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Field Validation of Cloud Properties Sensor – SAIL Field Campaign Report

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Acronyms and Abbreviations

AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
COD	cloud optical depth
CSPHOT	Cimel sunphotometer
GOES	Geostationary Operational Environmental Satellite
KAZR	Ka-band ARM Zenith Radar
LWC	liquid water content
LWP	liquid water path
MET	surface meteorological instrumentation
MODIS	Moderate Resolution Imaging Spectroradiometer
MWR	microwave radiometer
MWR3C	microwave radiometer, 3-channel
NOAA	National Oceanic and Atmospheric Administration
Reff	droplet effective radius
SAIL	Surface Atmosphere Integrated Field Laboratory
SGP	Southern Great Plains
SZA	solar zenith angle
TSI	total sky imager
TWST	three-waveband spectrally-agile technique
TWST-CPS	TWST cloud optical properties sensor
USB	Universal Serial Bus
UTC	Coordinated Universal Time

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1.0 Summary

The purpose of the Field Validation of Cloud Properties Sensor – SAIL campaign was to deploy Aerodyne's extended-wavelength TWST cloud optical properties sensor (TWST-CPS) in an operationally relevant environment with co-located, externally validated sensors. Colocation with The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's deployment of its second Mobile Facility (AMF2) on the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign at Crested Butte, Colorado was ideal because of the variety of operational sensors that can measure some of the same cloud properties using different modalities. While cloud property sensors have long existed, they tend to be costly to produce and maintain. Our sensor measures absolute spectral radiance over 440-1700 nm and retrieves cloud optical depth (COD), droplet effective radius (Reff), and thermodynamic phase (Phase). Our prototype is built predominantly from off-the-shelf components and uses uncooled spectrometers. A low-cost, easy-to-use sensor such as this could allow deployment at many more sites for greater spatial coverage. Instrument deployment to test robust operations and a new stray-light baffle design, and the continued development of analysis and retrieval algorithms using the data from this deployment, are central technical objectives of Aerodyne Research's U.S. Department of Energy Small Business Innovative Research Phase 2 contract (DE-SC0020473, Low-cost shortwave spectroradiometer for retrieval of cloud properties).

TWST was deployed at SAIL from July 2022 to June 2023. Over the 343-day deployment, the instrument had up time of 94%, generating 1-second spectra and correlated COD retrievals (RCOD algorithm). We have performed data and retrieval comparisons with several baseline sensors and value-added products. We were able to produce good real-time COD retrieval agreement under most conditions with microwave radiometer (MWR) and Geostationary Operational Environmental Satellite (GOES) measurements. Offline COD, effective radius, and phase-combined retrievals (V3 algorithm) compared well with GOES and the related liquid water path (LWP) from the MWR and microwave radiometer, 3-channel (MWR3C) under favorable circumstances (i.e., COD > X and no precipitation). Results from our data collection and analysis are discussed in detail in the following section.

Figure 1 shows TWST-CPS deployed at SAIL in proximity to the microwave radiometers, Cimel sunphotometer (CSPHOT), multifilter rotating shadowband radiometer (MFRSR), and total sky imager (TSI).

Figure 1. TWST deployed at SAIL.

Figure 2 is a snapshot from the TSI with TWST-CPS visible (upside down) at the top of the image. The instrument software runs on a laptop computer located in the climate-controlled optical trailer. Communication and power to the instrument is via a USB extender.

