Sunshape analysis and atmospheric influences

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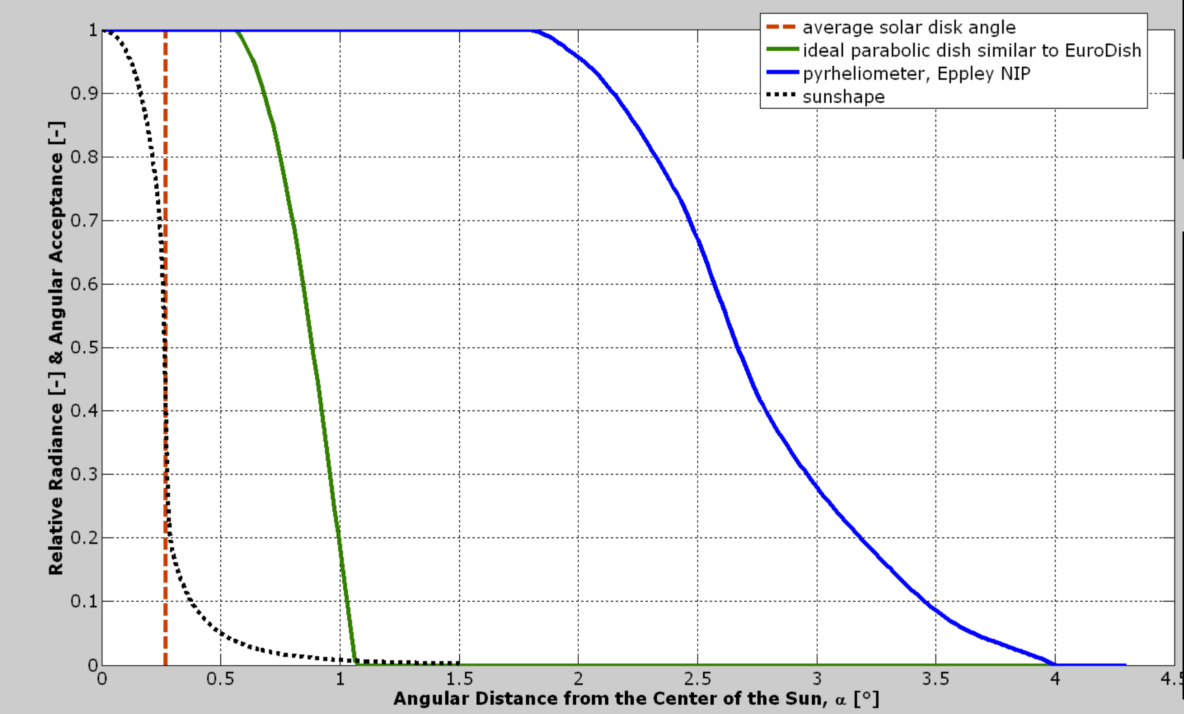
Overview

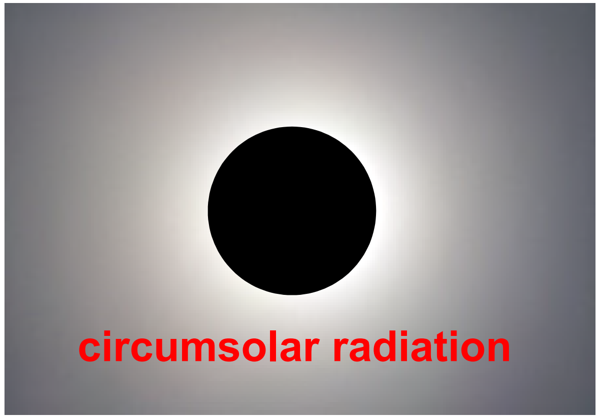
- Introduction and motivation
- Definitions
    - circumsolar radiation, sunshape
    - angular acceptance
    - optical performance
- Options to include the sunshape in CST efficiency calculation
- Exemplary results
- Sunshape measurements before Sfera project
- Currently used measurement systems for circumsolar radiation
    - reference measurement system
    - Black Photon Instruments System
    - RSI based system
- Modeled CSR using ground measurements
- CSR from satellite data

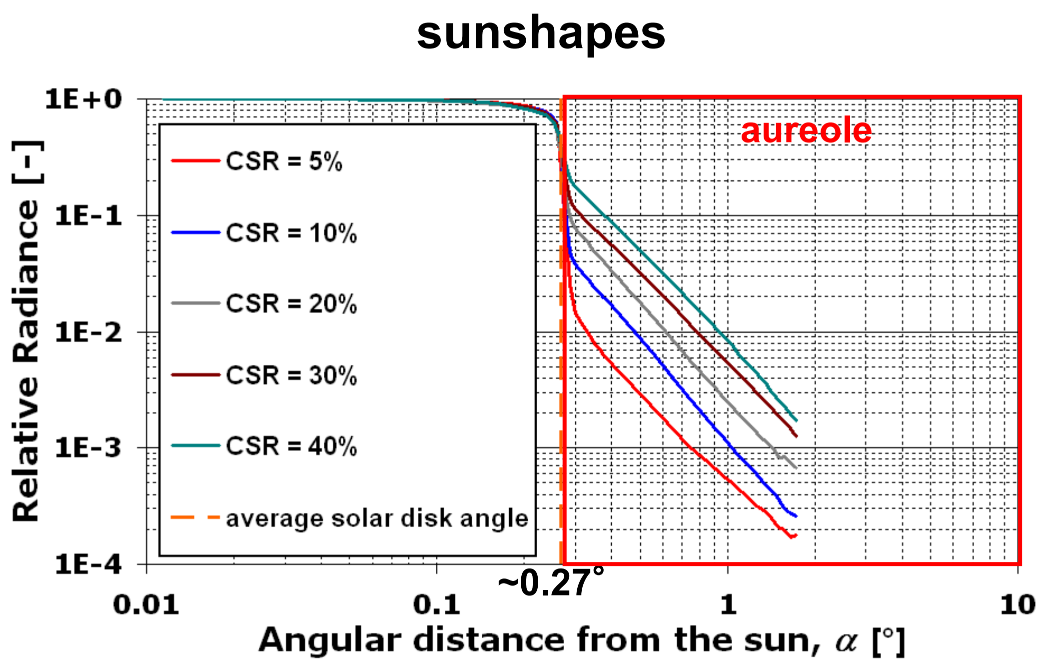
Motivation

- Angular sensitivity of different CSP technologies and irradiation sensors do not coincide …
- … nor is the luminosity of the sun and its environmental region always equal.



Circumsolar radiation





CSR = **C**ircum**S**olar-**R**atio

$$= \frac{\text{normal irradiance from } \textbf{aureole}}{\text{normal irradiance from } \textbf{disk} \text{ \& } \textbf{aureole}}$$

The sunshape varies strongly with time and climate:
→ Information required for CSP plants

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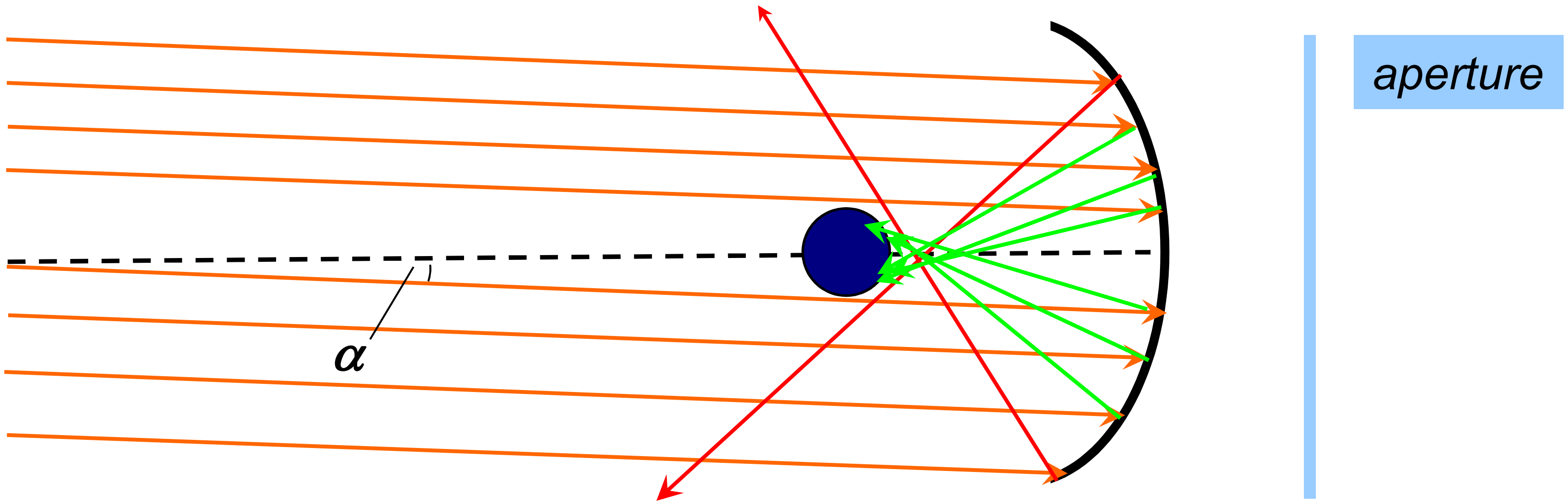
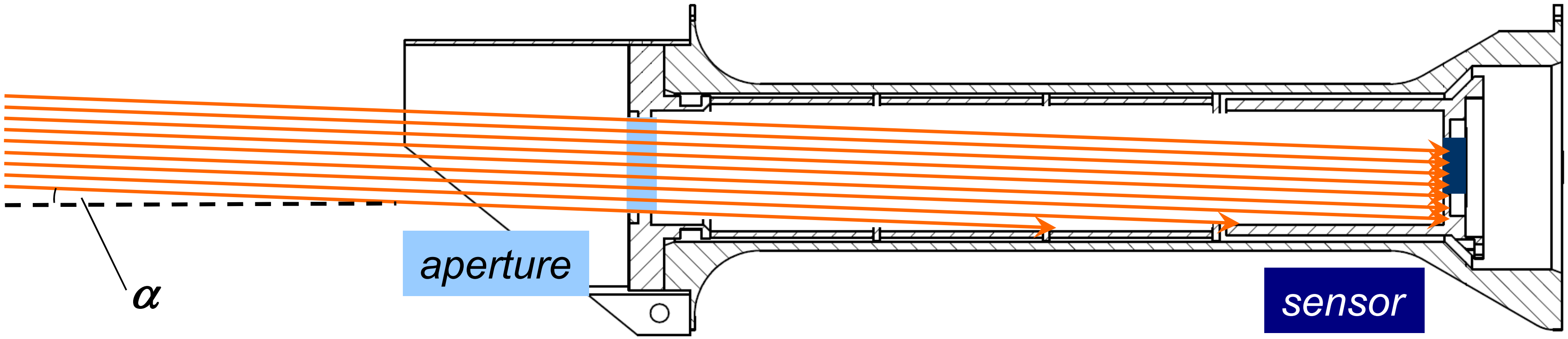
Acceptance function



- Angular Acceptance Function (α)

$$= \frac{\text{“number” of rays } (\alpha) \text{ which } \textbf{reach} \text{ the absorber}}{\text{“number” of } \textbf{all} \text{ rays } (\alpha)}$$

Response of pyrheliometer



- parallel rays incident on the aperture at an angle α
- Response of pyrheliometer given by
    - Angular Acceptance Function (α)

$$= \frac{\text{"number" of rays } (\alpha) \text{ which } \textbf{reach} \text{ the sensor}}{\text{"number" of } \textbf{all} \text{ rays } (\alpha)}$$

