Atmospheric properties measurement using sky images

== CSPIMP project ==

Project leader:

GE O&G Thermodyn (France)

List of partners:

Acciona Energia (Spain)
CNRS Promes(France)
ARTS (France)

Subcontractors:

GE O&G Nuovo Pignone (Italy)

Rémi Chauvin
remi.chauvin@promes.cnrs.fr

Supervisor: Stéphane Grieu
Co-director: Stéphane Thil
Project engineer: Julien Nou

June 23rd , 2014

Summary

1. Context
2. PROMES Sky imager
   1. *Hardware*
   2. *Software*
   3. *Camera calibration*
   4. *Pixel angles*
3. Clear sky model
   1. *Clear-sky intensity distribution*
   2. *Performance analysis*
   3. *Clear-sky images*
4. Applications
   1. *Clear-sky coefficients*
   2. *Sunshape*
   3. *Cloud detection*
   4. *DNI forecasting*
5. Conclusion & further work

Context

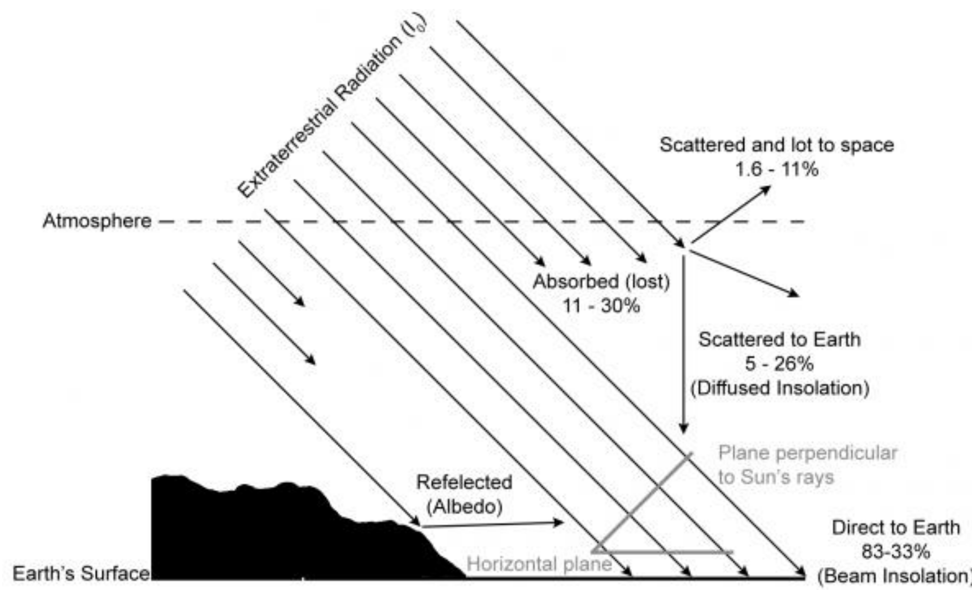
- The atmosphere scatters and absorbs some of the Sun's energy that is incident on the Earth's surface. Consequently, the atmospheric properties play a key role in the evaluation of the solar power plant output.

- From sky images it is possible to measure especially:

  - The cloud cover and cloud motion
  - Its distribution
  - The atmospheric turbidity

- These parameters strongly influence the solar resource availability and variability.

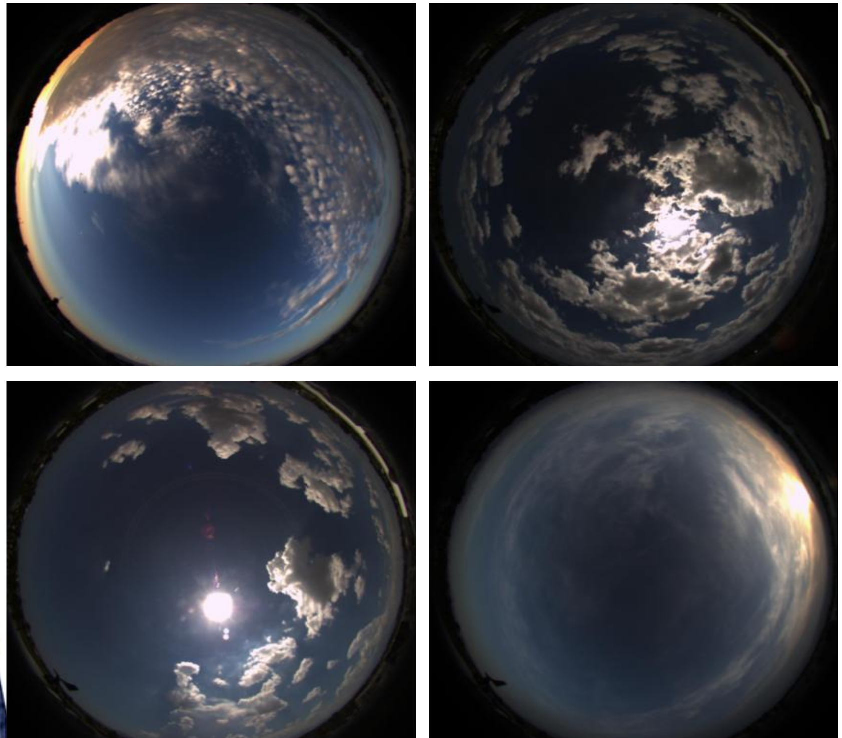
It is recommended to integrate such information into the plant control strategy in order to avoid over- or underestimation of the electricity generation.

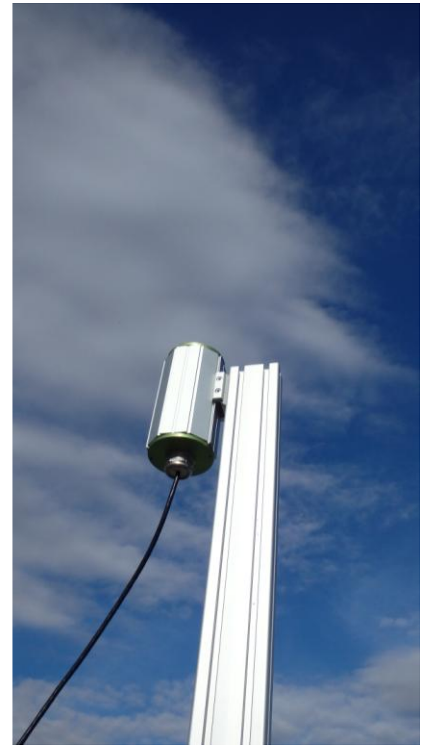


Summary

1. Context
2. PROMES Sky imager
    1. *Hardware*
    2. *Software*
    3. *Camera calibration*
    4. *Pixel angles*
3. Clear sky model
    1. *Clear-sky intensity distribution*
    2. *Performance analysis*
    3. *Clear-sky images*
4. Applications
    1. *Clear-sky coefficients*
    2. *Sunshape*
    3. *Cloud detection*
    4. *DNI forecasting*
5. Conclusion & further work

