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Validation of Sentinel-3 Land Surface Temperature datasets against ground-based measurements in support of the Copernicus LAW (LST, AOD, and Water vapour) project

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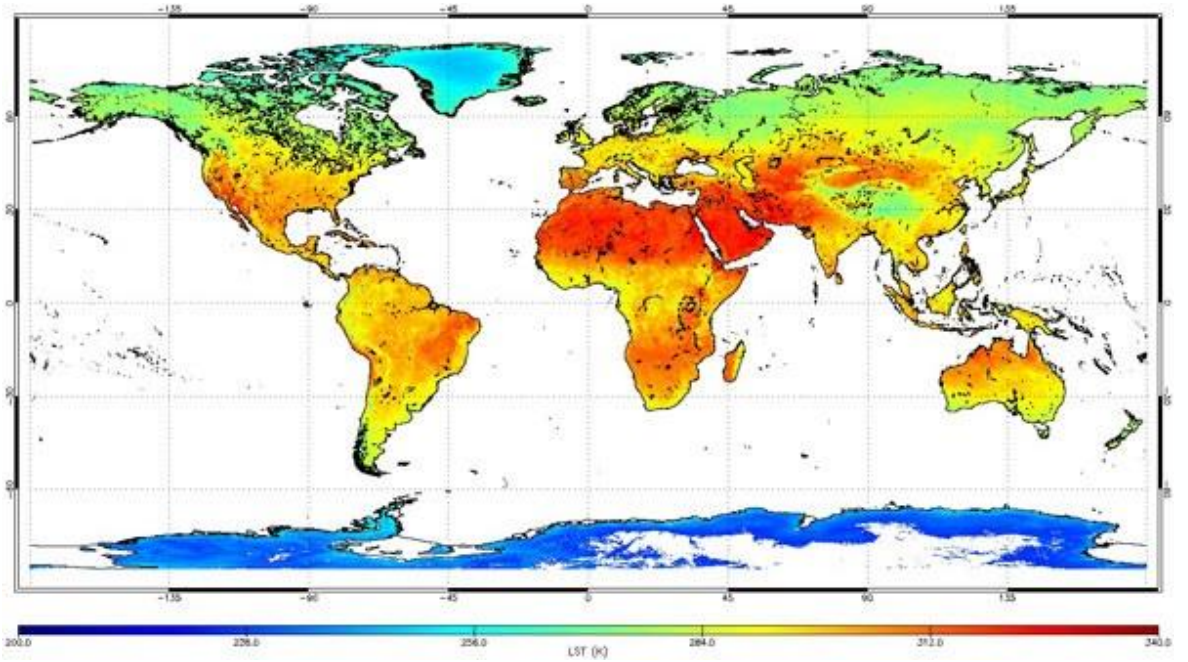
Land Surface Temperature (LST)

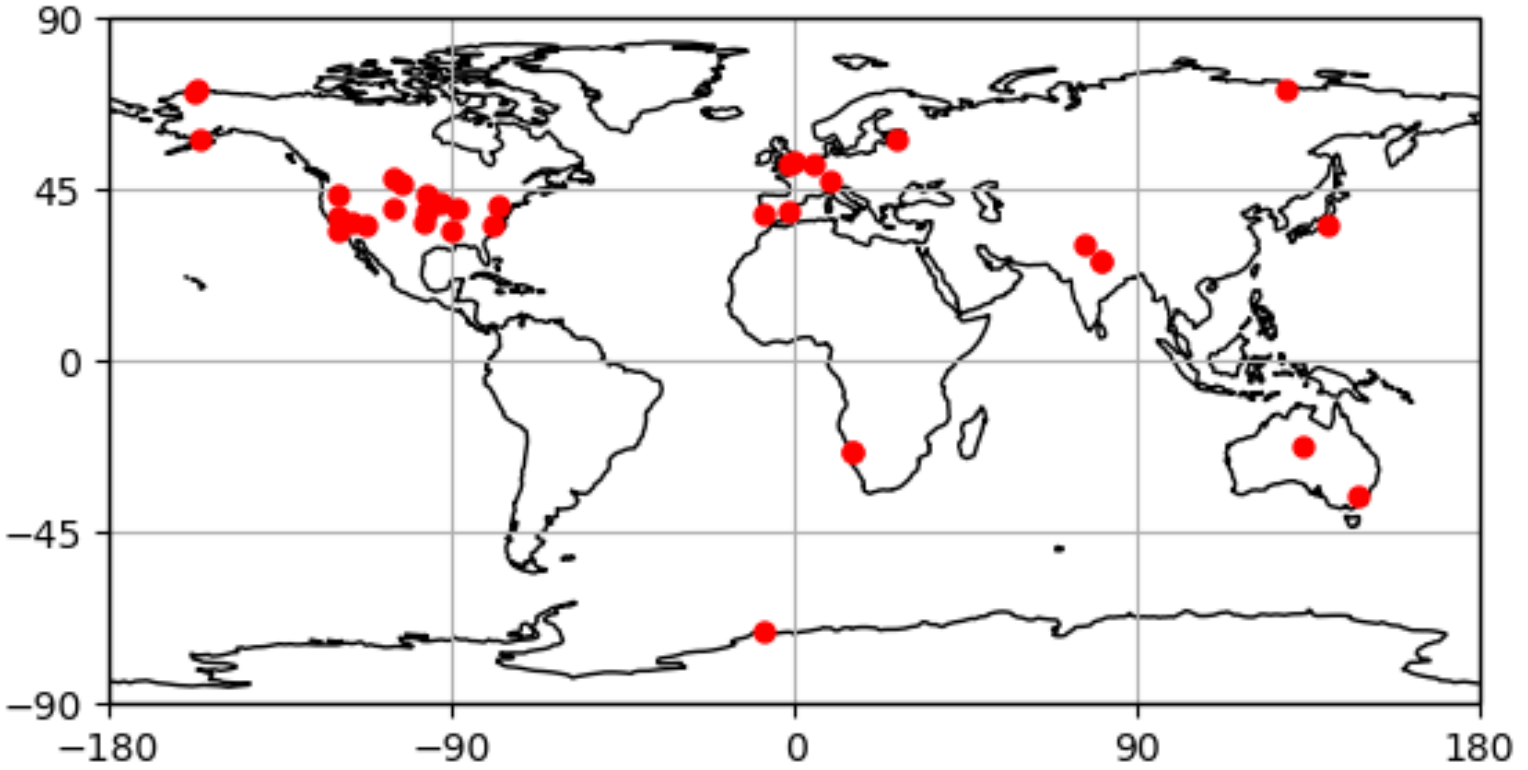
"The radiative skin temperature of the land derived from infrared radiation"

- LST is an **Essential Climate Variable (ECV)**, as it provides important information about the Earth's surface energy budget.
- This can also be used to monitor evapotranspiration of vegetation, urban heat stress, and as a useful proxy for air temperature.
- **Validation criteria:**
  - **Accuracy: < 1K** (Sentinel-3 Mission Requirements Document)
  - **Precision: < 1K** (GCOS 2016 Implementation Plan)
- **SL_2_LST retrieval algorithm is biome-specific**, so validation data must be sourced from a **variety of land cover types and climates.**
- Validation best performed by comparisons with in-situ LST data with similar λ, etc. (**"apples-to-apples"**). Use L3 data to minimise biases from sampling and to streamline analyses.
- Point-to-pixel comparisons: **potential biases from emissivity variations due to heterogeneous land cover**.



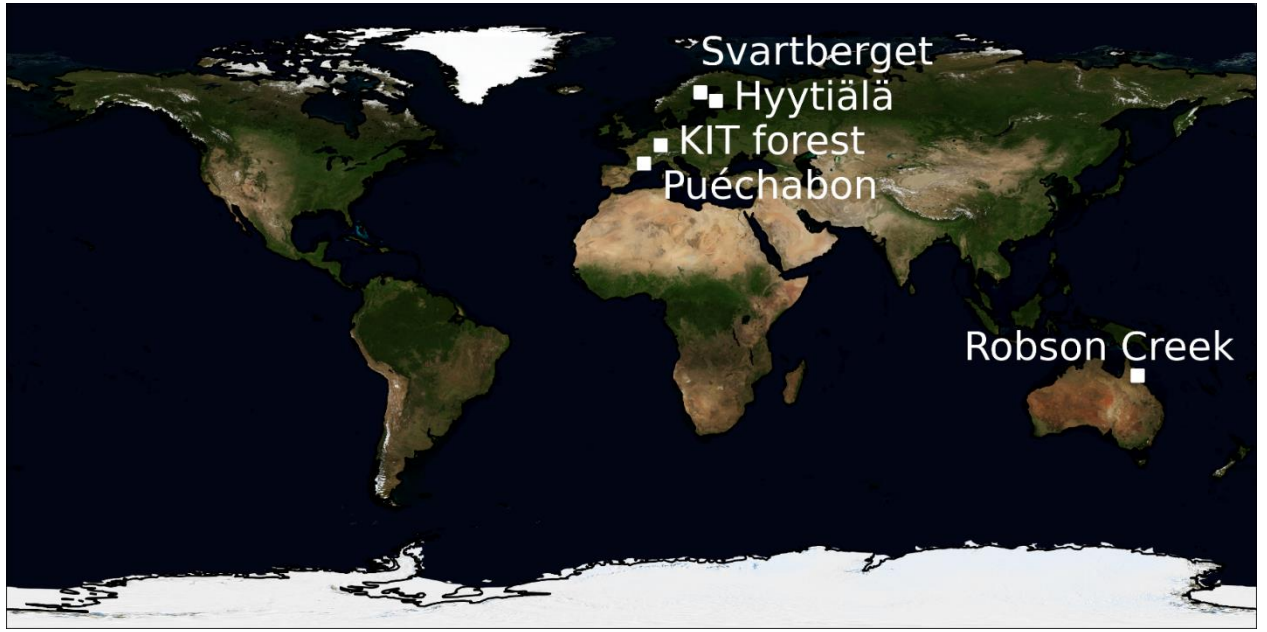
September 2016 Global LST from Sentinel-3A

Existing LST validation sites neglect coverage of certain biomes (e.g. Open needleleaved deciduous/evergreen forests)



Existing in-situ LST validation stations (LAW LST Gap Analysis Report)

LAW: deployment of new in-situ LST stations

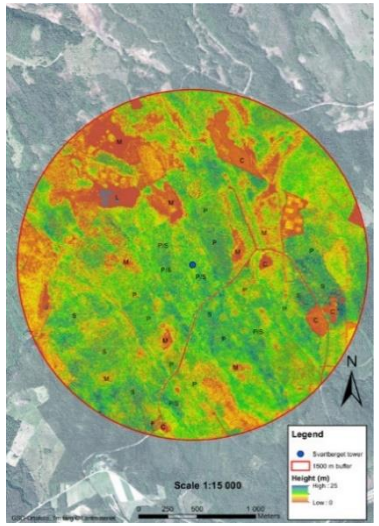


Site Name	Country	Biome (ALB2 class)	Valid Data From
Svartberget	Sweden	Open (15–40%) needleleaved deciduous or evergreen forest (>5 m) (9)	26/10/2021
Hyytiälä	Finland	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5 m) (10)	01/10/2021
KIT forest site	Germany	Closed (>40%) broadleaved deciduous forest (>5 m) (6)	30/07/2020
Robson Creek	Australia	Closed to open (>15%) broadleaved evergreen and/or semideciduous forest (>5 m) (5)	18/11/2021
Puéchabon	France	Sparse (>15%) vegetation (woody vegetation, shrubs, and grassland) (15)	05/10/2021

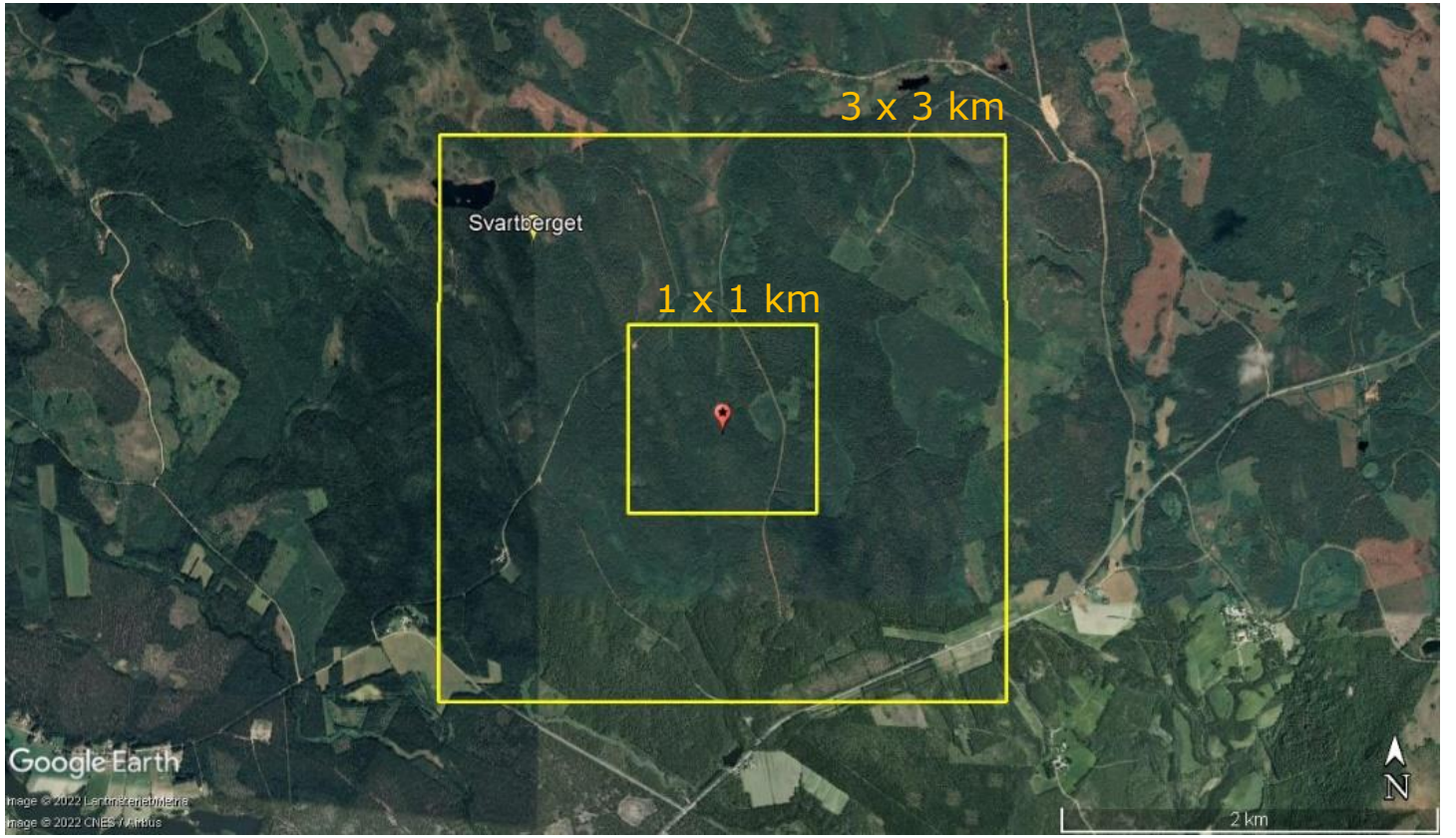
- LST derived from ground & skyward brightness temperature observations – parity with SL_2_LST retrieval
- Initial characterisation by KIT suggests that maximum **in-situ LST uncertainty ~ 0.5 K**
- **Measurement frequency: 1 minute**

