Benchmarking cloud height and cloud motion measurements

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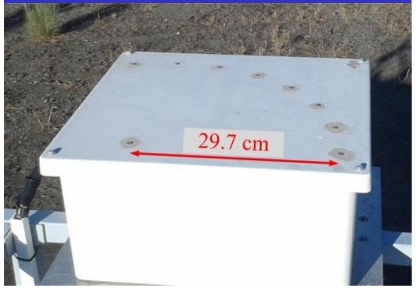
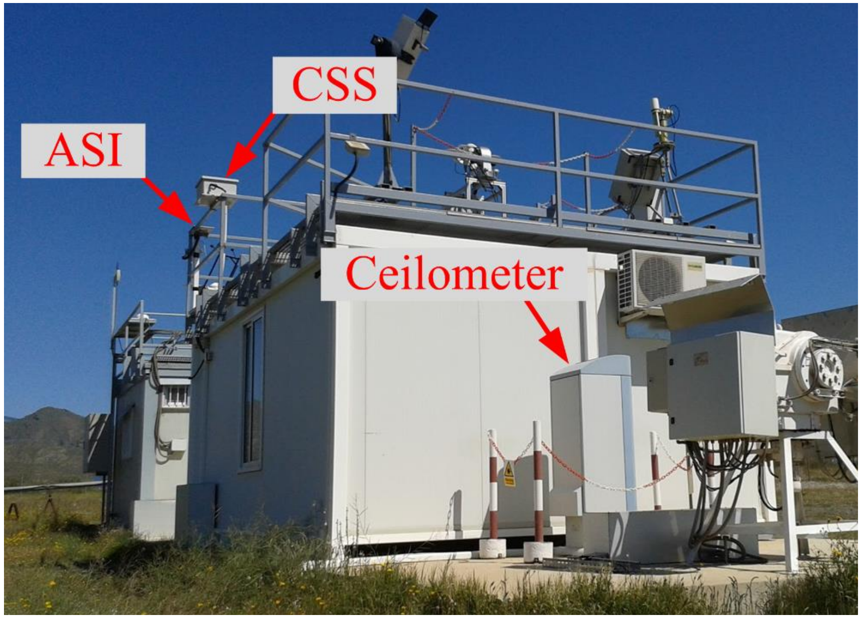
Overview

1. Relevance of cloud height and cloud motion vector 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

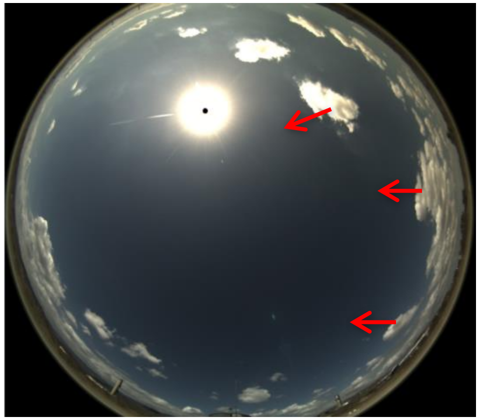


All-sky imager (ASI)



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.

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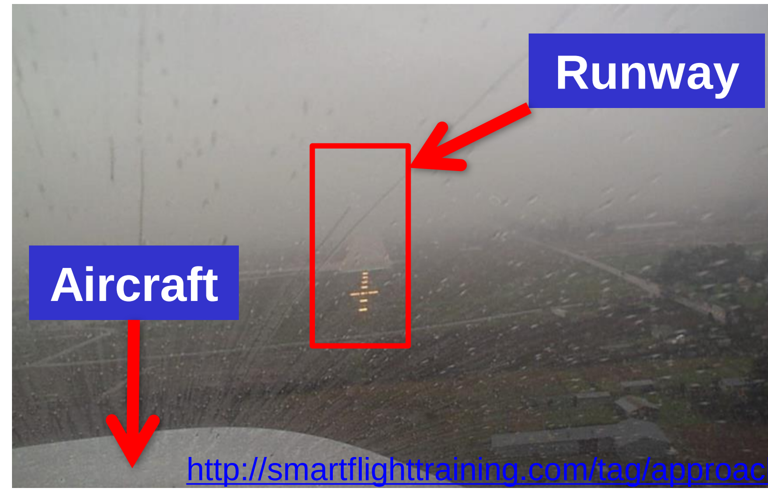
On the relevance of cloud height measurements