Hardware

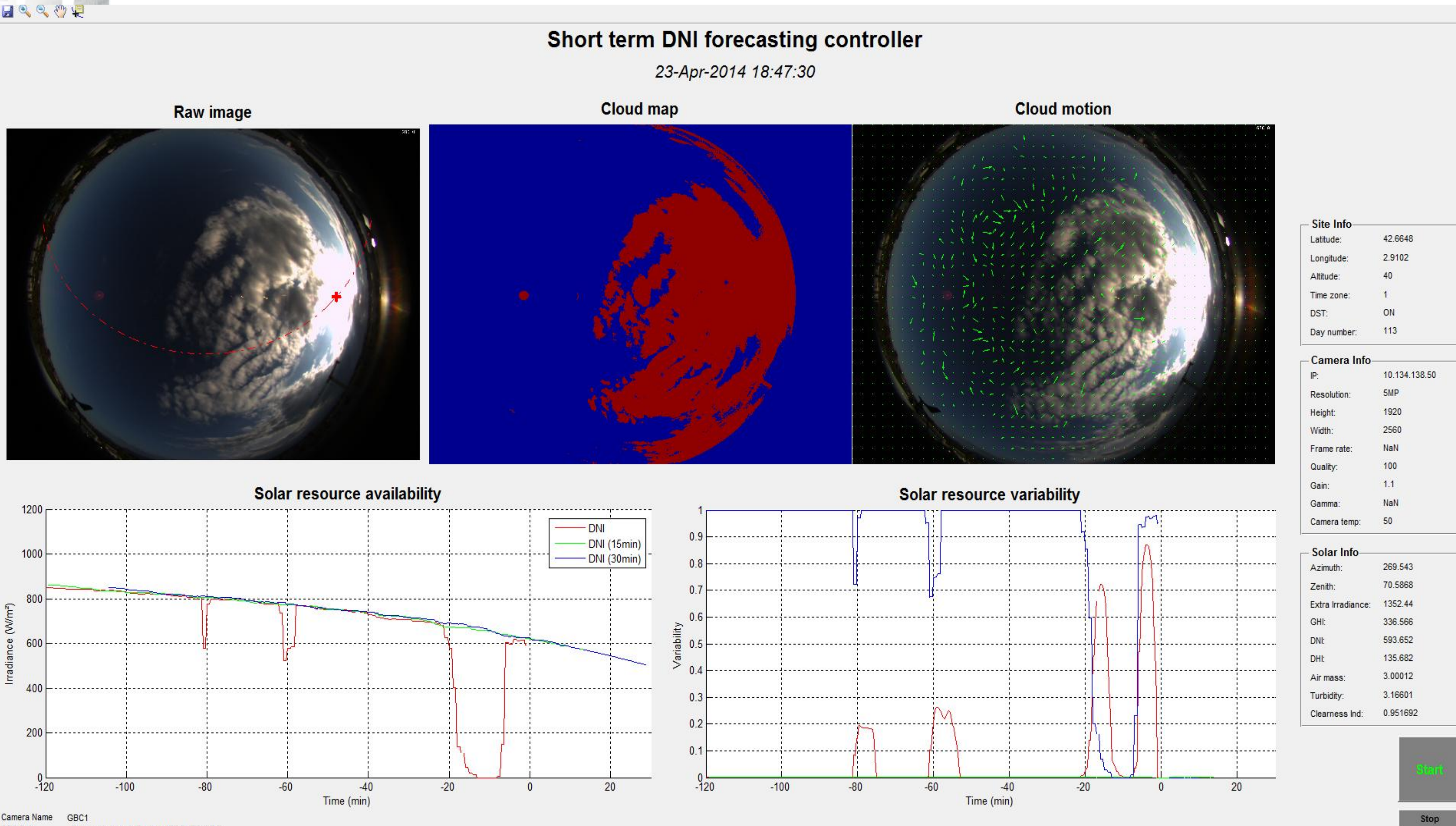




Sky imager	
Camera	IP 5481VSE-C from Ids-Imaging
Image sensor	*CMOS*
Resolution	*2560 x 1920 pixels*
Bit depth	*24 bit (8 bit per channel RGB)*
Interface	*RJ-45 GigE & PoE*
Lens	Fish-eye 185° from Fujifilm
Enclosure	Orca IP67 from AutoVimation

Data	
Image frequency	3 images/min
Format	JPEG
Images	≈ 480 000 images
Volume	≈ 7 Go/month
Site	
Latitude	≈ 42.6648° N
Longitude	≈ 2.91018° E

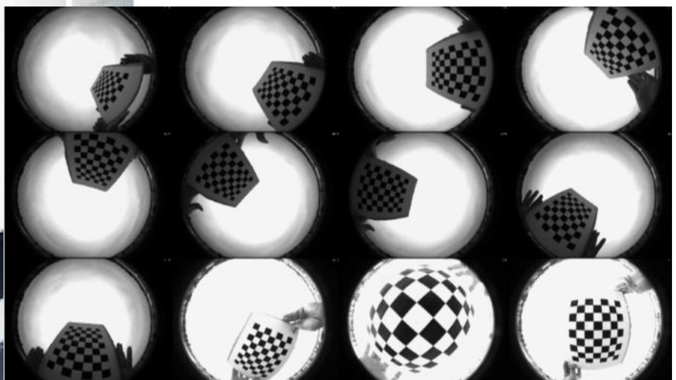
Software

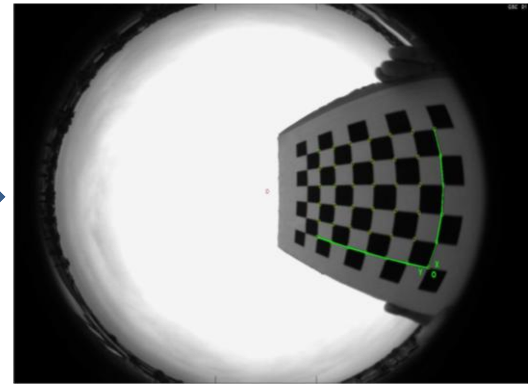


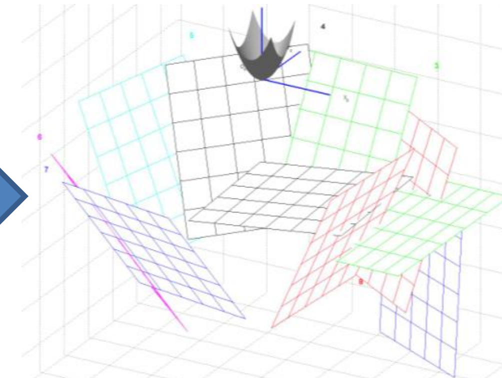
The PROMES sky imager is provided with a graphical user interface. This interface can display the last sky image, the sun position, the cloud position and cloud motion maps, solar information (azimuth, zenith, DNI, air mass) and beam attenuation information (atmospheric turbidity and clear-sky index).

