Benchmarking cloud height and cloud motion measurements

Pascal Kuhn, Pascal.Kuhn@dlr.de

M. Wirtz, S. Wilbert, N. Killius, J. L. Bosch, G. Wang, N. Hanrieder, B. Nouri, J. Kleissl, L. Ramirez, L. Zarzalejo, M. Schroedter-Homscheidt, D. Heinemann, A. Kazantzidis, P. Blanc, R. Pitz-Paal

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Overview

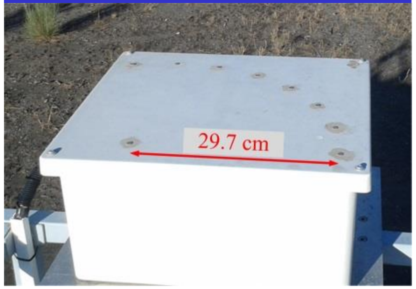
1. Relevance of <u>cloud height</u> and <u>cloud motion vector</u> measurements

2. Benchmarking five cloud height measurement systems

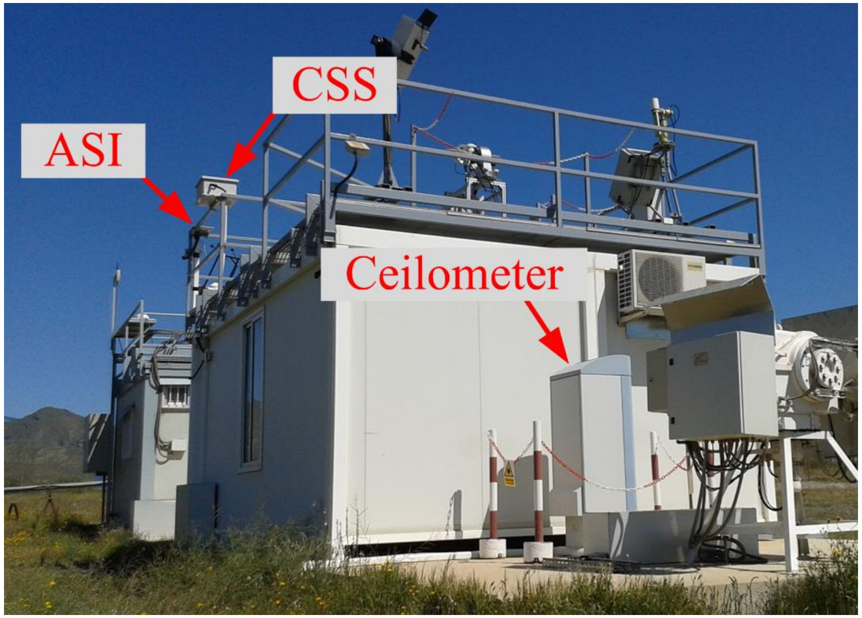
3. Development and application of a novel cloud motion vector reference

4. Conclusion and future work

Cloud Shadow Speed Sensor

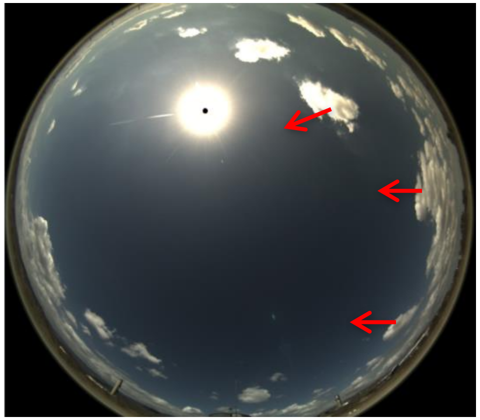


All-sky imager (ASI)



On the relevance of cloud motion vector measurements

Cloud motion vectors are important for forecasts and site evaluations



Cloud motion vectors are relevant for
- Solar forecasts
- Solar site assessments
  (expected max. ramp rates)
- Wind profiles at cloud heights
- Model inputs / reference measurements

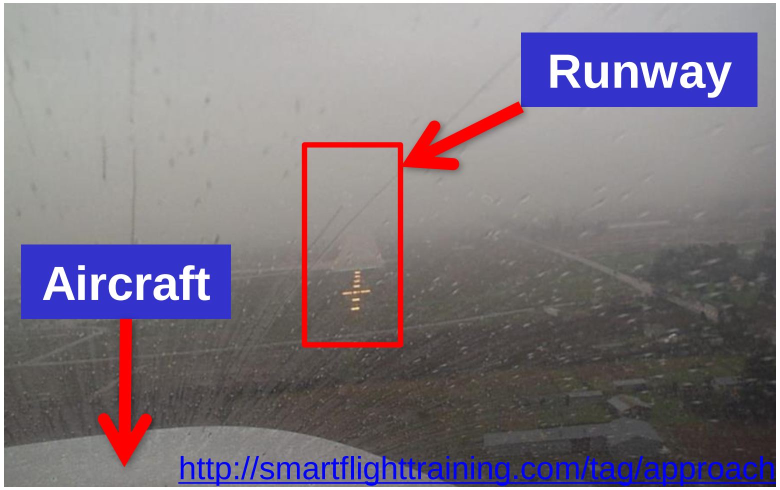
Reference cloud motion vectors could be used to validate
- NWP products
- Satellite-derived cloud motion vectors
- All-sky imager derived cloud motion vectors
- Cloud motion vectors derived by radiometer networks