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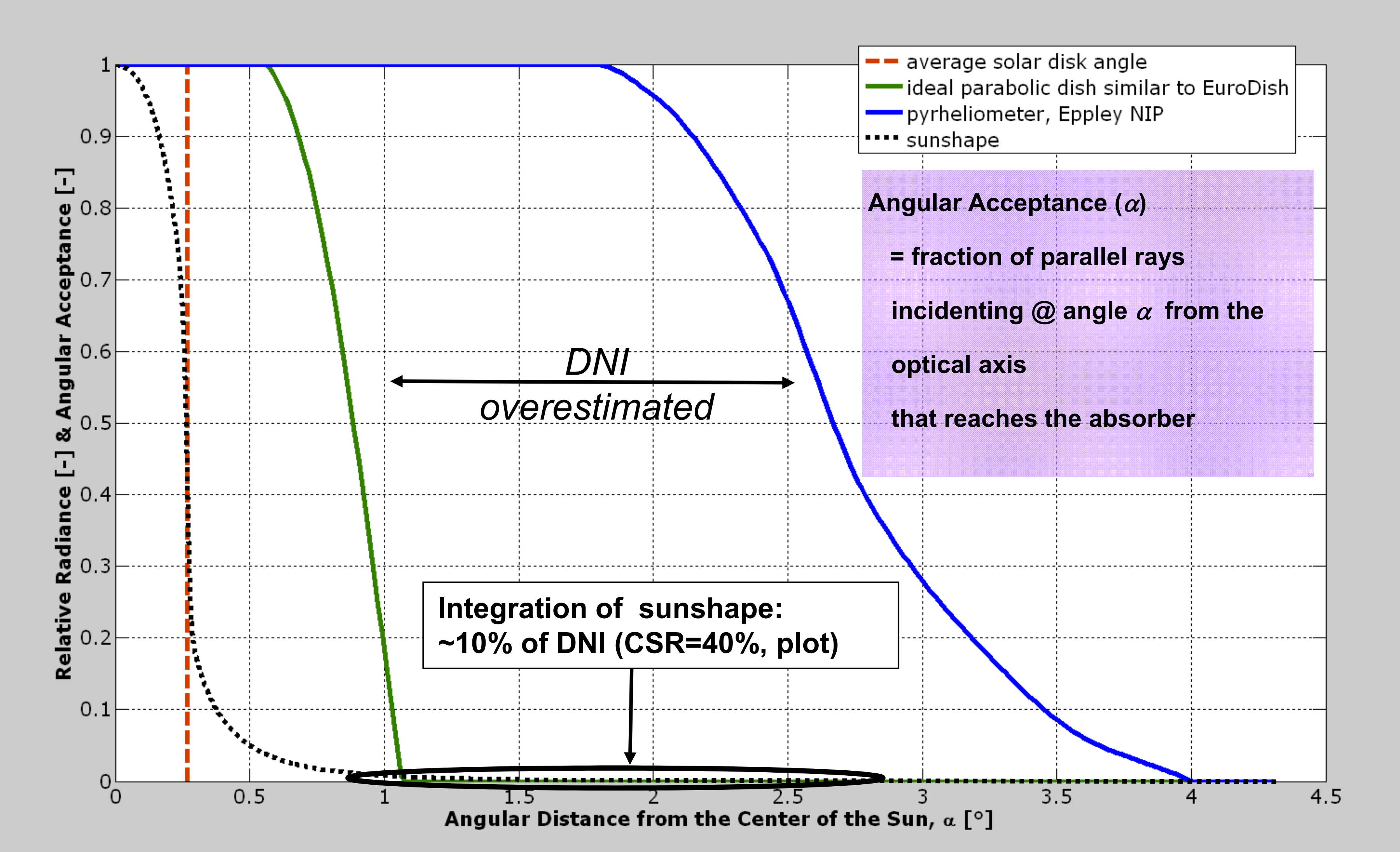
Angular Acceptance Functions

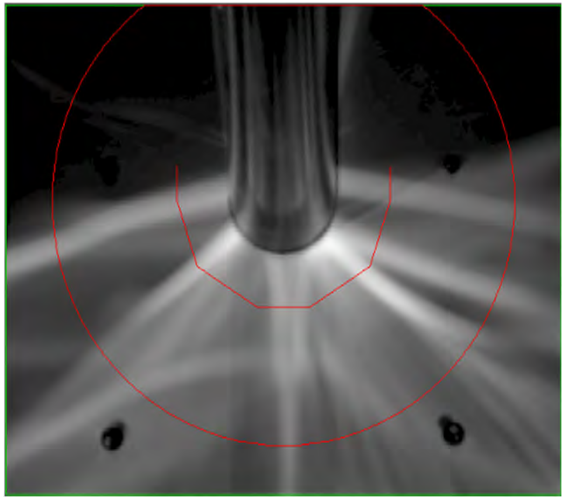


Definition: Intercept factor

- The intercept factor
  - is defined as the fraction of the rays incident on the aperture that are intercepted by the receiver

  - intercept factor = # accepted rays / # incident rays

- intercept factor refers to the question whether or not the rays hit the absorber
- Is proportional to the total optical efficiency of a concentrating collector



Options to include the sunshape in CST efficiency calculations

Option 1: Optical efficiency from experimental data

- Optical efficiency measured with test collectors
- Measurement series must include dependency on position of the sun relative to the collector
  - Reflectivity, transmittance, absorption & intercept factor change

  → **e.g. parabolic trough**: use Incident Angle Modifier (IAM) to describe dependency

$$\boxed{\eta_{opt}(\varphi) = \eta_{opt,0^\circ} \cdot IAM(\varphi)}$$

$\eta_{opt,0^\circ}$	optical efficiency (sun in zenith)
IAM	Incidence Angle Modifier
φ	incidence angle

Experiments only performed for clear days

⇒ **only valid for the sunshapes that were present during the measurement**

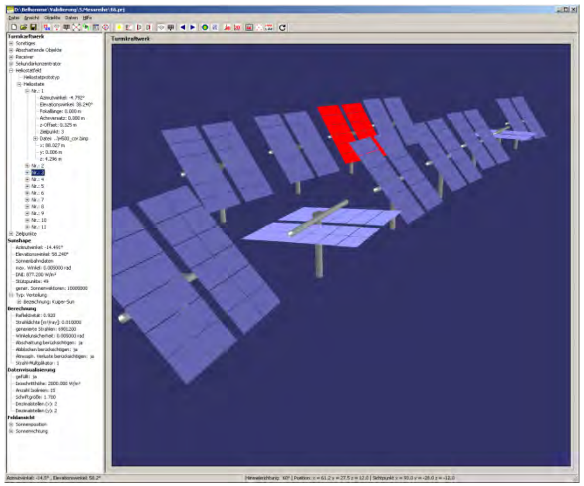
⇒ **efficiency should be changed for performance modeling corresponding to sunshape time series (usually not done)**

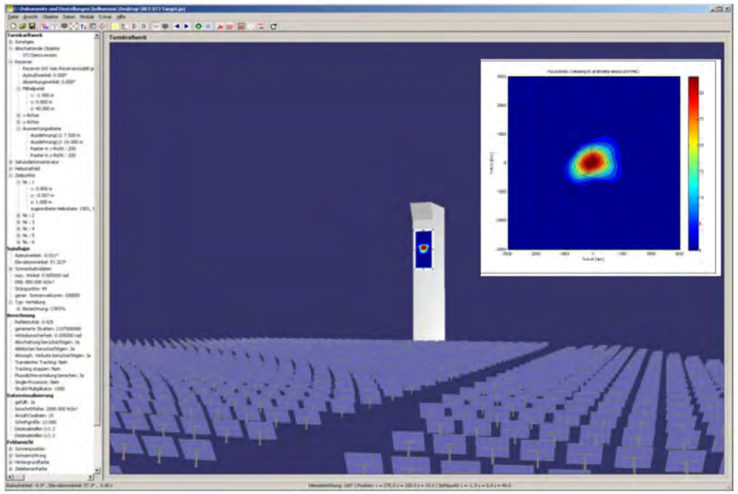
Option 2: Optical performance from raytracing

Principle:

- Real geometry of collector and receiver known (not just design geometry)
- Reflectivity, transmittance (air, entrance windows), absorptivity known
- Sunshape assumed
- Follow light rays on their way from the sun to the receiver using physics (basically law of reflection)

Usually performed only for constant “standard sunshape”





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Option 3: Rabl/Bendt's analytical model to describe the optical performance

- Analytical → fast
    - Performance prediction
- Concept:
    - Assume that the errors (mirror shape, tracking, etc.) just broaden the light source (sunshape) which is then focused on an absorber by a perfect collector.

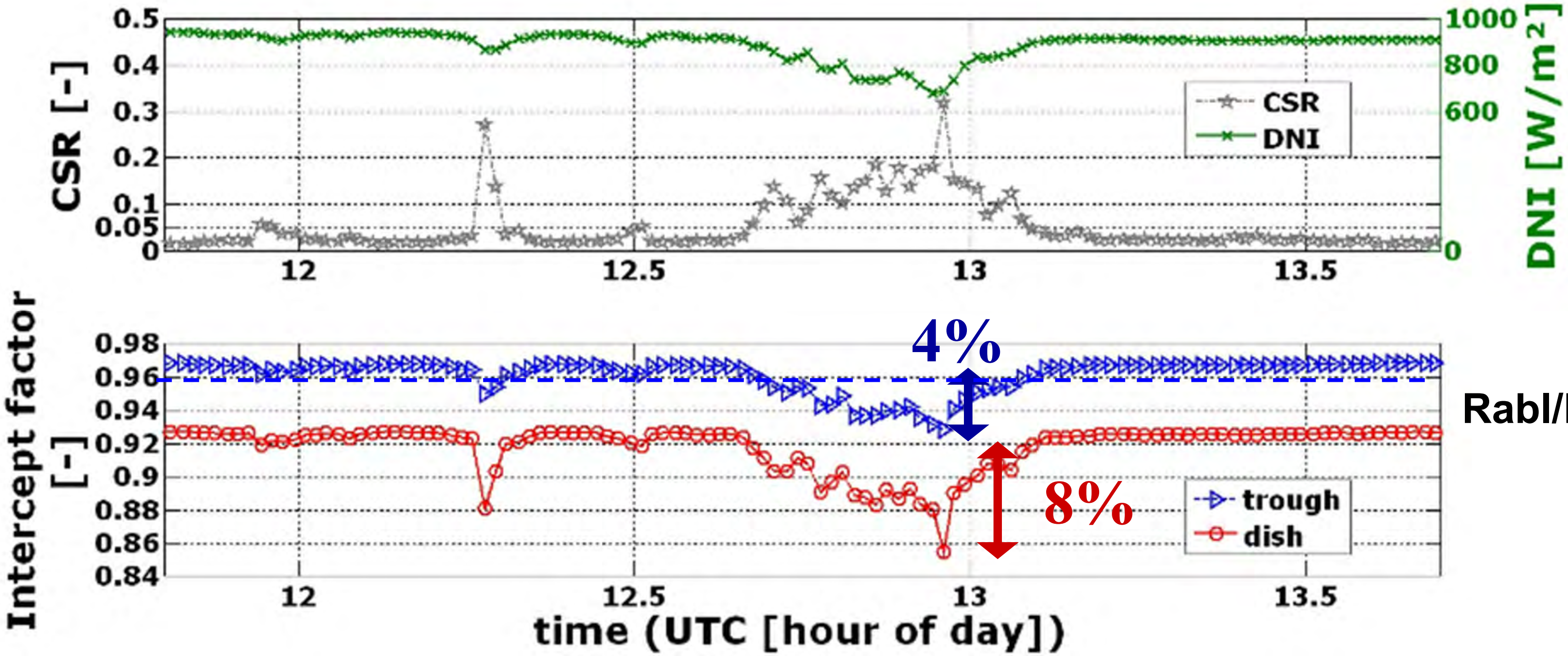
    → model for a perfect collector needed (Angular Acceptance Function)

    → model for the calculation of the broadened light source needed (Effective Source, convolve sunshape with Gaussian distributions representing the errors of the collector)

- Works for troughs and dishes
    - Similar concepts for towers (HFLCAL) and Fresnel collectors exist
        - More complicated and mathematically cumbersome because of shading and blocking

