Advanced Measurement Systems to evaluate CSP Plants

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DLR Institute of Solar Research

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Outline

- Challenges for measurements in CSP power plants
- Parabolic Trough Fields:
    - Airborne predictions of optical field performance
    - Hydrogen accumulation in parabolic trough receivers
    - Cloud shadow prediction in the solar field
- Solar Tower
    - Optical quality of heliostat field and flux distribution on receiver
    - Air return ratio in open volumetric receiver systems
- Summary

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Challenges for measurements in CSP power plants

- Measurement object extended or distributed over several square miles
- Limited access (e.g. tower)
- Measurement should not disturb operation
- Sensors preferably non invasive
- High measurement precision requirements

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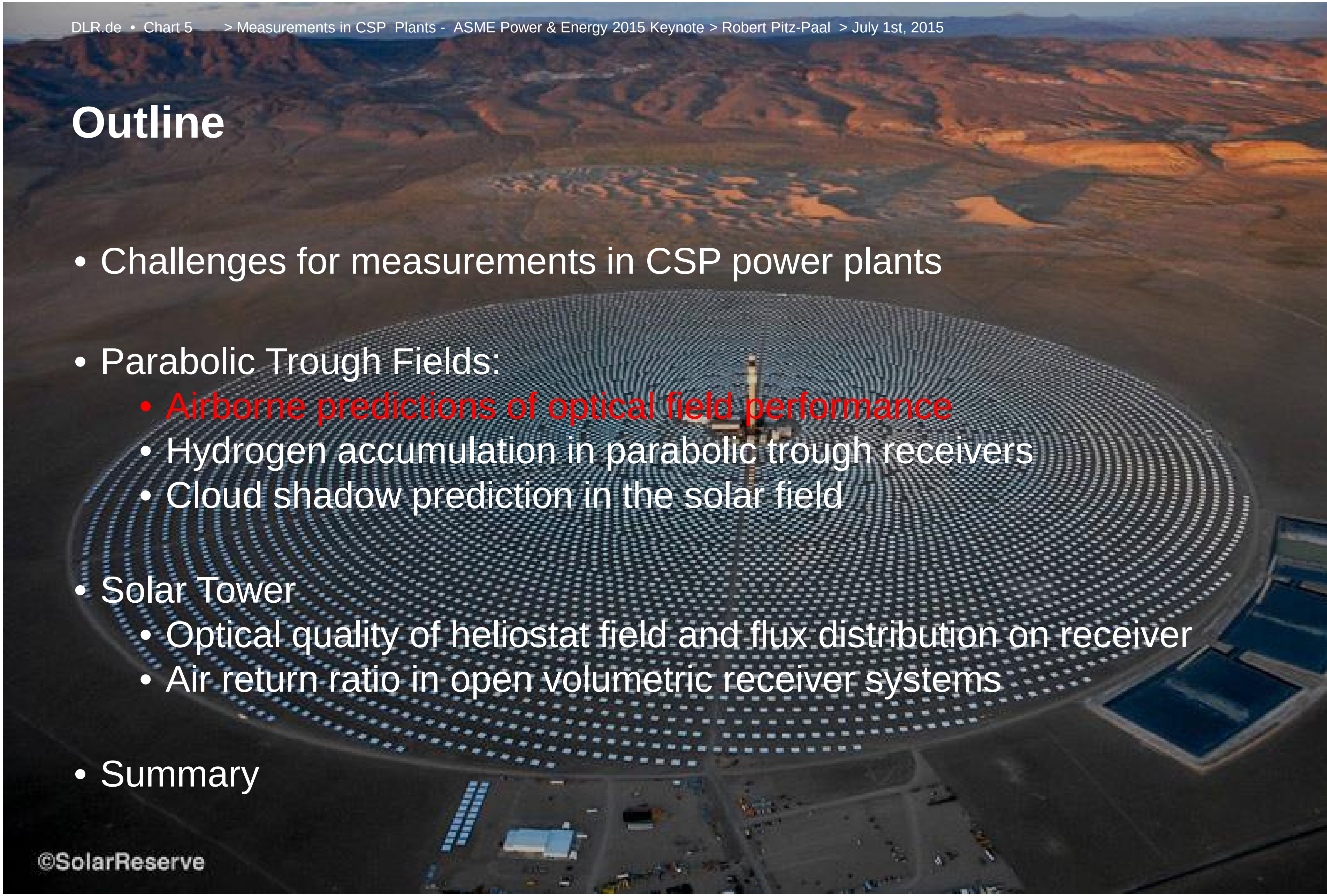

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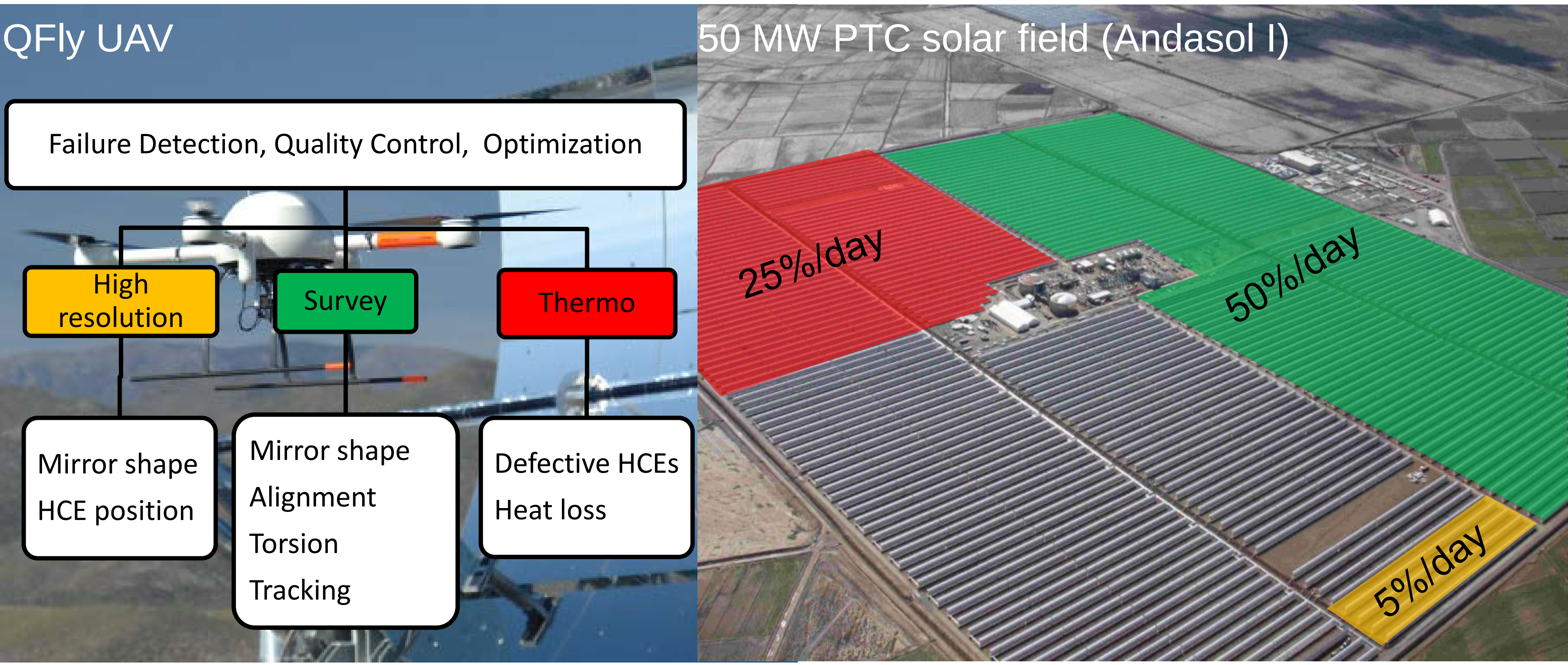
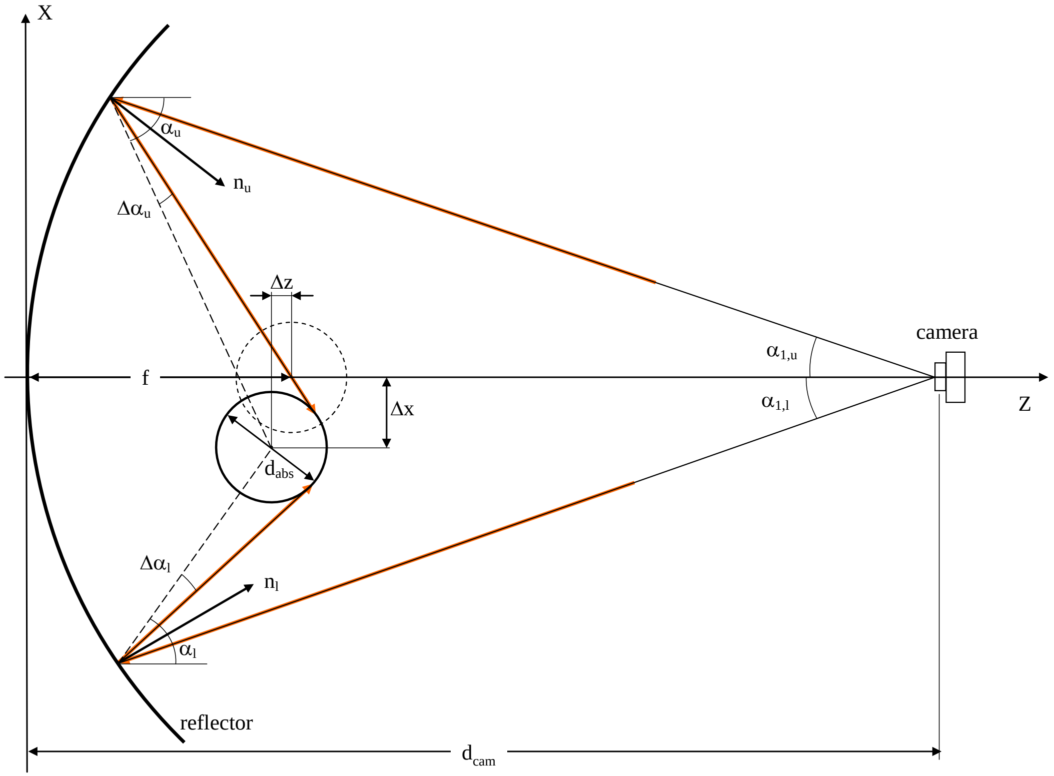
QFly – airborne prediction of the optical performance of parabolic trough collector fields

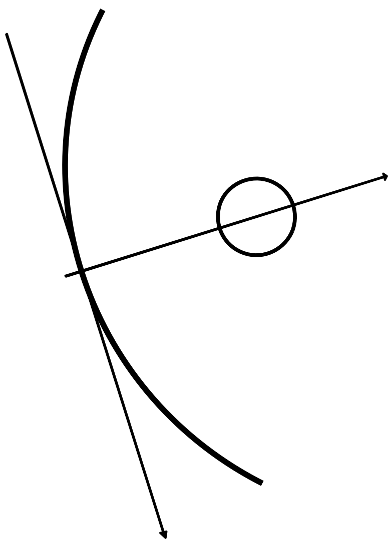


2. Qualification of Concentrators
Deflectometry



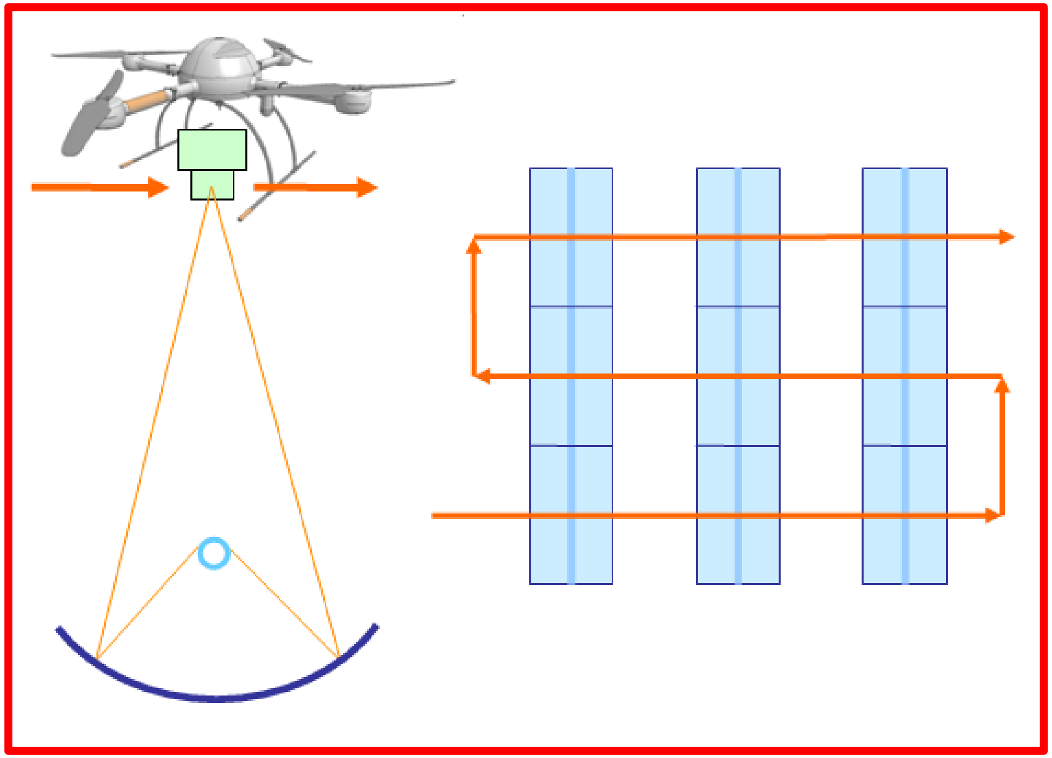
2. Qualification of Concentrators

Deflectometry – Image Acquisition



QFly measurement principle

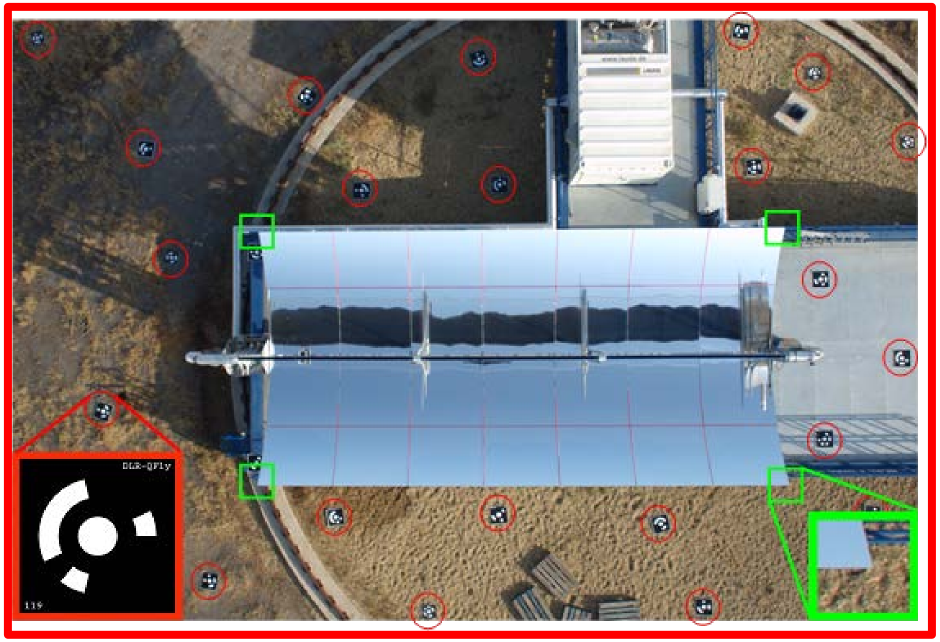
1



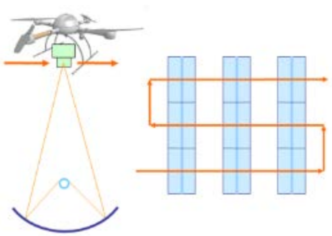
- Plan for Flight Route using GPS waypoints
- Aerial images showing absorber tube reflex
- Scaling/reference system for close-range photogrammetry