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
- …

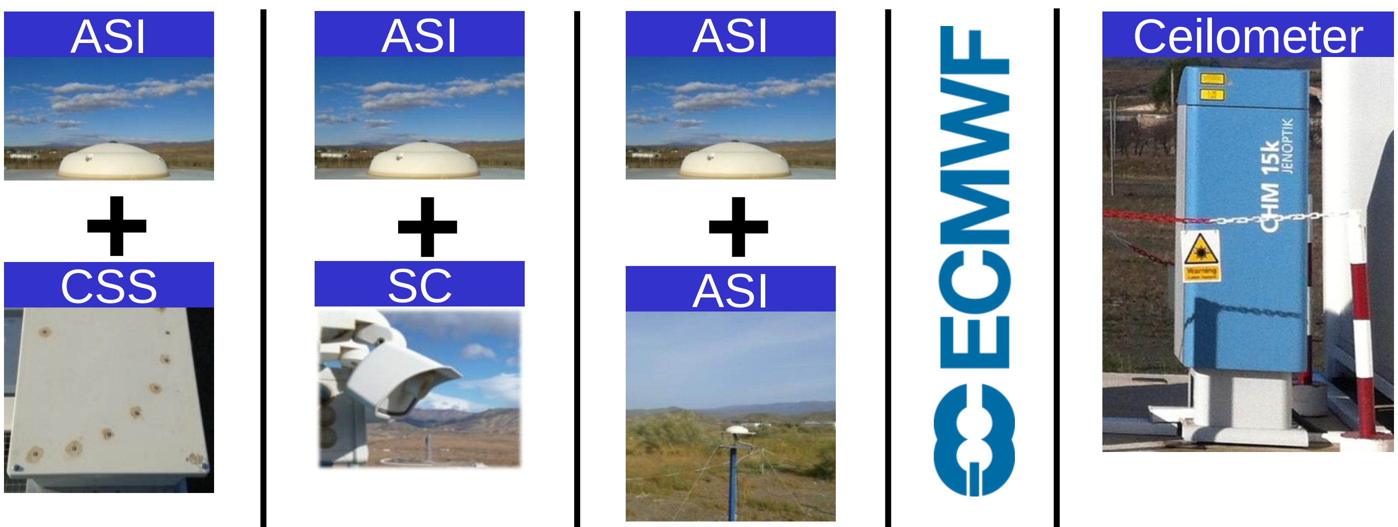
What is the best approach to measure cloud heights?

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

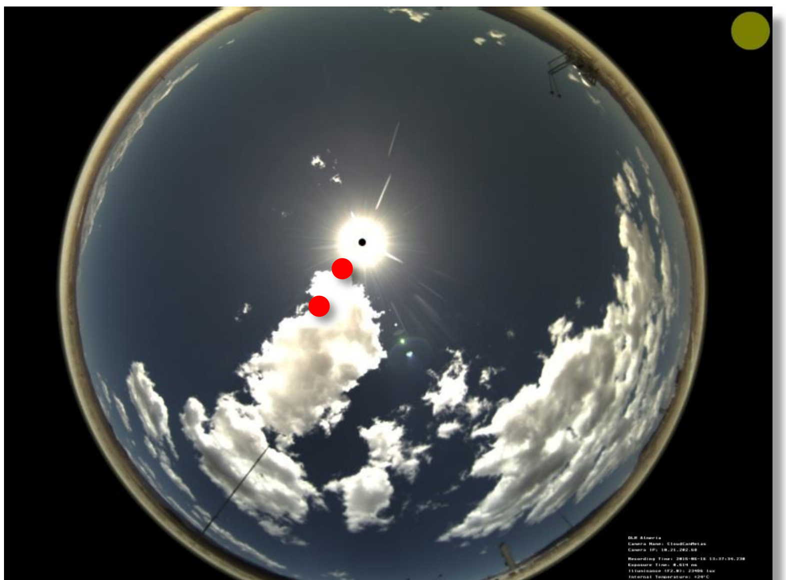
4. NWP cloud heights: Integrated Forecast System, ECMWF (3h data)
5. Ceilometer: CHM 15k NIMBUS, G. Lufft Mess- und Regeltechnik GmbH