Camera calibration

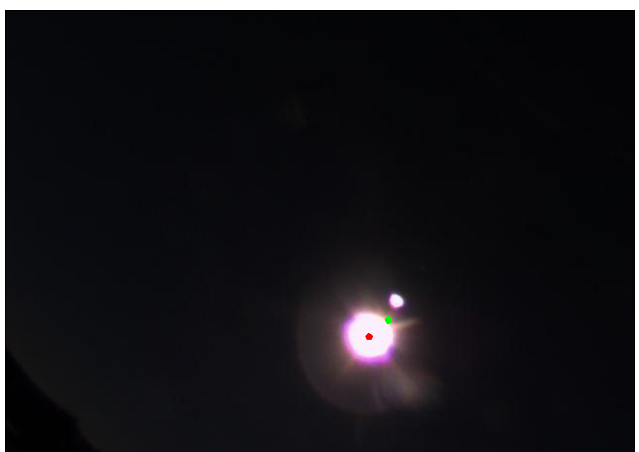
- A geometric angular calibration of the camera has been performed in order to get the relationship between a given pixel point and its projection onto the unit sphere. The OCamCalib[1], developed at the University of Zurich, has been used for that purpose.

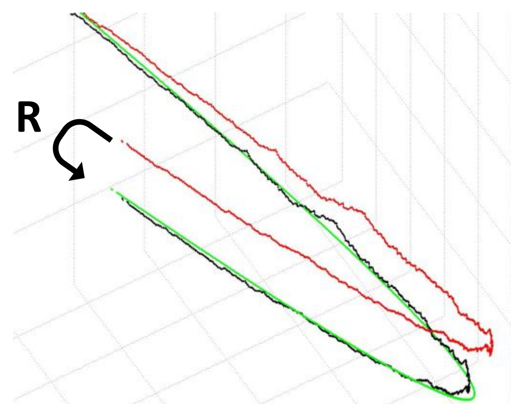






- In addition, the camera orientation is daily corrected comparing the real sun position (given by a solar position algorithm) with its position detected on the image.



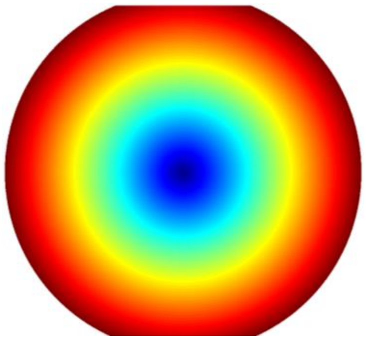


[1] ***Scaramuzza, D.***, *Martinelli, A. and Siegwart, R., (2006). "A Toolbox for Easy Calibrating Omnidirectional Cameras", Proceedings to IEEE International Conference on Intelligent Robots and Systems (IROS 2006), Beijing China, October 7-15, 2006.*

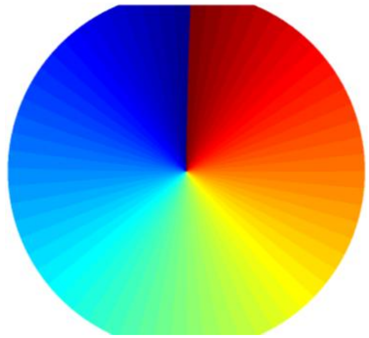
Pixel angles

- From these two calibrations, it is now possible to get the zenith and azimuth for every pixel on the image. Combined with the sun position, the Solar/Pixel Angle (SPA) can be calculated.

Pixel/Zenith Angle (PZA)



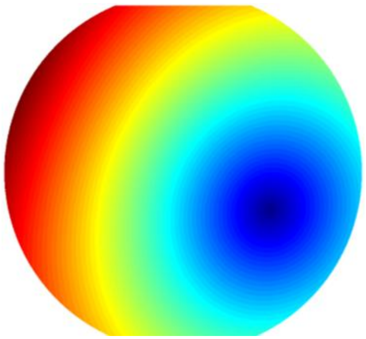
Pixel/Azimuth Angle (PAA)



Sun/Zenith Angle (SZA)

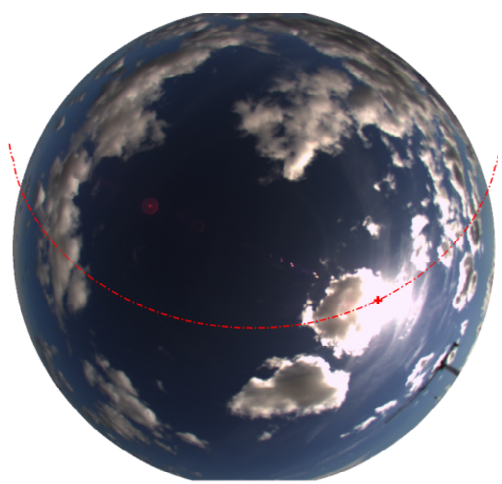
Sun/Azimuth Angle (SAA)

Solar/Pixel Angle (SPA)



$$\cos(SPA) = \cos(SZA) \times \cos(PZA) + \sin(SZA) \times \sin(PZA) \times \cos(SAA - PAA)$$

- The calibration allows the sun position to be compute on the image through the day. It results that sun position is known even during fully overcast days.



