Spatiotemporal Solar Forecasting Using a Single Sky Imager and Satellite Data

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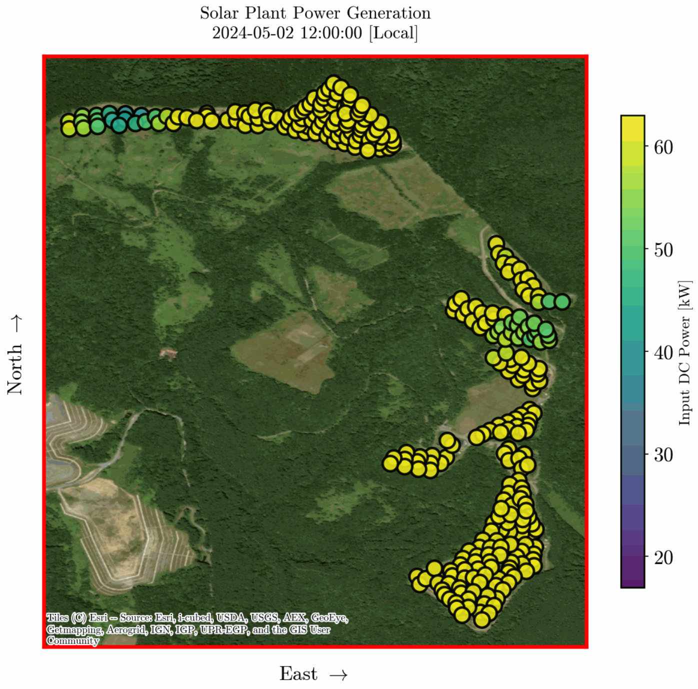
What do you notice in this image?

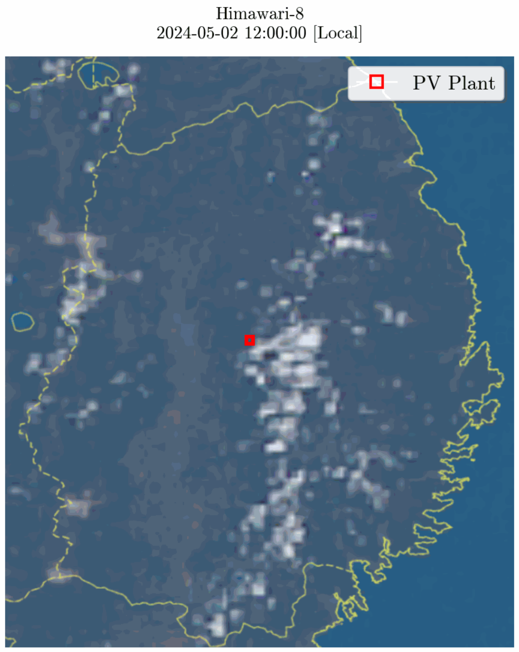
- Complex shapes of ground shadows
- Solar zenithal angle
- Binary variability regimes (e.g., sunlit vs. shaded)
- Presence of 3D cloud structures
- Local homogeneity of cloud appearance (similar texture between neighboring regions)
- Etc.

Context

- Meteorological factors, such as cloud cover, introduce uncertainty in solar power availability, which challenges grid integration and affects operational performance.



25 MW Solar Plant Live Power Production

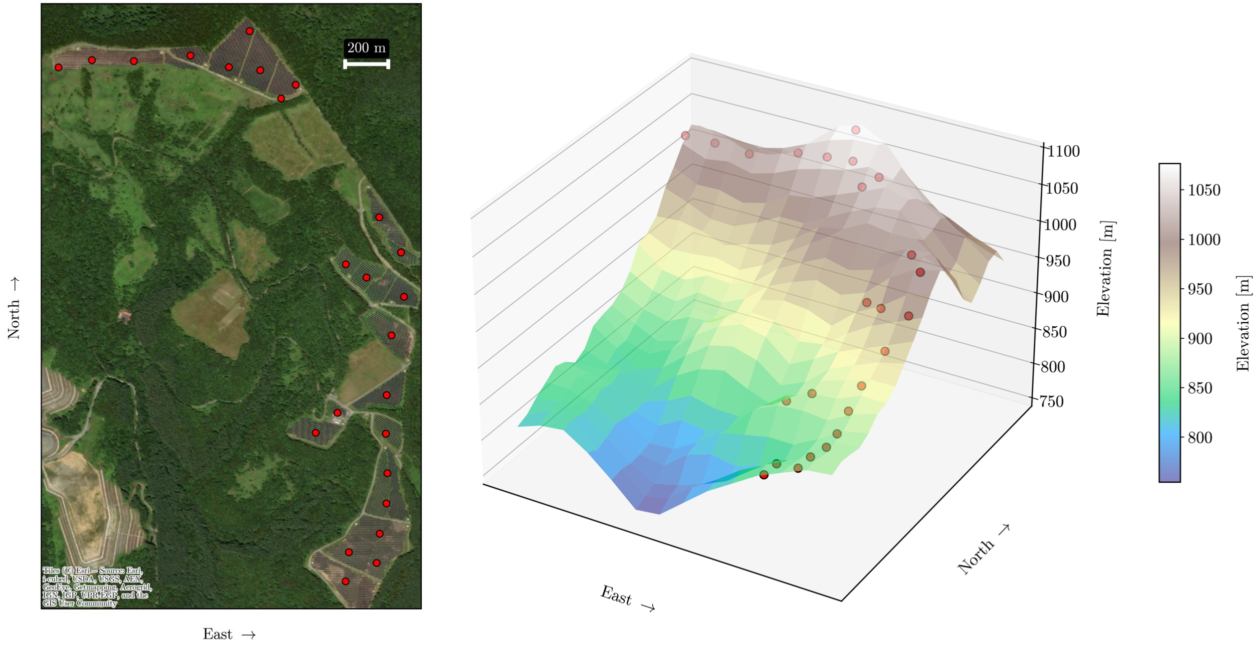


Corresponding Satellite View (Source: Himawari-8)

