# Cloud Base Height Estimation Using Sky Imager and Satellite

Amar Meddahi[1,2], Yves-Marie Saint-Drenan[1], Arttu Tuomiranta[2], Sebastien Guillon[2], and Philippe Blanc[1]

[1]Centre O.I.E. – Mines Paris – PSL, Sophia-Antipolis (France)

[2]TotalEnergies, Paris-Saclay (France)

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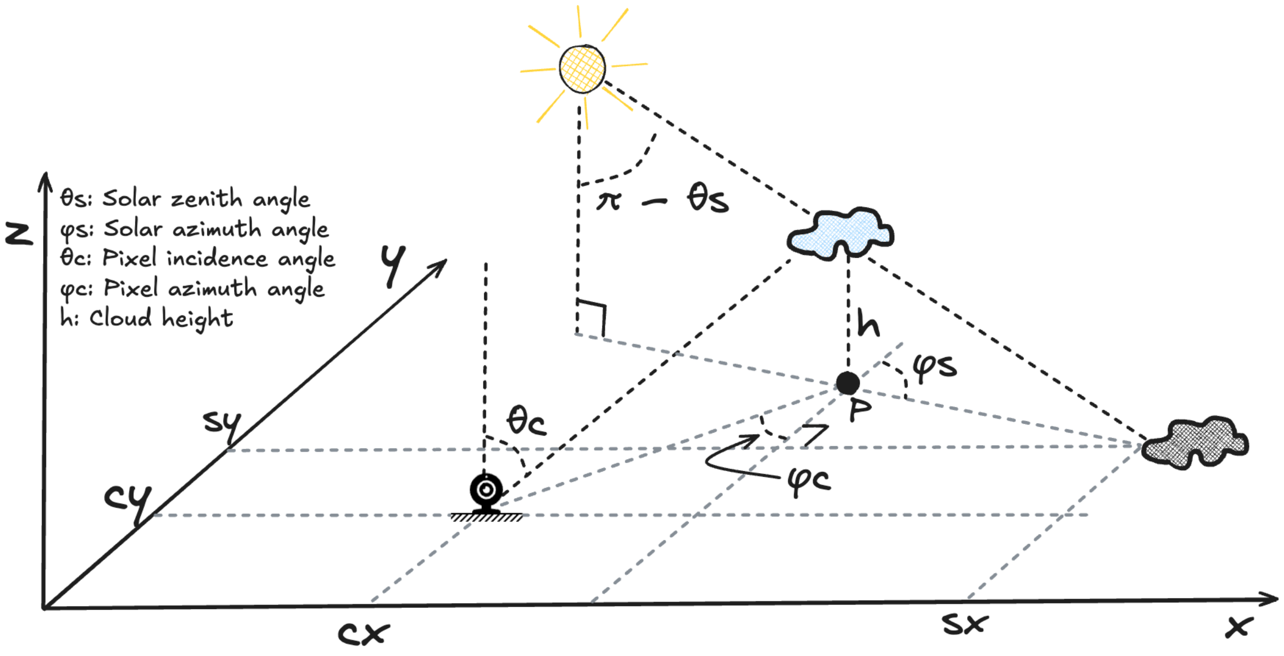
# Motivations

- **Cloud base height (CBH)** is the lowest altitude of the visible portion of a cloud.
- CBH is crucial for image-based solar forecasting, as it helps position cloud shadows more accurately on the ground and analyze the spatial variability of the solar resource.
- Existing spatiotemporal solar forecasting methods rely on:
  - Remote sensing technologies such as ceilometers
  - Ground-based cloud speed sensors
  - Distributed ground-based sky imagers for stereoscopy
- The need for additional sensors can be a limiting factor when deploying in operational sites.

