Evaluating Hail Spectrometer Data Quality and Uncertainty for Calculating Radar Reflectivity

November 17th, 2025
James Klinman

Photo provided by Tom Warner

- Annually, hail causes ~1.433 billion USD in damage to crops within the US (Changnon et al., 2009)

- Improved understanding will help forecasts and modeling of hail

Photo provided by Tom Warner

Photo by Jim George

Research Objectives

- Research group objective
  - Compare T-28 aircraft in-situ measurements of hail with CSU-CHILL radar observations.

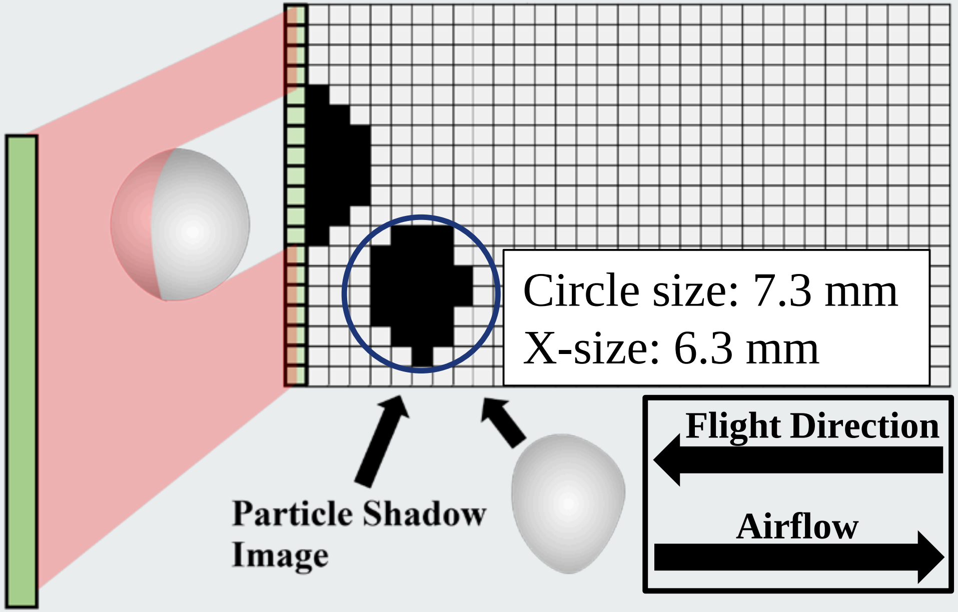
- UND specific objectives
  - Assess the data quality of Optical Array Probe (OAP) measurements.
  - Assess uncertainty in using T-28 in-situ data for calculating radar signatures such as reflectivity.

- The T28 Aircraft,
  - Could fly through hail up to 7.5 cm
  - 14 flights are used
  - Housed two optical array probes for multiple flights

Photo provided by Tom Warner

Photo provided by Tom Warner

- The Hail Spectrometer recorded data in two ways,
  - By sizing particles in real time and saving counts (1D counts)
  - By saving image buffers which can be later processed (2D images)



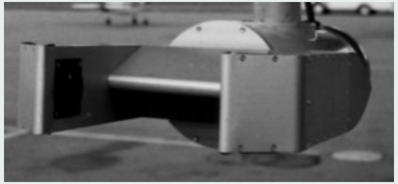
Example of 1 second of Hail Spectrometer 1D particle counts

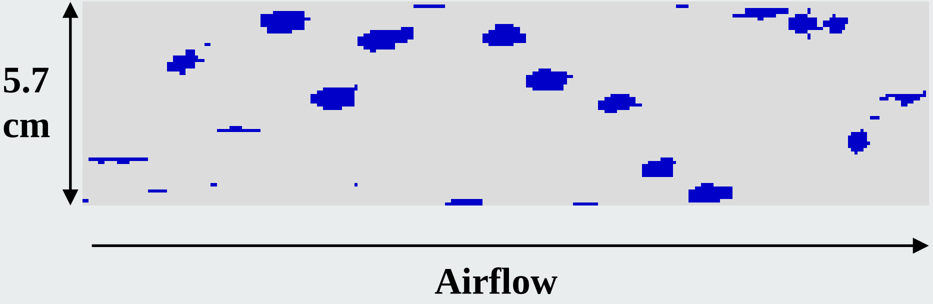
Size (mm)	**4.5**	**5.5**	**6.5**	**7.5**	**8.7**	**10.2**	**12.0**	**14.3**	**17.1**	**20.1**	**23.9**	**29.1**	**36.0**	**45.0**
Counts	4	10	1	10	33	37	8	4	1	1	1	1	1	0

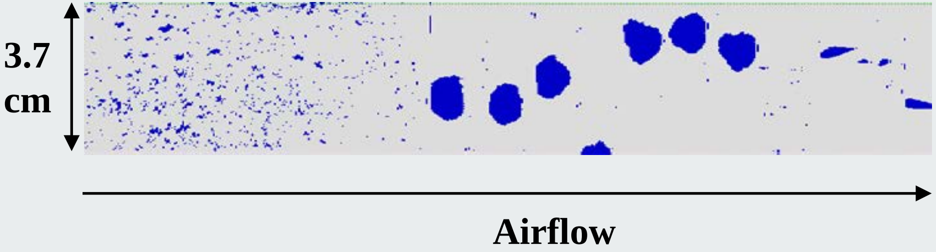
- Shown are two image buffers.

Hail Spectrometer

High Volume Particle Spectrometer (HVPS)







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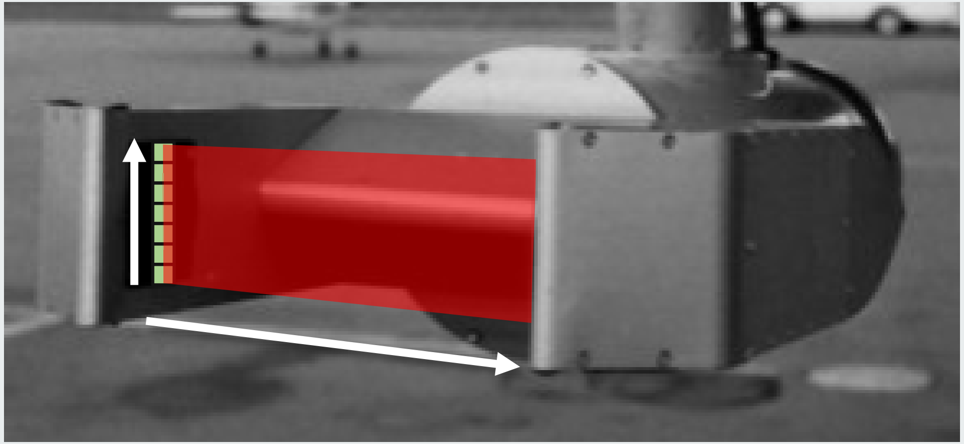
- The sample area determines how many particles will be observed

Sensor length



Arm width

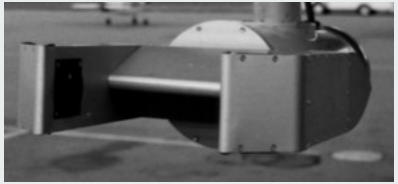
$$Sensor\ length\ \times Arm\ width\ = Sample\ area$$

$$Sensor\ length \times Arm\ width = Sample\ area$$

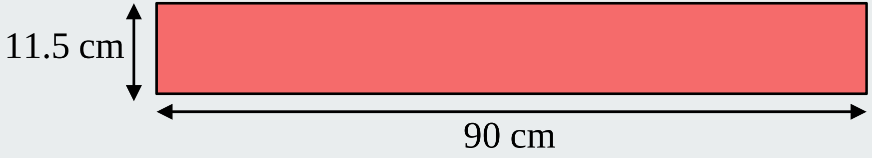
- The sample area determines how many particles will be observed
- HS sample area
  - 0.1040 m^2
  - 0.0520 m^2
- HVPS sample area
  - 0.0074 m^2