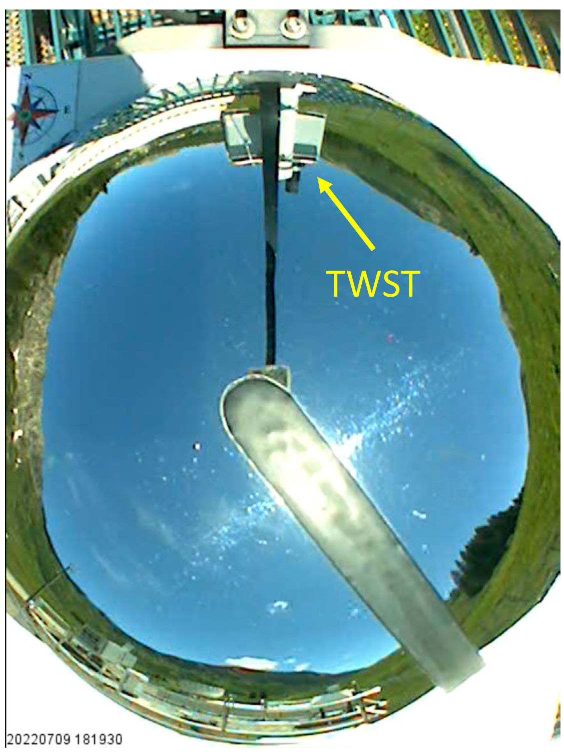

Figure 2. TSI snapshot showing location of TWST on platform with MWR, CSPHOT, and MFRSR.

The principal results and lessons learned were:

- Demonstration of high operational up time – 94% over 343 days
  - 94% real-time COD retrievals (RCOD algorithm)
  - Selected several days to run our offline COD, Reff, and Phase-combined retrieval (V3 algorithm)
- Successful comparisons of RCOD and V3 COD, Reff, and Phase with co-located CSPHOT, GOES, and MWR measurements
- Confirmation of the efficacy of the new baffle design
- Successfully performed retrievals under conditions from low- (summer, ground) to high-visible-wavelength surface albedos (winter, snow)
- Determined that operation at locations with substantial snowfall will require automated protection of the window from accumulation.

2.0 Results

This section presents the results of the instrument's campaign deployment in detail.

2.1 Operability

Figure 3 shows plots indicating the operability time of TWST-CPS over the entire SAIL campaign. There are two main down periods, one near day 270 of 2022 and the other around day 60 of 2023. Most of the down periods for TWST-CPS were due to unnoticed Microsoft Windows updates. We have since implemented a "watchdog" mechanism that restarts the program automatically and emails recipients specified in the configuration file. This has improved down-time durations considerably.

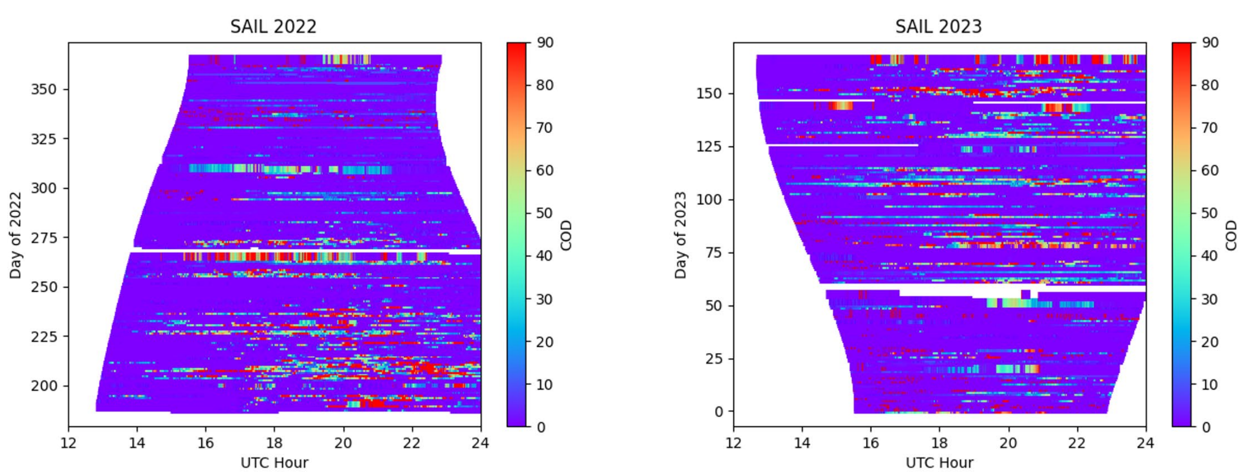

Figure 3. TWST-CPS operability time at SAIL. Over the 343 days of deployment, TWST-CPS was operable 94% of the time. White regions in figure indicate down time.