Problem Definition

- *“Solar forecasting estimates the total solar irradiance incident on oriented surfaces over a specified* ***spatial domain*** *and* ***temporal forecasting cycle****.”*

Example: Spatial Domain (D)



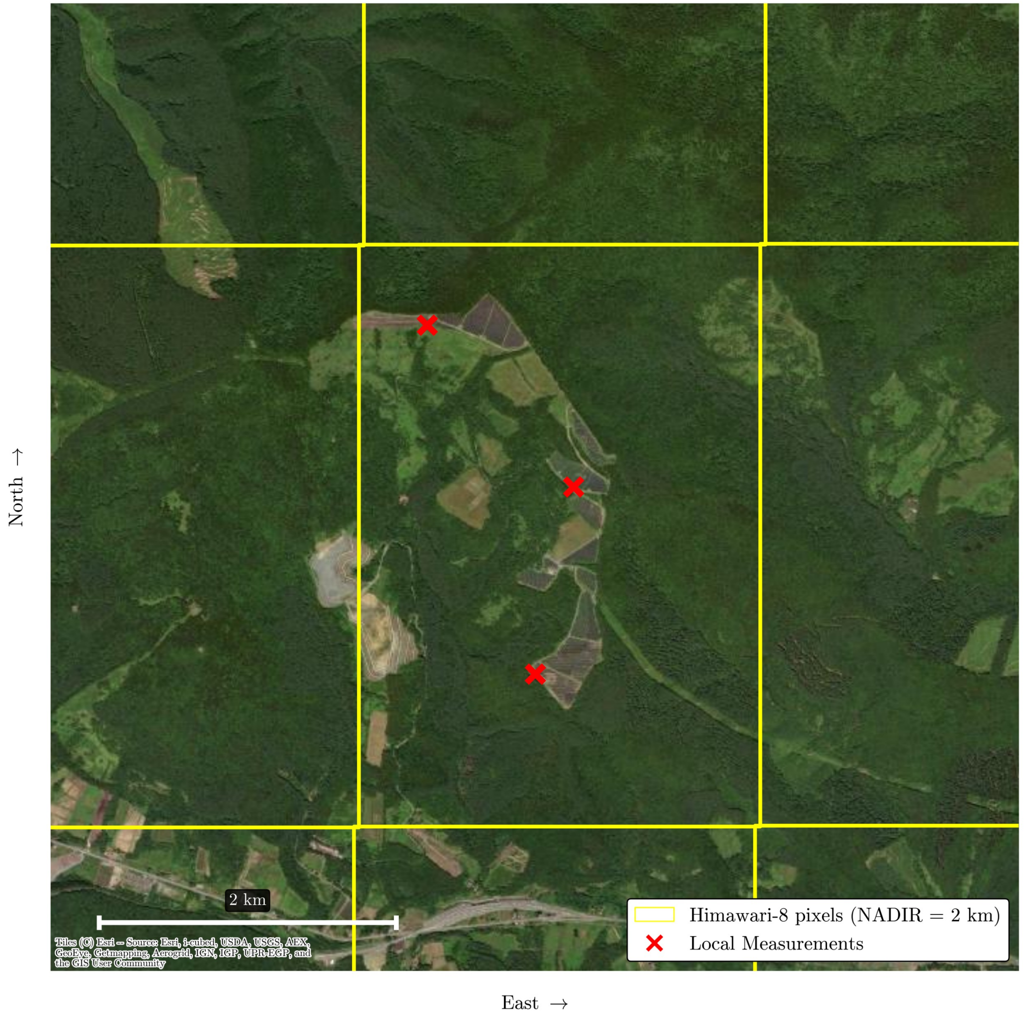
Example: Temporal Forecasting Requirements

- Hourly forecasts delivered during daytime with 5-minute lead time
- 60-minute forecasting horizon
- 1-minute temporal resolution

Motivations

- Bridge the spatiotemporal information gap between **local measurements** (e.g., reference cells, pyranometric sensors) and **global observations** (e.g., satellite-derived products).
- **Applications**: Estimation of solar local power generation and optimization of plant operations (e.g., tracking systems and EMS decisions).