QFly measurement principle

2



- Calculation of camera positions relative to each collector via photogrammetry
- Artificial, coded and natural markers
- Accuracy of 3D coordinates ~ 5 mm



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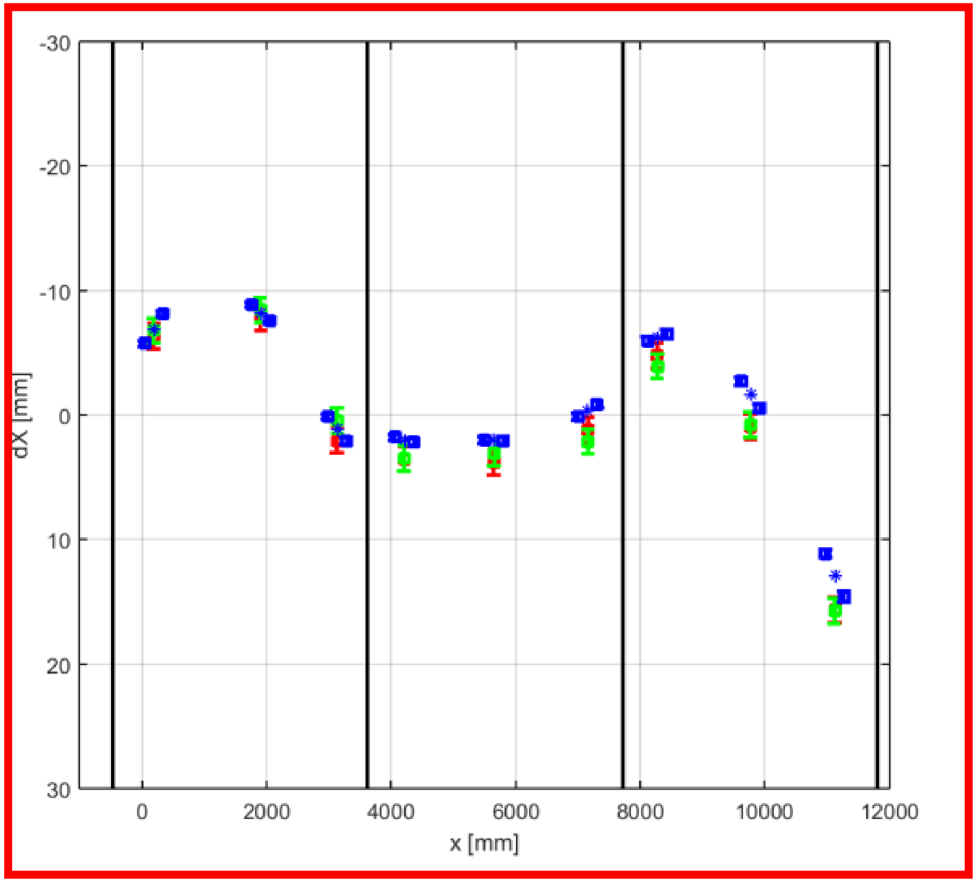
QFly measurement principle

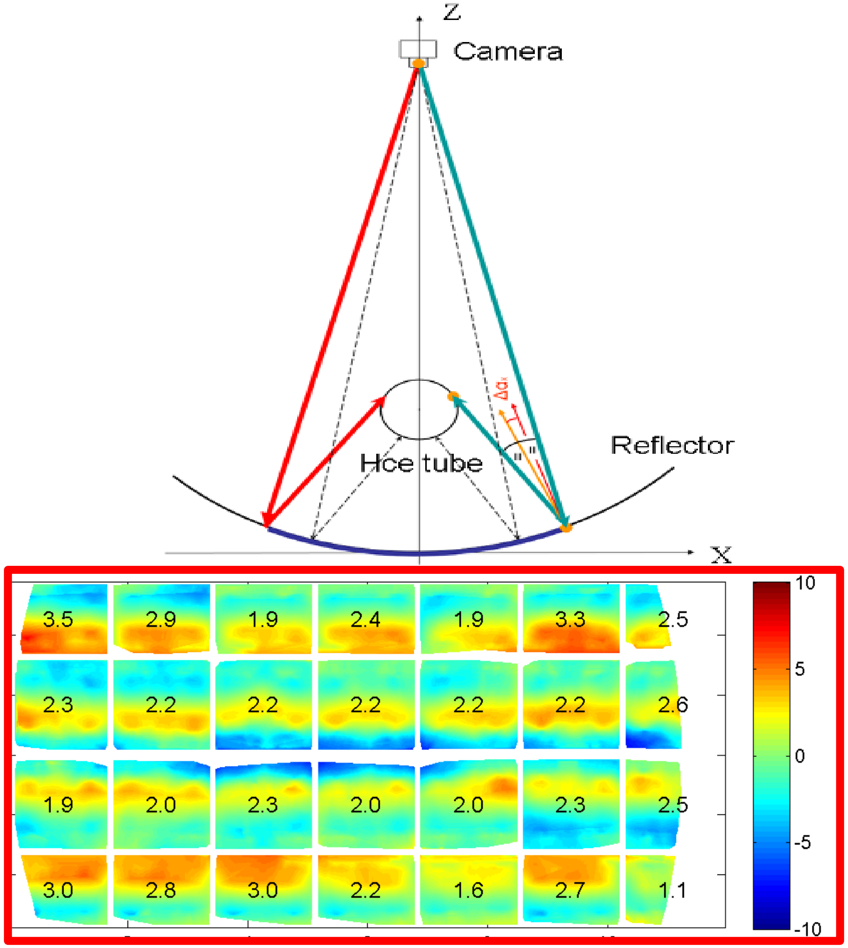
3



- Calculation of lateral and vertical HCE deviation from focal line via photogrammetric approach
- Deviations Qfly to reference:
  - RMS dX < 2.0 mm

QFly measurement principle

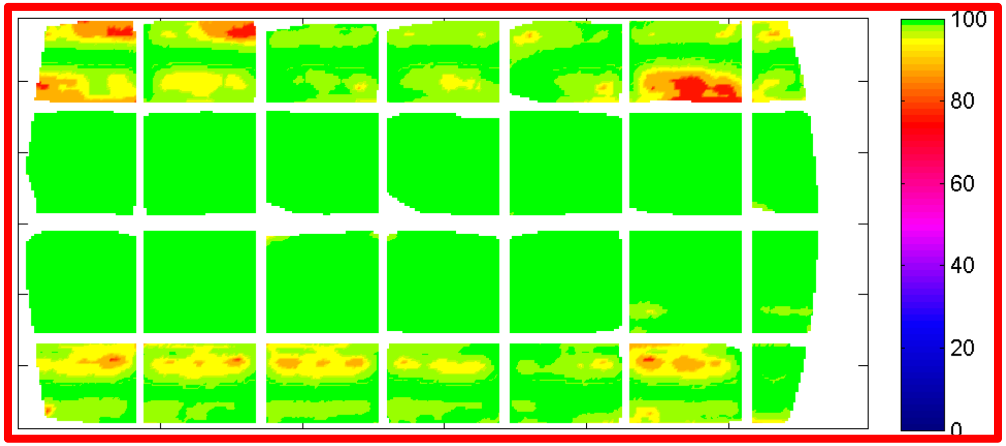
4



- Calculation of slope deviations in curvature direction (SDx, in mrad) from absorber reflex, camera positions and absorber position

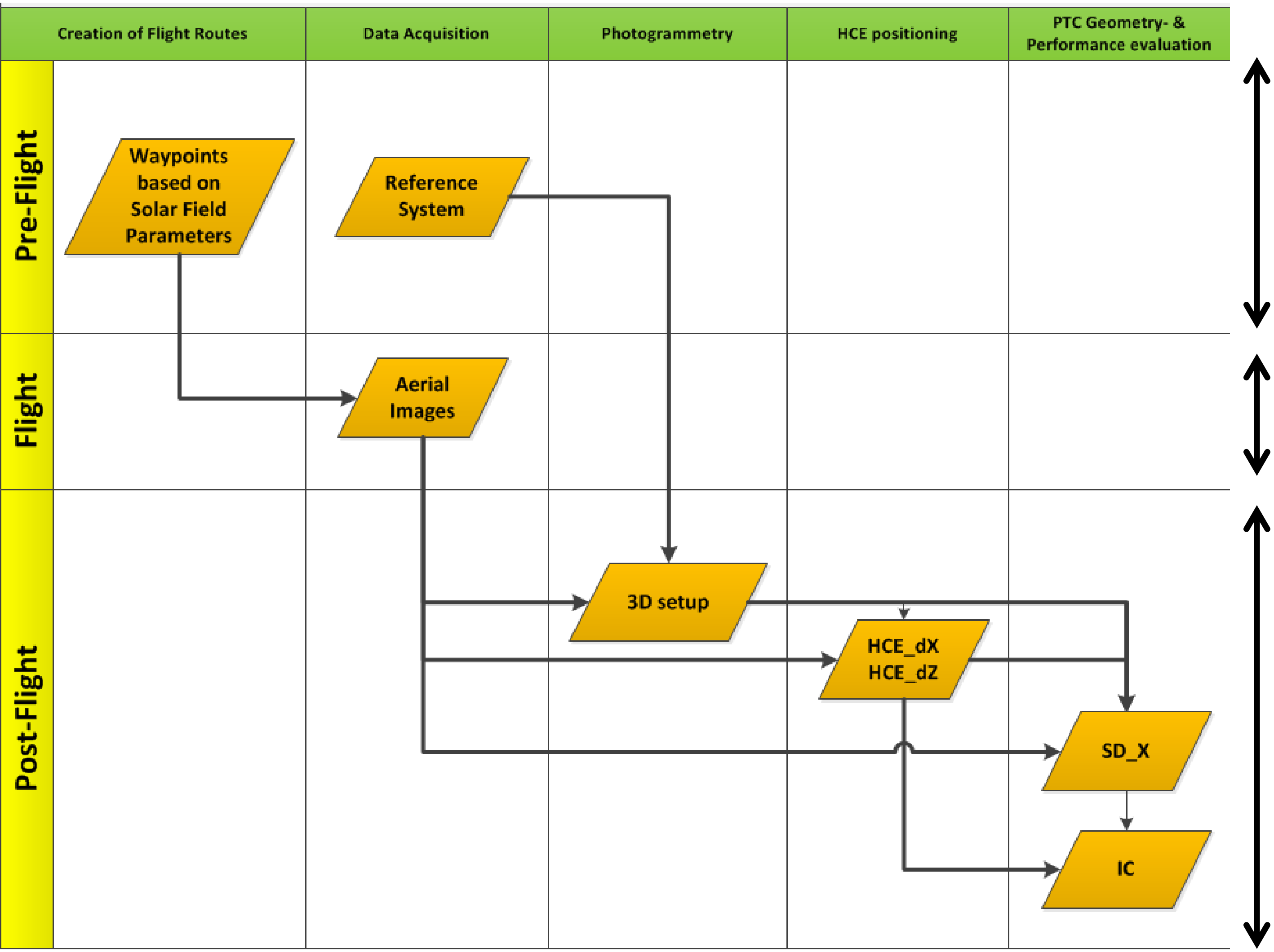
QFly measurement principle

6



- Intercept factor via ray-tracing based on measured geometry
- Includes blocking and shading effects
- Assumptions on other error sources

QFly measurement principle



Effort per collector (SCA) 150 m:

2 hours

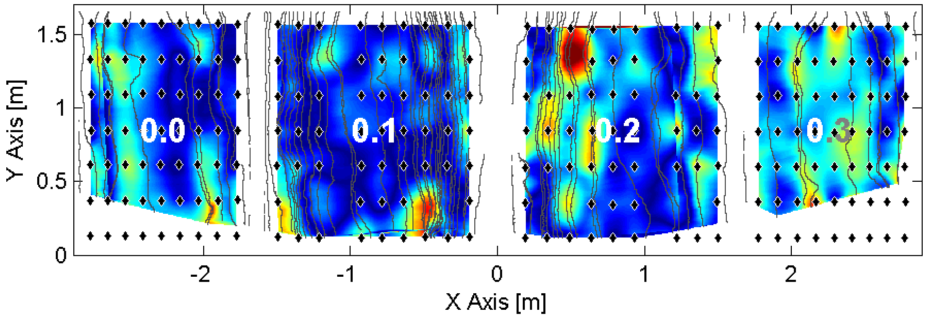
0.5 hours

4 hours

Validation

Optical:

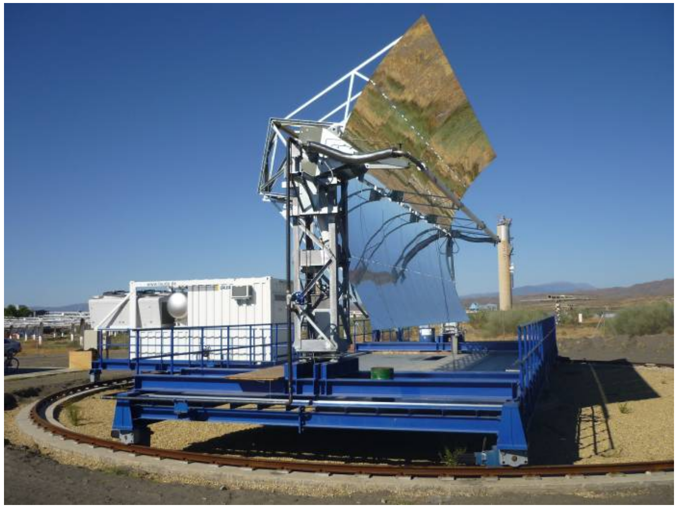
- Comparison with reference data from photogrammetry
- Mirror:
  - Difference of SDx
    RMS values < 0.4 mrad (due to limited spatial resolution of photogrammetry)



- Absorber tube position
  RMS of differences:
  - < 2.0 mm horizontal
  - < 2.1 mm vertical

Thermal:

- Comparison with thermal efficiency of EuroTrough module on Kontas test-bench (PSA Almeria)
- Good agreement between η_{opt} :
  - via thermal measurement
  - via QFly measurement



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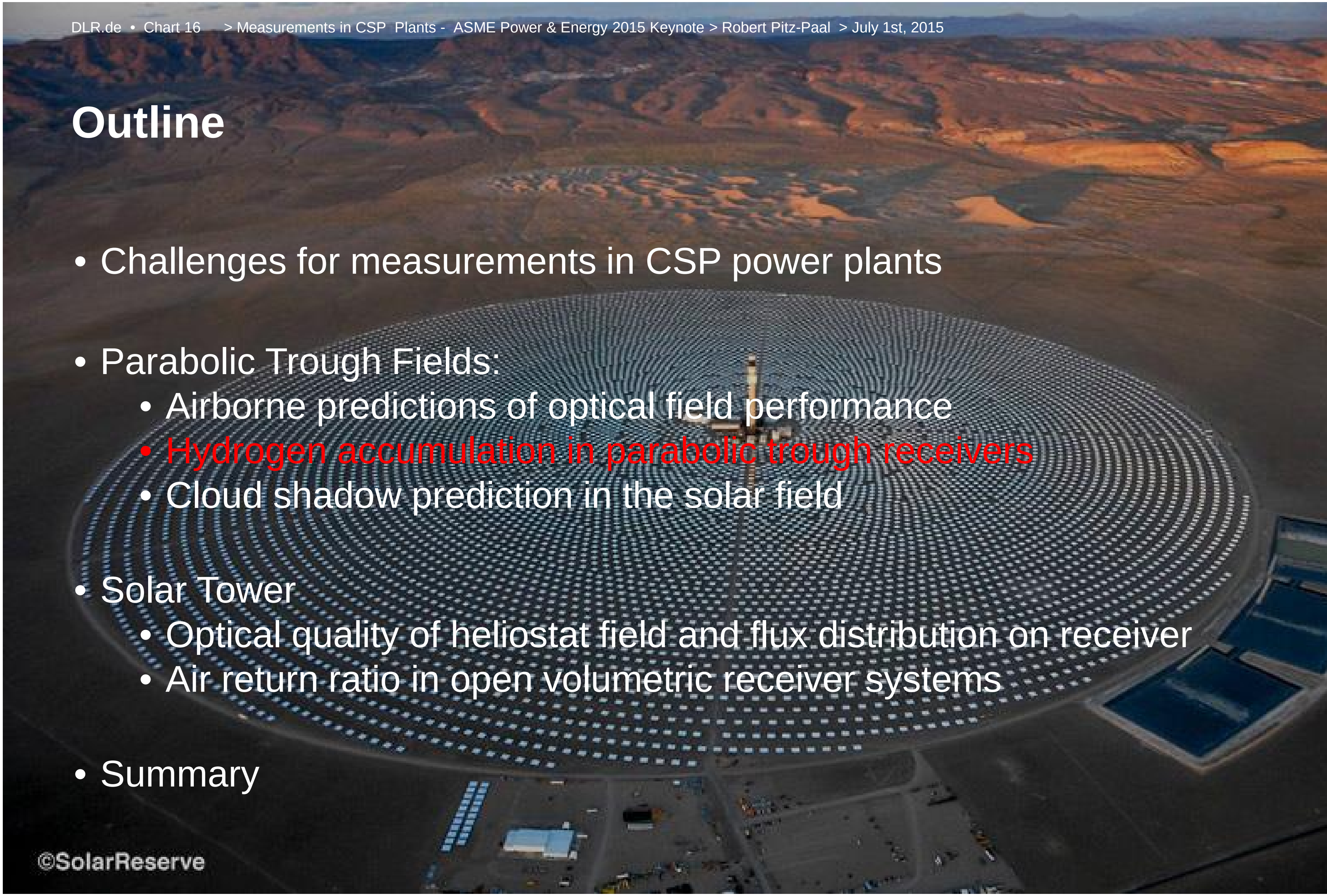

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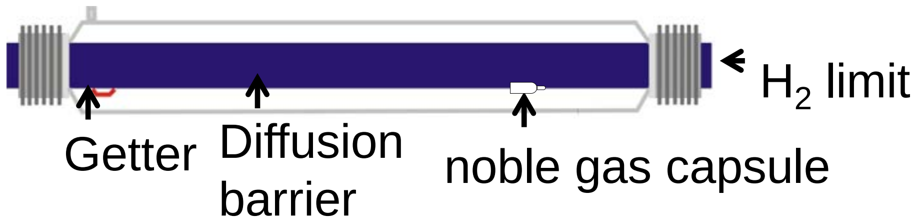
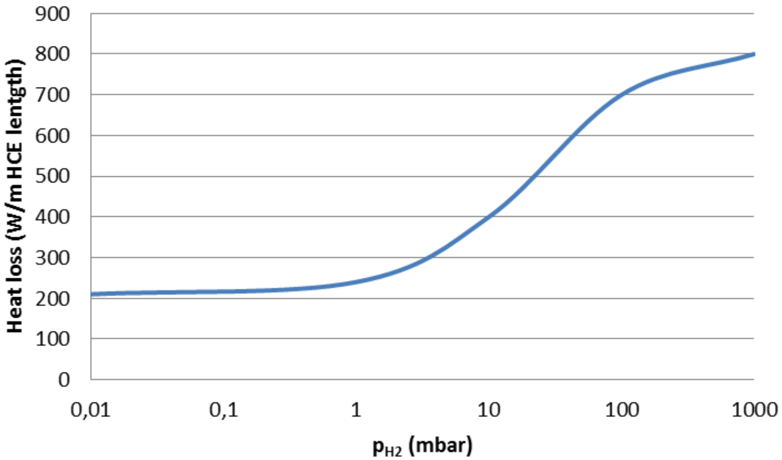
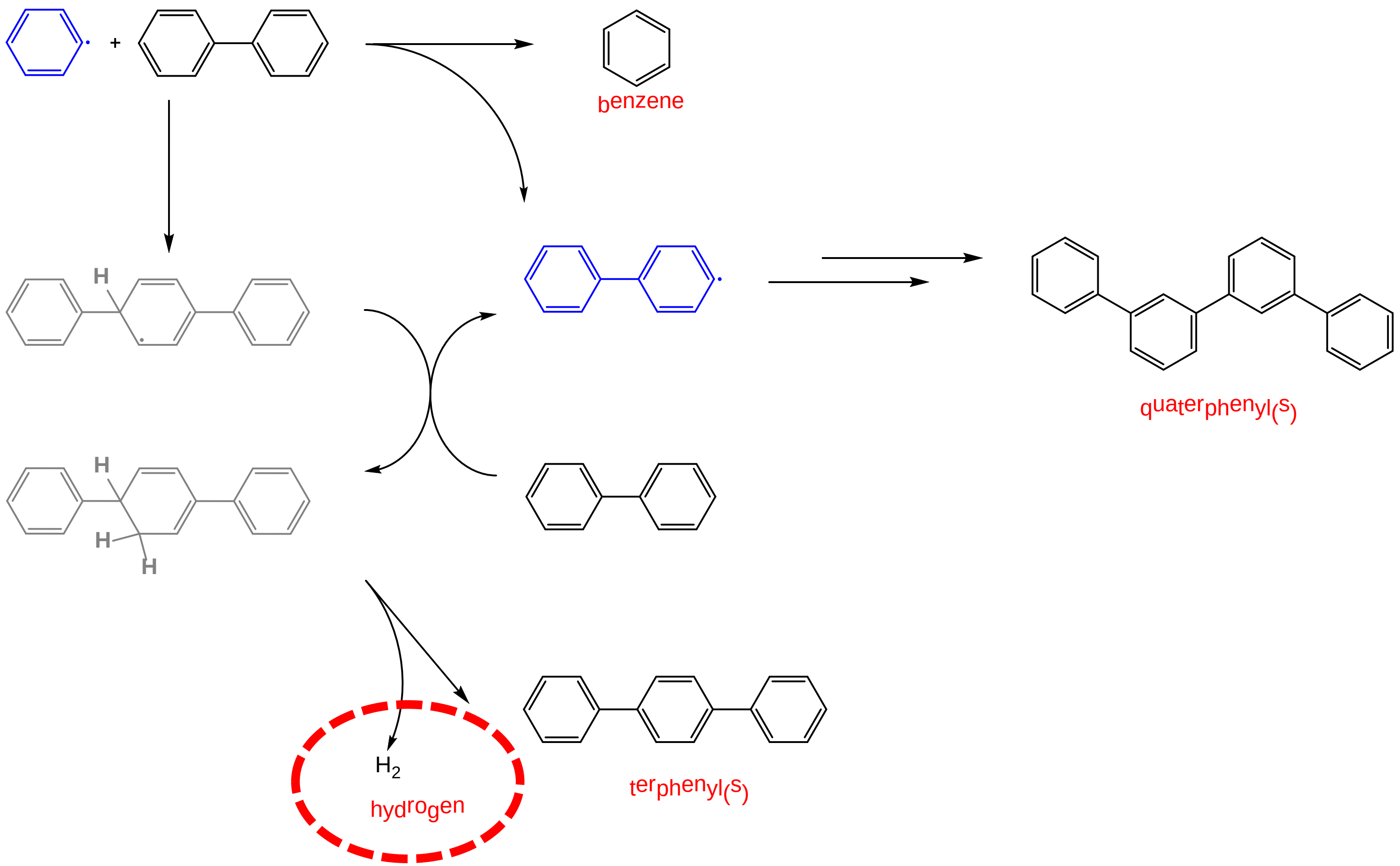
Hydrogen accumulation in parabolic trough receivers: Effects and Counteractions



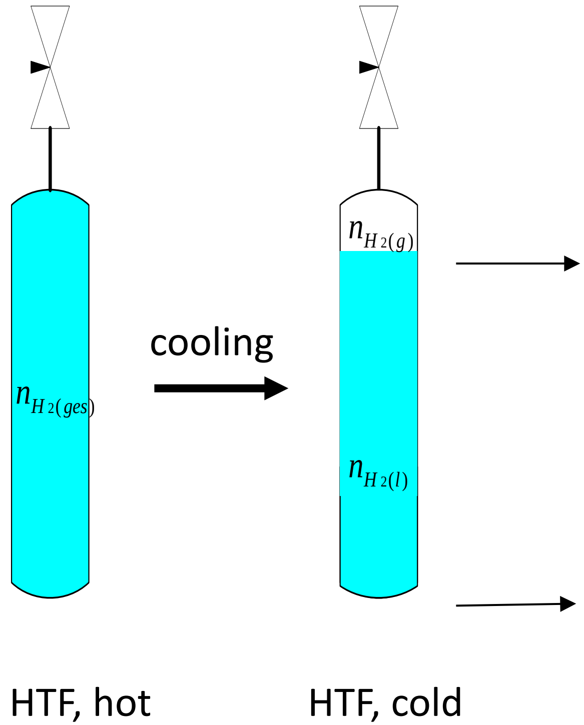


- Hydrogen accumulation would deteriorate vacuum insulation of receivers
- Counteractions against hydrogen in receiver (getter, barrier coating) designed for H_2 limit concentration / pressure in heat transfer fluid (HTF)
- H_2 monitoring and HTF processing focussed on H_2 removal, required to keep H_2 level below deterioration limit

Thermal aging of HTF causes slow hydrogen formation



Measurement of hydrogen in oil samples in solar field



Hydrogen in gas phase

$$n_{H2(g)} = \frac{p_{H2}(V_{ges} - \frac{m_{HTF}}{\rho_{HTF}})}{RT}$$

$$p_{H2} = p_{ges} x_{H2} \qquad x_{H2} \quad \text{via GC}$$

Hydrogen in liquid phase

$$p_{H2} = \frac{n_{H2(l)}}{n_{HTF}} H_{H2}$$

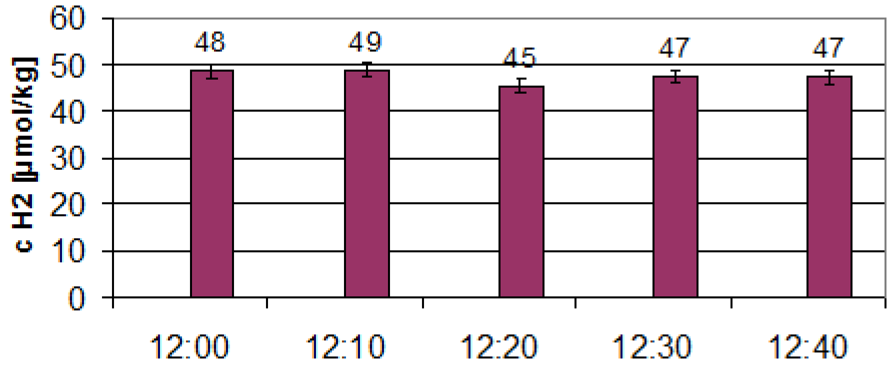
$$n_{H2(l)} = \frac{p_{H2} n_{HTF}}{H_2}$$

