EarthCARE CPR Spectral Width Retrieval: Signal-Level Simulation Assessment and Climatological Analysis

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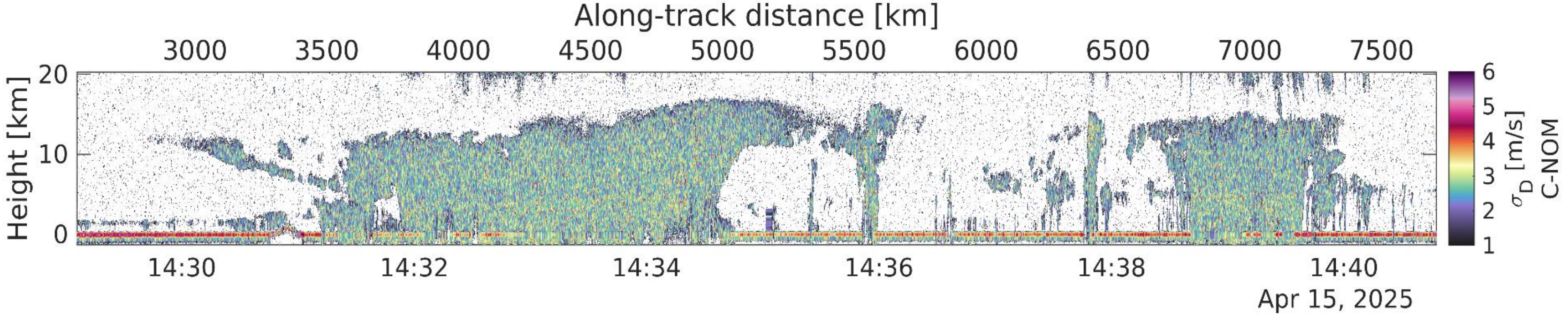
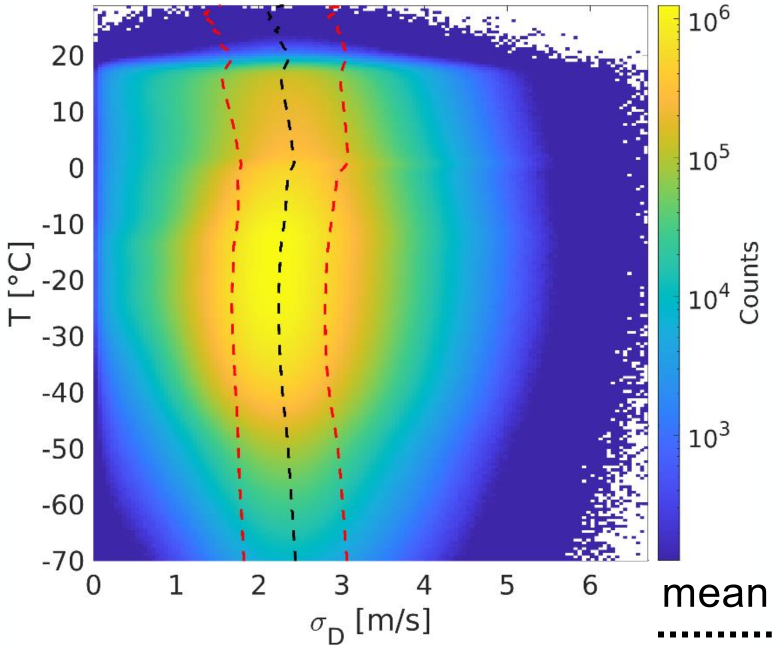
Motivation and Problem

- EarthCARE CPR is the first Doppler-capable W-band spaceborne cloud radar in low Earth orbit, providing first ever measurement of Doppler velocity and **spectral width**
- Spectral width can be used to infer additional geophysical meaning, but it's expected to be **dominated by spacecraft-motion induced broadening $\boldsymbol{\sigma_{sat}}$** (Sy and Tanelli, 2023)
- For EarthCARE, **theory predicts $\boldsymbol{\sigma_{sat} = 3.6}$ m/s**, therefore $\sigma_D^2 = \sigma_R^2 + \sigma_{sat}^2 \rightarrow \boldsymbol{\sigma_D \approx 3.6}$ **m/s** unless the return signal is significantly broadened

Level-1B data **shows systematic narrowing to ~2.5 m/s** even in smooth stratiform regimes, and very high σ_D at the surface peak



Temperature vs. σ_D climatology (1 year, 2025)



What could be the cause of this behavior? Can estimator error predict it?