Cheap, **low-maintenance**, **high-quality**, **long-term**
ground-based reference cloud motion vectors were previously not available.

On the relevance of cloud height measurements

Cloud height measurements are important for various applications

Reliable cloud height measurements are relevant for
- Solar forecasting
- Non-instrument rated flight operations
- Variety of leisure activities
- Model inputs / reference measurements



Report: Scottsdale attorney who died in plane crash not certified to fly in bad weather

Jason Pohl | The Republic | azcentral.com
Published 2:22 p.m. UTC Mar 16, 2018
https://goo.gl/9Hnc9e

Approaches to derive cloud heights:
- Ceilometer / LIDAR
- Radar
- Model-based (NWP)
- Satellite-based
- All-sky imager based
- …

What is the best approach to measure cloud heights?

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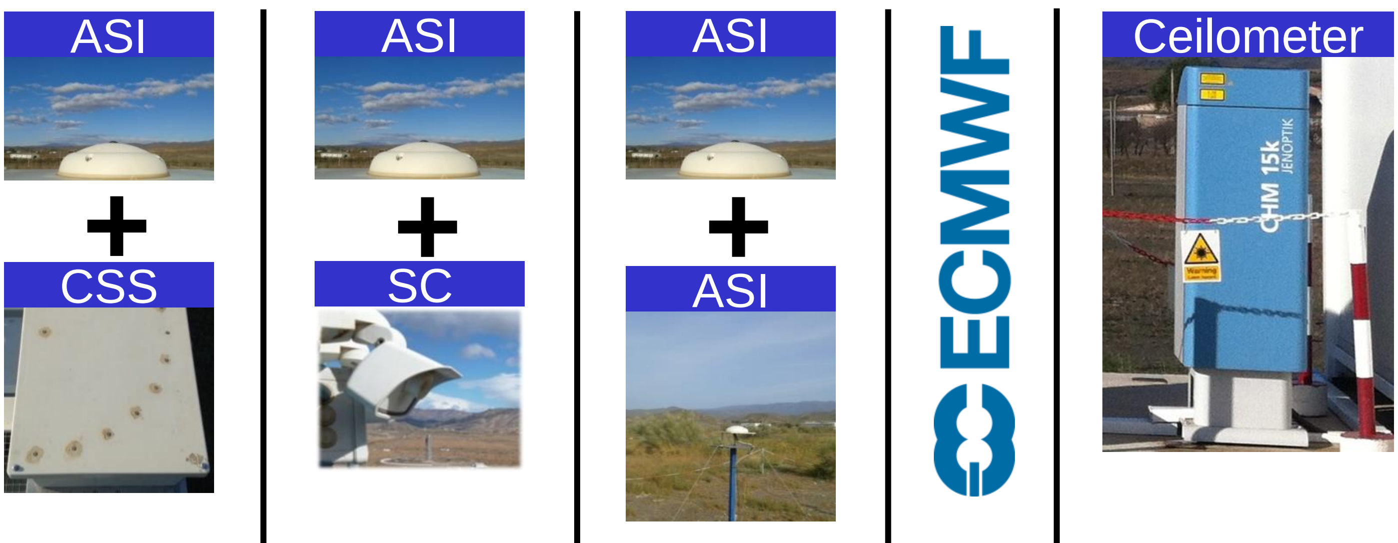
Benchmarking five cloud height measurement systems

Brief presentation of the considered approaches

1. Combination of one all-sky imager and a Cloud Shadow Speed Sensor
   - Adaption from Wang et al., https://doi.org/10.1016/j.solener.2016.02.027
2. Differential approach combining one all-sky imager and a shadow camera
3. Differential two all-sky imager approach
   - ➢ These approaches also provide cloud motion vector measurements