High-resolution solar irradiance observations is currently limited

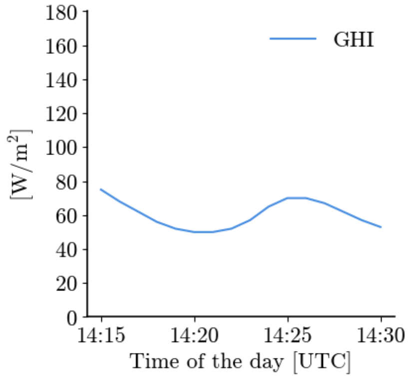


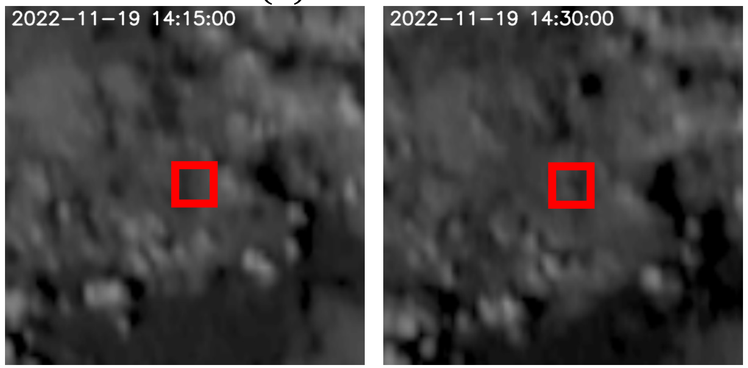
Problem Inputs

- Solar irradiance across the PV plant domain ($\boldsymbol{D}$) is typically observed from the following sources:
  - $S(3)$: in-situ irradiance measurements (GHI)
  - $S(2)$: Satellite Data
- To bridge the information gap, we introduce an additional sensor within $\boldsymbol{D}$:
  - $S(1)$: Sky imager

Current Status

$t^* - \Delta T_{S(2)} : \Delta T_{S(3)} : t^*$ $\quad$ $t^* - \Delta T_{S(2)}$ $\quad$ t^*

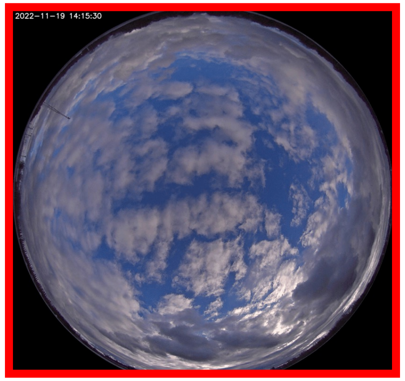




$S(3) \in \boldsymbol{D}$ $\quad$ $S(2)$

Our proposal: A single sky imager

$t^* - \Delta T_{S(2)} : \Delta T_{S(1)} : t^*$



$S(1) \in \boldsymbol{D}$

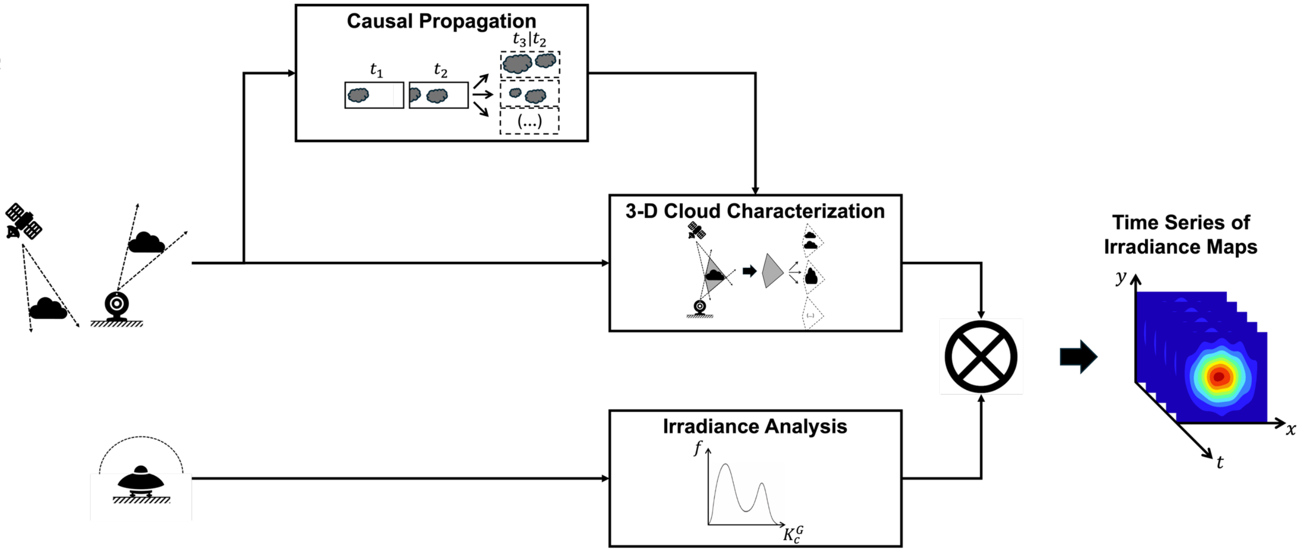
Research Question

- In this talk, we'll try to provide elements of an answer to the following question:

"How can a ground-based sky imager complement weather satellite data and in-situ measurements to reduce uncertainty in solar power availability?"