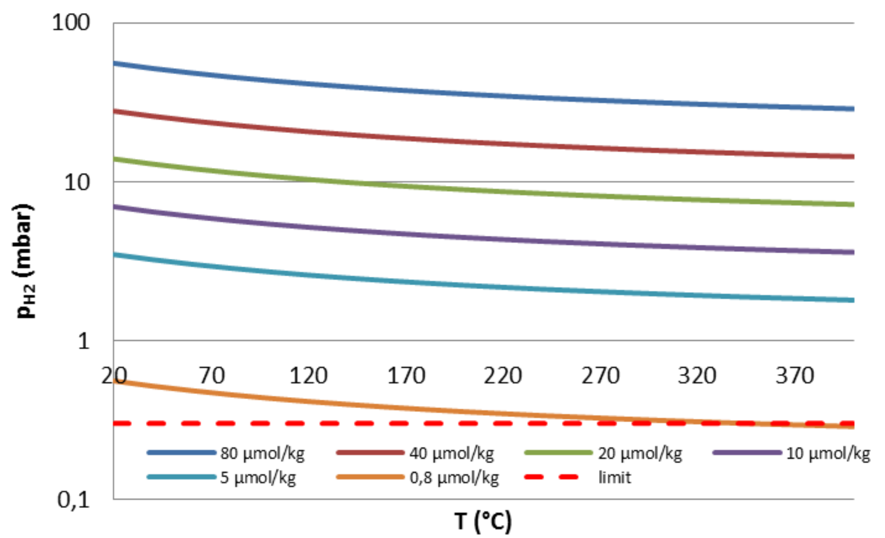
- Sampling of <u>liquid and gas phase</u> with steel cylinders inline (pressurized & hot)
- Analysis of (all) dissolved gases offline (lab)

Gas Content: Concentration vs. Pressure

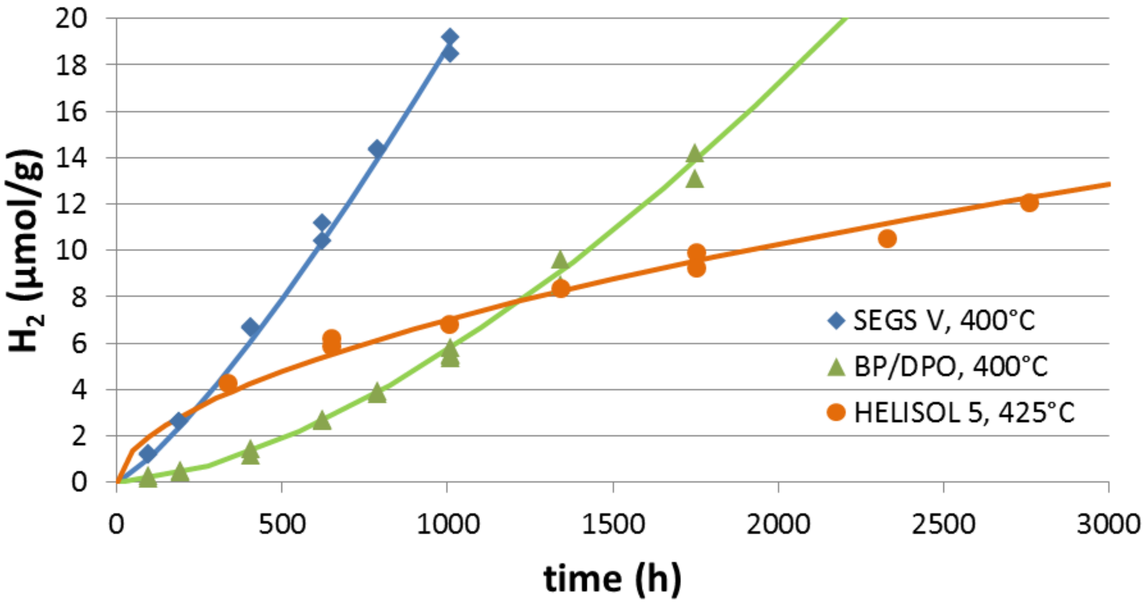
- Direct result of measurement: µmol/kg hydrogen in oil
- Receiver manufacturer's hydrogen limit: e. g. 0.3 mbar
- Conversion from concentration to pressure via Henry coefficient (gas solubility, H, from gas dissolution experiments)

$$p_{H2} = H_{H2}(T) * x_{H2}$$





Hydrogen in Heat Transfer Fluid
Reduced Formation using Silicone Fluids?



- Eutectic mixture of biphenyl (BP) and diphenyl oxide (DPO) forms hydrogen at increasing rate on prolonged operation
- New silicone fluids form less hydrogen on prolonged operation at elevated temperature

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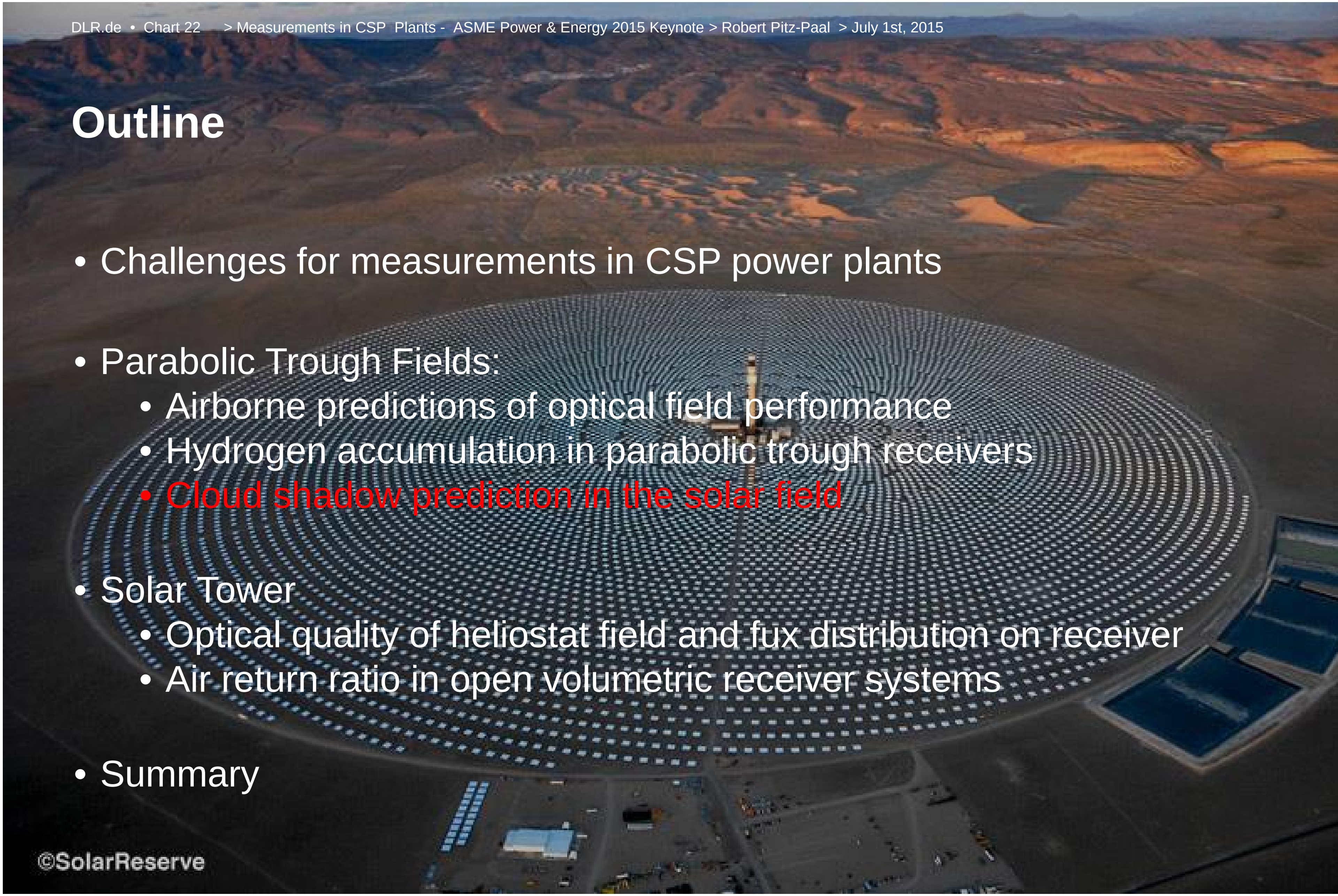

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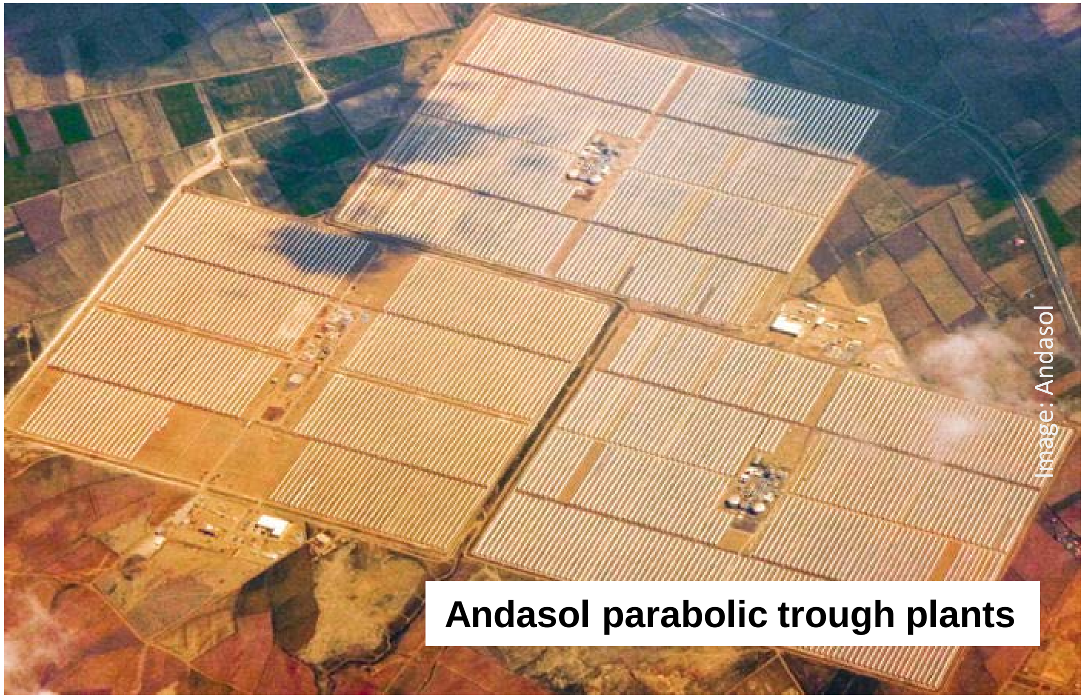
Cloud shadow prediction in CSP Plants

Optimize energetic and financial yield & plant life time

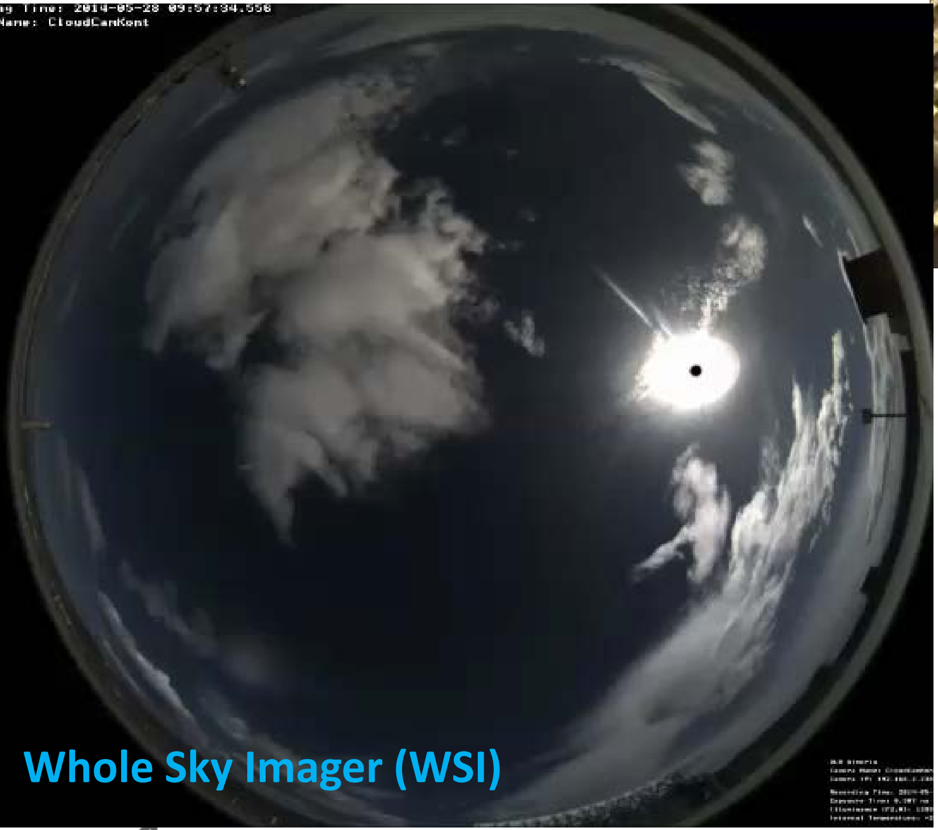
- CSP plant operation involves decisions, e.g.
  - selection of operation mode
  - tower plants: mirror focus control (avoid fast temperature changes of receiver, avoid overload dumping with dynamic aim-point selection)
  - trough plants: individual heat transfer fluid mass flow in different parts of the solar field

