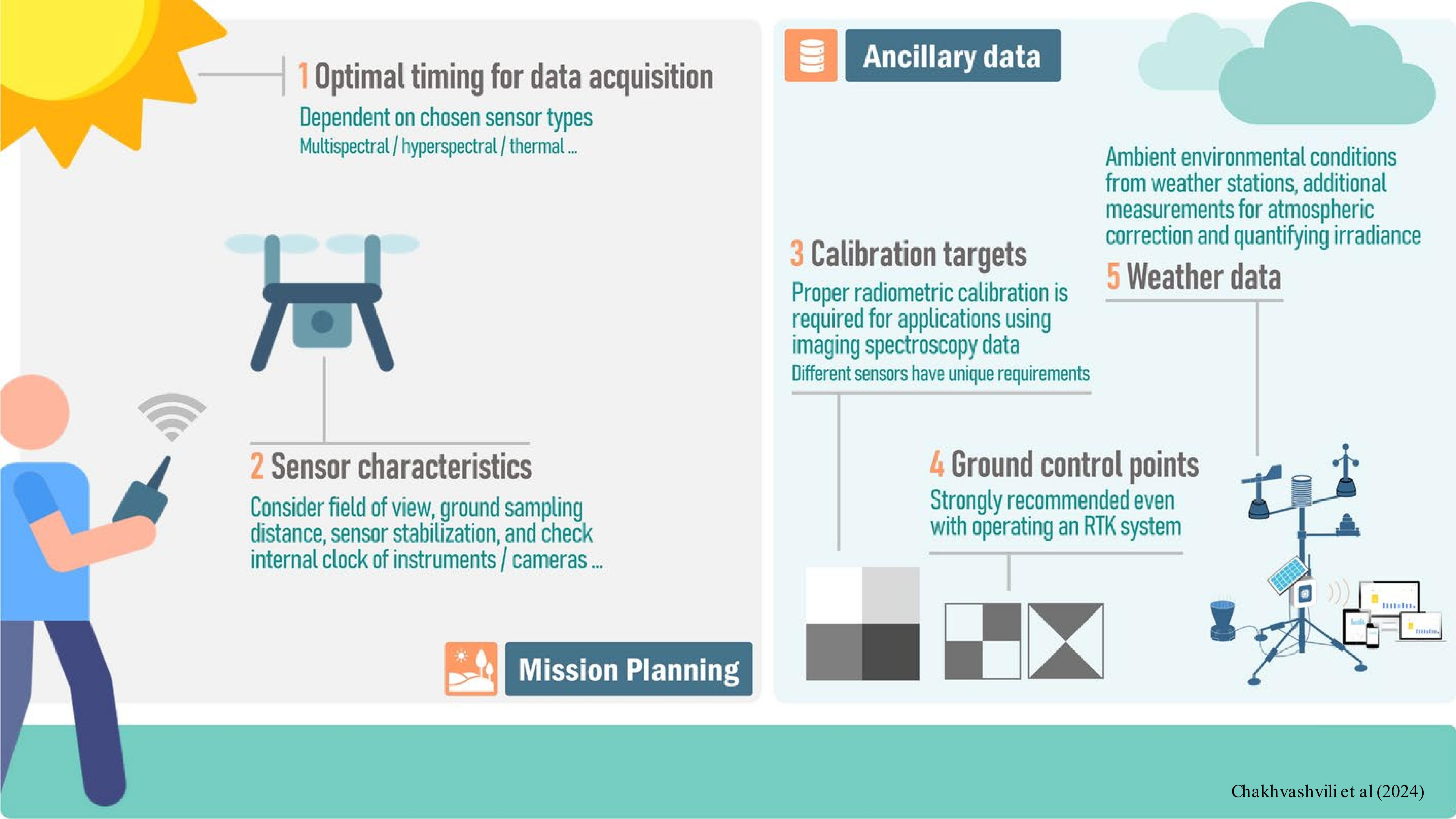
Zheng et al (2019) : 10.1109/TGRS.2019.2928525

Demonstration goal:

Provide some recommendations of how to account for some of these things and prioritise which ones to account for

Before the survey: UAV selection / flight planning

1

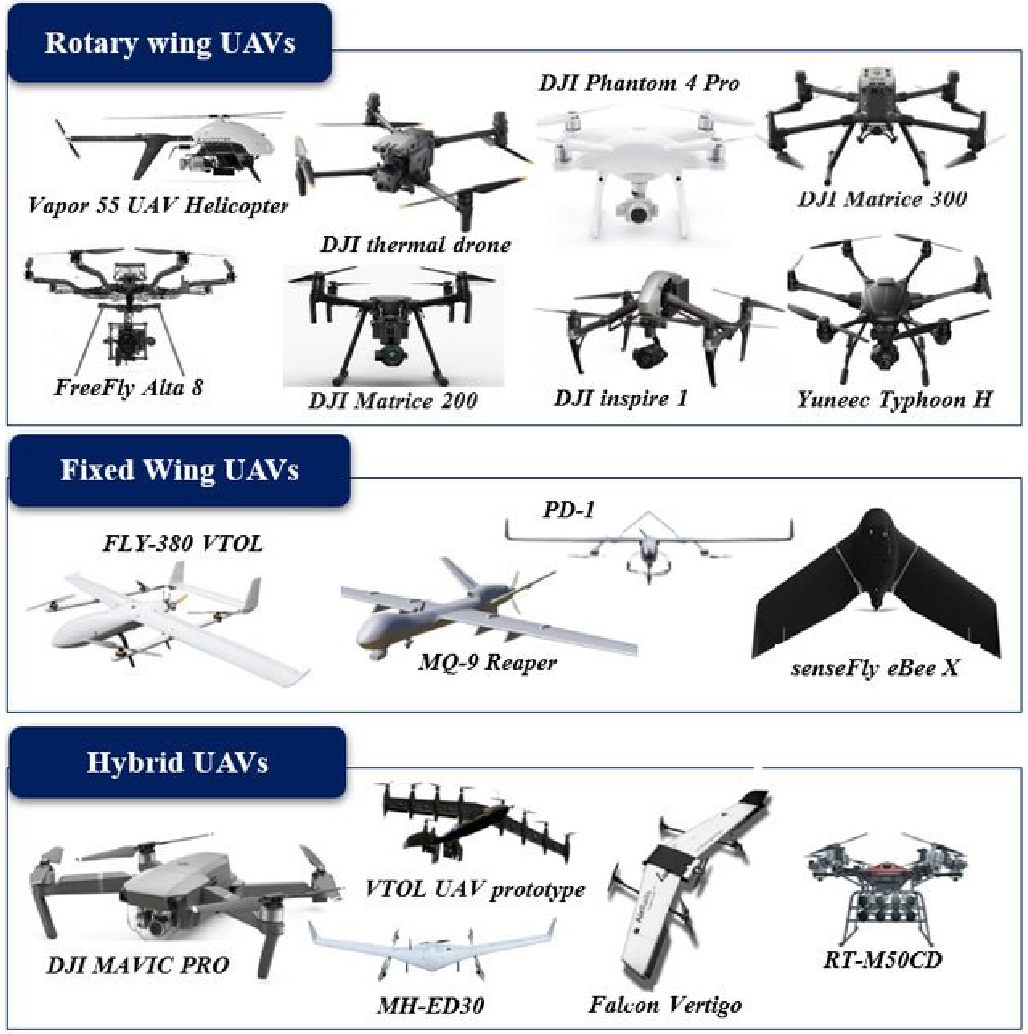


Chakhvashvili et al (2024)

Choosing the right TIR UAV for your purpose

	WIRIS 2nd Gen	FLIR Tau 2
Spectral band(s)	7.5 – 13 microm	7.5 – 13 microm
Shutter mechanisms	Global	Global
Camera resolution	640 x 512 pixels	640 x 512 pixels
Capture rate	1 fps	1 fps
Lens focal length	13mm	19mm
FOV	45 x 37	32 x 26
Automatic corrections	Every 2 - 30 min	6 secs
GSD@5m	0.65	1.19
Sensitivity	50 mK	<50 mK
Total weight	<390g	<72g
Radiometric accuracy	2 deg C	5 deg C
Temperature range	-25 to 150	-20 to 100

Partheepan et al (2023), doi:10.3390/drones7010047

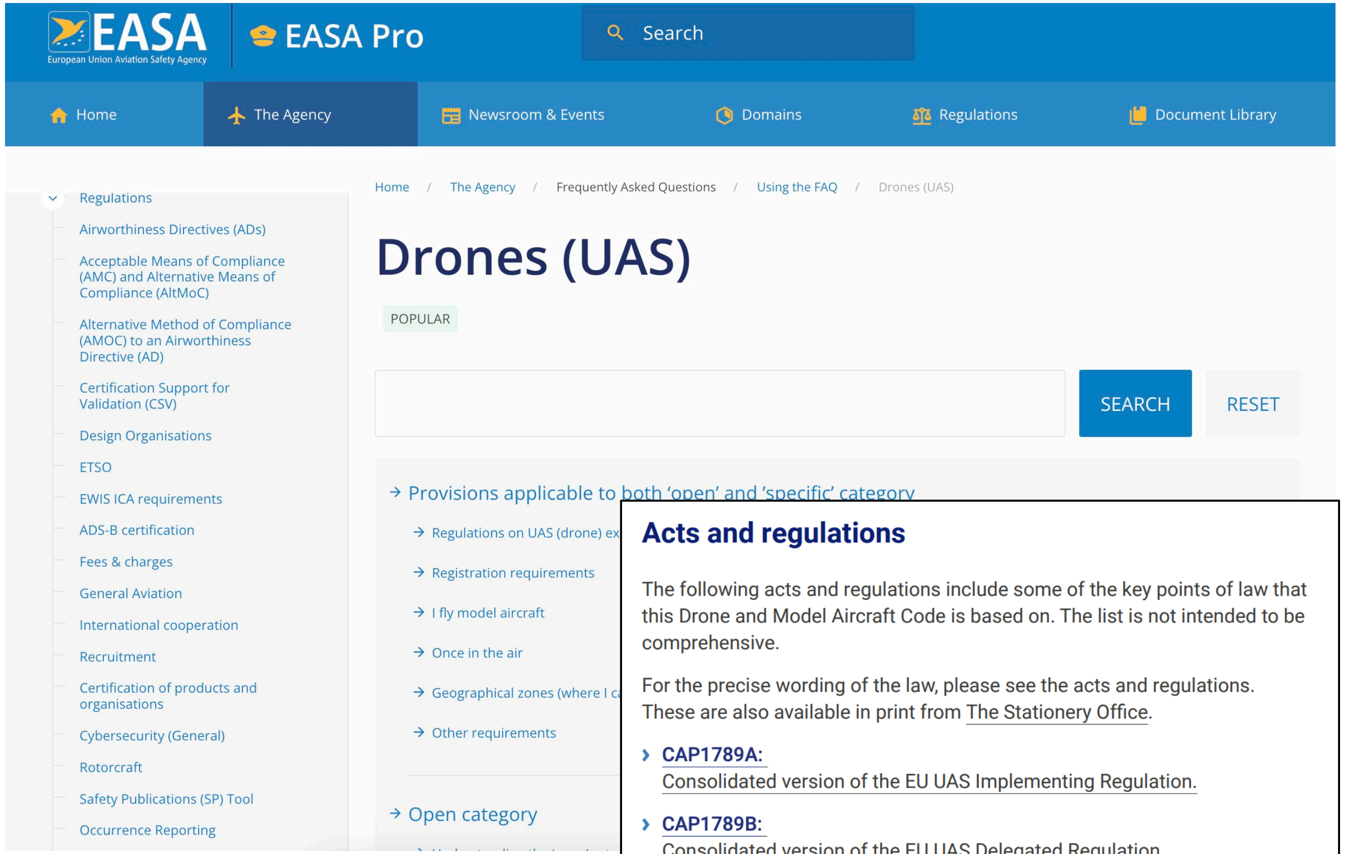


Specific considerations for TIR

- Battery life (due to large overlap needed)
- Sheltering from the wind (protection of sensor temperature)
- Launch method (site consideration)
- NUC automated correction

Always remember/remind yourself of legal rights for UAV surveys

EASA for Europe



Acts and regulations

The following acts and regulations include some of the key points of law that this Drone and Model Aircraft Code is based on. The list is not intended to be comprehensive.

For the precise wording of the law, please see the acts and regulations. These are also available in print from The Stationery Office.

- CAP1789A:
  Consolidated version of the EU UAS Implementing Regulation.
- CAP1789B:
  Consolidated version of the EU UAS Delegated Regulation.
- The Air Navigation Order 2016,
  including the 2018 amendment and 2019 amendment.
  The Civil Aviation Authority has published a copy of the Air Navigation Order with amendments inserted.
- The Data Protection Act 2018.

+ national authorities

Nice summary:

https://register-drones.caa.co.uk/drone-code/the_drone_code.pdf

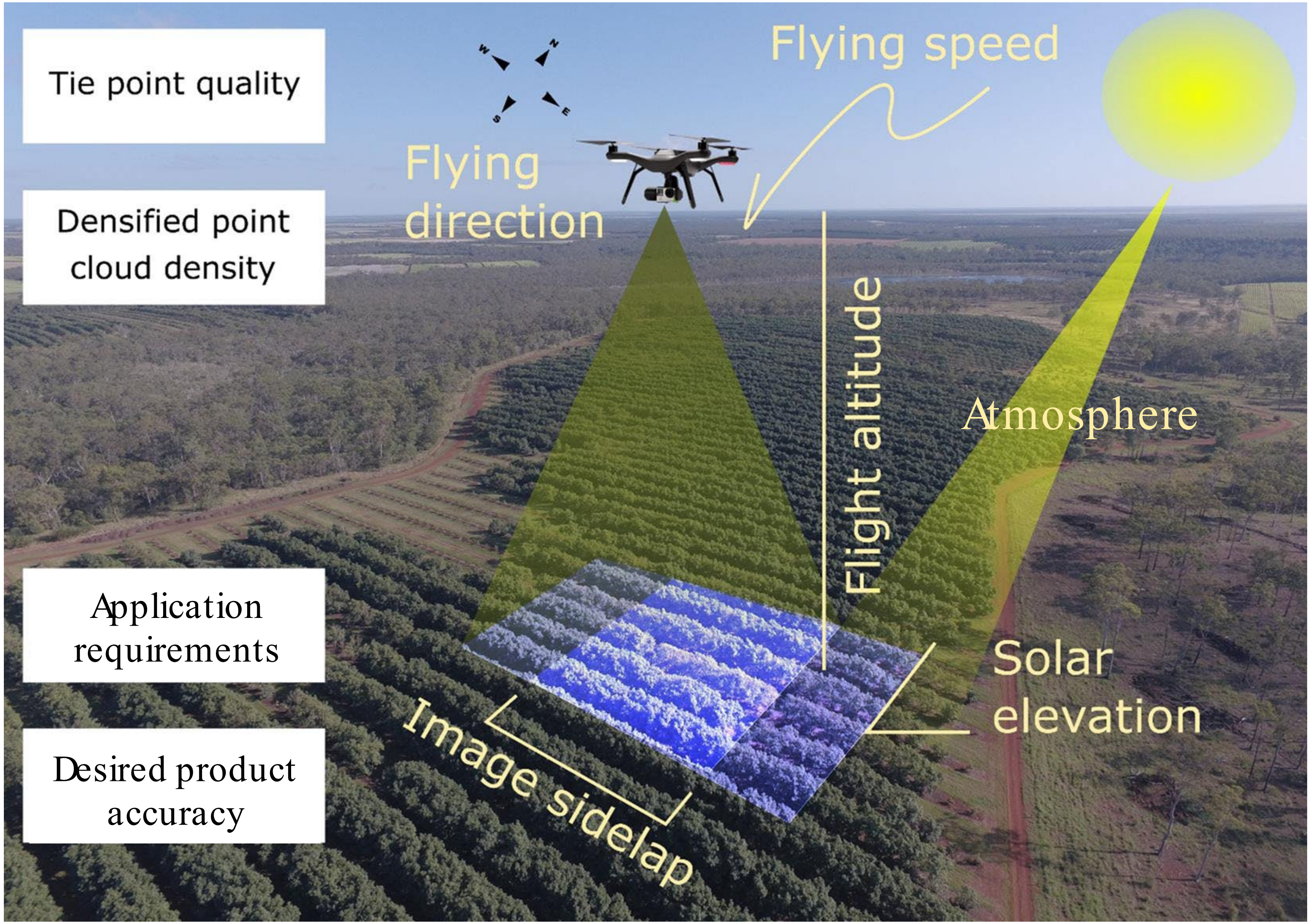
Planning a TIR UAV survey

Think about your application requirements

- Time of day
- Weather conditions
- Atmospheric effects

Other factors to consider

- Topography
- Directional effects (flight direction)
- Flight permits / height restrictions



Tu et al (2020), DOI: 10.1016/j.isprsjprs.2019.12.006

Considerations and recommendations for TIR UAV flight planning

GSD: TIR UAV sensor generally have lower resolution than RGB

- Function of flight altitude, focal length, FOV, sensor resolution, and pixel size.
- Differs between sensors and flights

Overlap: Minimum 80%, preferable 90-95% overlap

- Depends on UAV software
- Larger then VNIR
- Has implications for battery life
- Complexity of terrain
- Sensor type and resolution

Flight pattern

- Terrain following
- Planned to reduce directionality effects
- Battery life

2

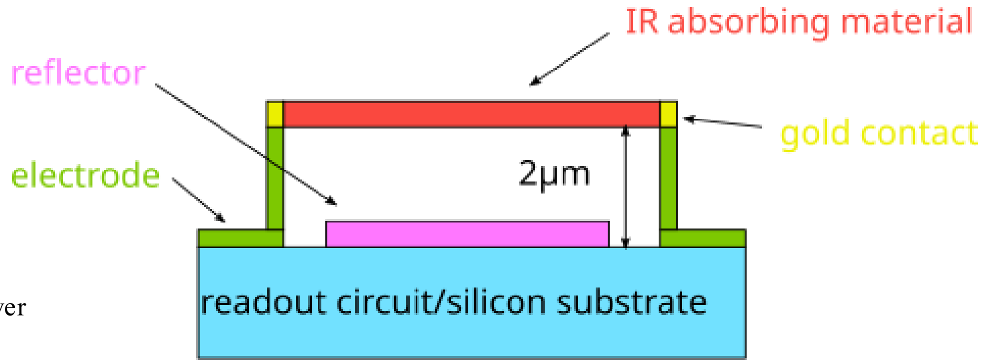
Before the survey: Sensor characterisation

Understanding and characterising your sensor before any survey

Wan et al (2021), DOI: 10.3390/s21248466
Kelly et al (2019), DOI: 10.3390/rs11050567