2.2 Stray-Light Baffle

The degree to which stray light from off-axis direct solar was affecting TWST measurements was discovered in 2021 during our deployment at ARM's Southern Great Plains (SGP) atmospheric observatory. Subsequently, we designed a new longer baffle with vanes. Modeling results from Zemax showed that this design should attenuate off-axis solar to a level well below our spectral radiance measurement noise level. However, the modeling requires assumptions about the optical properties of the black coating that may not be completely accurate. Thus, field validation is necessary to fully vet the design. Figure 4 shows the layout of the new baffle and its performance near the summer solstice. Spectral radiance was computed using a forward model (libRadtran). The aerosol optical depth was adjusted until the model result fit the clear-sky radiance well, particularly at high solar zenith angle (SZA) where there will be minimal stray solar. Note that the curves match well all the way to the minimum SZA of approximately 17 degrees. Stray light problems would show up as increased measured radiance at the lower SZAs. The afternoon curve indicates some relatively thin cloud.

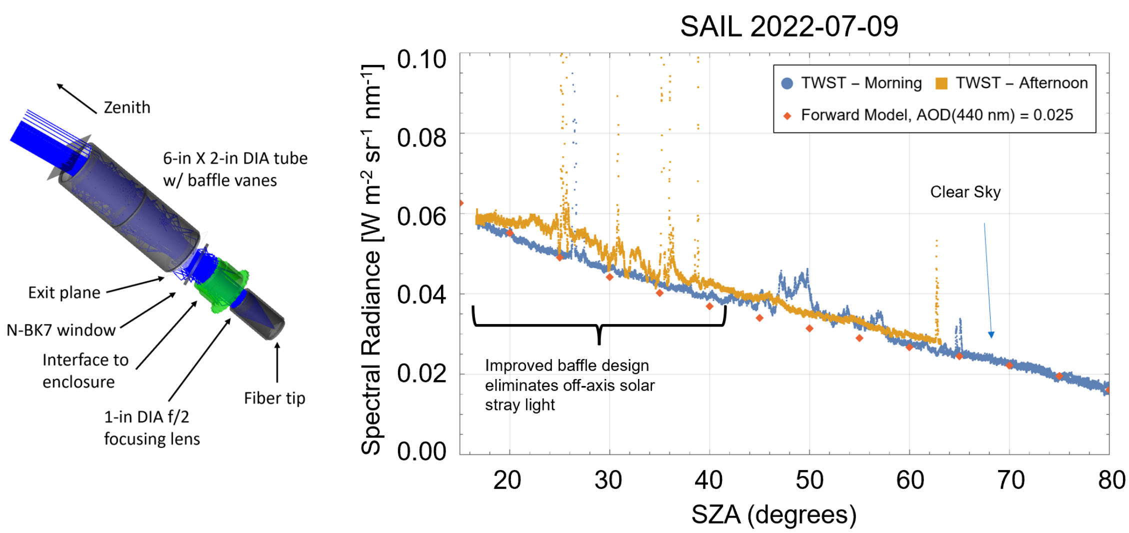

Figure 4. Effectiveness of new baffle design. Previous SGP data had shown a sensitivity to stray light at low solar zenith angles.

2.3 Surface Albedo

Figure 5 shows the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-based sensor MCD43A3 surface albedo product for the SAIL area for midwinter and late spring. Note that the short-wavelength surface albedo due to snow cover is about ten times higher than the snow-free period. This large difference in surface albedo has a significant effect on the zenith spectral radiance, particularly for low clouds. The COD lookup table was recomputed for the snow cover albedo and was changed on the instrument on 2022-12-12.