**Cloud shadows are height dependent**



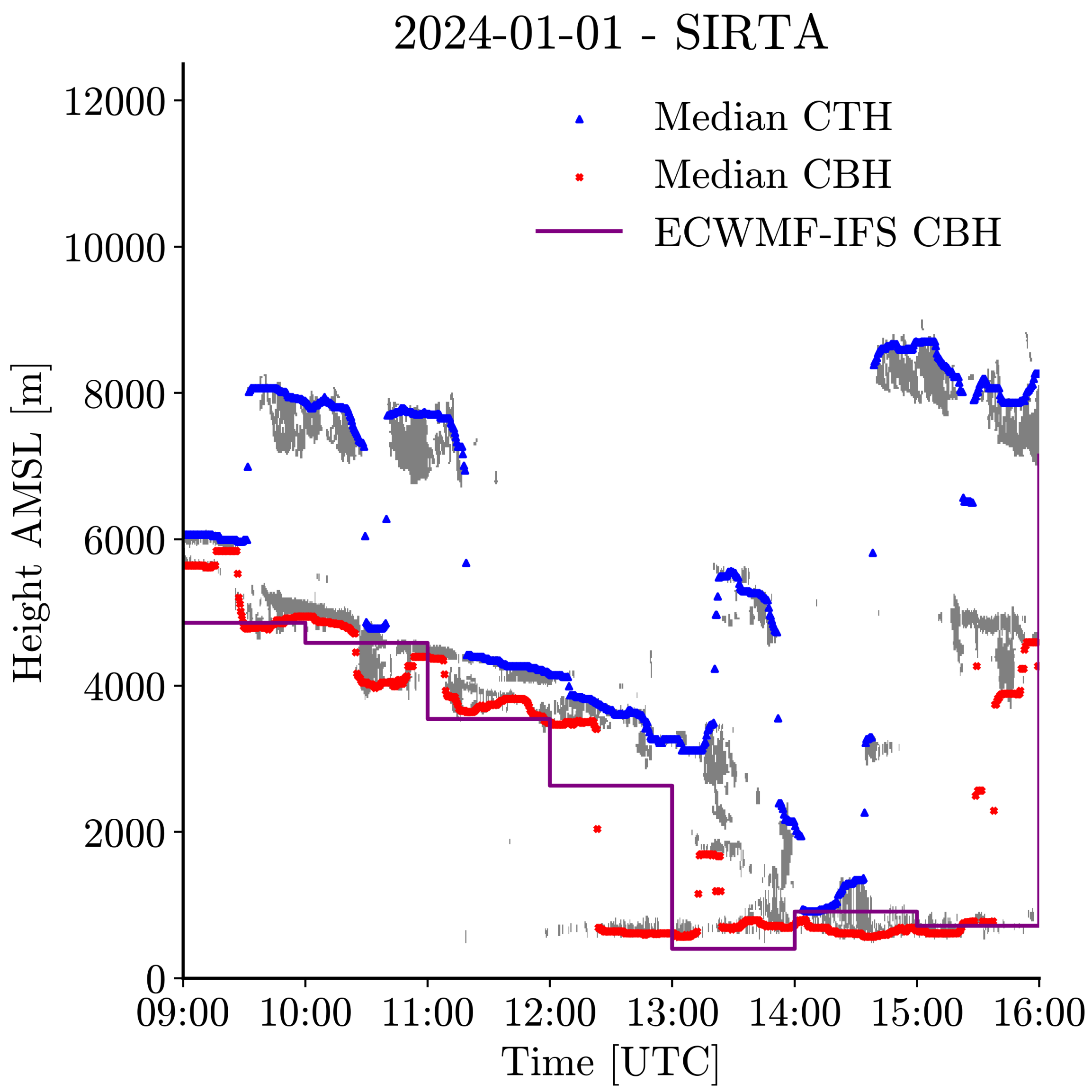


**Example of dual ground-based sensor setup for solar forecasting**

# Research Problem

(See Appendix for ECMWF-IFS CBH Validation @SIRTA)

- Research Question: Can a single ground-based sky imager combine with weather satellite data reduce the uncertainty in NWP-derived CBH estimates?
- Objective: Enhance the scalability of spatiotemporal solar forecasts by minimizing reliance on multiple ground-based sensors.
- Related work: (Killius et al., 2015; Kuhn et al., 2018)