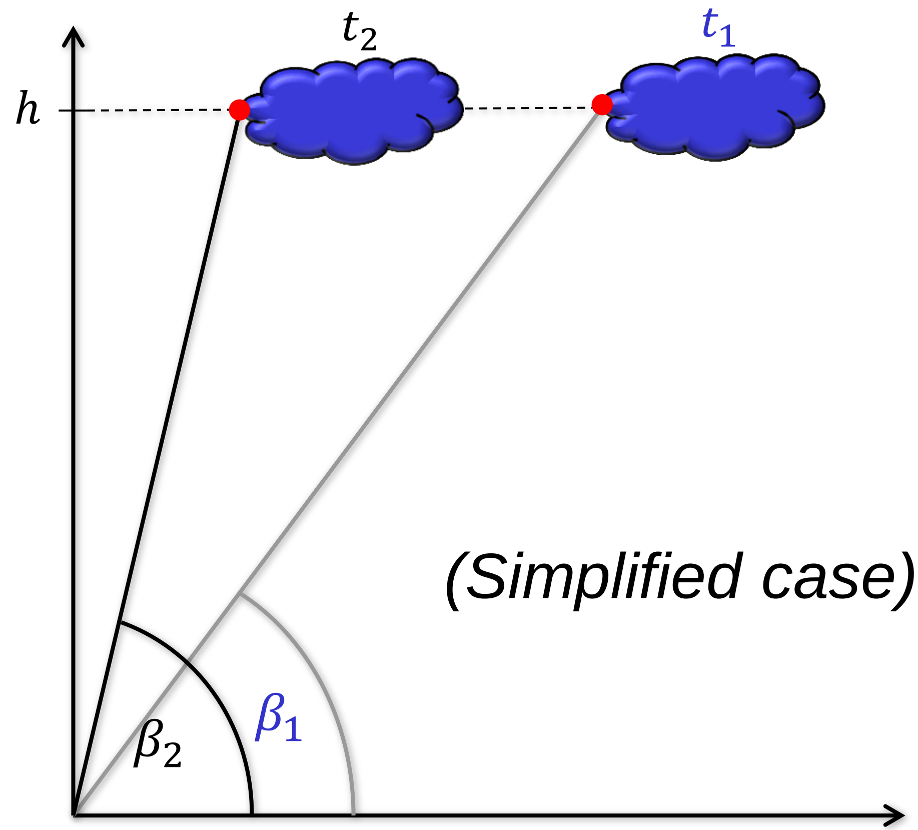
Ground-based cloud height measurement systems

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



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

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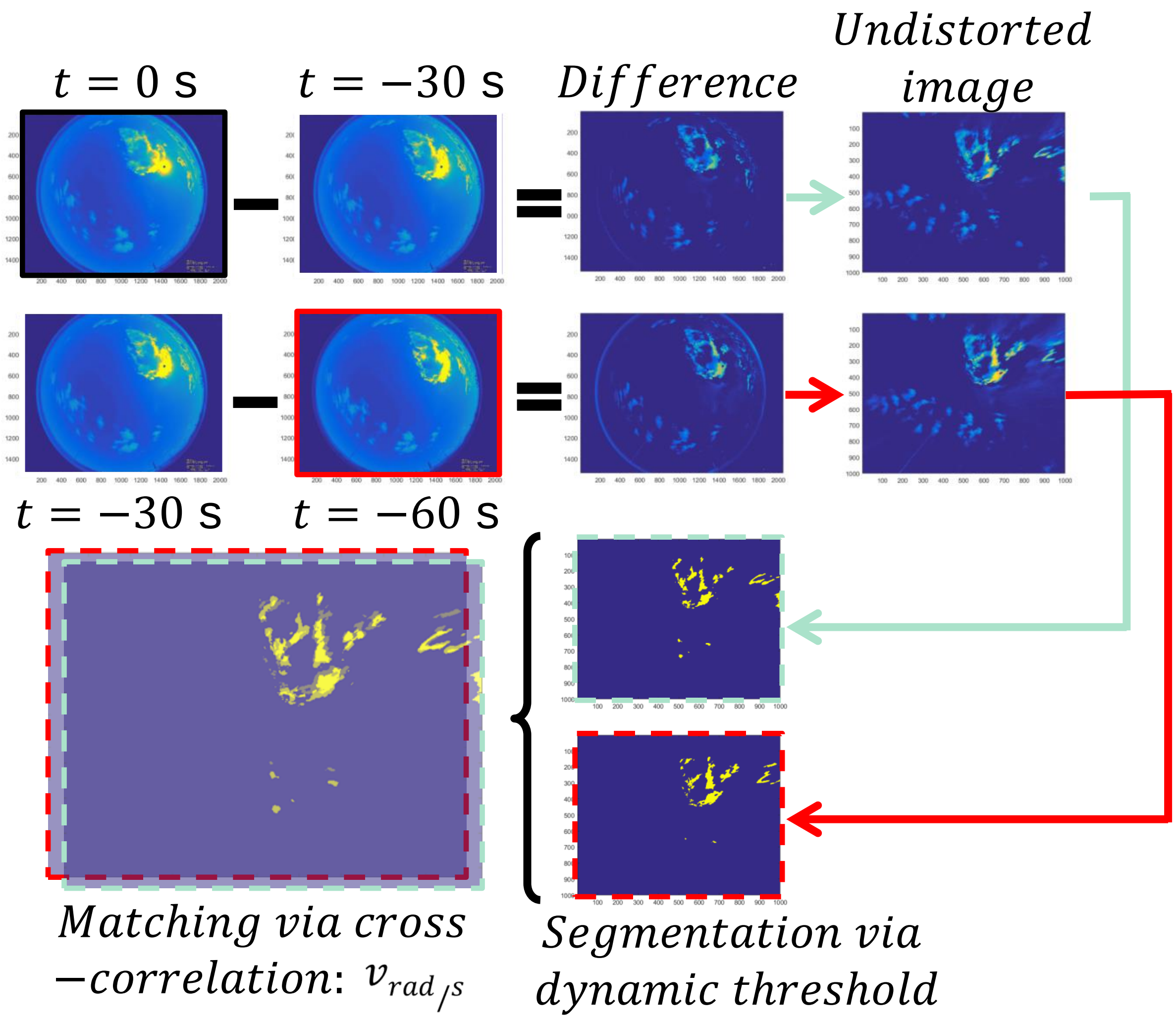
Deriving $v_{rad/s}$ without detecting clouds