Hail Spectrometer (HS)

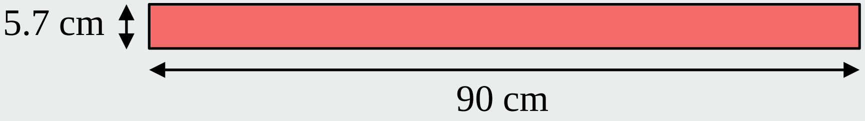
High Volume Particle Spectrometer (HVPS)



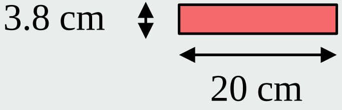
One-dimensional (1D) Setup



Two-dimensional (2D) Setup



HVPS1 Setup



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- UND specific objectives
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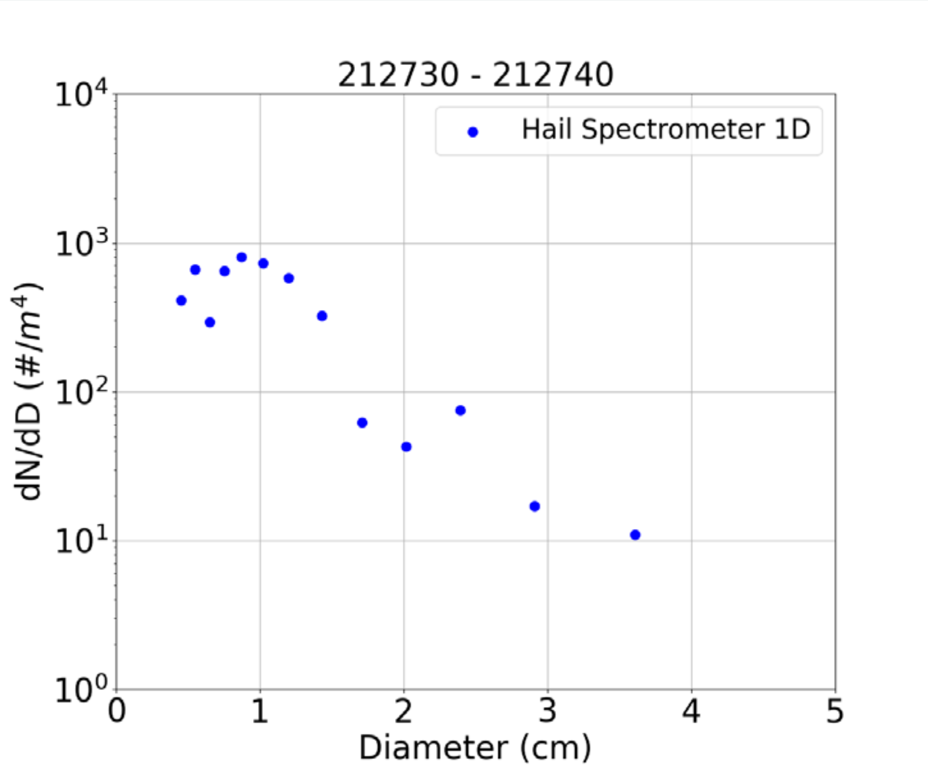
- Particle size distributions (PSDs) are used to calculate reflectivity
  - Count distribution
  - Sample volume
  - Channel width



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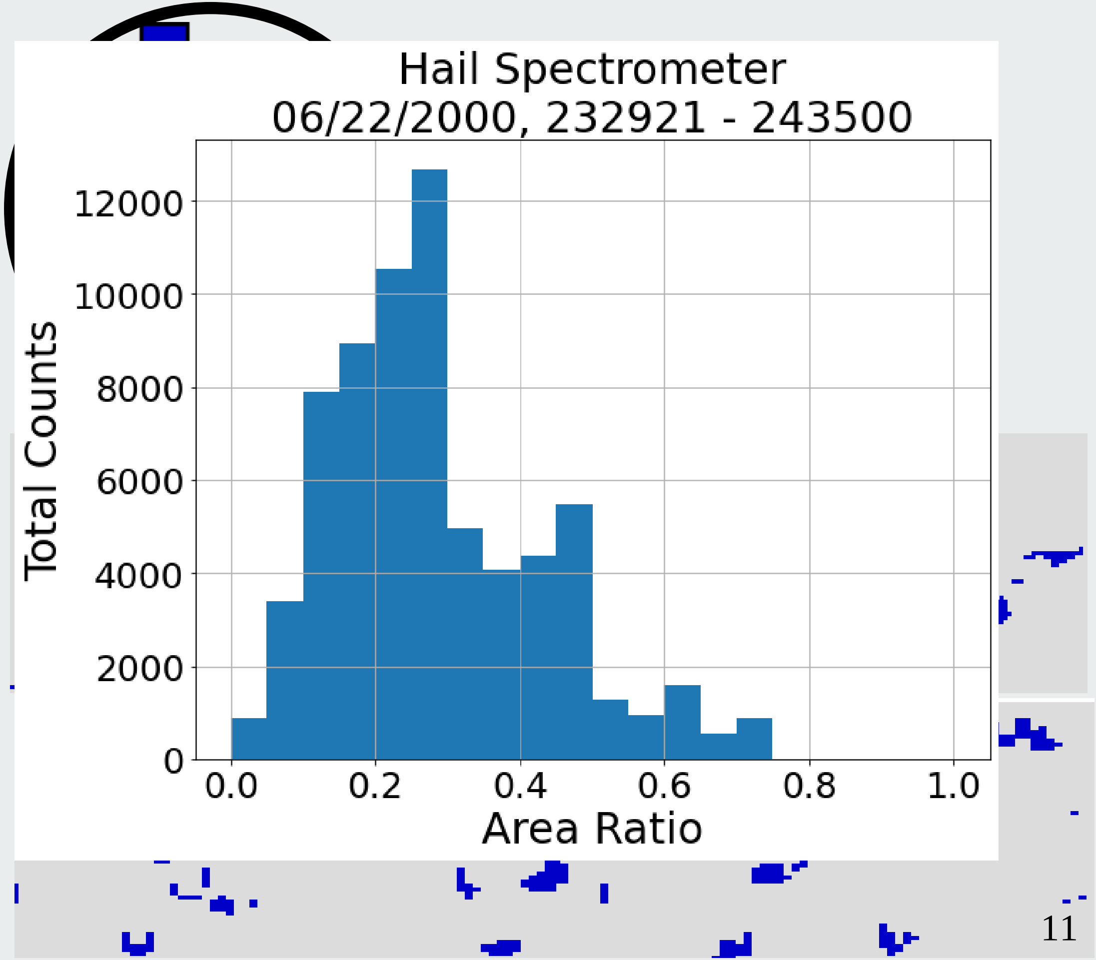
Size (mm)	**4.5**	**5.5**	**6.5**	**7.5**	**8**									**45.0**
Counts	4	10	1	10	3									0

C

Width (mm)	**1.0**	**1.0**	**1.0**	**1.0**	**1.4**	**1.6**	**2.0**	**2.6**	**3.0**	**3.1**	**4.4**	**6.0**	**7.9**	**10.0**

