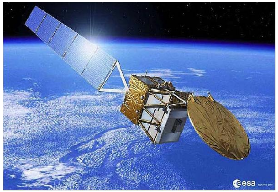
Novel methods to retrieve Doppler spectral widths from EarthCARE-like spaceborne radars

Ousmane O. Sy Simone Tanelli
ousmane.o.sy@jpl.nasa.gov simone.tanelli@jpl.nasa.gov

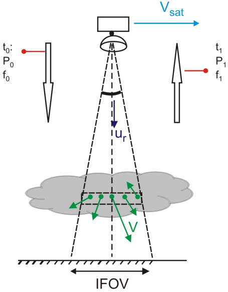
Jet Propulsion Laboratory
California Institute of Technology

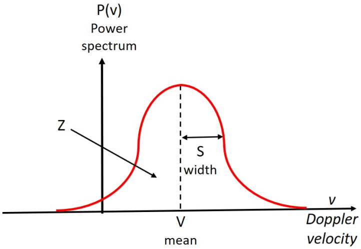
November 27, 2023

EarthCARE CPR: 1st radar of its kind: What Doppler results to expect?

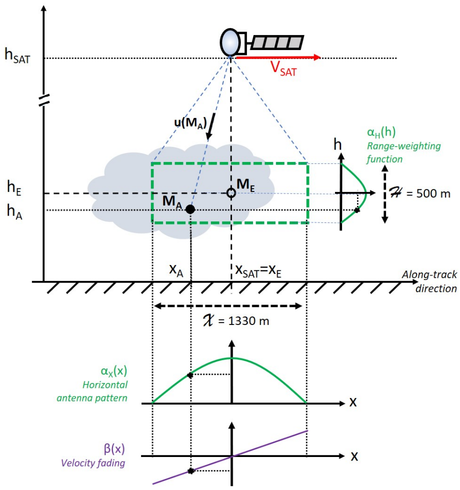


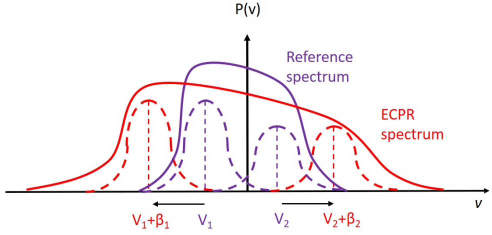
	Launch	f	XT scan	Observables
TRMM PR	1997	Ku	✓	Z
CloudSat CPR	2006	W	×	Z
GPM DPR	2014	Ku, Ka	✓	Z
RainCube PR	2018	Ka	×	Z
EarthCARE CPR	**2024**	**W**	×	Z, V, S





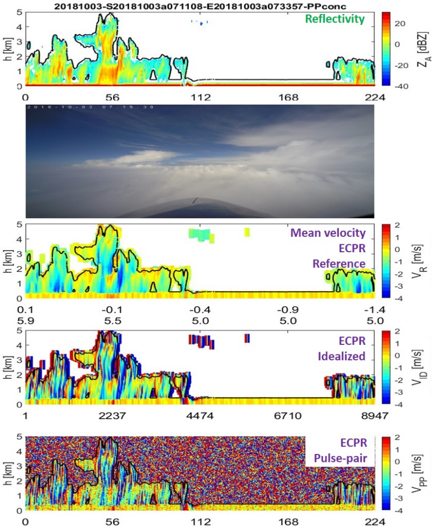
ECPR Idealized spectrum



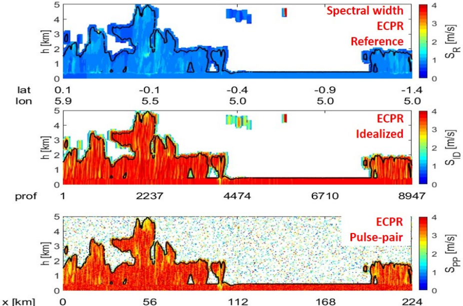


- Reference moments: $(Z_{\mathrm{R}}, V_{\mathrm{R}}, S_{\mathrm{R}})$
- Idealized moments: $(Z_{\mathrm{ID}}, V_{\mathrm{ID}}, S_{\mathrm{ID}})$
  - NUBF bias: $V_{\mathrm{ID}} \neq V_{\mathrm{R}}$
  - Spectral broadening: $S_{\mathrm{ID}} \gg S_{\mathrm{R}}$
- Pulse-pair moments: $(Z_{\mathrm{PP}}, V_{\mathrm{PP}}, S_{\mathrm{PP}})$
  - NUBF, broadening
  - random, noisy