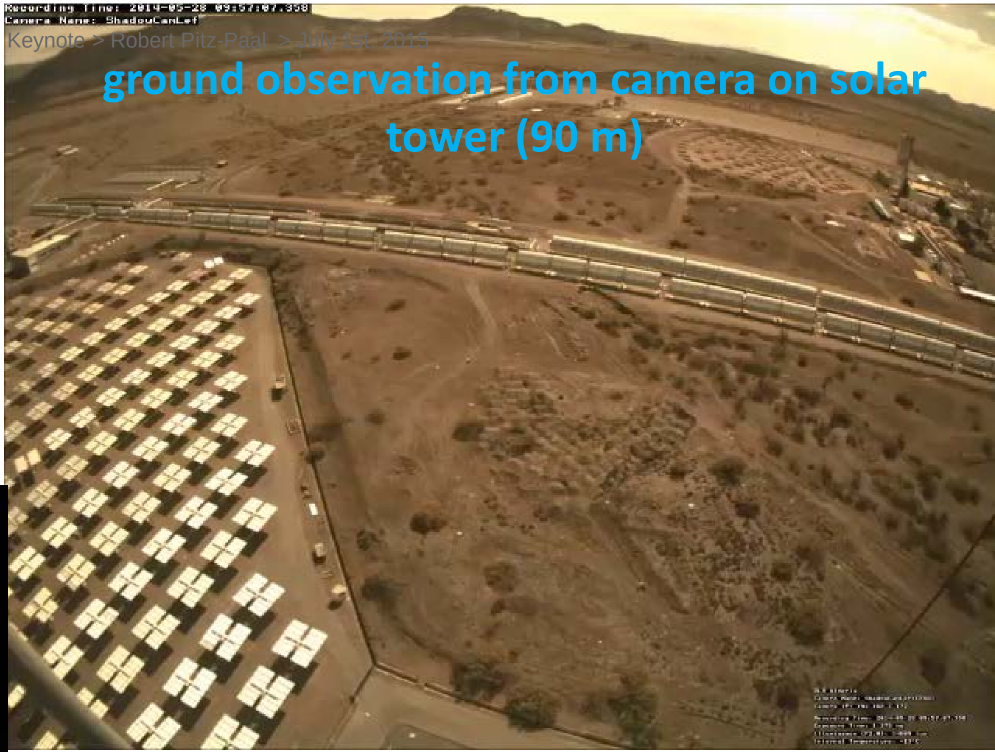


Andasol parabolic trough plants

Cloud Movement Analysis

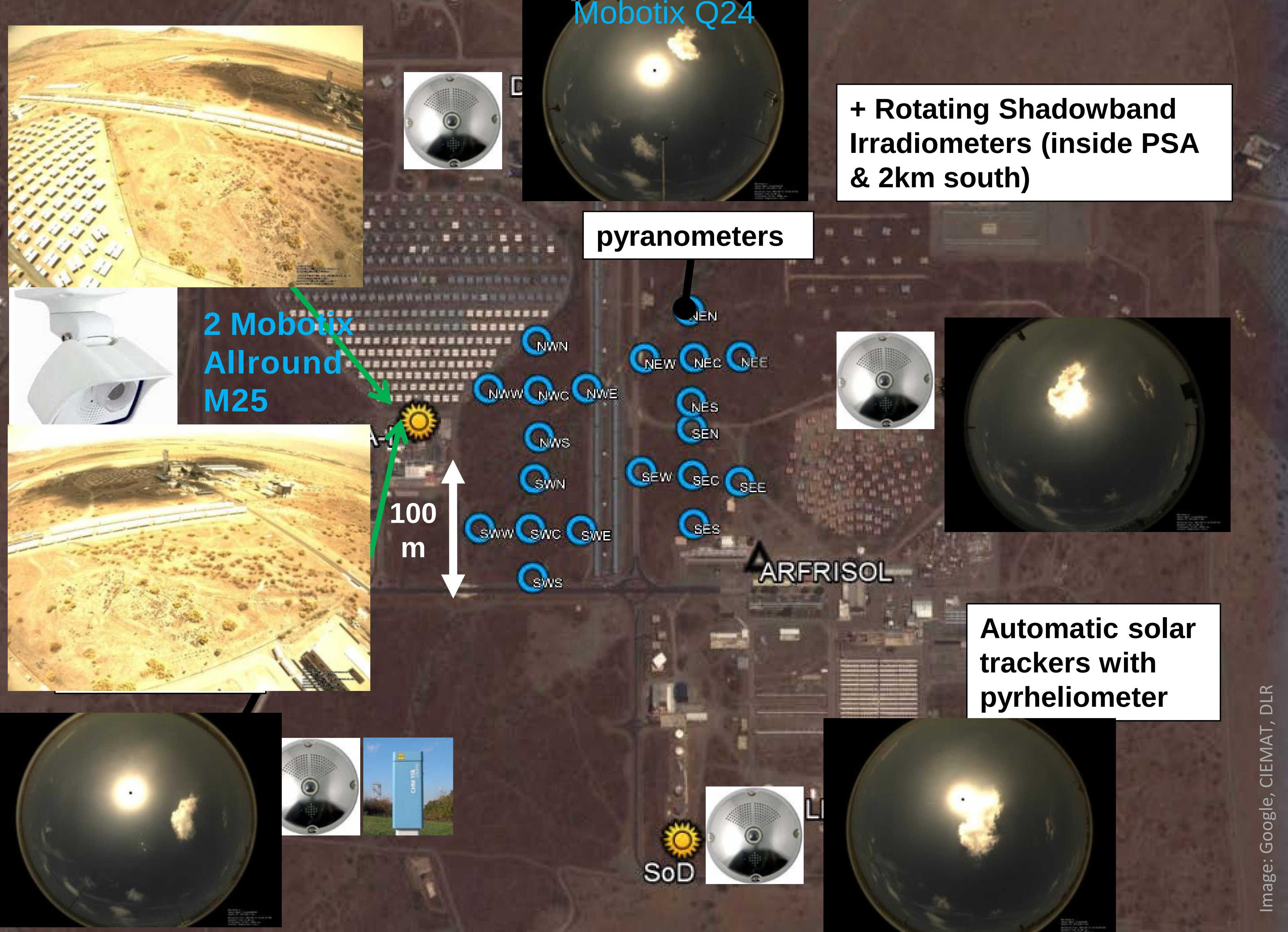
irradiance maps with high temporal and spatial resolution (nowcasts and live information) from cloud camera system





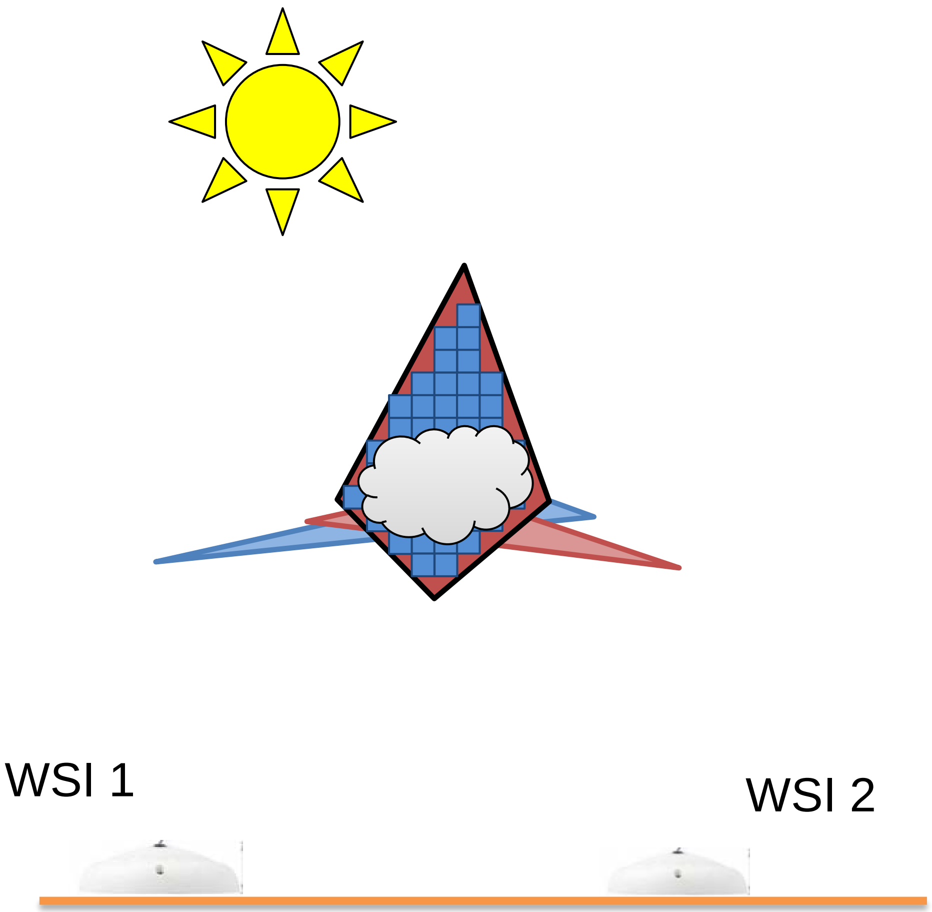
- Challenges:
  - High variability
  - Complex cloud formation/motion

  - Captured at PSA
    2014- 05-28, 10:00 - 17:00


Mobotix Q24
+ Rotating Shadowband Irradiometers (inside PSA & 2km south)
pyranometers
2 Mobotix Allround M25
NEN
NWN
NEW
NEC
NEE
NWW
NWC
NWE
NES
SEN
NWS
SWN
SEW
SEC
SEE
100 m
SWW
SWC
SWE
SES
ARFRISOL
SWS
Automatic solar trackers with pyrheliometer
SoD
Image: Google, CIEMAT, DLR

Approach: Voxel carving

1. Cloud-segmentation
2. Back-projection of detected clouds view cone
3. Intersection of view cones = cloud



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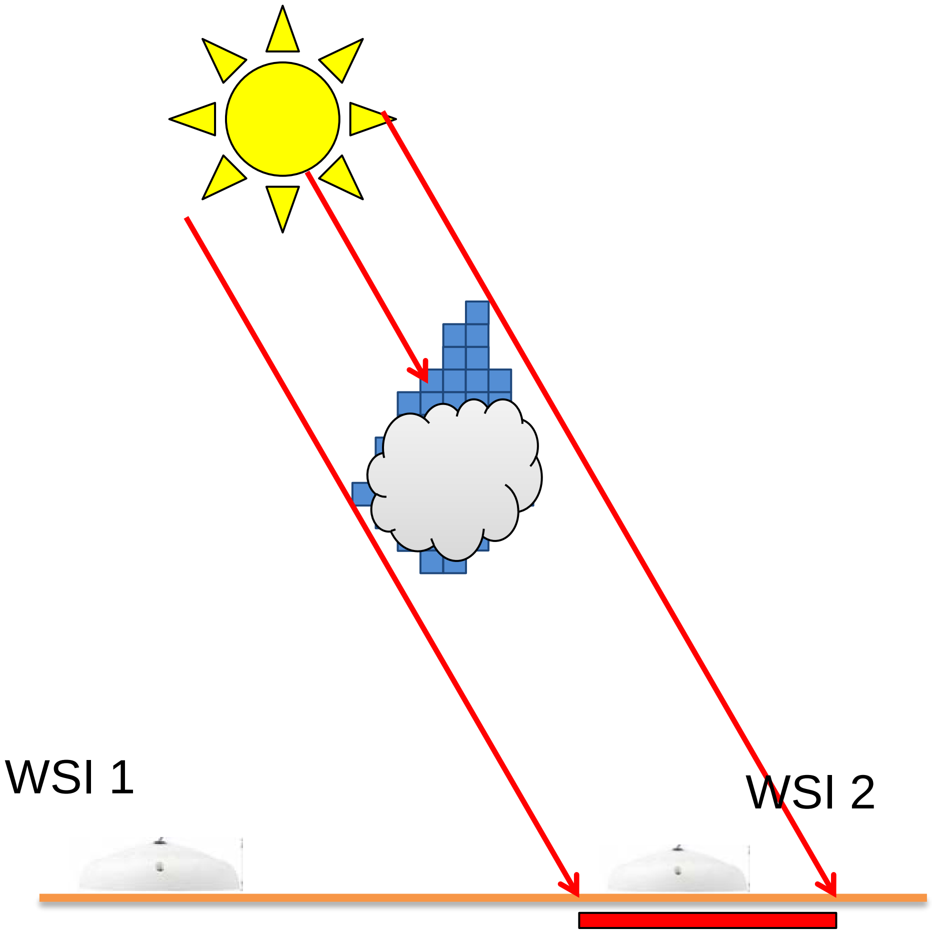
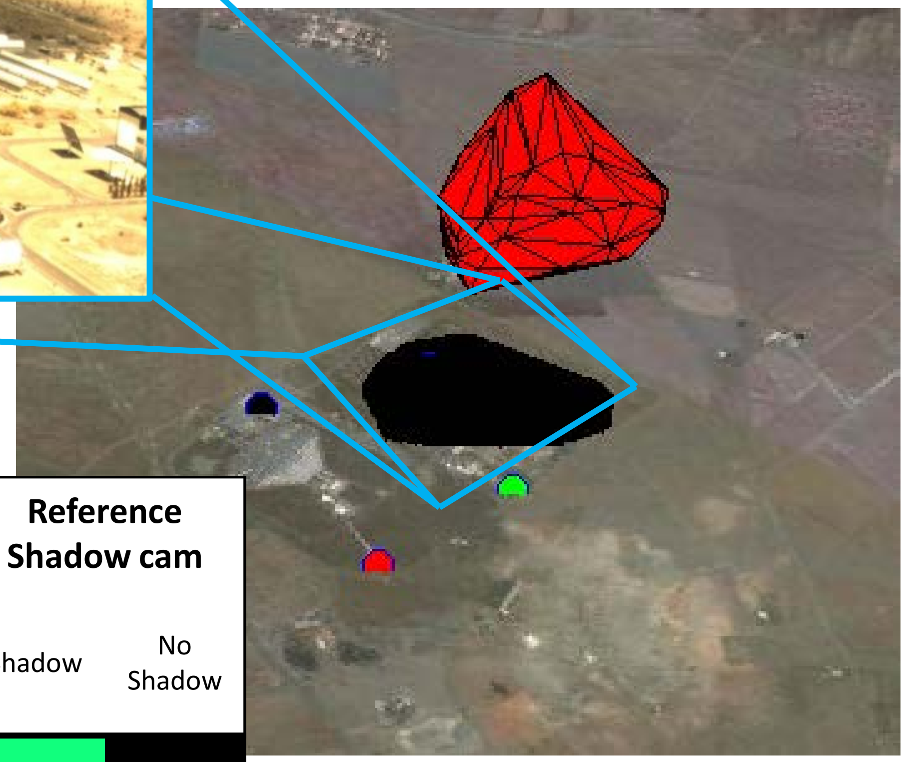
Approach: Voxel carving

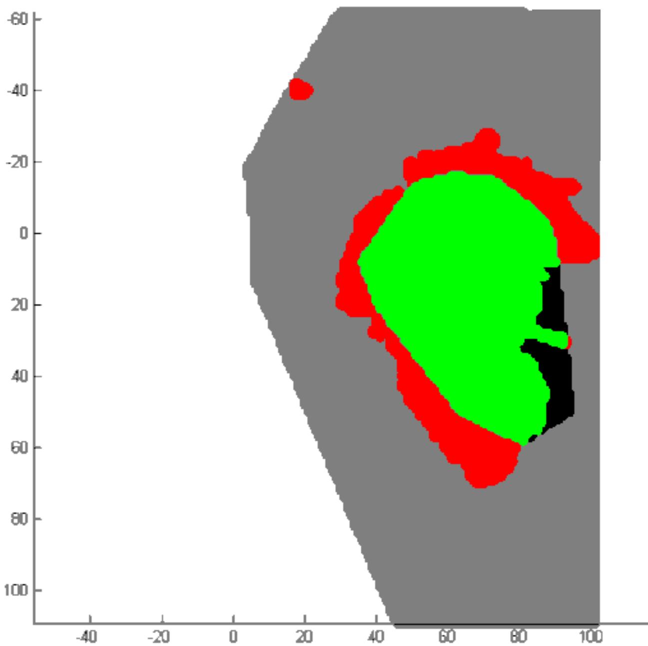
1. Cloud-segmentation
2. Back-projection of detected clouds view cone
3. Intersection of view cones = cloud
4. Calculation of modeled shadow