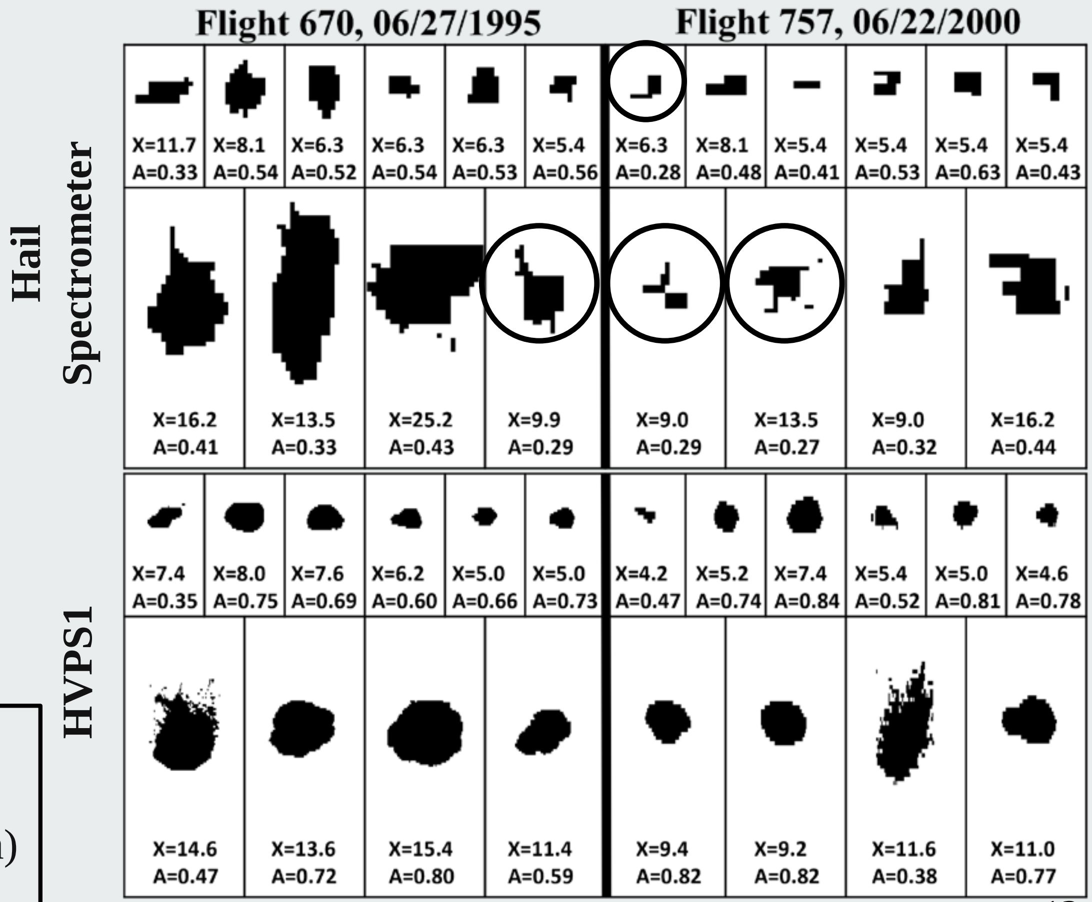
For the 2D PSDs, we need,

- Particle size
- Area ratio
    - Area of the shadowed diodes to the area of the smallest enclosing circle
    - The primary rejection criterion



- Qualitative inspection of individual particles is required to,
    - Provide confidence in area ratio threshold
    - Assess image quality overall

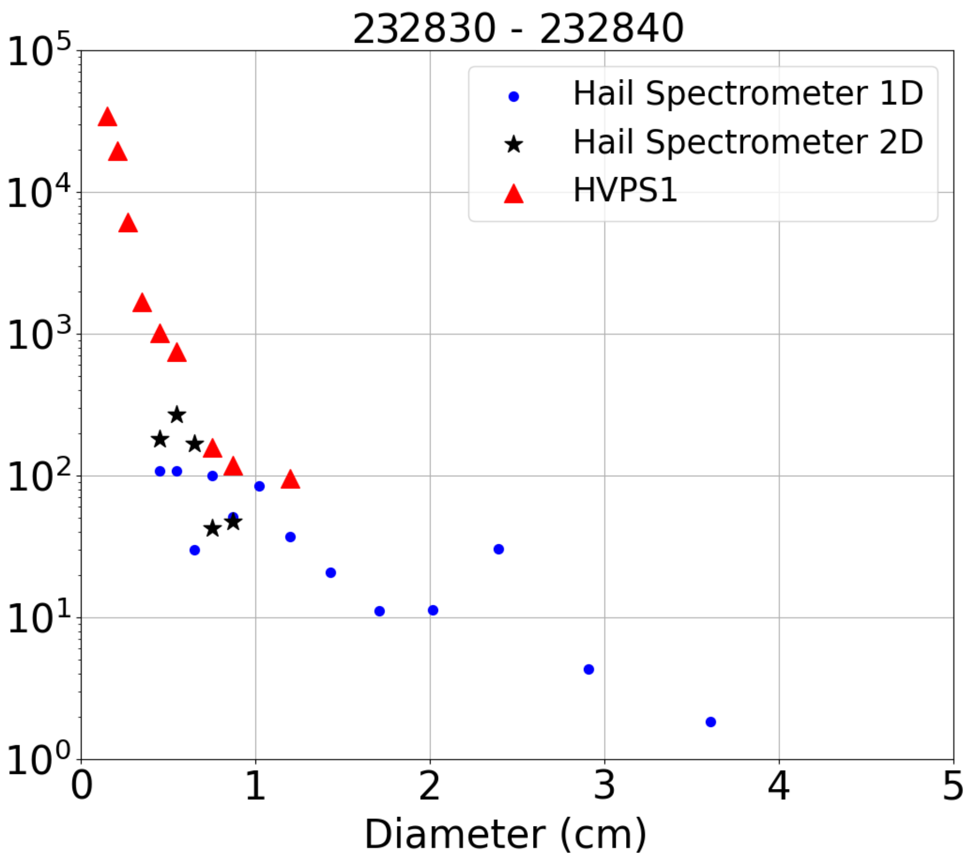
Legend:
- X = x-size diameter (mm)
- A =Area ratio



- To validate lower quality images, we look at,
  - Image Buffers
  - Reflectivity plots
  - Video recordings
  - Pilot report
- Data from Flight 757 (June 22, 2000)

24:18:26 UTC

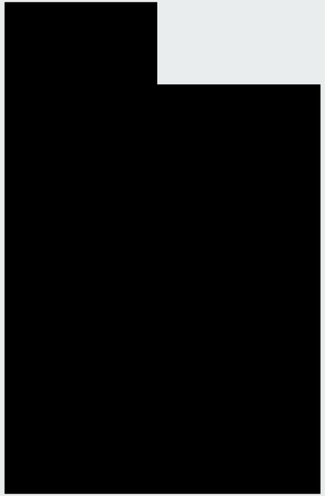
- Hail Spectrometer 1D and 2D x-size concentrations can now be compared
- They don't perfectly match
  - Different sample areas
  - Different sizing methods