Example: ECPR (PRF = 7 kHz) from sub-orbital APR3 in ORACLES (PI: dr. Jens Redemann)



Parameters	Ku-band	Ka-band	W-band
Frequency (GHz)	13.4	35.6	94.92
Polarization	HH, HV	HH	HH, VV
Antenna eff. Diamter	0.4 m	0.14 m	0.3 m
Antenna gain	34 dBi	34 dBi	50 dBi
Antenna Scan Angle	+/- 25	+/- 25	+/- 25
Peak Power	120 W	500 W	1400 W
Bandwidth	4 MHz	4 MHz	4 MHz
Pulsewidth	3-20 us	3-20 us	0.25, 0.5, 1us
PRF	5 kHz	5 kHz	5 kHz
Vertical resolution	60 m	60 m	50, 80, 150 m
Hor. Res. (@10 Km alt.)	800 m	1000 m	200 m
Ground Swath	10 km	10 km	10 km
Sens. M(@10km range)	**10 dBZ**	**-10 dBZ**	**-35 dBZ**
Doppler precission	**0.3 m/s**	**0.3 m/s**	**0.3 m/s**



Why no correction for S?

Mean velocity V - NUBF

- Tanelli et al. (2002), Durden et al. (2007), Kollias et al. (2014), Sy et al. (2014)

$$V = (W_{wind} - V_{term}) + \phi_{\text{NUBF}} \tag{1}$$

- $\phi_{\text{NUBF}} \propto (V_{\text{SAT}}, \mathbf{Z})$ (hierarchical) $\Rightarrow$ can be corrected

Spectral width S - broadening

- Meneghini & Kozu (1990), Tanelli et al. (2002), Kollias et al. (2014)

$$S^2 = (S^2_{\text{turb}} + S^2_{\text{shear}} + S^2_{\text{term}}) + \psi_{\text{BROAD}} \tag{2}$$

- $\psi_{\text{BROAD}}(V_{\text{SAT}}, \theta_{\text{3dB}}) \neq f(Z, V)$ (not hierarchical) $\Rightarrow$ (2) not useable for correction

Resampling Diagram / ExpliSyT / CConDoR

Canonical Doppler resampling: Fading(0), Znubf(0), Vnubf(0)

Reference config

- **$\theta_Z = dZ_A/dx = 0$**
- **$\theta_V = dV_A/dx = 0$**

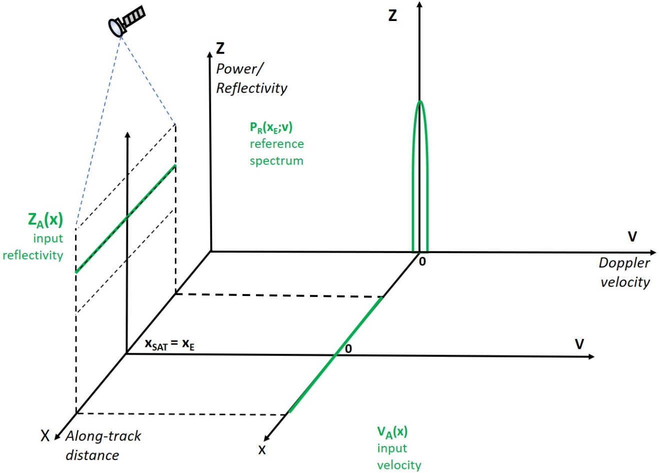
No velocity fading

- $V_{SAT} = 0$ m/s

Spectra

Reference vs Input

- **Bias(V) = 0**
- **No broadening**



Canonical Doppler resampling: Fading(0), Znubf(0), Vnubf(1)