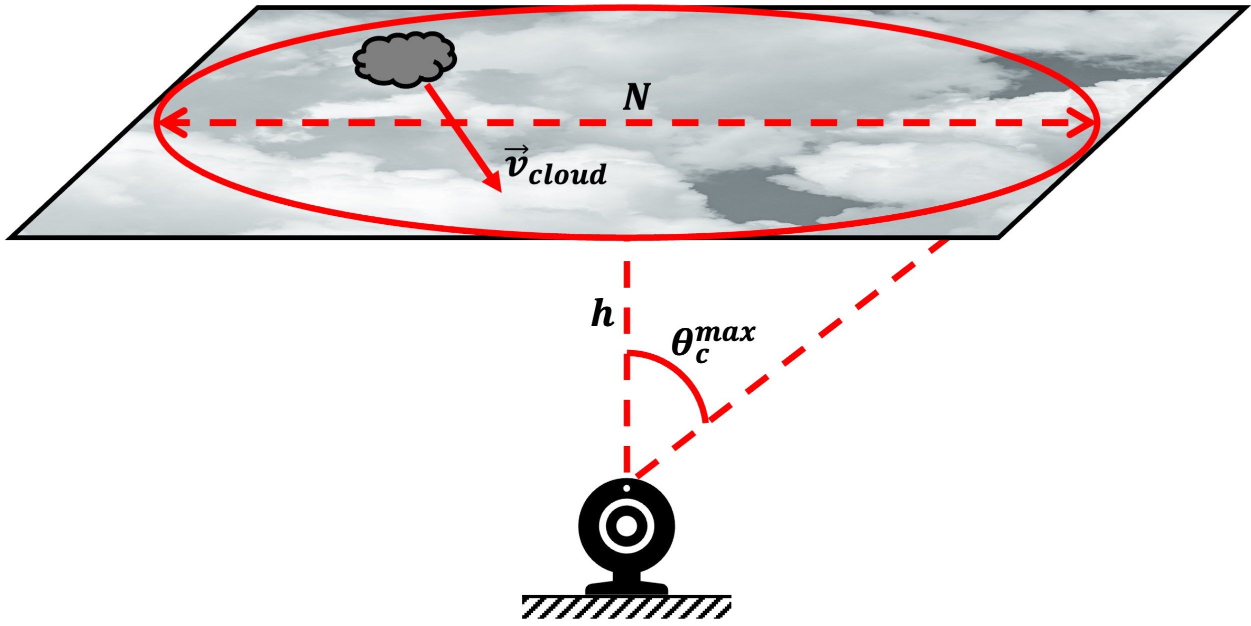


# Kinematic Relationship

- A cloud moving at a linear speed $\boldsymbol{v_{m/s}}$ can also be characterized from ground-based imaging, where its speed is expressed in pixel speed $\boldsymbol{v_{pixel/s}}$.
- The relationship between cloud pixel speed and effective cloud speed (Wang et al., 2016) is given by:

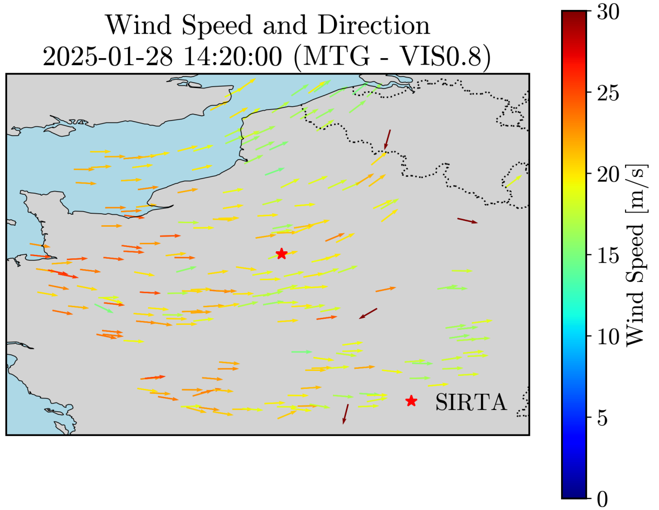
$$h = \frac{N \ * \ v_{m/s}}{2 \ * \ v_{pixel/s} \ * \ \tan(\theta_c^{max})}$$

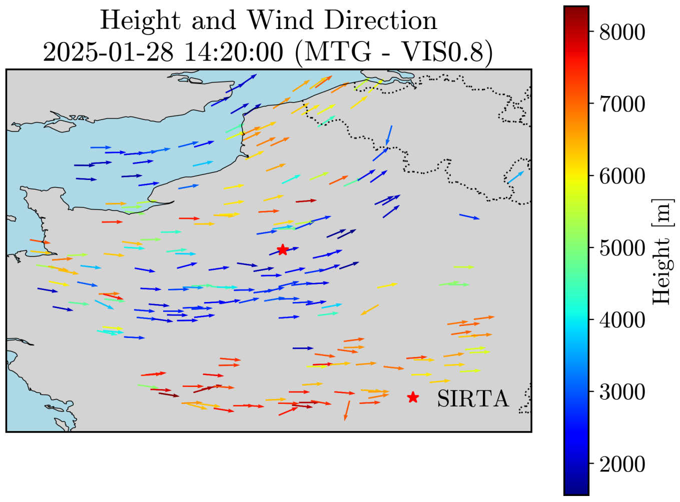
  - $N$: The number of pixels of the cloud map in one dimension
  - $\theta_c^{max}$: The maximum incidence angle of the sky imager

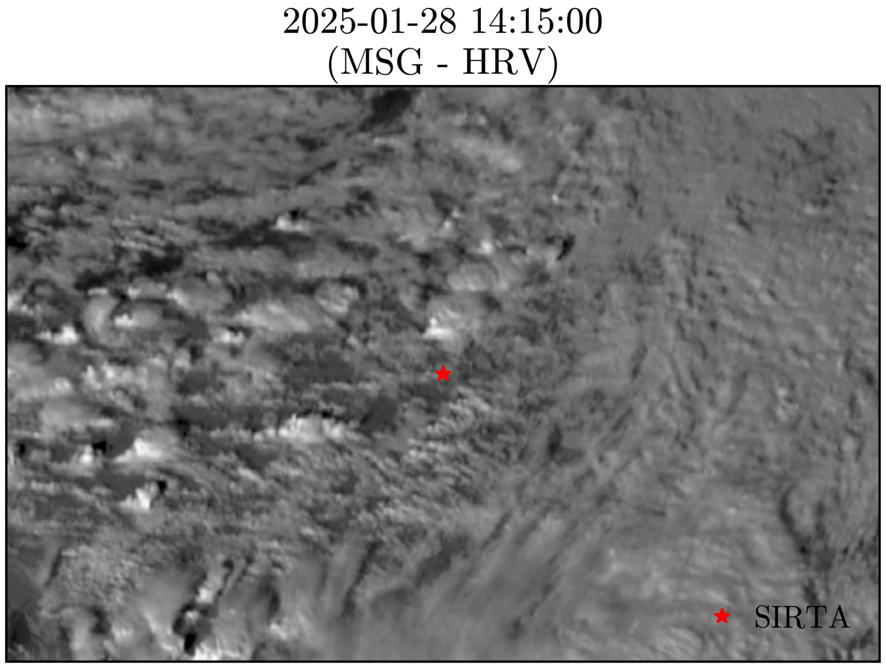


# Atmospheric Motion Vectors (AMV)

- Key steps in AMV generation:
  - Identify a trackable atmospheric feature
  - Track its displacement across sequential images
  - Assign an altitude (pressure level) to the motion vector
  - Evaluate the vector's quality
- AMV provide:
  - Wind speed and direction
  - Altitude (height/pressure)
  - Quality indicators