Validation of modeled shadow

- Tested with ~100 cases with average ACC = 0,72
- Prototype of system (hardware + processing) running live at PSA





		Reference Shadow cam	
	(Pixel)	Shadow	No Shadow
Model Voxel Carv.	Shadow	TP	FP
	No shadow	FN	TN

ACC = (TP + TN)/surface = 0.76

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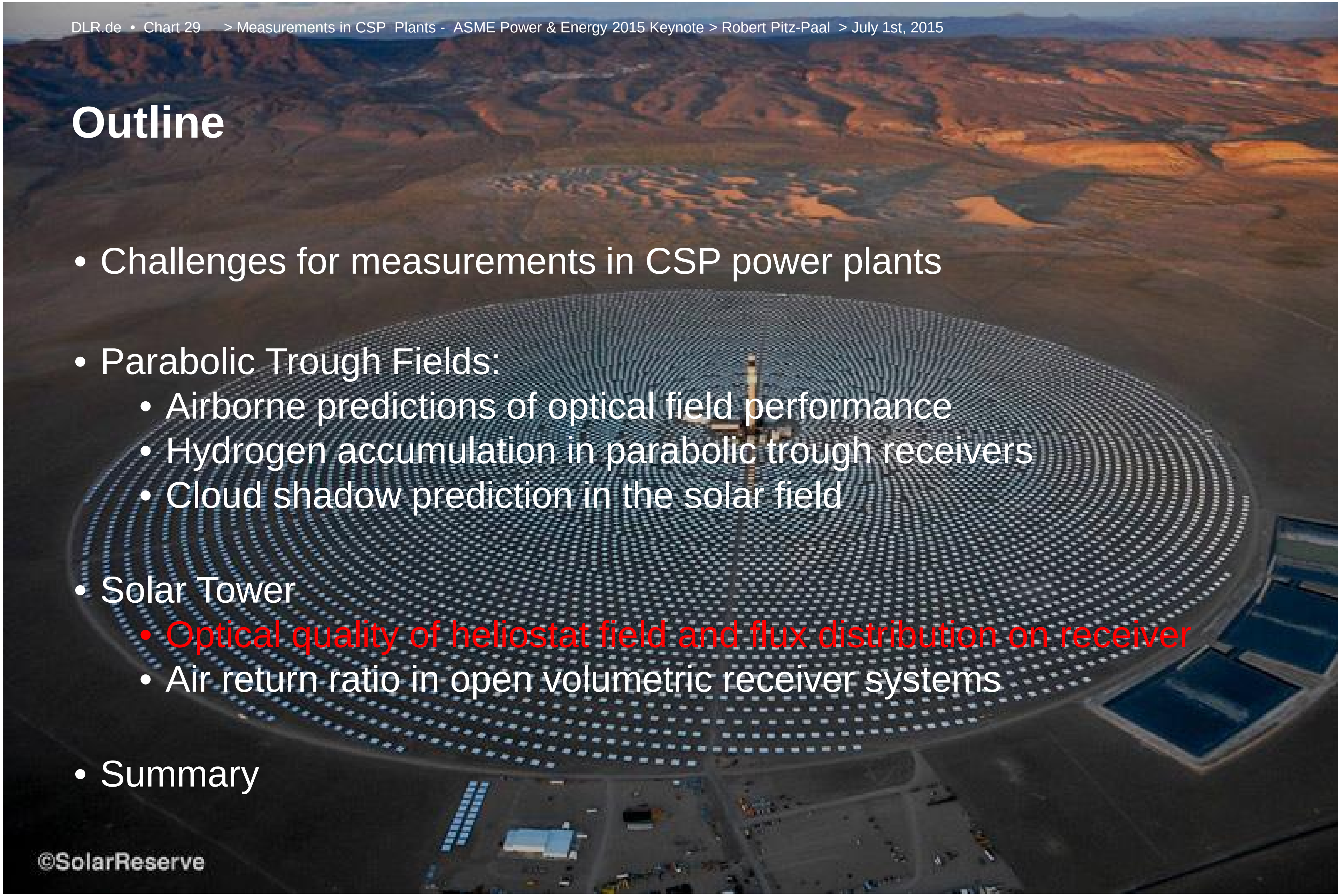

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Evaluation of Heliostat Field Optical Quality

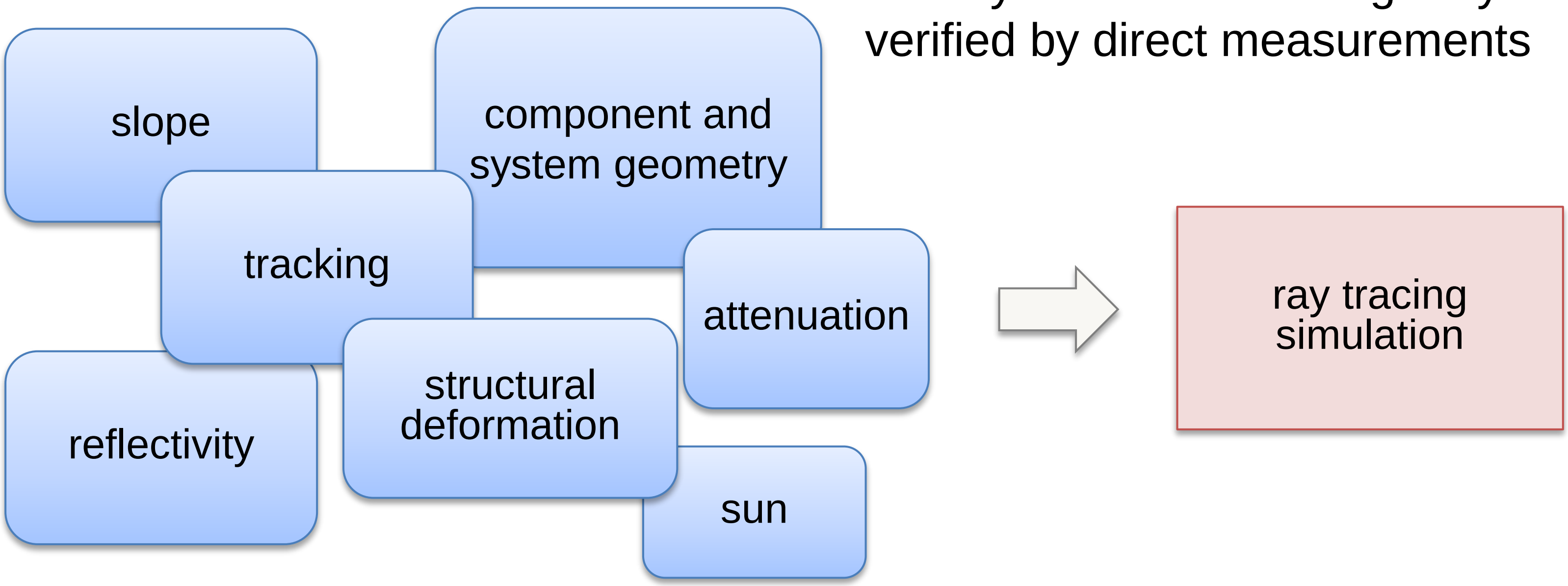
Problem:

Measurement of flux density distribution on aperture is not practical for large commercial (external) receivers

Solution:

Measurement supported simulation

= Assessment of field parameters by qualification of entire heliostat field (or random samples) as basis for flux density calculation through ray tracing, verified by direct measurements



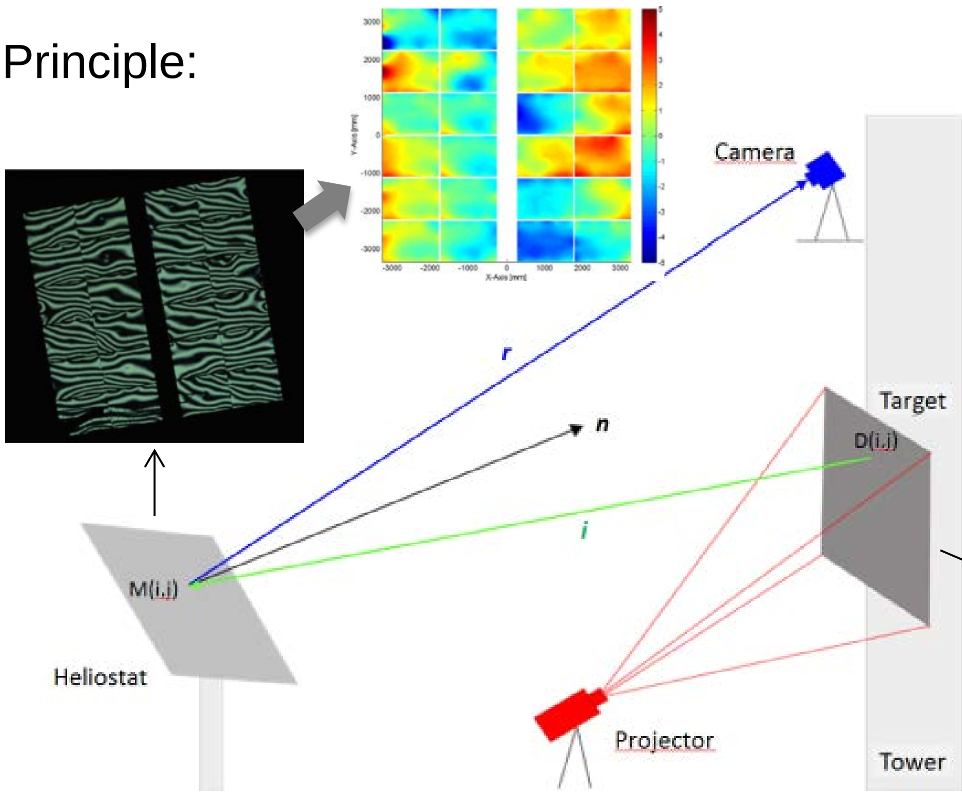
Assessment of Heliostat Field Parameters

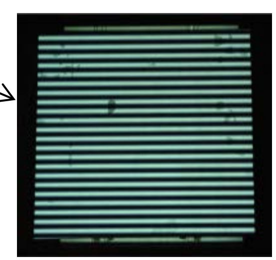
parameter(s)	assessment method	coverage
slope (mirror shape and canting)	automated deflectometry	total/ sample
structural deformation	on-site photogrammetry	sample
component and system geometry (size and positions of heliostats and receiver)	triangulation, stereo camera	sample
reflectance	on-site reflectometer device	sample
tracking accuracy	calibration (camera/target)	total
sun (DNI, sunshape)	on-site pyrheliometer and CCD camera	total
atmospheric attenuation	transmissometer, scatterometer	sample

Automated Deflectometry Measurement

Deflectometry (= fringe reflection): observation of deformation of regular stripe patterns through reflection

Principle:





- resolution: 10^6 points per heliostat
- accuracy: < 0.2 mrad*

can be used for

- prototype testing
- qualification during production

*Ulmer, S. et al. Automated high resolution measurement of heliostat slope errors. Sol. Energy (2010)

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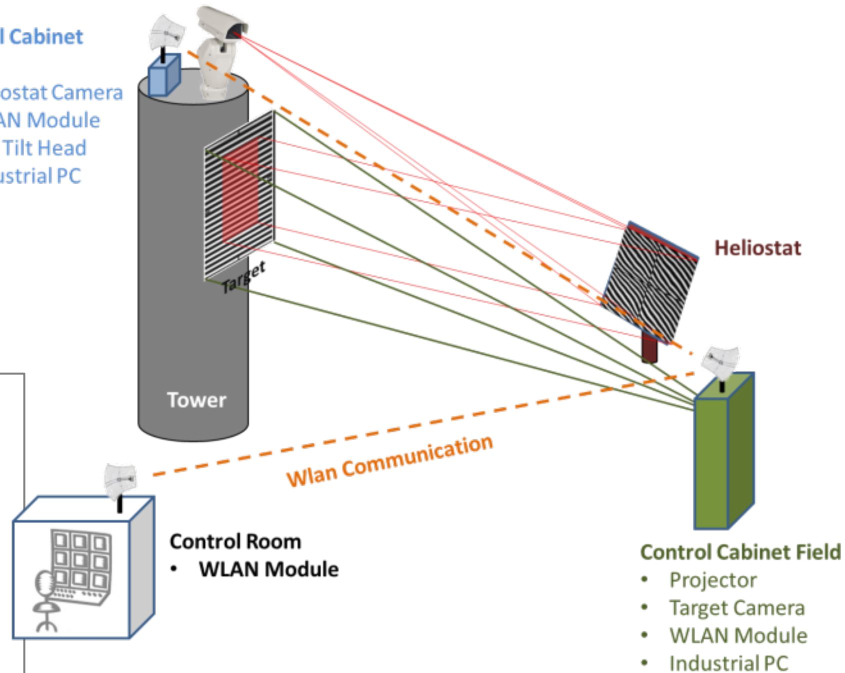
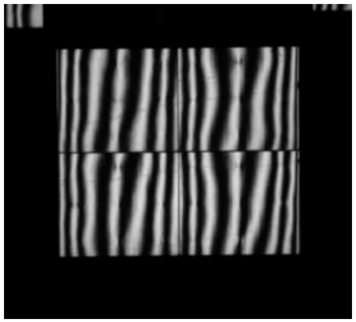
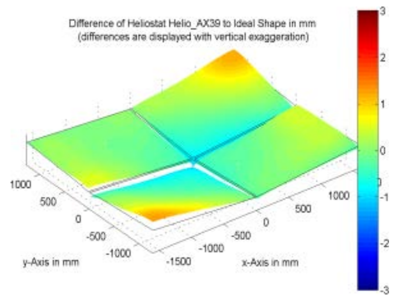
Automated Deflectometry Measurement

Automated deflectometry measurement of existing heliostat field (total/samples)







- automatic selection of single heliostats/groups
- automatic measurement and data processing
- output of report and input data file for ray tracing
- performance: ~60sec./hel.

can be used for:

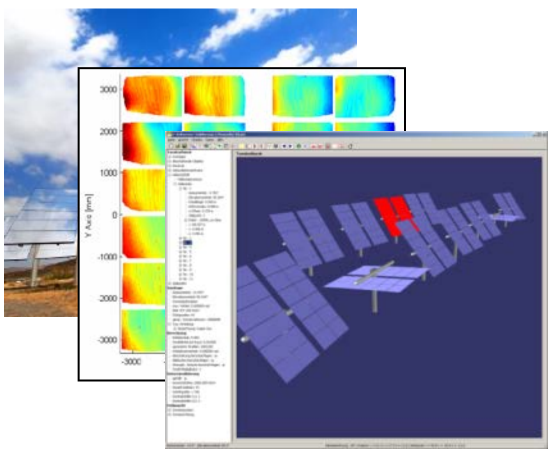
- field qualification during commissioning
- regular assessment of field quality during operation

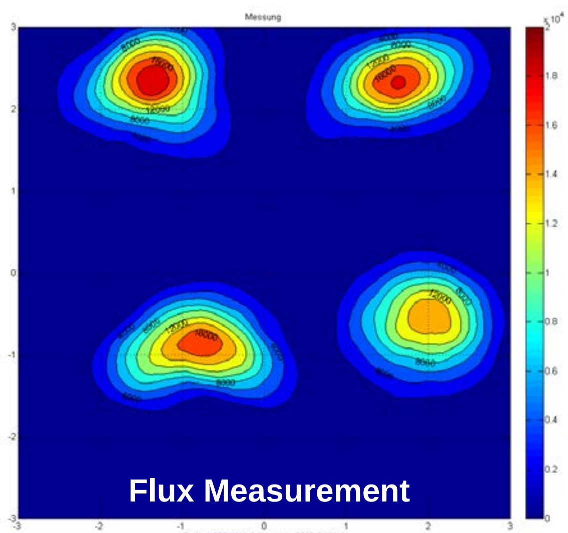
High Precision Ray-Tracing of Heliostat Field

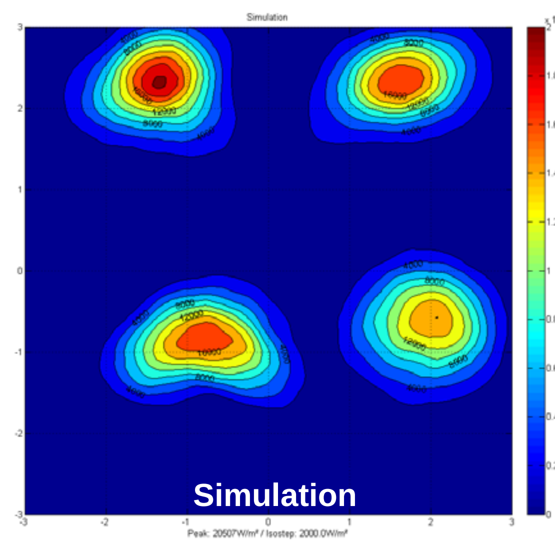
- ray tracing using deflectometry surface data in original resolution
- efficient ray generation and usage; utilization of modern cpu capabilites (SIMD, multi-threading)

→ calculation performance: > $60 \cdot 10^6$ rays/sec using a standard pc (8 cores)

- successful validation by comparison with flux measurement*

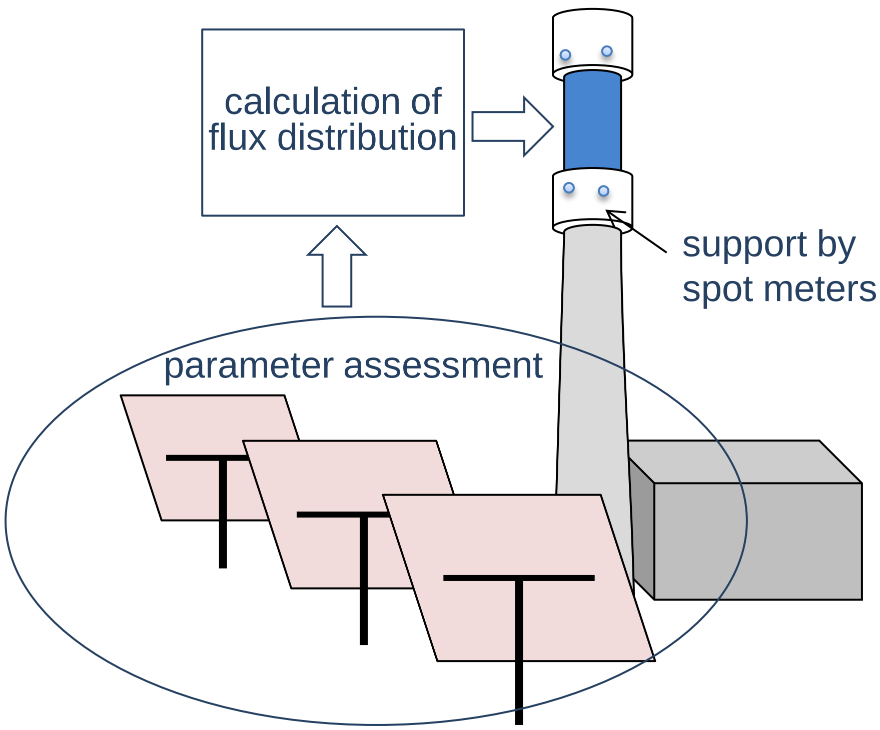






*Belhomme et al.
A New Fast Ray Tracing Tool for High-Precision Simulation of Heliostat Fields
ASME J. Sol. Energy Eng., (2009)

Measurement Supported Simulation of Heliostat Field



- high precision measurement systems
- calculation model covering all influence parameters
- reliability (confidence) improved by
  - high sampling rate
  - direct measurements

Application

<u>1. During hot commissioning:</u>
Which component is not meeting the contracted specifications?

- up to 100% measurement of guaranteed values
- calculation of intercept power with certain confidence level
- assessment of field and receiver efficiency

requirement: agree on measurement method and simulation model during contract negotiations

<u>2. During commercial operation</u>:
Why do we perform below expectation?
(… and what can we do to improve?)

- applicable to existing systems
- continuous / repeated measurements
- updated calculation every 15-60 minutes (for monitoring)

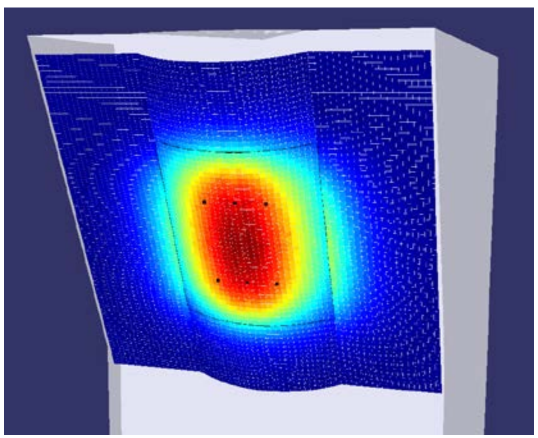
use gathered data to optimize aim point distribution on receiver surface (next slide)

Plant owner

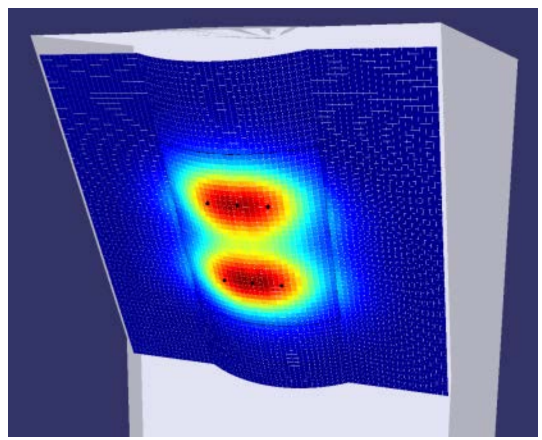
Simulation-Based Aim Point Optimization

Example: improvement of Solar Tower Jülich field performance

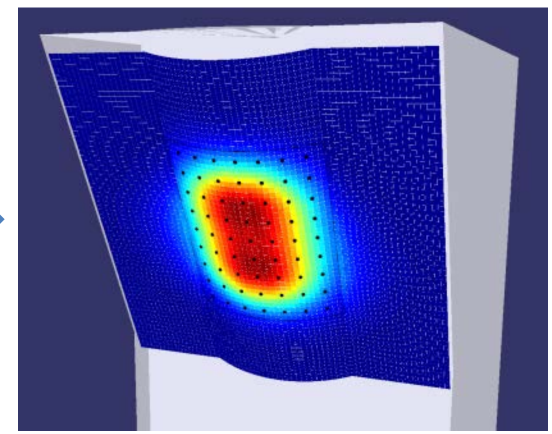
Ray tracing simulations based on deflectometry measurement of random samples



original heliostats
6 aim points
intercept: **0.706**



new heliostat facets
same aim points
intercept: **0.828**



new heliostat facets
aim point optimization
intercept: **0.861**

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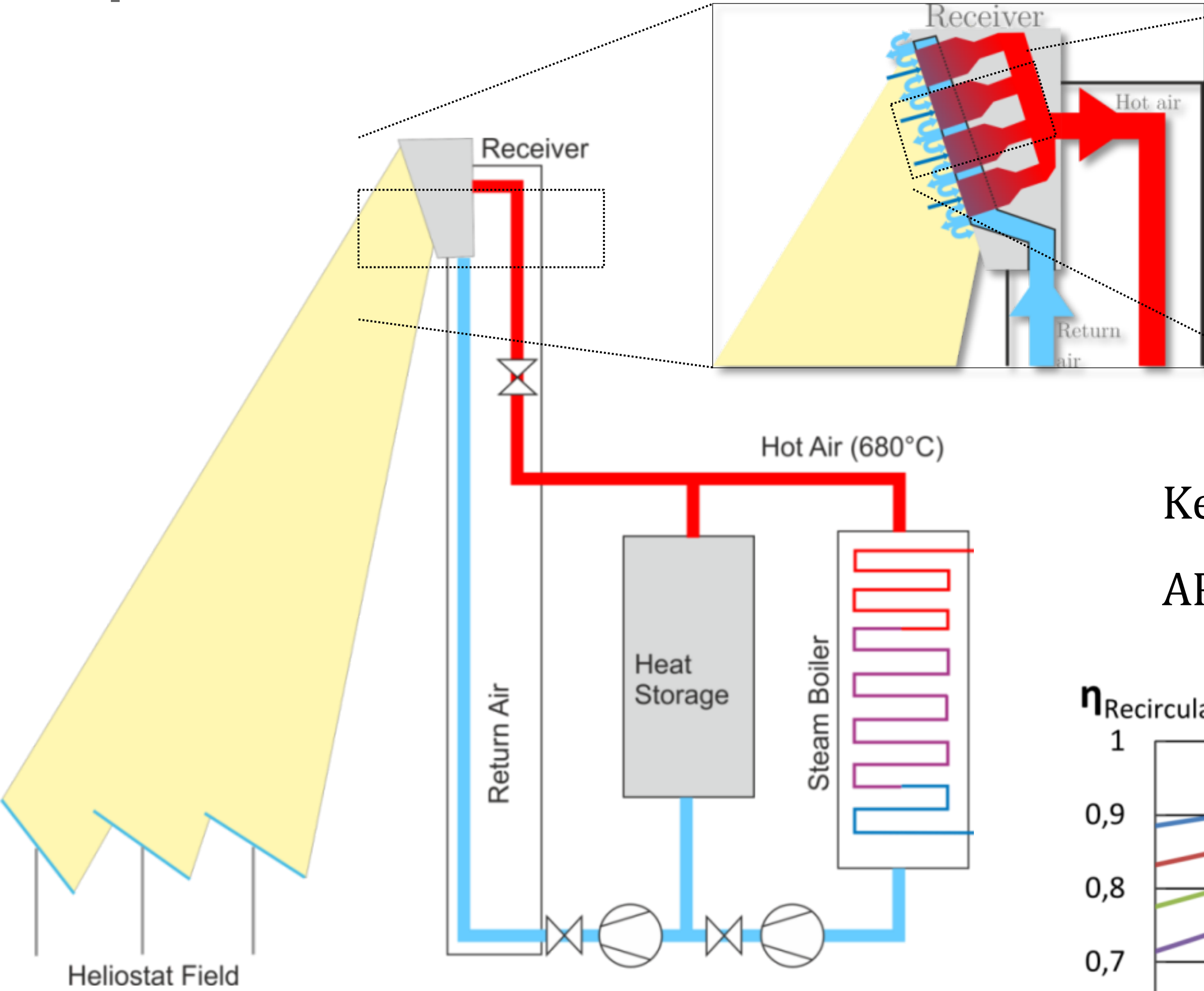
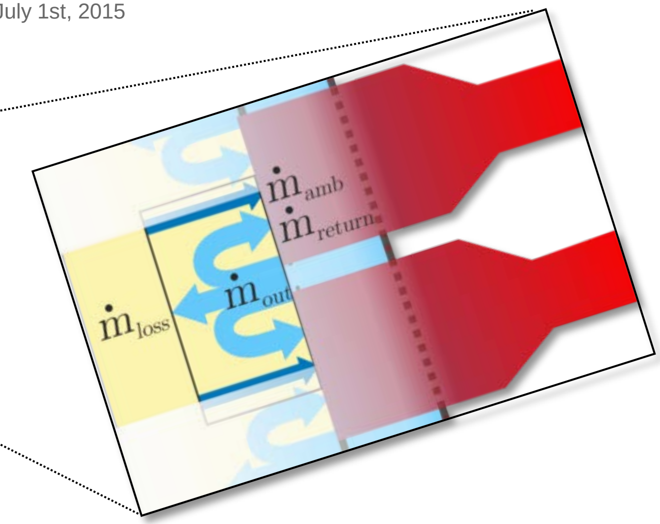
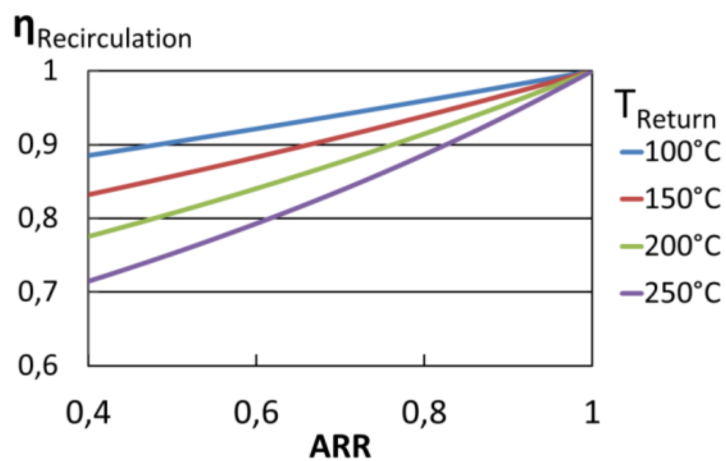
Open volumetric air receiver