- **Usually only used with constant "standard sunshape"**

Tools for evaluation of impact on CSP – Rabl/Bendt & SPRAY

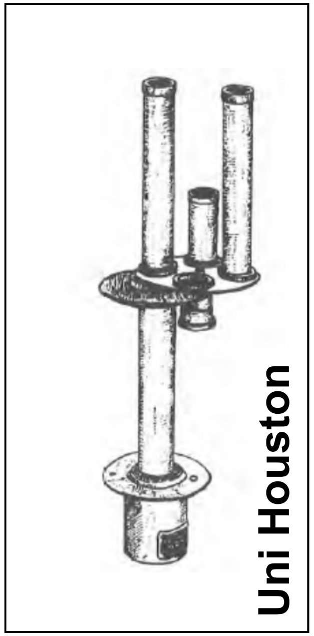


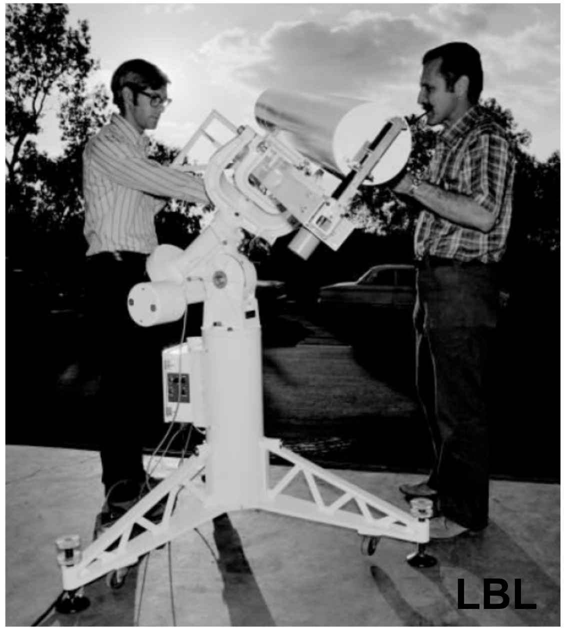
Rabl/Bendt

Sunshape measurements

Sunshape-Measurements before Sfera (2009)

- ~1750: only disk
- end of 19th century: only aureole
- Pyrheliometers with different apertures
    - e.g. University Houston 1975
- 1970s: Lawrence Berkeley Laboratory
    - scanning telescope, small aperture
- 1990s: PSI & DLR:
    - Sunshape camera (CCD)



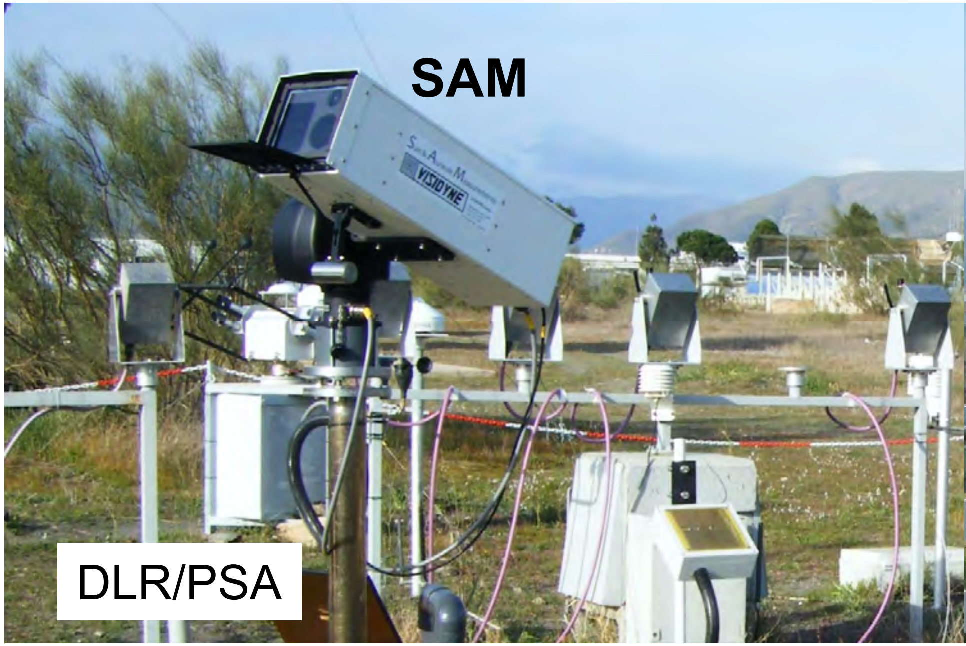


Typical sunshapes for USA and Europe have been derived, **but**:

- No data was available for regions that are now interesting for CSP
- Validation of sunshapes from radiative transfer models was not possible
    - requires new measurements with parallel additional measurements of the atmospheric conditions (clouds & aerosols)

SFERA - Sunshape Measurement System

- **SAM** (Sun & Aureole Measurement), **sun photometer** & **software**
  - **broadband** and **spectral** sunshape
  - **autonomous** measurements
  - additional determination of **aerosol & cloud properties**
  - instruments part of **Aeronet** & *SAMnet (Visidyne)*
    - data openly available on the internet
- **master-system** running at PSA
  - **2** replicas: CNRS/Odeillo, Masdar Institute



SFERA - Sunshape Measurement System

SAM (Sun & Aureole Measurement)

- narrow bandpass filter (670nm) necessary for

measurement of cloud properties

- data gap between information from 2 cameras

Post processing software

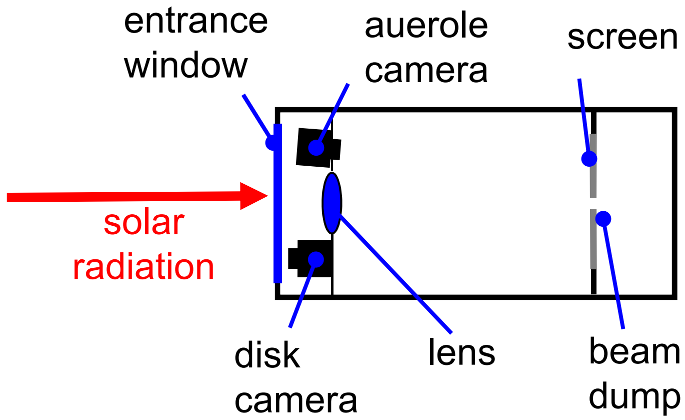
- gap fitting
- spectral correction
  - get **broadband & spectral sunshapes**

Sun photometer

- measurement of spectral DNI
  - 9 different wavelengths
- measurement of spectral sky radiance

→ **information on aerosols & solar spectrum**

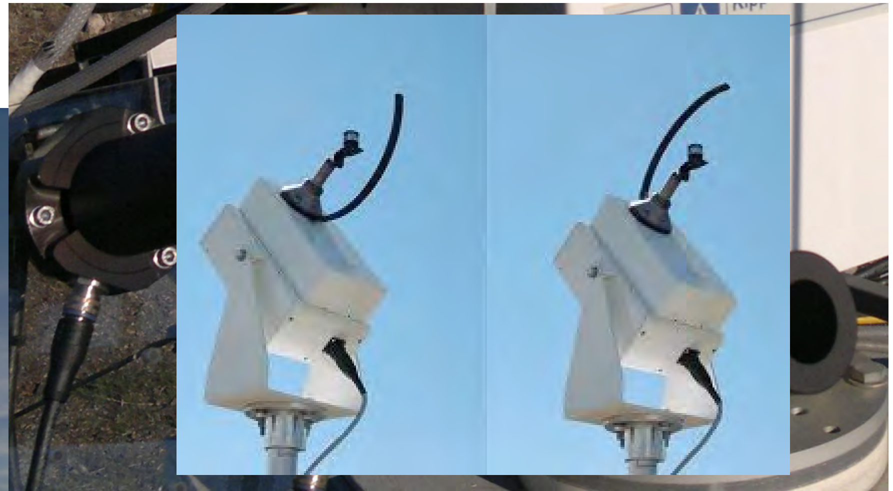
(using Gueymard's SMARTS software)



uncertainty ~30% lower than for previous DLR system (ΔCSR=0.02 for CSR = 0.2)

Wilbert et al. 2011 & 2013

Alternative measurement methods



- Depending on application less expensive and less maintenance intensive method required
  - 2 pyrheliometers with different fields of view
  - Rotating Shadowband Irradiometer, RSI

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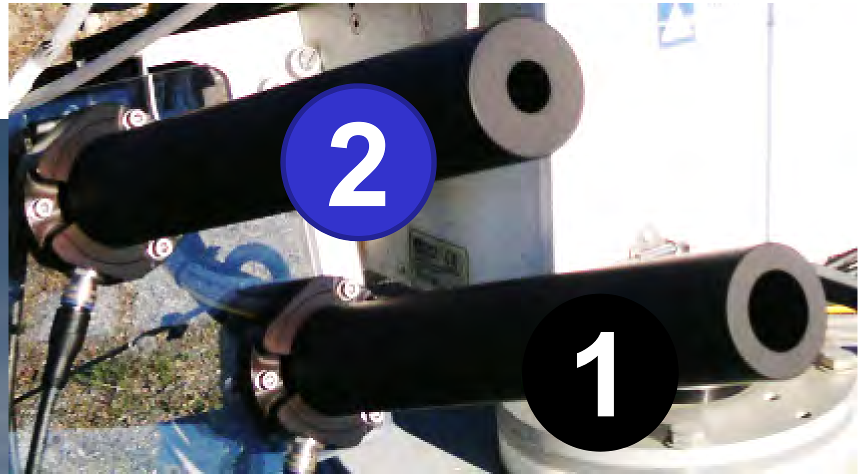
Wilbert et al. 2012 & 2013b

The Black Photon CSR 460 Sensor



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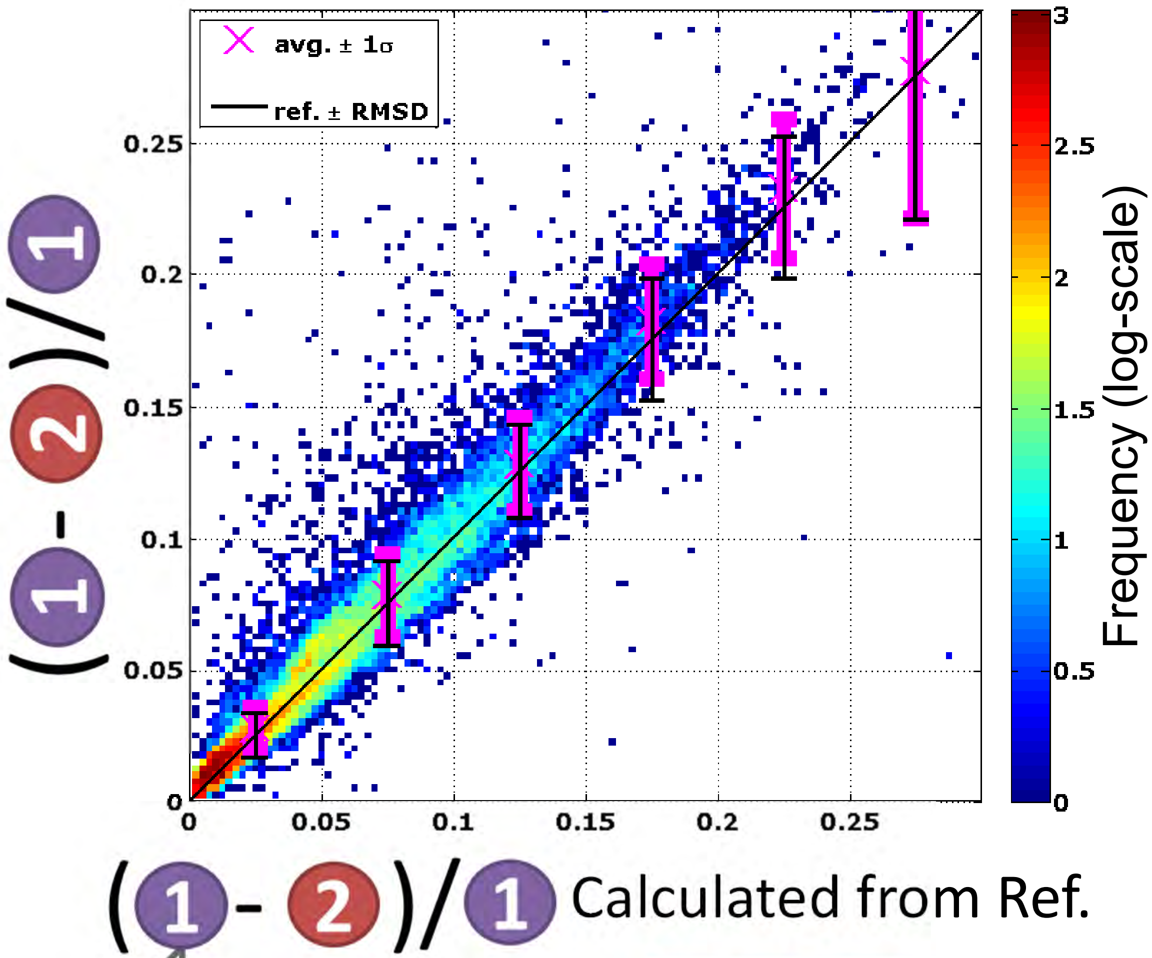
Results Step 1: Relative deviation of