Most UAV cameras are microbolometers

- Converting IR radiation into temperature and detection sensitivity weaker/lower than cooled sensors
- Miniaturisation causes reduction in accuracy/sensitivity
- Gain and offset of each microbolometer often change with the sensor (FPA) temp
- Radiation within/from sensor may be larger than target, resulting in low SNR



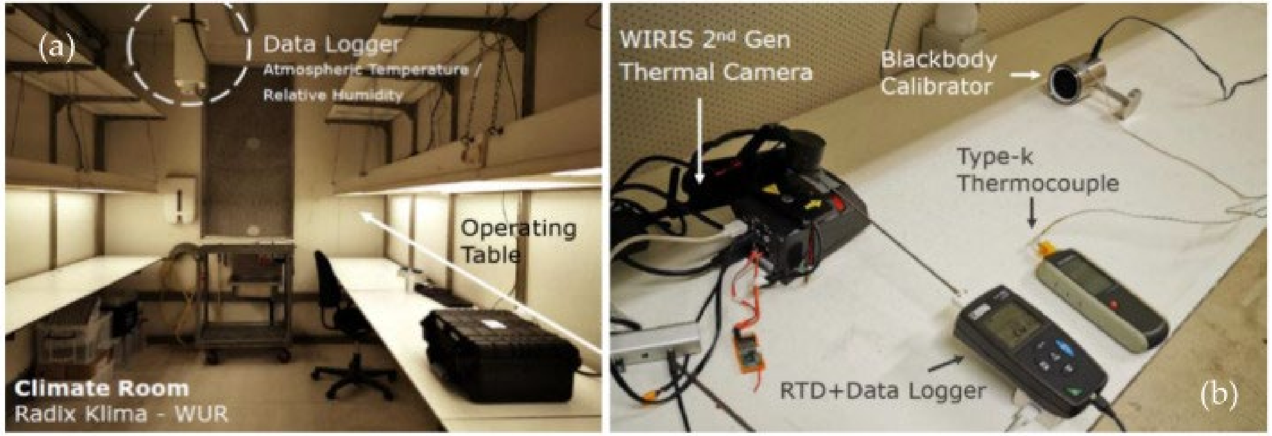
Meaning that UAV TIR cameras

- Are sensitive to ambient conditions, changes and sensor temperature
- Have relatively low accuracy and sensitivity compared to cooled

- adjacency effects
- resolution
- spectral response function
- Non Uniformity Corrections
- ΔT sensor-target
- **sensor characteristics**
- Temperature range/sensitivity
- temperature
- vignetting
- Meta data access

Characterising your sensor

Ideal Case: Laboratory blackbody + climate chamber



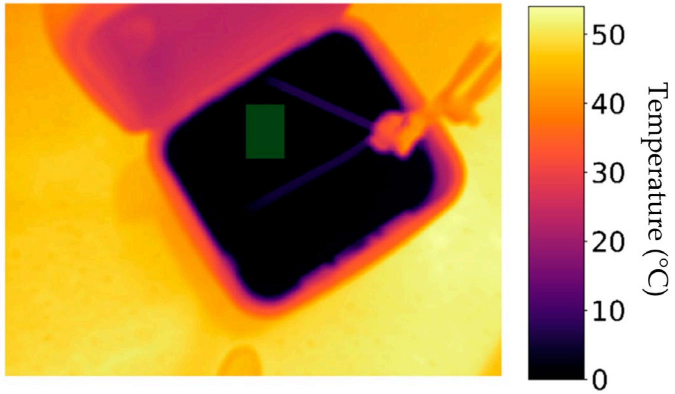
Wan et al (2021), DOI: 10.3390/s21248466

- → Fixed point blackbodies (fixed temperature)
- → Variable temperature (ideal)
- → Lamp sources (e.g. Tungsten lamp)
- → Caveat: costly and not so common. Recommendation: reach out to institutions/organisations that might have them!

If no access to laboratory

Ice bath

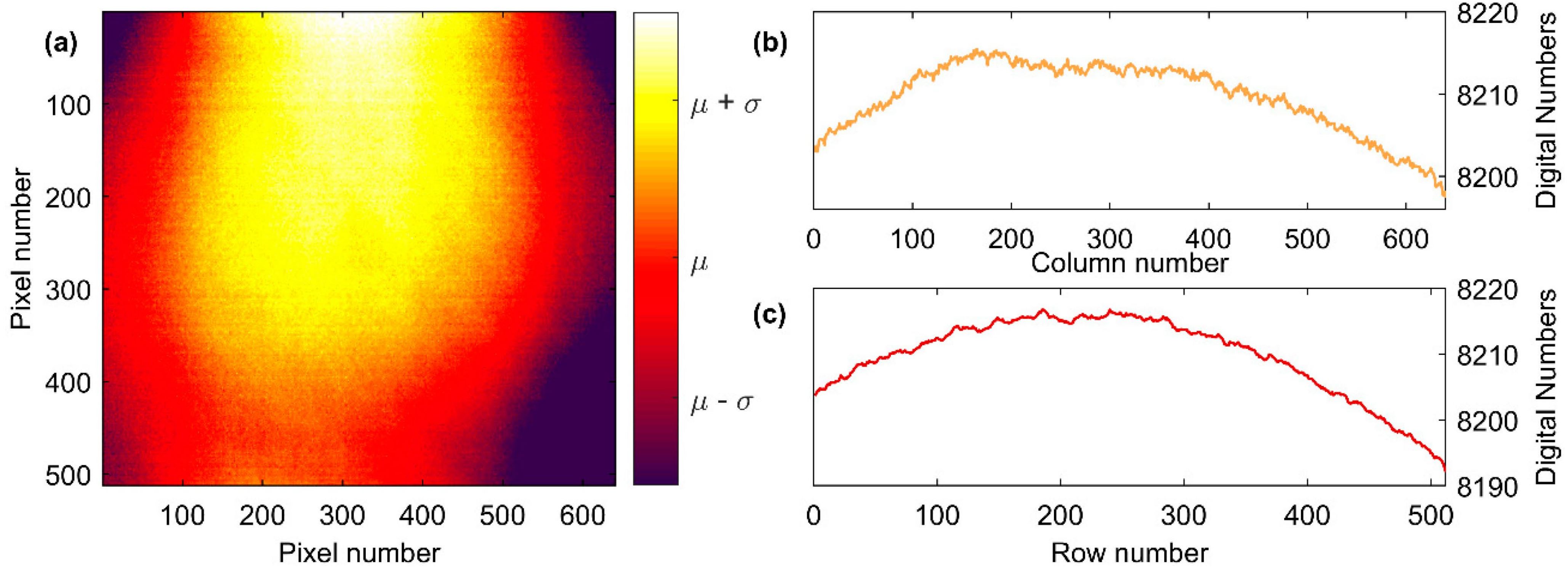
Aragon et al (2020), DOI: 10.3390/s20113316



Meat cooker

Caveat: lab calibration can usually obtain accuracy (±0.5 °C) but in the field, calibration uncertainty can increase to several degrees. Need field calibration too!

Vignetting and NUC (spatial and temporally)



Ideal: characterise this with a blackbody and correct for it

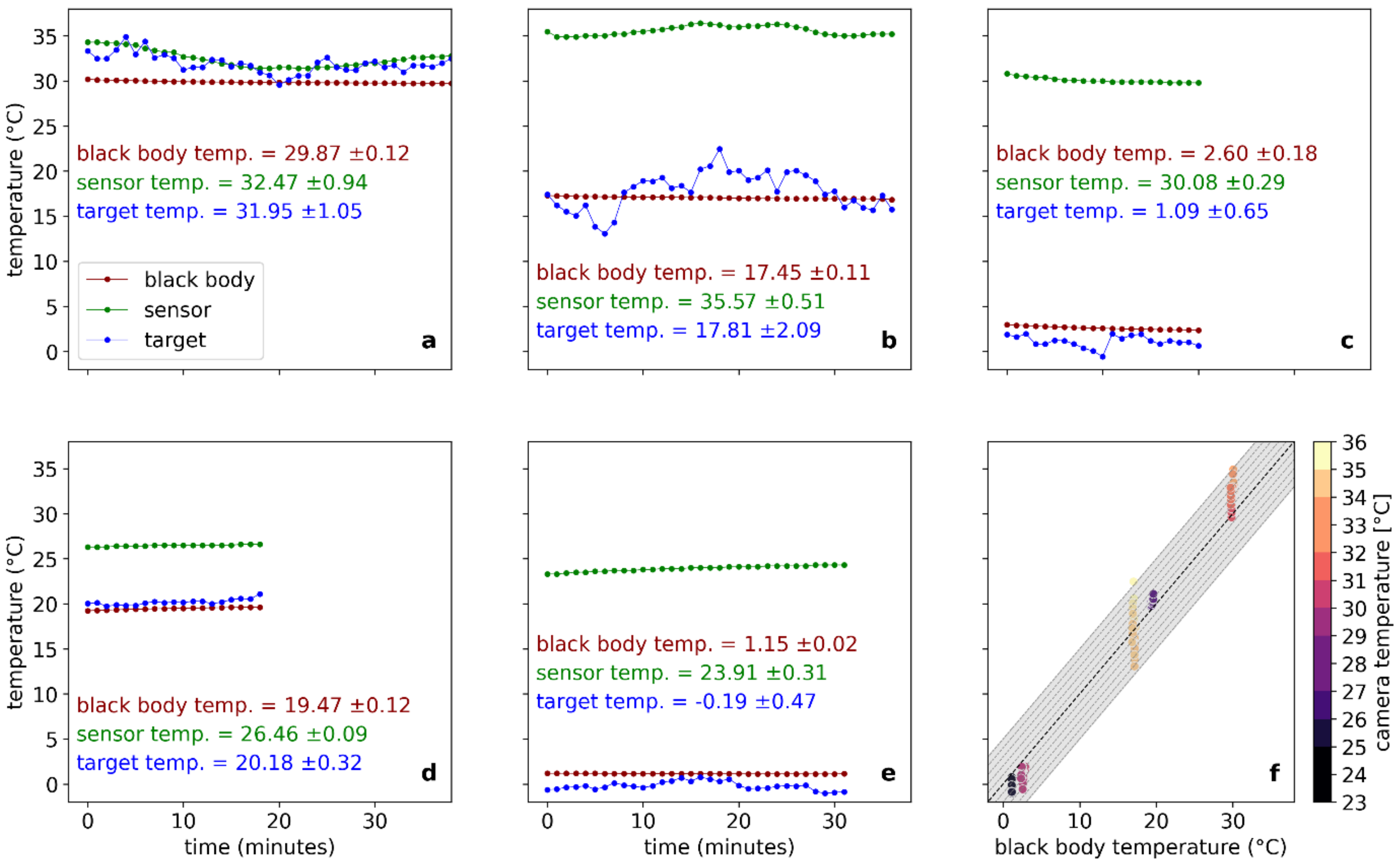
Realistic: only use centre of the image

Important for both relative and absolute temperatures!!
If you compare relative temps across an image, objects in the centre will appear warmer than those along the edges

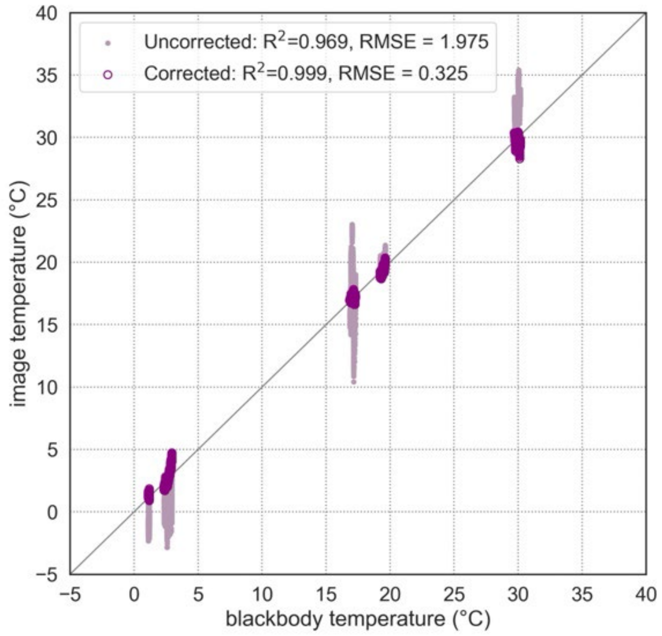
Kelly et al (2019)

Or follow approach of Lin et al (2021)
https://onlinelibrary.wiley.com/doi/full/10.1111/phor.12216

Correction for sensor temperature + other calibration



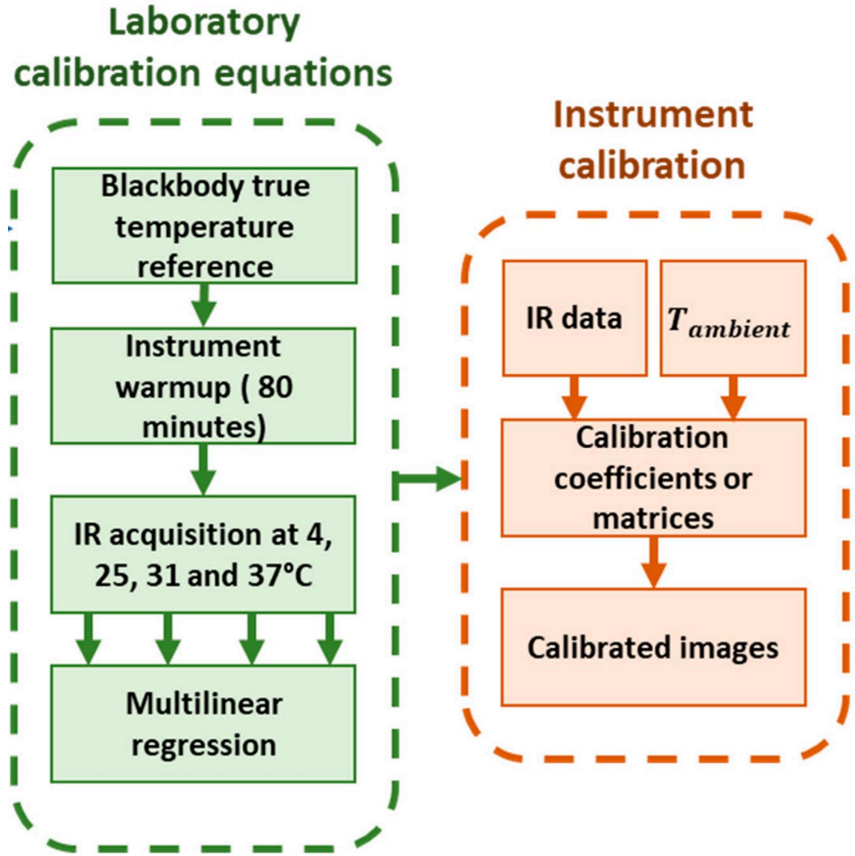
- Blackbody temperature changed from 0 to 30deg
- Sensor temperature altered with wind and cooling
- Centre of images chosen for correction
- Multi-variate polynomial linear regression between blackbody and image temperature

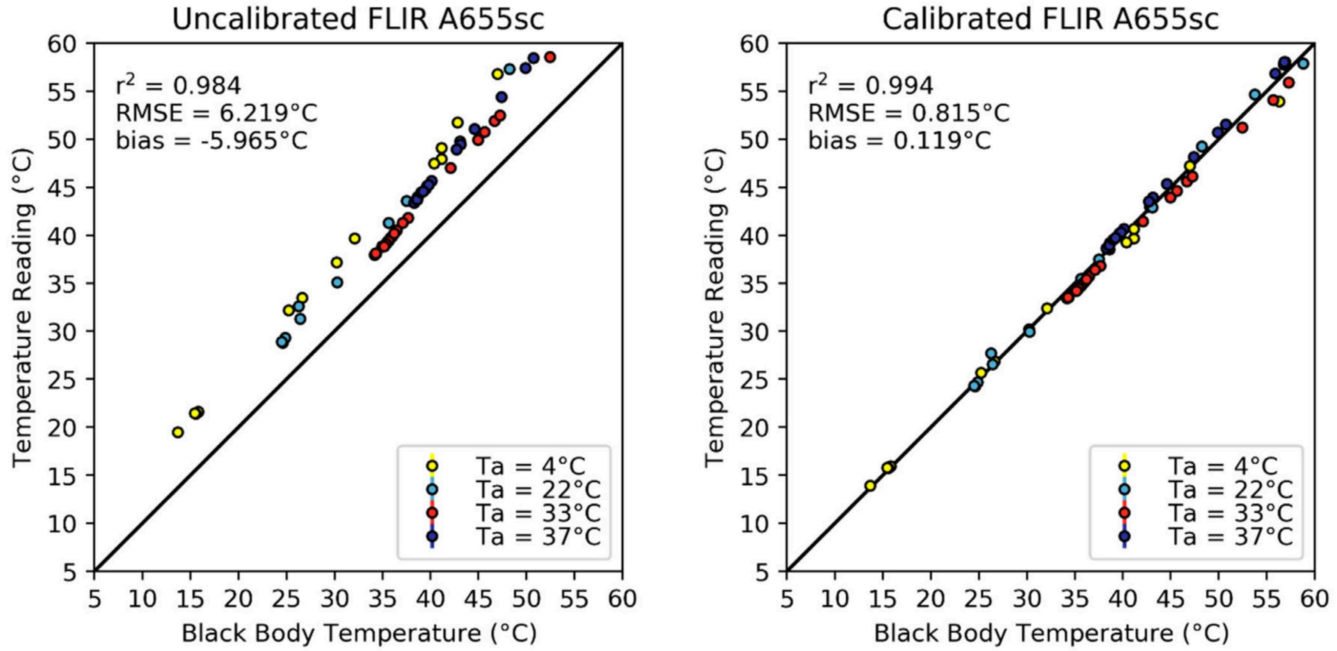


Naegeli et al (in prep)

Ambient temperature changes

- Polynomial regression between BB and UAV temperature reading
- Different ambient temperatures





(a) (b)