Svartberget (Svartberget Experimental Forest, Sweden)

View from tower above forest canopy at CEOS LPV Land Validation Supersite



LiDAR-based vegetation map of Svartberget:
- ***60% Scots Pine***
- ***40% Norway Spruce***

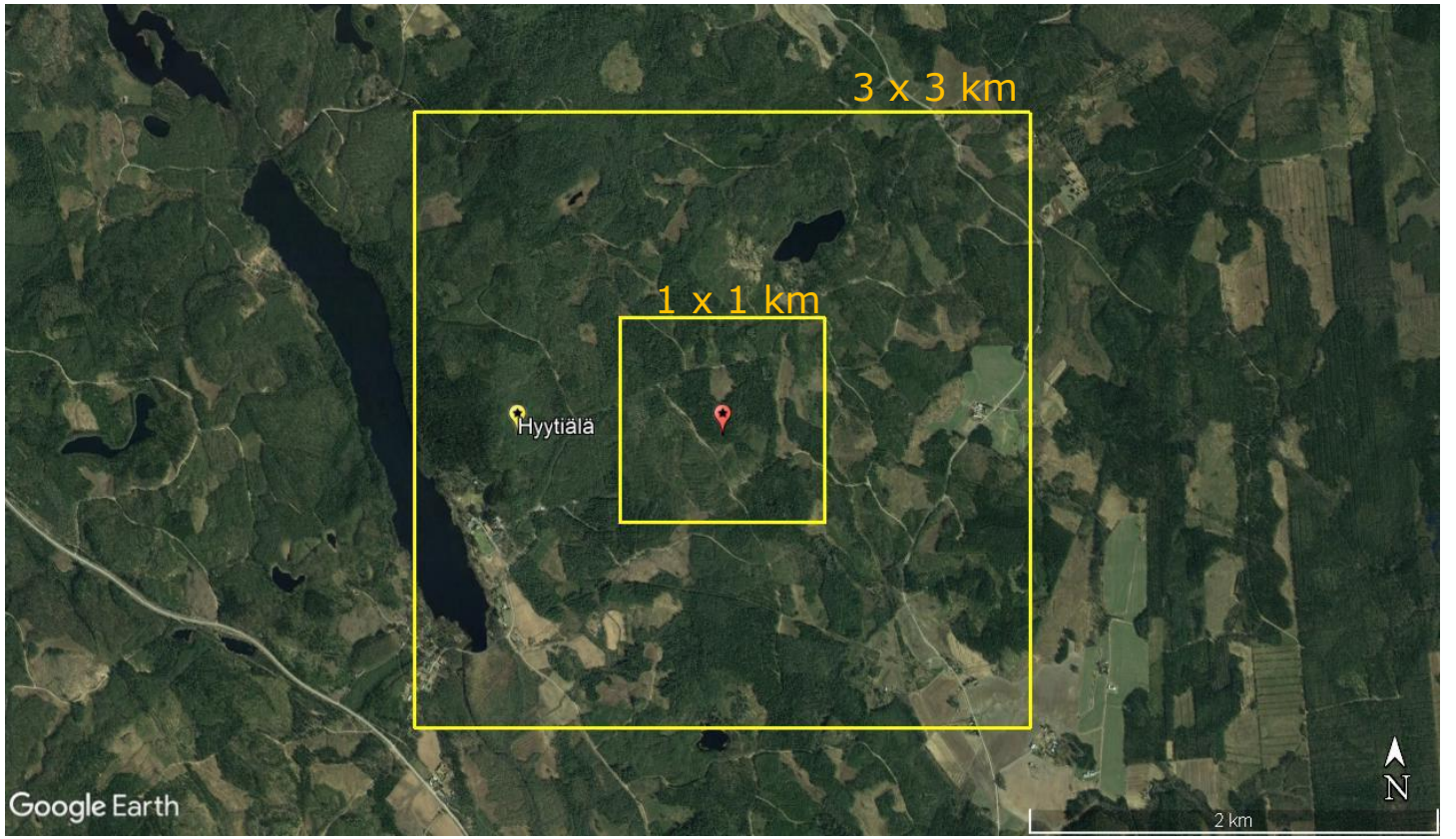


- Land cover around site (**yellow pin**) is ***not*** homogeneous – influence of lake, grassland, paths, etc.
- Solution: compare in-situ data with Sentinel-3 pixels overstriking more homogeneous proxy region (red pin)

Hyytiälä (Hyytiälä Forestry Field Station, Finland)

View from tower observing forest canopy at SMEAR II site

SMEAR II site tower and hut surrounded by mixed forest

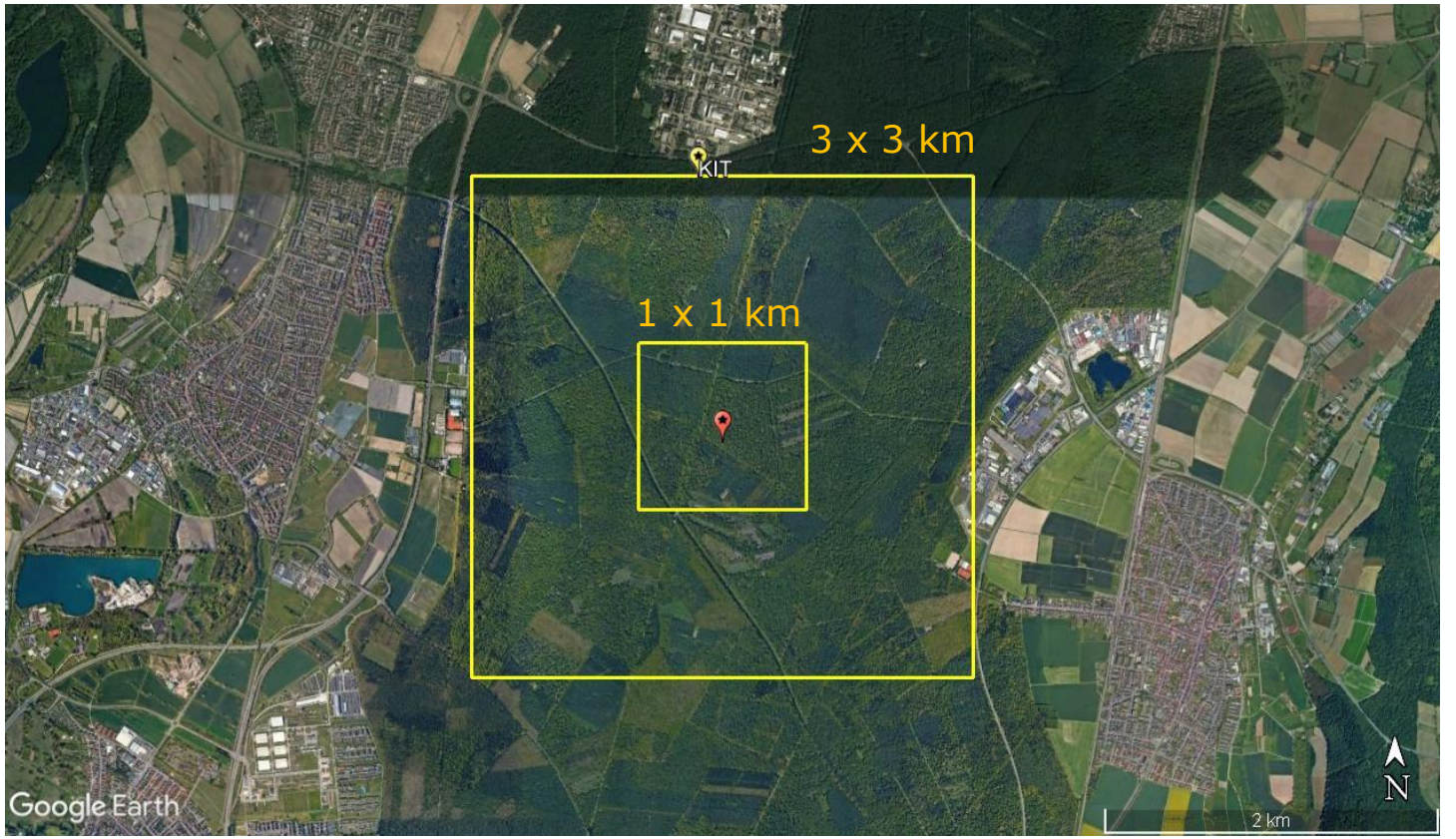


- Land cover around site (**yellow pin**) is ***not*** homogeneous – influence of lake, grassland, paths, etc.
- Solution: compare in-situ data with Sentinel-3 pixels overstriking more homogeneous proxy region (red pin)

KIT forest (Karlsruhe Institute of Technology, Germany)

Mixed forest Vegetation at the KIT forest site

The radiometers are installed on a 200 m tower at KIT Campus North

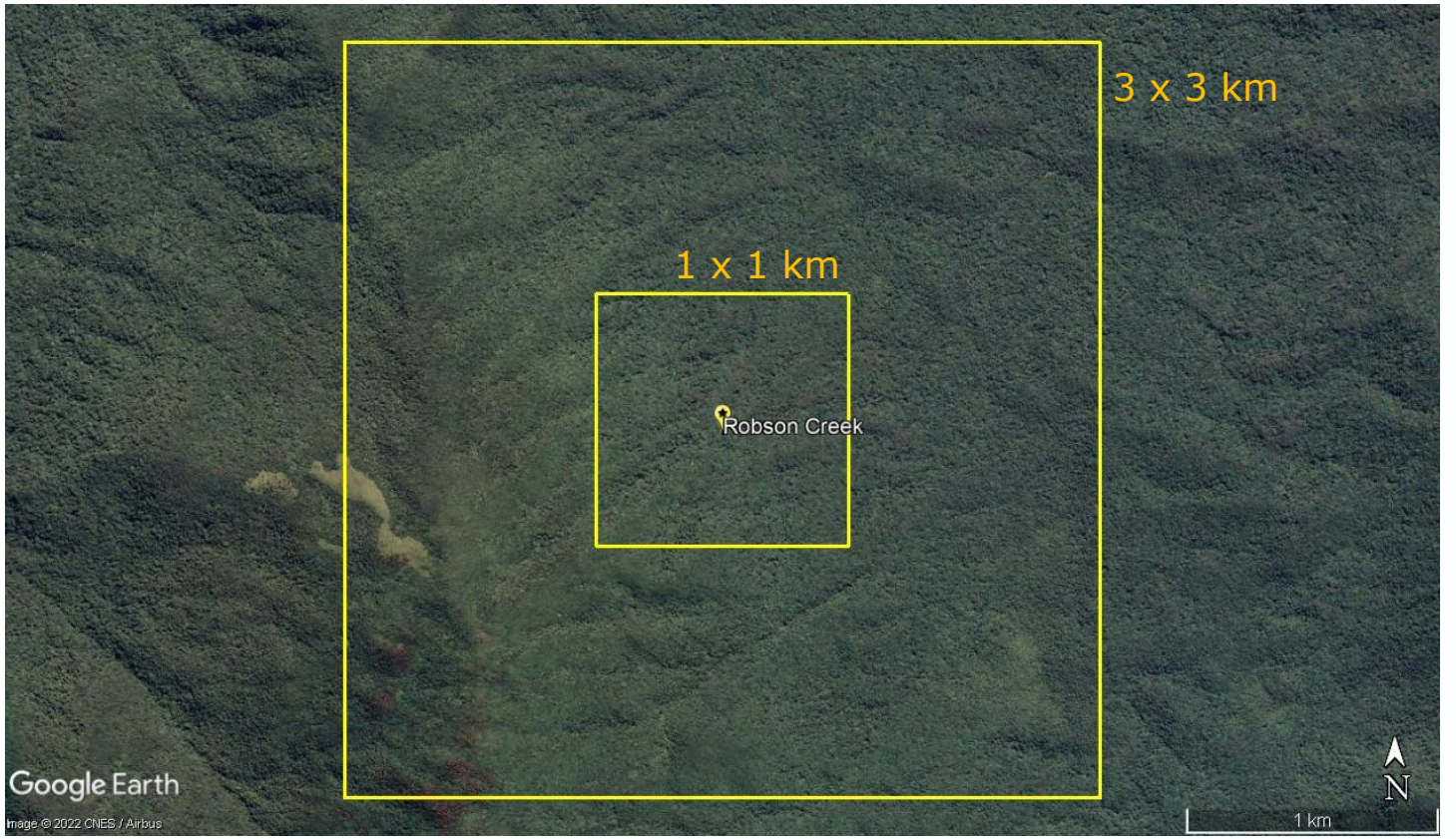


- Land cover around site (**yellow pin**) is ***not*** homogeneous – influence of KIT campus
- Solution: compare in-situ data with Sentinel-3 pixels overstriking more homogeneous proxy region (red pin)

Robson Creek (Robson Creek Rainforest SuperSite, Australia)