Reference config

- $\theta_Z = dZ_A/dx = 0$
- **$\theta_V = dV_A/dx > 0$**

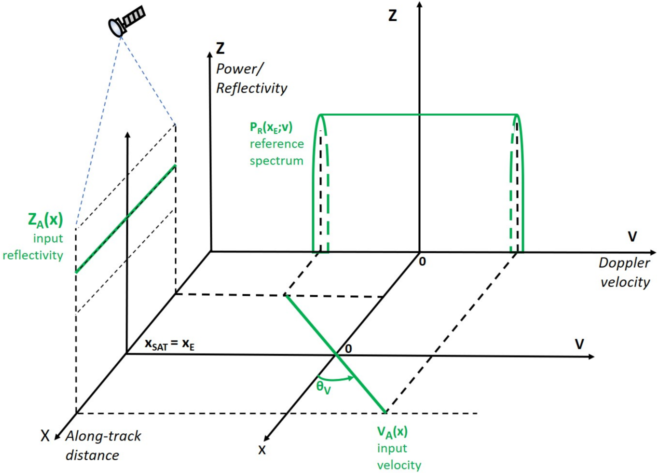
No velocity fading

- $V_{SAT} = 0$ m/s

Spectra

Reference vs Input

- **Bias(V) = 0**
- **Broadening**



Canonical Doppler resampling: Fading(0), Znubf(-1), Vnubf(1)

Reference config

- **$\theta_Z = dZ_A/dx < 0$**
- $\theta_V = dV_A/dx > 0$

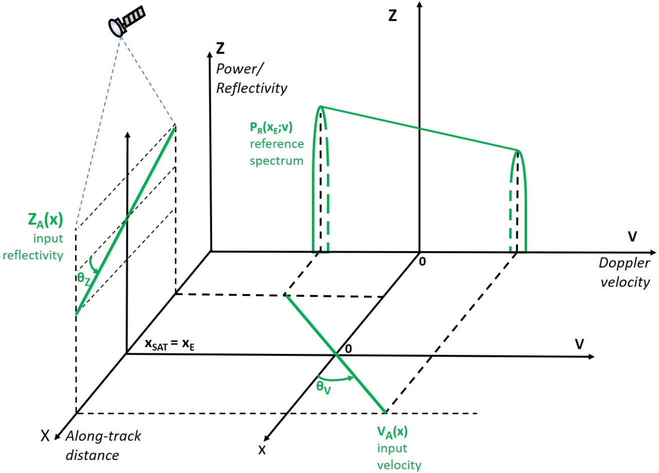
No velocity fading

- $V_{SAT} = 0$ m/s

Spectra

Reference vs Input

- **Bias(V) < 0**
- **Broadening**

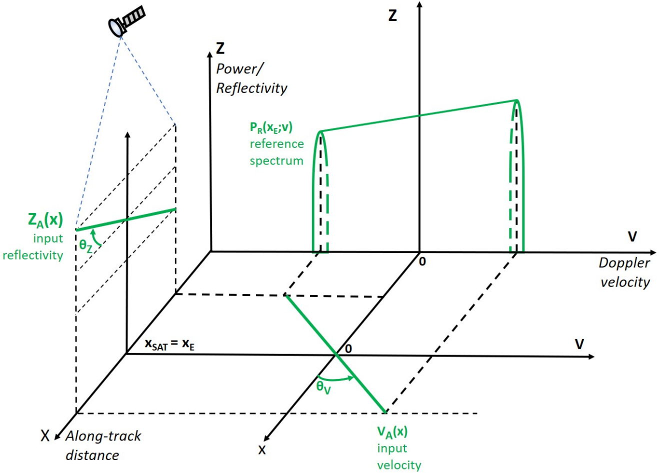


Canonical Doppler resampling: Fading(0), Znubf(1), Vnubf(1)

Reference config
- $\theta_Z = dZ_A/dx > 0$
- $\theta_V = dV_A/dx > 0$

No velocity fading
- $V_{SAT} = 0$ m/s

Spectra
Reference vs Input
- **Bias(V) > 0**
- **Broadening**



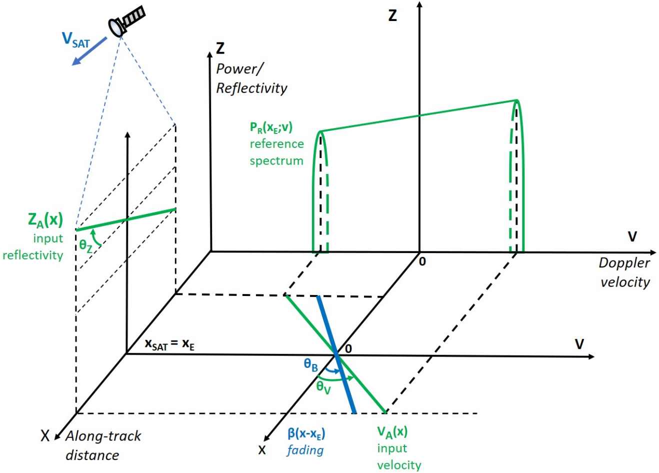
Canonical Doppler resampling: Fading(1), Znubf(1), Vnubf(1)