Cloud detection is a difficult task and an origin of deviations

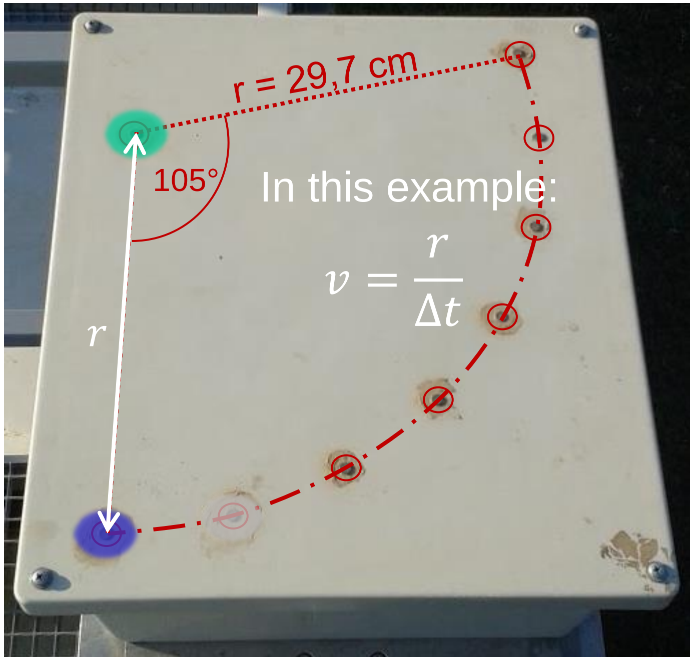
- Detecting clouds within all-sky images is surprisingly difficult
- Novel approach is independent from detecting clouds
- Difference images of the blue color channel are used
- More robust against dirt