MODIS data product MCD43A3 Version 6.1 Albedo Model at 500-meter resolution

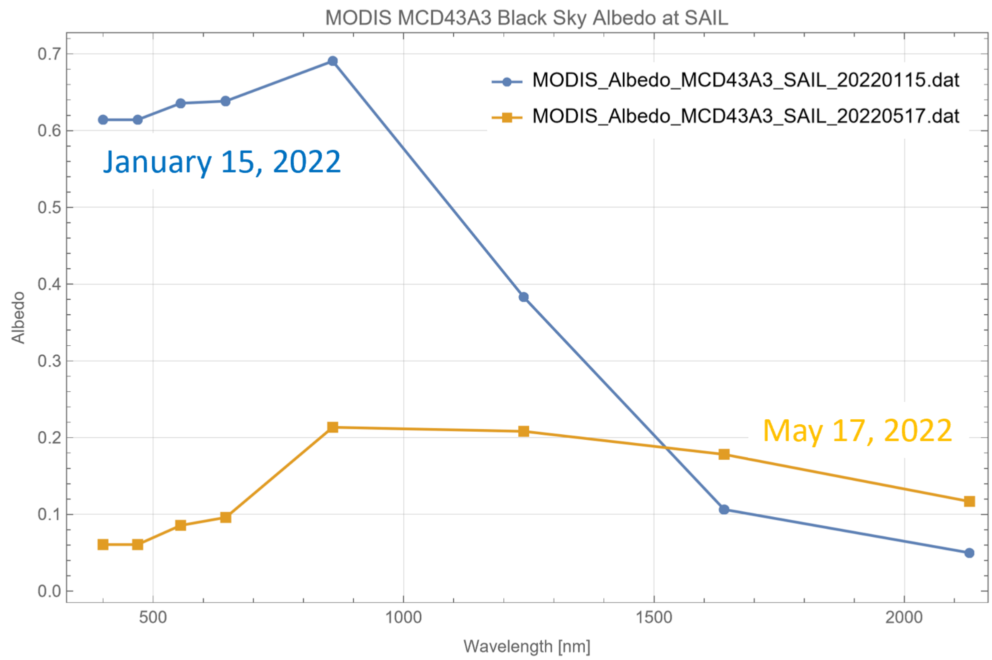

Figure 5. MODIS surface albedo for SAIL during periods with and without snow cover.

2.4 Data Comparisons

Figure 6 shows retrievals performed with lookup tables computed for the snow and vegetation cases. TWST-EN RCOD is the original retrieval algorithm that assumes liquid phase and a constant droplet effective radius of 8 µm. TWST-EN V3 uses both visible and near infrared wavelengths to determine phase and subsequently jointly retrieve effective radius and COD. The liquid water path (LWP) is computed from COD as:

$$LWP = \frac{2}{3} \rho \, \tau \, r_{eff}$$

where ρ is the density of water, τ is COD and r_{eff} is droplet effective radius (Stephens 1978). This relation assumes that liquid water content (LWC) is vertically constant. Agreement with the MWR is somewhat reasonable, but neither the snow nor vegetation case produces a close match for much of the day.