View from tower overlooking rainforest

Example of broadleaf vegetation around the tower

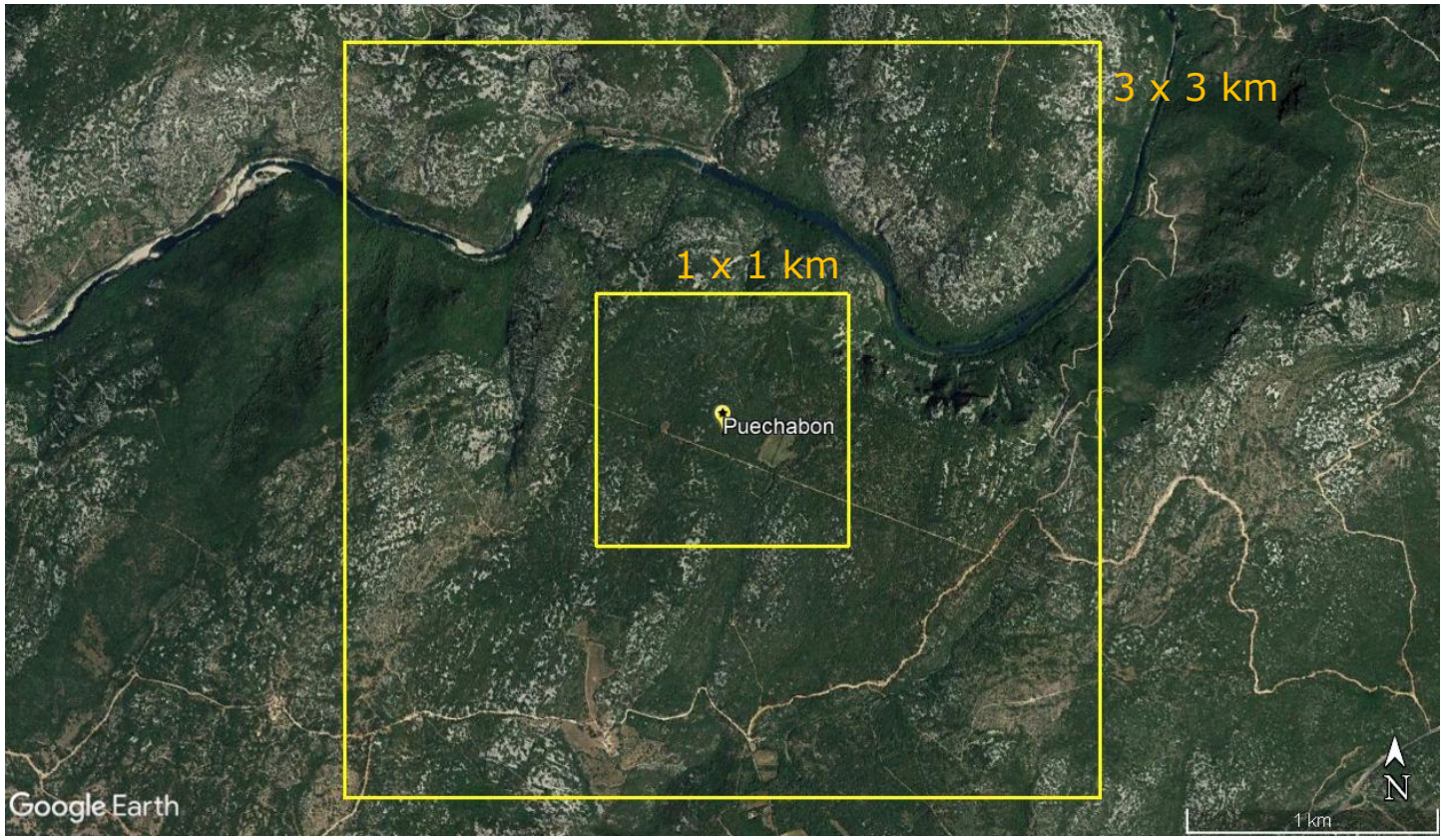


- Site surrounded by homogeneous forest cover – Sentinel-3 pixel overstriking site used in comparison

Puéchabon (France)

The tower overlooking vegetation at the site

View from the tower of the forest and shrub vegetation at the site



- Site surrounded by homogeneous land cover – Sentinel-3 pixel overstriking site used in comparison

Validation methodology (LST bias)

- Analysis period: July 2020 – July 2022.
- ACRI-ST provided **Level 3 (0.01°) Non-Time Critical (NTC) SL_2_LST data** from Sentinel-3A and 3B, processed using **IPF 6.16**, in order to avoid overlap with S3MPC activities.
- **51 × 51 pixel subsets centred on each site** were created and shared with LAW partners.
- **Cloud masking** performed using **Probabilistic Cloud Test** flags. Cosmetically filled grid cells were also excluded from analyses.
- **Satellite LST** was extracted from the **grid cell overstriking the in-situ site/proxy location** for each overpass.
- **In-situ LST** measured to the **closest minute** of the Sentinel-3 overpass time was compared against the satellite LST.
- **Additional cloud/error flagging** performed separately for Sentinel-3A and 3B using a **2σ Hampel filter**:
    1. Calculate the median satellite – in-situ LST bias for both day & night-time overpasses.
    2. Determine the robust standard deviation (σ) of the satellite – in-situ bias using the median value
    3. Remove all matchups where: $|\text{bias}| > 2\sigma$
- The filtered biases were then used to compute the following metrics for Sentinel-3A and 3B (day/night metrics computed separately):
    - **Accuracy**: Median bias between Sentinel-3 and in-situ LST data
    - **Precision**: Robust standard deviation of the bias between Sentinel-3 and in-situ LST

Validation methodology (LST uncertainty)

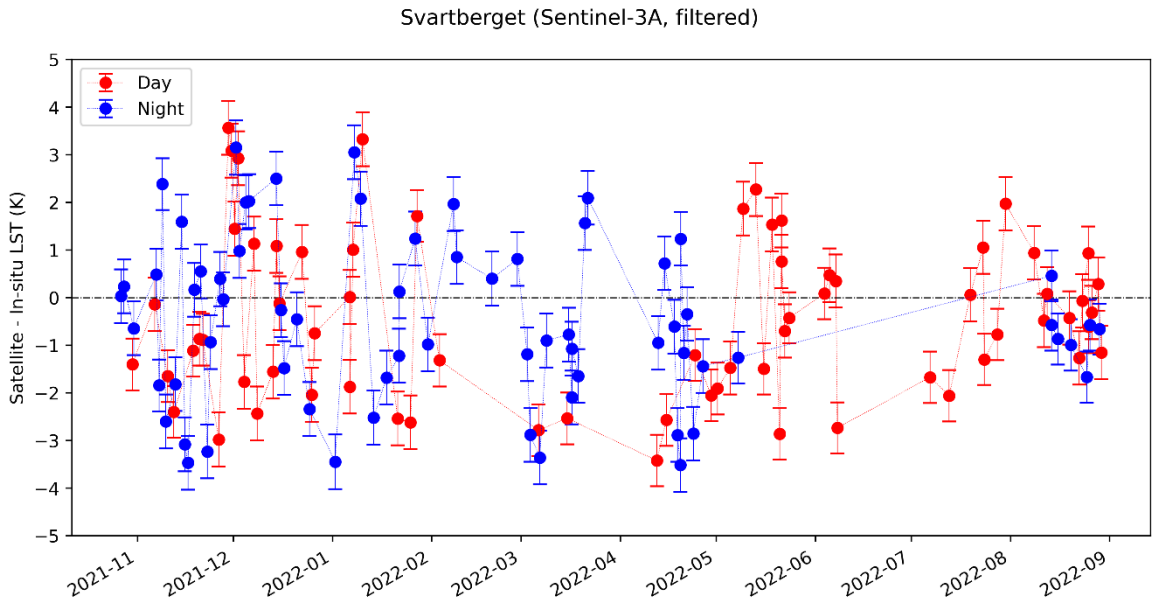
- The standard deviation of the satellite – in-situ LST bias was compared against the theoretical matchup uncertainty:

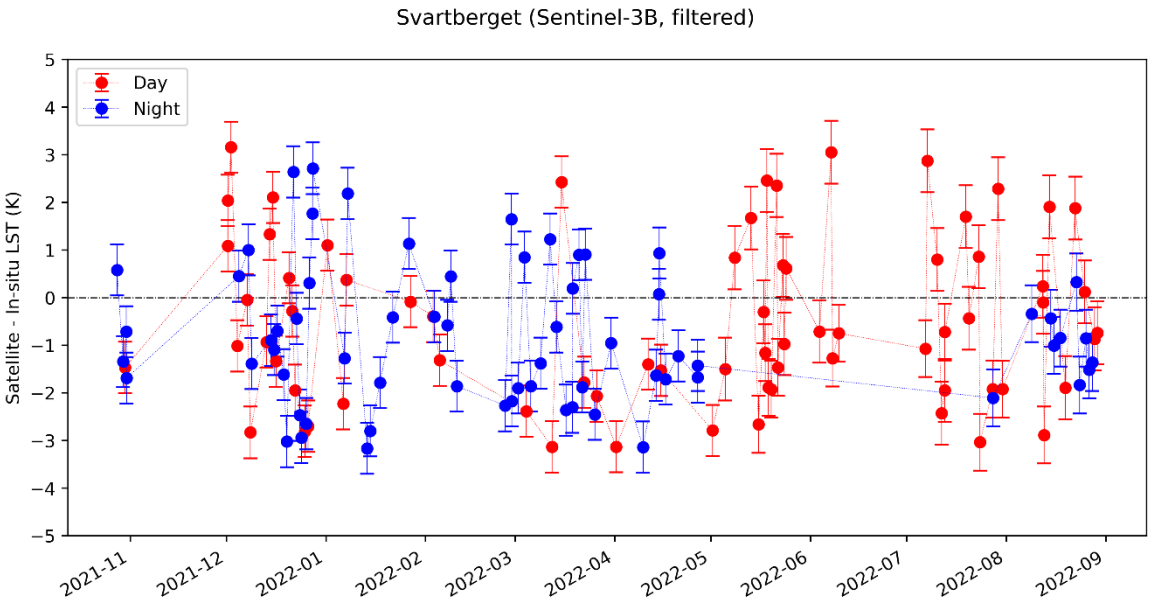
$$\sigma_{total} = \sqrt{\sigma_{sat}^2 + \sigma_{ground}^2 + \sigma_{space}^2 + \sigma_{time}^2}$$

Where:

- σ_{sat} = total LST uncertainty for the Sentinel-3 grid cell
- σ_{ground} = the uncertainty associated with the ground-based instrumentation (0.5 K)
- σ_{space} = uncertainty associated with matching a satellite and ground observation in a spatial context (σ of 5 x 5 satellite pixel grid surrounding in-situ site)
- σ_{time} = uncertainty associated with matching a satellite and ground observation in time (0 K, because Sentinel-3 – in-situ time difference < 1 minute)

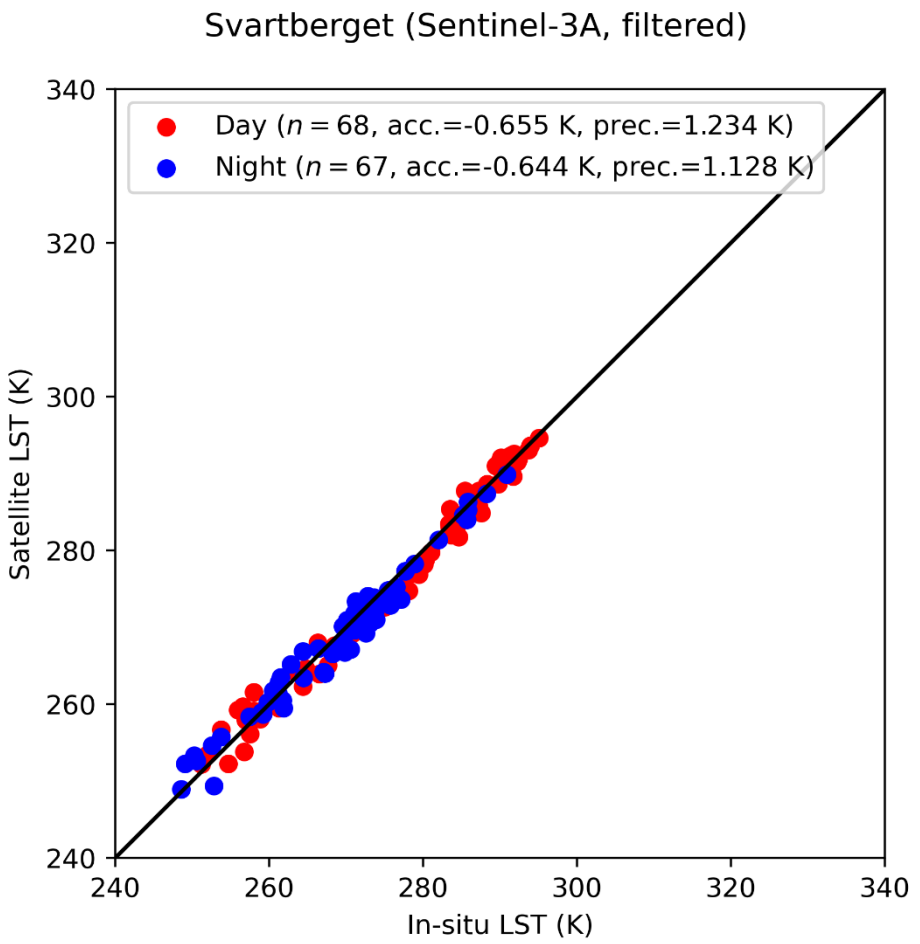
Svartberget results (filtered)