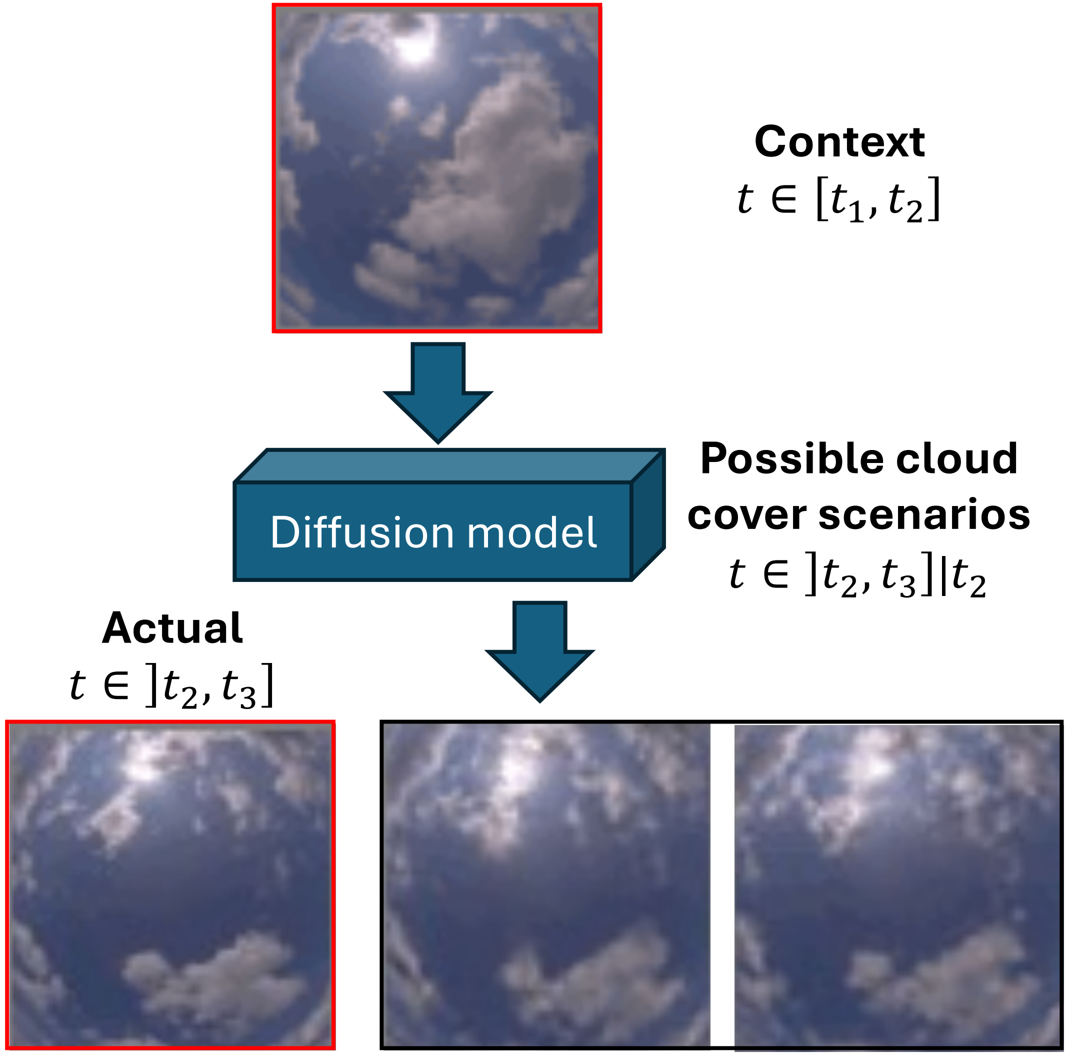
Methodology

1. **Causal Propagation**: Estimates the future cloud cover to provide the temporal dimension of the forecast.
2. **3-D Cloud Characterization**: Identifies the three-dimensional structure of clouds to localize spatial variability (i.e., ramps).
3. **Irradiance Analysis**: Estimates the expected irradiance levels across the spatial domain.



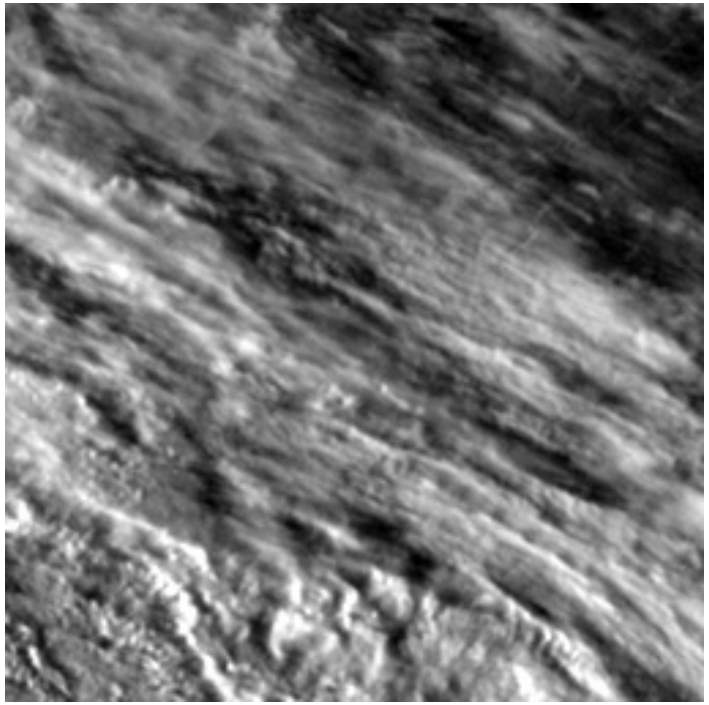
Causal Propagation

- **Sharp** and **multi-scenario** observation generation is essential for images.
    - **Sharpness** enables clear decisions between cloudy and clear pixels (i.e., **ramp detection**).
    - **Multi-scenarios** help present plausible outcomes tailored to specific applications (e.g., stochastic EMS operation).
- **Diffusion models** meet both requirements, making them a natural choice.
- **Challenges**:
    - How can we evaluate cloud cover forecasts against actual observations using a multi-scenario scheme (pixel-level metrics vs. downstream task proxies)?
    - Can such models be conditioned on multi-perspective cloud cover inputs? (e.g., Paletta et al., 2023)