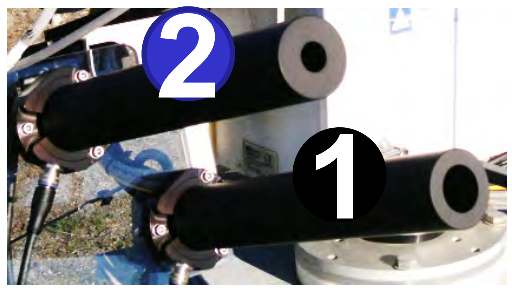
(1 - 2)/1



- Dataset:

  April 23rd 2012 –

  June 30th 2012



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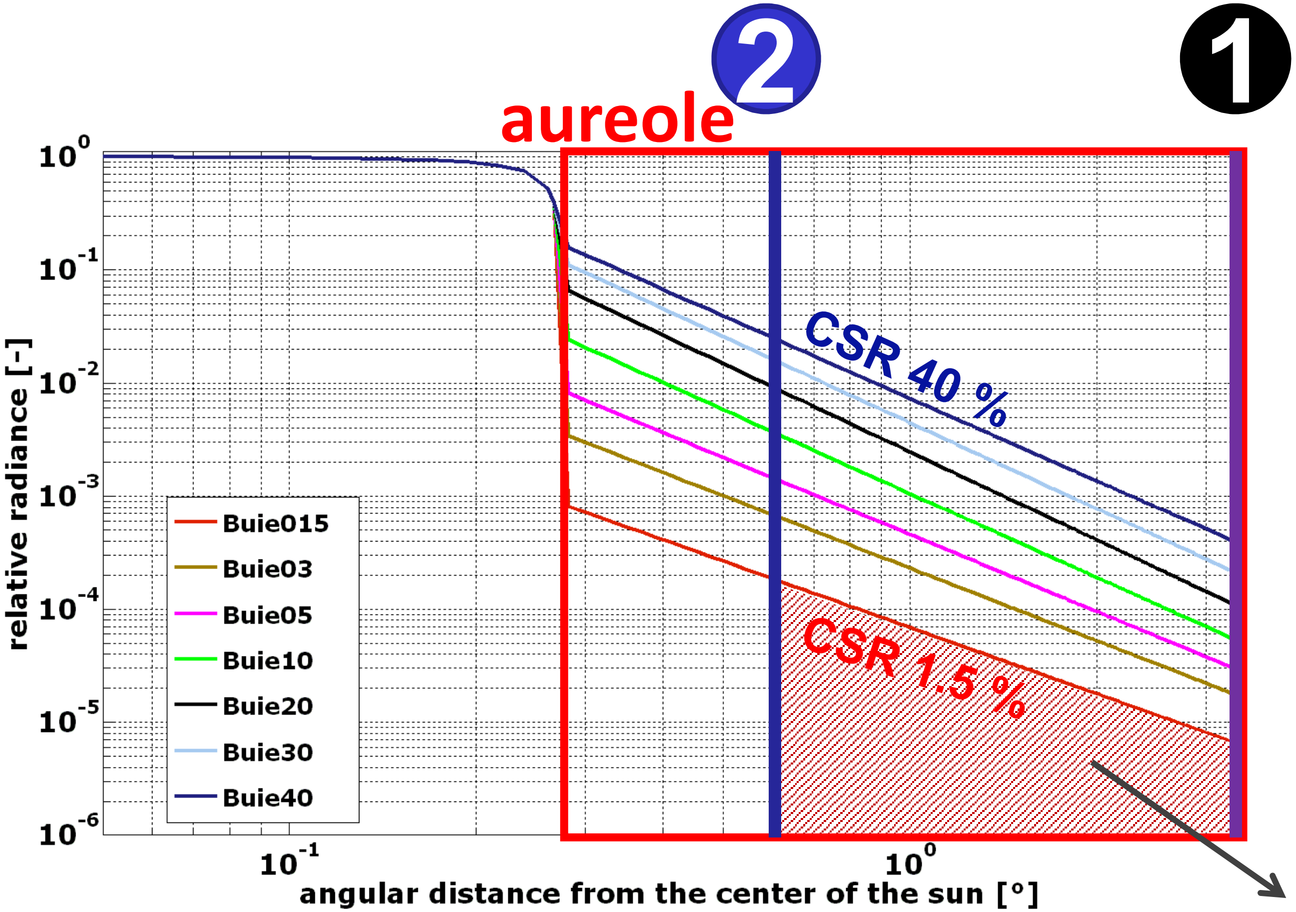
CSR determination - Principle



Buie's sunshape model: Standard sunshapes derived from 29411 measurements by Lawrence Berkeley Laboratories in 1970/80s at 11 locations in the U.S..

Calculation of look-up table

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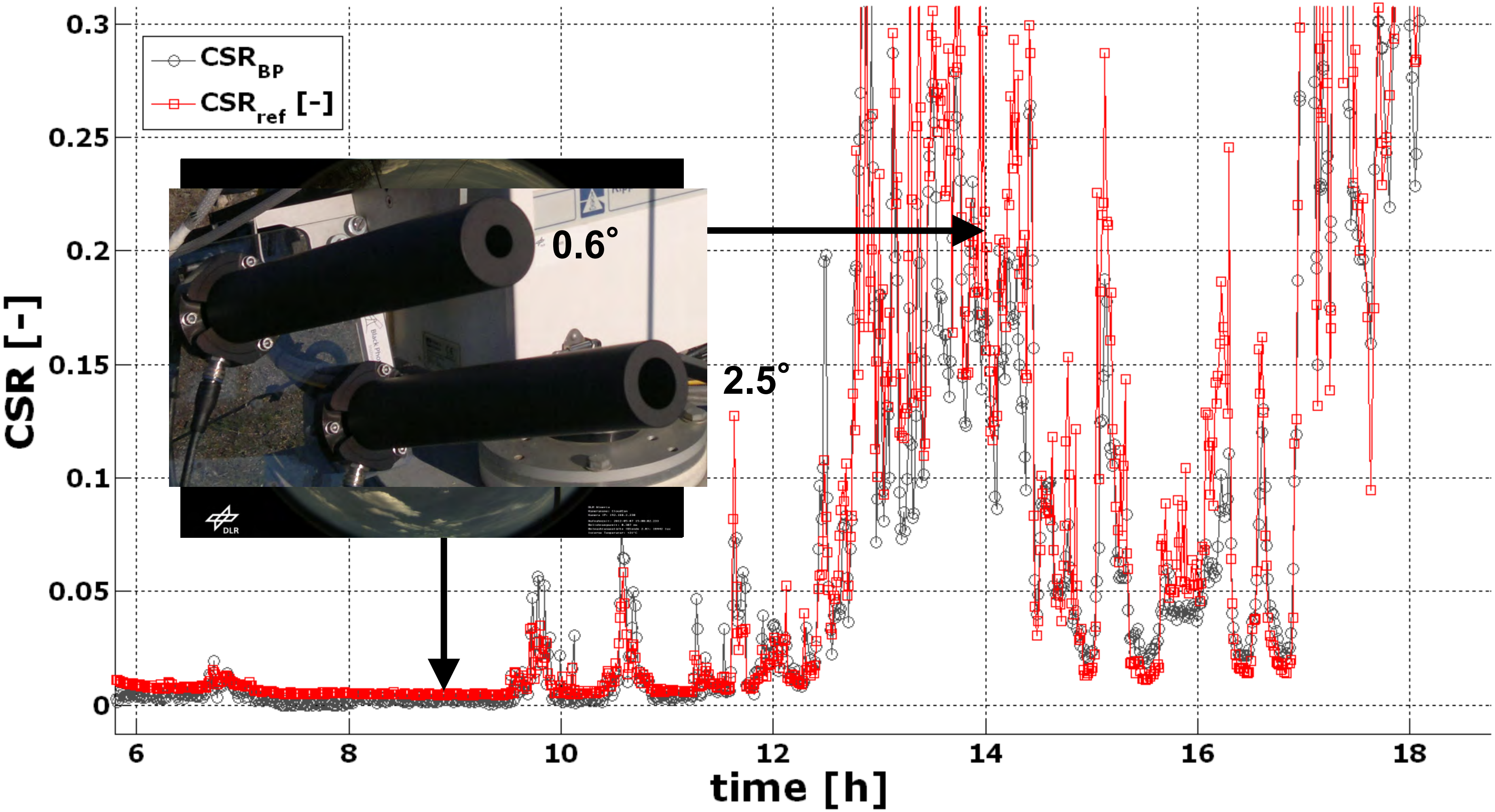
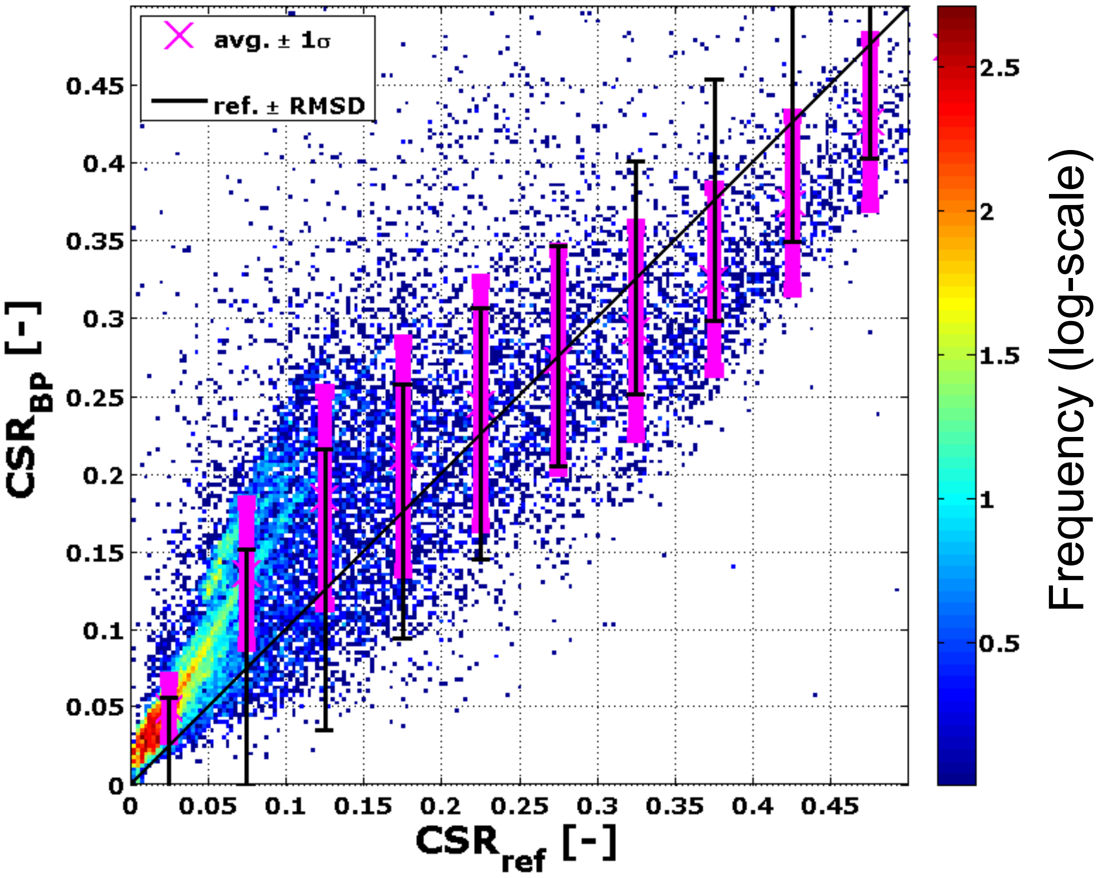
BPI CSR sensor – results (relative dev. translated in to CSR for standard sunshapes (Buie))