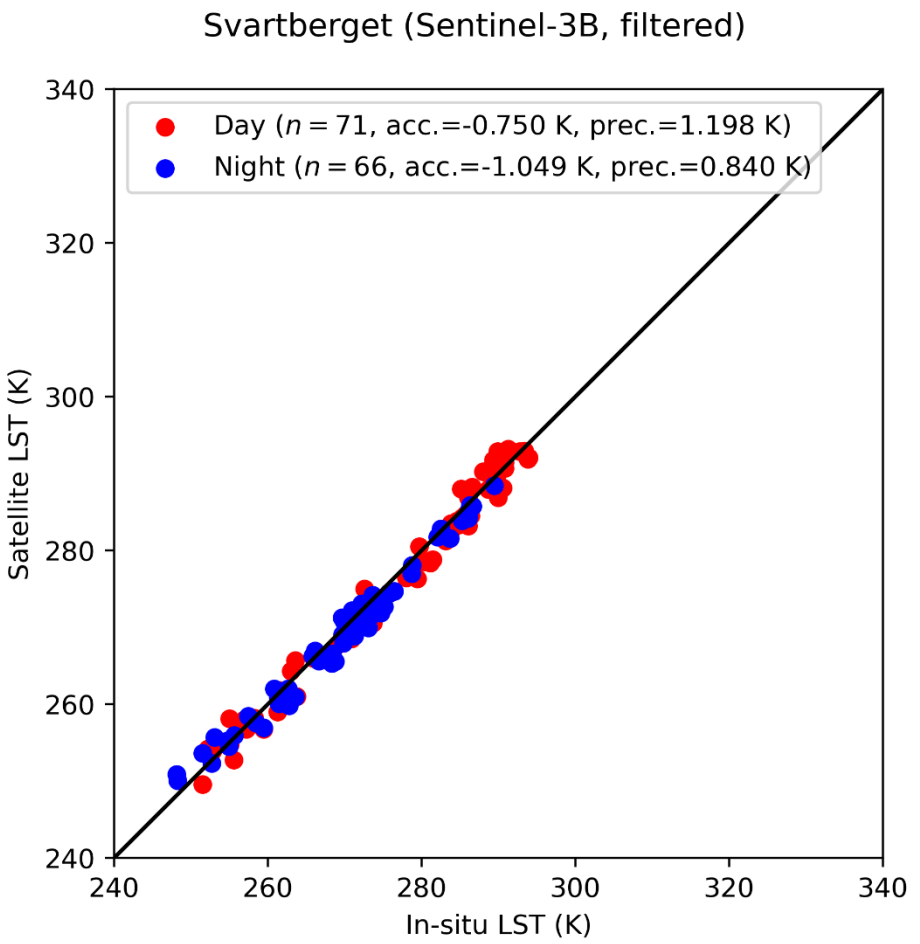




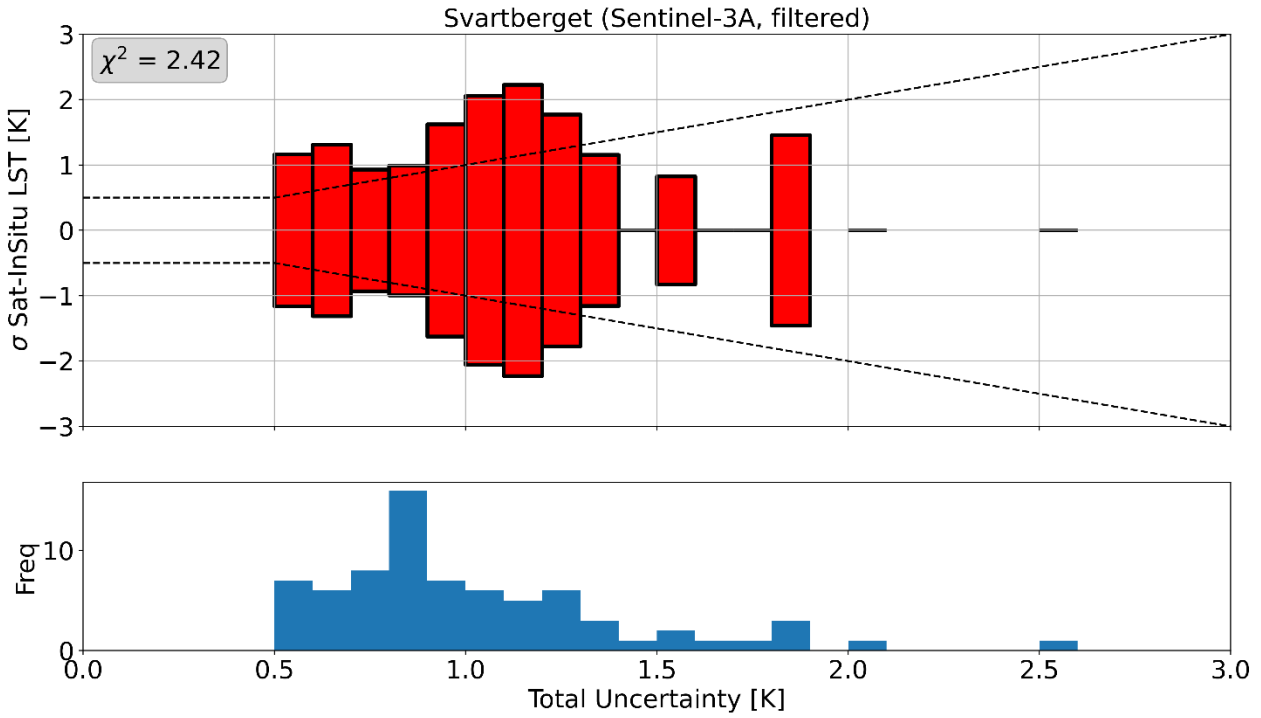
- From April 2022 onwards there was an unexplained positive trend in skyward brightness temperatures observed at this site.
- Trend was thought to be caused by water contamination of the radiometer lens. In-situ LST consequently biased by ~0.2 K uncertainty.
- Further analysis required to flag and remove problematic in-situ measurements.

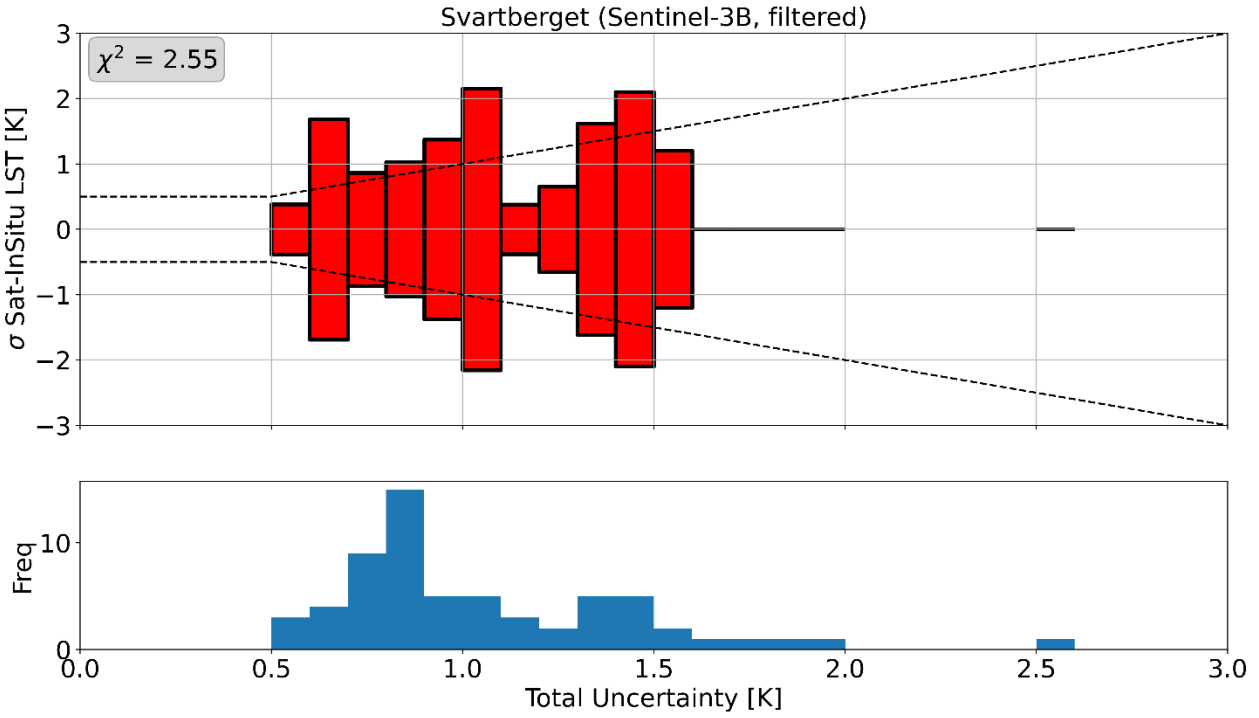
Svartberget results (filtered)





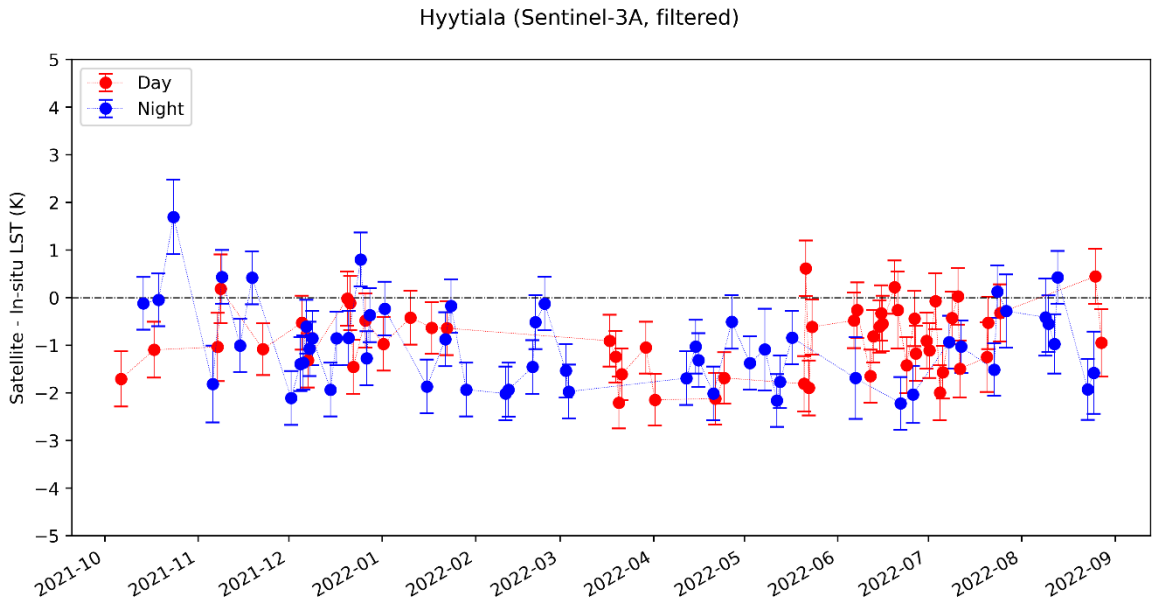
Svartberget results (uncertainty)

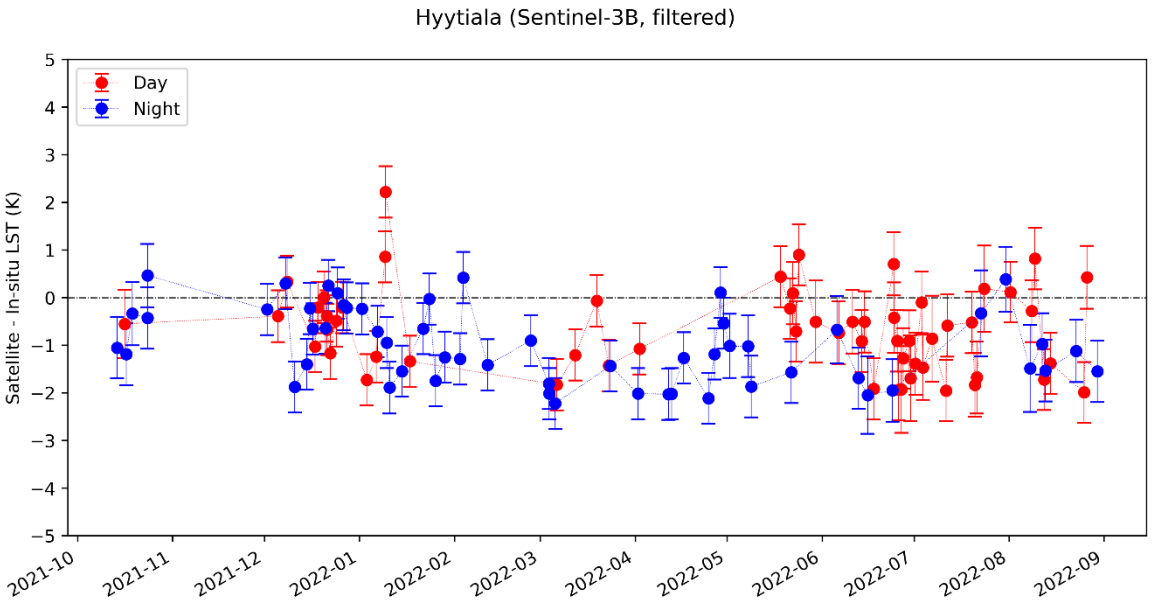




- σ_{total} appears to be an underestimate of the observed satellite – in-situ uncertainty.
- < 5 matchups binned for many bands, so σ of observed bias may be inaccurate.
- More cloud-free observations needed for robust conclusion.

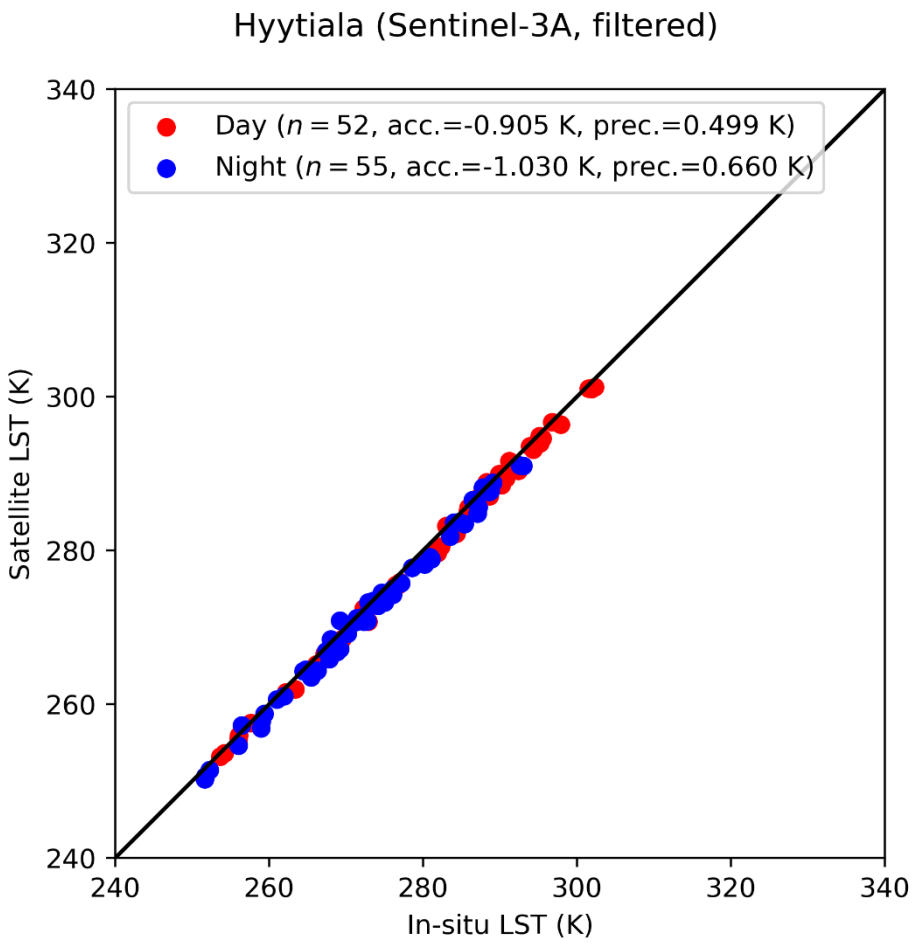
Hyytiälä results (filtered)