I&Q Simulation and Pulse-Pair Estimation of σ_D

Question:

- Can the observed σ_D narrowing be explained by pulse-pair estimation biases?

Method:

- Covariance-based synthetic I&Q generation (Battaglia et al., 2025), to produce oversampled complex voltage time series from prescribed radar moments
- EarthCARE's CPR PRF and noise floor with Level-1B 500 m integration (~400 pulses)
- EarthCARE acquisition scheme: 22 coherent pulses + 2 silent intervals (complete decorrelation)

Aim:

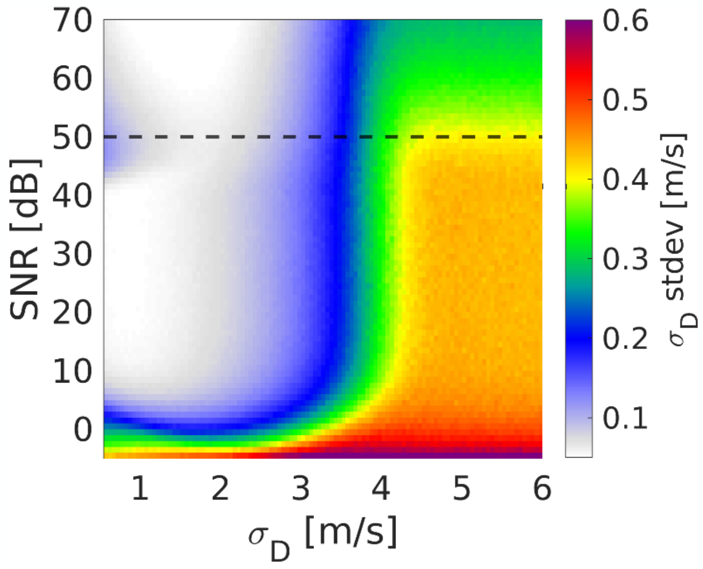
- Characterize σ_D pulse-pair estimator error statistics as a function of SNR and σ_D

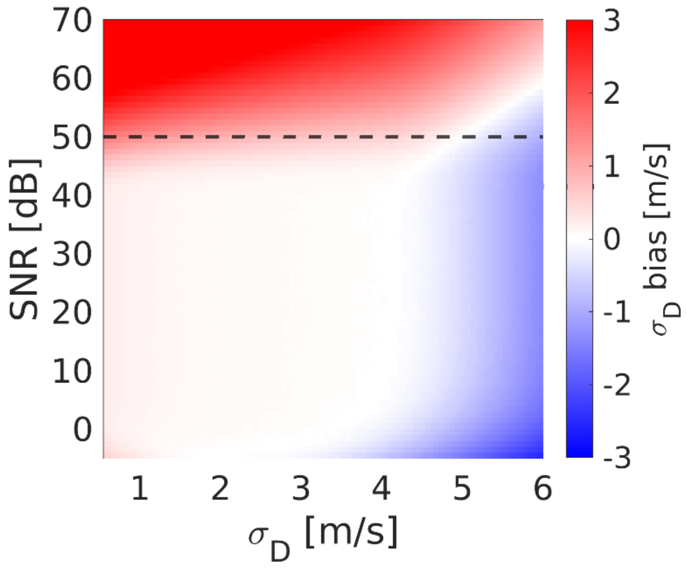
$$\hat{\sigma}_D = \frac{\lambda\,\mathrm{PRF}}{2\sqrt{2}\pi}\sqrt{\ln\left(\frac{R_0 - N_f}{|R_1|}\right)}$$