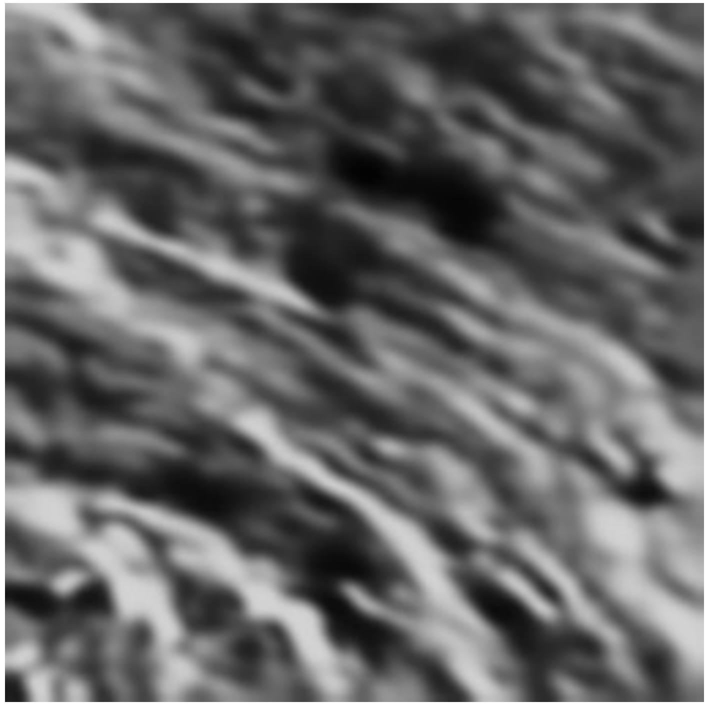


Causal Propagation: Satellite Example

Actual $t \in]t_2, t_3]$



Possible cloud cover scenario $t \in]t_2, t_3] | t_2$

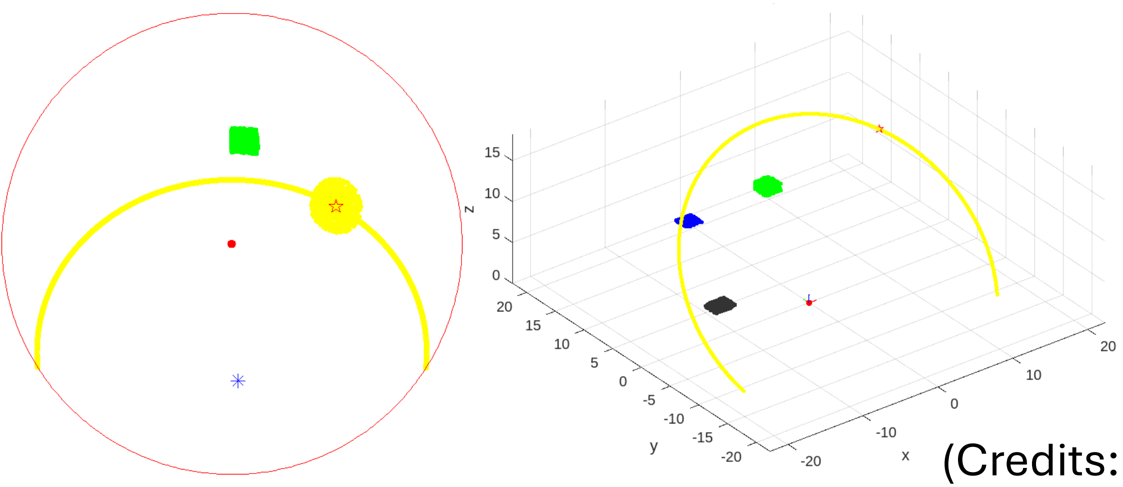


(Credits: Great ongoing work by Nicolas Chea)

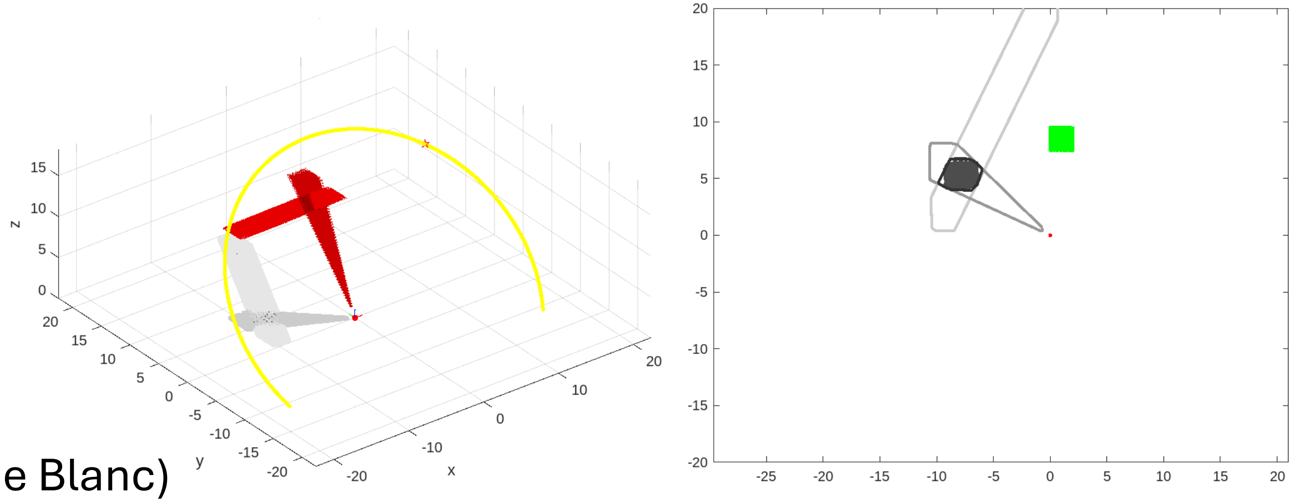
Importance of accurate 3-D Clouds

- The combined use of ground-based sky imagers and satellite data enables moving beyond ground-level pixel assumptions in satellite products (e.g., parallax effects) and the flat cloud assumptions of sky imagers. This can significantly reduce errors in the localization of ground-level cloud shadows (Vallance et al., ICEM 2018).