- Two types of uncertainty
  - Poisson
  - Sizing method
- Poisson uncertainty is used for 1D v 2D evaluation
- Both Poisson and sizing method uncertainty are used for reflectivity

$$\sigma = \sqrt{N(D)}$$

$$10 = \sqrt{100}$$



Circle-fit: 6.15 mm

X-size: 5.4 mm

X-extent: 5.4 mm

Y-size: 3.6 mm

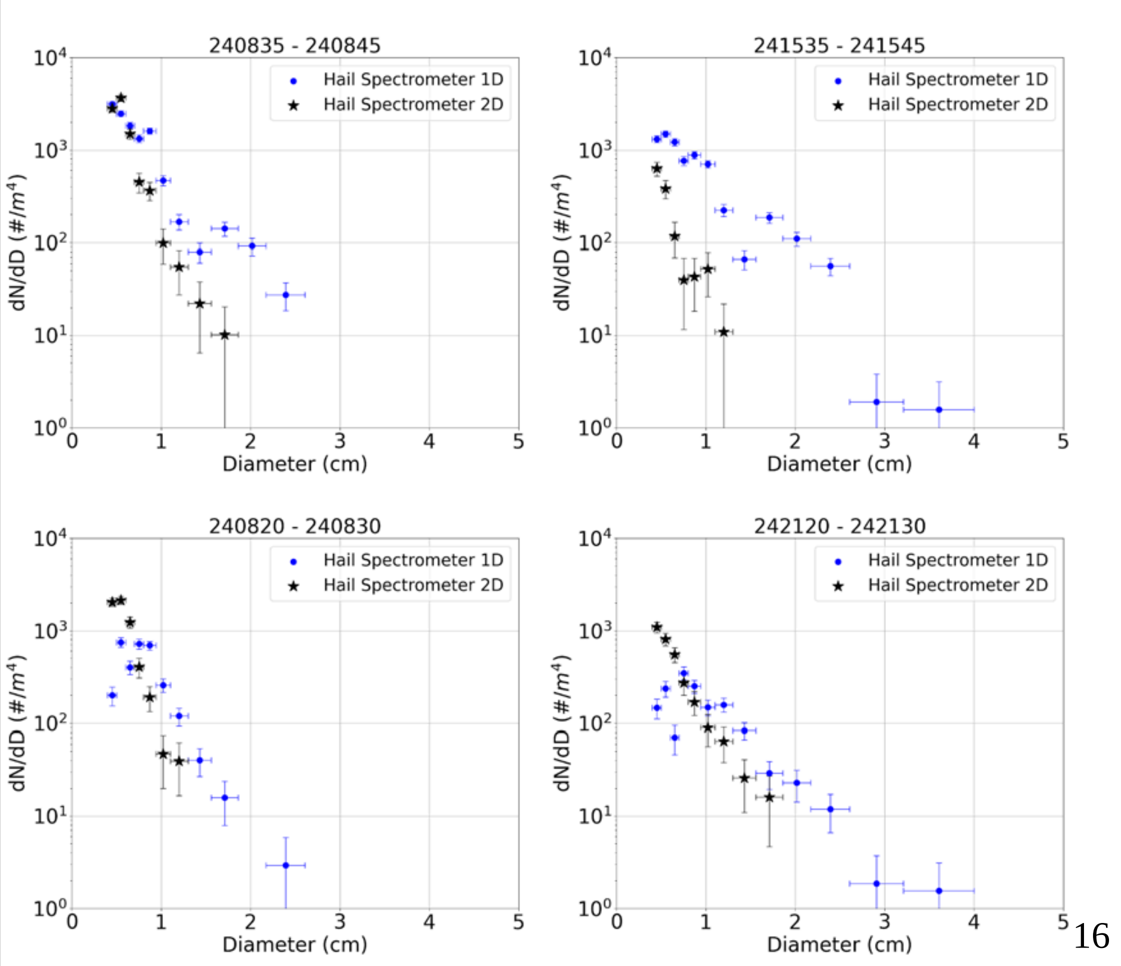
Area-size: 4.76 mm

Particle Size Distributions

- Wide range of uncertainties, from under 10% up to 100%
- Still see regular discrepancies, primarily that the 1D typically records the largest particles

Flight 815

Flight 757

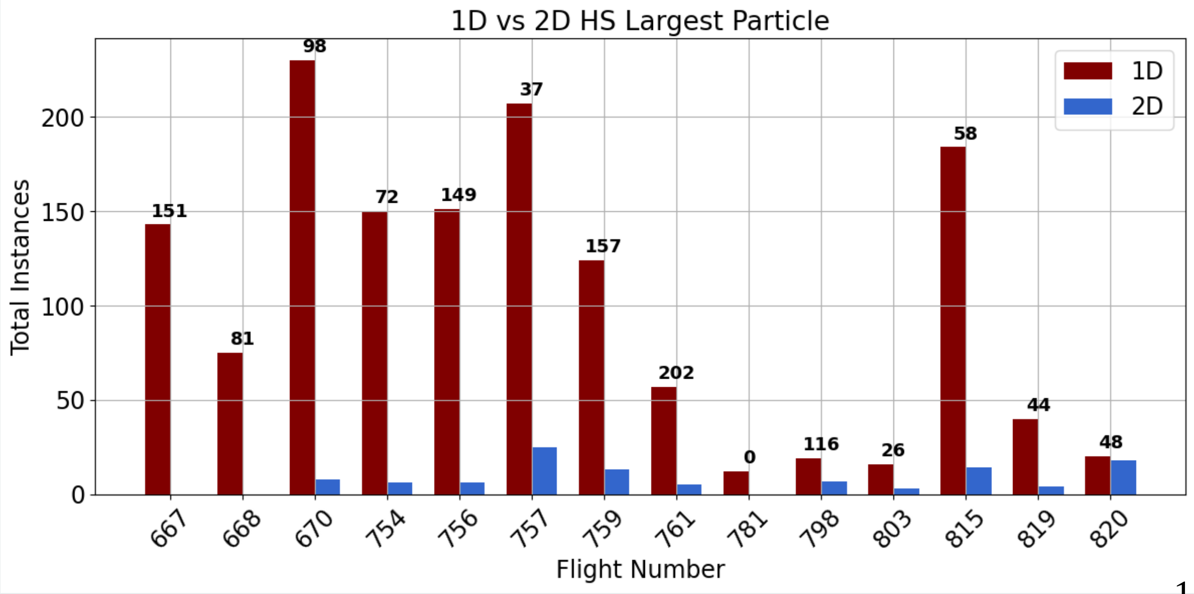


Evaluating Data Quality

$$Z_e = 10 * log_{10}\left(\frac{0.197^2}{0.93^2}\sum_{i=1}^{14} D_i^6 * C_i\right)$$

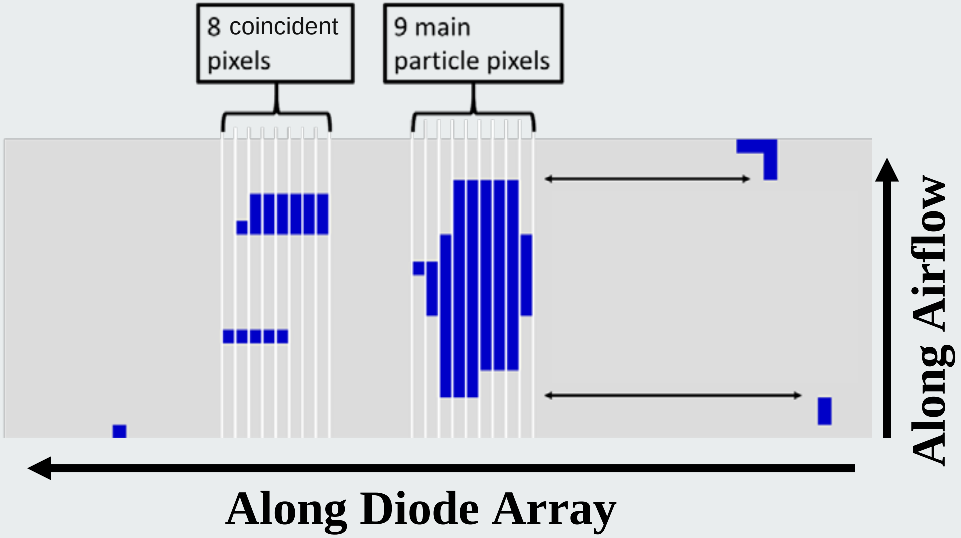
For a single 1 cm particle: Z_e = 37.6 dBZ
2 cm particle: Z_e = 56.4 dBZ (x76)
3 cm particle: Z_e = 67.2 dBZ (x917)