Aragon et al (2020), DOI: **10.3390/s20113316**

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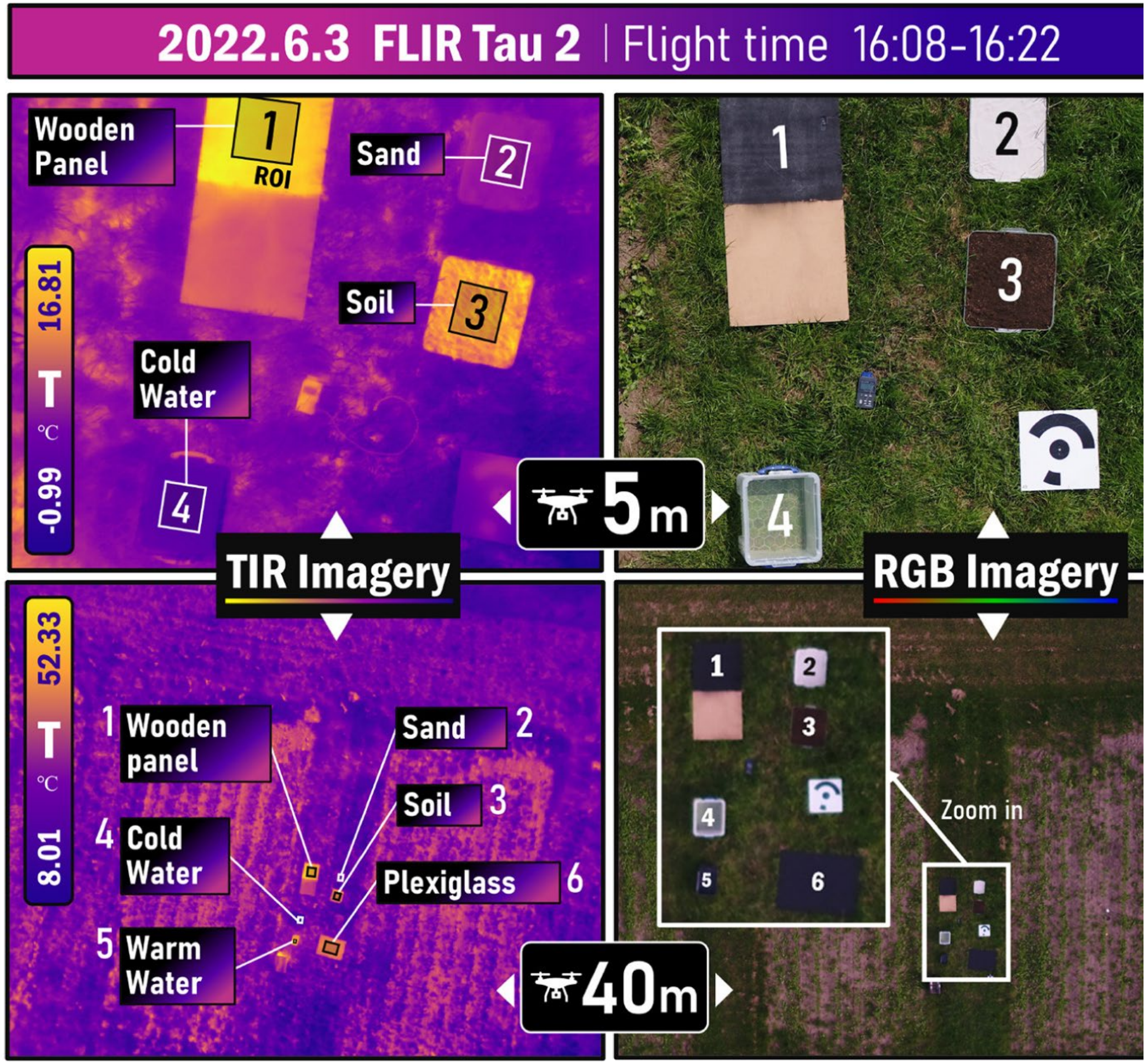
Before the survey: Ancillary data

Temperature Calibration Plates (TCPs)



Wan et al (2024), DOI: 10.1016/j.jag.2024.104184

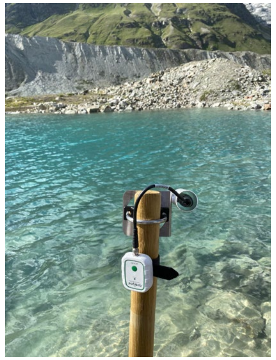
Ideal requirements :

- A large temperature range
- Built-in insulation to avoid temperature fluctuations
- High emissivity
- Be stable over time
- Have a uniform surface
- Be durable
- Related to your about your application, e.g. in vegetation you want warm/dry and cold/wet targets

Common TCPs

- InfraGold Diffuse Panel (expensive)

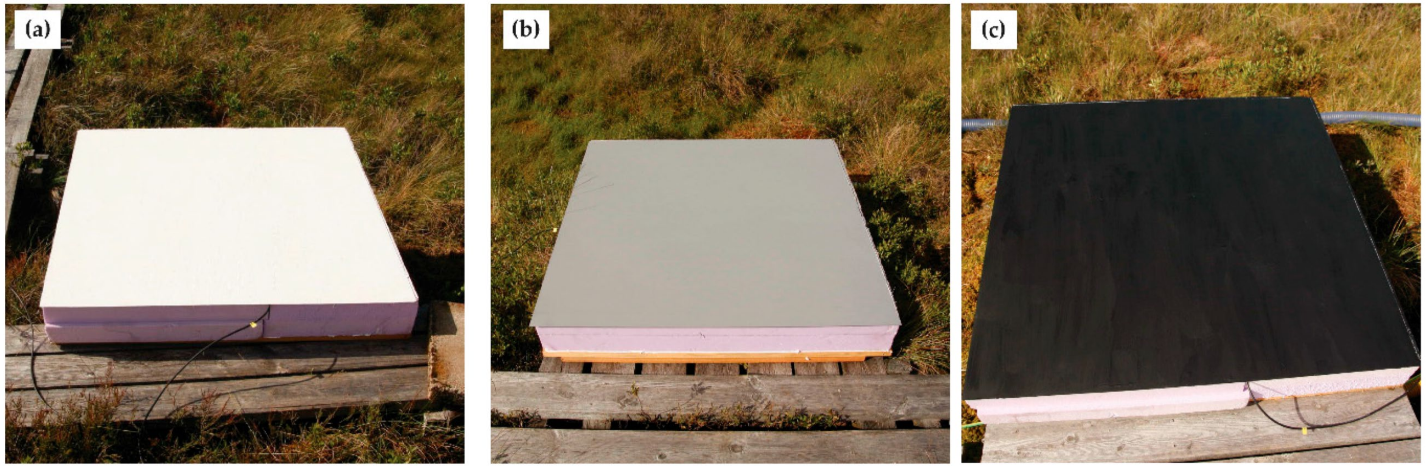
- Cold water / ice bath / warm water / lake or water pond or melting snow → well known emissivity and relatively stable temperature



- Something in your scene that has known emissivity and is stable (concrete)

Kelly et al (2019) (a-c)
Zmutt Glacier campaign in 2023, UZH

DIYTCPs (most common method)



→ Aluminium (cheap) or copper (expensive) plate
→ Known emissivity paint (either stated by manufacturer or measured in the lab)
→ Polystyrene
→ Wooden board
→ PT100 resistance thermometer + logger (ideally) or another way to measure (radiometer, thermogun)

Recommendation: cover different temperatures with different materials, or keep one covered from solar radiation and uncover before acquisition

Building your own TCP

Calibration plates protocol

How many and where?

Minimum 3 (Kelly et al 2019)

Calibration area next to the flight lines that you ideally monitor a few times at the beginning, during and end of flight

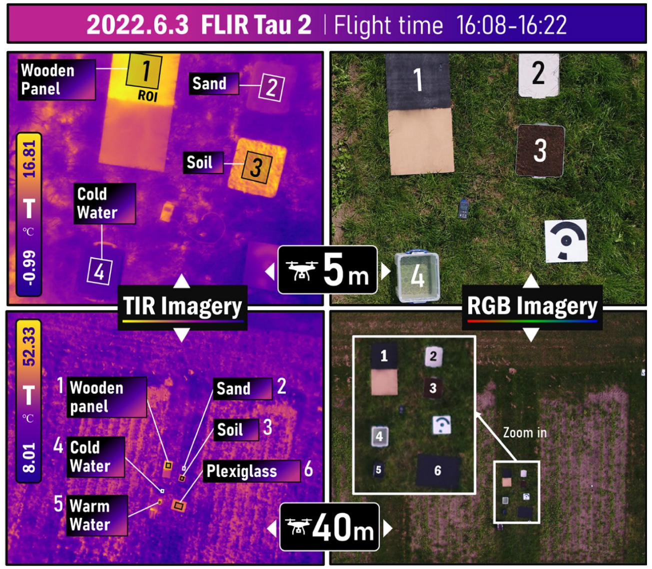
How big?

Depends on how high you are flying (GSD, spot size effect) which depends on your sensor (Wan et al 2024)

Other measurements?

Ideally measure radiometric temperature using a radiometer as well as skin temperature using thermocouple / resistance measurement

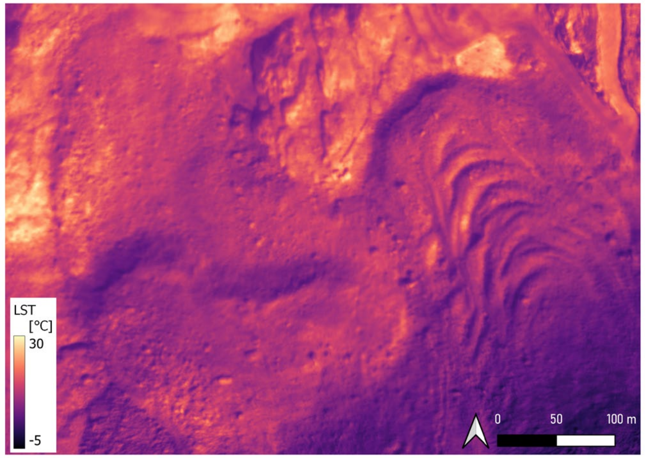
J.Adams



Wan et al (2024)

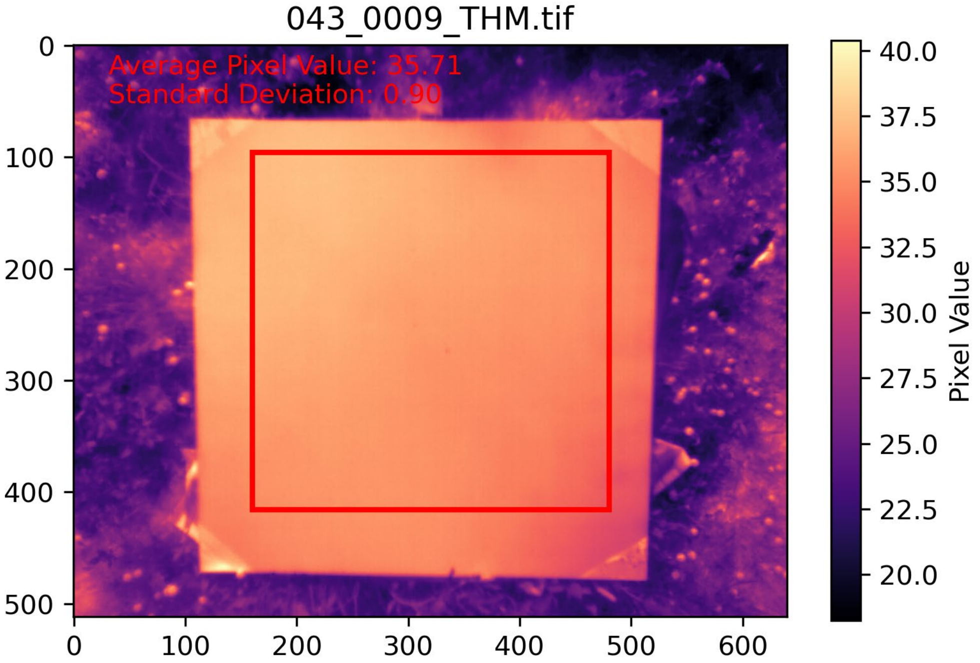
J.Adams

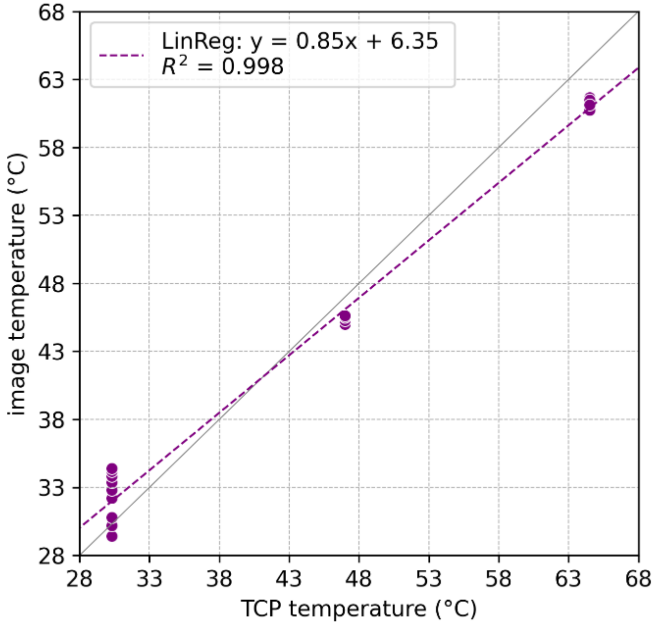
Example of TCP calibration in the field



Temperature control points in the field

→ Hot, cold, before, after
→ Sky T



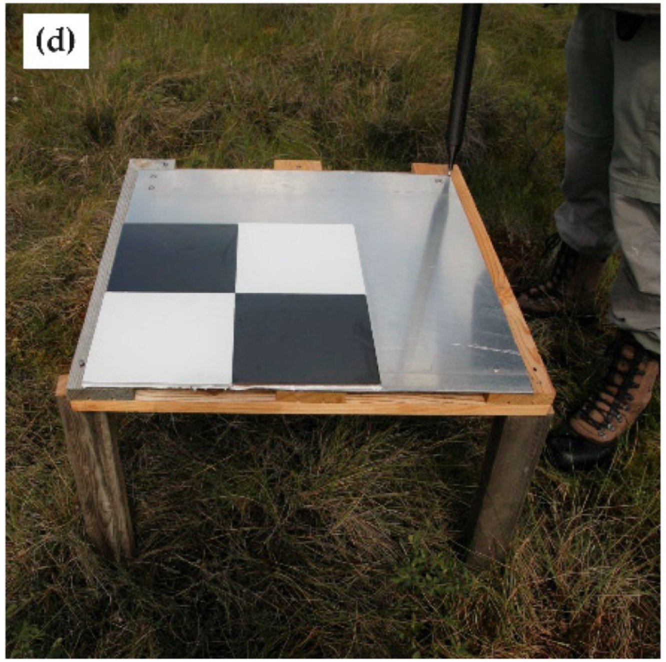


Naegeli et al (in prep)

Georeferencing

Ground control points (GCPs)

→ Should have different enough temperatures from surroundings to distinguish them
→ Large enough, depending on flight height
→ Black and white tiles arranged in a checkerboard pattern for RGB
→ + accurate measurement of GCPs

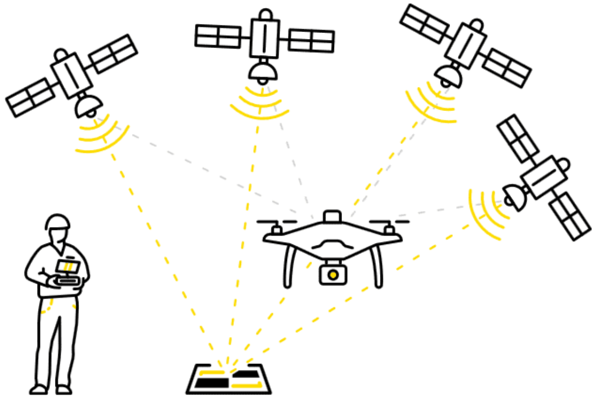


Kelly et al (2019)

PPK/ RTK: most new UAVs have this

RTK: **Real-time kinematic (RTK)**
→ GPS information recorded in flight
→ Good, but loss of contact with base station can be a problem

https://www.propelleraero.com/blog/how-it-works-ppk-vs-rtk-drone-surveying/



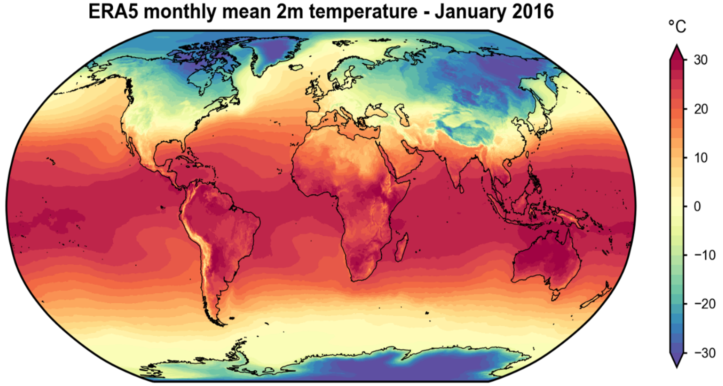
PPK: **post-processing kinematic**
→ UAV associates X, Y, and Z coordinates with each image based on its onboard GPS unit
→ A base unit (base station, CORS network) also records positional information with more accurate triangulation.
→ After the flight is over, the two sets of GPS data are matched together using image timestamps
→ **Adds an additional layer of reliability**

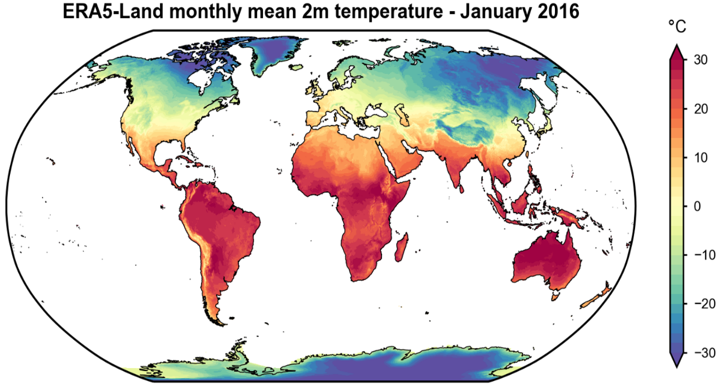
Atmospheric conditions: Air temperature and relative humidity

Ideal: Meteo station

Or: Aluminium plate / crinkled aluminimum foil for sky temp

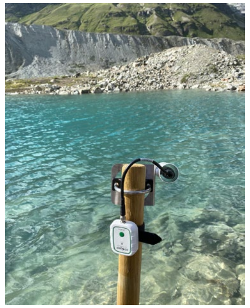
Or: Climate data (e.g. ECMWF reanalysis)





https://climate.copernicus.eu/climate-reanalysis

Thematic validation

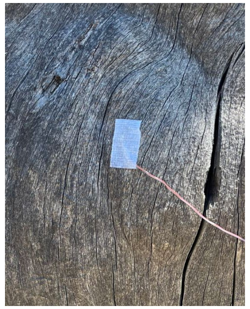


IR radiometers

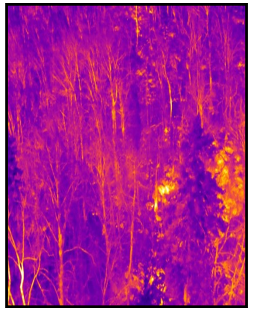
Sub-surface temperature measurements + modelling