Wilbert et al. 2012

Comparison of Long Term CSR Measurements

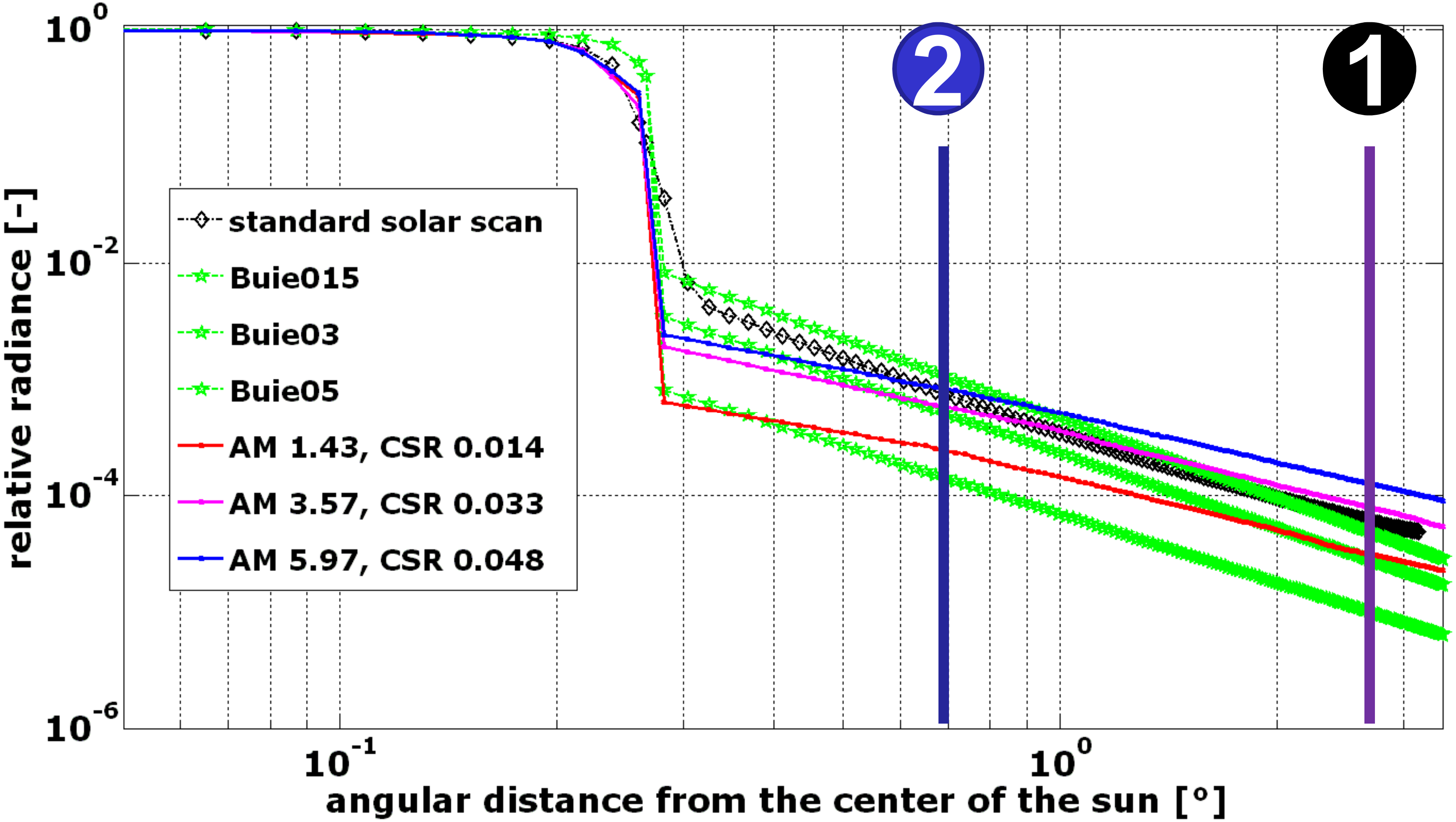


- Dataset:

  April 23rd 2012 –

  June 30th 2012

Comparison of Buie‘s Sunshape Model to Measured Sunshapes



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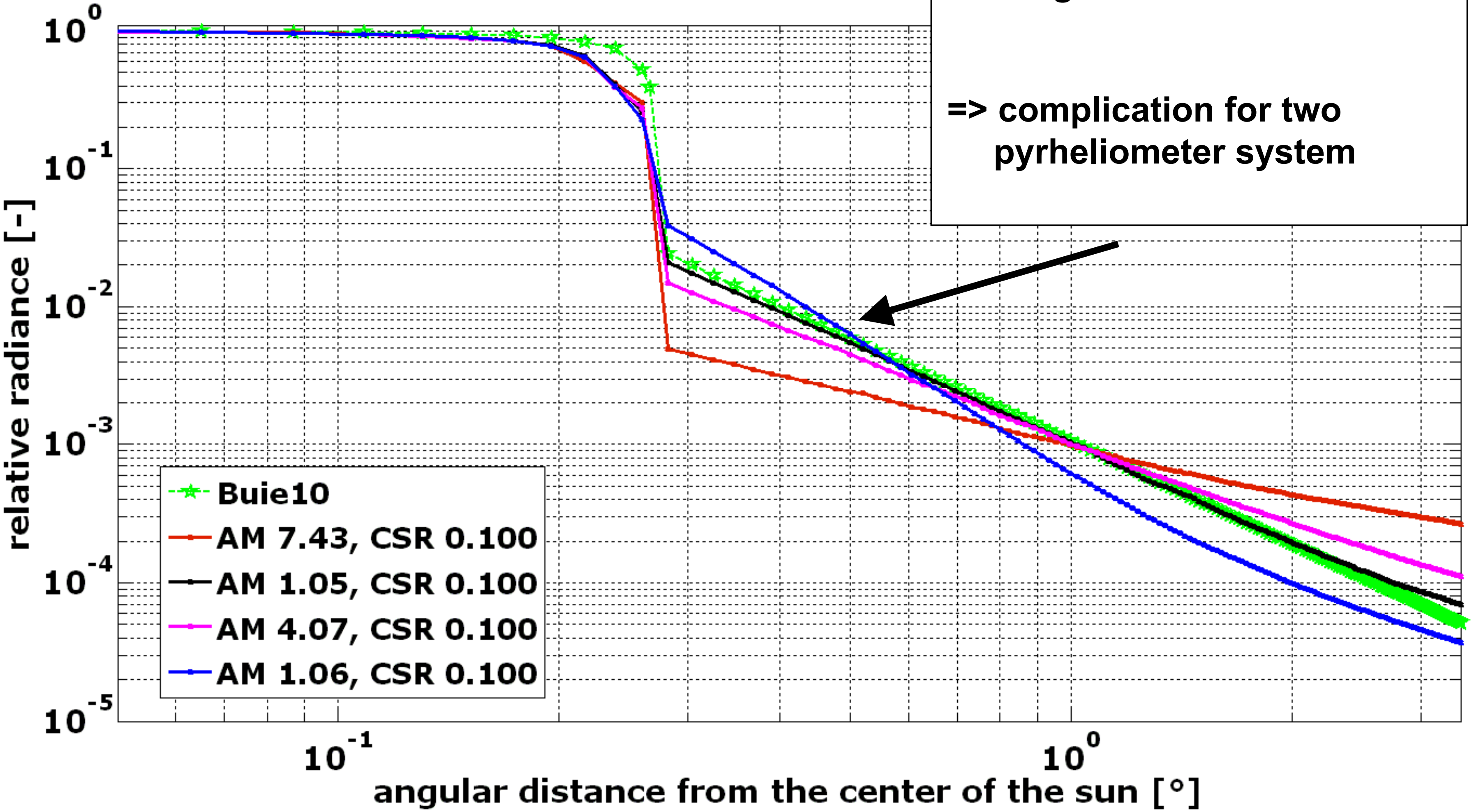
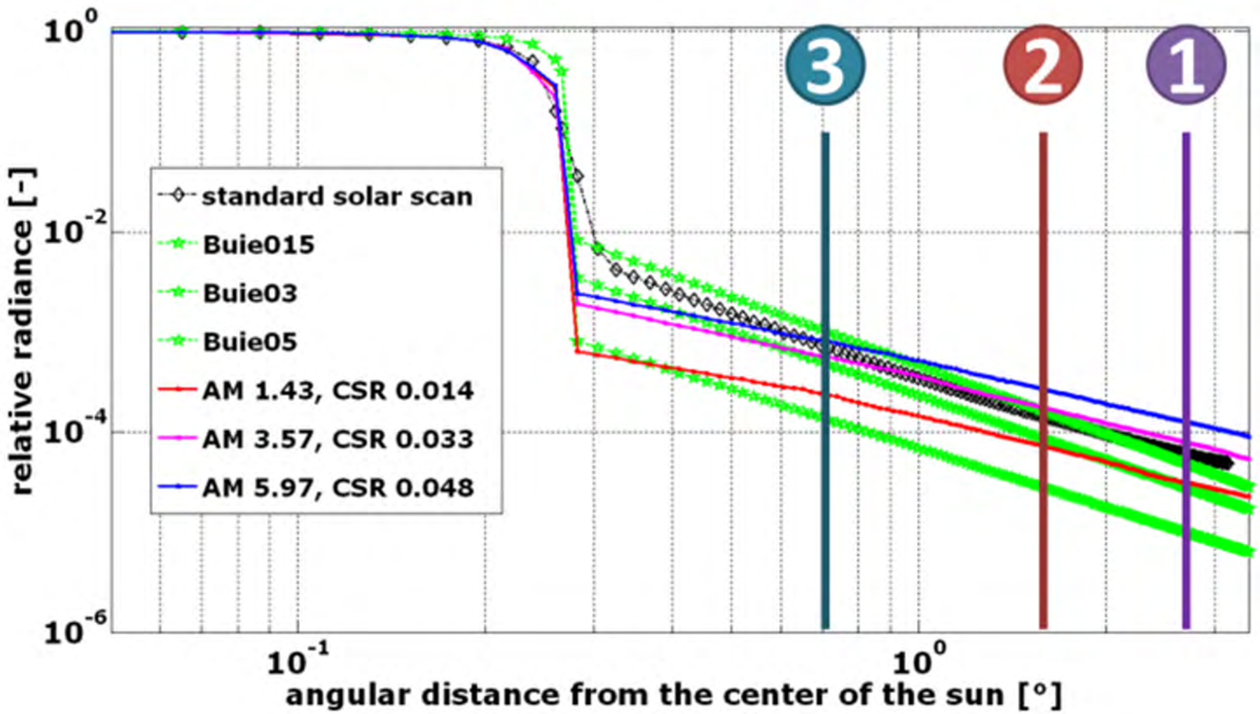
Deviations between CSR_{ref} and CSR_{BP} occur because the sunshape can be different although the CSR is the same

=> complication for two pyrheliometer system

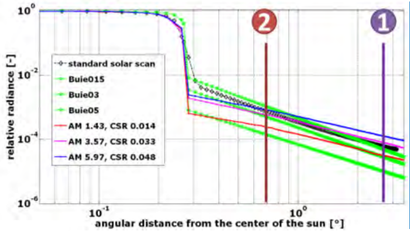


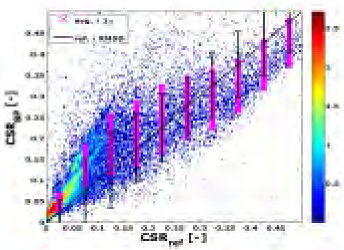
Future Development for pyrheliometer method

-Add 3rd detector to determine steepness of CSR sunhape
-more sophisticated sunshape model (CSR + AM + cloud presence from DNI => sunshape with correct slope)