Cloud Scene

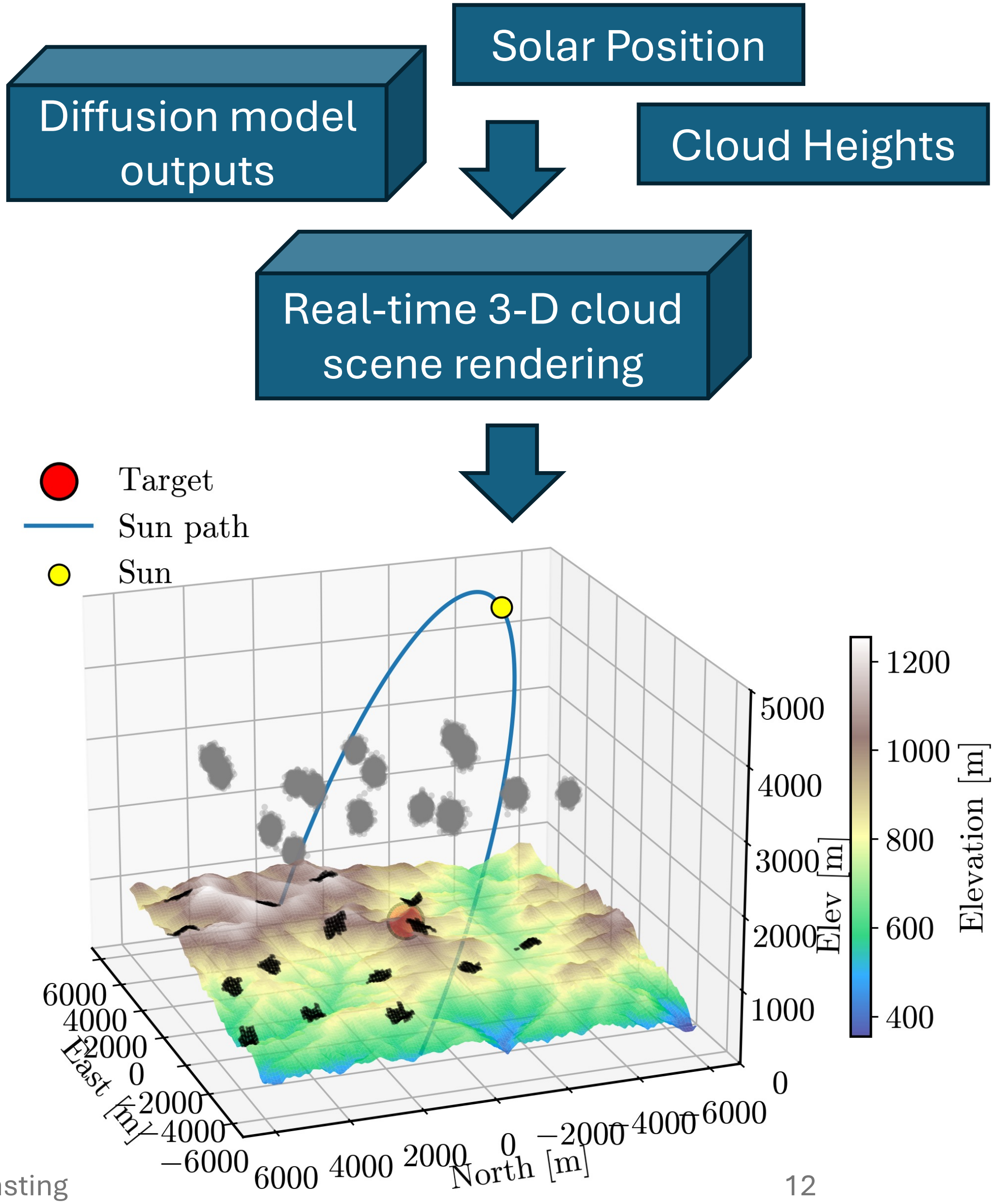


3-D cloud reconstruction



(Credits: Philippe Blanc)