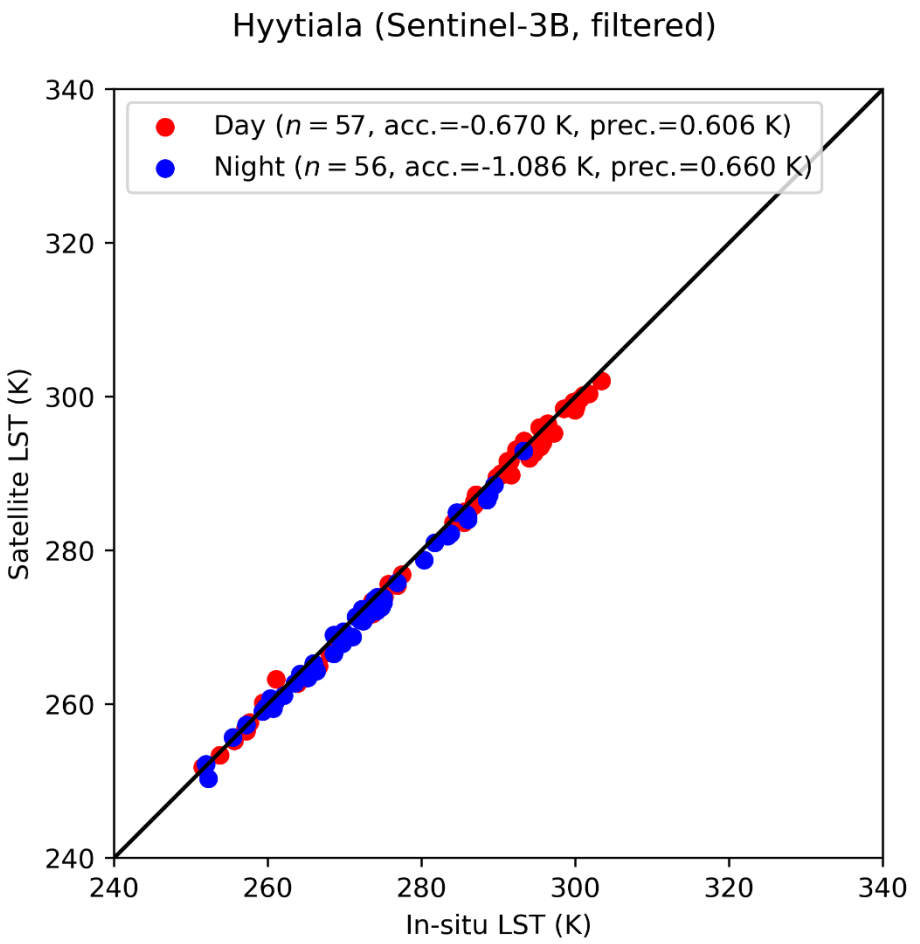




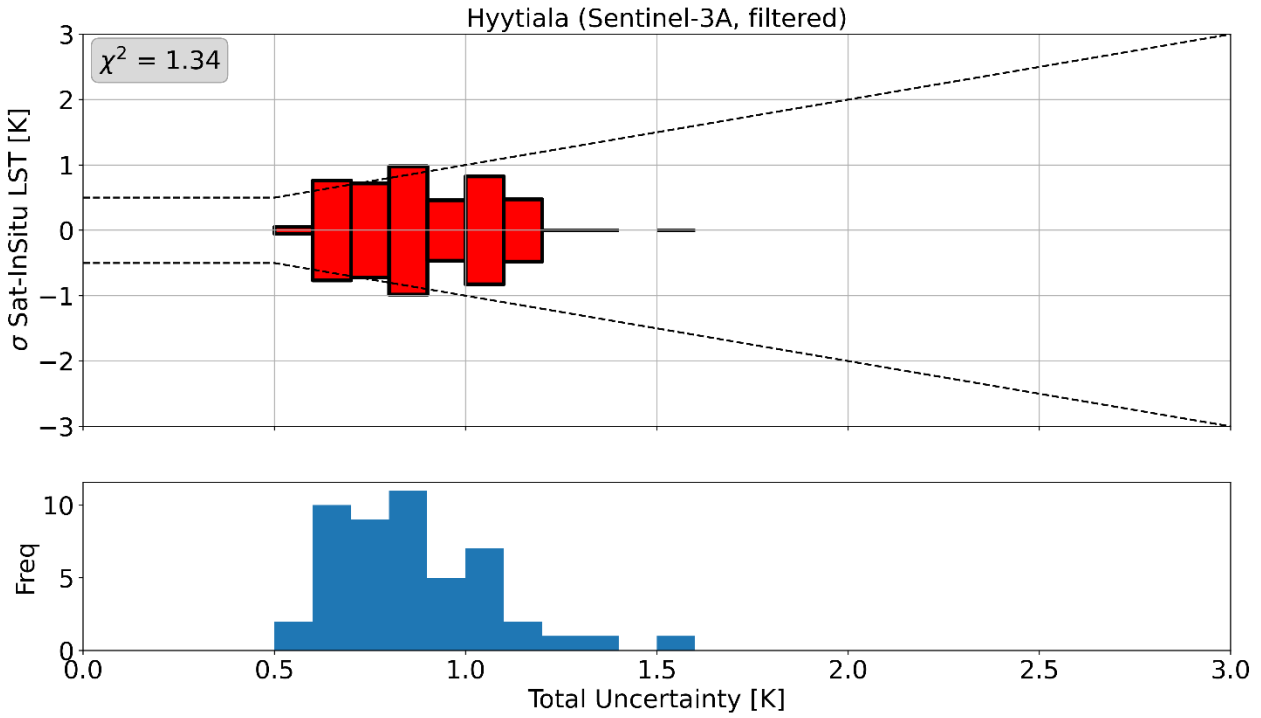
- Hampel filter removes ~36% of all matchup pairs, suggesting that cloud detection algorithm & SL_2_LST cloud coefficients are performing well
- Approximately equal day and night-time matchup pairs – no coverage bias

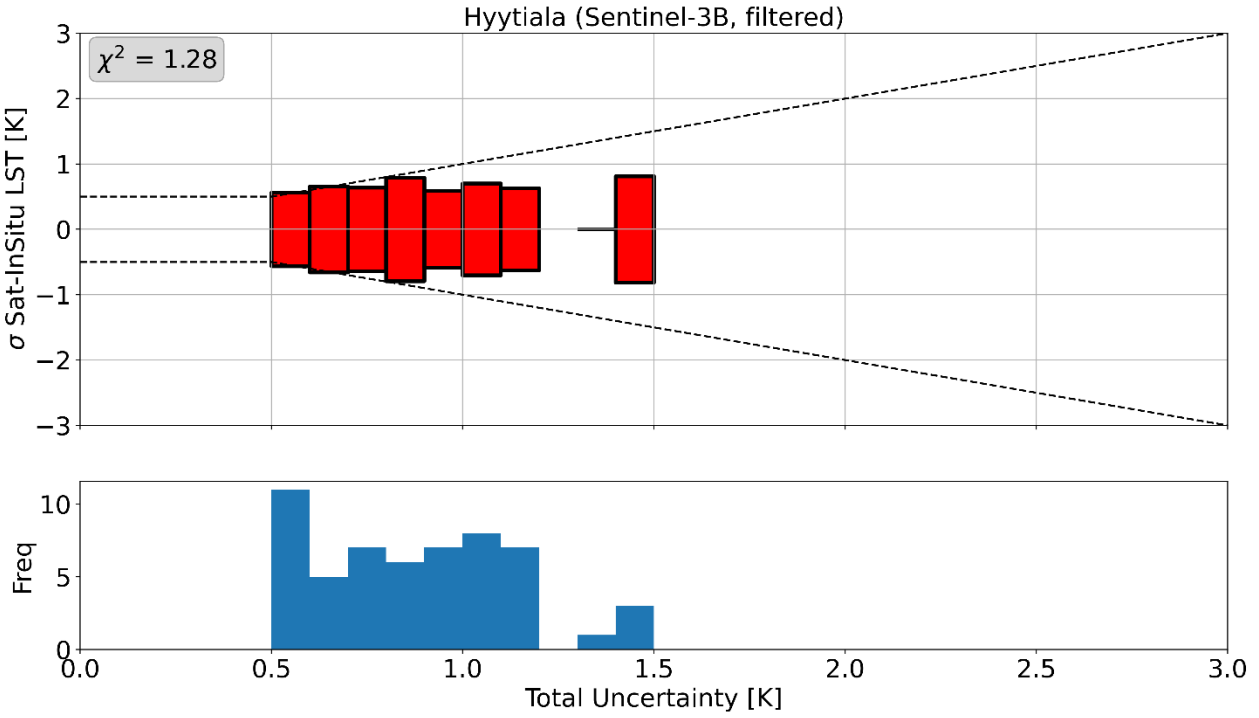
Hyytiälä results (filtered)





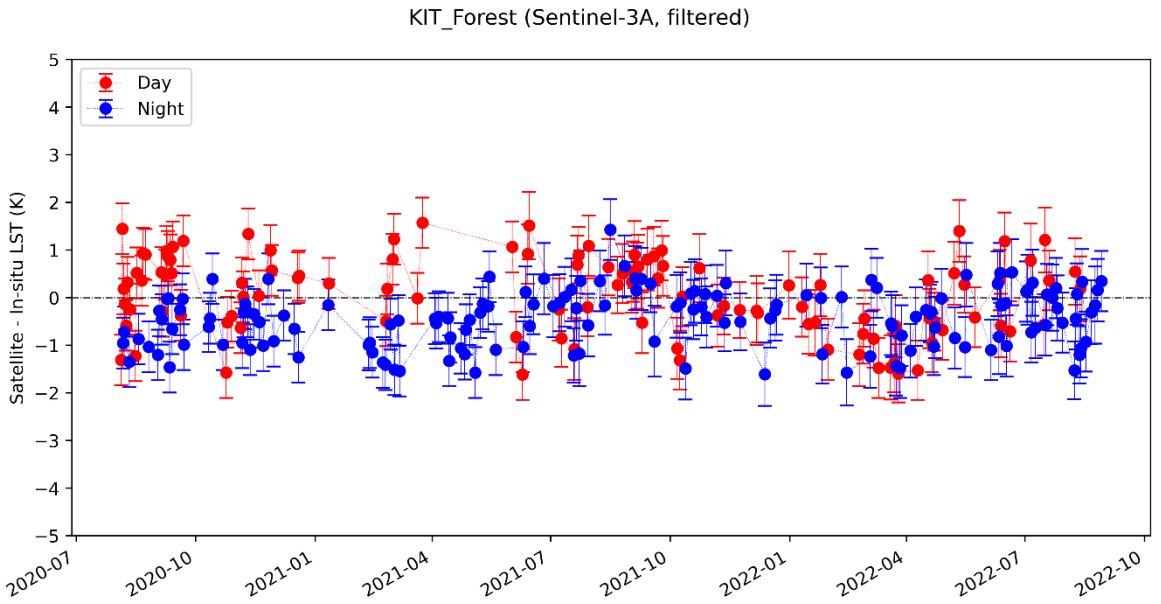
Hyytiälä results (uncertainty)

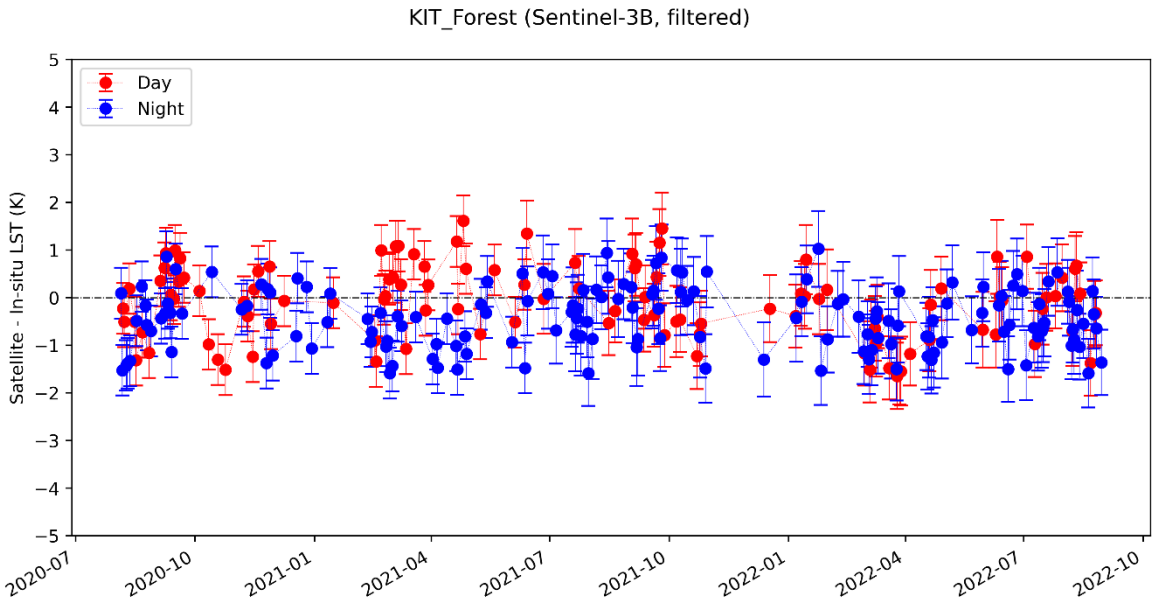




- σ_{total} appears to match the observed satellite – in-situ uncertainty for most matchups
- Underestimates for bands where < 5 matchups are binned for many bands, so σ of observed bias may be inaccurate.

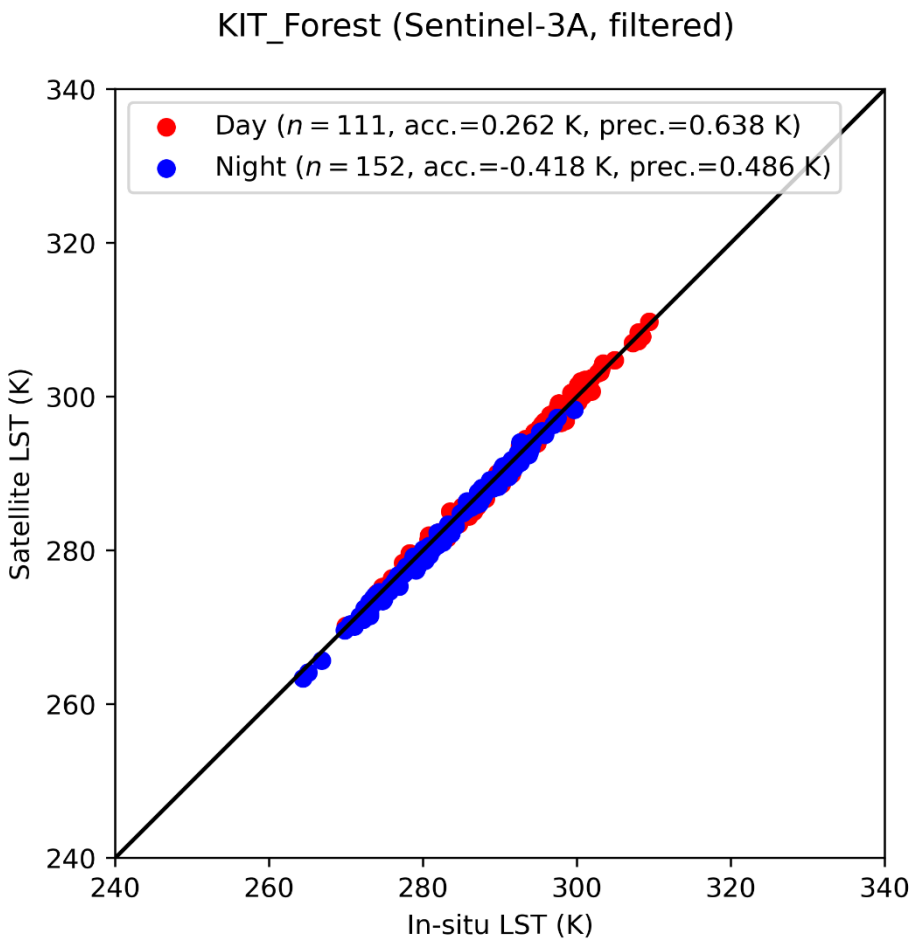
KIT forest results (filtered)