Ground surface temperature loggers

TOMST



Thermocouples



Thermal cameras on the ground

Attention! Some of the measurements observe skin temperature, and not radiometric temperature

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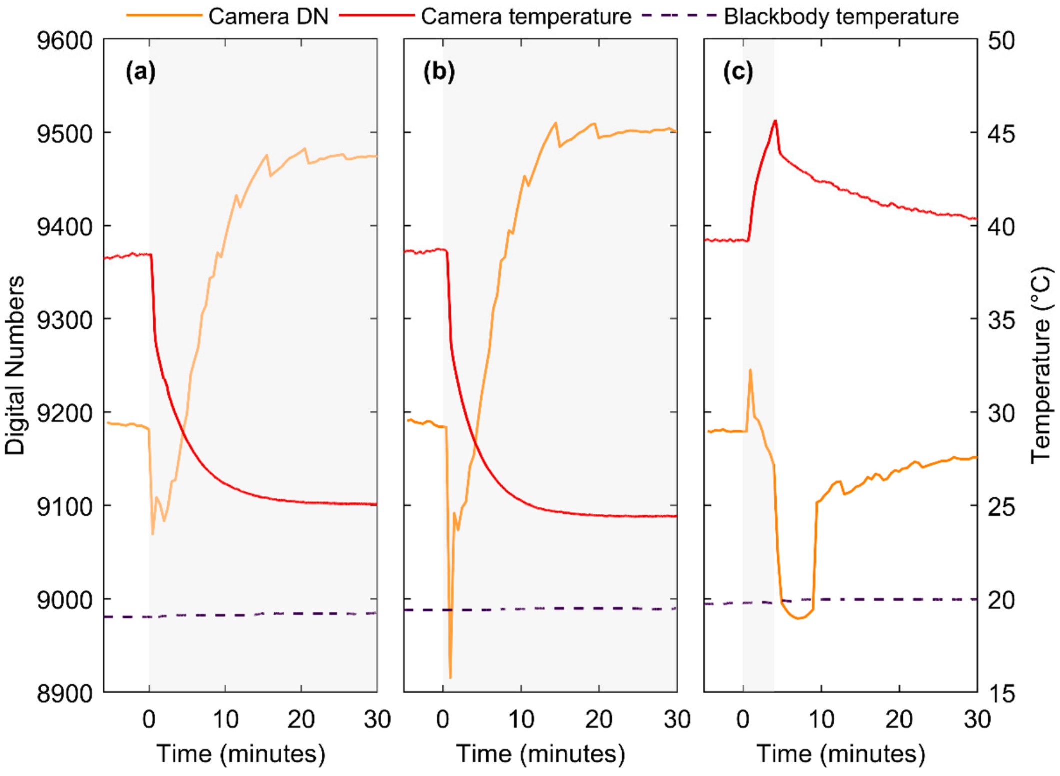
On the day of / during the survey

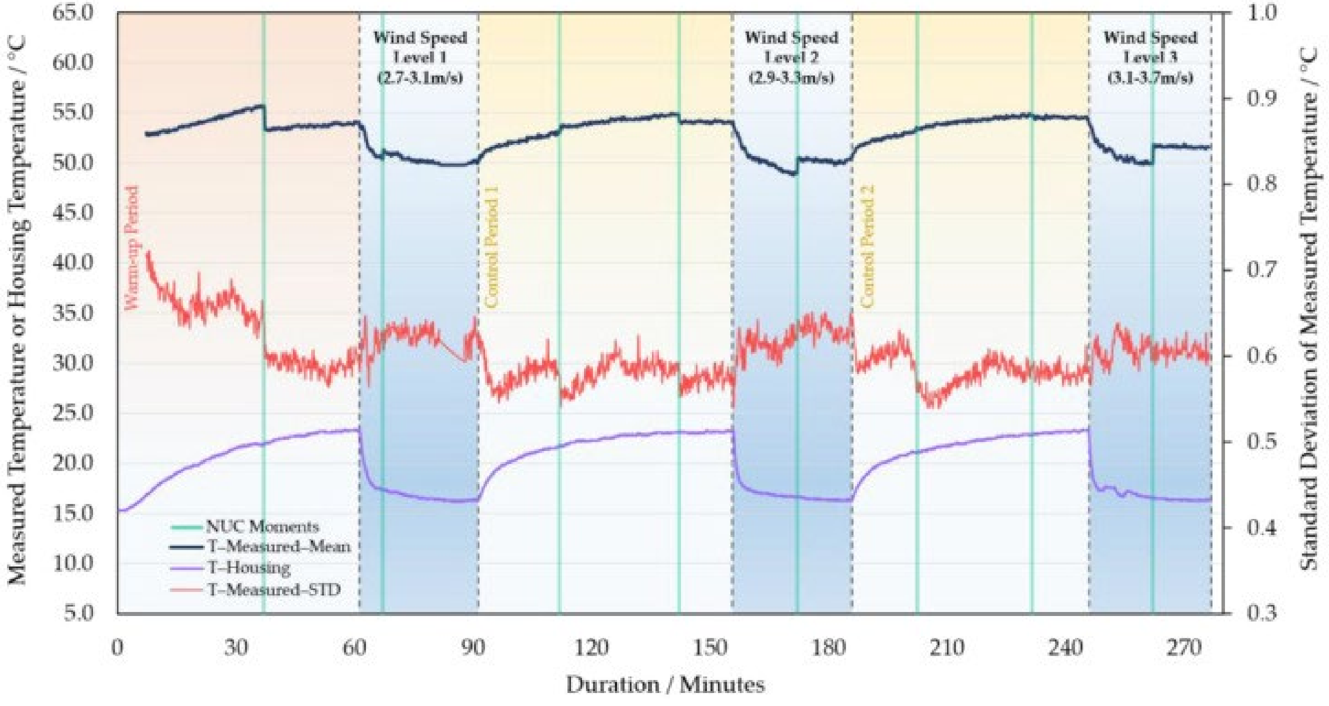
Assess the weather conditions

- Too much wind, ideally you want less than 2m/s (Kelly et al (2019))
- Depending on the surface (e.g. Urban) this could be increased to 5m/s (Leblanc et al (2021): 10.3390/drones5040132)

Define a clear criteria beforehand

- maximum wind/gust speed thresholds
- Radiation
- Clouds



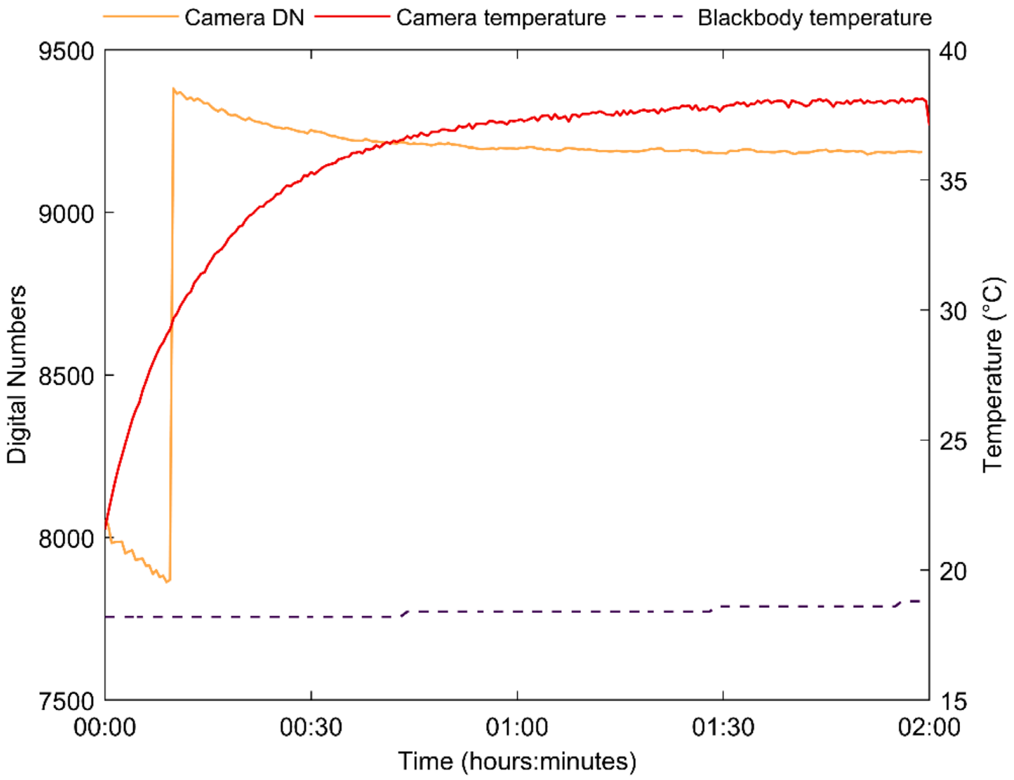


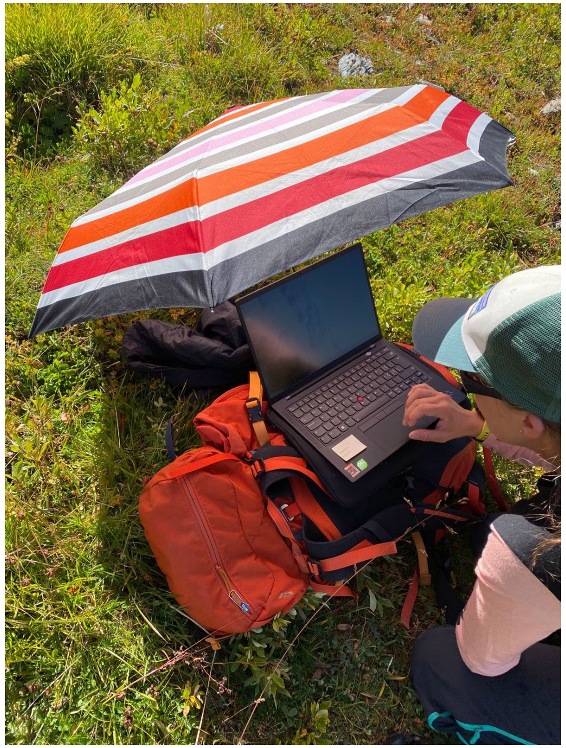
Wan et al (2021), DOI: 10.3390/s21248466

Camera stabilisation + avoid overheating

Camera stabilisation at least 15 mins Kelly et al (2019)
→ Before calibration plots
→ Ideally in the air if possible due to sensor drift (otherwise correct for it afterwards)

Avoid equipment overheating (e.g. tablets for UAV operation, UAV batteries, spectrometers etc.)
→ Particularly the thermal camera





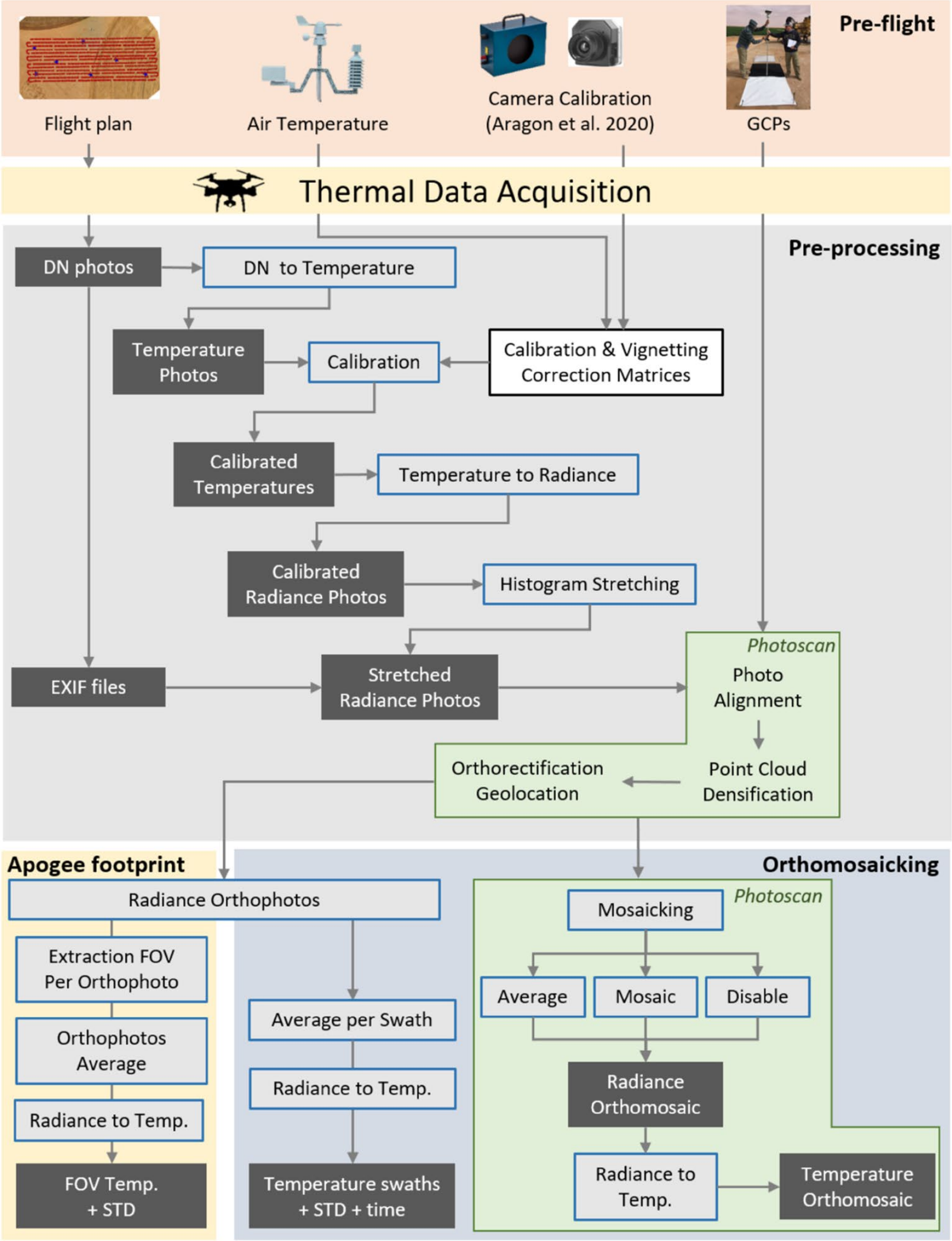
Before and during the survey checklist

- Ensure frequent NUC correction is enabled before flying
- Check wind speed, ideally less than 2m/s
- Camera stabilisation of at least 15 minutes (add some extra flight lines)
- Repeated passes over calibration points
- Fly slowly to avoid blurry pictures
- Keep note of any changes in the weather to help interpretation

5

After the survey

Post processing steps + photogrammetry process



First visually select the best set of images for post-processing by removing any blurred images

+ emissivity and drift correction

Either enter the images/coordinates of the targets or download PPK information from flight time and upload (software dependent)

To aid interpretation, try to understand how your software calculates the OM

May need to redo process a few times / select and change tie points due to low thermal contrast (depends on survey area)

Malbéteau et al (2021), DOI: doi.org/10.3390/rs13163255

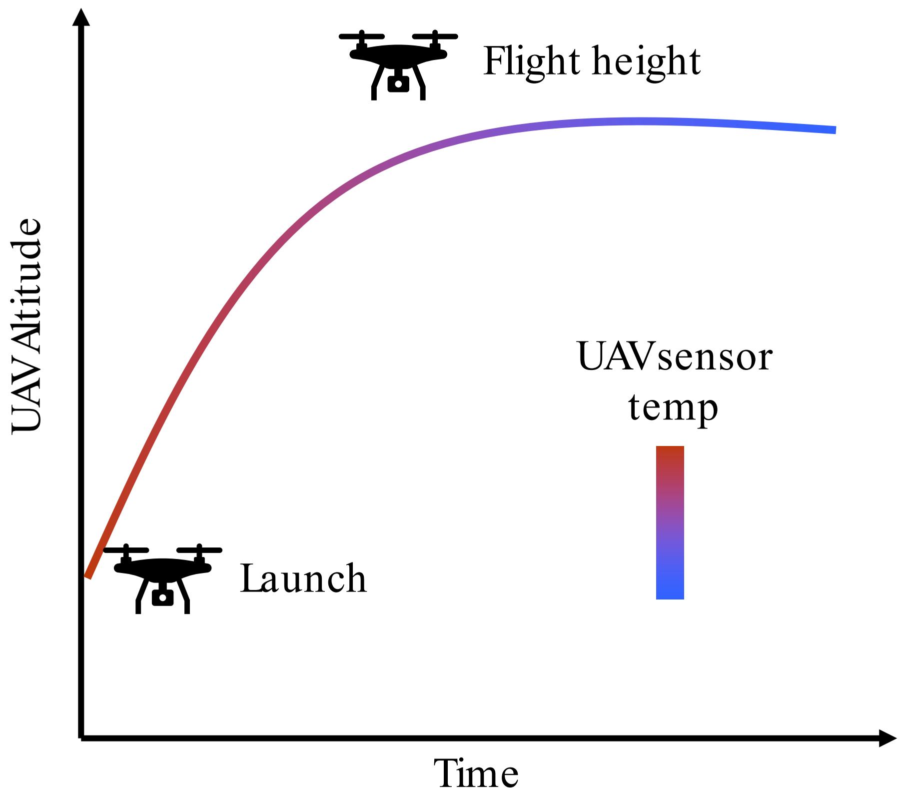
Post-processing softwares: Many options, some common ones….