- The 1D data records a larger particle than the 2D data 1428 times.
- The 2D data only records a larger particle 109 times.
- This will have a big impact on reflectivity calculations

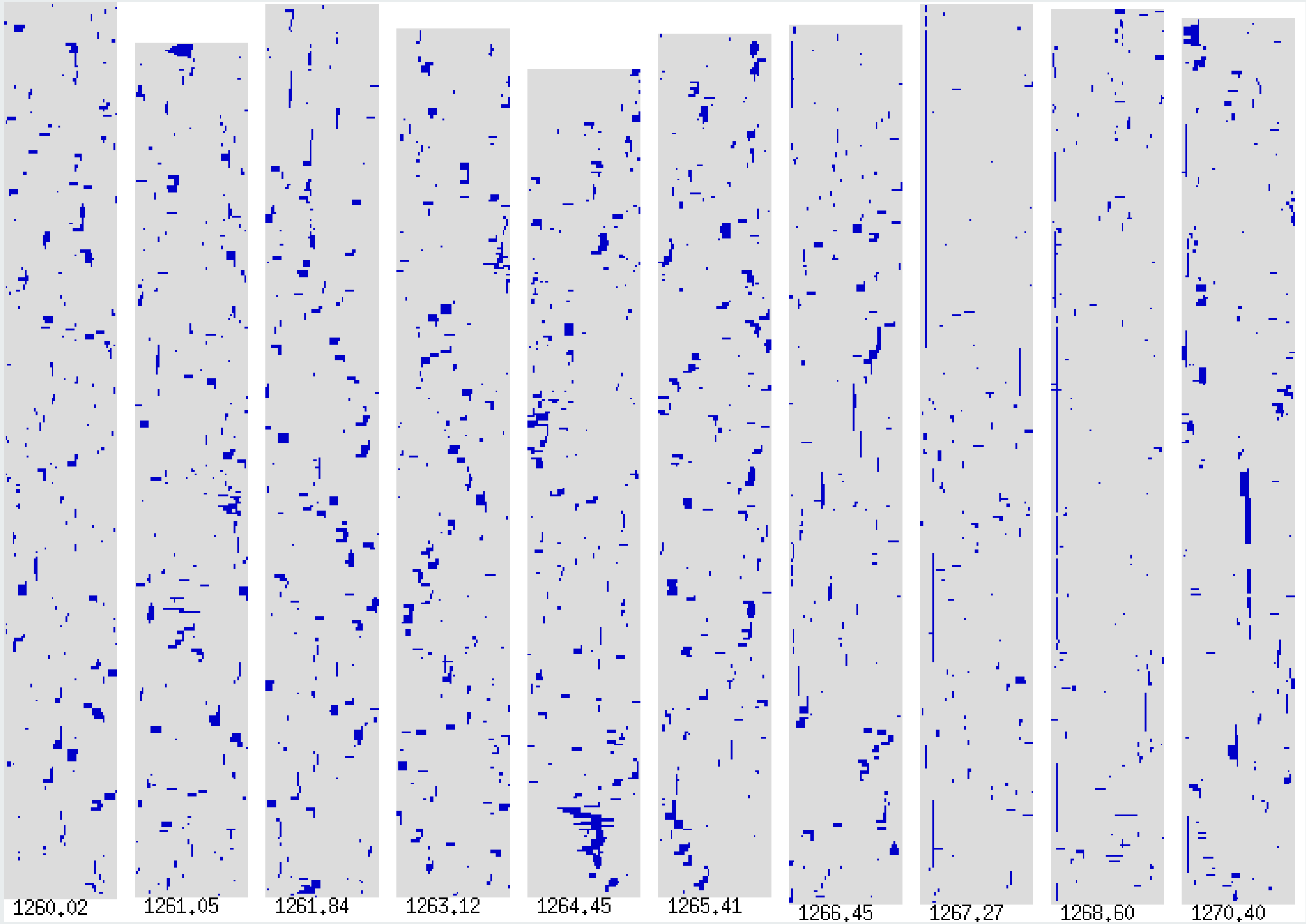


Evaluating Data Quality

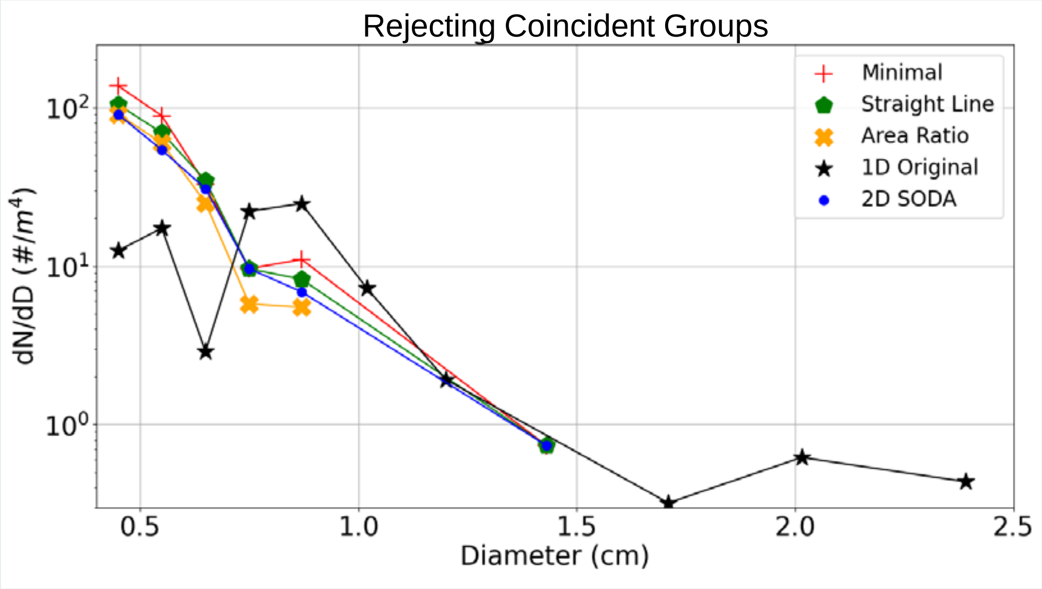
- To learn why there are PSD discrepancies, 10 seconds of image buffers are processed manually.
- When using 1D processing methods, particle groups may contain coincident particles
- 9 unique ways to process the data are tested