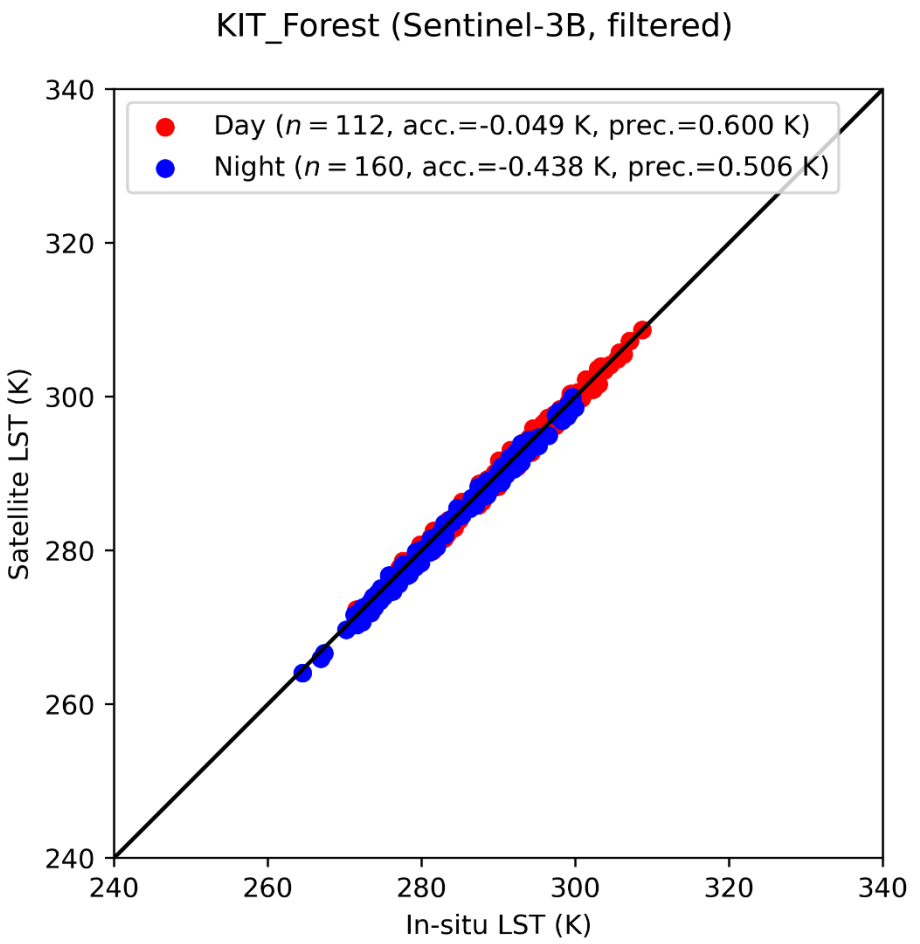




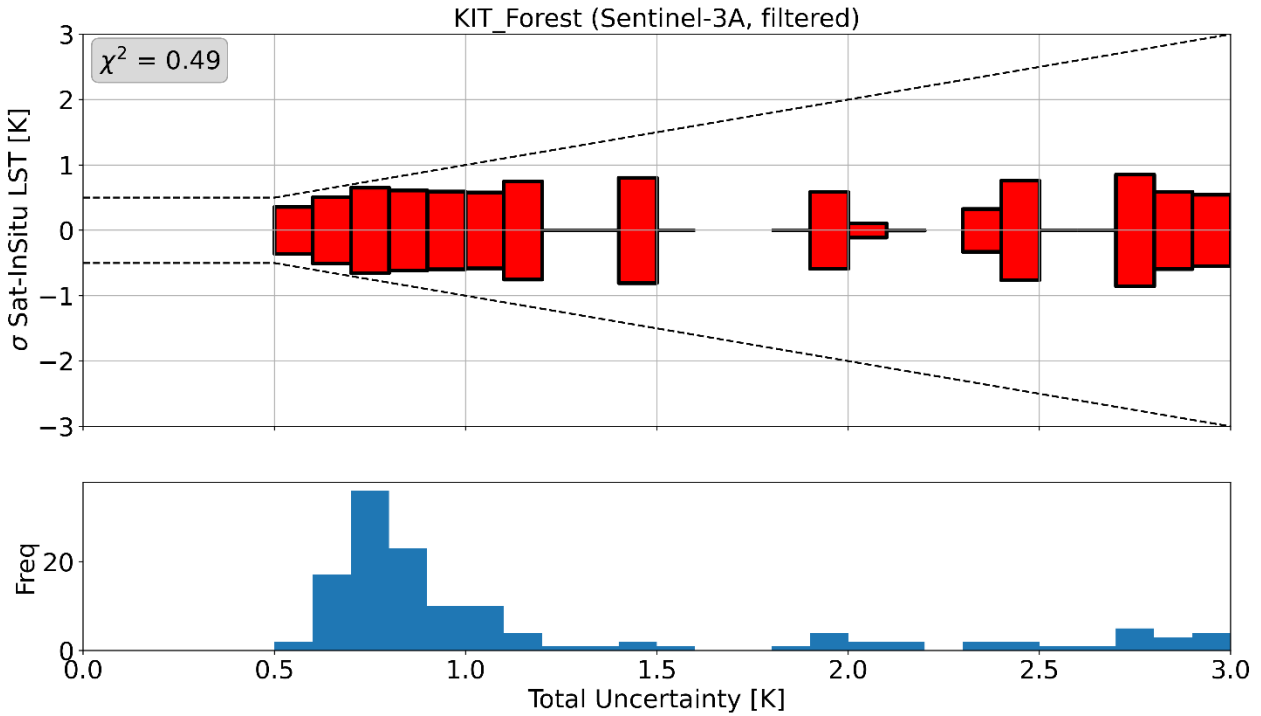
- Hampel filter removes ~27% of all matchup pairs, suggesting that cloud detection algorithm & SL_2_LST cloud coefficients are performing well
- More night-time than daytime matchup pairs – coverage bias?

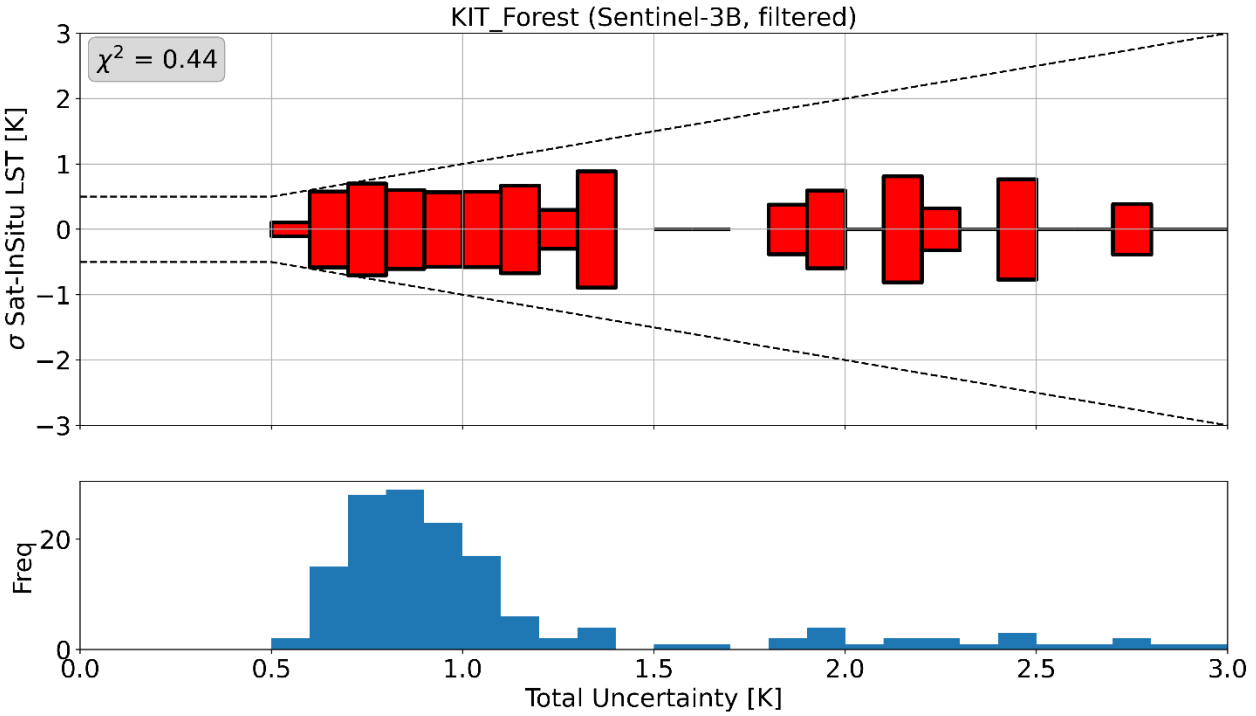
KIT forest results (filtered)





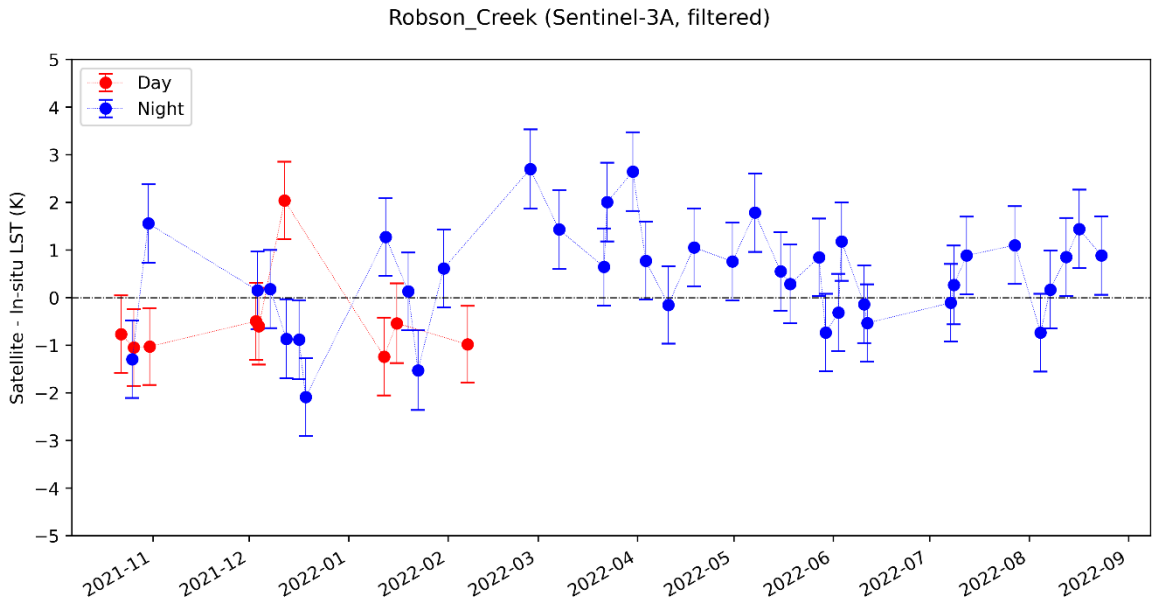
KIT forest results (uncertainty)

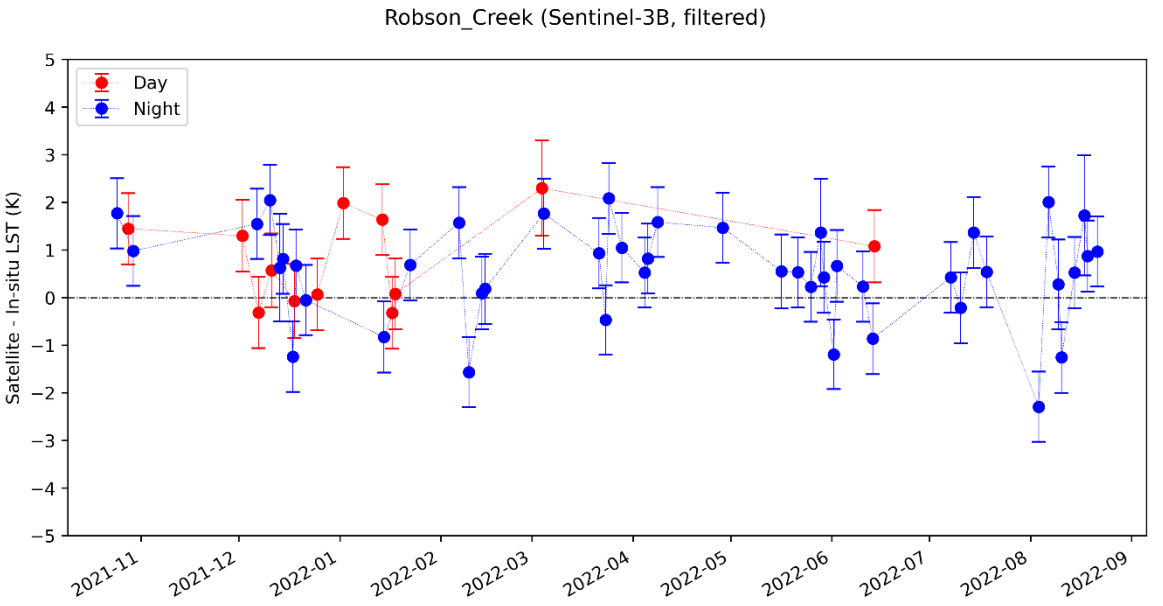




- σ_{total} appears to match the observed satellite – in-situ uncertainty for most matchups
- Long tail in σ_{total} distribution suggests potential influence of scene inhomogeneity on matchups, or incomplete cloud masking