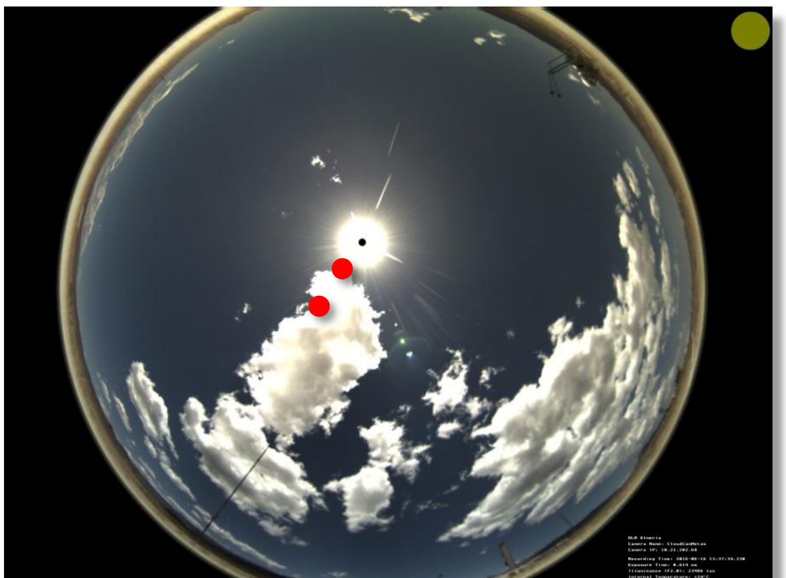
4. NWP cloud heights: Integrated Forecast System, ECMWF (3h data)
5. Ceilometer: CHM 15k NIMBUS, G. Lufft Mess- und Regeltechnik GmbH



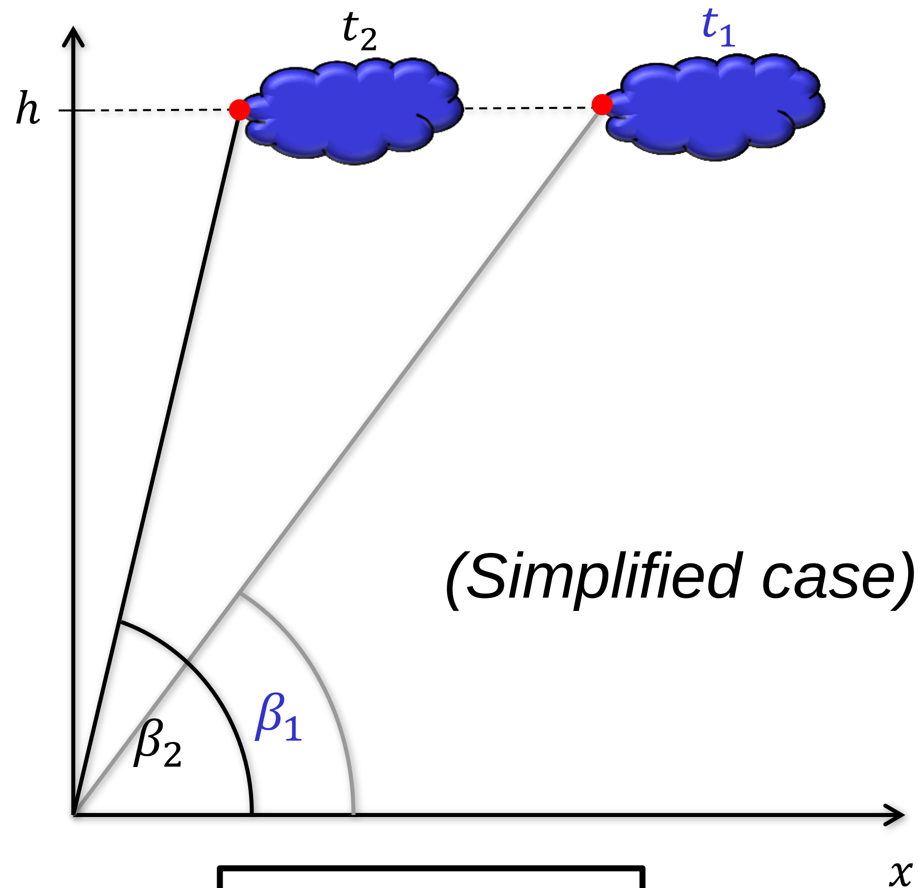
Ground-based cloud height measurement systems

Cloud heights are derived from cloud speeds in [rad/s] and [m/s]