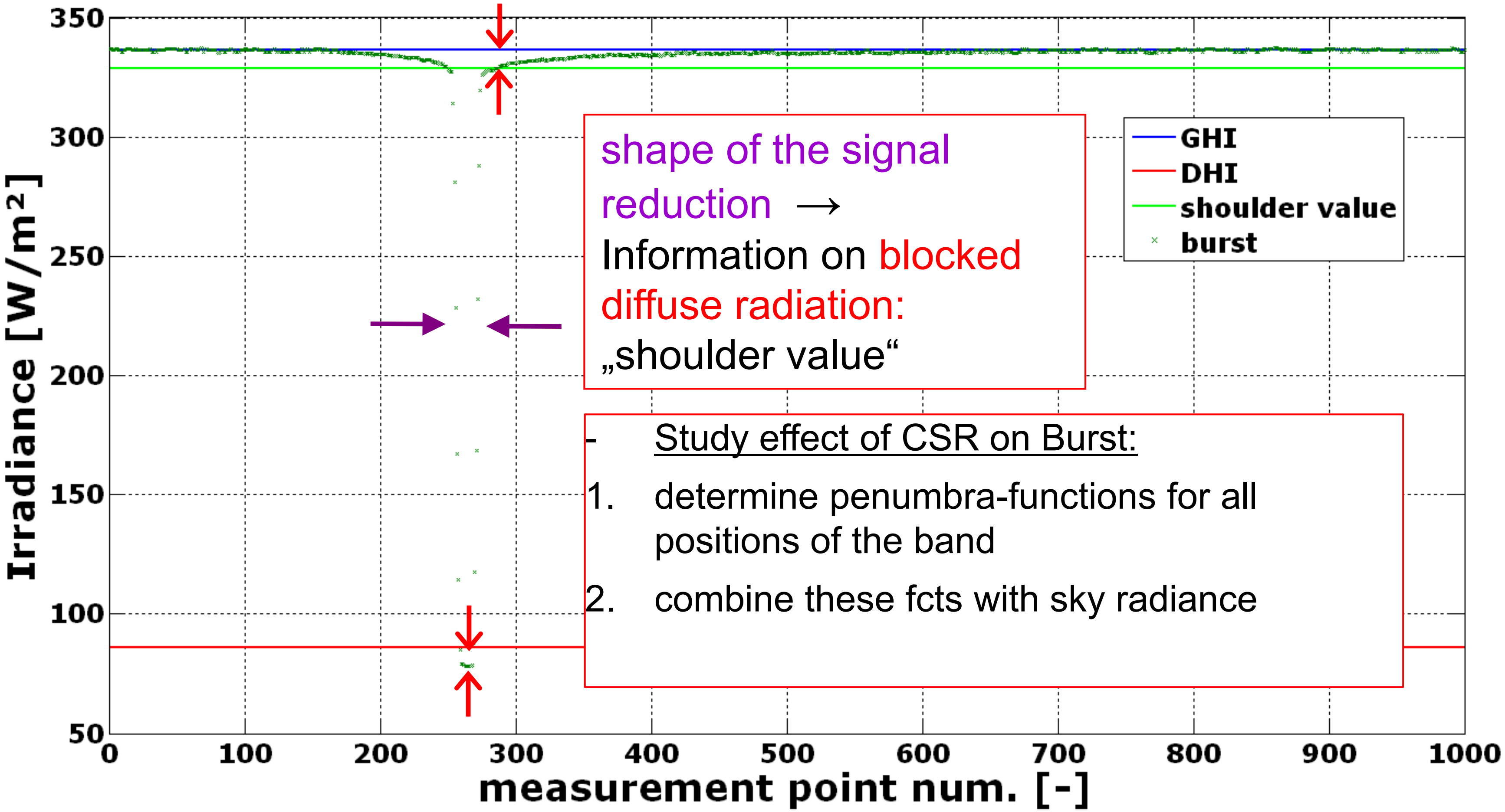
BPI Sensor: Summary & Conclusion

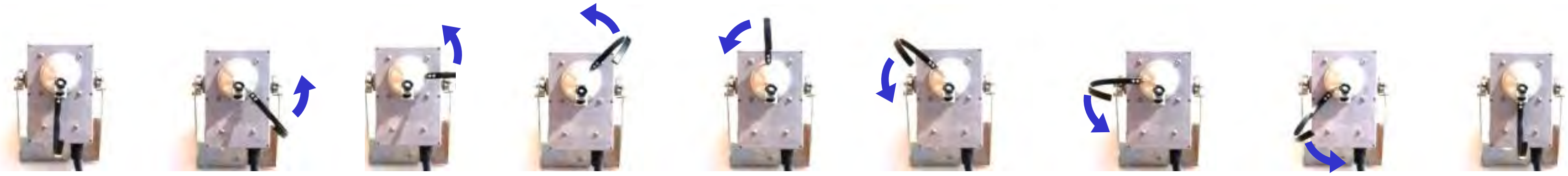




- New System BPI CSR 460 has been developed
- Accurate measurement of circumsolar irradiance in specific angular region
- Difference between Sensor 1 and 2 can be used to calculate CSR using Buie's sunshape model.
- Model allows for good CSR results for many days, but bias towards overestimation of CSR.
- Overestimation is result of Buie's standard sunshape being steeper than average measured CSR sunshape in Tabernas, Spain May-June 2012.
- 3rd sensor will be used in the future for higher accuracy of CSR determination

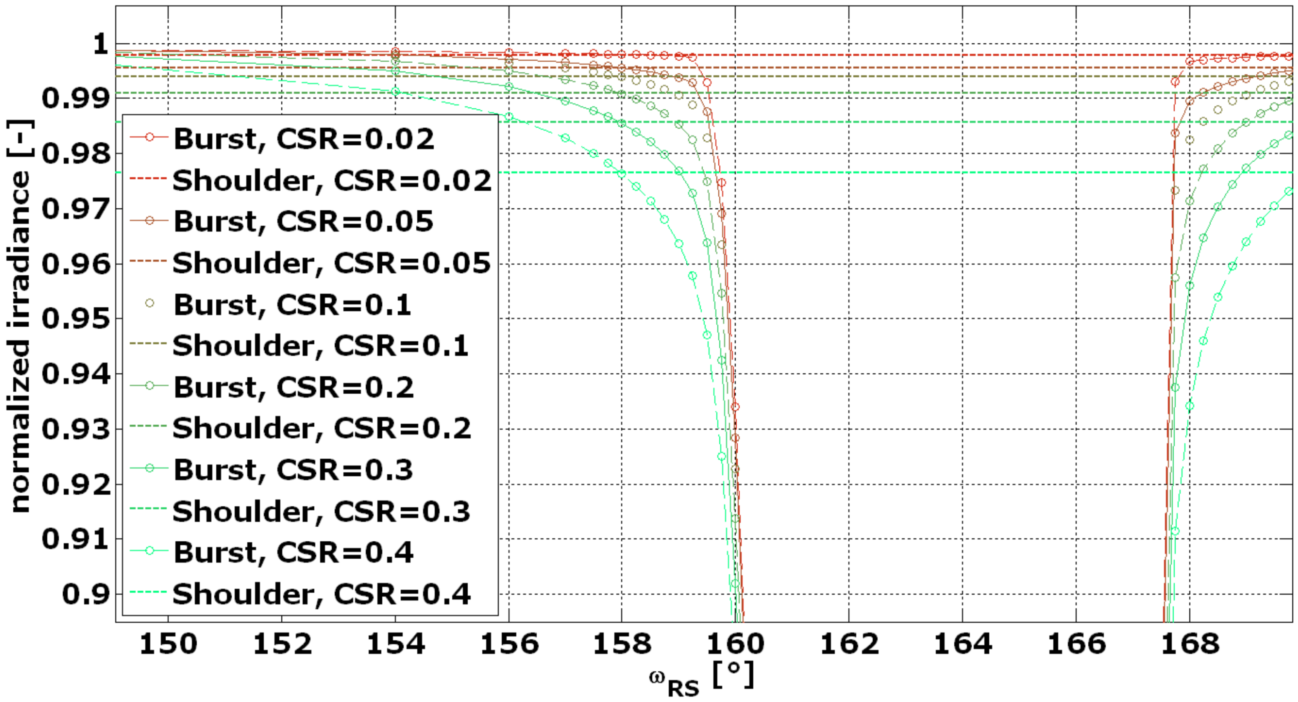
CSR from RSI – burst analysis





Simulation results – Information on CSR from the Burst

- Shoulders vary with CSR => they contain information on CSR
- 4 parameters used to find blocked circumsolar & blocked further sky irradiance starting at the steep parts of the burst
- Blocked circumsolar irradiance is proportional to total circumsolar irradiance
- Find 4 parameters by searching min of *R²(CSR(RSI) vs. CSR(ref, SAM))*
- Find linear equation for this parameter set for *CSR(RSI) vs. CSR(ref, SAM)*



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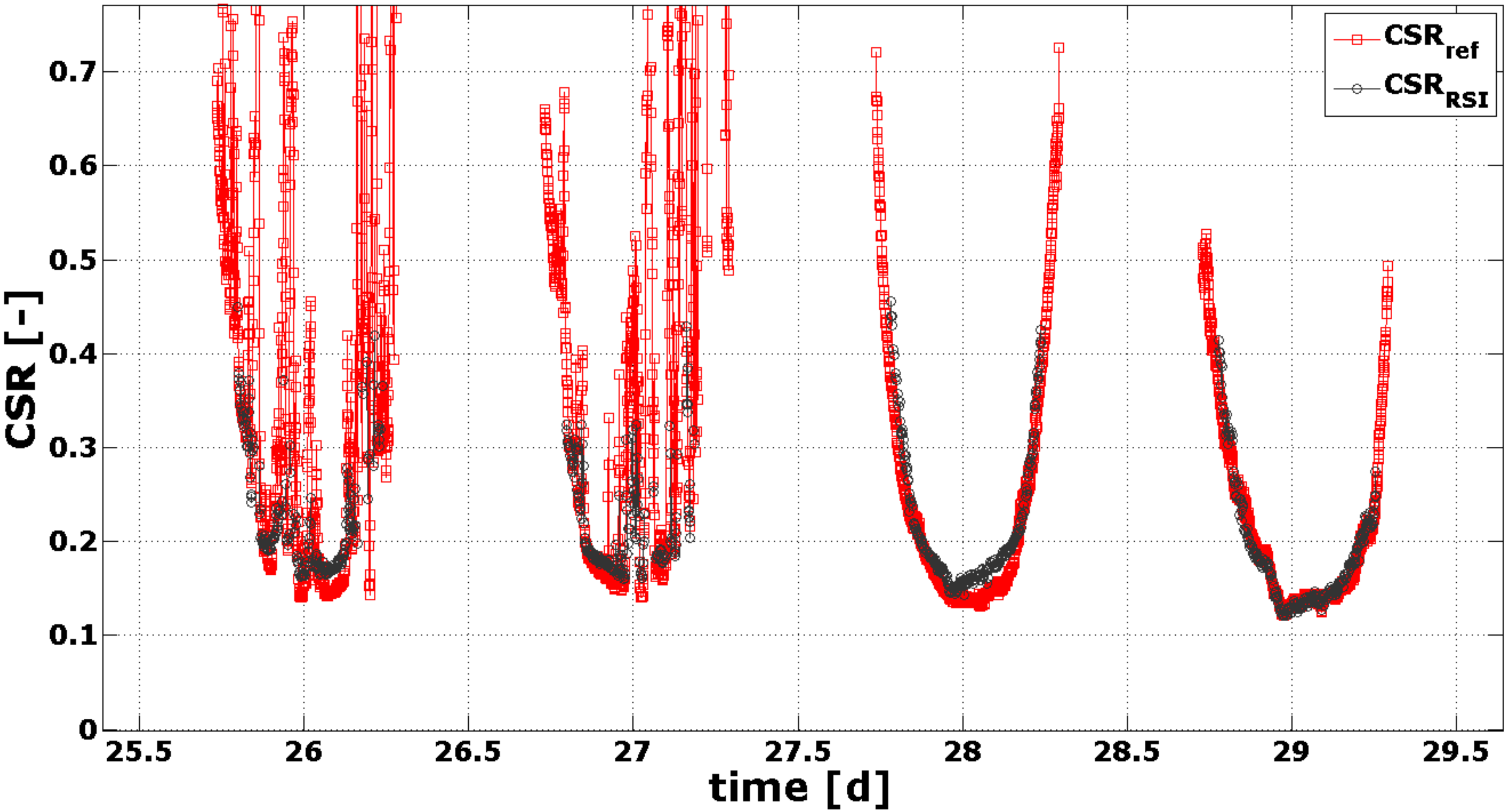
CSR from RSI: validation with reference



Available Sunshape Measurement data (status 05/2013)

- **LBL reduced data base** (200.000 measurements, 11 sites, USA)
- **DLR measurements PSA, Cologne, Odeillo** (only CSR saved, 1990s)
- **New reference-system**
    - **at PSA**: >2 years
    - CNRS replica set up: some months
    - **Masdar Institute replica: ~1 year**
- **RSI** @ PSA: 3 years

Alternative method to determine CSR

Modeled CSR pt. 1 – ground based

Required:

- **DNI measurement** (recommended 1min pyrheliometer)
- Aerosol information (recommended: **Aeronet data**)
- **SMARTS**

Derivation method:

1. Calculate clear sky CSR and DNI with SMARTS
2. Compare clear sky DNI with measured DNI
   Output: cloud transmittance
3. Use cloud transmittance to determine the effect of the clouds on the CSR
   Based on sunshape measurements and Aeronet data (e.g. from PSA)