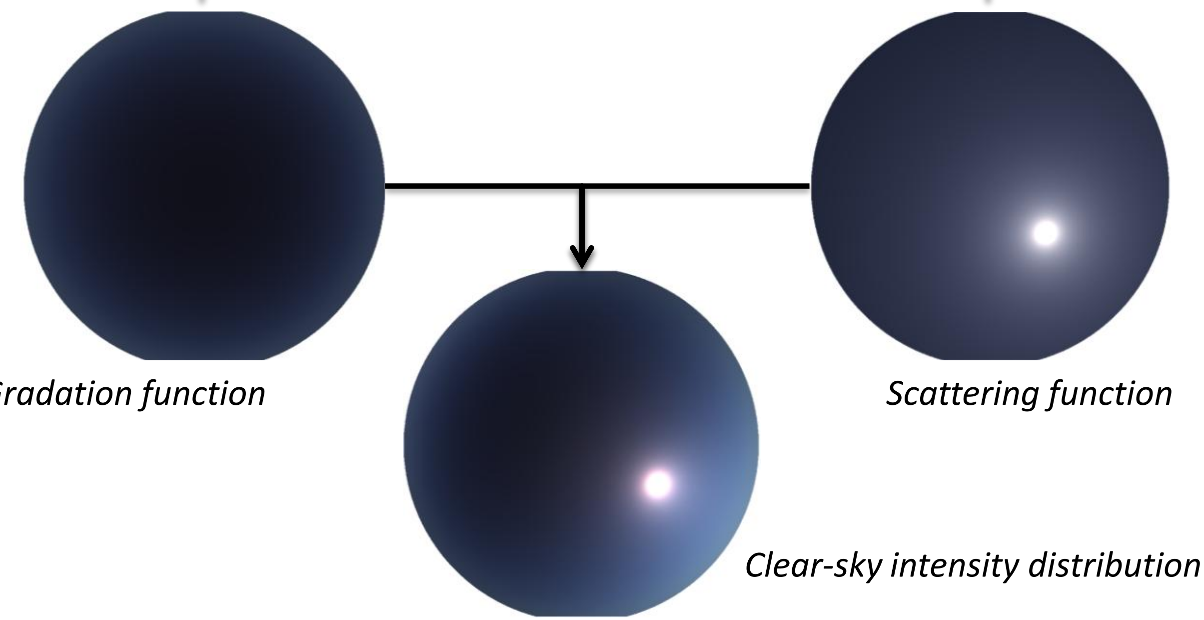
Summary

Clear-sky intensity distribution

- According to the CIE clear sky standard model[2], the clear sky luminance distribution can be modelled as a function of PZA and SPA. This function has been used to simulate both sky luminance and sky radiance distribution for various sky conditions.

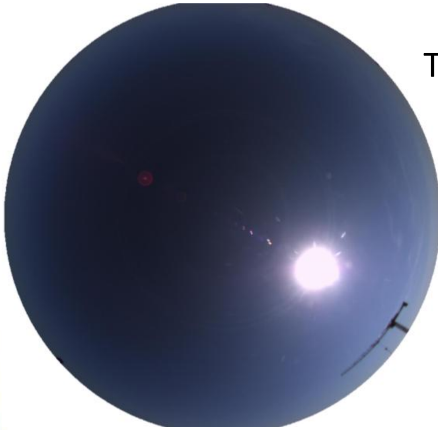
- A new equation, inspired by these works, has been developed to fit with the clear-sky pixels distribution provided by our sky imager.

$$I_p = a_1 \times \left[1 + a_2 . \exp\left(\frac{a_3}{\cos(PZA)} \right) \right] \times \left[a_4 + a_5 . SPA^{a_6} + a_7 . \cos(SPA)^2 \right]$$



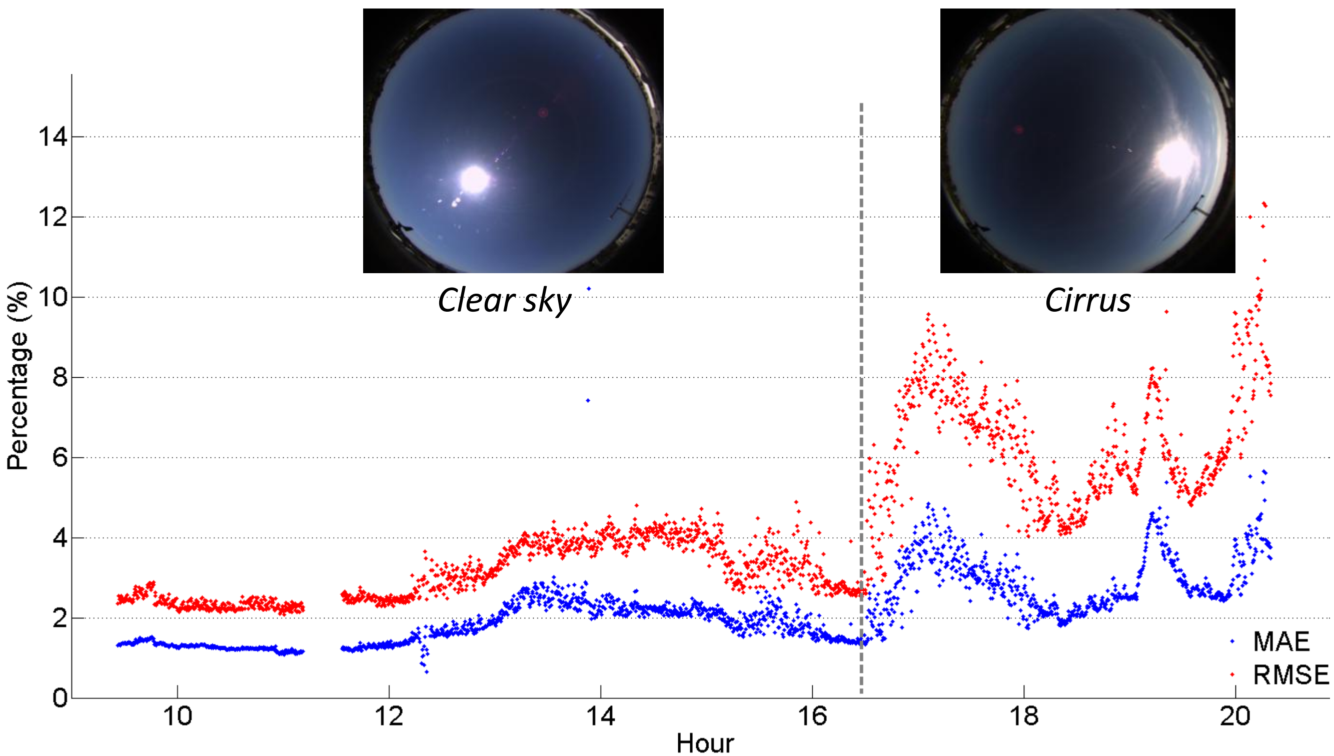
[2] **S. Darula, R. Kittler, and D. Road**, “CIE general sky standard defining luminance distributions,” 1967.