Cloud height can be derived if $v_{rad/s}$ and $v_{m/s}$ are known



Time t_2

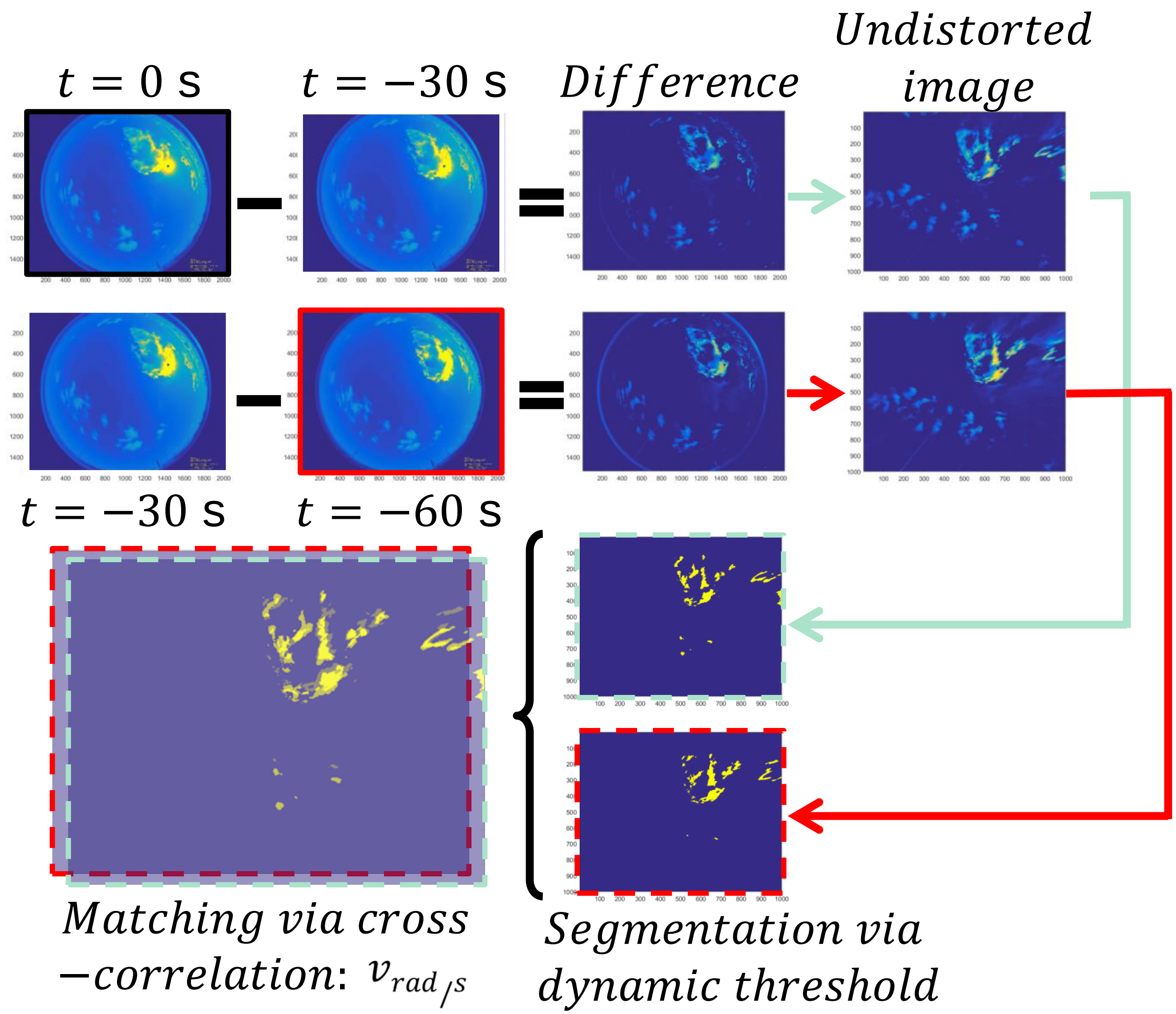


$$h = v_{m/s} \cdot \frac{(t_2 - t_1)}{\cot(\boldsymbol{\beta_1}) - \cot(\boldsymbol{\beta_2})} \rightarrow \sim \frac{\mathbf{1}}{v_{rad/s}}$$

Deriving $v_{rad/s}$ without detecting clouds

Cloud detection is a difficult task and an origin of deviations

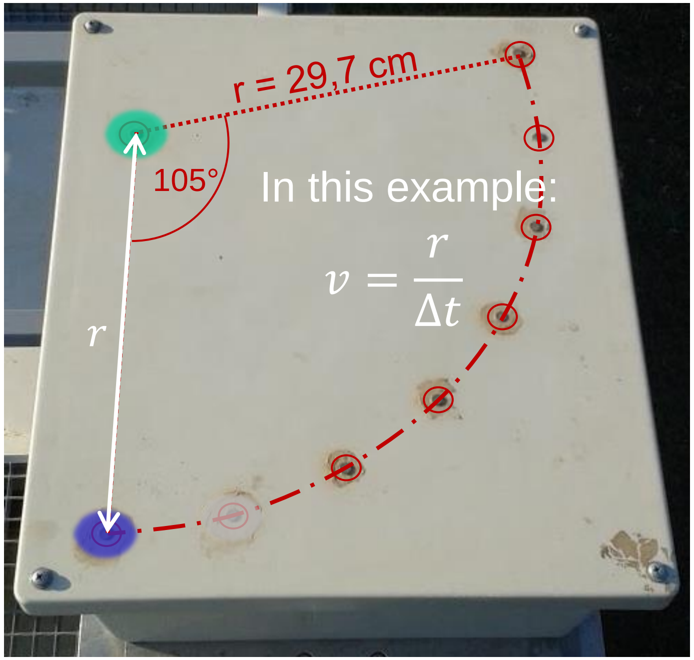
- Detecting clouds within all-sky images is surprisingly difficult
- Novel approach is independent from detecting clouds
- Difference images of the blue color channel are used
- More robust against dirt



