Scanning cloud radar observations
Lessons learned using the SWACR at Azores and SGP
Anticipated data products and linkages to science questions

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• Six scanning dual-wavelength cloud radars are scheduled to deploy at the fixed and mobile ARM sites.

• Radars—Primary: **35-GHz** radar frequency channel for cloud detection frequency; Secondary: **94-GHz or 9.4-GHz**: enhanced detection and additional constraints in quantitative cloud properties retrievals.

• **Doppler, polarimetric** and **radiometer** mode: enhance the data quality and improve cloud properties retrievals.

• Early efforts: defining sampling strategies, hydrometeor detection, data quality control and gridding of 3D radar observations.
**SWACR deployments at Azores and SGP**

**SWACR**: a vertically pointing W-band ARM Cloud Radar (WACR) modified to operate on a scanner (S-WACR).

Deployed at Azores and SGP to sample 3D cloud structures and to evaluate various sampling strategies.

Azores: stratocumulus and scattered cumulus

SGP: precipitation and cirrus clouds

SWACR is a 94-GHz radar, e.g., not the primary SACR frequency, with smaller antenna, less sensitivity and limited hardware/software (processing/scanning) capabilities.
SWACR – Azores: Initial Scan Strategies

PPI Reflectivity Scan (Duration: 1-hr)
- 120 degree azimuth sector scan with a center at 315 degrees. The elevation angles range from a 1 degree grazing tilt to 24 degrees (1, 2, 3, 4, 5, 6, 7, 8, 10, 15, 20, 24).

RHI Reflectivity Scan (Duration: 1-hr)
- Sequence of RHI scans (0-45 degrees) repeated over a set of azimuth (direction) angles. The sector is limited to 90 degrees and the azimuth step set to 2 degrees.

Crosswind RHI Scan (Duration: 1-hr)
- Crosswind horizon - to - horizon RHI scan provides cross-wind scans of the atmosphere that passes over and around the radar location.
Highest metric of performance of a particular scan strategy:
Ability to capture (detect) the 3D structure of clouds

- Constant elevation scans (360° or sector) exhibited poor performance in detecting cloud locations and defining their boundaries. This is attributed to the:
  - **Narrow beamwidth** of the SWACR/SACR’s
  - **Nature of clouds**: Shallow layers, important to detect cloud boundaries (need good vertical resolution)
  - **Cone of silence** – where all other ARM instruments are sampling

**Recommendation:** Contrary to the practice used in weather radars, the SACR’s should develop sampling strategies that are based on sequences of constant azimuth scans.
Another lesson learned at Azores: Important to sample the atmospheric column over the ARM site to enhance synergy with other ARM sensors

- Frequent revisiting of the zenith pointing is needed for description of cloud conditions near the ARM site. This lead to the modification of the RHI sector scan

- Cross-wind horizon-to-horizon scans satisfy this requirement

- Need to introduce a general (“all clouds”) sampling mode for climatology purposes

- Maintain same scan strategy for 30-60 min
SWACR/SGP: Introduction of “all-cloud conditions” mode
Possible to have temporal gaps between such measurements

Hemispheric Sky Cross Sections
6 - Horizon-to-Horizon scans
Implemented at the SWACR/SGP

HS-RHI model

Takes 3-min to complete all six scans
SWACR/SGP: Modification of the RHI sector scan to cover cloud conditions near and on top of the ARM site.

Azores

90° azimuth sector
Centered along BL wind direction
2-degrees azimuth step
Oversampling from 0° to 45° elevation
Max elevation angle 45°
Cone of silence (gap over the ARM site column)

SGP

90° azimuth sector
Centered along BL wind direction
2-degrees azimuth step
Oversampling from 0° to 60° elevation
A subset of the RHI scans (every 10° azimuth goes zenith (90°)
No cone of silence (spacing of above 60° elevation scans sufficient for gridding)

BL-RHI model
First generation of sampling modes for the SACR’s

Cloud conditions (no measurable amount of rain at the ground)
Repeat HS-RHI scan every 30 min (takes 3 min to complete)
Repeat BL-RHI between HS-RHI’s (~ 5 times)
Repeat CW-RHI between HS-RHI’s

Precipitation conditions (measurable amount of rain at the ground)
Vertically pointing mode (Doppler spectra)
## Scanning Cloud Radars
### Scientific objectives and data products

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<th>Scientific objective</th>
<th>Recommended Data product</th>
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<tr>
<td>3D cloudy atmosphere radiative transfer issues</td>
<td>- “Frozen” 3D-structure of clouds properties (boundaries, LWC etc)</td>
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<tr>
<td>Model subgrid cloud variability</td>
<td>- Possible to have temporal gaps between such measurements</td>
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<tr>
<td>Evaluation of satellite retrievals of cloud system properties</td>
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<tr>
<td>Lifecycles of clouds and convective systems and cloud-aerosol interactions</td>
<td>- “Volume-Imaging” of cloud properties (boundaries, WC, dynamics)</td>
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<td>Cloud turbulence, entrainment</td>
<td>- Repeat several times to capture evolution/lifecycle</td>
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<tr>
<td>Strengthen the microphysical/dynamical column retrievals</td>
<td>- Vertical pointing, Doppler spectra recording</td>
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Scanning Cloud Radars
High-level description of 3D cloud sampling