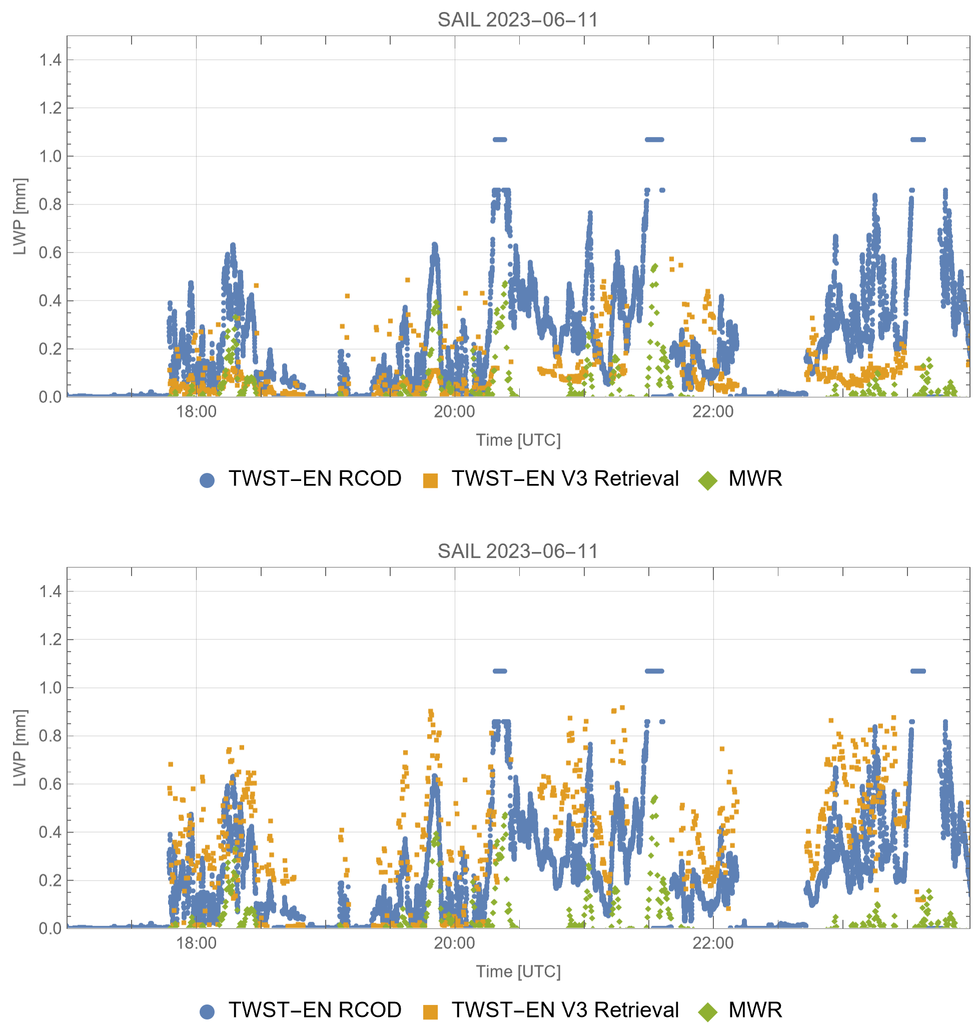

Figure 6. TWST/MWR LWP retrieval comparisons for different forward model surface albedos for (top) snow and (bottom) vegetation. The retrieval using the snow surface albedo agrees better with MWR, which is expected from the National Oceanic and Atmospheric Administration (NOAA)'s snow cover estimate product.

Figure 7 shows the NOAA-modeled snow depth in the Crested Butte, Colorado area for this day. There is clearly mixed surface albedo in the vicinity of the instrument site. Based on calculations for flat terrain, averaging measured albedo over a radius of 5 km appears to be sufficient. This would likely yield a significantly different retrieval result. An improved retrieval product would use the actual MODIS surface albedo. While this sounds straightforward, the computational burden of producing the lookup tables is significant but not necessarily prohibitive.