R_0: lag-0 autocovariance (power)
R_1: lag-1 autocovariance
N_f: noise floor

Estimator Performance

- In the expected 2 to 4 m/s range, estimates are **essentially unbiased** at good SNR
- Estimator noisiness is around 0.2 − 0.3 m/s





- Black dashed lines are **saturation threshold**, which happens at high return power
- **Two separate chains**: R_1 signal ("linear" processing) is assumed to saturate at a threshold of 50 dB, whereas the R_0 signal ("log" processing) is not clipped, driving overestimation of σ_D

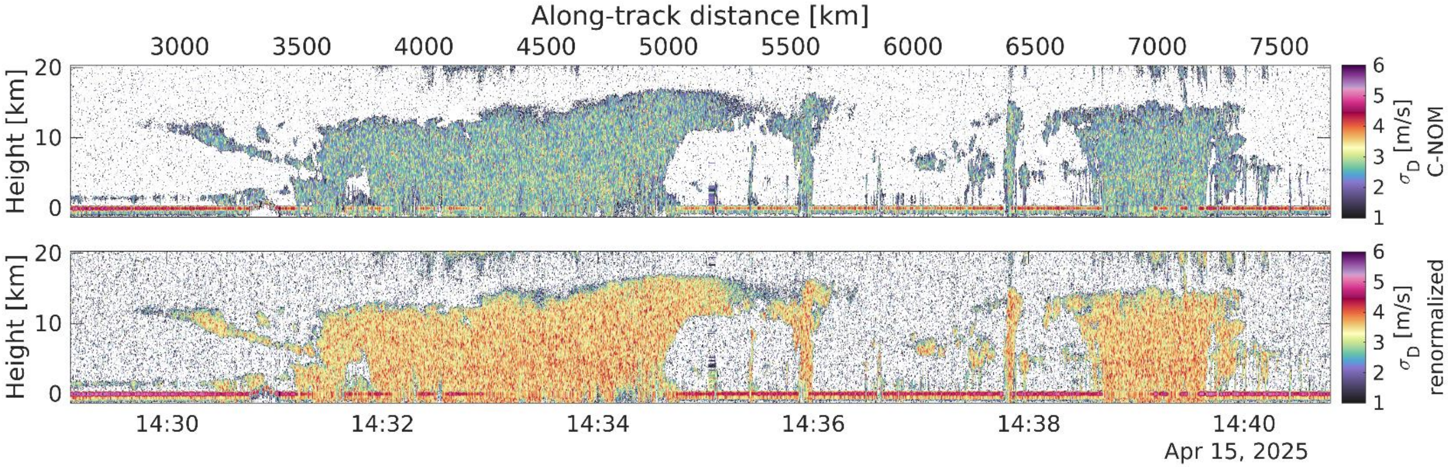
Conclusions: estimator error does not explain the observed systematic narrowing in the Level-1B data, and saturation and I&Q clipping may explain the σ_D peak in the surface clutter

Renormalization

- A factor K is applied to the lag-1 covariance to calibrate for any unknown mismatch in the processing chain:

$$\sigma_D = \frac{\lambda\,\mathrm{PRF}}{2\sqrt{2}\pi}\sqrt{\ln\left(\frac{R_0 - N}{\boldsymbol{K}|R_1|}\right)}$$

- Smooth stratiform ice used as reference regime with target $\sigma_D = 3.6$ m/s
- K is obtained by inversion of the estimator formula and averaging over each granule, then σ_D is recomputed



- The new renormalized σ_D climatology is studied to identify characteristic features in the signal in different regimes (stratiform clouds, multiple scattering and surface clutter selected as most significant)