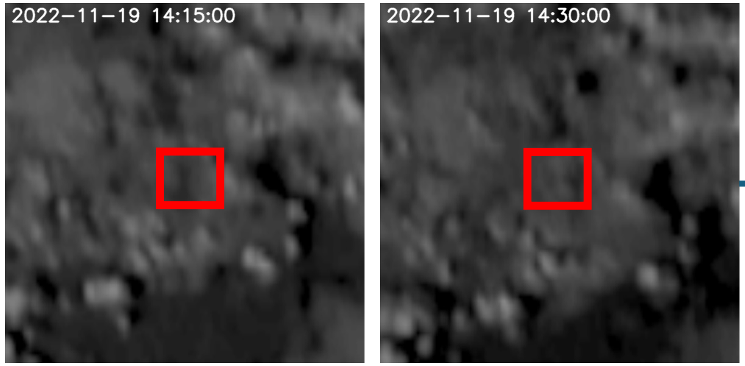



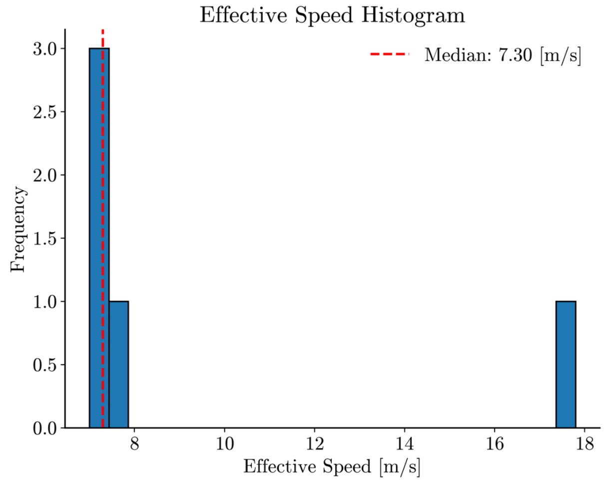
# Methodology

$$CBH\ SAT + SKY = \frac{v_{m/s} * N}{2 v_{pixel/s} \tan(\theta_c^{max})}$$

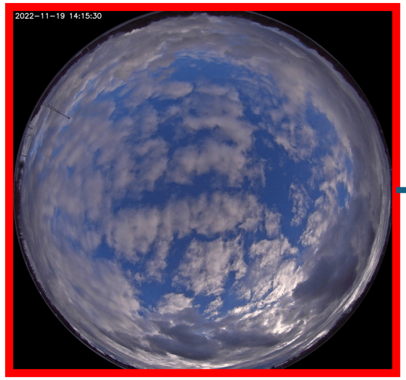
$t^* - \Delta T_{SAT}$ $\quad$ $t^* = 14{:}30$