We have the angular velocity – how do we get the absolute velocity [m/s]?

Cloud shadow speed sensor (CSS)

Detecting cloud shadow speeds by measuring signal ramps



(Simplified case)

Fung, V., Bosch, J. L., Roberts, S. W., and Kleissl, J.: Cloud shadow speed sensor, Atmos. Meas. Tech., 7, 1693-1700, doi:10.5194/amt-7-1693-2014 2014.

Shadow camera system (SC)

Detecting cloud shadow speeds by imaging an area

Off-the-shelf surveillance camera

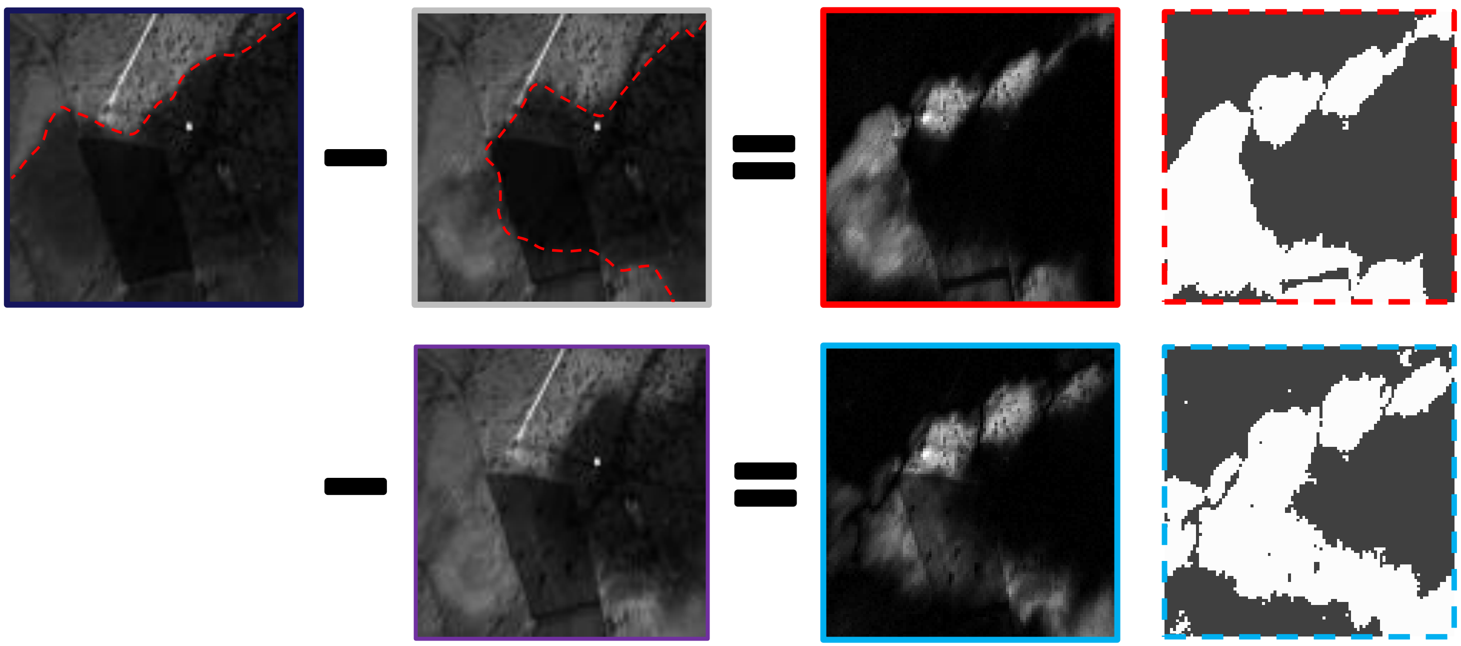
Shadow camera image (4 per minute)

Orthoimage (5m per pixel)