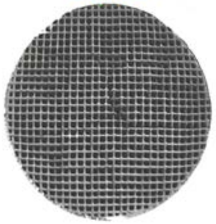
Keyfactor air return ratio:

$$ARR = \frac{\dot{m}_{\text{return}}}{\dot{m}_{\text{out}}}$$



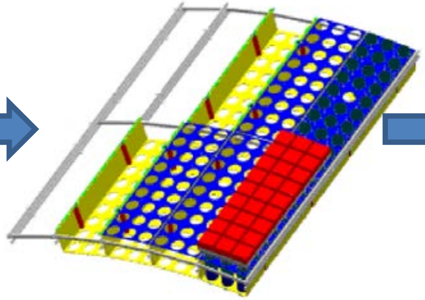
Solar Tower Jülich

Porous ceramic absorber



Absorber moduce

Sub-Receiver

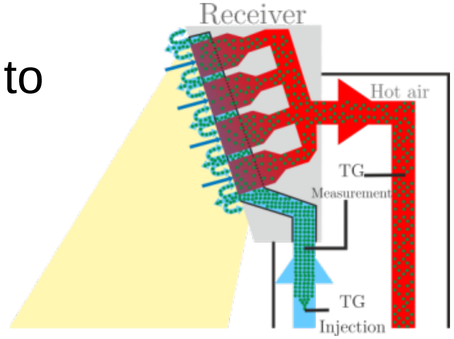


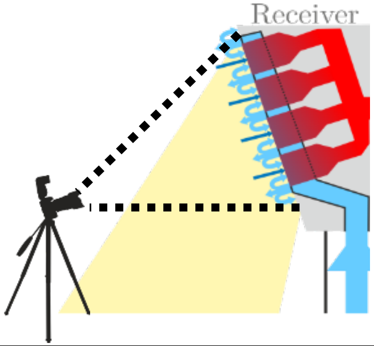
Receiver

Difficult measurement environment:

- High air mass flows
- High surface temperatures
- Concentrated solar radiation
- Large scales

Two approaches to measure ARR:



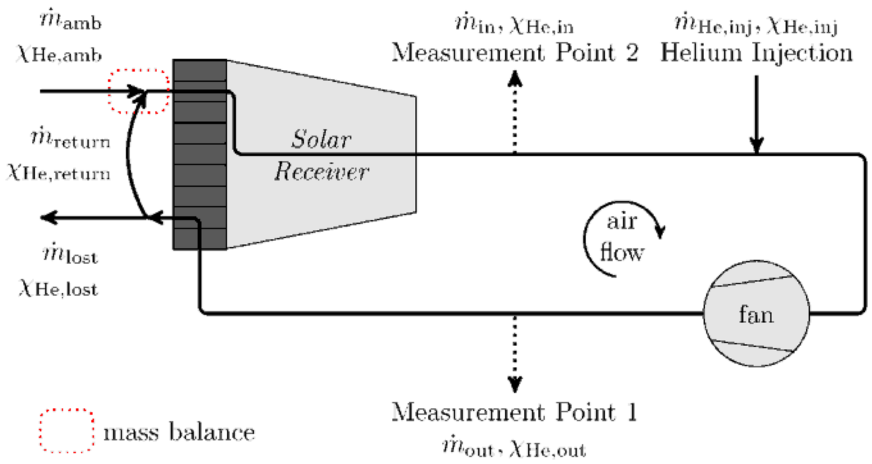


Quantitative ARR measurement with tracer gas	Qualitative ARR measurement with Induced Infrared Thermography

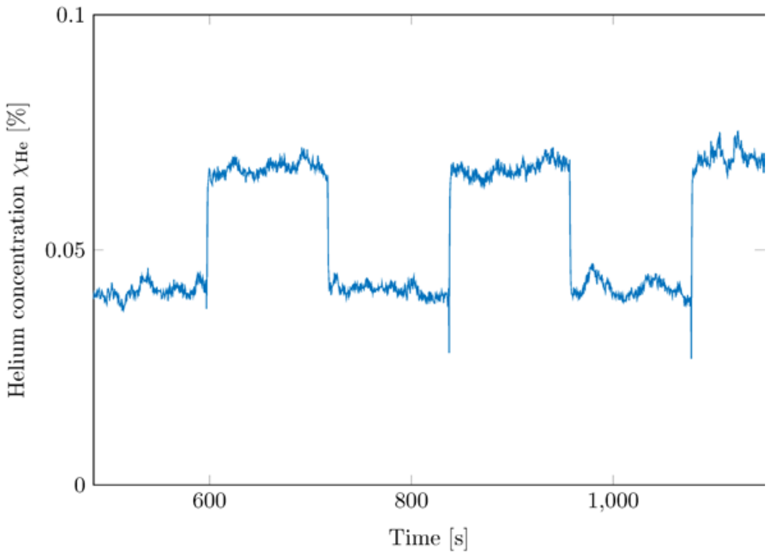
DLR

Tracer Gas Measurement

- Helium is used as tracer gas
- Helium is added to the system
  - Statically
  - Dynamically
- The Helium concentration response χ_{He} is measured using a mass spectrometer



Static Tracer Gas Measurement



- Both measuring points needed
- Straight forward measurement

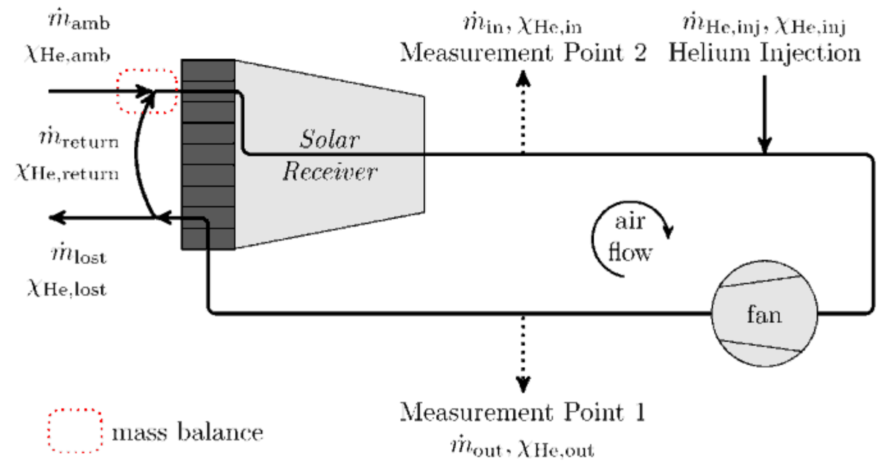
$$\mathrm{ARR}_{\mathrm{stat}} = \frac{\chi_{He,in}}{\chi_{He,out}}$$

Measurement at receiver model:

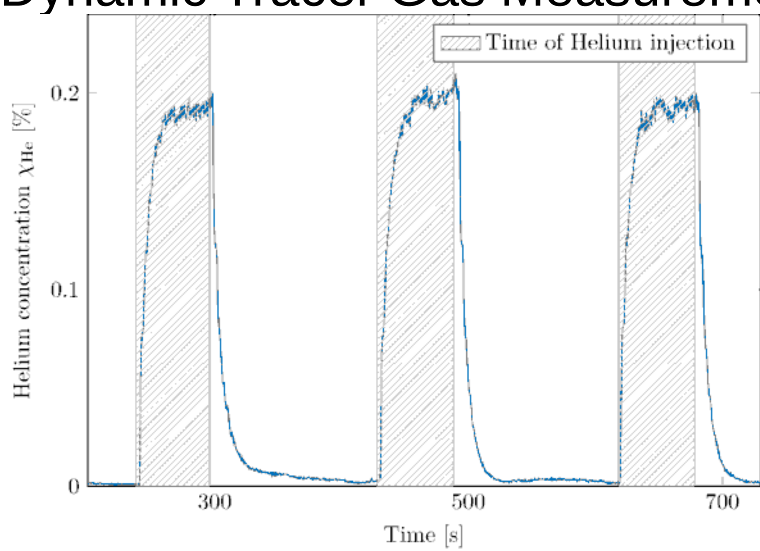
$$\mathrm{ARR}_{\mathrm{stat}} = (61.5 \pm 2.5)\%$$

Tracer Gas Measurement

- Helium is used as tracer gas
- Helium is added to the system
  - Statically
  - Dynamically
- The Helium concentration response χ_{He} is measured using a mass spectrometer



Dynamic Tracer Gas Measurement



- Only one measuring point needed
- ARR from dynamic response

$$\chi_{He,leading}(t) = A\left(1 - ARR^{t\backslash\mathrm{T}}\right)$$

$$\chi_{He,trailing}(t) = A \cdot ARR^{t\backslash\mathrm{T}}$$

Further measurements needed:

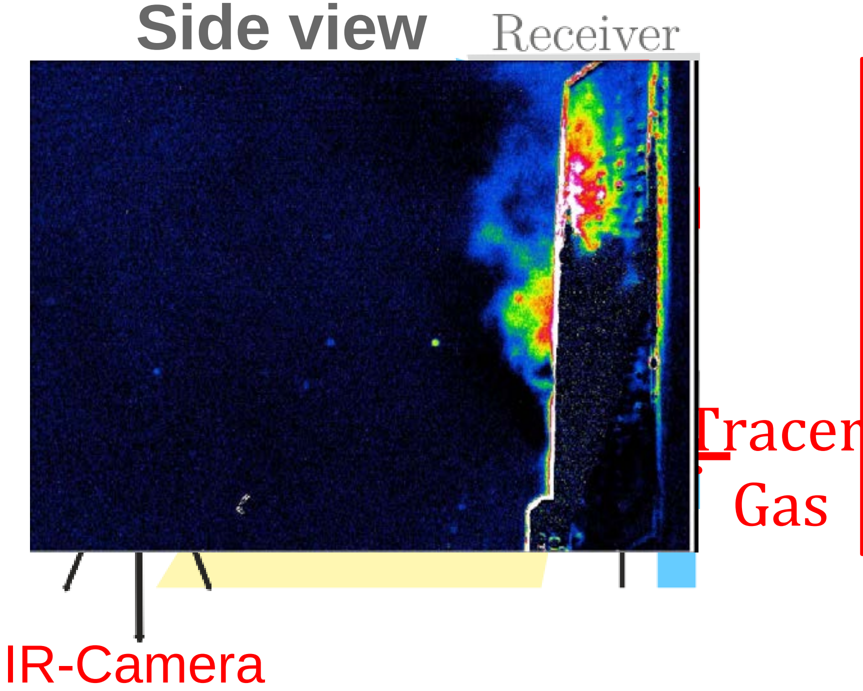
- Circulation period T
- Transfer function for dynamic error correction using system identification

Measurement at receiver model:

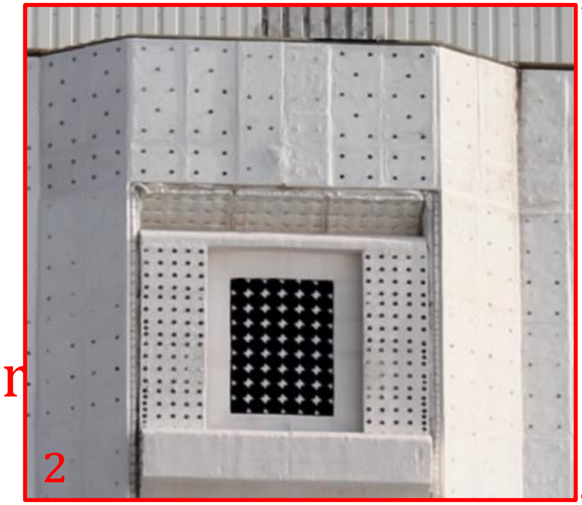
$$\mathrm{ARR}_{\mathrm{dyn}} = (63.2 \pm 4.0)\%$$

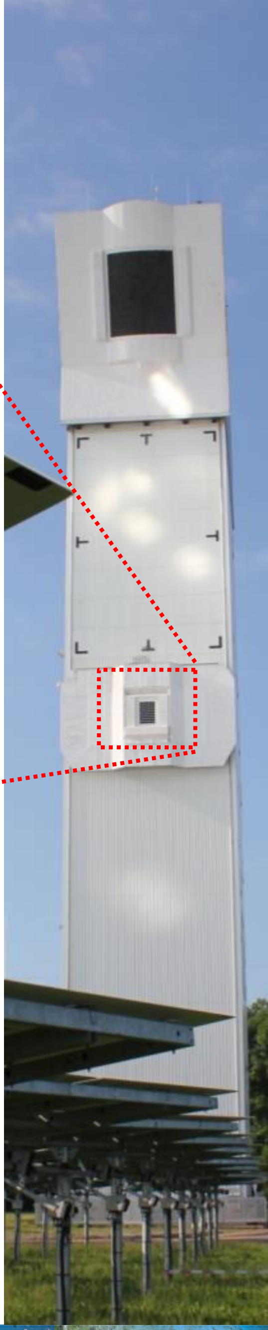
Induced Infrared Thermography (IIT)

Side view



Front view





Summary and Conclusion

- DLR has developed a variety of tools in order to perform measurements in commercial scale trough and tower systems that go far beyond simple heat balance measurements
- All measurements have been validated in large scale facilities like the Plataforma Solar de Almería or the Research Facility Solar Tower Jülich
- Some of the measurements have been applied already in commercial full scale power plants in cooperation with the DLR Spin-off company CSP Services
- Commercial CSP applications require new methods under commercial conditions DLR and partners have the tools and validations to provide solutions

In addition we have extensive laboratory testing facilities for industrial components ……

QUARZ Test and Qualification Center
Performance and Durability Testing

Mirror Panels
- Shape accuracy (also sag under different load conditions)
- Reflectance (specular and spectral hemispheric)
- Corrosion and abrasion tests
- Outdoor exposure at desert and coastal sites

Parabolic Trough Receiver
- Optical efficiency
- Thermal power loss
- Overheating & thermal cycling (aging of coating)
- Bellow fatigue tests (mechanical aging)
- Anti-reflective coating of glass envelope
- Operability tests under real solar conditions

Collectors
- Peak efficiency, Thermal characteristics, Incident angle modifier, behavior under different load conditions, Torsion


Mirror shape measurement


Receiver optical performance test


Rotary collector test bench (KONTAS)

Thank you for your attention

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