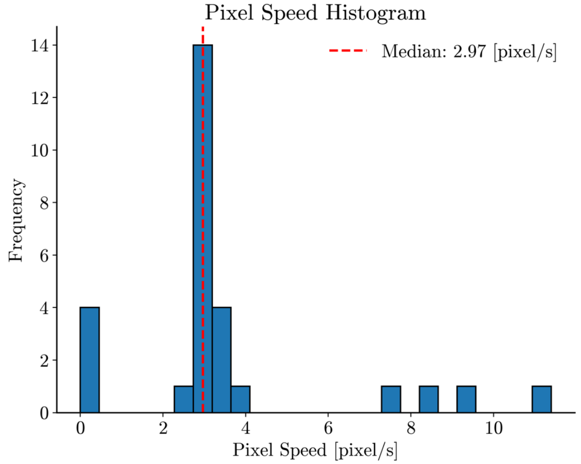

AMV Algorithm + Selection

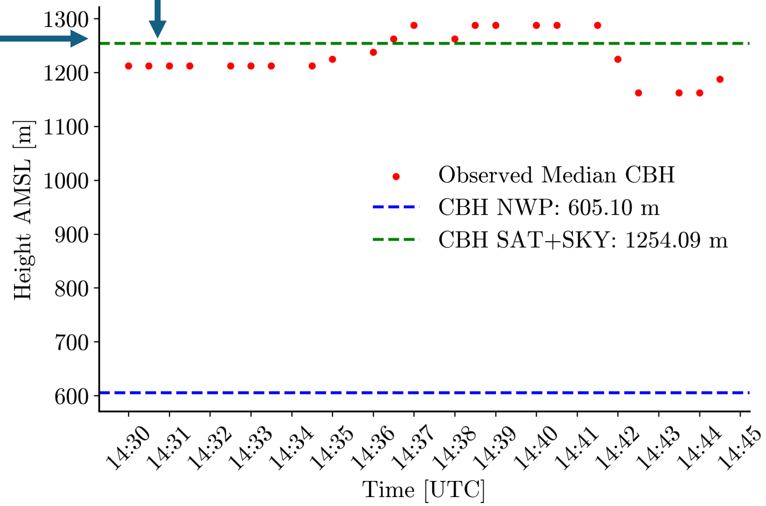



$t^* - \Delta T_{SAT} : \Delta T_{SKY} : t^*$




Cloud Motion Algorithm + Selection

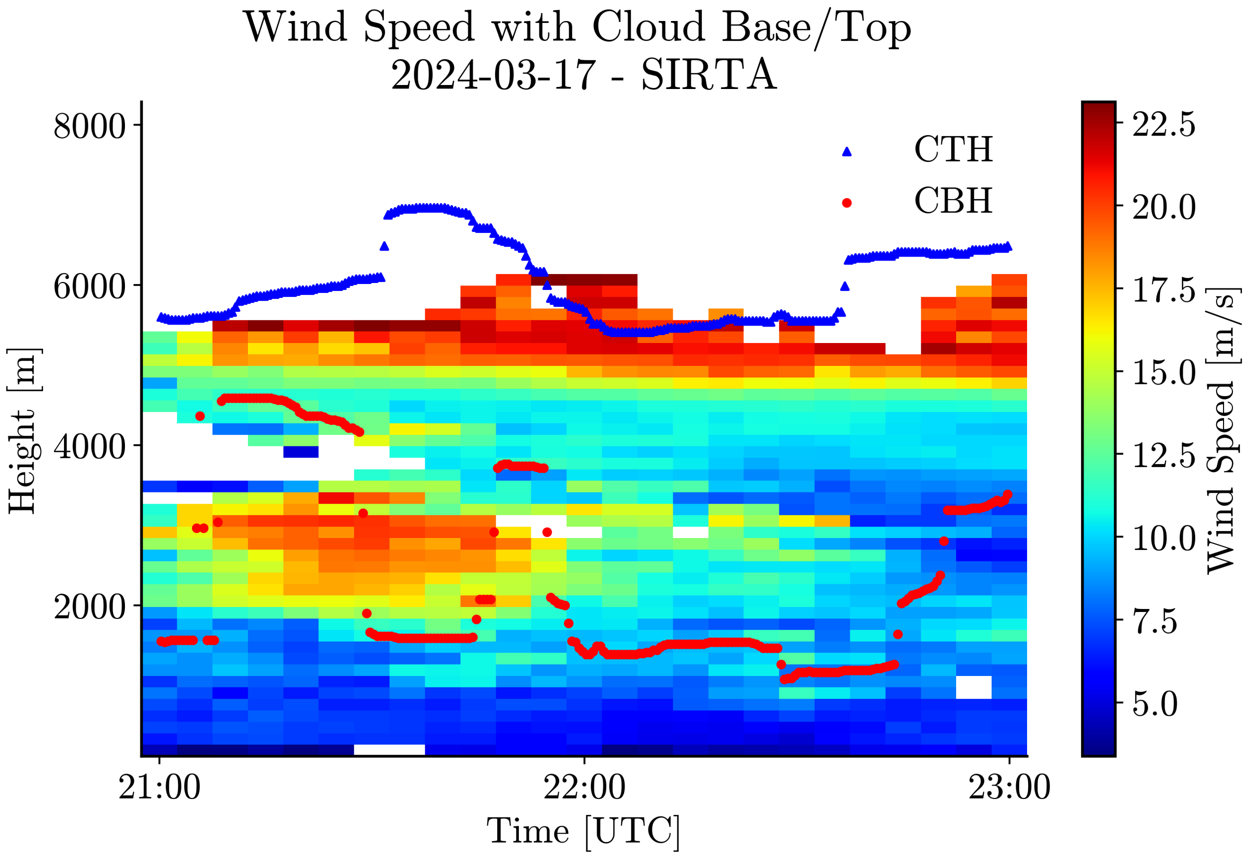


# Technical Challenge: One Example

- The AMV algorithm relies on two key assumptions:
  - Assumption 1 — Local Wind Representation:
    - The tracked cloud or water vapour feature is assumed to move at the same speed and direction as the local wind.
    - ➤ Good, as cloud motion itself is the primary interest.
  - Assumption 2 — Motion at Cloud Top:
    - The extracted motion vector is assumed to occur at the top of the tracked feature, using Cloud Top Height (CTH) as its altitude reference.
    - ➤ Problematic, as the actual motion may not correspond to the CTH level.