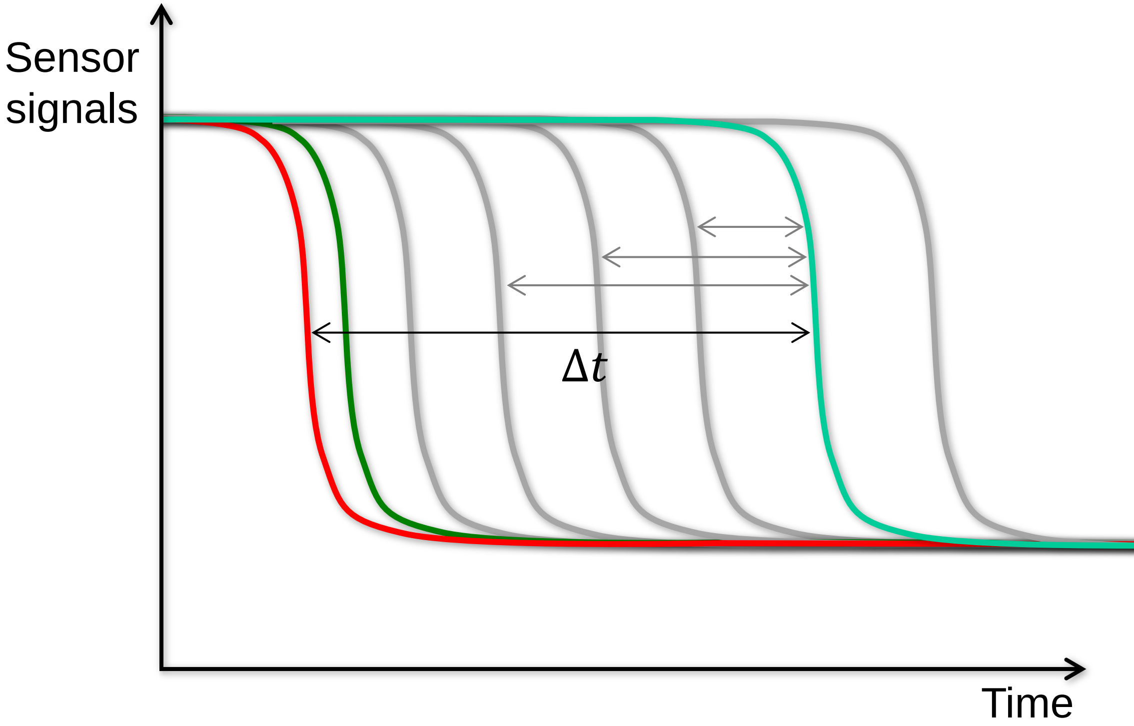


We have the angular velocity – how do we get the absolute velocity [m/s]?