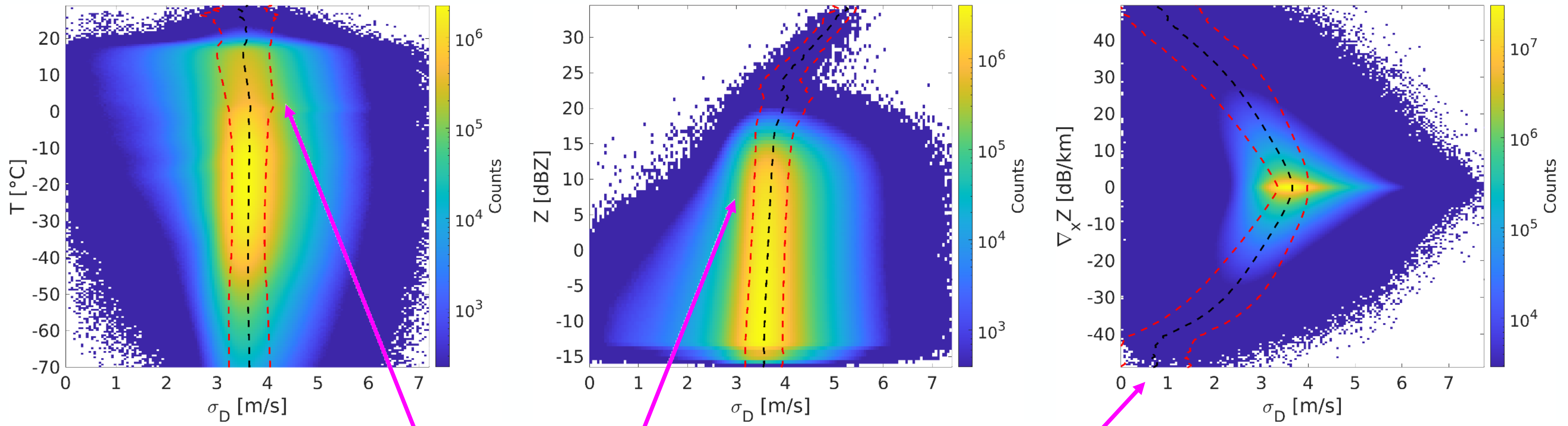
Atmospheric Climatology (1/2) – Stratiform Clouds

(1 year, 2025)

Temperature vs. σ_D | Reflectivity vs. σ_D | Along-track reflectivity gradient vs σ_D