Evaluating Data Quality



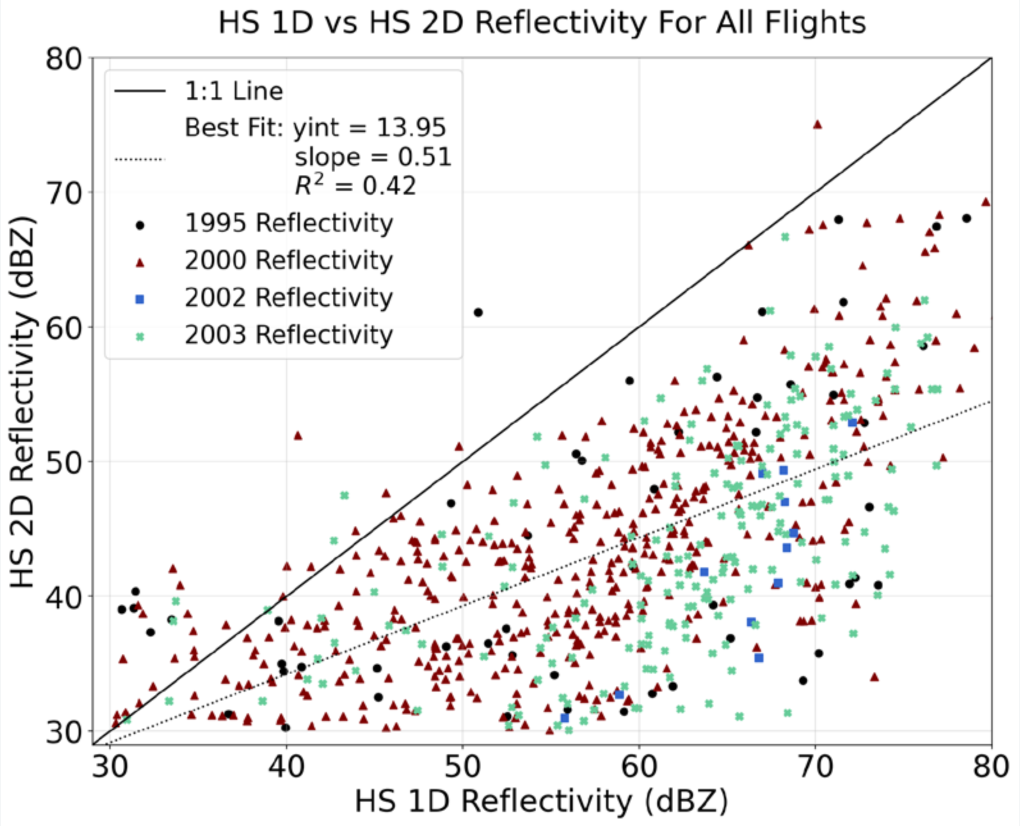
- Including coincident particles matches the largest particle
- Excluding coincident particles improves large particle overcounting
- Rejecting coincidence is intended to match the 1D sizing but results in the least similar PSD



- So, we know that maximum particle sizes are different and how important that difference is.

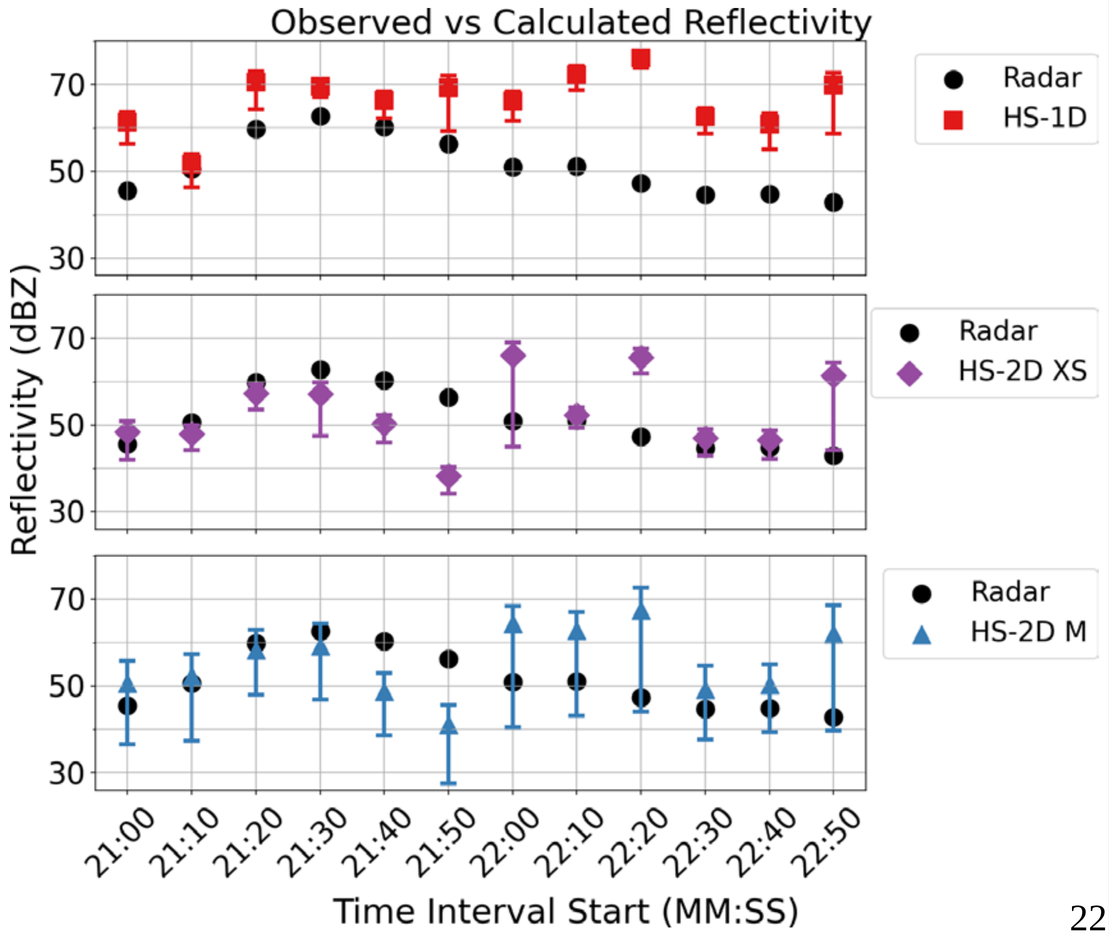
$$Z_e = 10 * log_{10}(\frac{0.197}{0.93}\sum_{i=1}^{14} \boldsymbol{D_i^6} * C_i)$$

- This results in significant difference in computed reflectivity when all other variables are kept the same



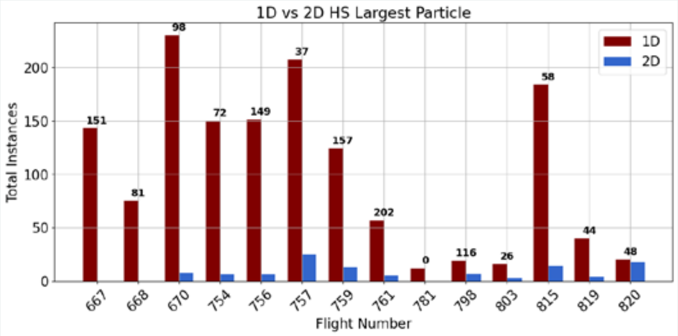
Reflectivity Comparisons

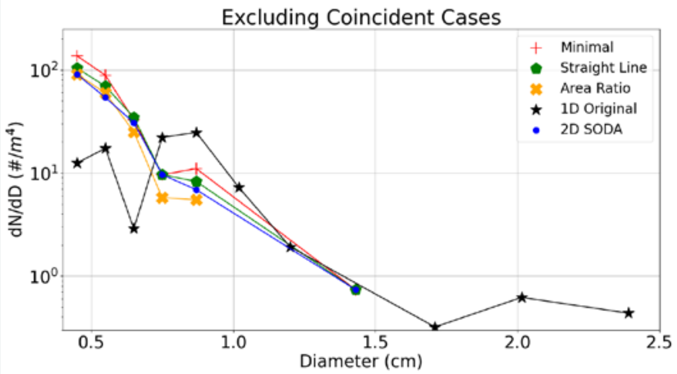
- 1D reflectivity is consistently higher than radar observations.
- 2D x-size (XS) reflectivity yields over and underestimates, along with matches to the radar observations.
- 2D mean (M) overlaps in 10/12 intervals



Conclusions

- 1D and 2D PSDs show different distributions with the 1D data recording a higher concentration of large particles
- Based on image analysis and comparison to radar, the 2D data is likely a better representation of the particles
- Future work could solve for particle composition using information such as temperature, updraft, and liquid water content.