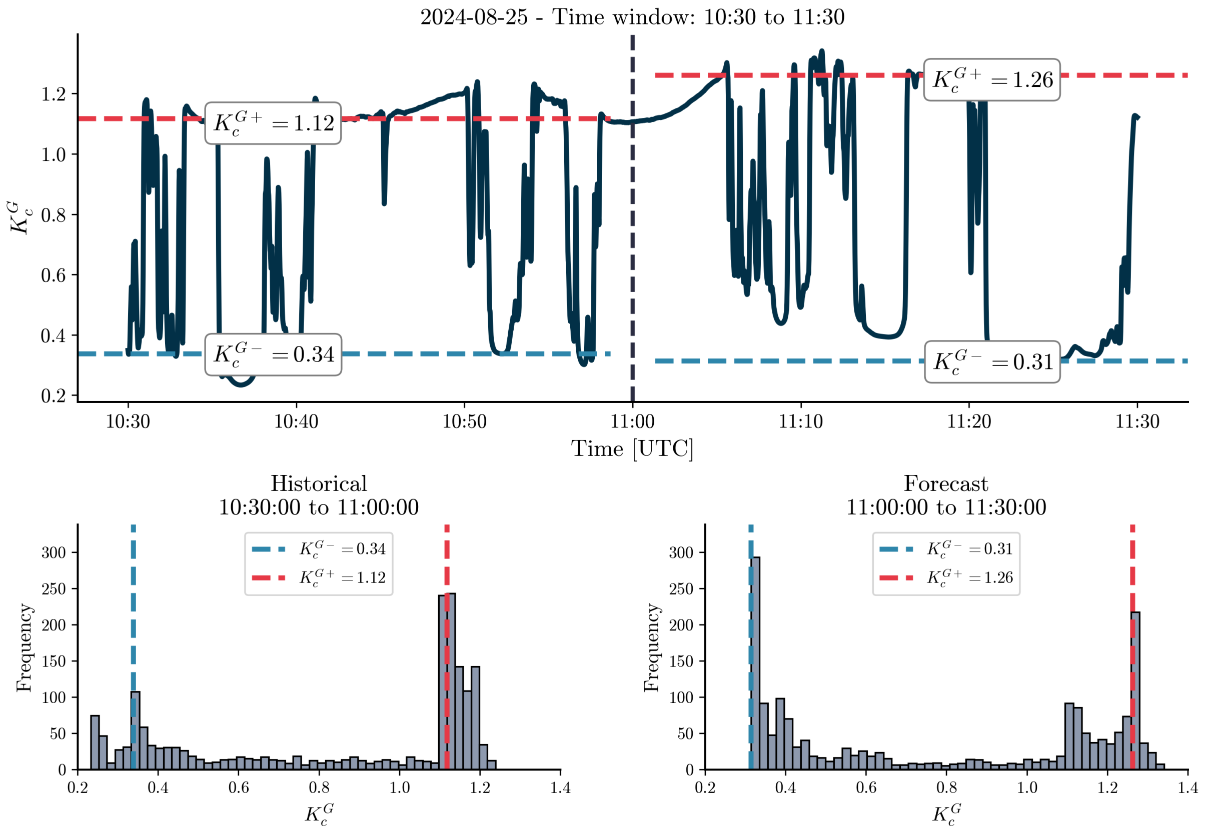
3-D Cloud Characterization



- Thorne (1997) and Vallance (2017) proposed methods to estimate potential 3-D cloud volumes (binary) using a single sky imager combined with satellite observations.
- Based on these 3-D cloud reconstructions and the solar position, shadowed and non-shadowed ground areas can be inferred over local topography.
- This information is used to detect and localize irradiance ramp events.

Irradiance Analysis

- Local irradiance variability typically exhibit intra-hour persistence (Schmidt et al., 2016):
  - $K_c^{G-}(t \in]t_2, t_3] | t_2) = K_c^{G-}(t \in [t_1, t_2])$
  - $K_c^{G+}(t \in]t_2, t_3] | t_2) = K_c^{G+}(t \in [t_1, t_2])$
- This is likely due to the spatial homogeneity of cloud properties affecting solar irradiance, such as cloud type, cloud optical depth, etc., but this needs to be verified.