Reference config
- $\theta_Z = dZ_A/dx > 0$
- $\theta_V = dV_A/dx > 0$

Velocity fading
- $\theta_B = V_{SAT} / H_{SAT}$

Spectra

Reference vs Input
- Bias(V) > 0
- Broadening



Canonical Doppler resampling: Fading(1), Znubf(1), Vnubf(1)

Reference config

- $\theta_Z = dZ_A/dx > 0$
- $\theta_V = dV_A/dx > 0$

Velocity fading

- $\theta_B = V_{SAT}/H_{SAT}$

Spectra

Reference vs Input

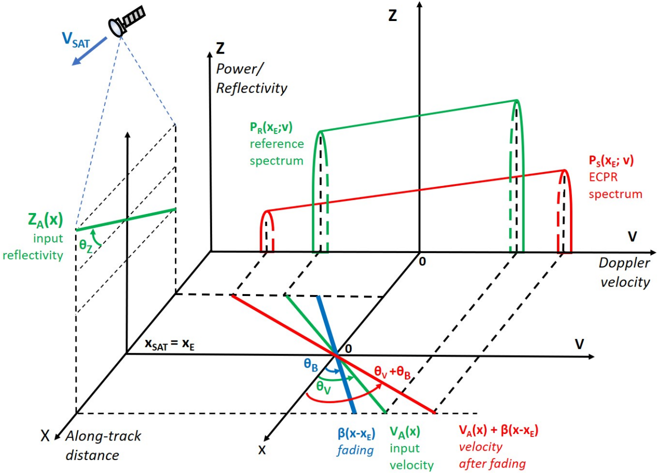
- Bias(V) > 0
- Broadening

ECPR vs Input

- Bias(V) > 0
- Broadening

ECPR vs Reference

- **Bias(V) > 0**
- **Broadening**



Canonical Doppler resampling: Fading(1), Znubf(1), Vnubf(-1)

Reference config
- $\theta_Z = dZ_A/dx > 0$
- $\theta_V = dV_A/dx < 0$

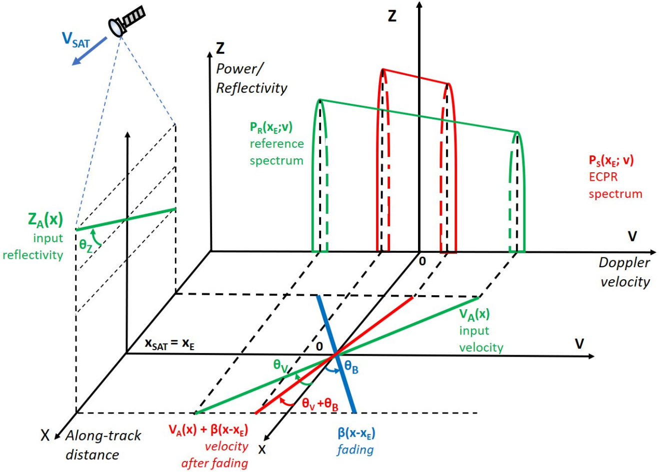
Velocity fading
- $\theta_B = V_{SAT} / H_{SAT}$

Spectra

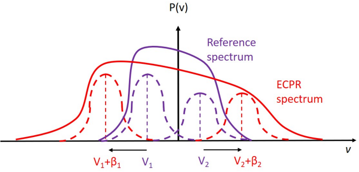
Reference vs Input
- Bias(V) < 0
- Broadening

ECPR vs Input
- Bias(V) < 0
- Broadening

ECPR vs Reference
- **Bias(V) > 0**
- **Shrinkage**



Idealized ECPR moments



$$\mathcal{P}_{\mathrm{I}}(x_{\mathrm{I}}; v) = \int_{\mathcal{L}} U_J(x_{\mathrm{I}} - x_{\mathrm{E}}) \int_{\mathcal{X}} \alpha_{\mathrm{X}}(x_{\mathrm{E}} - x_{\mathrm{A}}) P_{\mathrm{A}} \left[x_{\mathrm{A}}; v + \beta(x_{\mathrm{E}} - x_{\mathrm{A}})\right] dx_{\mathrm{A}}\, dx_{\mathrm{E}}$$