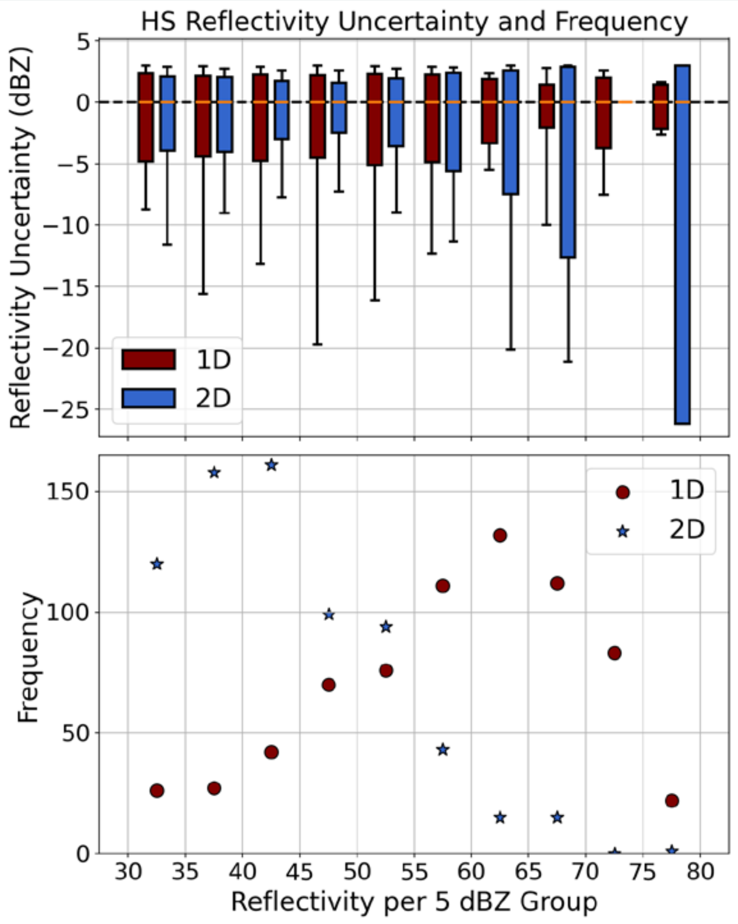




- Thank you to all my committee members
- Thank you to Wanda and Sue
- Thanks to all my friends
- Thanks to my family

Questions?

- Because of large PSD uncertainties and reflectivity being logarithmic, the upper and lower uncertainties are unbalanced.
- Can see that it's roughly +3 -5 for about half of the data (frequency).

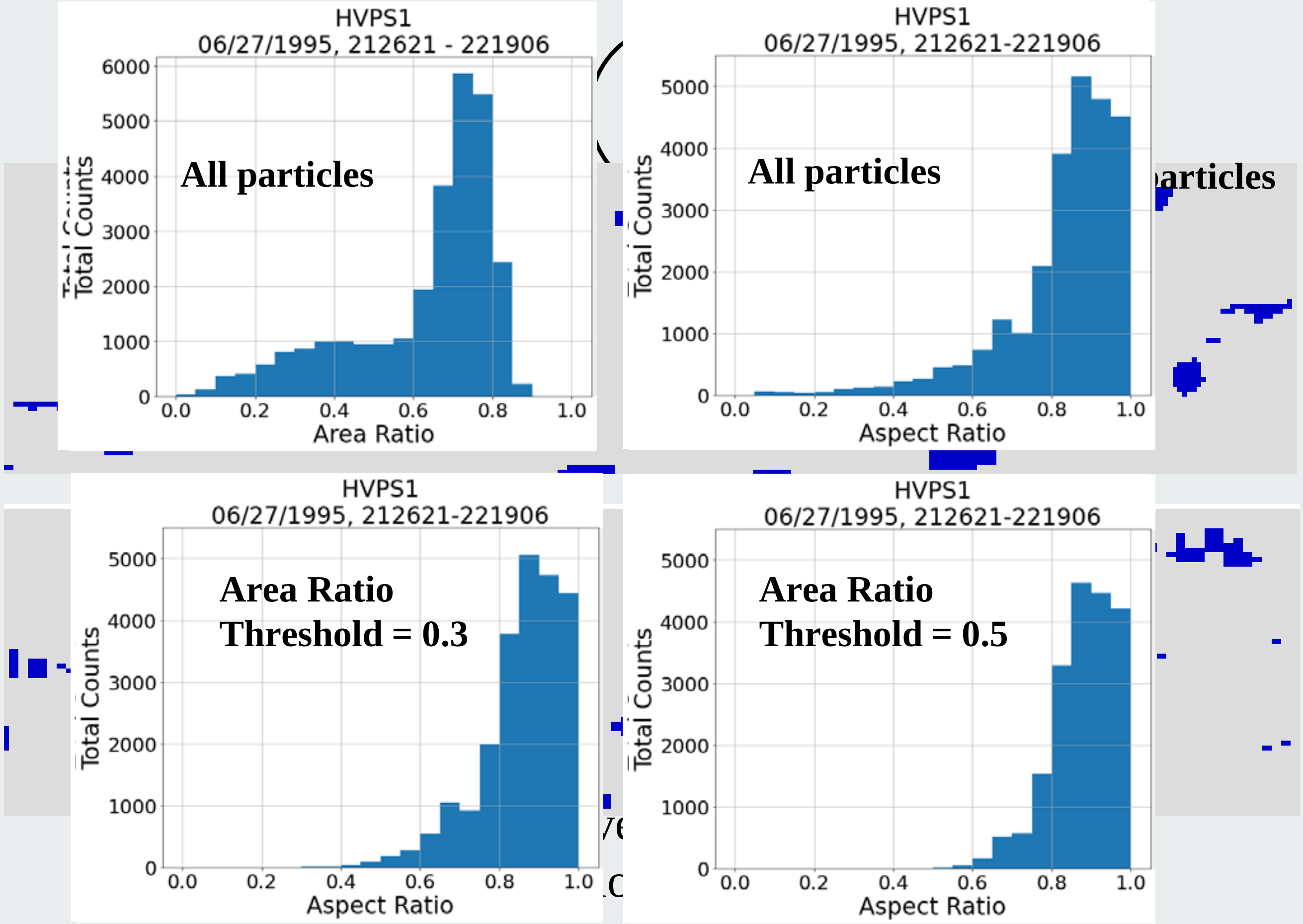


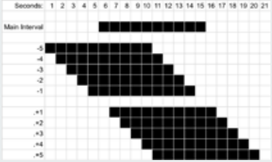
- In this project, an Optical Array Probe can record data two ways,
  - Two-dimensional method
    - Circle-fit, x-size, x-extent, y-size, area-size.
  - One-dimensional method

Particle Size Distributions

- For the 2D data, we need,
  - Particle sizes
  - Area ratio to accept or reject particles