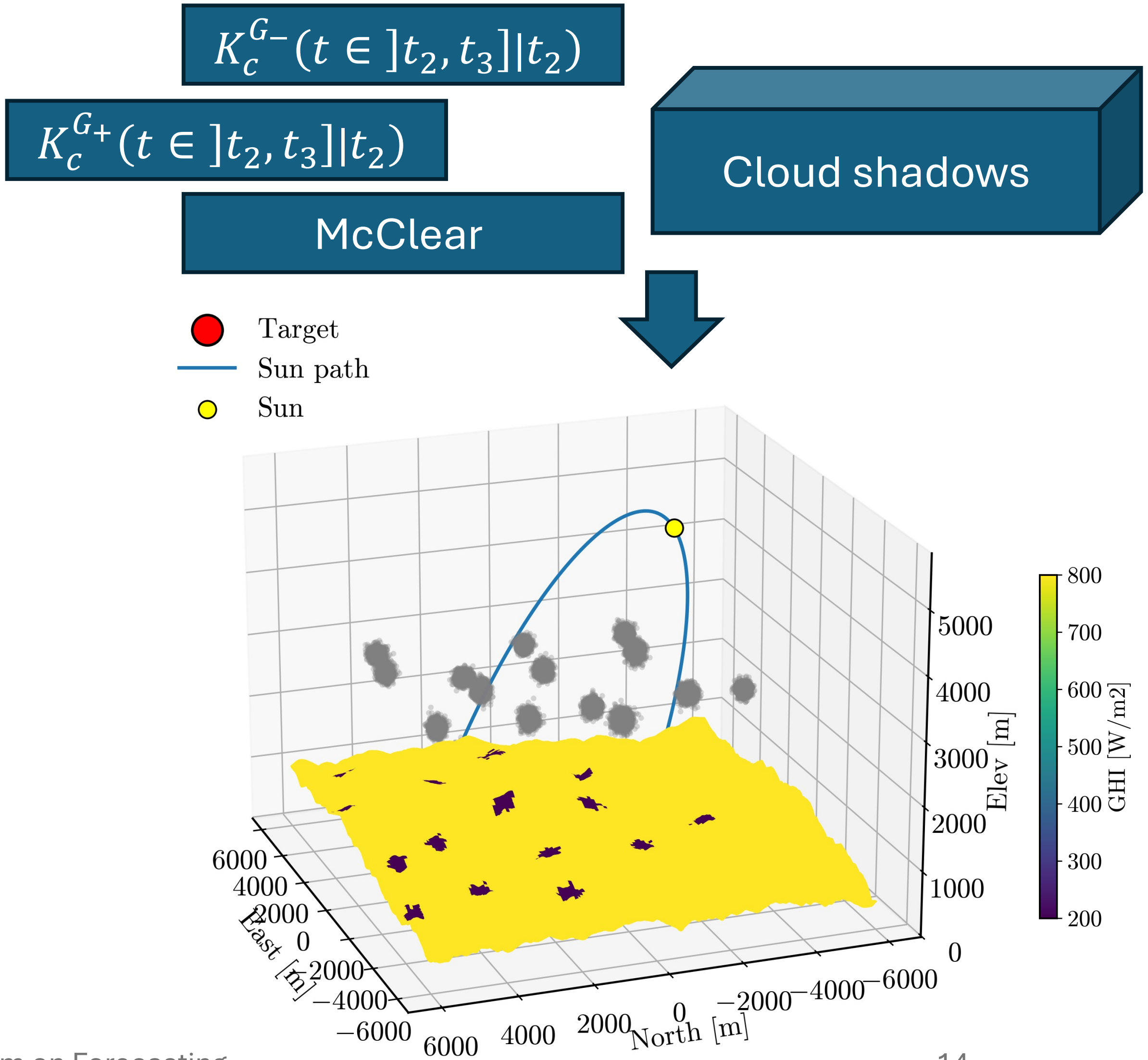


K_c^{G-}: under shadow — K_c^{G+}: no shadow

Corresponding Sky Conditions (10:30-11:30)

Final Forecasts

- Shadow maps are converted into clear-sky index maps K_c^G, which are then transformed into irradiance maps using a clear-sky model (e.g., McClear).
- Spatial and temporal interpolation of K_c^G is applied to meet user resolution requirements if needed.
- GTI can be estimated by using:
    1. Decomposition models (e.g., Ineichen et al., 1992)
    2. Transposition models (e.g., Perez et al., 1987; Perez et al., 1990)



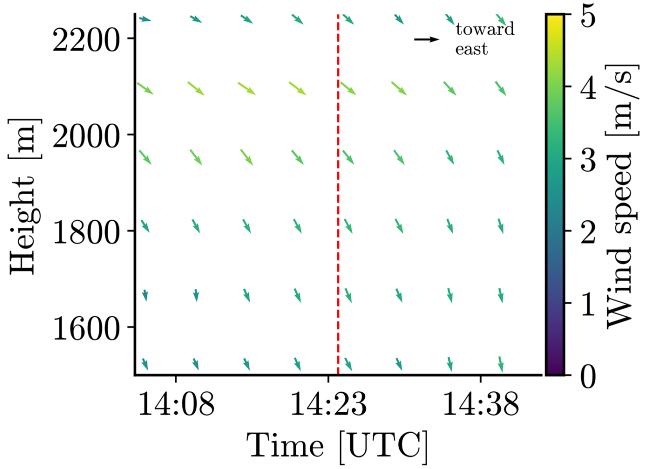
Validation

- The proposed approach involves a set of interdependent components.
- A key contribution of this work is the component-level validation of each module (e.g., causal propagation, 3D cloud structures, and cloud–radiation interactions), in addition to end-to-end forecasting evaluation.
- SIRTA observations are used to assess the individual components uncertainty throughout the pipeline.
- Operational PV plant data is leveraged for overall forecasting validation (in-situ measurements and inverter level data).

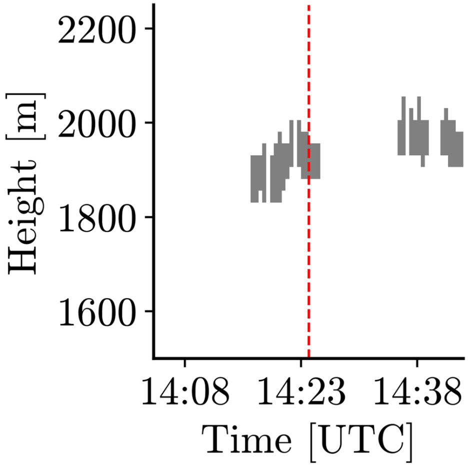
All necessary measurements at the same place

Cloud Imaging

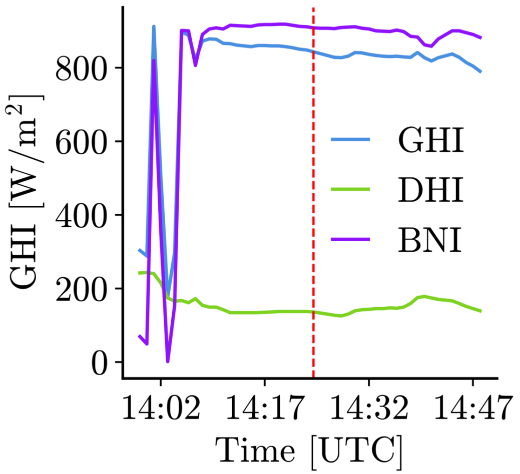
Wind Components



Cloud Layers



Solar Radiation



Summary

- In this talk, we presented how to leverage three different data sources by exploiting **cross-synergies**.
- The core added value of ground-based sky imaging combined with satellite data lies in enabling more accurate 3-D cloud reconstruction and improving the spatial representation of irradiance variability. This supports localization of ramp events and mitigates satellite parallax effects.
- Pyranometric on-site measurements provide essential support for accurate solar irradiance estimation.
- Next steps will focus on component-level validation and forecast evaluation.

Thanks for your attention!

- Acknowledgments:

  - This work is funded by TotalEnergies and ANRT via a CIFRE grant (2023/1435).
  - The authors would like to acknowledge SIRTA for providing part of the data used in this study (Haeffelin et al., 2005).

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Passionate about understanding the impact of weather on solar energy systems!

If you're interested in my work, feel free to reach out!

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