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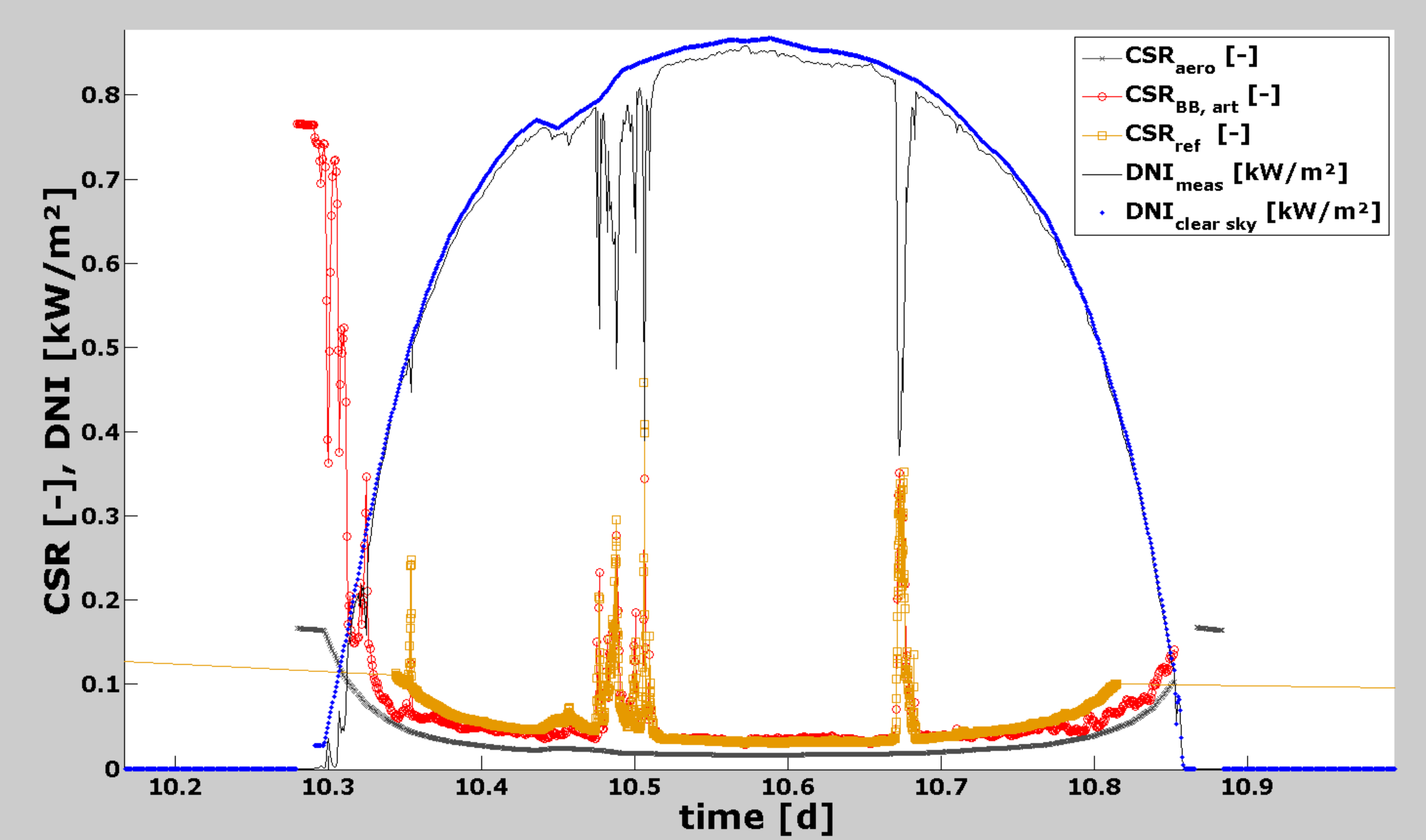
Modeled CSR based on ground measurements



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Sunshape derived from satellite data

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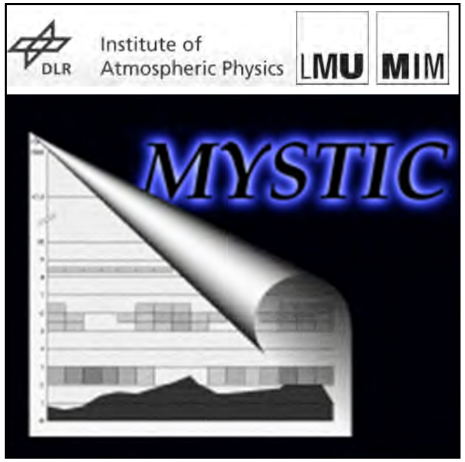
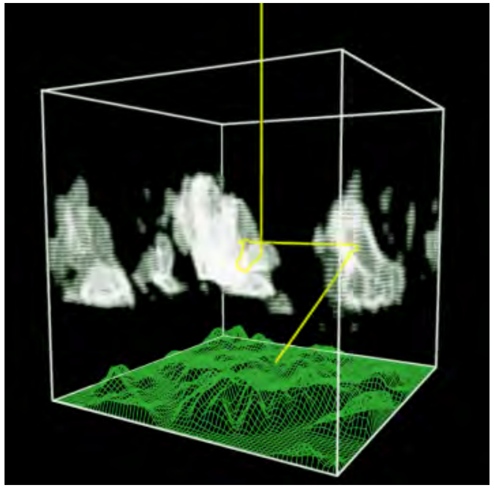
Satellite based retrieval of Sunshape

- Step 1:
  - Simulate sunshape for different atmospheric conditions
  - 3D simulation by MYSTIC model

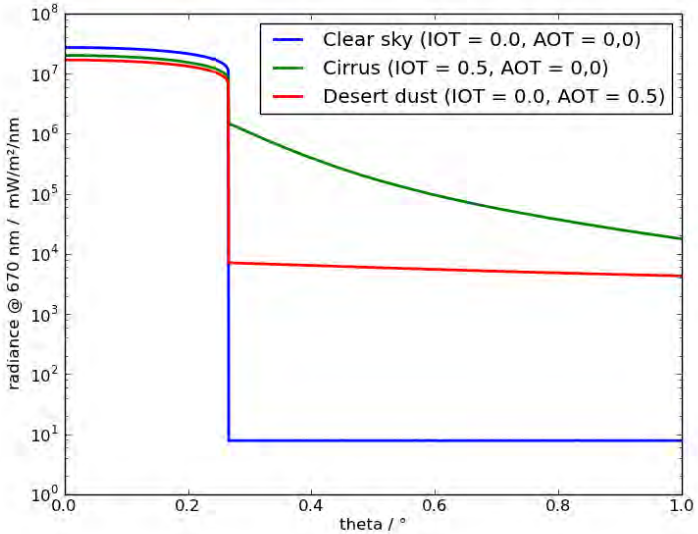


Buras & Mayer 2011



Montecarlo simulation

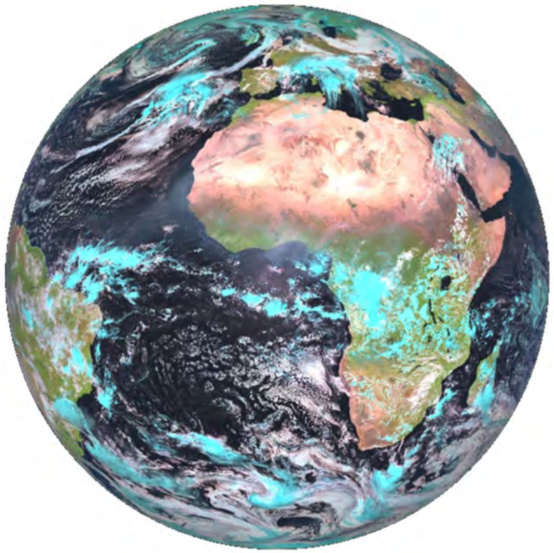
panoramic output



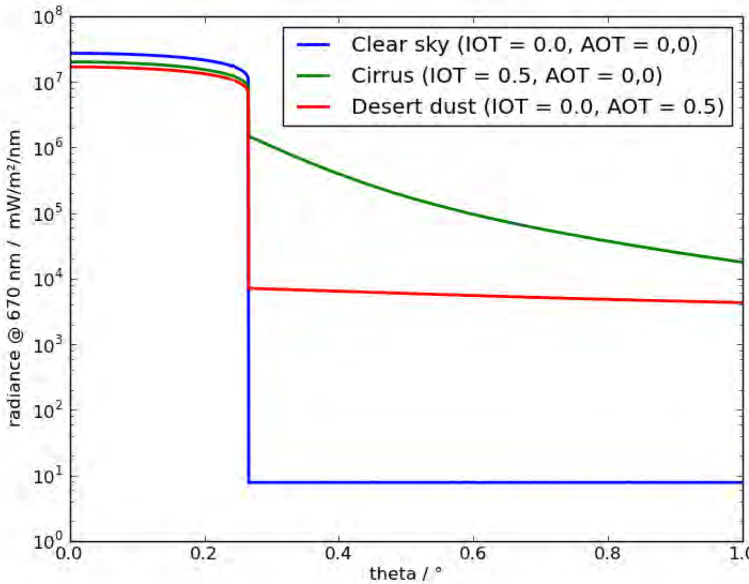
sunshapes

Satellite based retrieval of Sunshape

- Step 2:
  - Use satellite based retrievals of cloud & aerosol properties
  - Parameterization of sunshape in terms of cloud & aerosol properties allows fast conversion to circumsolar radiation



Parameterization based on calculations with MYSTIC



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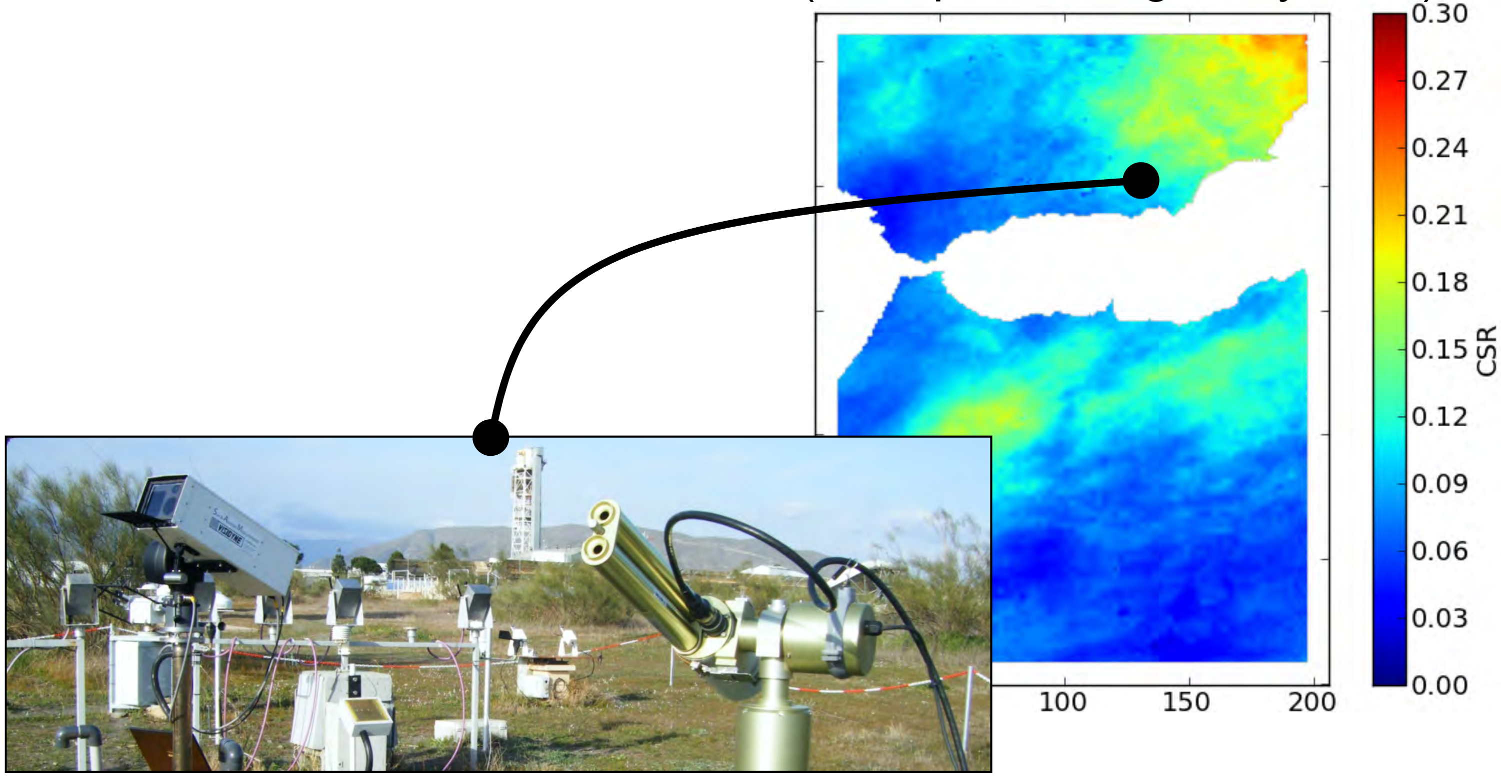
Ongoing work

- Validation of satellite based retrievals of CSR

CSR map
(example, average May 2009)



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Outlook

- More ground based sunshape measurements
  - More replicas of the SFERA measurement system
  - Use CSR algortihm with RSI stations
  - Two or better 3 pyrheliometer setup (Black Photon Instruments)
- Continued analysis and studies on sunshape impact
- Implementation of sunshape in plant performance calculation models
- Validation and further developement of satellite based sunshape determination and modelled CSR

- Thanks to Norbert Geuder for presenting the topic!
- Thanks to Bernhard Reinhardt for providing the slides on satellite based retrieval of the CSR!