mean

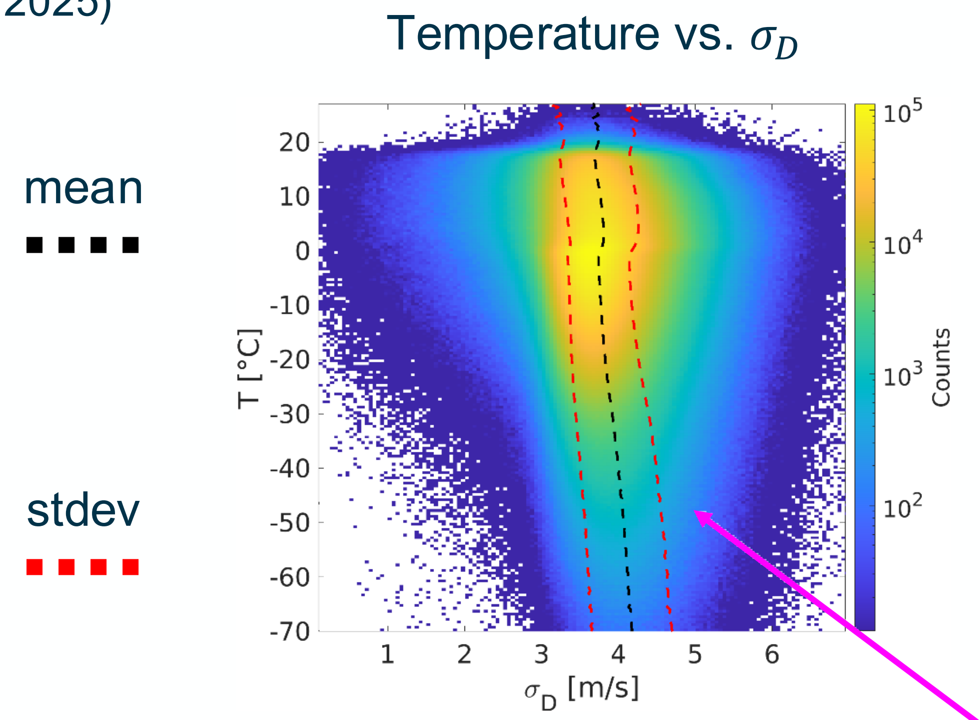
stdev

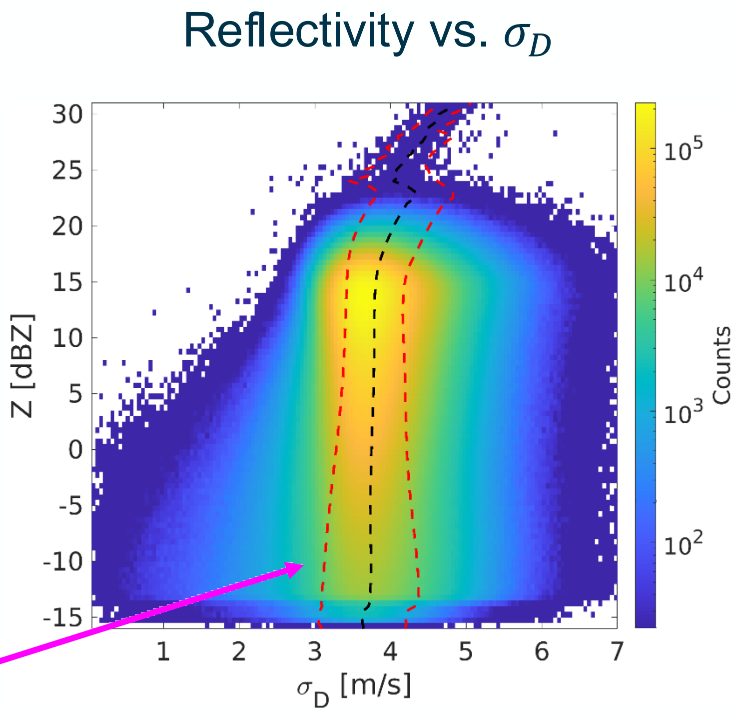


- Dominant effects are platform-induced broadening at ~3.6 m/s mean value and estimator noisiness at ~0.3 m/s
- Slight separation between **liquid and ice** visible
- Reflectivity shows a slight **trend of broadening with higher power**
- Strong reflectivity gradients seem to produce **narrowing rather than broadening** (NUBF effect?)

Atmospheric Climatology (2/2) – Multiple Scattering

(1 year, 2025)





- In multiple scattering the **broadening becomes relevant**, around 4 m/s
- Especially at lower temperatures: **broadening increases with decreasing temperatures**
- More **dispersion at lower power** due to NUBF effects