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

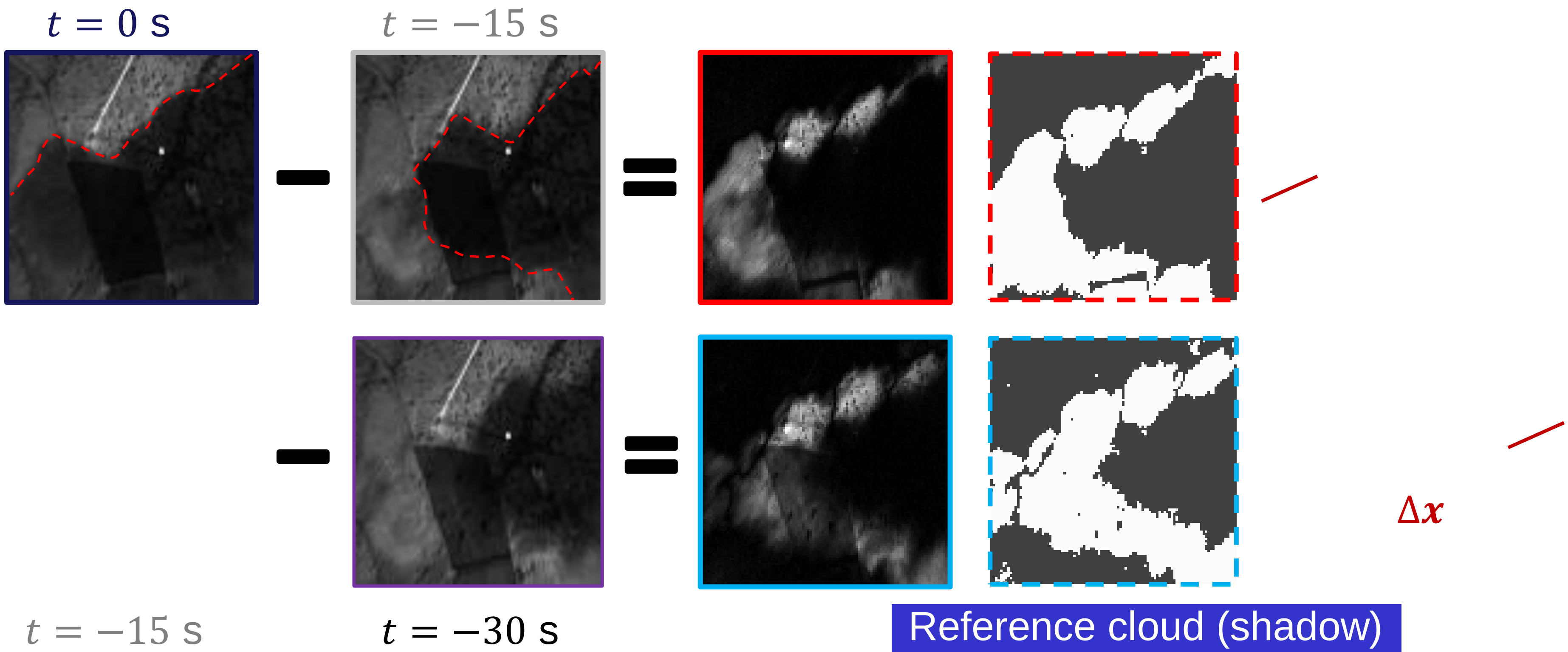
Off-the-shelf surveillance camera

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



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

- Δx: displacement [pixel]
- k: meter/pixel
- Δt: 15 s

Reference cloud (shadow) motion vectors:

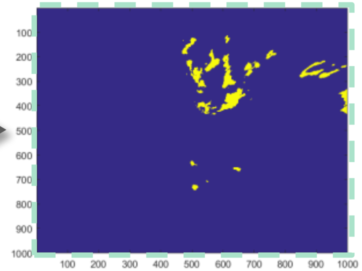
- Low cost sensor
- Little maintenance is needed
- Aperture problem is less relevant

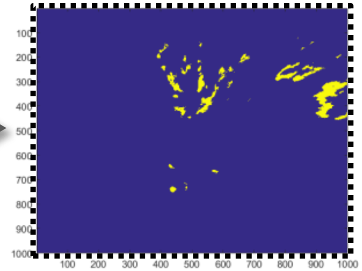
Using two all-sky imagers (ASI)

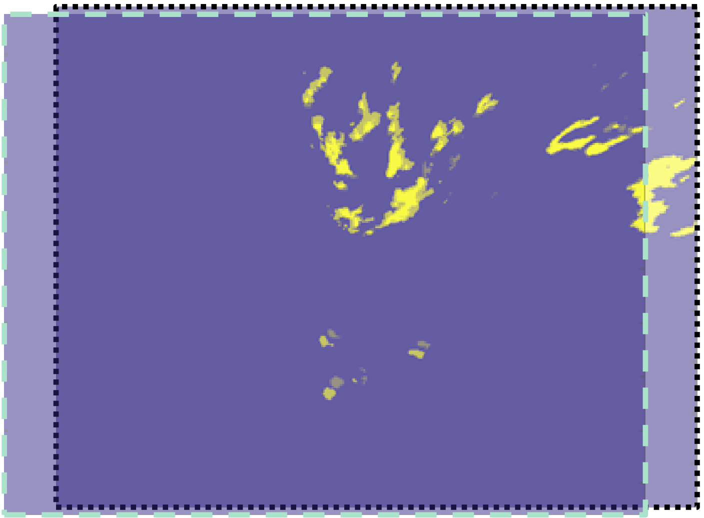
Measuring cloud speeds by matching difference images

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

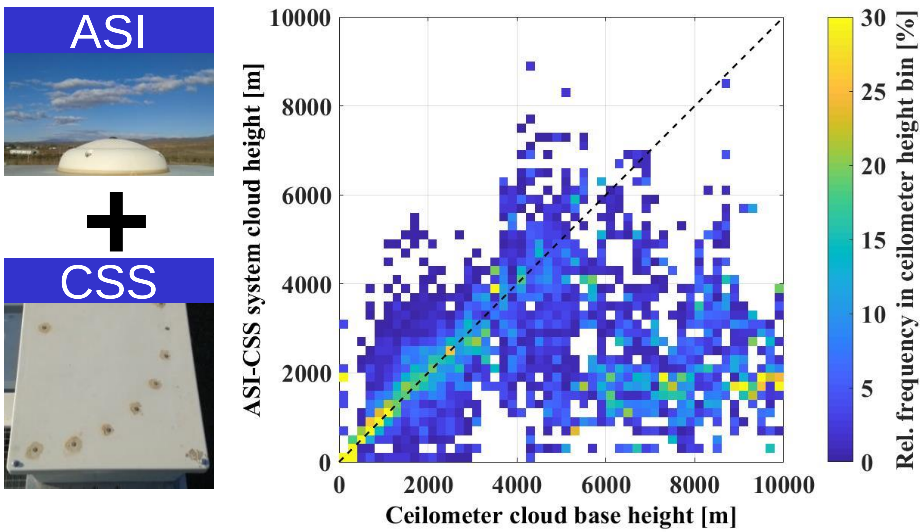
- Benchmarking campaign on 59 days
- Benchmarking site:

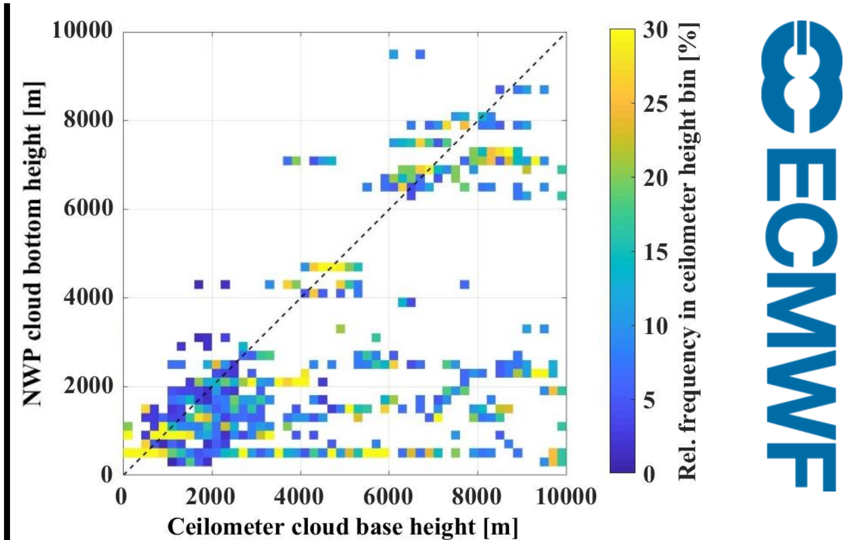
  Plataforma Solar de Almería, Spain
- Validation period contains large variety of cloud heights
- Multilayer cloud situations are included
- All considered systems provide one cloud height
  - For the ASI-ASI-approach, individual cloud heights can be derived
  - Systematic differences between point-like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

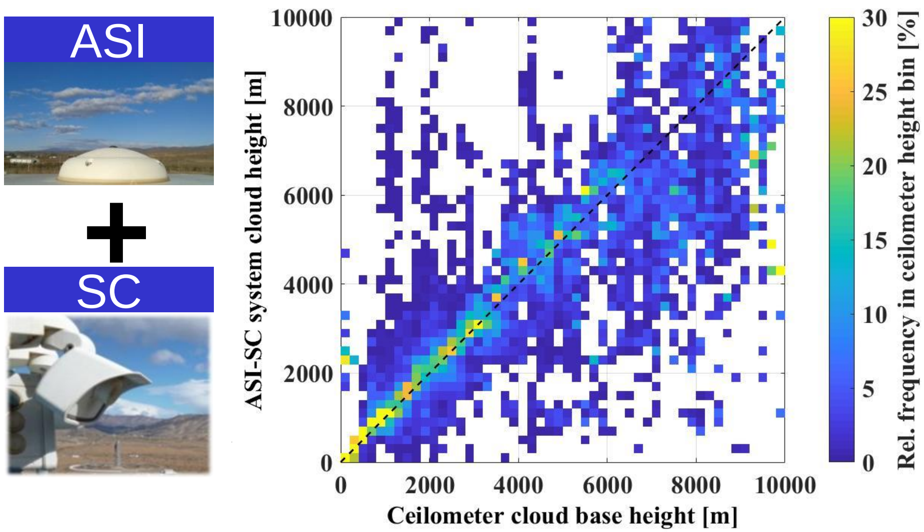
This study is published in
Kuhn et al., *Benchmarking three low-cost, low-maintenance cloud height measurement systems and ECMWF cloud heights against a ceilometer*, Solar Energy, 2018, https://doi.org/10.1016/j.solener.2018.02.050