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Definition: Optical efficiency of a concentrating collector

$$\boxed{\eta_{opt} = \rho \cdot \tau \cdot \alpha \cdot IC}$$

η_{opt} opt. efficiency

includes the effects until radiation is absorbed by the receiver

ρ reflectivity, mirrors

τ transmittance, entrance window of receiver

(+air between mirror and receiver)

α absorption, receiver

IC intercept-factor

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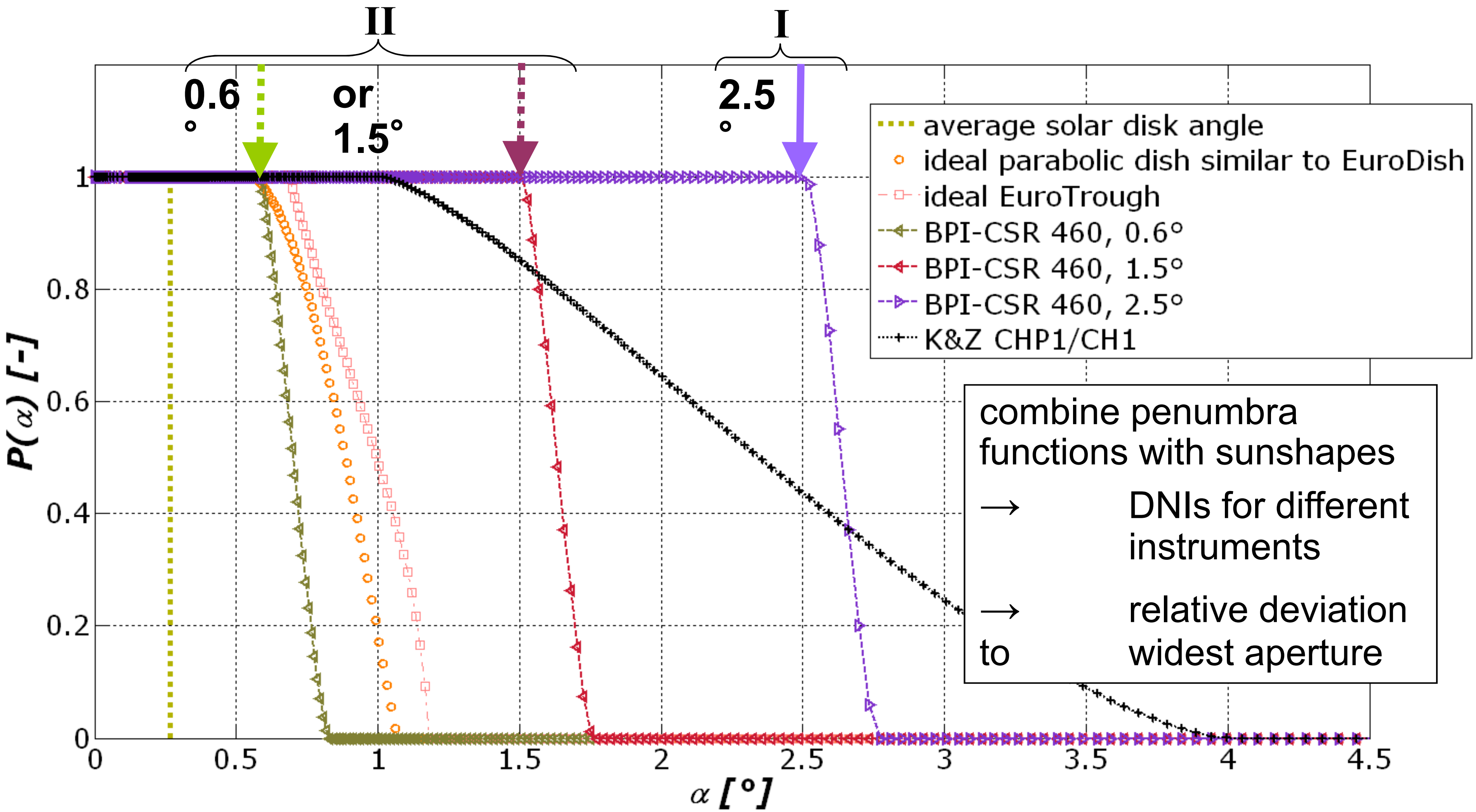
BPI CSR sensor – two pyrheliometers

- … with different penumbrafunctions



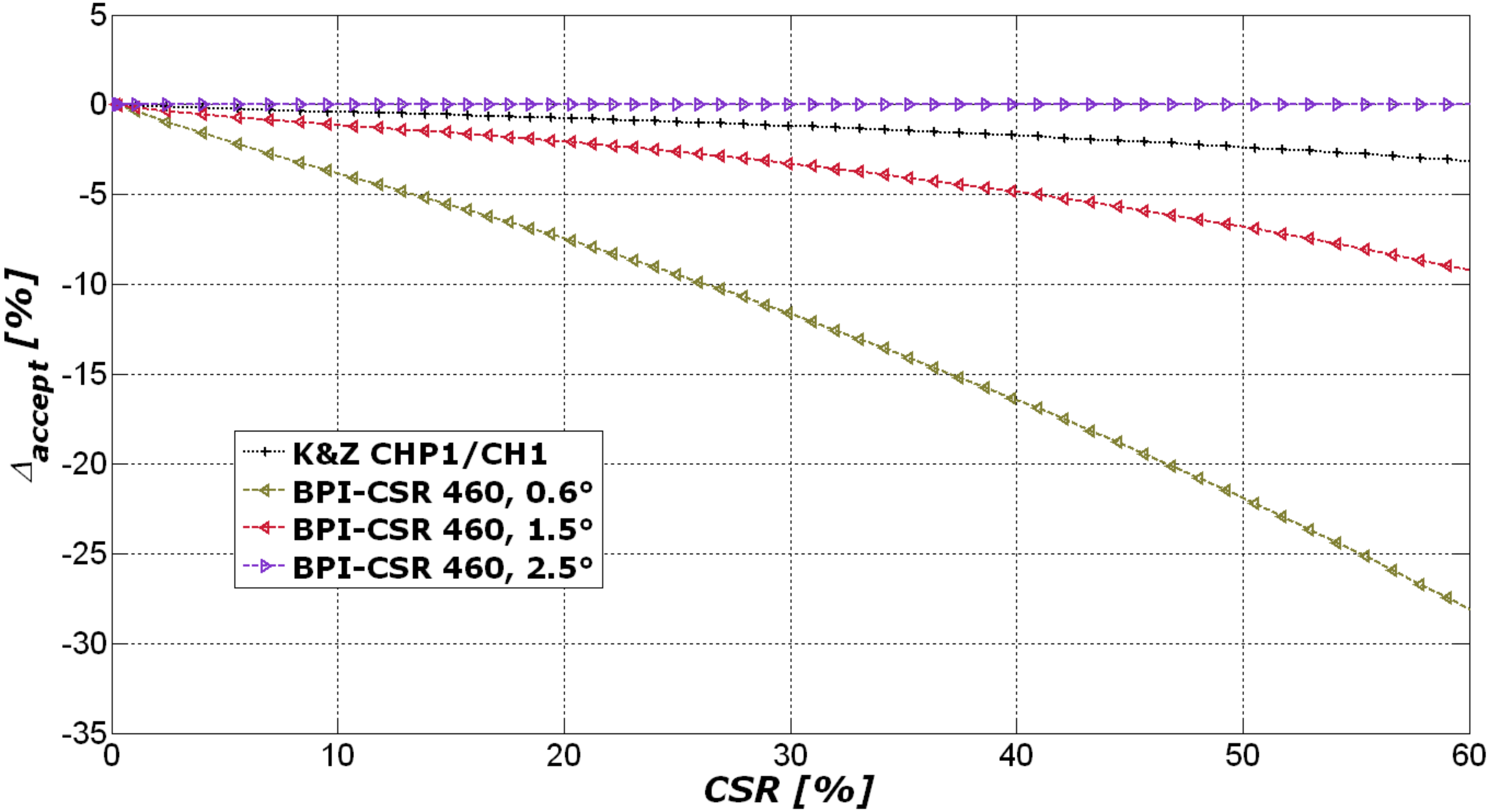
combine penumbra functions with sunshapes

→ DNIs for different instruments

→ relative deviation to widest aperture

BPI CSR sensor – two pyrheliometers

- **Relative deviation of DNI** measurement with respect to instrument with widest slope angle caused by circumsolar radiation ***vs.* CSR**
- standard sunshapes from Buie's model for given CSR [Buie 2003]

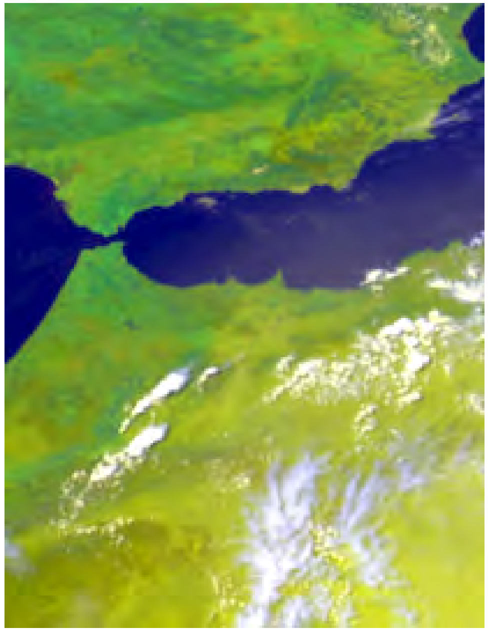


Satellite based retrieval of Sunshape

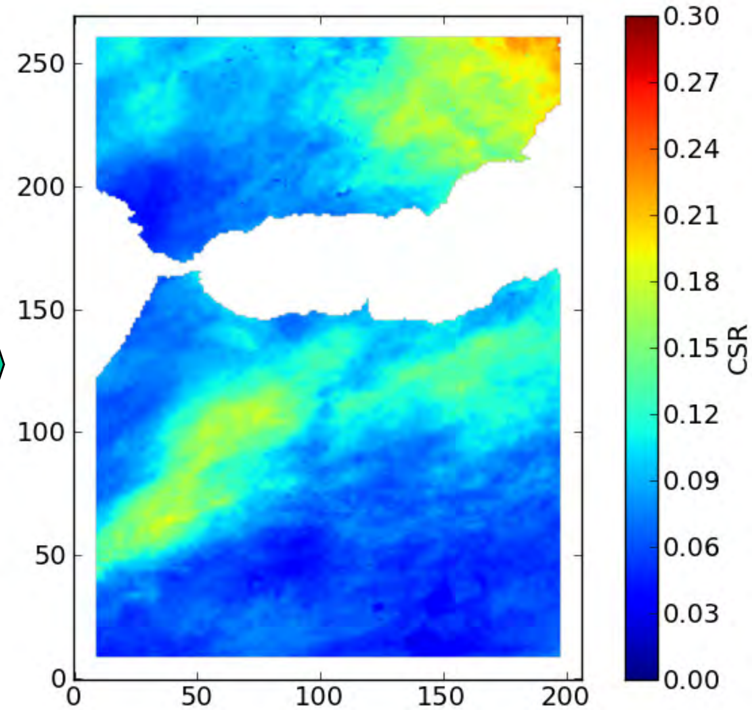
- Result: CSR maps, time series, long time averages

Information from satellite:

- Aerosols
- Clouds (especially ice clouds)



CSR map
(example, average May 2009)



DLR