**HS-RHI**
Hemispheric Sky Cross Sections
6 - Horizon-to-Horizon scans
Duration: 3 min
Repeat: Every 30 min
All-cloud-conditions mode

**CW-RHI**
Cross-Wind Range Height Indicator
Requires wind direction input
Repeat Horizon-to-Horizon scan N-times
Duration: 15 min to 60 min
Best scan strategy for high clouds
Scanning Cloud Radars
High-level description of 3D cloud sampling

**BL-RHI**
+90° azimuth sector around wind direction. 2° azimuth resolution
Duration: 5 min
Repeat: 3-6 times (lifecycle)
**Best scan strategy for low clouds**

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**VPR**
Vertically pointing mode
All modes visit zenith frequently
Collection of Doppler spectra
Duration: always in rain
**Best scan strategy for precipitation**
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<td>3D cloudy atmosphere radiative transfer issues</td>
<td><img src="image1.png" alt="Image" /></td>
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<td>Strengthening the microphysical/dynamical column retrievals</td>
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Scanning Cloud Radars
Data Products – Processing structure

**Input files**
- Ingested SACR data: Calibrated reflectivity and polarimetric values
- Auxiliary data: Atmospheric sounding, ceilometer and surface rainfall

**Radar coordinate system**
- Hydrometeor mask
- WV attenuation correction
- Doppler folding correction

**Gridding (3D-ARSCL)**
- 3D locations and radar Observables - Cloud field statistics
- All scanning modes will be gridded

**Radar data file (netcdf)**
- Visualization (image/movie)
- Archiving
- Web interface

**3D-ARSCL data file (netcdf)**
- Visualization (image/movie)
- Archiving
- Web interface
3D-structure of mid-level cloud
3D-structure of precipitation
3D-structure of a single-layer stratus cloud
Sample data products from HS-RHI “all clouds” sample mode

Products: Cloud top height
Cloud thickness
Number of layers
Cloud types

Grid RHI scans
Apply cloud classification
3D-Gridded Data (ARSCL) sample from Azores

Horizontal structure at different cloud levels
3D-ARSCL (Gridded Hydrometeor Locations) from SGP using the new BL-RHI sampling strategy
The short-term deployment of the SWACR at Azores and SGP provided the opportunity to test various 3D cloud sampling strategies.

Use of RHI scans is favored due to the narrow radar antenna beamwidth, the nature of clouds and the desire to sample the sky over the ARM site.

Four scan strategies that meet these requirements are considered:

**HS-RHI**: “All cloud conditions” sampling mode – Cloud state

**BL-RHI**: “Suitable for BL clouds”, provides temporal evolution

**CW-RHI**: “Suitable for high clouds”, time is one the dimensions and,

**VPR**: “Precipitation mode”, dual-frequency retrievals in precipitation.

Automatic detection of wind direction and surface precipitation is required to provide “close-loop” adaptive scan strategies (e.g., for centering the BL-RHI and CW-RHI scans and for changing to VPR mode).
**Data products status**

- The scanning cloud radar hydrometeor mask algorithm is completed. Refinements needed for insect removal using polarimetric measurements and clutter removal at 9.4-GHz.
- WV attenuation correction algorithm is completed using nearest sounding
- Doppler velocity unfolding algorithm prototype is completed, evaluation is underway
- Prototype radar data gridding algorithm (for HS-RHI, BL-RHI and CW-RHI scan modes) has been developed, evaluation/refinement is undergoing
- Prototype images/movies format and netcdf data file formats (radar coordinate system and 3D-ARSCL) are completed

**Challenges**

- New radars have several new technological aspects and we need to evaluate their performance in the field
- A web interface for fast review/validation of prototype algorithms as more radars come online is needed
- Gridded data and higher order products (e.g., cloud boundaries, cloud phase and cloud types) are highly desirable, however, an extensive evaluation is required.
Proposed Small Cumulus Lifecycle Studies using Scanning Cloud Radar Observations

- **Cu Cloud Life Cycle Observations**
  - **Cloud Statistics**
    - Time evolution of cloud elements at different stages in their lifetime
  - **Aerosol Effects**
    - Changes in cloud life cycle characteristics with different subcloud aerosol loading
  - **Context for measurements from upward facing sensors**

- **Related Process Studies (3-D)**
  - Precipitation
    - Formation
    - Temporal and spatial variability
    - Evaporation
  - **Entrainment**
    - In cloud circulations at cloud top and sides
Tracking Cloud Lifetime with LES

Tracking 100s of clouds

No influence of aerosol on cloud lifetime
Tracking Cloud Lifetime with LES

Tracking 100s of clouds

No influence of aerosol on cloud lifetime

LES for small Cu

Cloud lifetime, min

Aerosol conc., cm⁻³

No influence of aerosol lifetime
Small Cu Time Lapse
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Precipitation and Lifetime of Small Cumulus

5 minutes

Photos from Barbados; Courtesy Joe Prospero
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