Performance of the delay-Doppler Scattered Power Volume observable for wind speed estimation with CYGNSS

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Wind speed retrieval algorithms for GNSS-R

- retrieval based on regression of geophysical parameters using observables derived from the DDM;
- least squares (LS) fitting of the measured DDM to the theoretical Zavorotny-Voronovich model;
- best linear combination of different observables (introduced in the retrieval algorithm for CYGNSS Level 2 data product).
- More recently, the Principal Component Analysis (PCA) has been proposed as a method to optimize a generalized observable (Alvarez-Garrison).
Proposed algorithms

The approach considered in this paper consists in the Least Squares matching of the volume of the measured Scattered Power Function (SPF) and the volume of the theoretical SPF.
The average DDMs can be expressed as the 2D convolution

$$\mathbb{E} [ |Y(\tau, f)|^2 ] = |\chi(\tau, f)|^2 \ast [\xi_1(\tau, f) + \xi_2(\tau, f)] + \mathbb{E} [ |N(\tau, f)|^2 ]$$

where $\chi(\tau, f)$ is the ambiguity function of the transmitted waveform and $\mathbb{E} [ |N(\tau, f)|^2 ]$ is the noise at the correlator output.

The SPFs are defined as

$$\xi_i(\tau, f) = \frac{T^2 D^2(\rho_i) |R(\rho_i)|^2}{4R(\rho_i)^2 R_0(\rho_i)} \frac{q^4(\rho_i)}{q_z^4(\rho_i)} \cdot P_{\xi_x \xi_y} \left( -\frac{q_{\perp}(\rho_i)}{q_z(\rho_i)} ; w_s, w_d \right) |J_i(\tau, f)| .$$

- The wind speed appears as parameters of the slopes pdf whereas all other quantities are functionally independent by such parameter.
- The volume of the SPF is invariant with respect to rotations (wind direction).
The Scattered Power Volume (SPV) observable

If we take the two-dimensional Fourier transform of the DDM with $\tau \rightarrow f_1$ and $f \rightarrow f_2$, the DDM volume can be written as

$$V_Y = \int \int \langle |Y(\tau, f)|^2 \rangle \, d\tau \, df = \mathcal{F} \langle |Y(\tau, f)|^2 \rangle |_{f_1=f_2=0}.$$

Therefore, the volume $V_\xi$ can be simply evaluated as the ratio

$$V_\xi = \frac{V_Y - V_N}{V_\chi} = \frac{V_{Y-N}}{V_\chi}$$

between the volume of the DDM (with output noise subtracted), and the volume $V_\chi$ of the square modulus of the ambiguity function.
The wind speed retrieval algorithm

The wind speed can be estimated by minimizing the square difference between the volume $V_\xi$ computed for a given value of the wind speed and the corresponding volume $\hat{V}_\xi$ computed from the DDM observable by substitution of the estimated volume $\hat{V}_{Y-N}$

$$\hat{w}_s = \arg \min_{w_s} |V_\xi - \hat{V}_\xi|^2$$
Remark

Letting $\chi_0(\tau, f) = |\chi(\tau, f)|^2 - \overline{\chi}_{NF}$, we get

$$
\mathbb{E}[|Y(\tau, f)|^2] = [\chi_0(\tau, f) + \overline{\chi}_{NF}] * \xi(\tau, f) + \mathbb{E}[|N(\tau, f)|^2]
$$

$$
= \chi_0(\tau, f) * \xi(\tau, f) + \overline{\chi}_{NF} \cdot V_\xi + \mathbb{E}[|N(\tau, f)|^2]
$$

$$
= \chi_0(\tau, f) * \xi(\tau, f) + \mathbb{E}[|Y_N(\tau, f)|^2].
$$

Therefore, by subtracting the DDM noise volume we obtain $V_\xi V_{\chi_0}$ and not $V_\xi V_{\chi}$. Indeed

$$
V_\xi = \frac{V_Y - V_{Y_N}}{V_{\chi_0}}
$$
Ambiguity function

- Any point of the non-zero noise floor of $|\chi(\tau, f)|^2$ contributes to the overall value of a DDM point through the convolution operation.
- After resizing the volumes ratio includes a positive bias.
- The bias becomes almost zero if we estimate and set to zero the mean of the noise floor.
Removing effect of reduced DDM size