Obtaining cloud motion vectors with a shadow camera

Determination of motion vectors is independent from segmentation

$t = 0$ s $t = -15$ s



$\Delta \boldsymbol{x}$

$t = -15$ s $t = -30$ s

Shadow speed $v_{m/s} = \dfrac{\Delta \boldsymbol{x} \times k}{\Delta t}$

- $\Delta \boldsymbol{x}$: displacement [pixel]
- k: meter/pixel
- Δt: 15 s

Reference cloud (shadow) motion vectors:

- Low cost sensor
- Little maintenance is needed
- Aperture problem is less relevant

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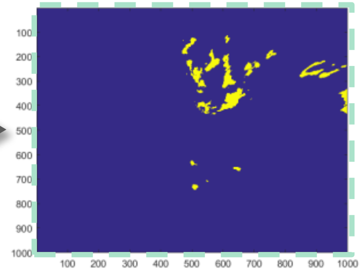
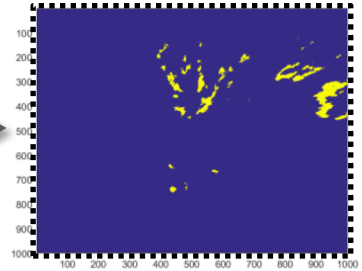
Using two all-sky imagers (ASI)

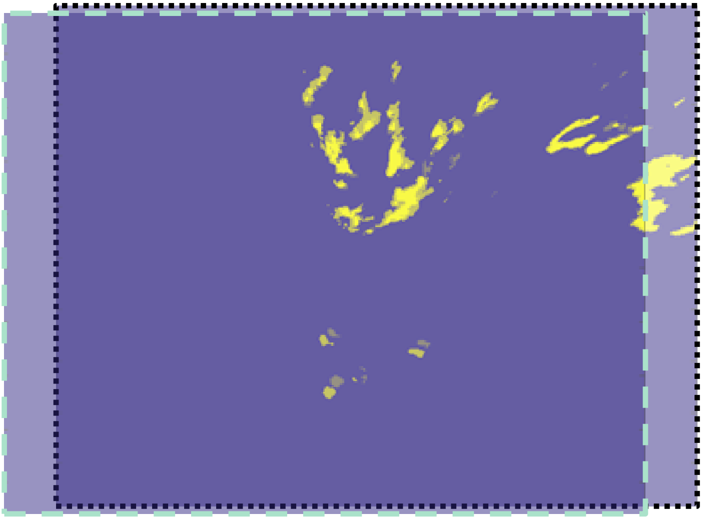
Measuring cloud speeds by matching difference images

All-sky imager 1

All-sky imager 2







Difference images of two ASIs at the same time

Matching via cross-correlation: $v_{m/s}$ is determined by the known distance between the cameras

- Two all-sky imagers are used
- Difference images are calculated as shown for $v_{rad/s}$

- No cloud detection needed - more resilient against dirt, more hardware-independent

Benchmarking five cloud height measurement systems

Results of the benchmarking campaign

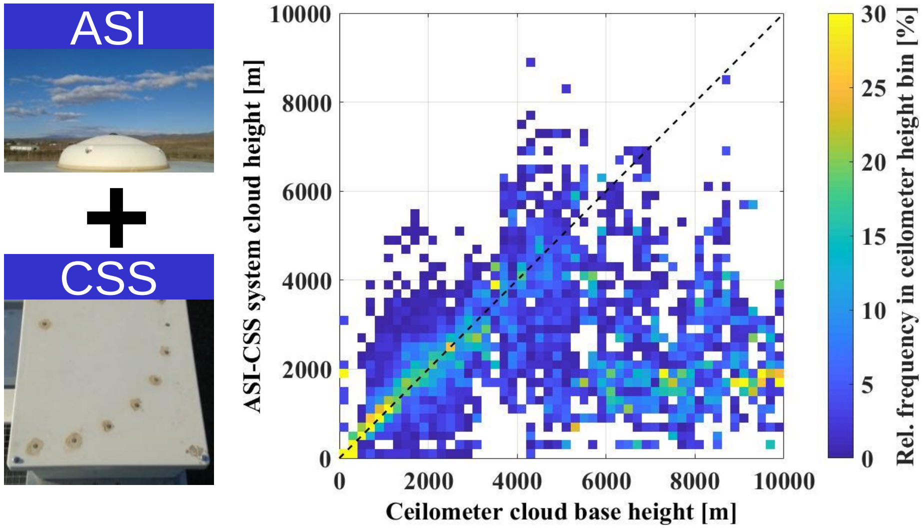
- Benchmarking campaign on 59 days
- Benchmarking site:

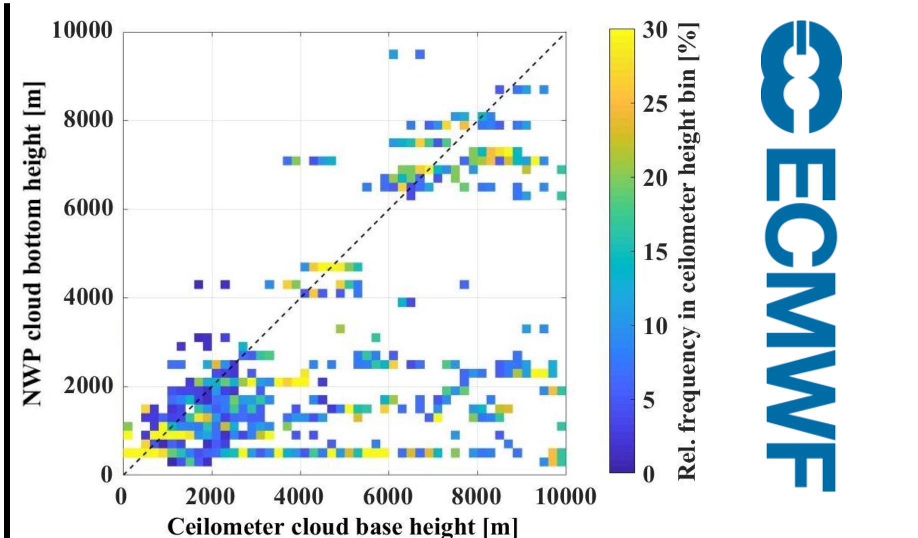
  Plataforma Solar de Almería, Spain
- Validation period contains large variety of cloud heights
- Multilayer cloud situations are included
- All considered systems provide one cloud height
  - For the ASI-ASI-approach, individual cloud heights can be derived
  - Systematic differences between point-like ceilometer cloud base heights and cloud heights derived by developed systems

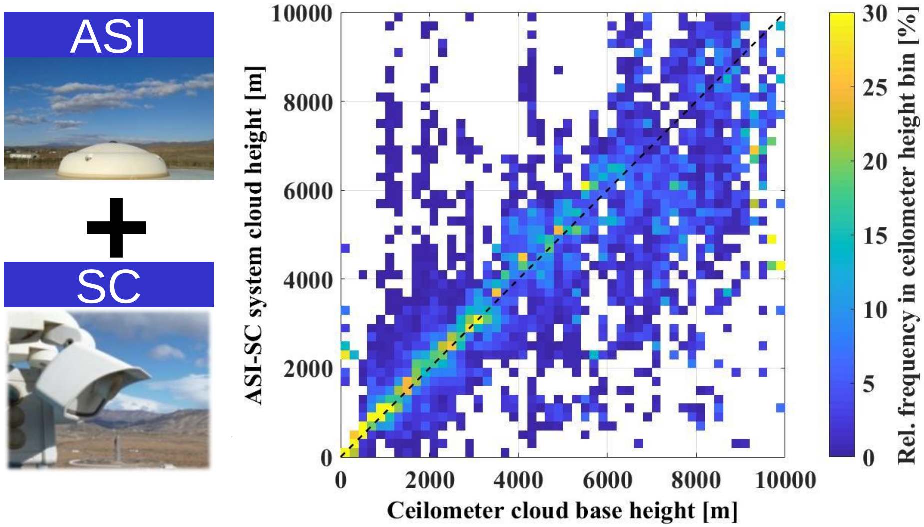
This study is published in
Kuhn et al., *Benchmarking three low-cost, low-maintenance cloud height measurement systems and ECMWF cloud heights against a ceilometer*, Solar Energy, 2018, https://doi.org/10.1016/j.solener.2018.02.050

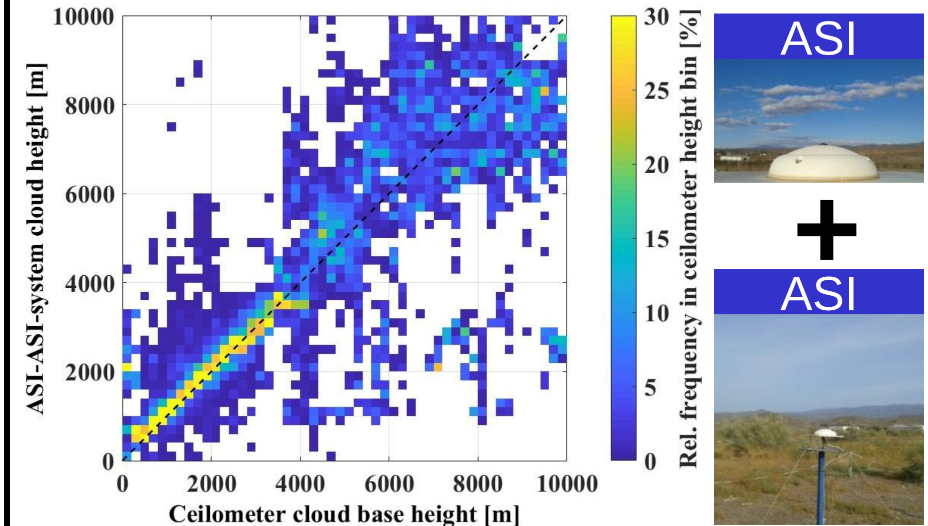
Benchmarking five cloud height measurement systems