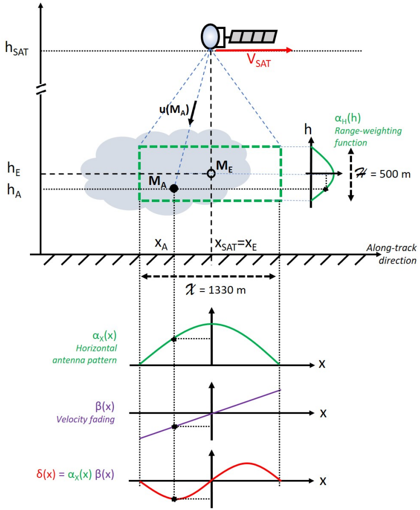
Doppler moments by integration wrt v

$$Z_{\mathrm{ID}} = U_J * \alpha_{\mathrm{X}} * Z_{\mathrm{A}} = Z_{\mathrm{R}}$$

- U_J: along-track integration
- α_{X}: antenna pattern
- $(*)$: convolution [1]

[1] for any functions F_1 and F_2, $F_1(x_{\mathrm{I}}) * F_2(x_{\mathrm{I}}) = \int_{x \in \mathbb{R}} F_1(x_{\mathrm{I}} - x) F_2(x) dx$.

Idealized ECPR moments: by *v*-integration Analytical



$$V_{\mathrm{ID}} \sim V_{\mathrm{R}} + \phi_{\mathrm{L}}$$

$$\phi_{\mathrm{L}} \propto \frac{V_{\mathrm{SAT}}}{h_{\mathrm{SAT}}} \mathcal{A}_2 \frac{Z'_{\mathrm{ID}}}{Z_{\mathrm{ID}}}$$

$$S^2_{\mathrm{ID}} \sim S^2_{\mathrm{R}} + \psi_{\mathrm{V,L}} + \psi_{\mathrm{Z,L}}$$

$$\psi_{\mathrm{V,L}} \propto \frac{V_{\mathrm{SAT}}}{h_{\mathrm{SAT}}} \mathcal{A}_2 V'_{\mathrm{ID,C}}$$

$$\psi_{\mathrm{Z,L}} \propto \left(\frac{V_{\mathrm{SAT}}}{h_{\mathrm{SAT}}}\right)^2 \mathcal{A}_2 \frac{1 + \mathcal{D}_4 \frac{Z''_{\mathrm{ID}}}{Z_{\mathrm{ID}}}}{1 + \mathcal{D}_2 \frac{Z''_{\mathrm{ID}}}{Z_{\mathrm{ID}}}} - \phi^2_{\mathrm{L}}$$

- in uniform beamfilling: $\psi_{\mathrm{UBF}} = \left(\frac{V_{\mathrm{SAT}}}{h_{\mathrm{SAT}}}\right)^2 \mathcal{A}_2 \sim (3.6\ \mathrm{m/s})^2$
- $\mathcal{A}_2$, $\mathcal{D}_2$, $\mathcal{D}_4$: factors of variance and kurtosis of U_J and α_X

Example: ECPR idealized scale analysis

Input V_A

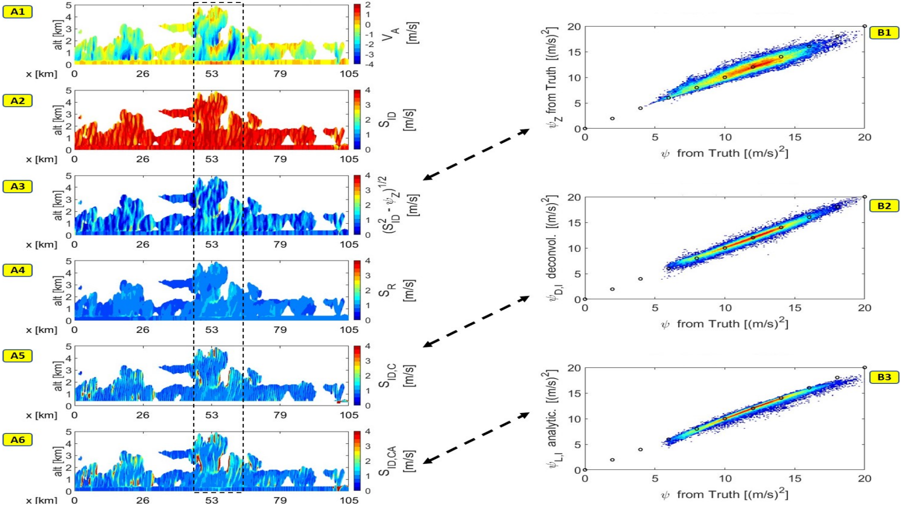
ECPR S_{ID}

corr. only by ψ_Z

Ref S_R

corr. by ψ (numerical)

corr. by ψ (analytical)