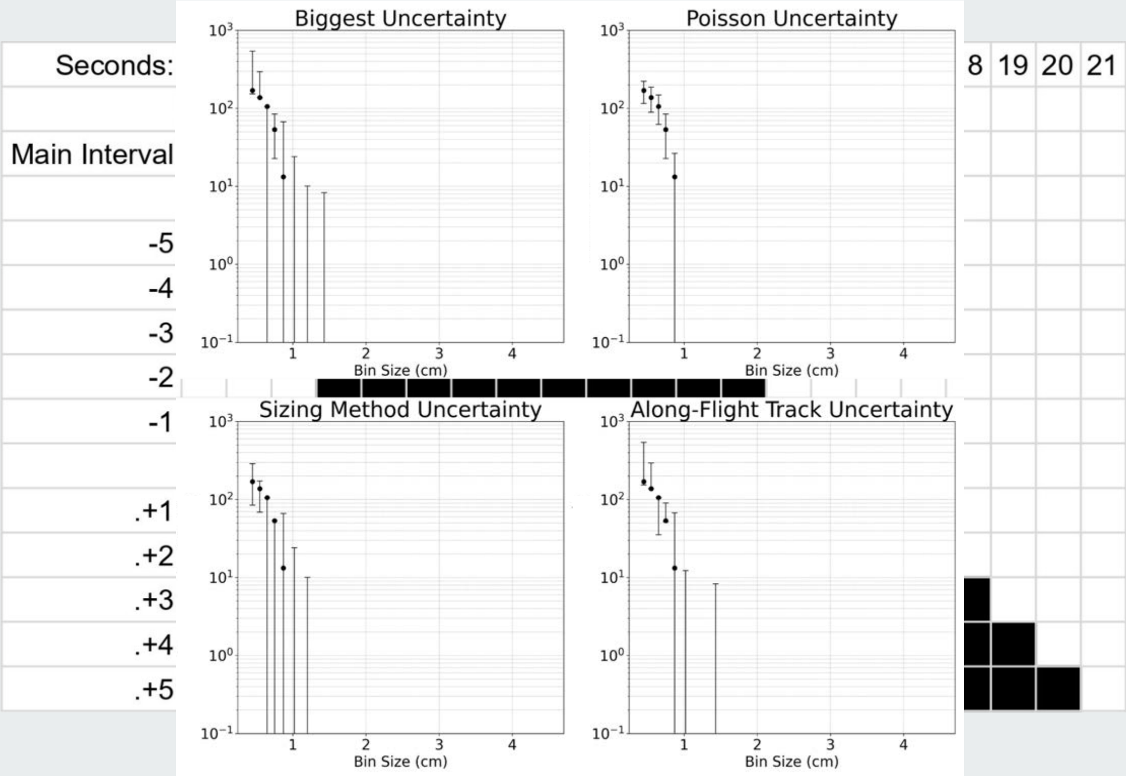
- A threshold of 0.3 appears to work for the Hail Spectrometer

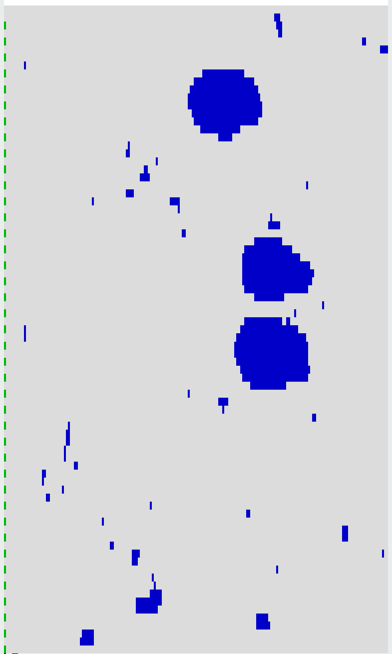




$$\sigma = \sqrt{N(D)}$$

- Three types of uncertainty
  - Poisson
  - Sizing method
  - Along-flight-track
- We select the largest individual range of uncertainty for each bin





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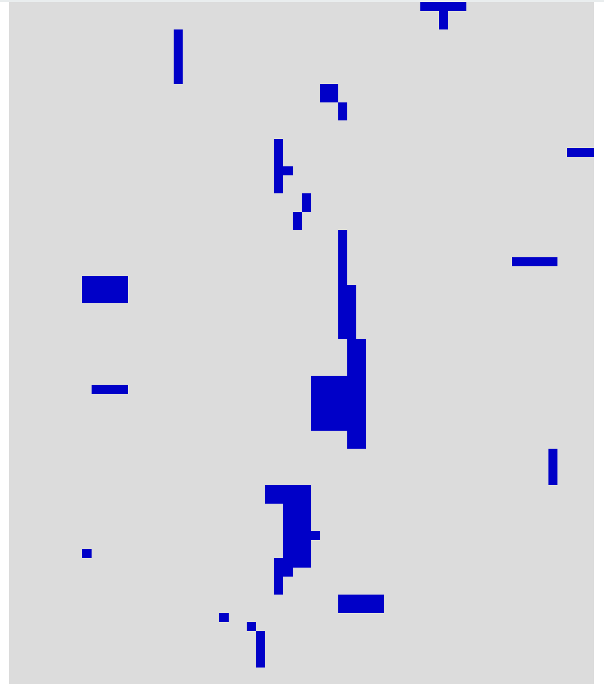

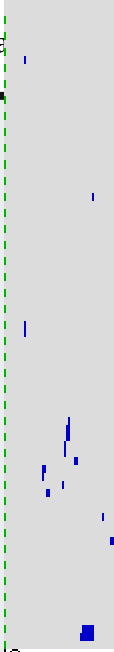

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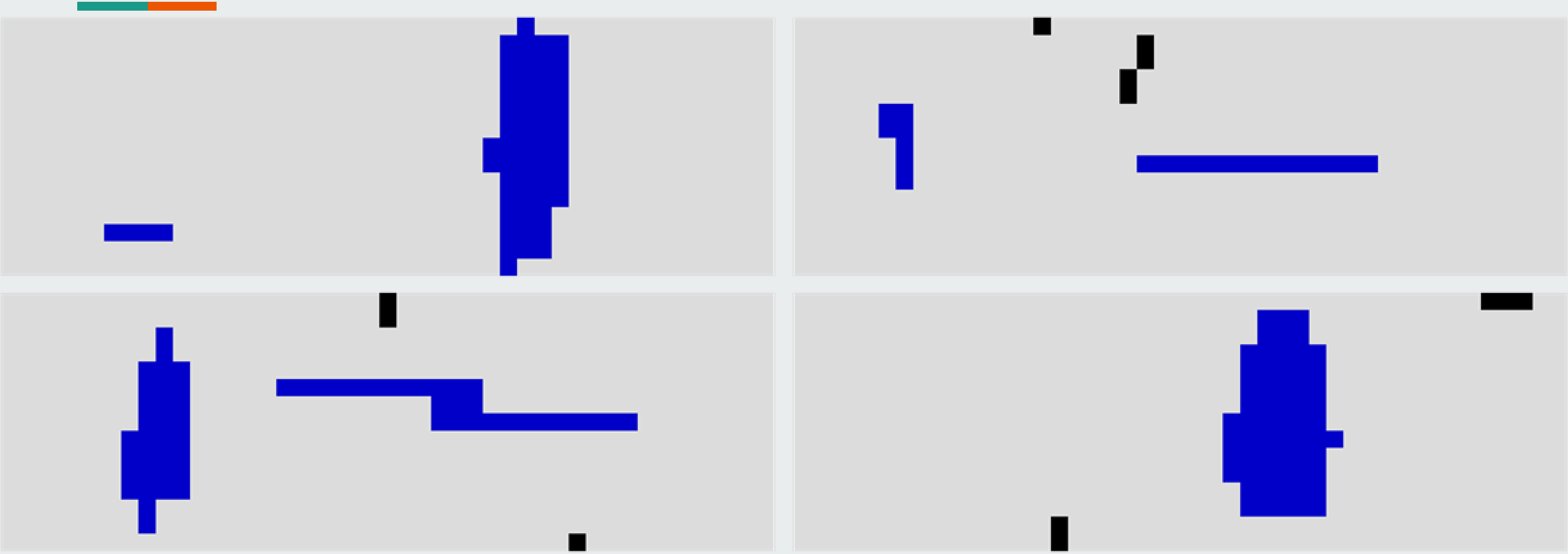
Particle Size Distributions



Evaluating Data Quality

- The 1D first bin was higher 611 times whereas the second bin was higher 800 times
- The 2D first concentration bin is higher 701 whereas the second bin is higher 294 times