Performance analysis



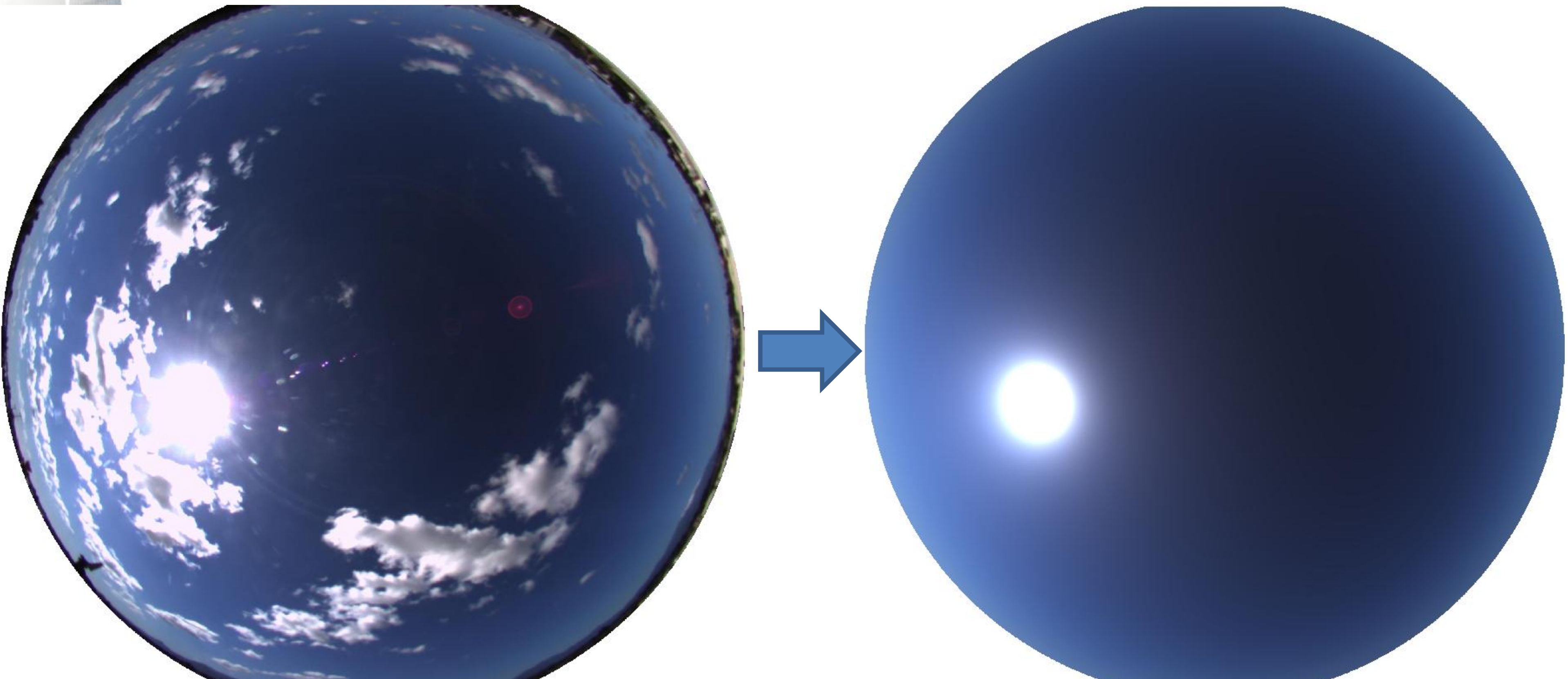
PZA and SPA are known thanks to the camera calibration. The clear-sky intensity distribution function is fitted to the sky images using a regression analysis based on a least square error minimization method.

MAE ≈ 1.5%
RMSE ≈ 2.9%



Clear-sky images

- Once the clear-sky intensity distribution function is well defined, it is possible to generate clear-sky images from various sky images (clear-sky & partially cloudy).



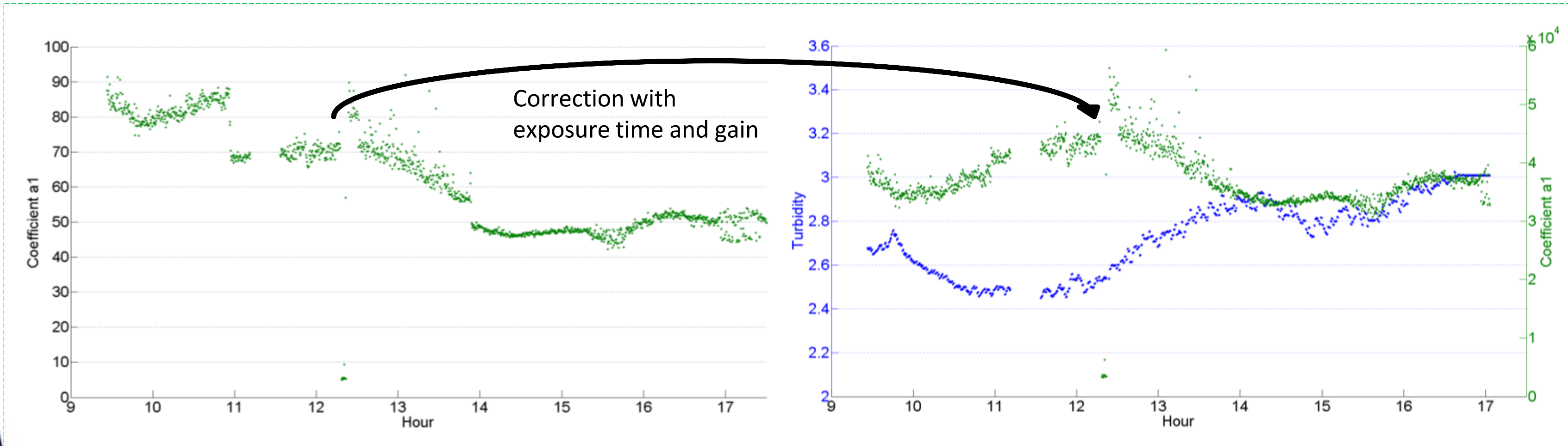
- The clear-sky image is highly helpful in order to optimize the cloud detection algorithm, by removing the clear-sky background from sky images.

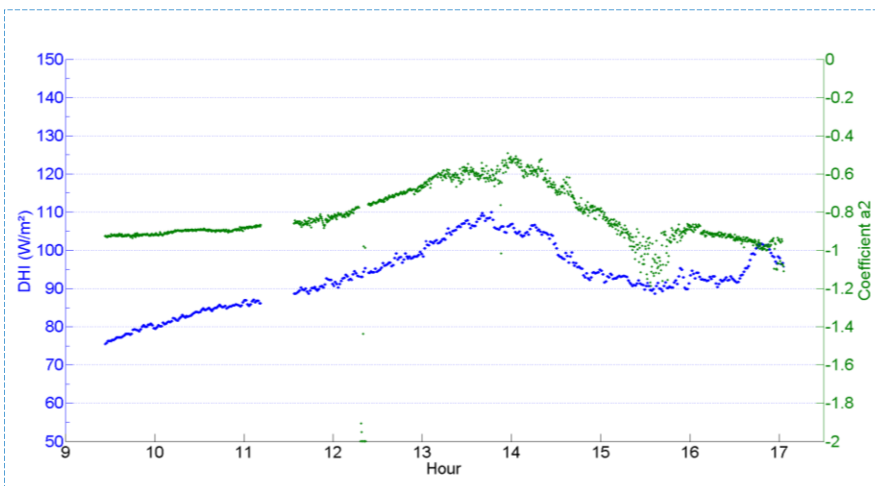
Summary

1. Context
2. PROMES Sky imager
    1. *Hardware*
    2. *Software*
    3. *Camera calibration*
    4. *Pixel angles*
3. Clear sky model
    1. *Clear-sky intensity distribution*
    2. *Performance analysis*
    3. *Clear-sky images*
4. Applications
    1. *Clear-sky coefficients*
    2. *Sunshape*
    3. *Cloud detection*
    4. *DNI forecasting*
5. Conclusion & further work