(See Appendix for more info on data)




**Ground-based: Wind Radar + Ceilometer + Cloud Radar**

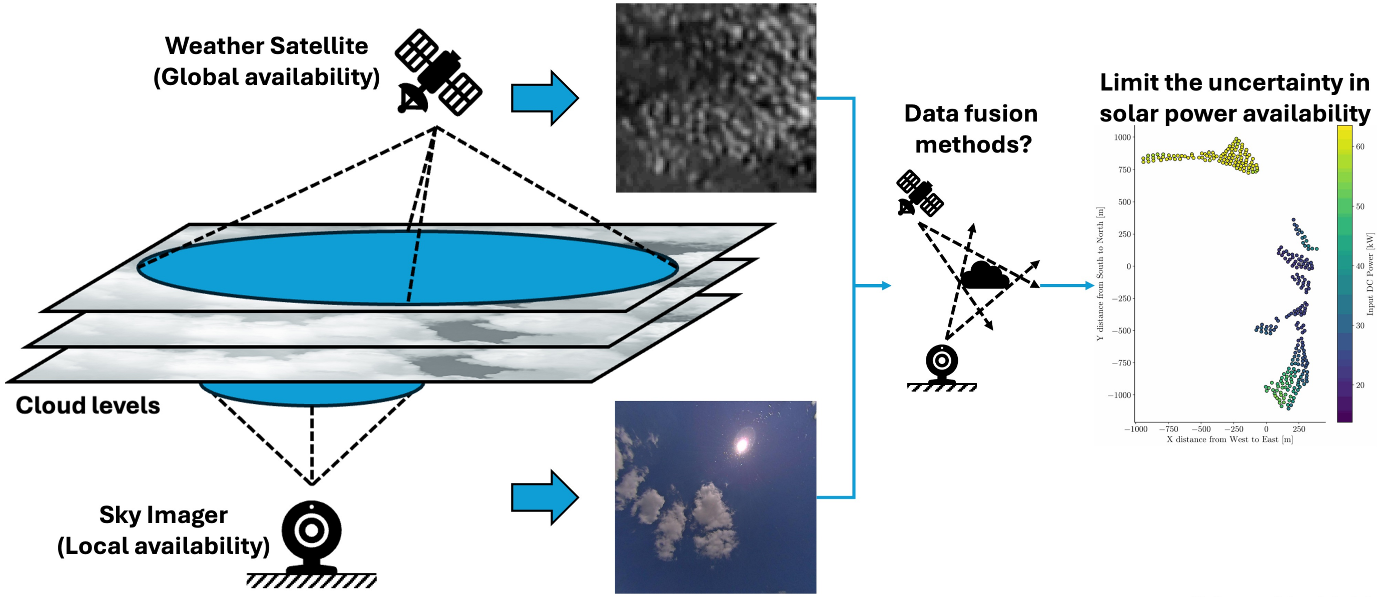
# Next Steps

- Evaluate the accuracy of different selection strategies
- Develop methods for distinguishing multiple cloud layers
- Perform validation
- Test replication on other sites and weather satellite datasets

# Thanks!

- **The authors would like to acknowledge SIRTA for providing the data used in this study. (Haeffelin et al., 2005) https://doi.org/10.5194/angeo-23-253-2005**

**How can ground-based sky imagers complement weather satellite data to reduce uncertainty in solar power availability?**