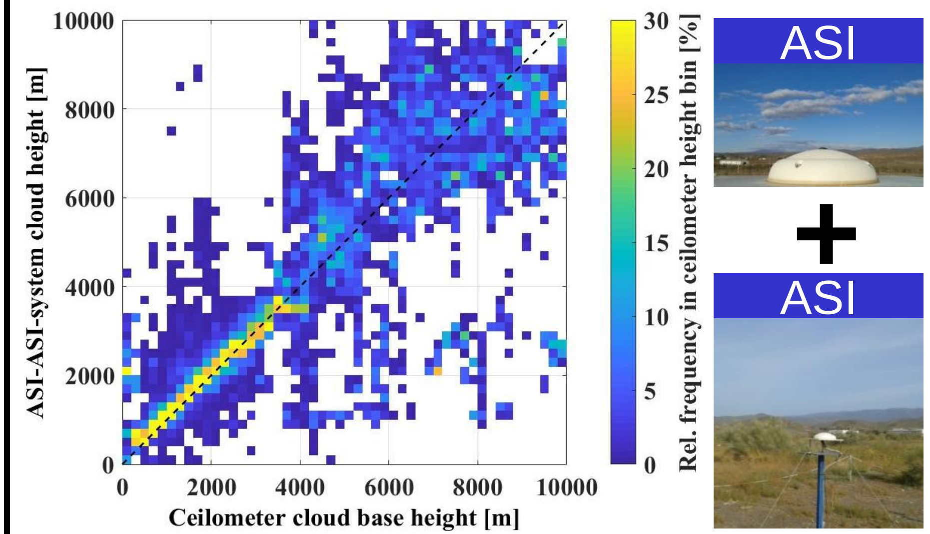
Benchmarking five cloud height measurement systems

Results of the benchmarking campaign



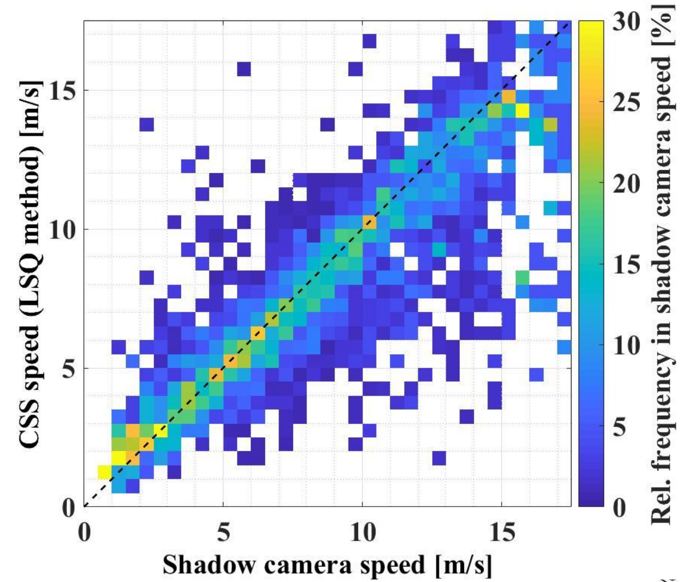


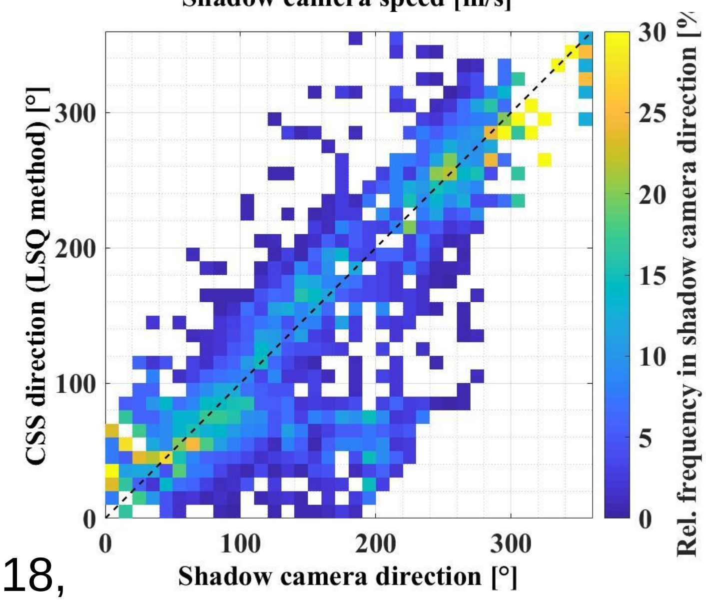




Development and application of the novel cloud motion vector reference on 59 days

- 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

- 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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