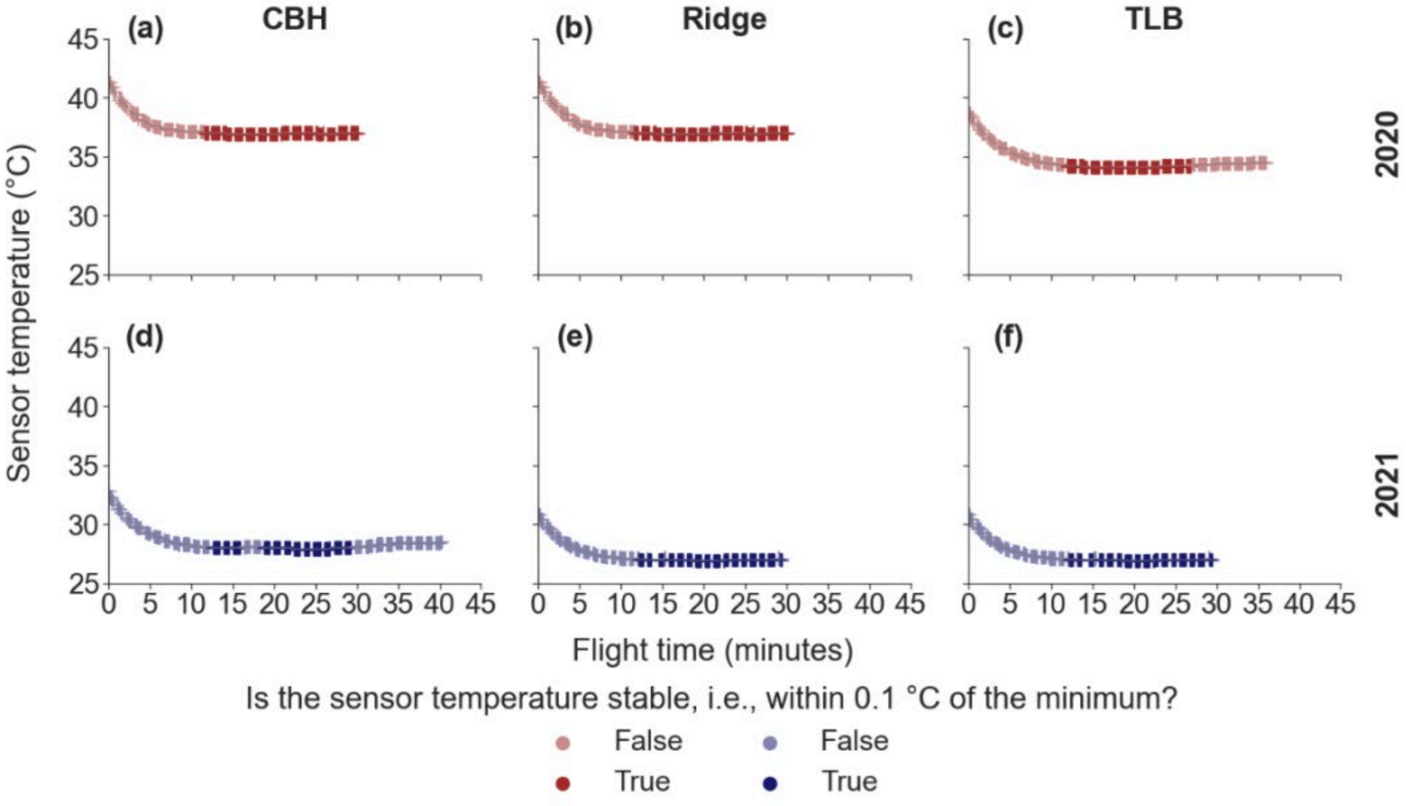
	Agisoft Metashape	Pix4D Mapper	Correlator 3D	OpenDroneMapper
Price	$$	$$$	$$$	-
Processing time	Fastest for small datasets	Slowest overall	Fastest overall	Slowest for large datasets
Ease of use	Hardest to automate	Easy templates, many options	Easiest automated templates	Harder to install but easy templates
Georeferencing accuracy	Similar at center of dataset	Similar at centre of dataset	Similar at centre of dataset, better at edges	Similar at centre
Image acquisition recommendations	Highest overlap recommended	Mid range overlap recommended	Lowest overlap recommended	Mid range overlap recommended
Pros	flexibility, nonlinearity, python script support, distributed processing	highly automated computing, user-friendly interface, support of a wide range of cameras	can process a huge amount of data, complete processing automation	user-friendly, quick processing
Cons	no pre-existing scenarios, “advanced” functionality difficult to use	user has limited impact on processing, limited manual edition and terrain generation	not possible to upload images if missing camera parameters, working with GCPs difficult	all images must have EXIF parameters, different versions have max number of images

*** Also consider: documentation (understanding how these softwares process TIR OMs is not easy), stability, community, cameras support and flexibility, user influence, academic pricing

Source: https://geonadir.com/software-for-drone-mapping/, https://www.50northspatial.org.ua/uav-image-processing-software-photogrammetry/

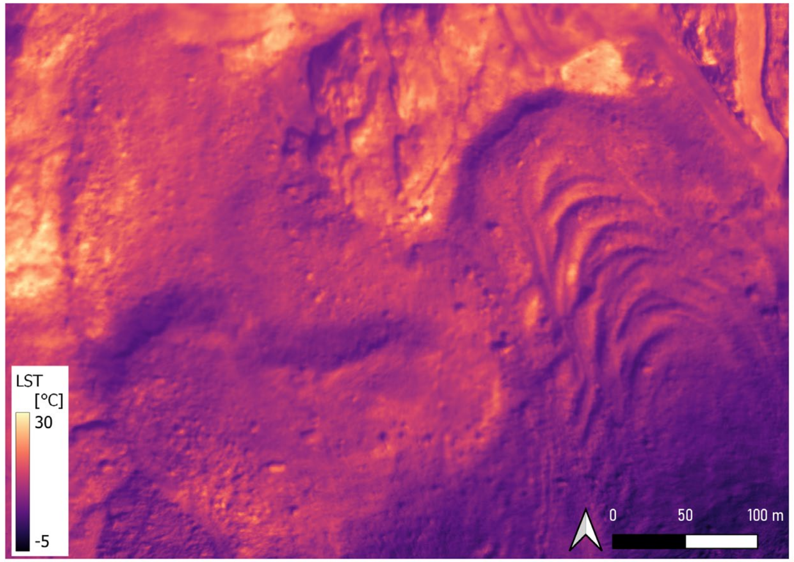
Sensor temperature drift correction

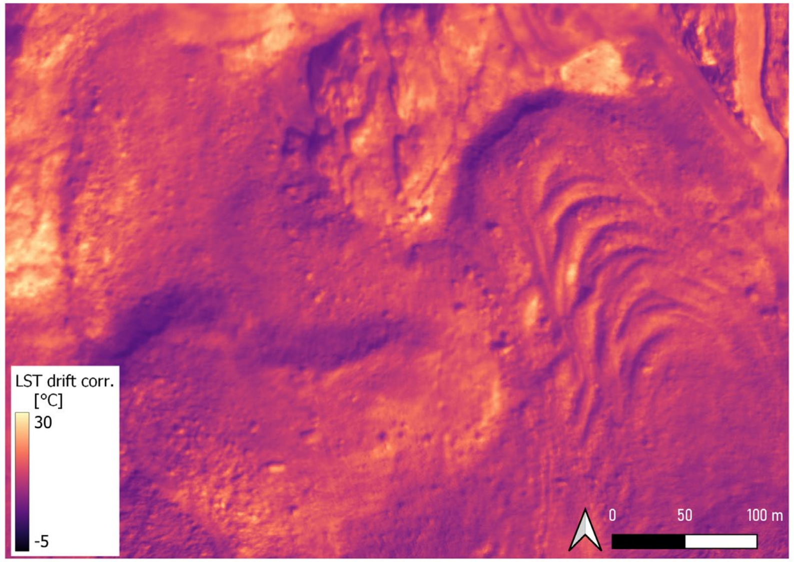


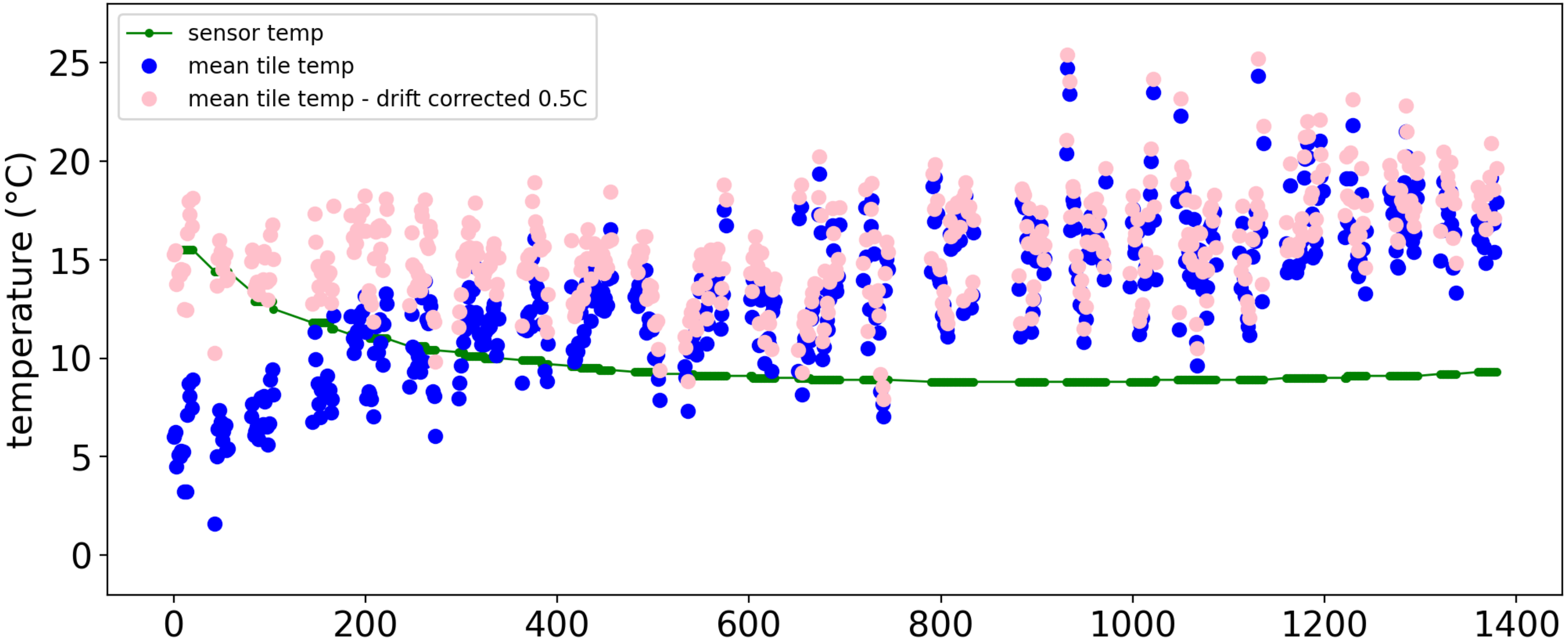


Rietze et al (2023), DOI: 10.1088/1748-9326/ad345e

Drift correction applied to other data





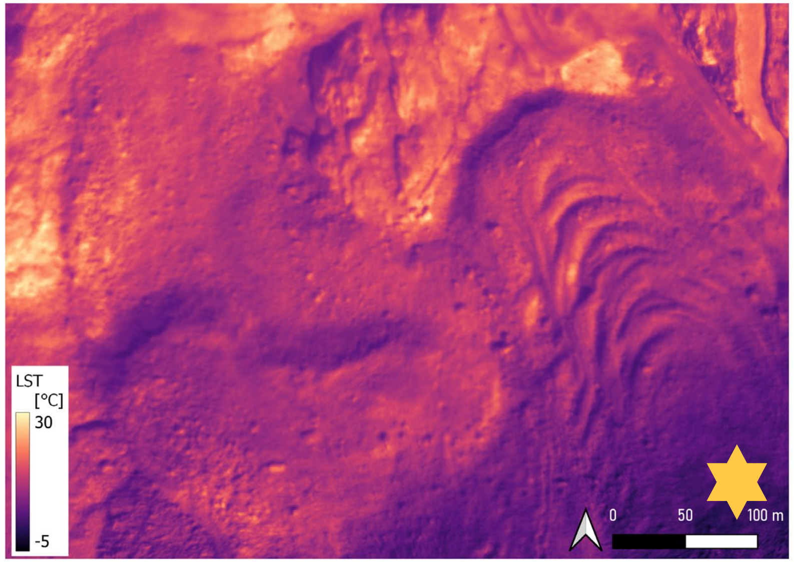


** Performed on images before image processing

Rietze et al (2023), https://github.com/nrietze/ArcticDroughtPaper

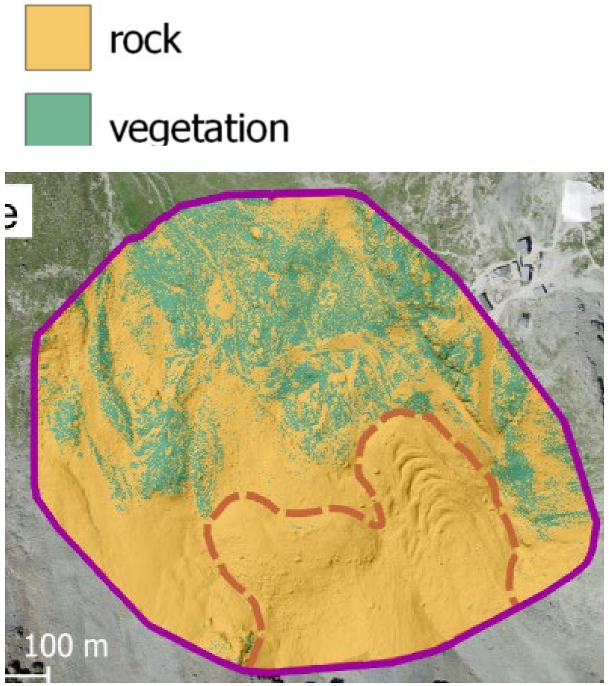
Naegeli et al (in prep)

BUT be careful →always consider your study area ☺



Naegeli et al (in prep)

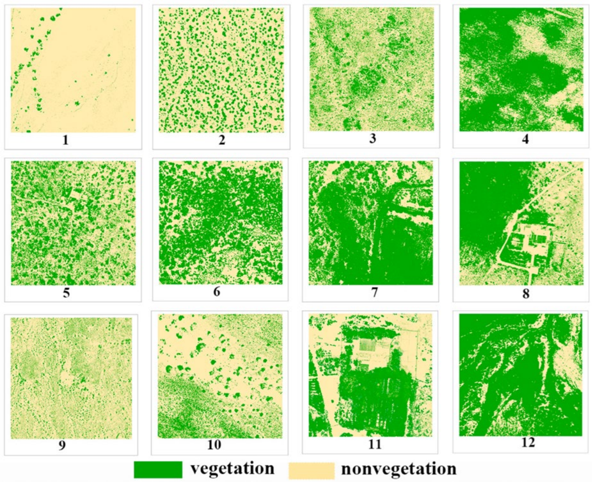
Emissivity characterisation: what options are available?



Surface classification + literature / spectral emissivity library / lab sampling

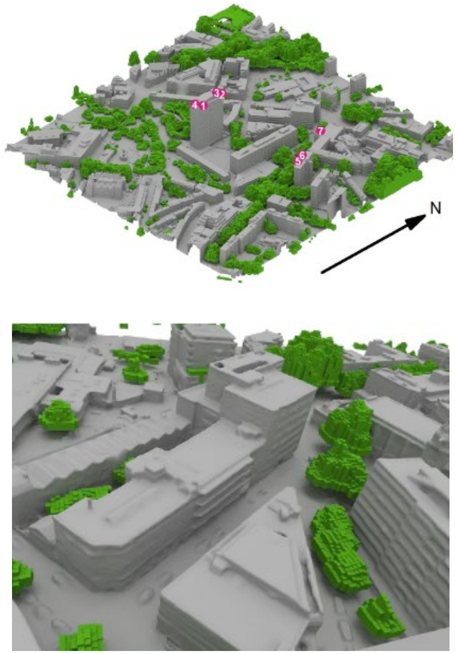
Naegeli et al (in prep)

$$\epsilon_c = (1 - c_v)\epsilon_s + c_v \cdot \epsilon_v$$



Use Fcover (vegetation only) + literature / spectral emissivity library / lab sampling

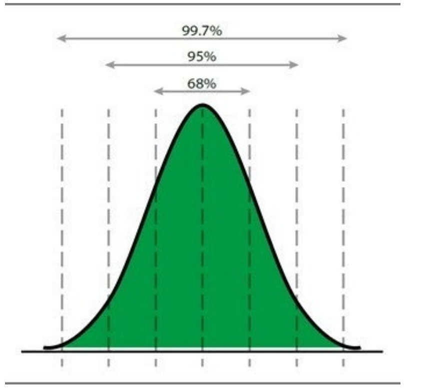
Ermida et al (2014)
Sun et al (2024)

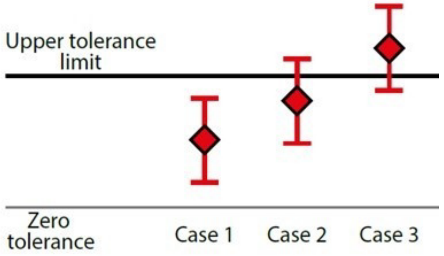


RT modelling

Can be used to simulate angular emissivity

Morrison et al (2020)





Range of emissivities and set up your further processing to account for uncertainty

https://blog.beamex.com/calibration-uncertainty-for-dummies-part-1

Radiometric calibration: From DNs to reflectance (if you have TCPs)

Empirical line correction (simple)