Clear-sky coefficients

$$I_p = \boxed{a_1} \times \left[1 + \boxed{a_2}.\exp\left(\frac{a_3}{\cos(PZA)} \right) \right] \times \left[a_4 + a_5.SPA^{a_6} + a_7.\cos(SPA)^2 \right]$$





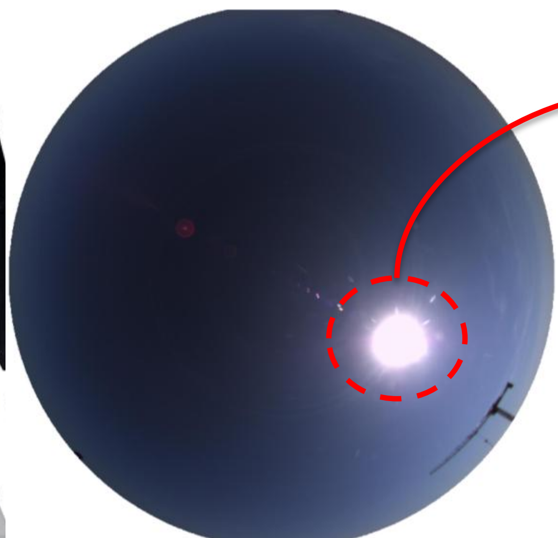
- The coefficients of the clear-sky intensity distribution are related to atmospheric properties.
- Coefficient a_1 seems dependent to the atmospheric turbidity. Coefficient a_2 seems related to the diffuse irradiance.
- Work is still ongoing to clearly connect these coefficients to atmosphere properties and solar resource.

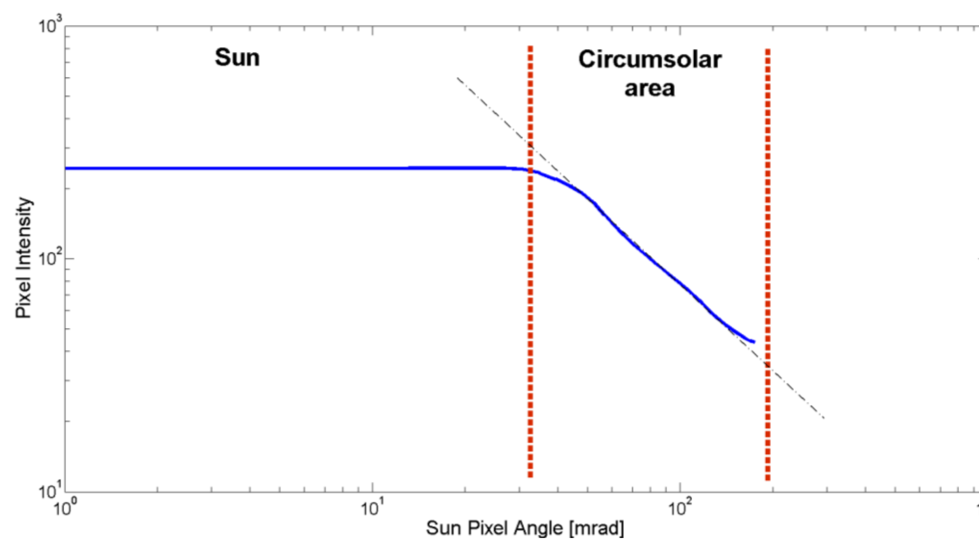
Sunshape

$$I_p = a_1 \times \left[1 + a_2 . \exp\left(\frac{a_3}{\cos(PZA)}\right)\right] \times \left[a_4 + \boxed{a_5 . SPA^{a_6}} + a_7 . \cos(SPA)^2\right]$$

- In the evaluation of the collector optical efficiency, the energy distribution of the sun has to be included because of the angular sensitivity of CSP technologies. Indeed, CSP systems collect only a small portion of the circumsolar region whereas it is nearly completely detected by pyrheliometers, producing an overestimation of the solar resource, resulting in an overvaluation of the power plant output.

- According to the Buie sunshape model, the sunshape profile is almost linear in log-log space in the circumsolar region of the sky. From the clear-sky intensity distribution function, it seems feasible to measure this energy distribution using a sky imager. It would be a cheap and robust way to get the sunshape profile.