To improve precision for computation consider the volume of the truncated DDM

\[ V_Y - V_{Y_N} = \text{Vol} \left[ \chi_0(\tau, f) \ast \xi(\tau, f) \text{rect} \left( \frac{\tau}{M \Delta \tau} \right) \text{rect} \left( \frac{f}{N \Delta f} \right) \right] \]

where \( \text{rect}(\cdot) \) is the unit rectangular function. A first-order Taylor approximation in the Fourier domain provides

\[ V_Y - V_{Y_N} \approx V\chi_0 \text{Vol} \left[ \xi(\tau, f) \text{rect} \left( \frac{\tau}{M \Delta \tau} \right) \text{rect} \left( \frac{f}{N \Delta f} \right) \right] = V\chi_0 V\xi_T \]

where \( V\xi_T \) is the volume of the truncated scattered power function. This correction removes most of the truncation bias.
Simulation of CYGNSS DDMs

The geometric parameters for simulations are extracted from a real track of CYGNSS.

Figure: CYGNSS simulated data: left side: RCG for simulated track. Left side: SNR for different simulated wind speeds, 5 m/s (black), 10 m/s (blue), 20 m/s (green), 30 m/s (red). CYG-02, DAY:44 SNR ≥ 3dB
Error analysis for SPF volume approximation

DDM: (-4500, 4500 Hz, -2, 6.65 chip)

Figure: Error $\epsilon = \left( \frac{\hat{V}_{\xi T} - V_{\xi T}}{V_{\xi T}} \right) \cdot 100$ for noise-free DDM after bias correction with fixed wind speed: 5 (black), 10 (blue), 20 (green), 30 (red) m/s. $\mu_\epsilon = 4.29\%$
Motivation

DDM model

Error analysis for SPF volume approximation

DDM: (-2000, 2000 Hz, -1, 3 chip)

\[ \epsilon = \frac{\hat{V}_\xi - V_\xi}{V_\xi} \cdot 100 \]

for noise-free DDM after bias correction with fixed wind speed: 5 (black), 10 (blue), 20 (green), 30 (red) m/s. \( \mu_\epsilon = 2.31 \% \)

Figure: Error \( \epsilon = (\hat{V}_\xi - V_\xi)/V_\xi \cdot 100 \) for noise-free DDM after bias correction with fixed wind speed: 5 (black), 10 (blue), 20 (green), 30 (red) m/s. \( \mu_\epsilon = 2.31 \% \)
Error analysis for SPF volume approximation

DDM: (-1000, 1000 Hz, -0.5, 0.5 chip)

Figure: Error $\epsilon = \frac{(\hat{V}_{\xi T} - V_{\xi T})}{V_{\xi T}} \cdot 100$ for noise-free DDM after bias correction with fixed wind speed: 5 (black), 10 (blue), 20 (green), 30 (red) m/s. $\mu_\epsilon = 19.94\%$
Wind speed estimation

Figure: Performance for wind speed retrieval on simulated data in terms of sample mean ($\hat{\mu}$) and standard deviation ($\hat{\sigma}$), for several values of RCG and wind speed. A (-2, 6.65 chip, -5000, 4500 Hz), B (-1, 3 chip, -2000, 2000 Hz), C (-0.5, 0.5 chip, -1000, 1000 Hz)
Results from TDS-1 real data

Figure: Scatter plot of estimated and ASCAT collocated wind speeds for track IDs: RD035-TD049 on the left and RD047-TD158 on the right. Samples selected with SNR $\geq -1 \text{ dB}$
Comparison with TDS-1 Level 2 WS

Figure: Scatter plot of estimated and ASCAT collocated Wind Speeds (on the left); scatter plot of TDS-1 Level-2 WS versus ASCAT collocated Wind Speeds (on the right) for track IDs: RD047-TD158. Samples selected with SNR $\geq -1$ dB.
Conclusions

- The volume of the scattering function is a useful observable for wind speed estimation.
- Bias affects volume computation but is almost independent on wind speed.
- Results for wind speed estimation for CYGNSS data are under investigation.