Time domain stationary clutter filtering of staggered PRT sequences

A beneficial approach with matched inversion filtering

Motivation: Clutter filter for staggered PRT

- **Stationary clutter** affects all ground-based weather radar data and needs to be removed.
- **Traditional methods only work with regularly sampled data** (e.g. FFT/DFT-based spectral editing or time domain IIR filter).
- When processing **staggered PRT sequences**, these methods can **not** be applied directly.
- **Regression methods** (Sebastian M. Torres, Dušan S. Zrnić and John C. Hubbert) or cubic spline interpolation could be used instead.

Approach: Matched inversion filter

- **A matched inversion (MI) filter is used to attenuate the unwanted signal (ground clutter)** instead of emphasizing the wanted signal (weather).
- Multiplication of the complex time series with the inverse of the covariance matrix of a clutter model → **ground clutter can effectively be removed.**
- Sometimes also called *whitening*.
- **Gaussian model** is used for the clutter. If the clutter spectrum is Gaussian, its autocorrelation function (in slow-time) is also Gaussian → **easy estimation of the covariance matrix**.
- Similar technique is used in STAP processing and was also proposed in GMAP-TD.
- **Frequency response** of a Gaussian notch filter at frequency zero.

Calculation: Inverse of covariance matrix

- The MI filter is applied by multiplying the inverse matrix with the IQ data.
- Computation of the matrix is computationally expensive (milliseconds), while the application is cheap → pre-compute and cache matrices for given number of samples and PRT staggering.
- Assuming IQ data with M pulses the **computation of the covariance matrix** R_c ($M \times M$) for staggered sequence of two times $t(m)$ and $t(n)$ with σ^2 the variance of the Gaussian distribution is:

$$R_c(m,n) = \exp(-2\pi^2 \sigma^2 dt^2)$$

$$dt = t(m) - t(n)$$

- Inverting a matrix is usually not recommended (numerically unstable for larger matrices). **Numerical stability with *diagonal-loading***: Before inversion, an identity matrix E_M multiplied by a small value ε is added.
- The larger ε, the lower the stop- band attenuation. Even for large ε of 1e-5, attenuation still exceeds what would be technically possible due to phase noise limitations in the radar frontend.
- The final inverted matrix is computed as follows:

$$R_{inv} = (R_c + \varepsilon E_M)^{-1}$$

- Final filtering of IQ data:

$$IQ_{filt} = IQ \cdot R_{inv}$$

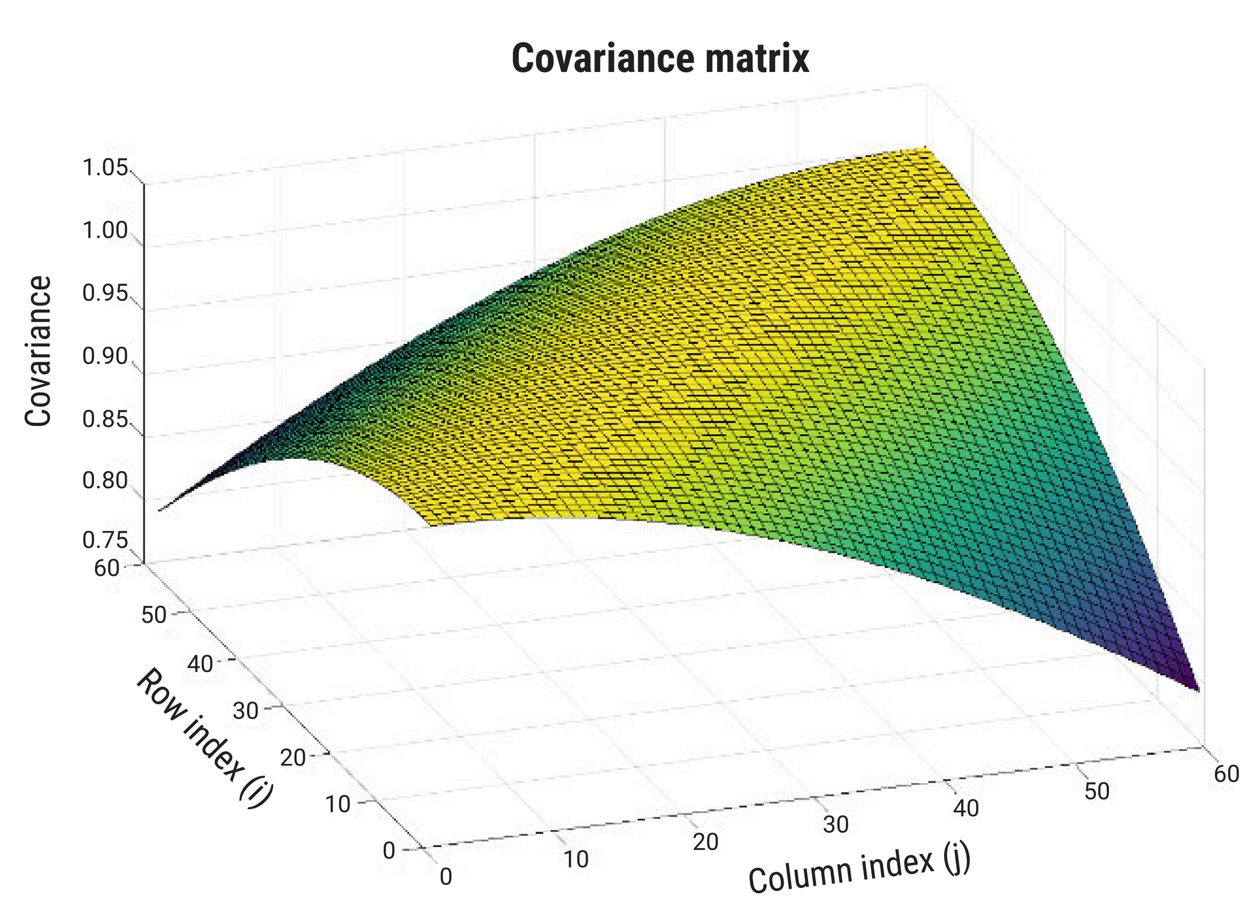

Fig. 1: Visualization of an example covariance matrix.

Results: Stable with good unfolding

- The MI approach has proven to produce **stable results for time-series up to 128 samples** → sufficient for operational use with weather radar where number of integrated pulses typically is 64.

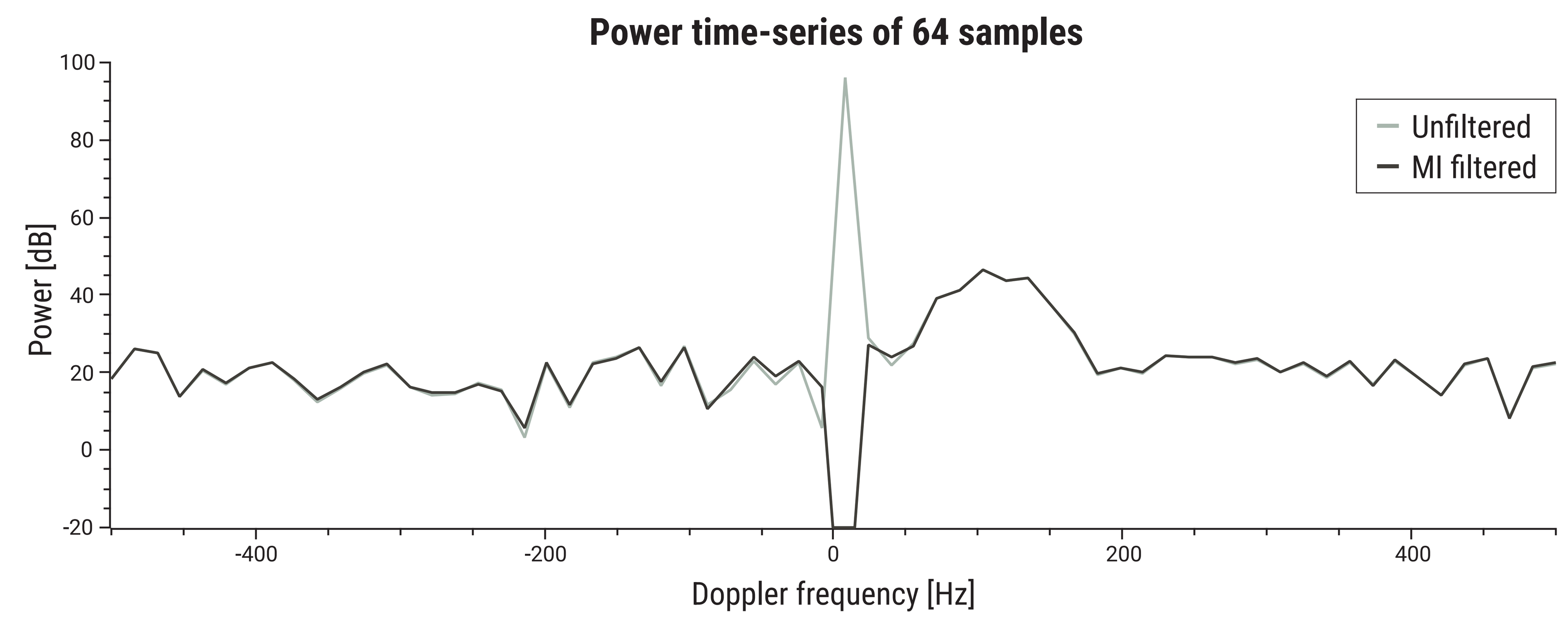

Fig. 2 (top): Example power time-series of 64 samples at 1000 Hz PRF. The unfiltered power is the sum of weather, noise, and clutter power. The clutter peak is removed in the matched inversion (MI) filtered data without losing the wanted weather signal.