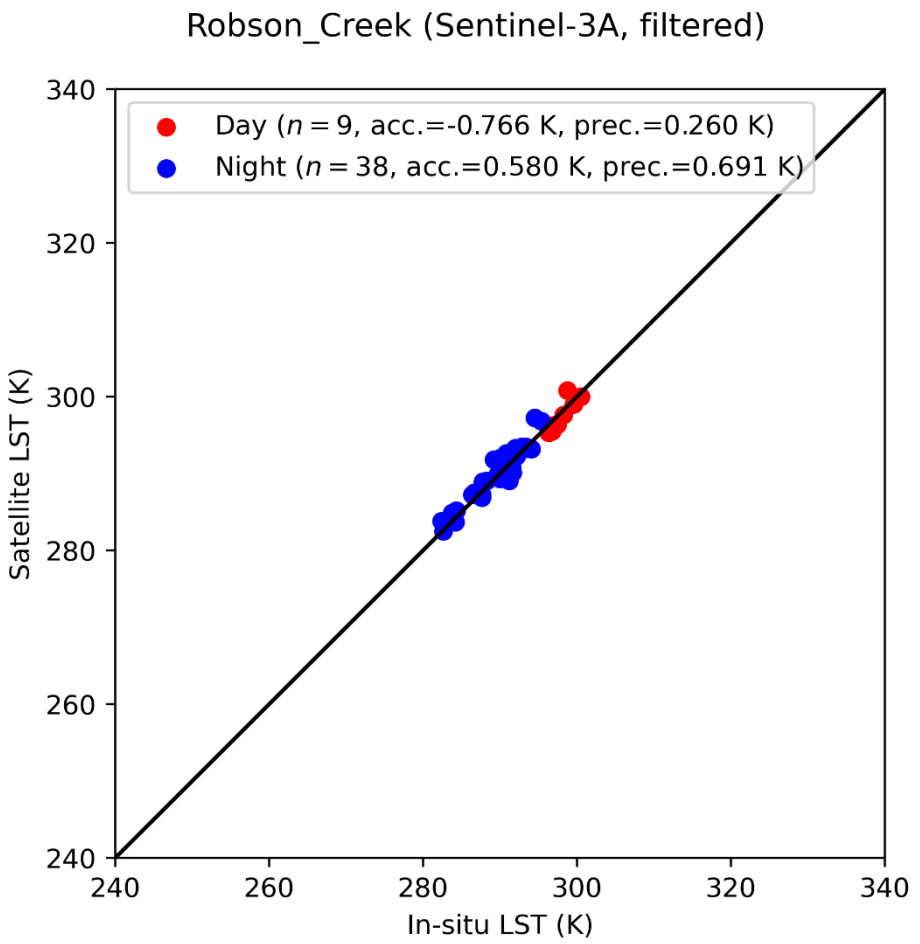
Robson Creek results (filtered)

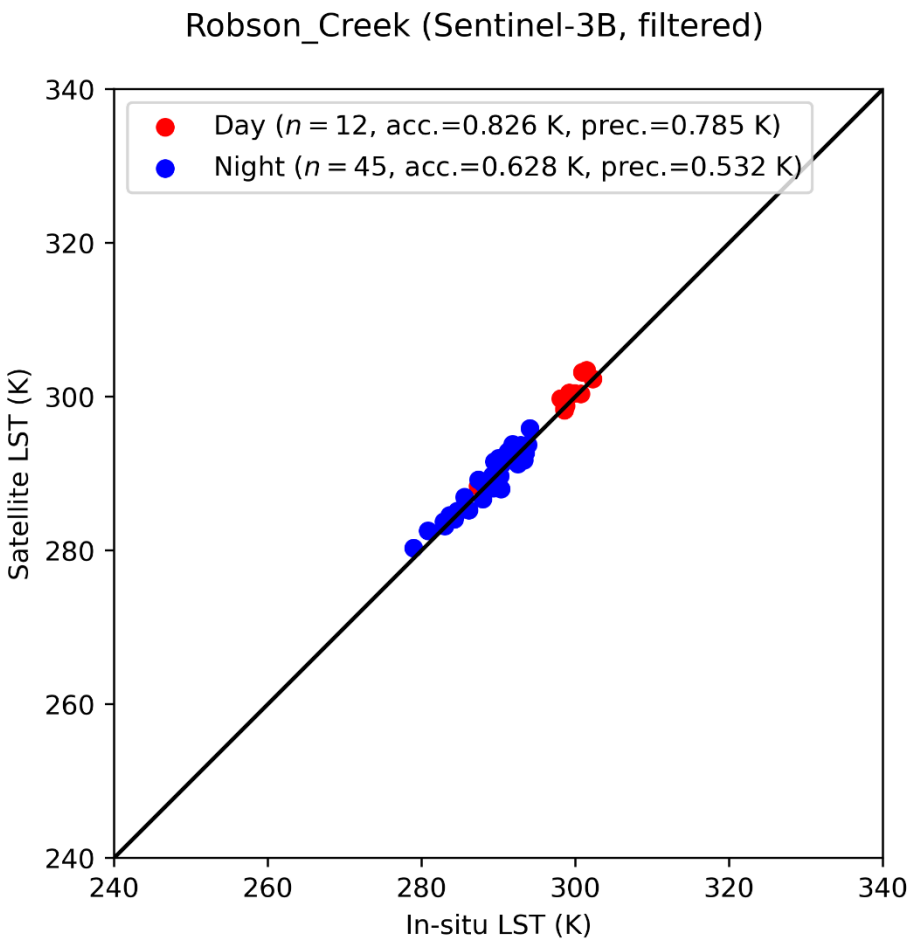




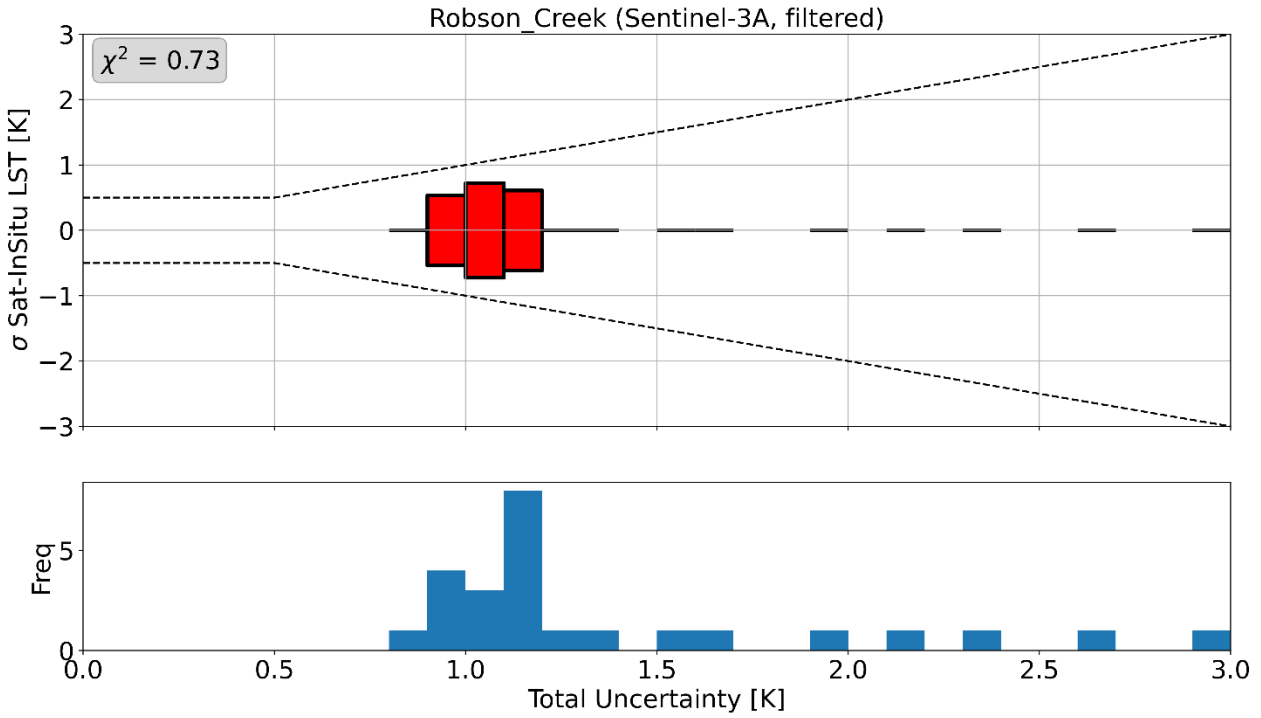
- Extremely large biases reported throughout observation period, with also almost no daytime overpasses after April 2022.
- As with Svartberget, skyward BTs also affected by water contamination, with similar consequences for the in-situ LST
- Another possibility: non-optimal setting of the across-track parameters in the SL_2_LST algorithm for this site which have higher impact in high water vapour regions

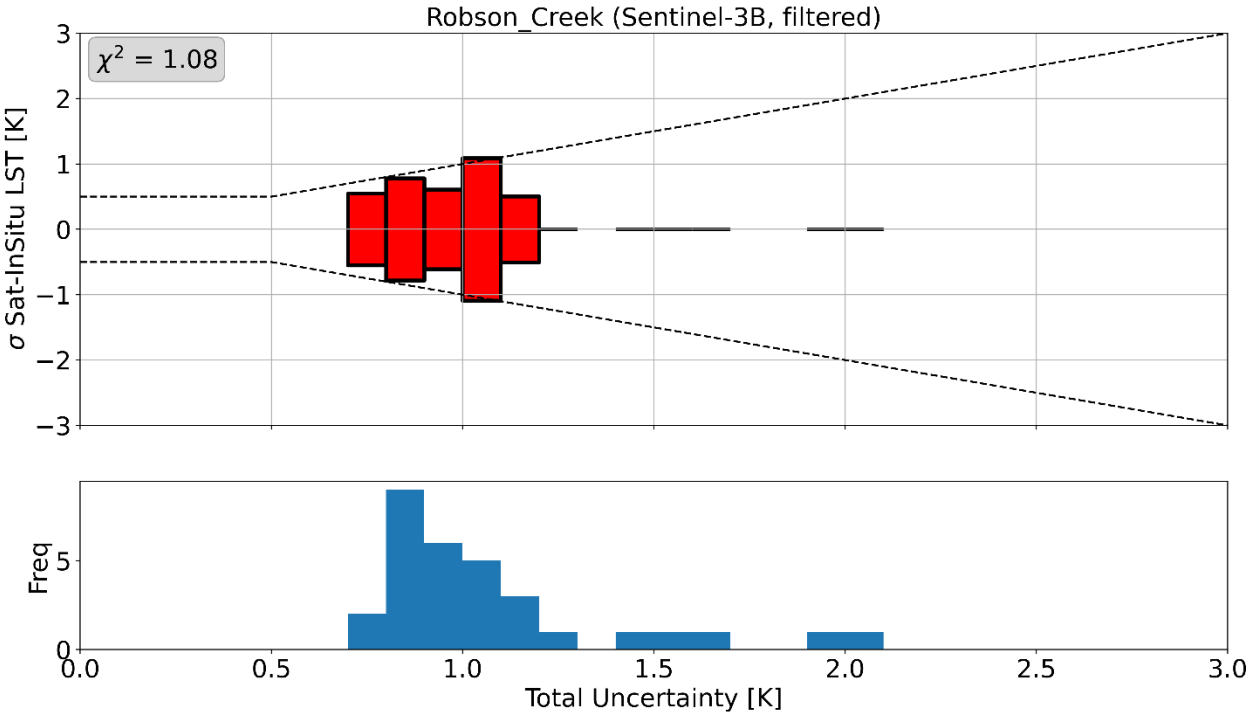
Robson Creek results (filtered)





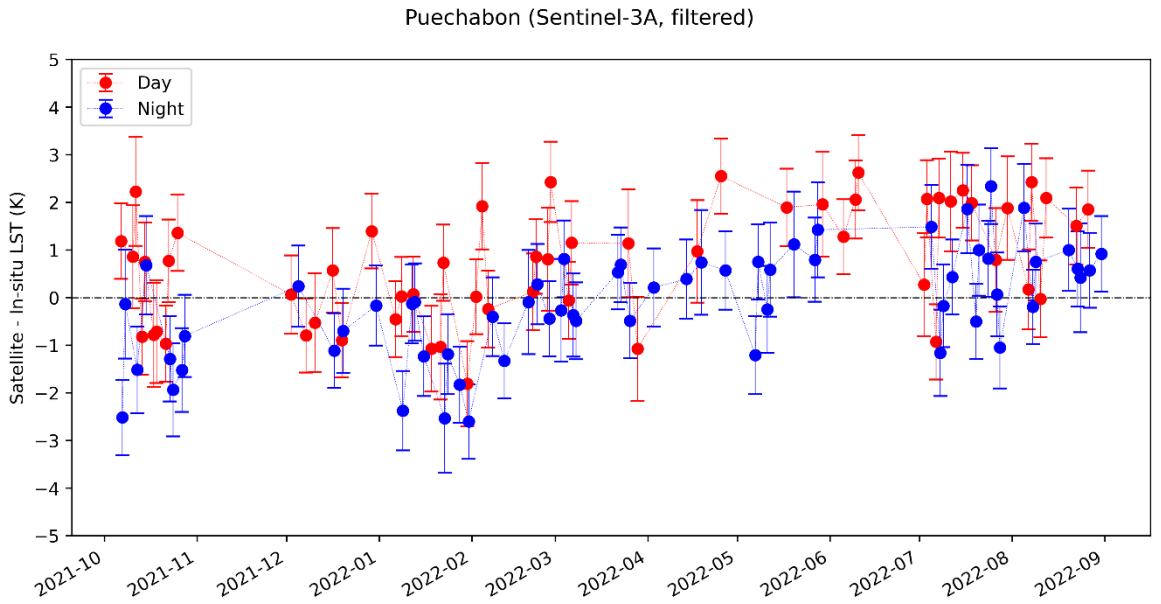
Robson Creek results (uncertainty)

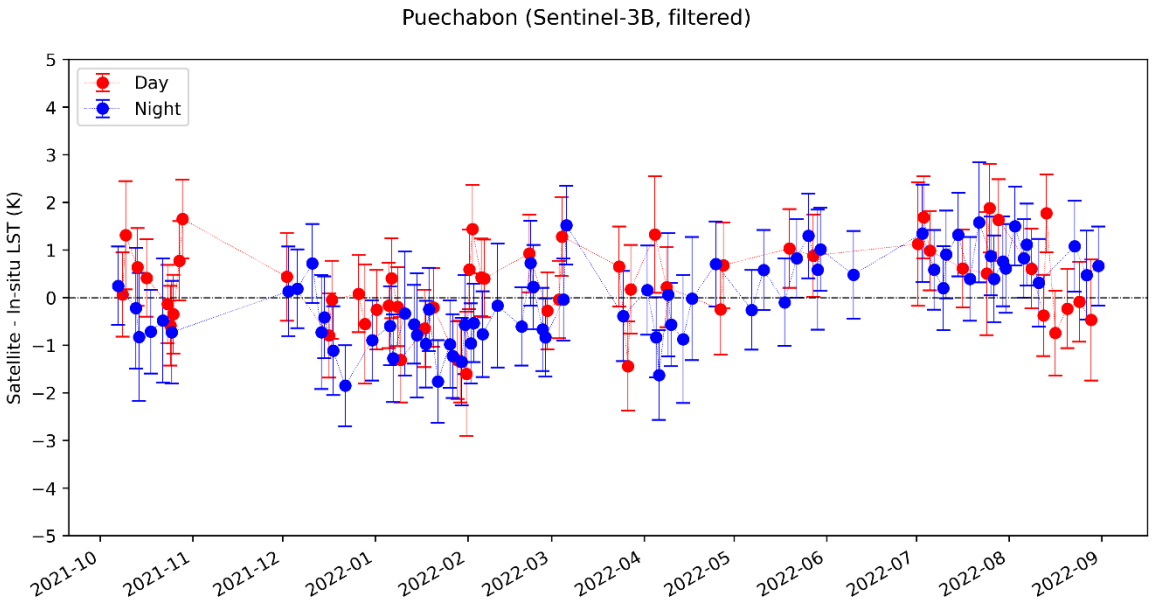




- σ_{total} appears to overestimate uncertainty for Sentinel-3A, but agrees with observed uncertainty for 3B.
- Very few observations binned due to aforementioned issues – observed σ values may be biased.