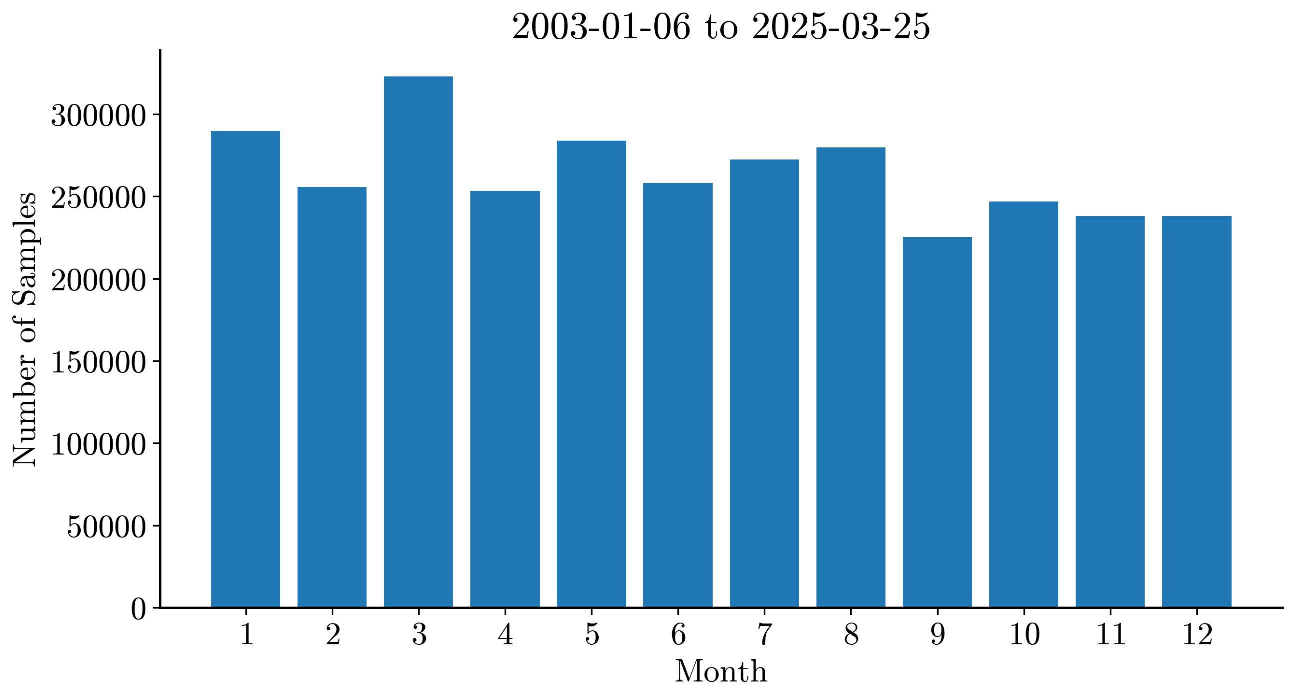


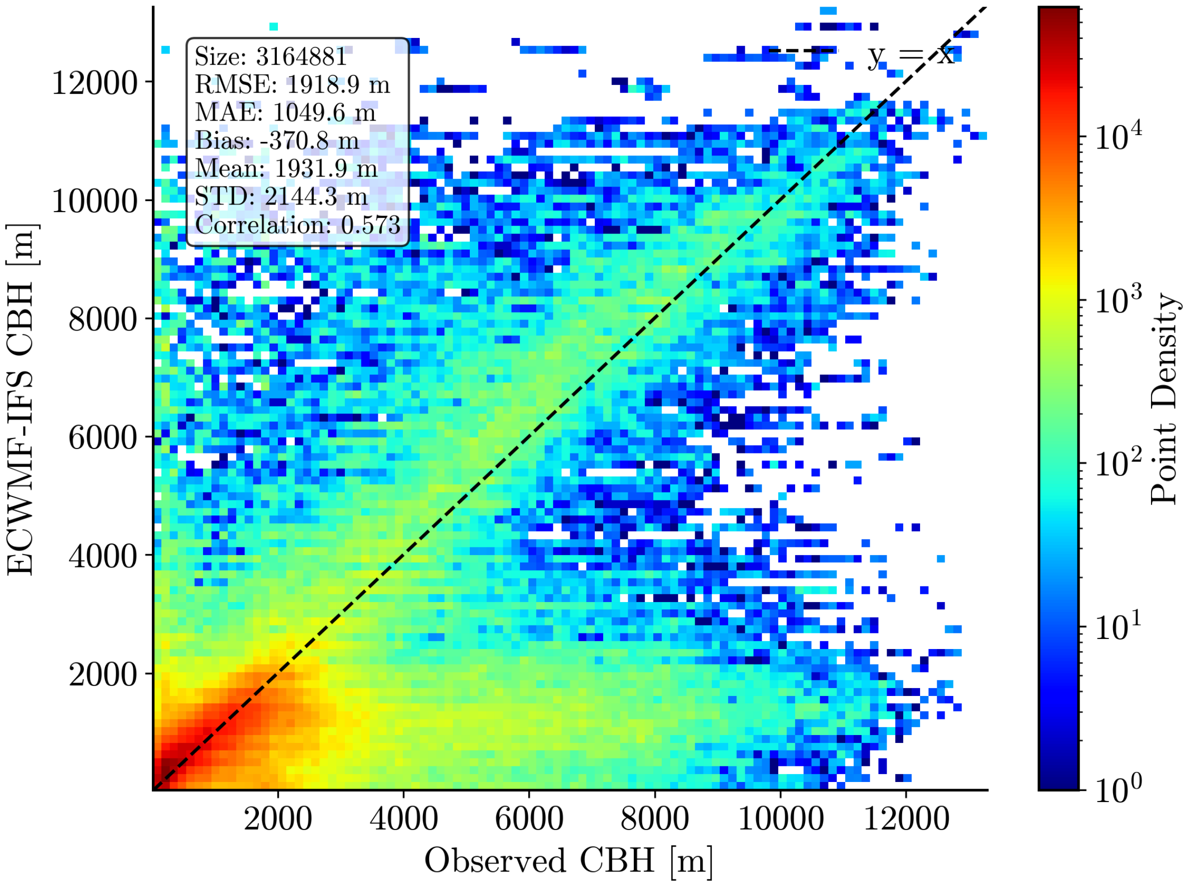

@Amar Meddahi

**Feel free to reach out!**

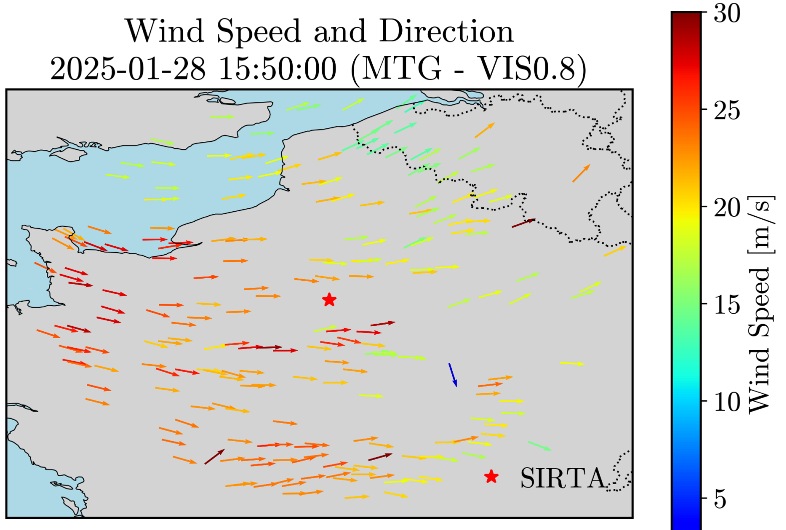
amar.meddahi@minesparis.psl.eu

# ECWMF-IFS CBH

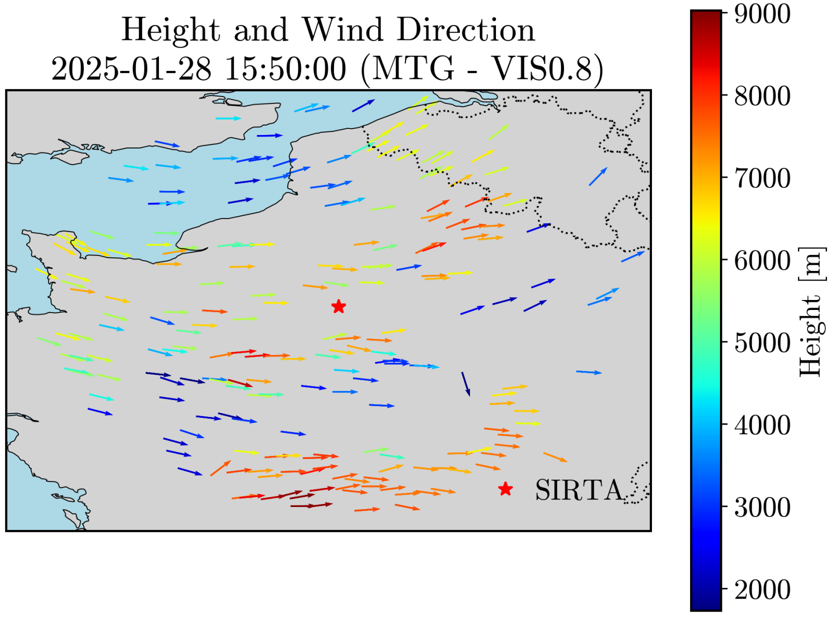


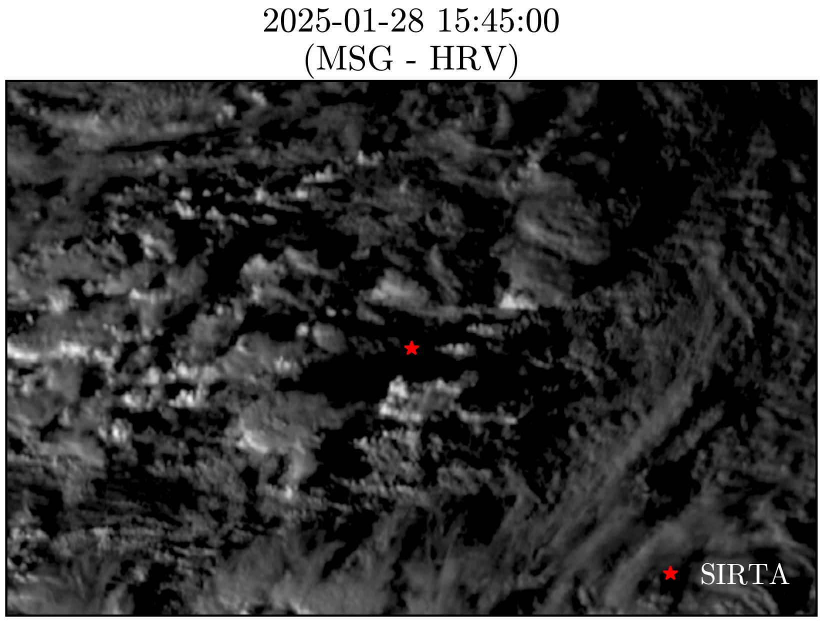
# AMV: Example



Wind Speed and Direction
2025-01-28 15:50:00 (MTG - VIS0.8)
SIRTA
Wind Speed [m/s]
30
25
20
15
10
5
0

Height and Wind Direction
2025-01-28 15:50:00 (MTG - VIS0.8)
SIRTA
Height [m]
9000
8000
7000
6000
5000
4000
3000
2000

2025-01-28 15:45:00
(MSG - HRV)
SIRTA

# Data

- Data at SIRTA
  - Sky imager: 30s resolution
  - Cloud mask: fusion of ceilometer and cloud radar (Illingworth et al., 2007)
- Satellite-derived wind speed
  - We used EUMETSAT AMV product.
- Preprocessing
  - Solar elevation > 0° (sufficient luminosity for sky imager)
  - Cloud heights:
    - Threshold <= 12500m
    - Applied a 15-min centered median filter (sensitive to the dominant cloud layer), aligned with previous studies.