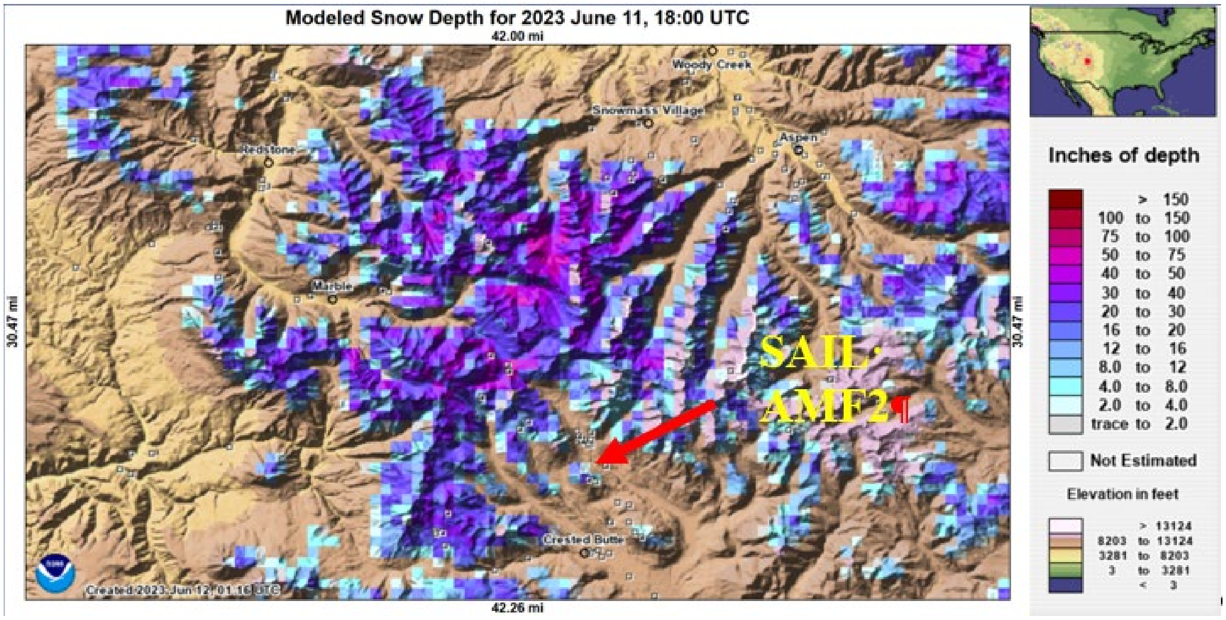

Figure 7. NOAA-modeled snow depth.

Figure 8 shows another retrieval example during a period when there was widespread snow cover. The comparison with MWR is quite good in this case until about 1800 UTC.