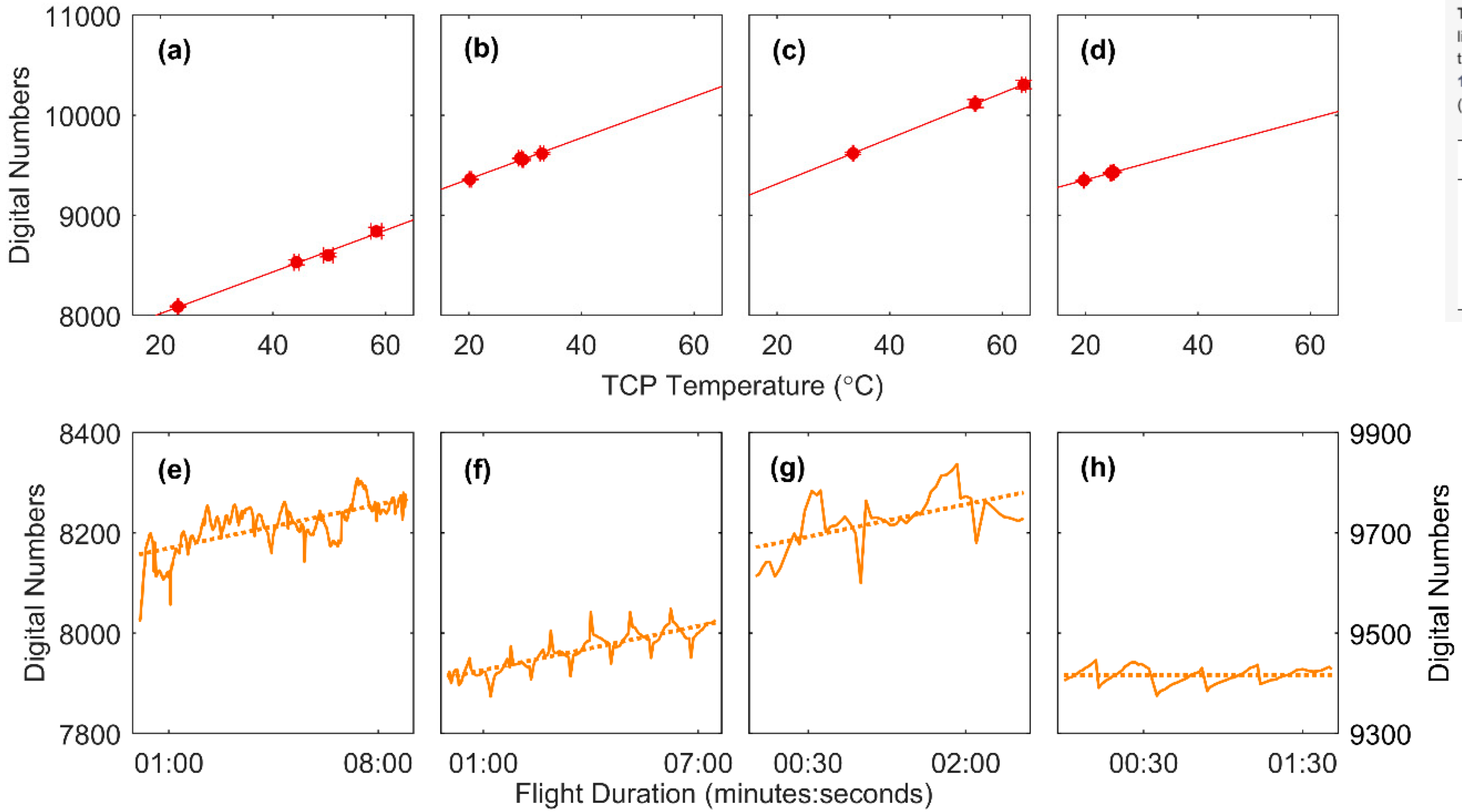


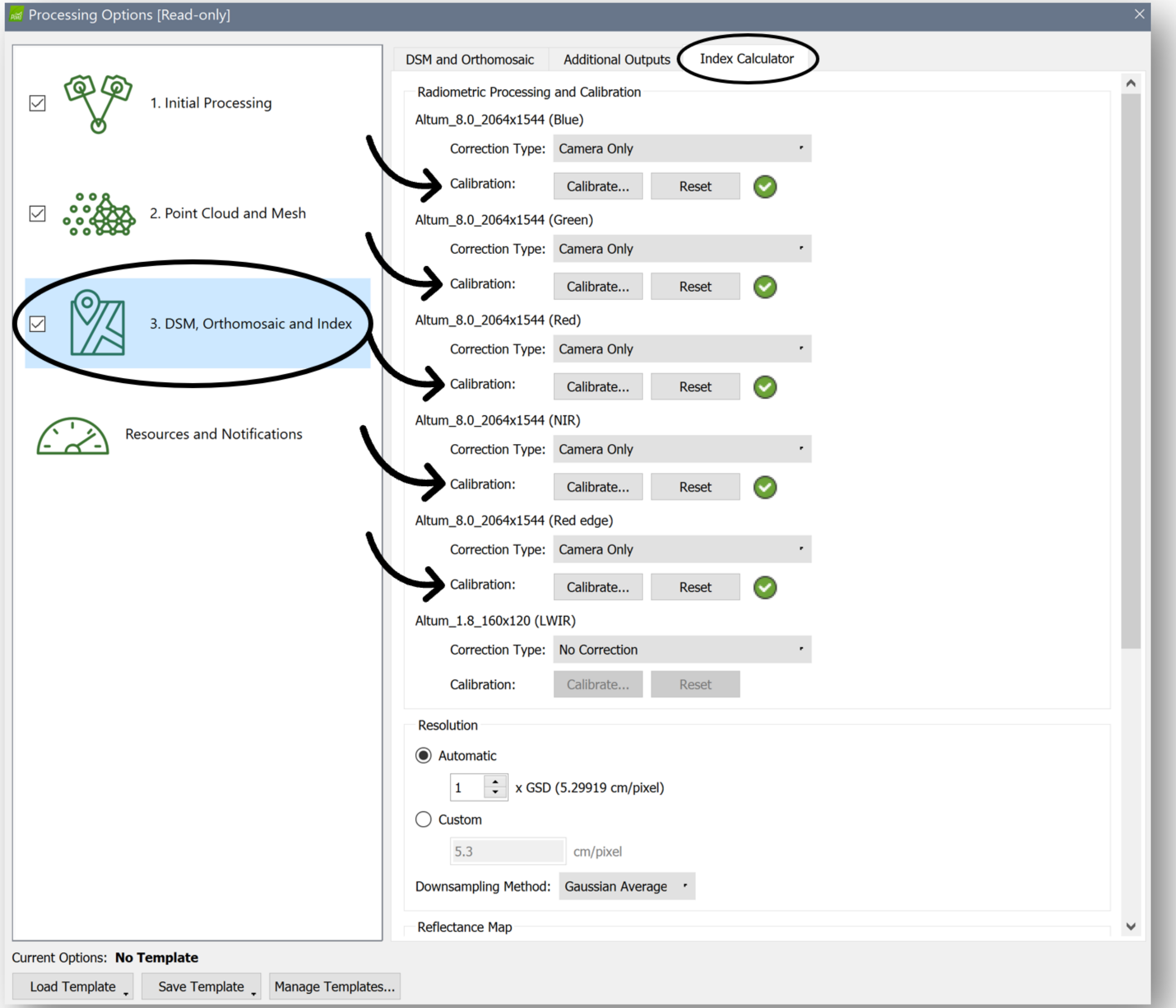
Table 2. Linear regression for calibration of TCP temperature against DN ('Calibration') and linear regression of mean image DN against flight duration (in minutes, 'Mean image DN'), for the four UAV flights. Number of TCPs used for the calibration regressions are listed in Table 1. Sample size (i.e., number of images) used for the 'Mean DN' regressions are n = 538 (Flight A), n = 134 (B), n = 53 (C) and n = 80 (D).

Flight	Calibration	R^2-adj	*p*-Value	Mean image DN	R^2-adj	*p*-Value
A	DN = 20.8(TCP) + 7601	0.99	<0.01	DN = 12.4(mins) + 8157	0.46	<0.001
B	DN = 20.6(TCP) + 8950	0.97	<0.01	DN = 14.6(mins) + 9411	0.74	<0.001
C	DN = 22.7(TCP) + 8861	0.99	<0.01	DN = 43.0(mins) + 9670	0.34	<0.001
D	DN = 15.2(TCP) + 9050	0.99	<0.05	DN = 0.37(mins) + 9416	0	>0.05

Kelly et al (2019)

Radiometric calibration: From DNs to reflectance (if you have TCPs)
Empirical line correction (simple)

Most softwares will take your calibration / TCP files, and may also provide options to add camera calibration coefficients (in the metadata), and solar irradiance and angle information



Kelly et al (2019)

Radiometric calibration: From DNs to reflectance
Atmospheric correction (more complex)

Inputs: Air temperature and relative humidity (meteo), emissivity and distance (UAV metadata or DEM)

$$\Phi_{leaf} = \frac{1}{\tau \varepsilon_{leaf}} \left(\Phi_{tot} - \tau \left(1 - \varepsilon_{leaf}\right) \varepsilon_{sky} \Phi_{sky} - (1 - \tau) \Phi_{air} \right)$$

$$\Phi = \left(\frac{R_1}{R_2} \frac{1}{e^{\frac{B}{T}} - F} \right) - O$$

$$c_{H_2O} = RH \cdot e^{\left(1.5587 + 6.939 \times 10^{-2} T_{atmC} - 2.7816 \times 10^{-4} T_{atmC}^2 + 6.8455 \times 10^{-7} T_{atmC}^3\right)}$$

$$\tau = X \cdot e^{\left(-\sqrt{d} \cdot \left(\alpha_1 + \beta_1 \sqrt{c_{H_2O}}\right)\right)} + (1 - X) \cdot e^{\left(-\sqrt{d} \cdot \left(\alpha_2 + \beta_2 \sqrt{c_{H_2O}}\right)\right)} \qquad (7)$$

Aubrecht et al (2016), DOI: 10.1016/j.agrformet.2016.07.017

Thermimage (version 4.1.3)

raw2temp: Converts raw thermal data into temperature (oC)

Description

Converts a raw value obtained from binary thermal image video file into estimated temperature using standard equations used in infrared thermograp

Usage

```
raw2temp(raw, E = 1, OD = 1, RTemp = 20, ATemp = RTemp, IRWTemp = RTemp, IRT = 1,
RH = 50, PR1 = 21106.77, PB = 1501, PF = 1, PO = -7340, PR2 = 0.012545258,
        ATA1=0.006569, ATA2=0.01262, ATB1=-0.002276, ATB2=-0.00667, ATX=1.9)
```

https://www.rdocumentation.org/packages/Thermimage/versions/4.1.3/topics/raw2temp

Or an atmospheric correction algorithm, e.g. DROACOR

https://droacor.com/

Orthomosiac generation / post processing

OM generation was not designed for thermal images ☹

Mosaic method

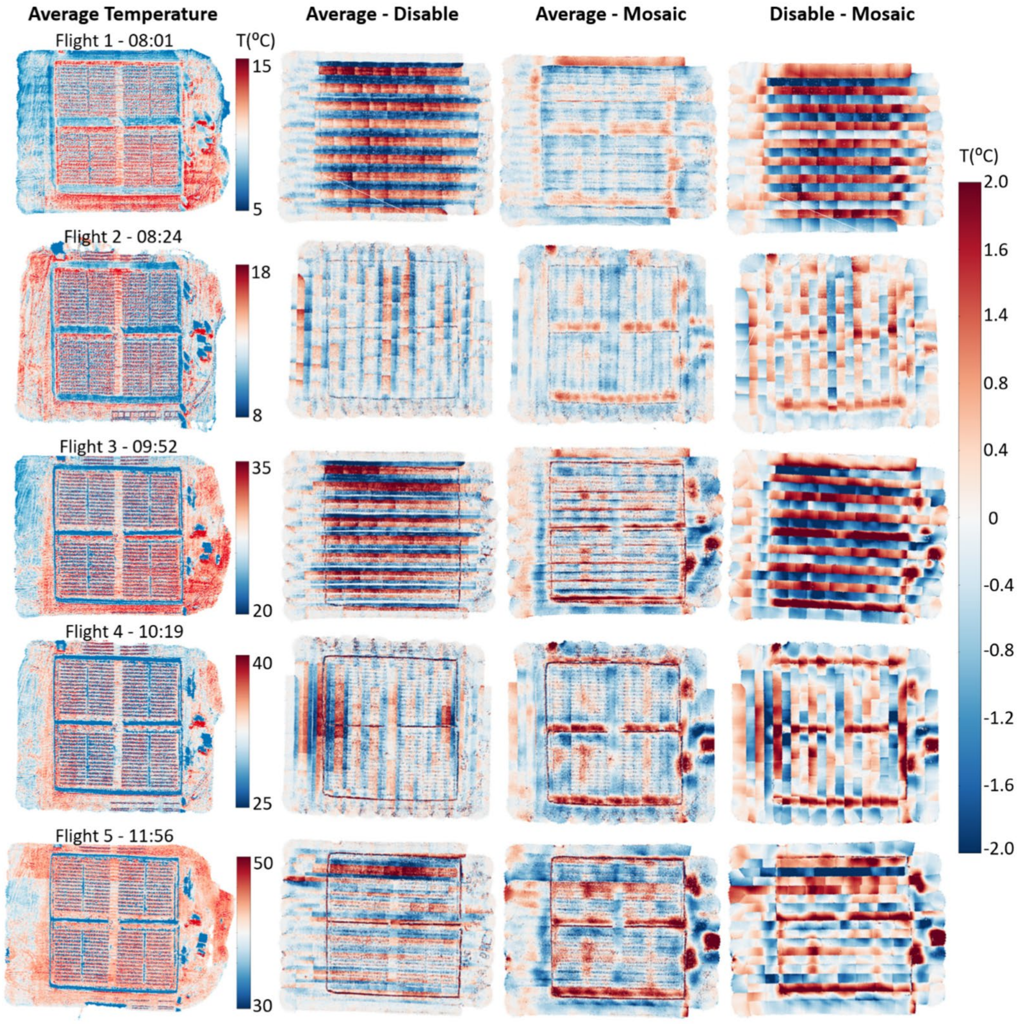
- Orthophotos decomposed into high- and low-frequency components
- Weighted average is calculated separately with different weights and combined into the final OM, where pixels closer to nadir have higher importance
- Sensitive to flight conditions, smooths retrieved temps

Averaging method

- The weighted average pixel value from all available overlapping orthophotos is assigned to the corresponding pixel
- Smoothing effect from off-nadir and nadir

Disable method

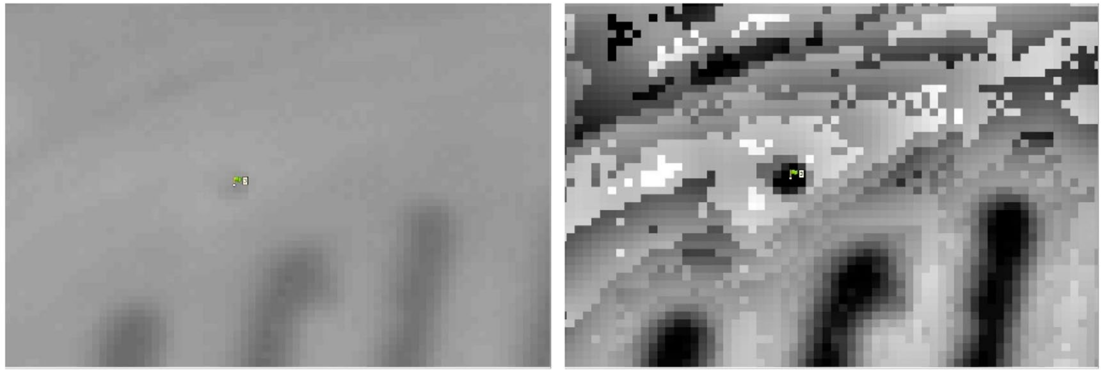
- Each pixel value in the resulting OM is selected from a single orthophoto among all overlapping orthophotos based on the photo having the view closest to nadir
- Strongly sensitive to flight conditions (e.g. striping)



Malbéteau et al (2021), DOI: doi.org/10.3390/rs13163255

OM generation and lack of contrast in TIR images

Apply a filter, or enhance the contrast of the thermal images to improve the OM generation / automatic selection of GCPs



(a) (b)

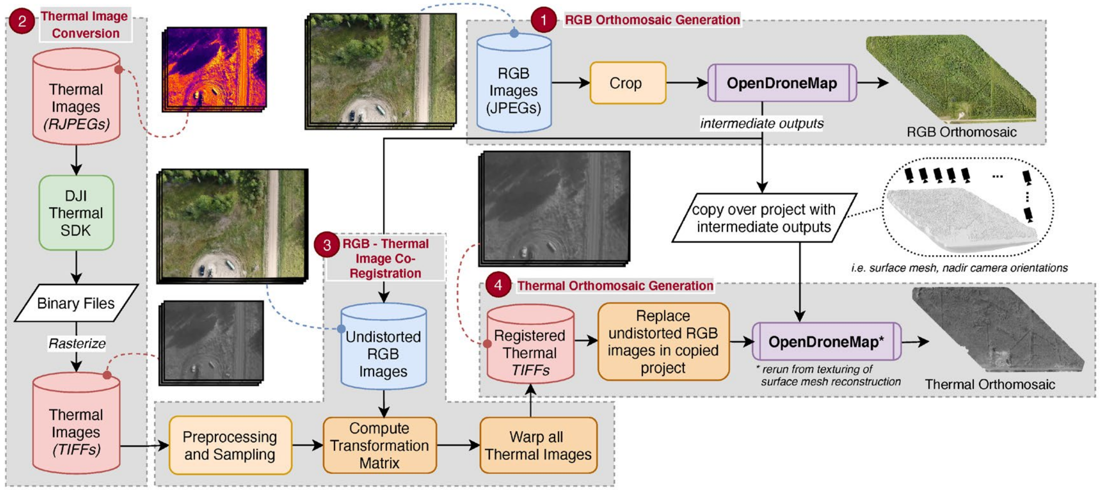
Ribeiro-Gomes et al (2017), "Wallis filter"

→For the processes of alignment of the images, determination of the dense cloud of points, and creation of the mesh, we used the set of thermal images treated with the Wallis filter.

→To texture and generate the final orthoimages, these images were replaced by the set of radiometrically-calibrated images.