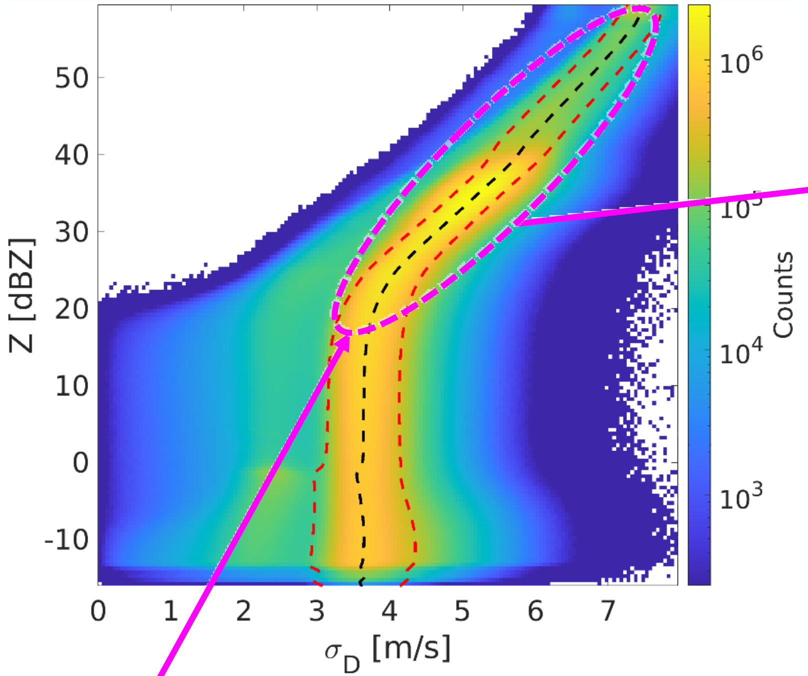
Surface Clutter Climatology

(1 year, 2025)

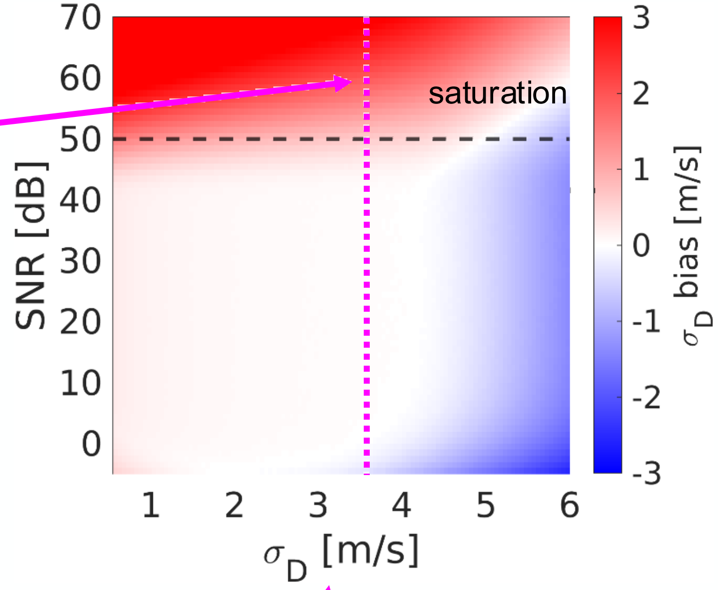
mean

stdev

Reflectivity vs. σ_D



σ_D estimator bias



- **Strong broadening near clutter peak**, onset around $Z \approx$ 20/25 dBZ (~45/50 dB SNR)
- Climatological behaviour in surface return signal **consistent with simulations** over saturation threshold