ψ_Z vs ψ (truth)

ψ(numeric) vs ψ(truth)

ψ(analytic) vs ψ(truth)

Example: ECPR idealized ($V_{\mathrm{FAD}} = 7.2$ km/s)

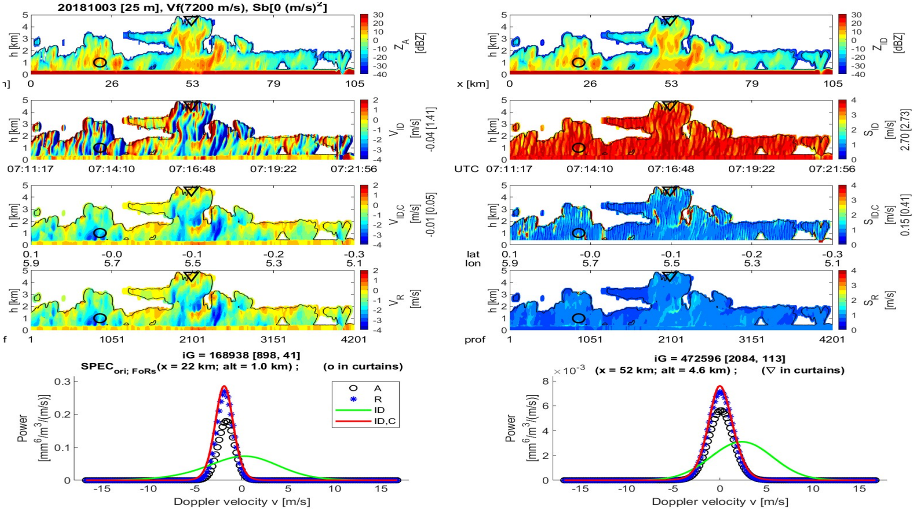
Input Z_A

ECPR V_{ID}

Corrected V_{ID}

Ref. V_R

Post spectra O



ECPR Z_{ID}

ECPR S_{ID}

Corrected S_{ID}

Ref. S_R

Post spectra ∇

Example: ECPR pulse pair ($V_{\mathrm{FAD}} = 7.2\ \mathrm{km/s}$)