Results of the benchmarking campaign



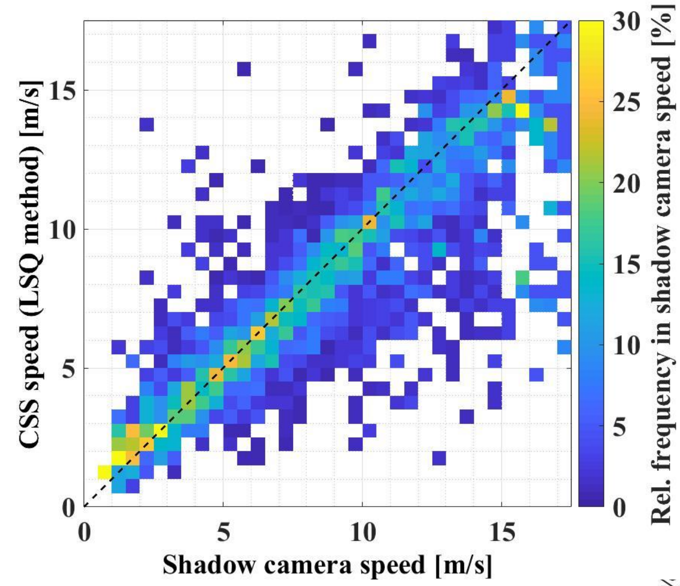


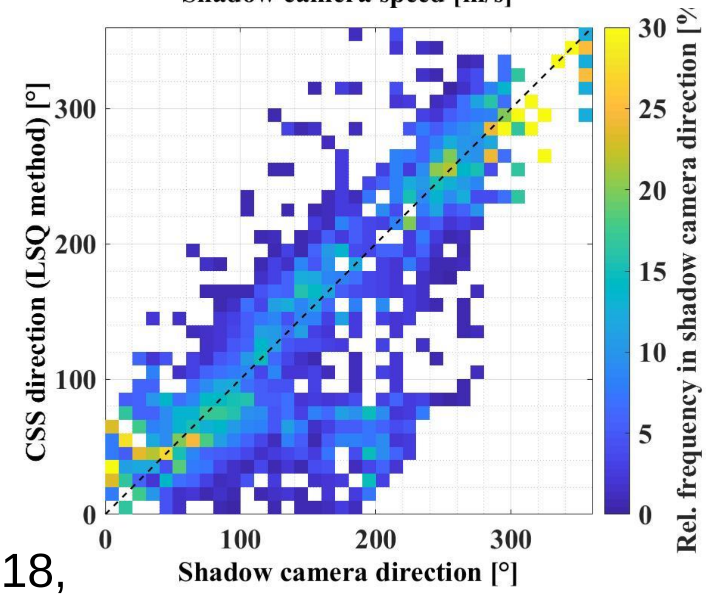




Development and application of the novel cloud motion vector reference on 59 days

- Validation of the Cloud Shadow Speed Sensor:
  - MAD: 1.6 m/s (21.9 %) w/o temp. avg.
  - MAD: 30.4°(16,8 %) w/o temp. avg.
  - Detection rate on 223 days: 3.7 % - 21.6 %
  - Aperture problem
- Data availability of the shadow camera reference system:
  - Years, 2015-2017
  - Currently looking for new setup, imaging a larger area
- Validation of all-sky imager derived cloud speeds conducted, publication in review





This study is published in
Kuhn, P., et al., *Field validation and benchmarking of a cloud shadow speed sensor*, Solar Energy, 2018, https://doi.org/10.1016/j.solener.2018.07.053.

Conclusion and further work

DNICast

- Three low-cost, low-maintenance systems to derive cloud motion vectors and cloud heights are developed and benchmarked to ECMWF and ceilometer data on 59 days
- A system consisting of two all-sky imagers shows the best accuracy in comparison to a ceilometer
- A novel method to derive reference cloud motion vectors was developed and applied to a Cloud Shadow Speed Sensor
- Cloud motion vectors can be derived and used as a reference for ground based sensors, satellite based products and NWP models
- Study on optimal distance between all-sky imagers finalized
- Future work: Camera-derived cloud heights for aviation

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Pascal Kuhn
Pascal.Kuhn@dlr.de

Thank you! Questions?

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Pascal.Kuhn@dlr.de