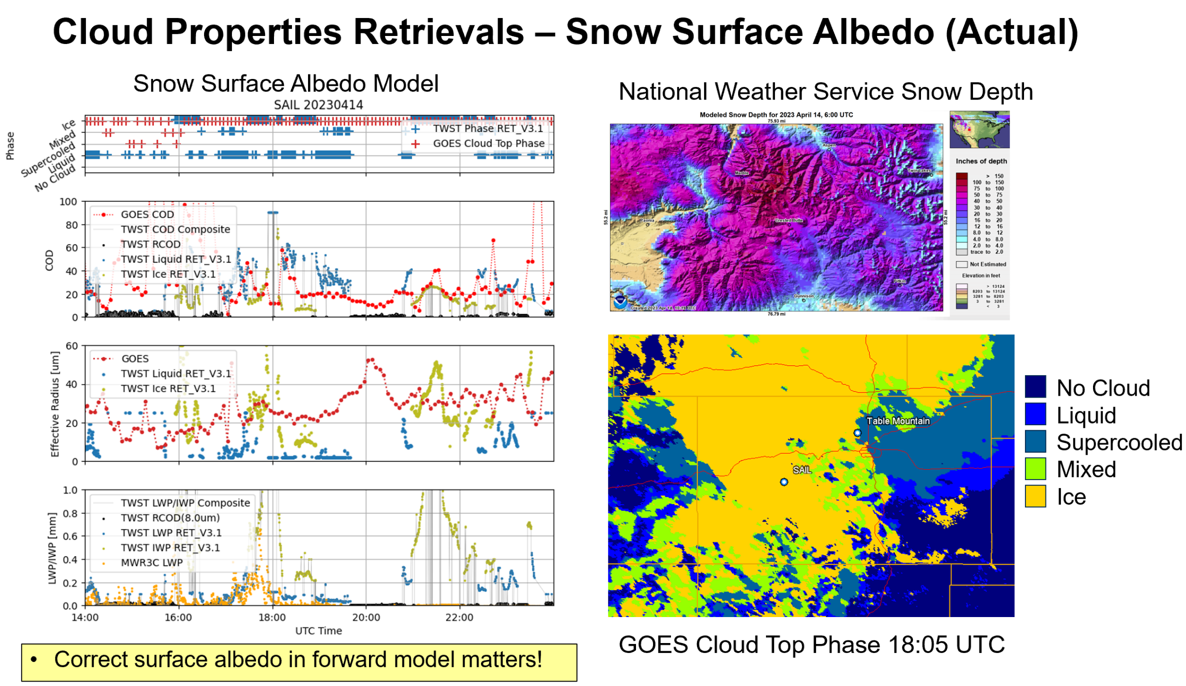

Figure 8. Retrievals during period of snow cover. High surface albedo of snow must be accounted for in forward model to obtain accurate retrievals.

After that, the Ka-band ARM Zenith Radar (KAZR) reflectivity and Doppler (Figure 9) seem to indicate precipitation events that would corrupt both measurements. Also of note is that GOES is detecting cloud top phase of ice for almost the entire period. TWST is reporting both ice and liquid with some frequency, which is consistent with the GOES image that suggests two or more layers of different phase.

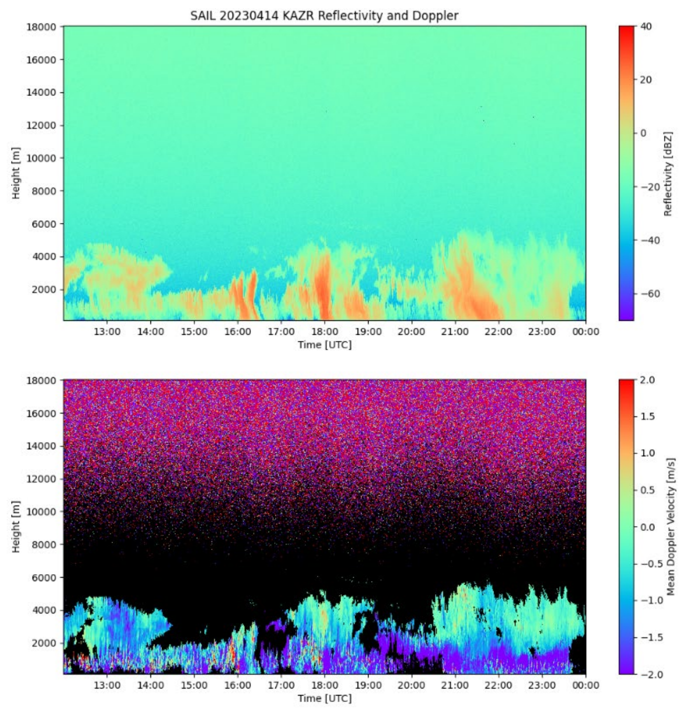

Figure 9. KAZR reflectivity and Doppler data.

2.5 Snowfall

Finally, a lesson learned is that we need to devise a solution to snow accumulation in the TWST baffle. Figure 10 shows the Vaisala PWD weather sensor cumulative snow data from surface meteorological instrumentation (MET) for four months in 2023. The SAIL operational people were instructed to clear snow and were as attentive as could possibly be expected. The snowfall amounts at SAIL would have required this to be done on a near daily basis for many periods and this is well beyond expectation. Unfortunately, reliable retrievals cannot be done with a snow-covered window. We are investigating the possibility of adding a precipitation sensor and a shutter mechanism to keep snow and rain off the window.