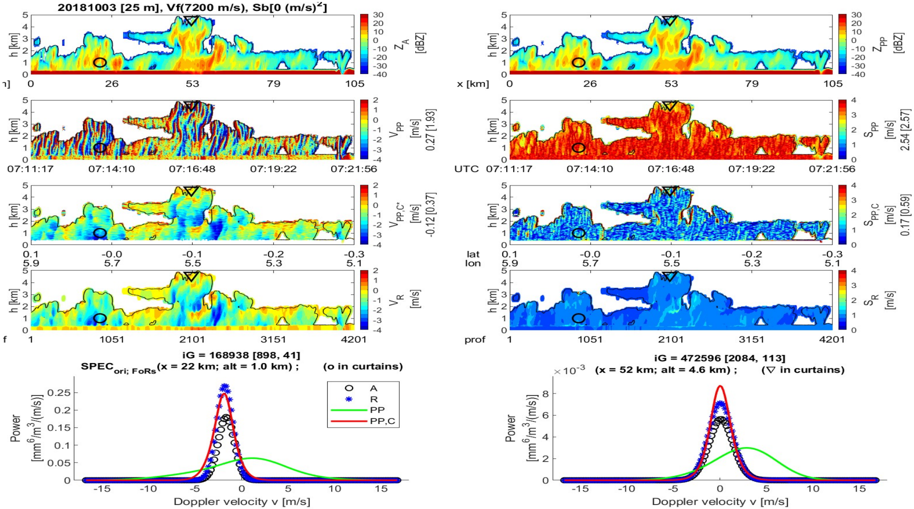
Input Z_{A}

ECPR V_{PP}

Corrected V_{PP}

Ref. V_{R}

Post spectra O



ECPR Z_{PP}

ECPR S_{PP}

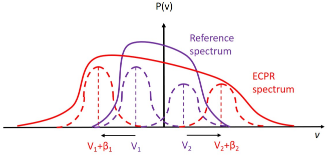
Corrected S_{PP}

Ref. S_{R}

Post spectra ∇

CConDoR approach: Complex Convolutional Doppler Resampling

$$\mathcal{P}_{\mathrm{I}}(x_{\mathrm{I}};v)=\int_{\mathcal{L}} U_J(x_{\mathrm{I}}-x_{\mathrm{E}})\int_{\mathcal{X}} \alpha_{\mathrm{X}}(x_{\mathrm{E}}-x_{\mathrm{A}})P_{\mathrm{A}}\left[x_{\mathrm{A}};v+\beta(x_{\mathrm{E}}-x_{\mathrm{A}})\right]dx_{\mathrm{A}}\,dx_{\mathrm{E}}$$



Inverse Fourier transform wrt v

$$\mathcal{Q}_{\mathrm{I}}(x_{\mathrm{I}},\tau)=\Gamma_{\mathrm{I}}(x_{\mathrm{I}},\tau)*Q_{\mathrm{A}}(x_{\mathrm{I}},\tau)$$

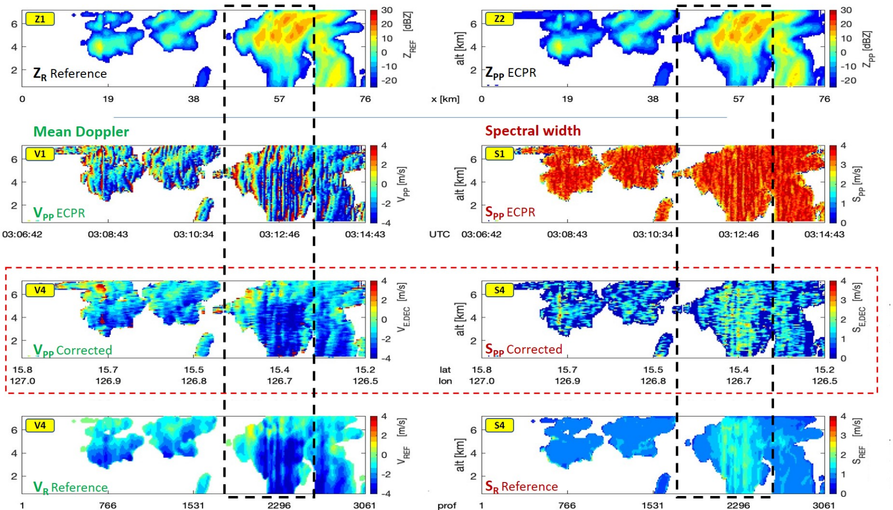
- $\mathcal{Q}_{\mathrm{I}}=\mathcal{F}_v^{-1}[\mathcal{P}_{\mathrm{I}}]$: ECPR correlation (lag τ)
- $Q_{\mathrm{A}}=\mathcal{F}_v^{-1}[P_{\mathrm{A}}]$: Input correlation (unaffected by V_{SAT})

$$\Gamma_{\mathrm{I}}(x,\tau)=U_J(x)*\left[\alpha_{\mathrm{X}}(x)e^{-i4\pi\frac{\tau}{\lambda}\beta(x)}\right]$$

By deconvolution

- NUBF correction
- broadening correction
- resolution enhancement

Example from CAMP^{2}EX 2019/09/16: ECPR pulse pair



Thank you for your attention

References

- ExpliSyT: O.O. Sy and S. Tanelli, **Recovering the Elusive Spectral Width from Spaceborne Doppler Profiling Radar Measurements: the "ExpliSyT" Approach**, *IEEE TGRS, vol. 61, 2023*
- CConDoR: O.O. Sy and S. Tanelli, **Dynamic Retrievals From Spaceborne Doppler Radar Measurements: the CConDoR Approach**, *IEEE TGRS, vol. 60, 2022*

Acknowledgements

- NASA's Earth Science US PI program
- NASA's ORACLES and $\mathrm{CAMP^2EX}$ campaigns (EVS-2 program)