Ribeiro-Gomes et al (2017), DOI: 10.3390/s17102173

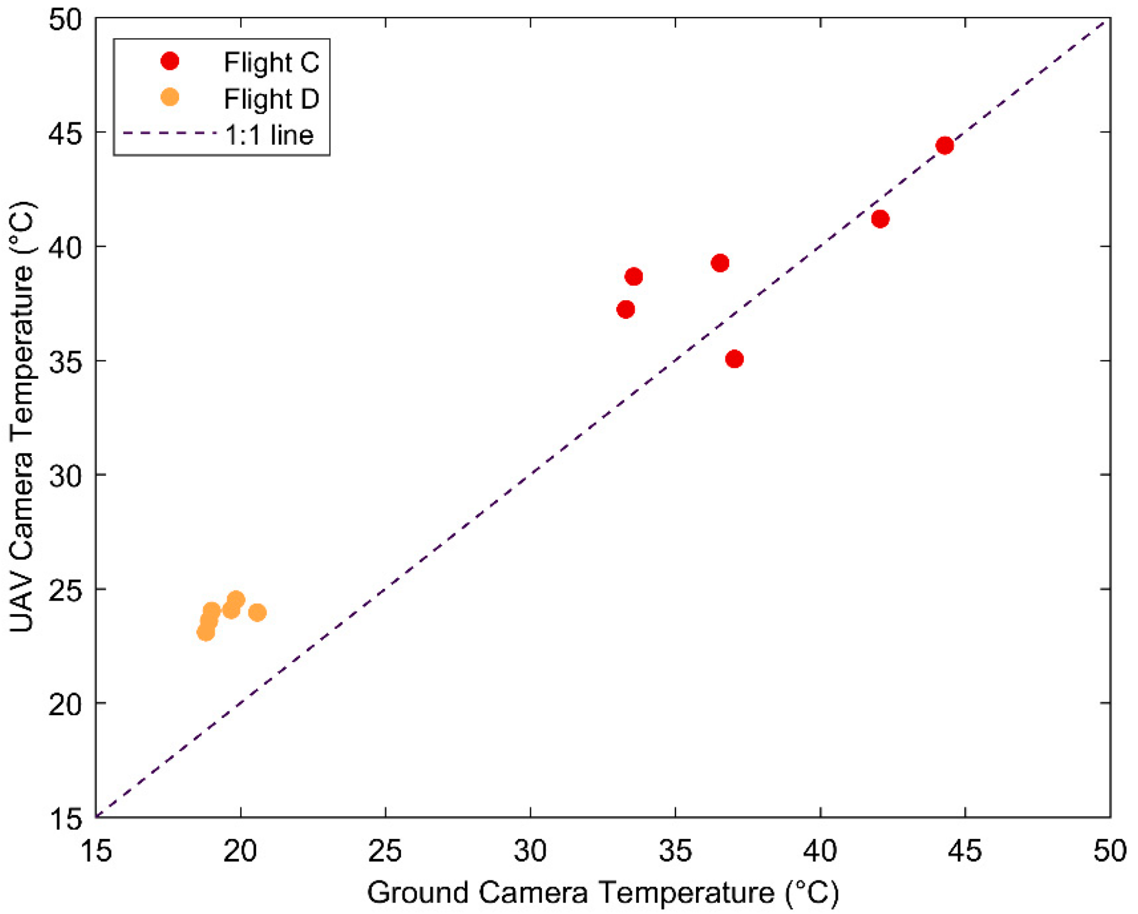
Use RGB images to create the mesh, then overlay thermal images on top (e.g. Kapil et al 2023, DOI: 10.3390/rs15102653)



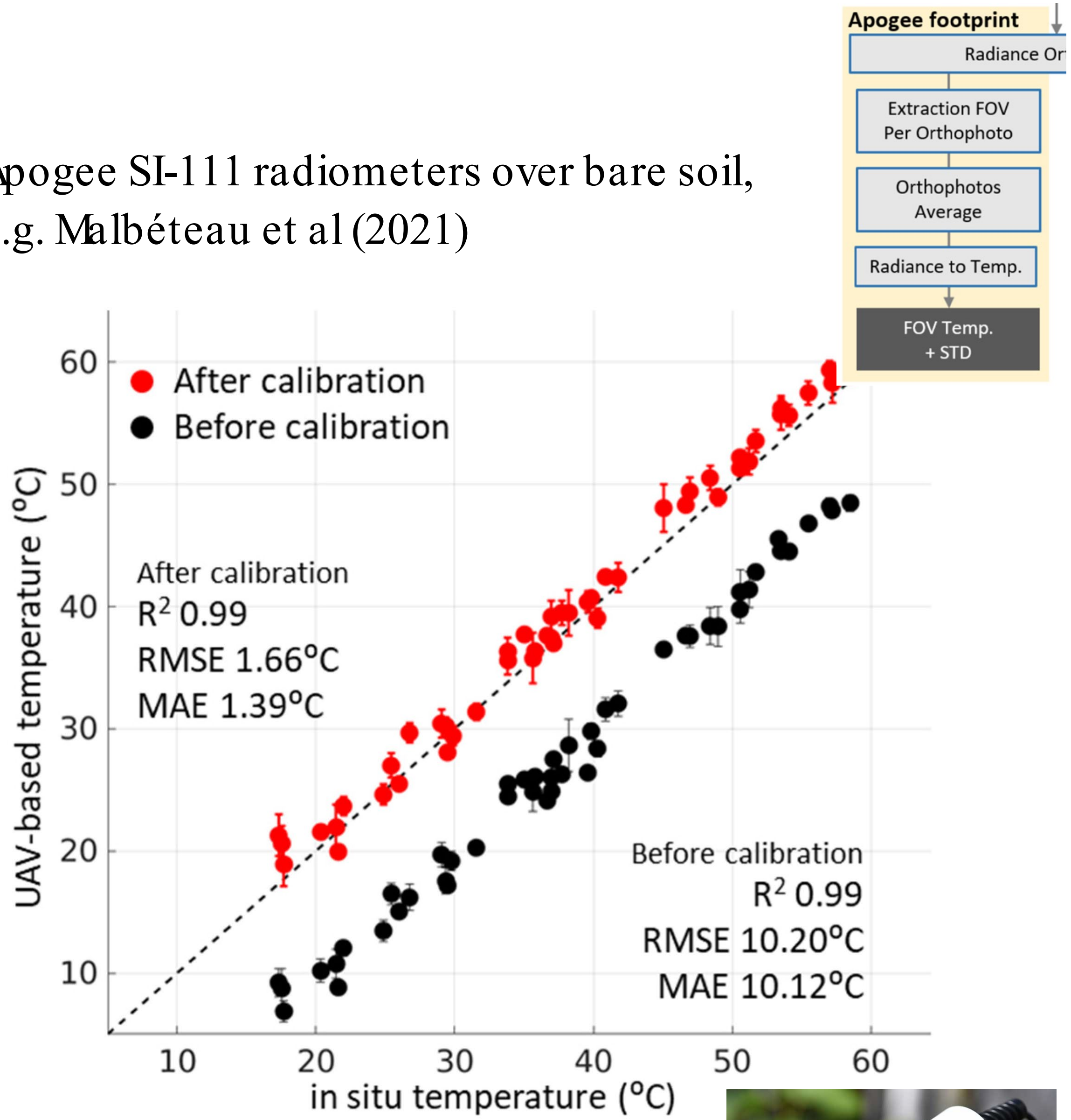
* Your chosen software may also be able to do this, i.e. in pix4d you can merge thermal and RGB projects

Performing thematic validation

Ground thermal cameras e.g. Kelly et al (2019)



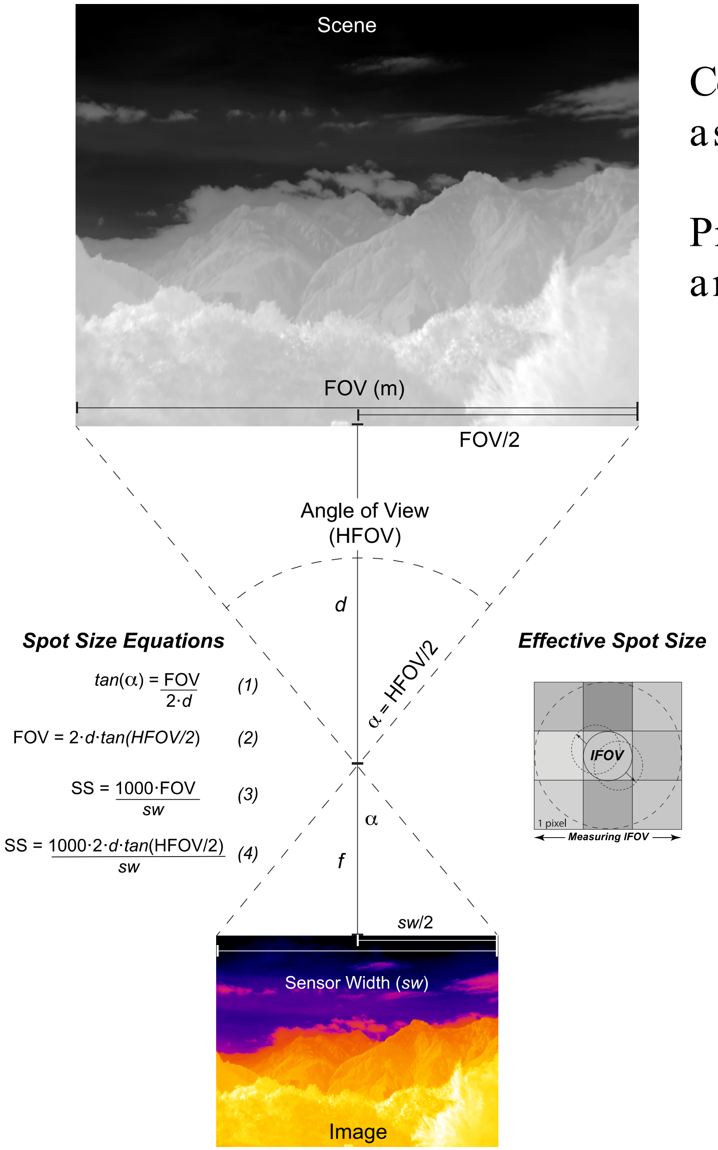
Apogee SI-111 radiometers over bare soil, e.g. Malbéteau et al (2021)



5½

Other factors

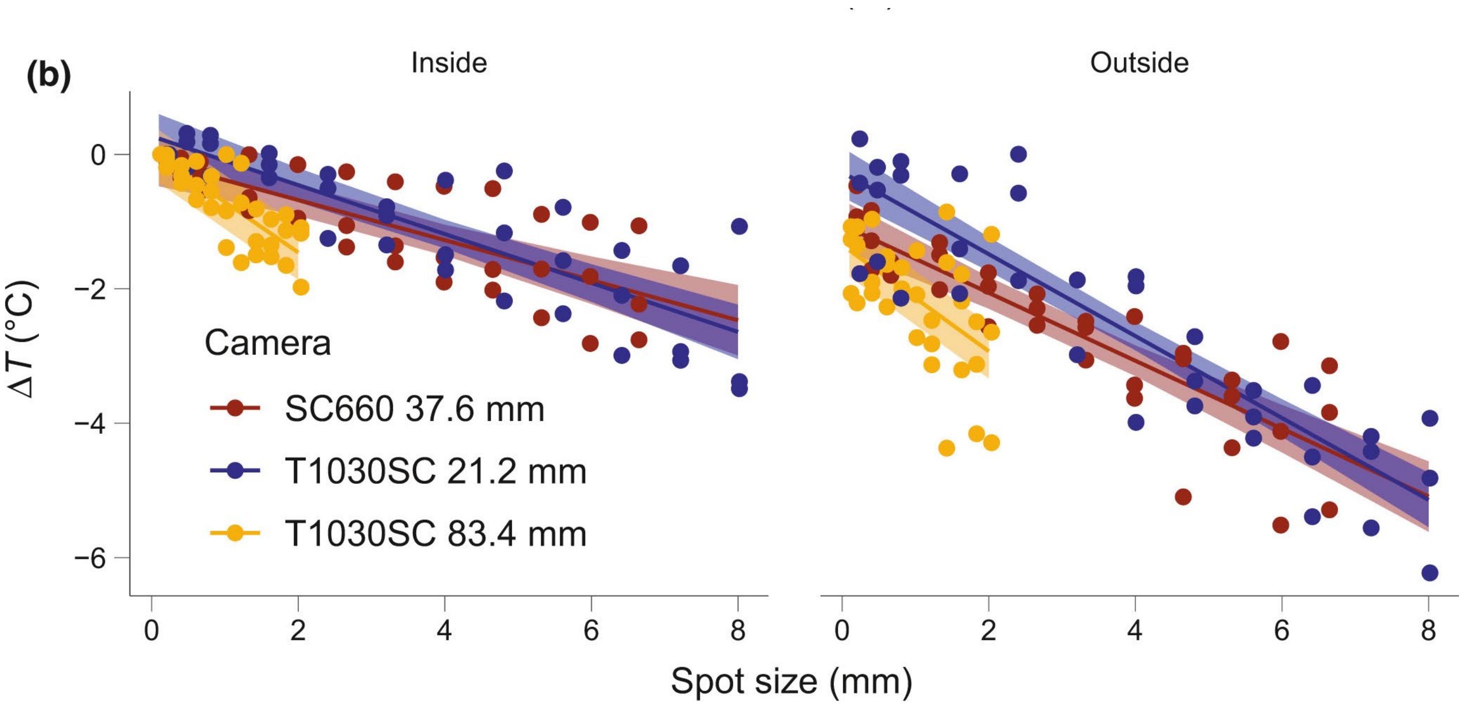
Spot size effect (check your processing software how it deals with this)



Corresponds to the size of the smallest object whose temperature can be accurately assessed, at a set distance.

$$\theta_{MIFOV} = 3 \times \theta_{IFOV}.$$

Practically measurable spot size is **three times** the true spot size, due to vibration and uncertainty over spatial alignment of the spot and the sensor pixel (Holst 2000)

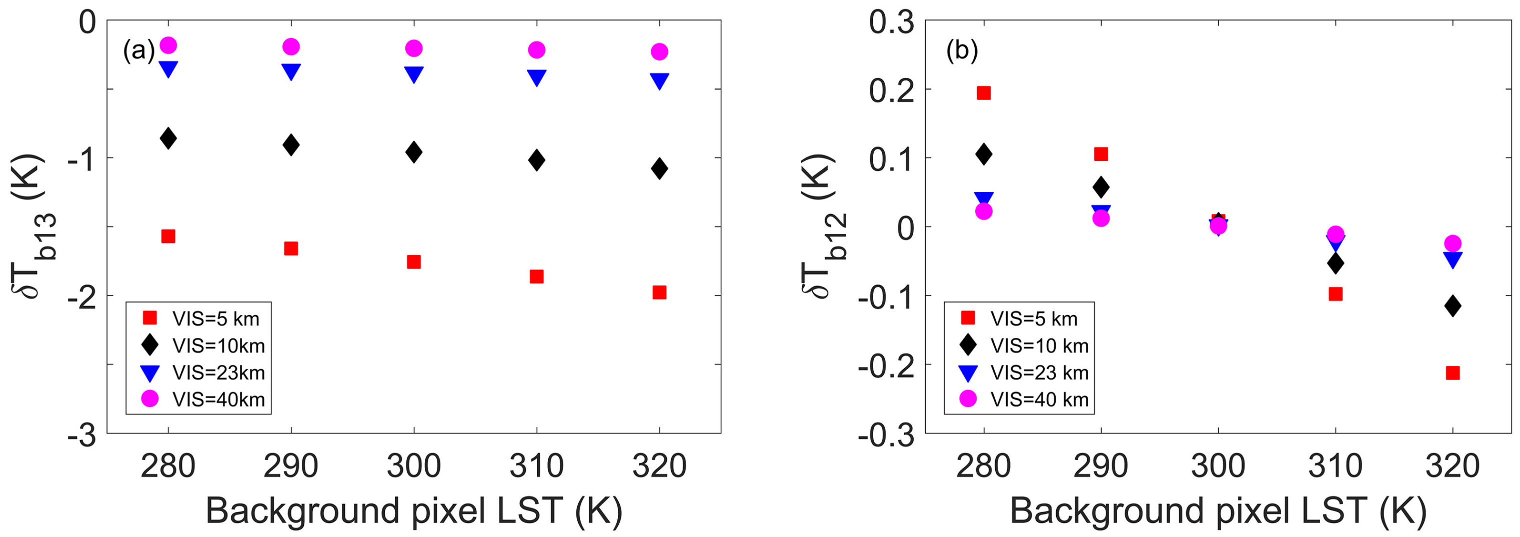


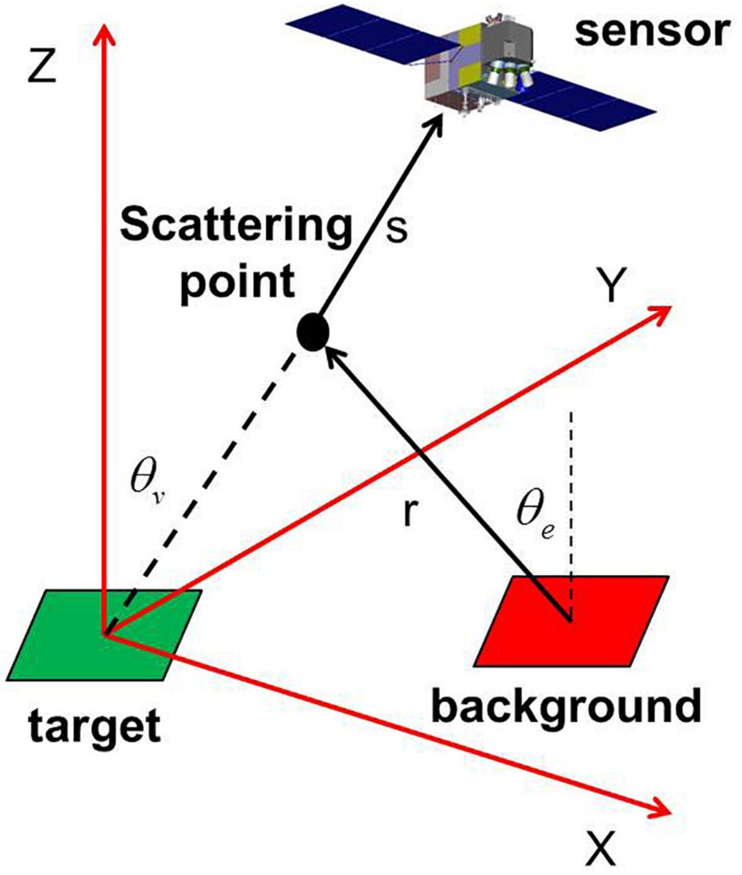
Playà-Montmany and Tattersall (2021), DOI: 10.1111/2041-210X13563

Radiation and adjacency effects

Combine with an RT model to understand radiation effects from km away

- MODTRAN (Duan et al 2020, DOI: 10.1016/j.rse.2020.111852)
- FAERTM (Zheng et al 2019, DOI: 10.1109/TGRS.2019.2928525)
- Results indicate it might not be needed when AOD>0.3
- Still needs work in complex terrain (mountains, forest, urban, topography)





What impacts adjacency: Atmospheric visibility, WVC, sensor spectral band, and background pixel LST

What doesn't: Background pixel LSE, pixel spatial resolution, and adjacency range on the adjacency effect is nearly negligible