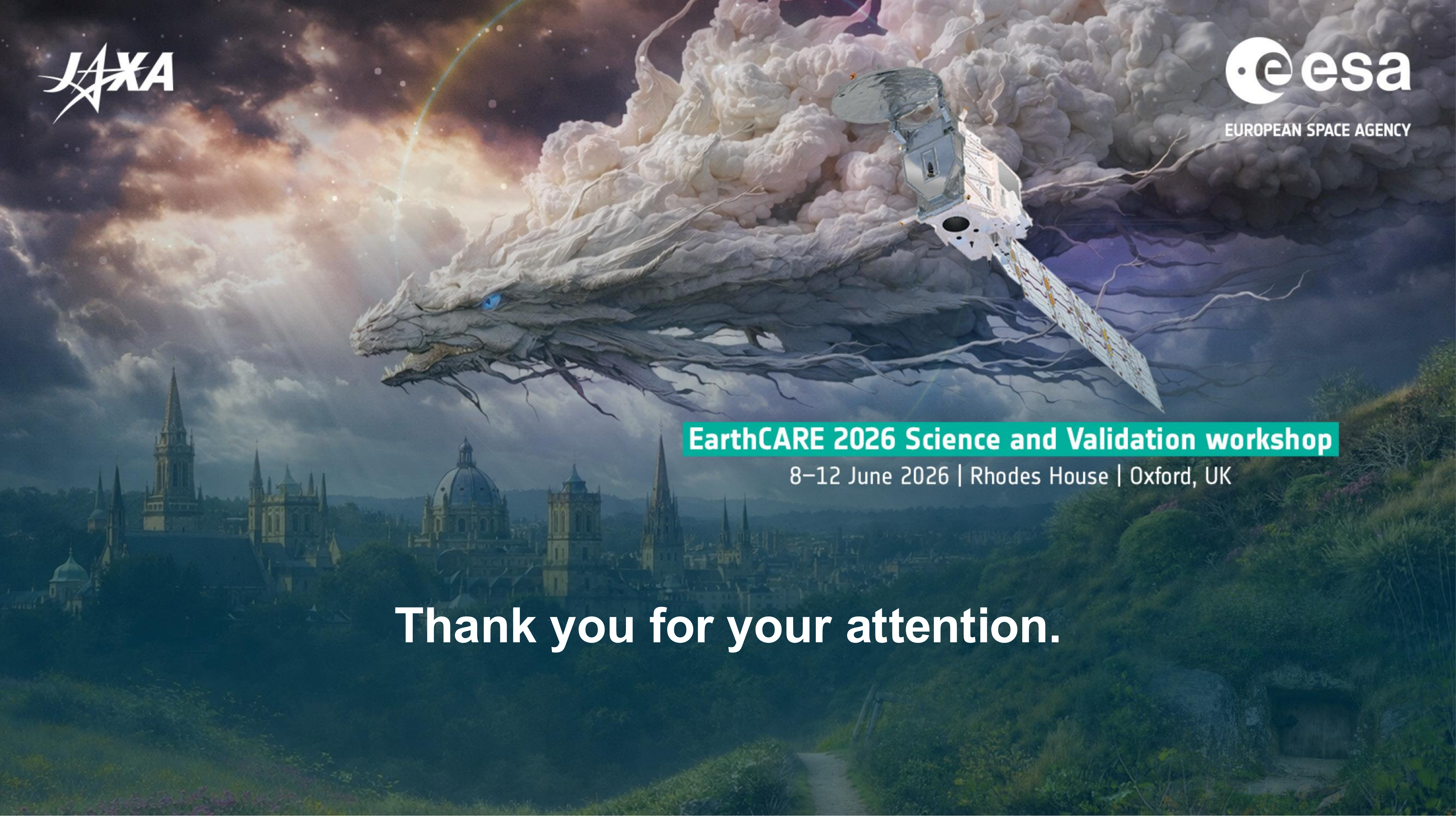
→ I&Q clipping drives overestimation

- **Clear trend in saturation regime**: $\sigma_D \propto \sqrt{\ln(R_0 - N)}$, when $|R_1|$ becomes bounded in the PP estimator formula

Conclusions

- EarthCARE σ_D **should be dominated by the spacecraft-motion broadening** term $\sigma_D \approx \sigma_{sat} = 3.6$ m/s
- Level-1B C-NOM products exhibits **systematic narrowing to ~2.5 m/s**
- Pulse-pair estimator error statistics and clipping **do not explain these low values**
- **Renormalization** restores expected mean value around 3.6 m/s
- Climatological **most relevant features** are
    1. Normally, **in homogeneous regions the signal dynamics is weak**, dominated mainly by spacecraft motion broadening and estimator noisiness
    2. **Broadening in strong convection**, especially driven by multiple scattering
    3. Strong **overestimation in surface clutter signal** (due to saturation effects and I&Q clippping)
- Because of these reasons, the σ_D value is of **difficult interpretation alone**, at least at Level-1B resolution

The σ_D parameter should be primarily used for qualitative diagnostic rather than for quantitative studies



EarthCARE 2026 Science and Validation workshop

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Thank you for your attention.

References and Acknowledgements

References

- Battaglia, A., Rizik, A., Sikaneta, I., and Tridon, F. (2025). I and Qs Simulation and Processing Envisaged for Spaceborne Polarization Diversity Doppler Radars. IEEE Transactions on Geoscience and Remote Sensing, 63:1–14
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