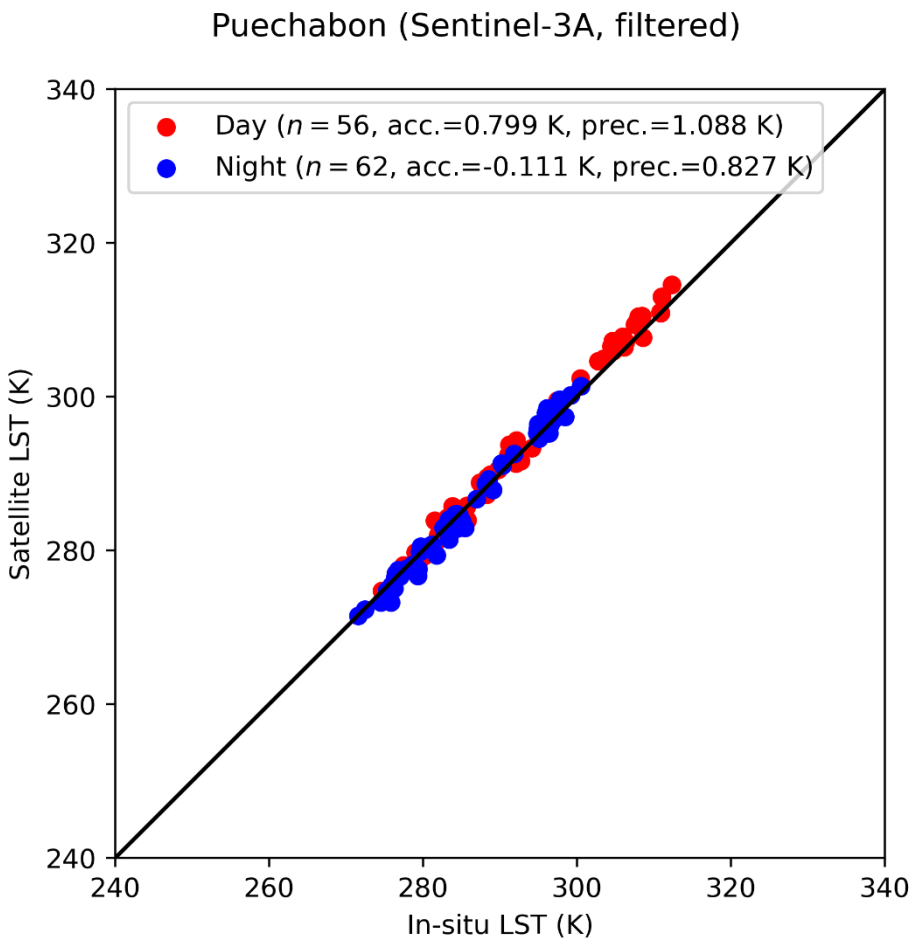
Puéchabon results (filtered)

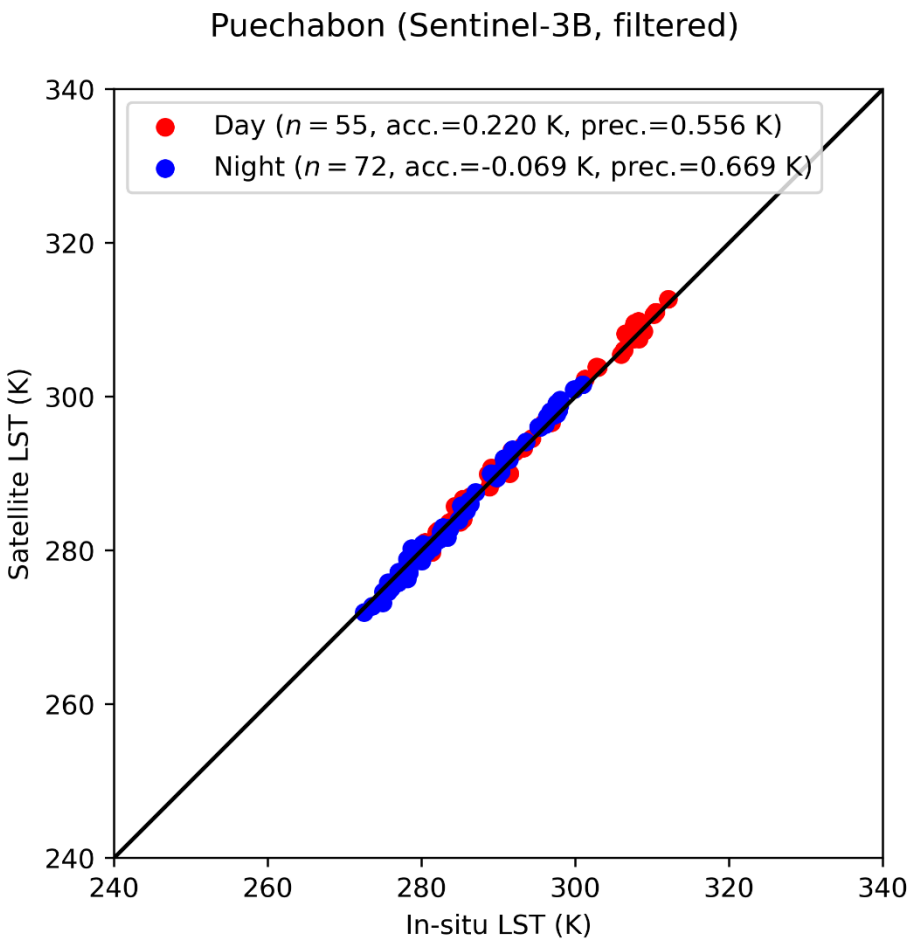




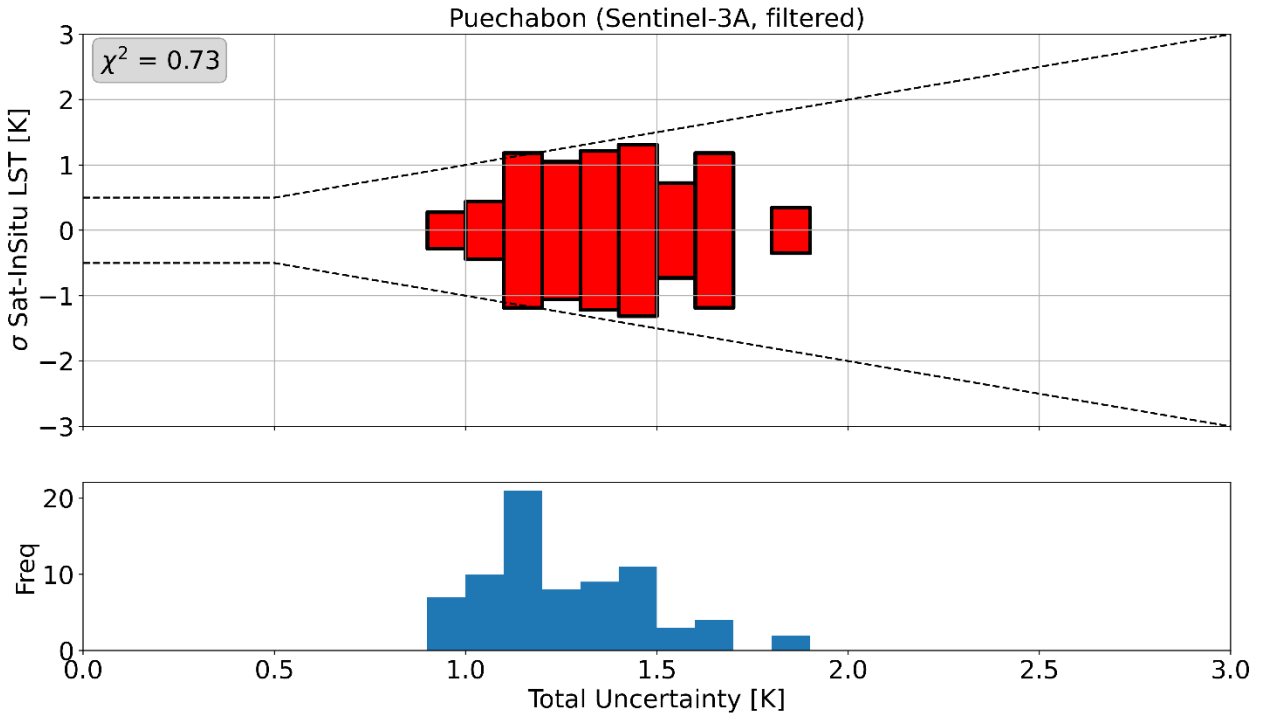
- Hampel filter removed ~24% of observations - suggesting that cloud detection algorithm & SL_2_LST cloud coefficients are performing well
- More night-time than daytime observations after Hampel filtering – coverage bias?
- Statistically significant positive trend persists after filtering – biases are not stable for this site.

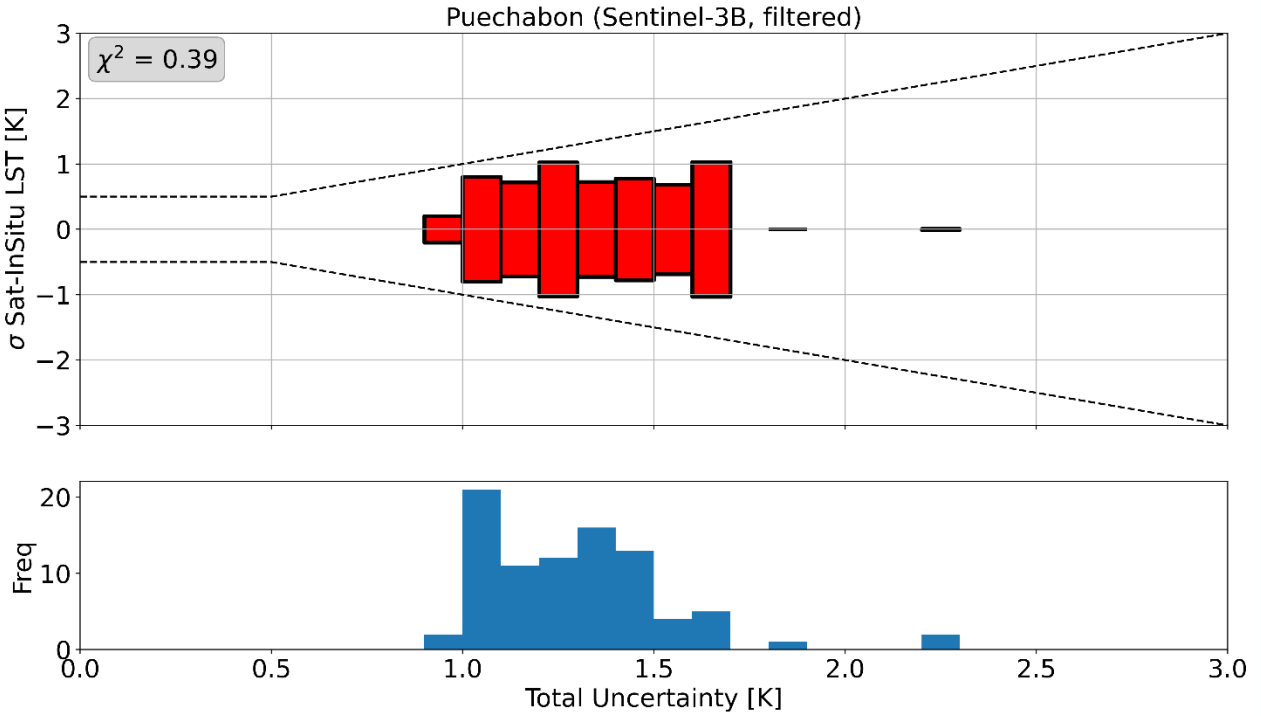
Puéchabon results (filtered)





Puéchabon results (uncertainty)





- σ_{total} appears to closely match observed uncertainty for Sentinel-3A where >5 matchups are binned, but overestimates observed uncertainty for 3B.
- Very few observations binned due to aforementioned issues – observed σ values may be biased.

Overall results

Site name	Sentinel-3A						Sentinel-3B					
	Day			Night			Day			Night		
	N	Acc	Prec	N	Acc	Prec	N	Acc	Prec	N	Acc	Prec
Svartberget	68	-0.655	1.234	67	-0.644	1.128	71	-0.750	1.198	66	-1.049	0.840
Hyytiälä	52	-0.905	0.499	55	-1.030	0.660	57	-0.670	0.606	56	-1.086	0.660
KIT forest site	111	0.262	0.638	152	-0.418	0.486	112	-0.049	0.600	160	-0.438	0.506
Robson Creek	9	-0.766	0.260	38	0.580	0.691	12	0.826	0.785	45	0.628	0.532
Puéchabon	56	0.799	1.088	62	-0.111	0.827	55	0.220	0.556	72	-0.069	0.669

Median Absolute Accuracy for Sentinel-3

	Day [K]	Night [K]
Sentinel-3A	0.677	0.557
Sentinel-3B	0.503	0.654

Conclusions

- **Overall, Sentinel-3 meets the MRD Accuracy and GCOS Precision criteria ($\lesssim$ 1 K) for all sites.** These results are consistent with the performance of the SL_2_LST product across multiple sites as reported in the S3MPC Cyclic Reports.
- **Matchups over Robson Creek show anomalously large biases**, despite the homogeneous land cover & minor site instrument issues. It is **possible that non-optimal setting of the across-track parameters in the SL_2_LST algorithm for this site are to blame**, which have higher impact in high water vapour regions.
- After Hampel filtering, **large satellite – in-situ biases were also observed over Svartberget and Hyytiälä at night. SL_2_LST retrieval coefficients may need to be updated for these biomes.**
- **Night-time coverage bias exists for many sites**, especially for Sentinel-3B: **cloud flagging/masking may require updating**
- Only 11 months of data available for 4/5 sites – cannot resolve seasonal properties of biases. While KIT forest time series appears stable, **Puéchabon biases show a positive trend**.
- Uncertainty validation showed that σ_{total} **is largely accurate for KIT forest & Hyytiälä**, but **overestimates uncertainty for Puéchabon** and **underestimates the uncertainty for Svartberget**. However, σ_{total} could not be calculated for a lot of matchups, due to a lack of cloud-free satellite data in the surrounding region to calculate σ_{space}. **More observations are needed to perform a robust uncertainty validation.**