- **The blind velocities are quite benign.**
- When using **PRF staggering (ray to ray)**, both PRF's will suffer from the blind velocities of a single PRF sampling → **problems unfolding the radial velocity**.
- When using **multi-PRT staggering (dual or triple)**, attenuation at blind velocities much less pronounced → **potentially less unfolding errors**.

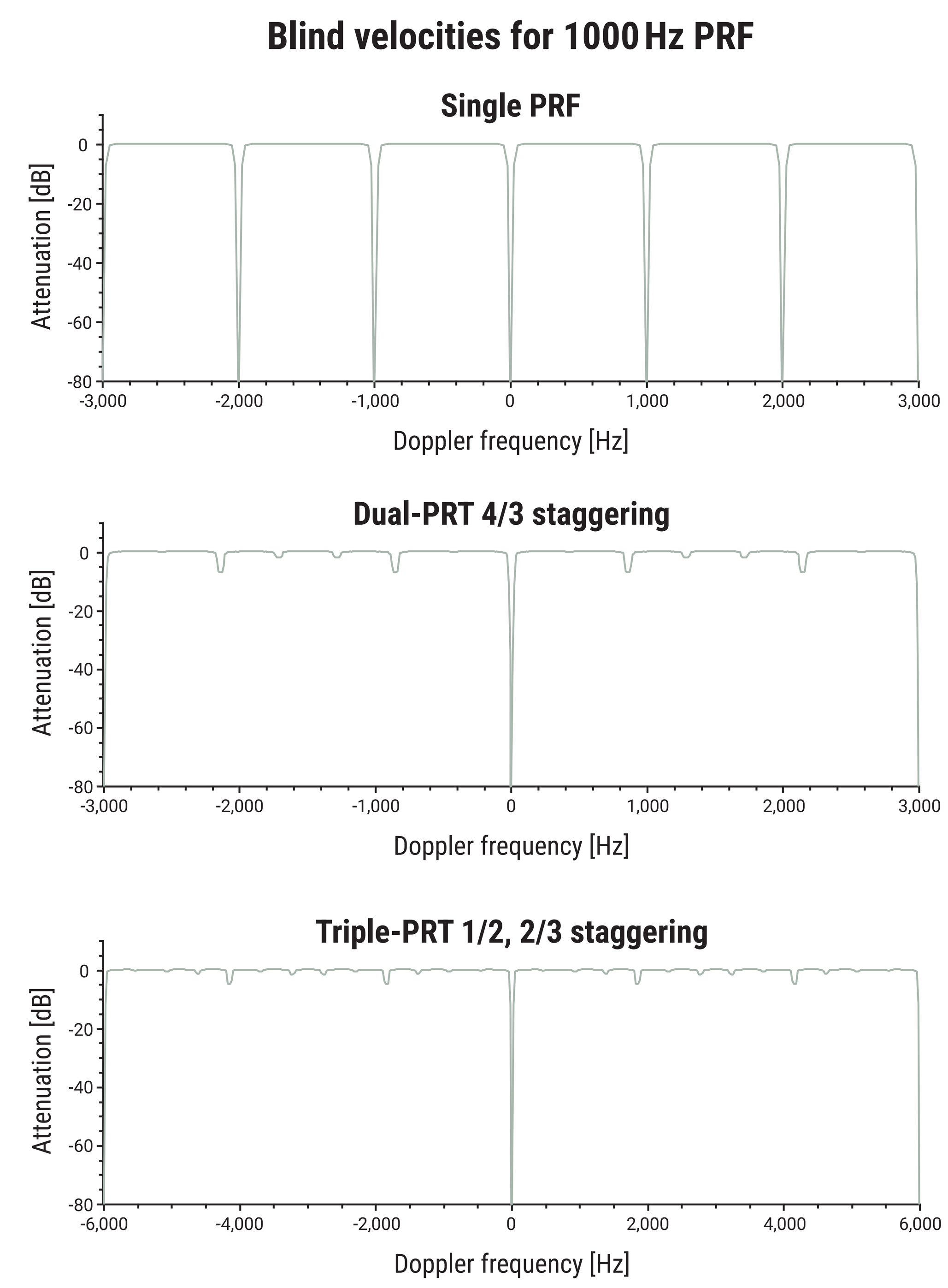

Fig. 3 (right): Example blind velocities for different staggering methods with a base PRF of 1000 Hz. The plots show attenuation with respect to Doppler frequency; blind velocities are at the short but strong attenuation dips.

Evaluation: Viable alternative to regression filter

Similarities with regression filter:

- Similar pattern in the blind velocities.
- Possible application to staggered (non-uniform) sampling and to time series data with missing samples.
- No windowing required.

Disadvantages of MI filtering:

- Computationally expensive and numerically unstable for large time series (but fast enough for normal operational processing needs).
- Needs double precision math.

Advantages of MI filtering:

- Matrices can be pre-computed; filter application to short time series is very fast (matrix multiplication) → possibility to use several filters with increasing attenuation for adaptive filtering.
- Computation time is constant and independent from filter width (regression filter time depends on order of polynom).
- Fine control on filter width.
- Suitable for large filter width (can be used as whitening filter in second trip processing).

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