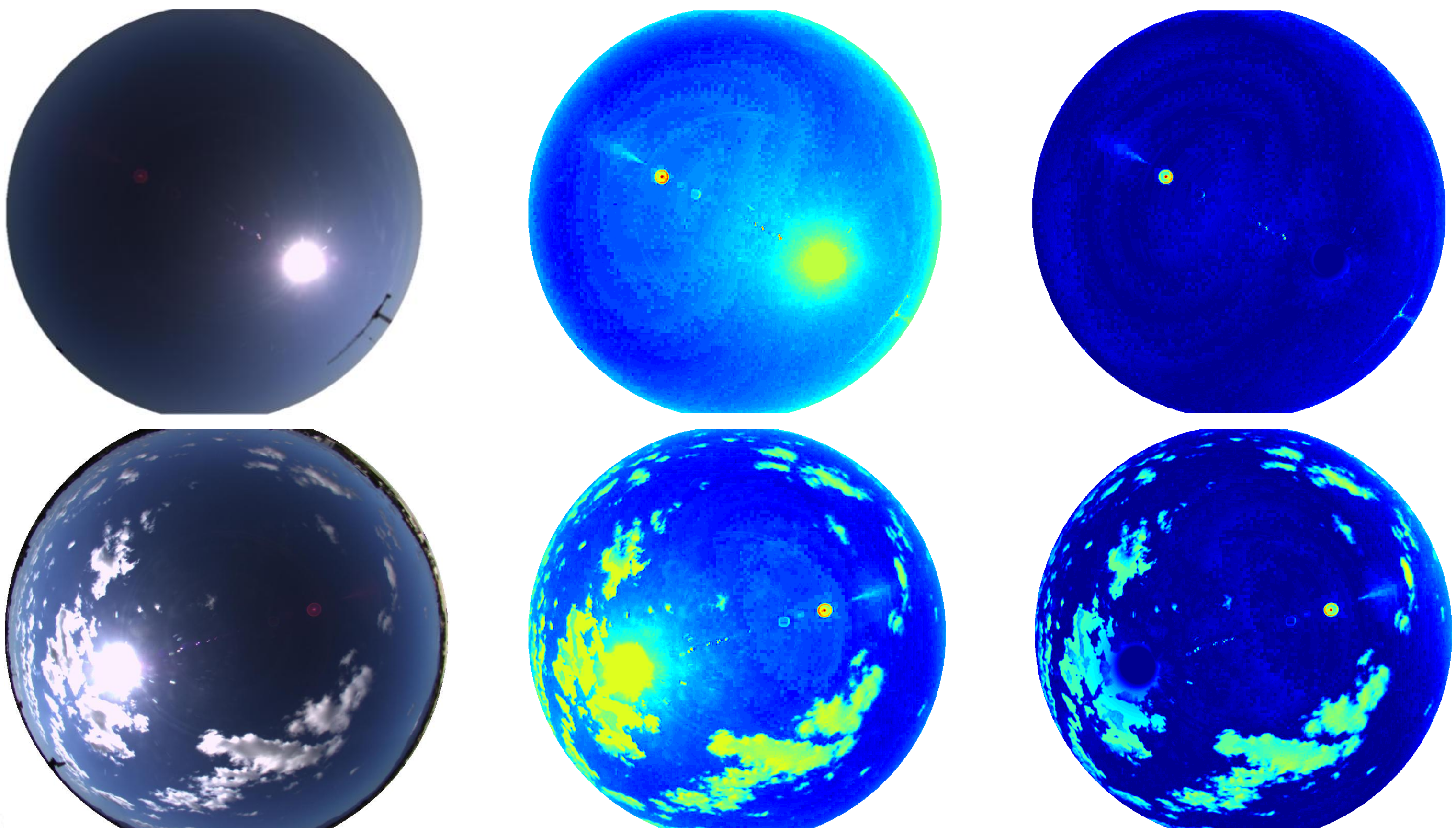




Cloud detection

- Pixels on sky images can be generally classified more easily with a threshold applied on features adapted to the sky characteristics rather than a threshold applied directly on the RGB components of the image.
- The Normalized Red/Blue Ration (NRBR) well represent the physical properties of the sky. Indeed, sky is blue due to Rayleigh scattering (high NRBR), whereas cloud scatters light homogeneously (low NRBR)

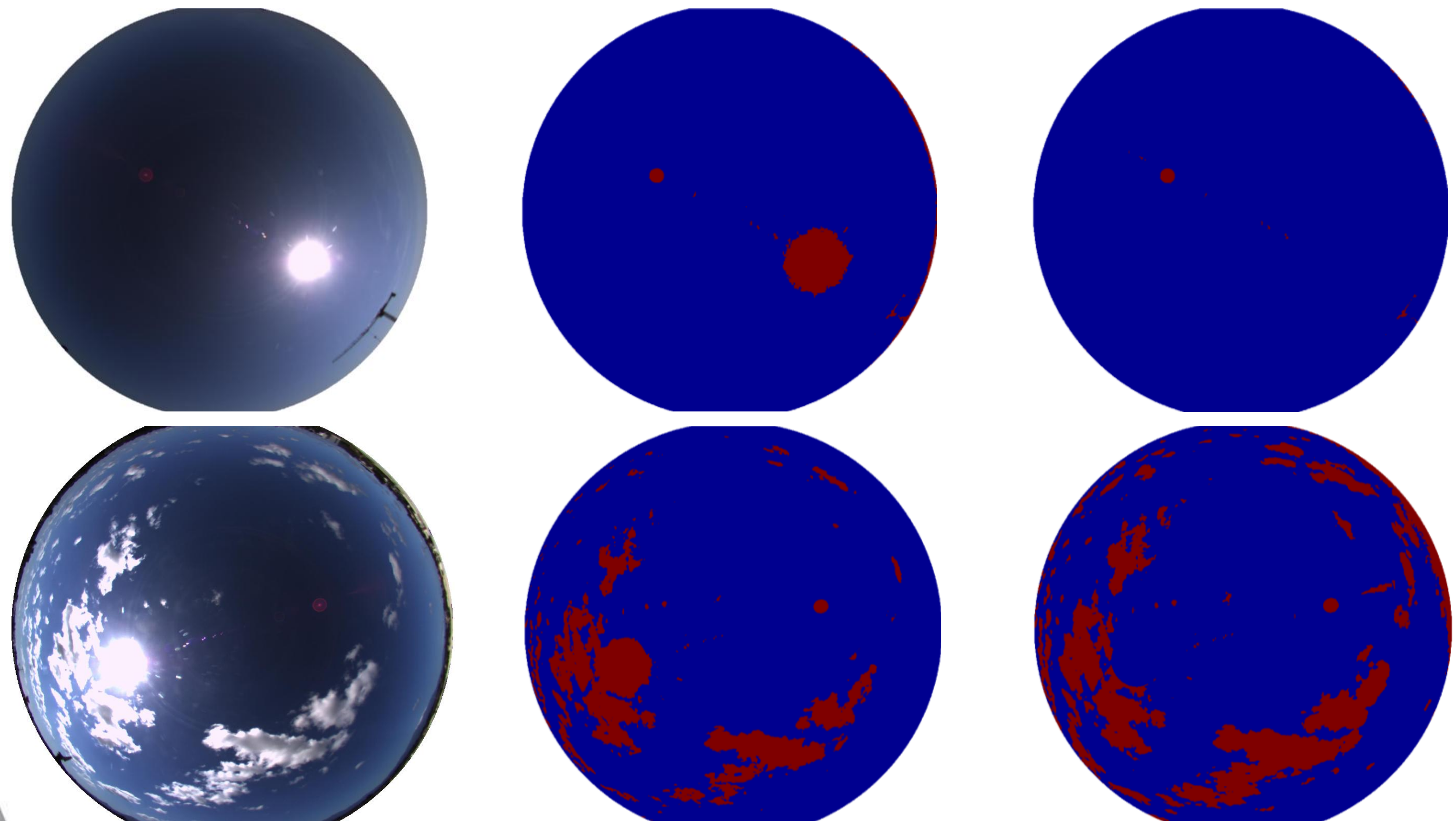
Raw image	NRBR image	NRBR corrected image
$\langle R, G, B \rangle$	$NRBR = \frac{R-B}{R+B}$	$\Delta_{NRBR} = \lvert NRBR - NRBR_{clear-sky} \rvert$



Cloud detection

- Pixel classification for cloud detection applications is mainly based on thresholding techniques due to their simplicity and the limited amount of computational time.
- In our application, a fixed threshold is applied on the NRBR feature to compute the cloud map.
- The cloud cover and cloud brokenness information can be derived from the cloud map.