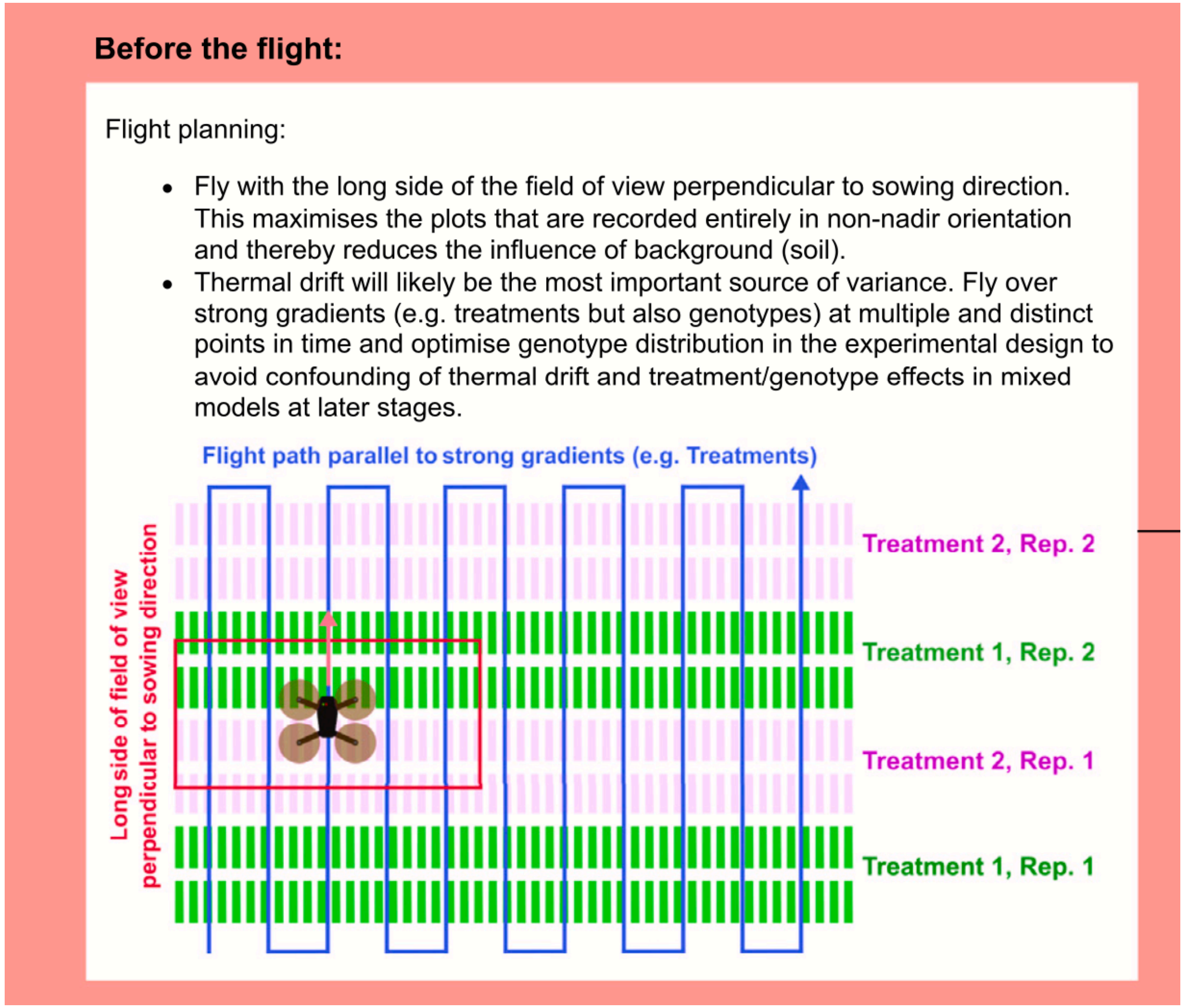
Directionality: Recommendations to reduce impacts

Tu et al (2020)

1. Flying along the hedgerow improved data quality
2. Smaller image pitch angle improved data quality
3. Higher solar elevation improved data quality in general

Other recommendations suggest to fly perpendicular to sun direction to avoid hotspot / glint and largest shadowing

Treier et al (2024) →


Before the flight:

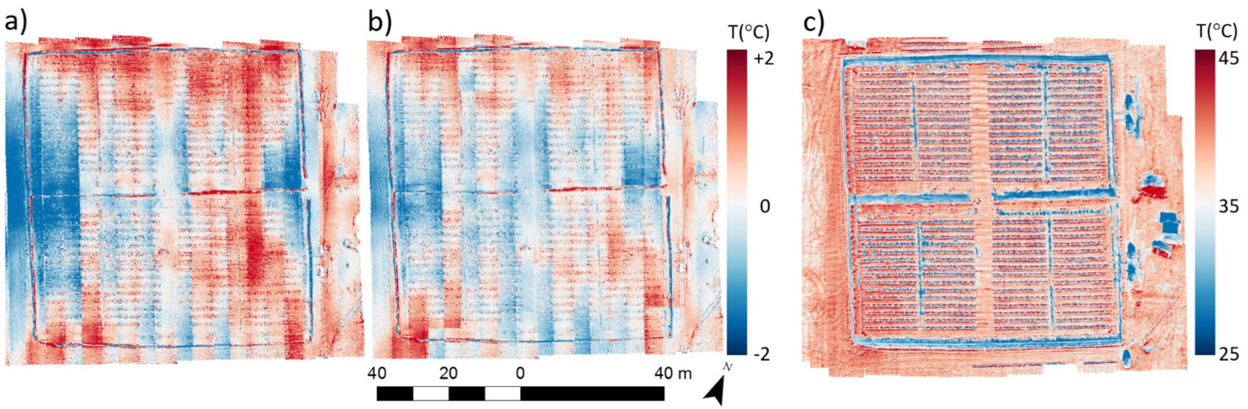
Flight planning:

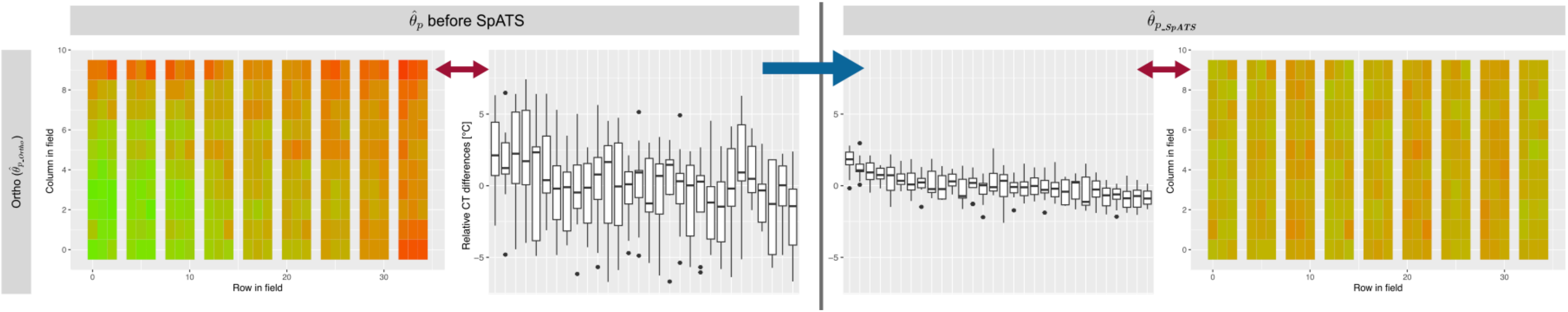
- Fly with the long side of the field of view perpendicular to sowing direction. This maximises the plots that are recorded entirely in non-nadir orientation and thereby reduces the influence of background (soil).
- Thermal drift will likely be the most important source of variance. Fly over strong gradients (e.g. treatments but also genotypes) at multiple and distinct points in time and optimise genotype distribution in the experimental design to avoid confounding of thermal drift and treatment/genotype effects in mixed models at later stages.

Directionality: Correction options

1. Empirical BTDF correction, adjusting weights for surface
2. Physically-based RT modelling correction
3. Multi-view acquisitions (e.g. Treier et al 2024, DOI: 10.1016/j.isprsjprs.2024.09.015)
4. Swath based corrections (e.g. Malbéteau et al 2021)

Malbéteau et al (2021)





Treier et al (2024)

Topography and complex scenes

Large variance of slope and aspect / directionality

Radiation exposure, terrain roughness

Harsh environmental conditions

Stronger and colder winds, larger delta-T between sensor and target

Small surface contrast or extremely heterogeneous

May need further contrast enhancing

Large gradient in atmospheric conditions

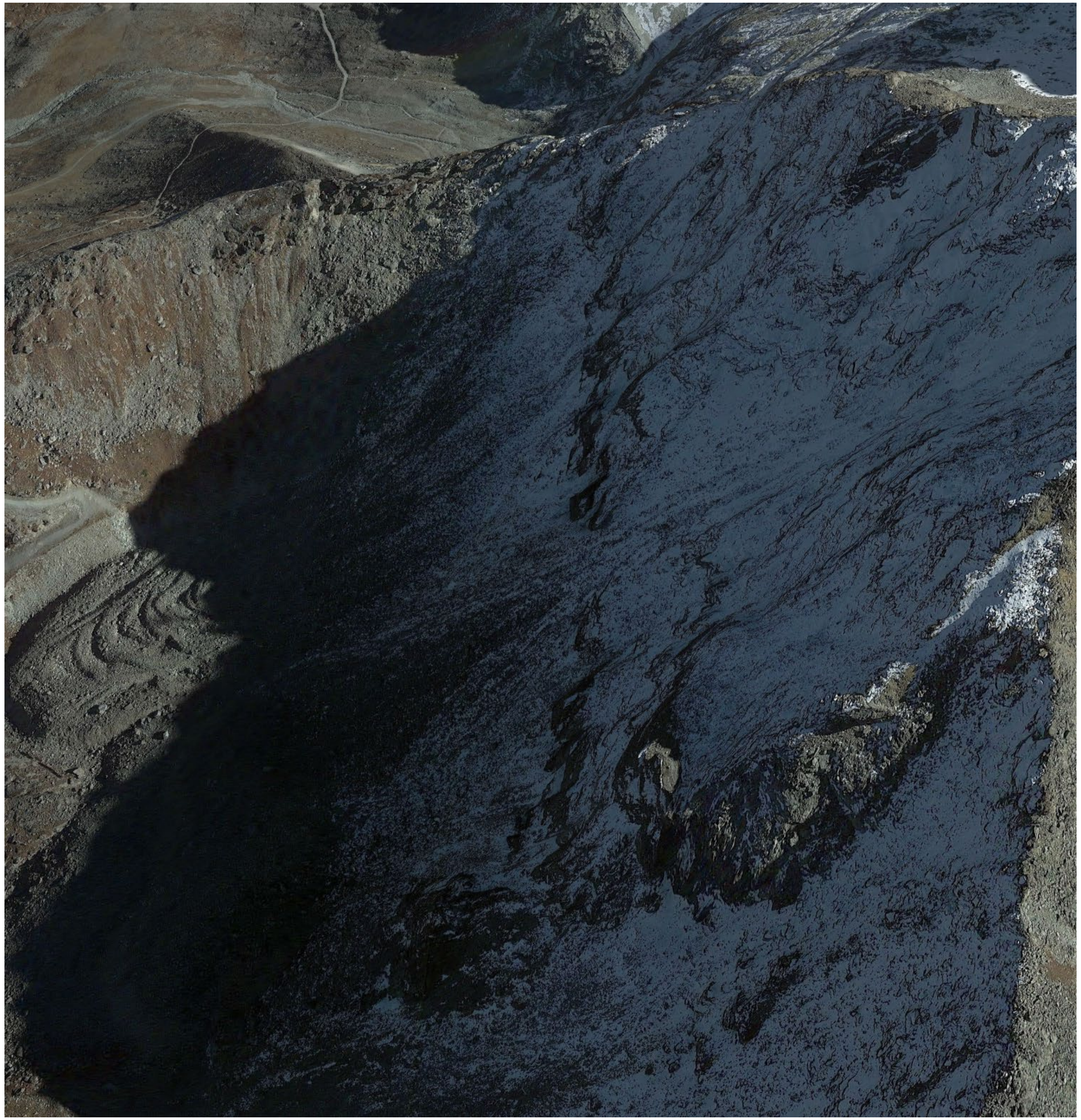
Exacerbates sensor temp drift and complicates atmo correction

Mosiacing technique choice can have a large impact

Off-nadir/nadir differences large due to topography and flight direction

Difficult to access

Placing TCP/GCPs in the field not always possible, size of TCP to carry

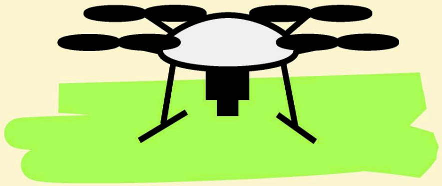


6

A summary of cascading recommendations

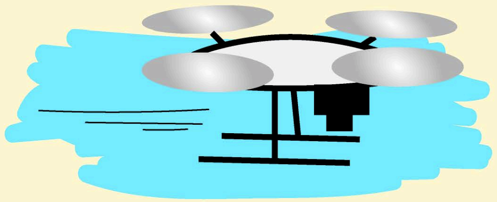
Summary of recommendations: Kelly et al (2019)

Before flight:



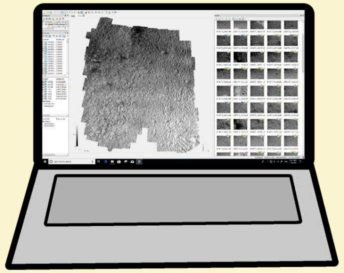
- At least 15 mins stabilization time [2,9]
- Minimum 3 ground calibration points
- Ground calibration points with wide temperature range that spans the target object temperatures
- Enable frequent NUC [3]
- Mount camera so it is sheltered from wind

During flight:



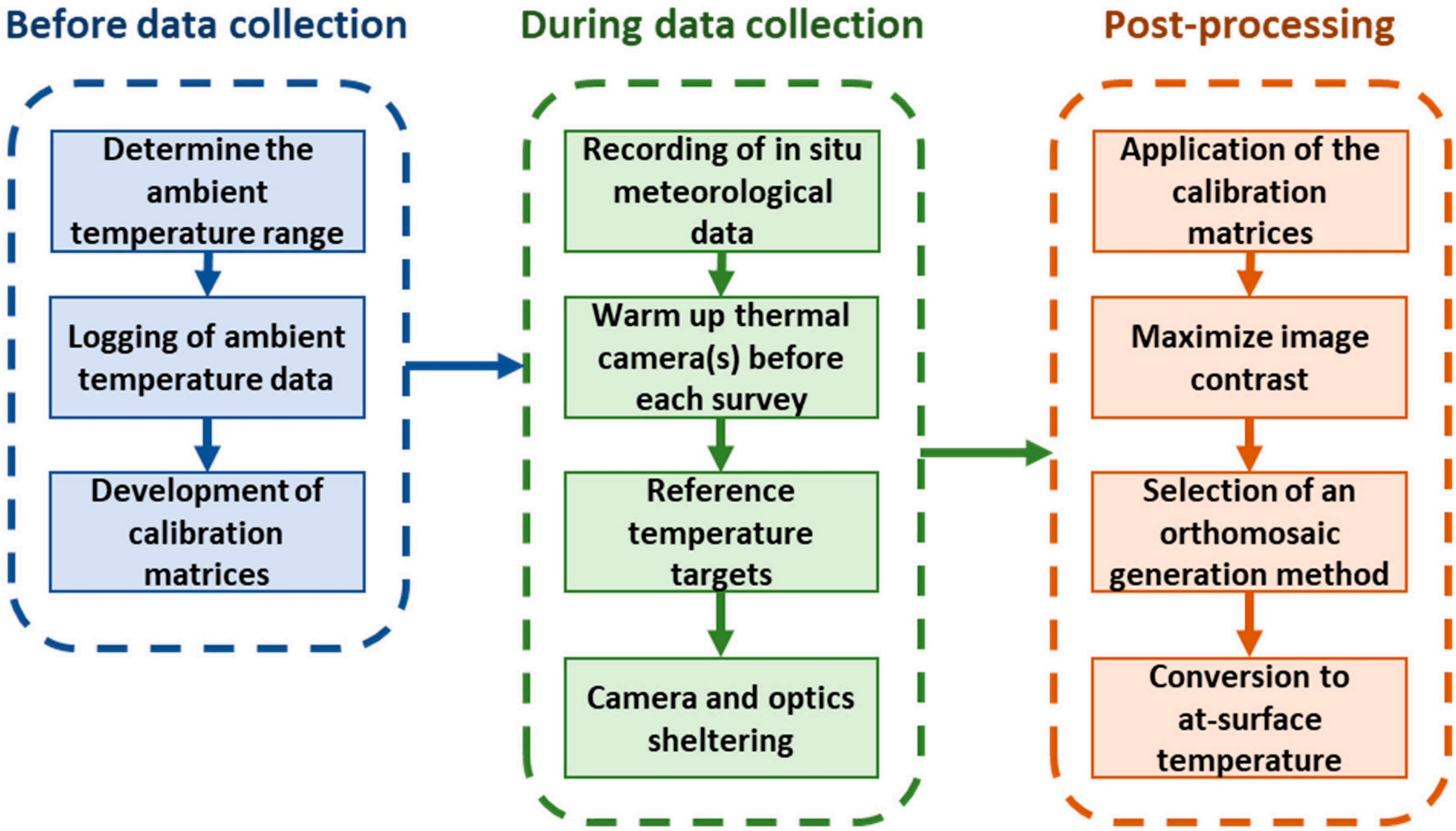
- Fly slowly to avoid blurry images and wind effects
- Extra flight lines at start of flight, at least 15 mins
- Repeated passes over ground calibration points [3]

After flight:



- Correct for vignetting or use only centre of images [19,31]
- Correct for temperature drift [17]

Summary of recommendations: Aragon et al (2020)



+more cascading recommendations

Complexity

Sensor in lab
- Ambient temperature changes
- Sensor temperature
- Response to wind

Vignetting and NUC
- Use centre of images
- Characterise with ice bath
- Characterise with blackbody

TCPs
- Ice bath / hot water / survey area available water
- DIYTCP (single temp)
- DIYTCP (temp range)
- Diffuse panel

Radiometric calibration
- Empirical line correction
- Atmospheric correction (ECMWF or alu)
- Atmospheric correction (meteo station)
- Atmospheric correction algorithm
- Adjacency effects

Drift correction
- Use open source code
- Develop your own correction based on data

Emissivity
- Assume single value
- Range of values for uncertainty
- Pixel-based classification + literature derived values
- Pixel-based classification + lab sampling
- RT modelling

Thematic validation
- None
- Thermocouples / GST logger / TOMST
- Radiometer
- Thermal camera

Relative temperature

Absolute temperature

Great references / open source tools for all these corrections

Raw2temp for FLIR: https://www.rdocumentation.org/packages/Thermimage/versions/4.1.3/topics/raw2temp
Drift correction: https://github.com/nrietze/ArcticDroughtPaper/tree/main/code/thermal_drift_correction
ThermoSwitcher (extracting radiometric TIFF from DJI JPEG): https://www.mdpi.com/1424-8220/24/19/6267
OpenDroneMapper
Georeferencing/mosiacing in python: https://github.com/SeadroneICMAN/MosaicSeadron

Kelly et al (2019): https://www.mdpi.com/2072-4292/11/5/567#
Maes et al (2017): https://www.mdpi.com/2072-4292/9/5/476
Aubrecht et al (2016): https://www.sciencedirect.com/science/article/pii/S0168192316303434
Chakhvashvili et al (2024): https://link.springer.com/article/10.1007/s11119-024-10168-3
Wan et al (2024): https://www.sciencedirect.com/science/article/pii/S1569843224005405?via%3Dihub#b8
Lin et al (2021): https://onlinelibrary.wiley.com/doi/full/10.1111/phor.12216
Tu et al (2020): https://www.sciencedirect.com/science/article/pii/S0924271619302941#f0020
Wan et al (2021): https://www.mdpi.com/1424-8220/21/24/8466#B44-sensors-21-08466
Aragon et al (2020): https://www.mdpi.com/1424-8220/20/11/3316#B67-sensors-20-03316
Duan et al (2020): https://www.sciencedirect.com/science/article/pii/S0034425720302224#f0025

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Thanks!

Questions?