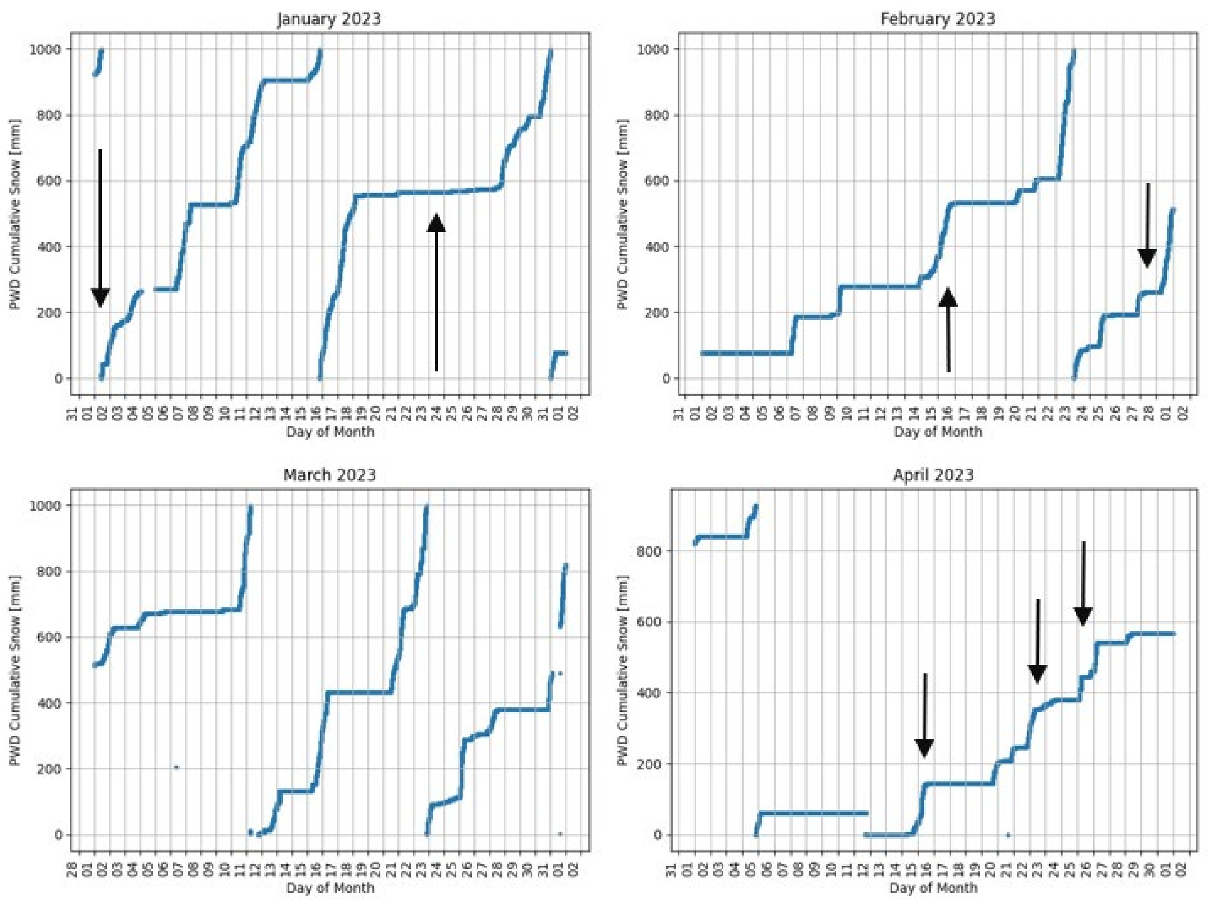

Figure 10. Cumulative snowfall data from MET instrument at SAIL (gucmetM1.b1). Black arrows indicate times when snow was cleared from baffle.

3.0 Publications and References

Jones, SH. 2023. "TWST Cloud Properties Sensor SAIL 2022-2023." SAIL/SPLASH Biweekly Meeting, 30 October. https://sail.lbl.gov/events/regular-meetings/

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Stephens, GL. 1978. "Radiation Profiles in Extended Water Clouds. II. Parameterization Schemes." *Journal of the Atmospheric Sciences* 35(11): 2123–2132, https://doi.org/10.1175/1520-0469(1978)035<2123.RPIEWC>2.0.CO;2

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