Raw image	Cloud map	Corrected cloud map
$\langle R, G, B \rangle$	$Cloud \Leftrightarrow (NRBR < -0.1)$	$Cloud \Leftrightarrow (\Delta_{NRBR} < 0.15)$

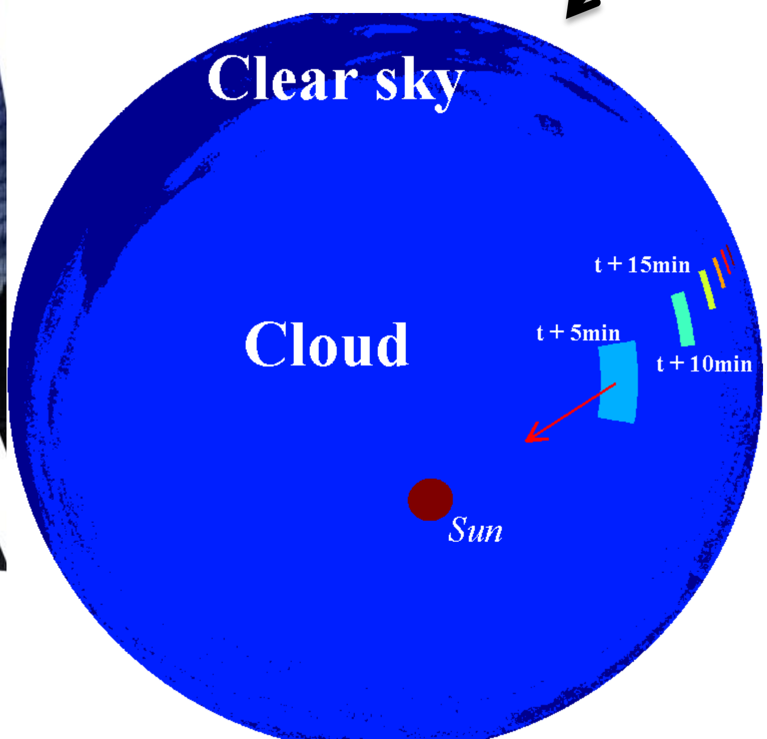


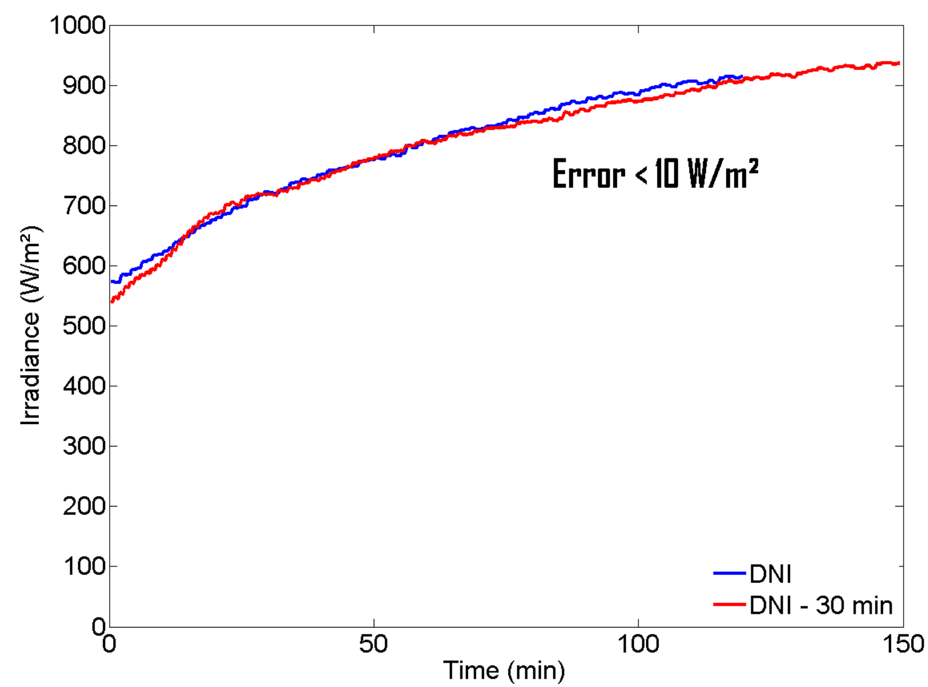
DNI forecasting

- Intra-Day Direct Normal Irradiance (DNI) forecast is also possible using sophisticated cloud detection and cloud motion algorithms. Indeed, the sky-imaging system can achieve DNI forecasts under various sky conditions at short-term horizon (5-30 minutes) and high spatial resolution (about 1km²).

- The DNI forecast can be separated into two main steps:

$$DNI = CI \times DNI_{clear-sky}$$





Conclusions

- Because sky imagers are able to provide an hemispherical view of the sky, they allow the measurement of many atmospheric properties which is highly valuable to better manage solar power plants.

- A sky imager is operational since June 2013 at the PROMES-CNRS laboratory. It provides 5 Mp sky images every 20 seconds.

- A calibration of the camera has been performed to estimate angles between zenith, sun and pixels.

- From this calibration and using sophisticated algorithm, it is possible to generate clear-sky images using a clear-sky intensity distribution function. The coefficients of this function are closely correlated to important parameters of the atmosphere, like the atmospheric turbidity.

- The clear-sky images are also useful for optimizing the cloud detection algorithm using a fixed thresholding technique. Such cloud map gives us valuable information about the variability of the solar resource in the coming minutes.

- Finally, DNI forecasting can also be performed with a sky imager and a clear-sky DNI forecasting algorithm. It would lead to 5-30 minutes forecast which could help the plant operator to adjust the strategy of the plant at real-time scale.

Further work

- Continue to highlight correlations between the 7 clear-sky coefficients and the different atmospheric properties (air mass, DNI, DHI, turbidity, ...).

- Continue to develop the DNI forecasting model based on the sky images analysis.

Atmospheric properties measurement using sky images

== CSPIMP project ==

Project leader:

GE O&G Thermodyn (France)

List of partners:

Acciona Energia (Spain)
CNRS Promes(France)
ARTS (France)

Subcontractors:

GE O&G Nuovo Pignone (Italy)

Rémi Chauvin
remi.chauvin@promes.cnrs.fr

Supervisor: Stéphane Grieu
Co-director: Stéphane Thil
Project engineer: Julien Nou
Project assistant: Adama Traoré

June 23rd , 2014