Detection of Anomalies in BPM Signals at the VEPP-4M

I.A. Morozov and P.A. Piminov, BINP SB RAS, Novosibirsk, Russia

Abstract

Beam position monitors (BPMs) are widely used for beam diagnostics in particle accelerators. Turn-by-turn (TbT) beam centroid data provide a means to estimate performance-critical accelerator parameters, like betatron frequency and optical functions. Parameter estimation accuracy is heavily related to TbT data quality. BPM faults might lead to erroneous estimation of accelerator parameters and should be accounted for achieving accurate and reliable results. Several anomaly detection methods for TbT data cleaning are considered. Derived features of BPM signals along with their robust dispersion estimation are used to flag faulty BPM signals. Estimated contamination factor is used with unsupervised learning methods (Local Outlier Factor and Isolation Forest). Application of anomaly detection methods for the VEPP-4M experimental TbT data is reported.

Examples of anomalies in BPM signals

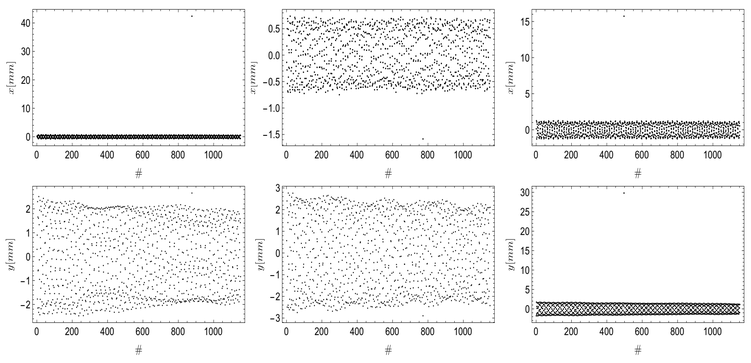

Fig. 1: Examples of spike anomalies in BPM signals at the VEPP-4M. Spike anomalies are correlated across planes.

Anomaly detection loop

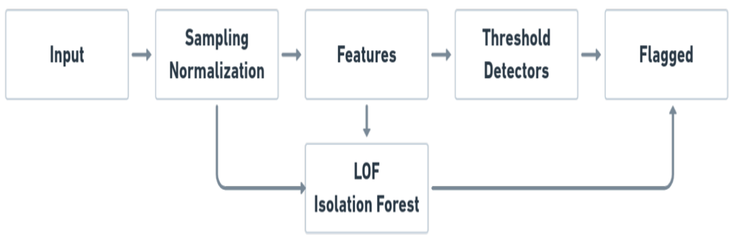

Fig. 2: Anomaly detection loop workflow.

- LAYER-1: Threshold detectors for derived features
  - Anomaly score for each feature
  - Data normality
  - Combination of detectors
  - Contamination estimation
- LAYER-2: Unsupervised methods for expected contamination
  - Local Outlier Factor
  - Isolation Forest

Signal sampling

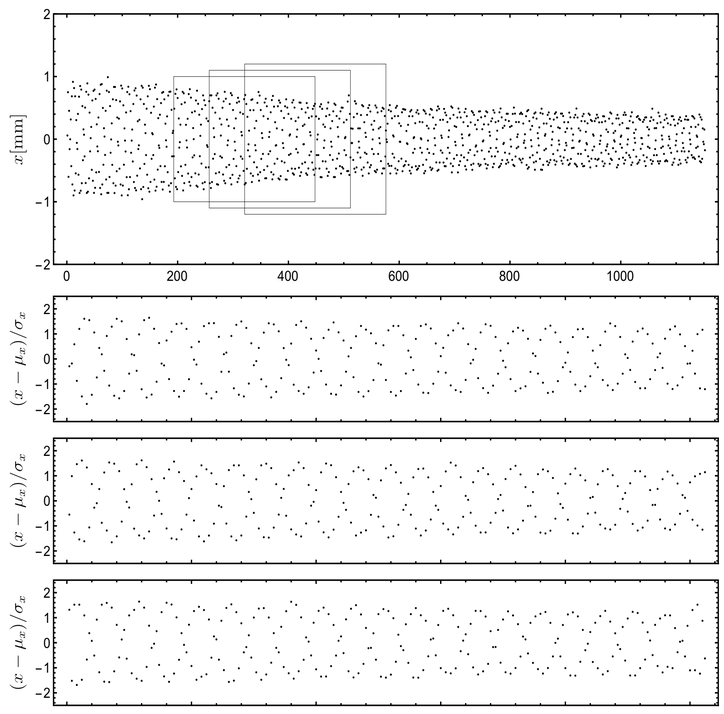

Fig. 3: Signal sampling. Each BPM signal is divided into smaller shifted samples.

Derived features

- SAMPLE: Absolute amplitude value
- SAMPLE: Frequency
- SAMPLE: Spectrum noise floor
- SAMPLE: Quasiperiodic decomposition error
- MATRIX: SVD space modes maximum absolute deviation
- SAMPLE: Noise from optimal SVD truncation
- SAMPLE: Hankel filter error
- MATRIX: Robust PCA

Hankel–Prony matrix:

$x = [x_1\ x_2\ x_3\ x_4\ x_5\ x_6\ x_7\ x_8]$

$$X = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ x_2 & x_3 & x_4 & x_5 \\ x_3 & x_4 & x_5 & x_6 \\ x_4 & x_5 & x_6 & x_7 \\ x_5 & x_6 & x_7 & x_8 \end{bmatrix}$$

VEPP-4M lattice

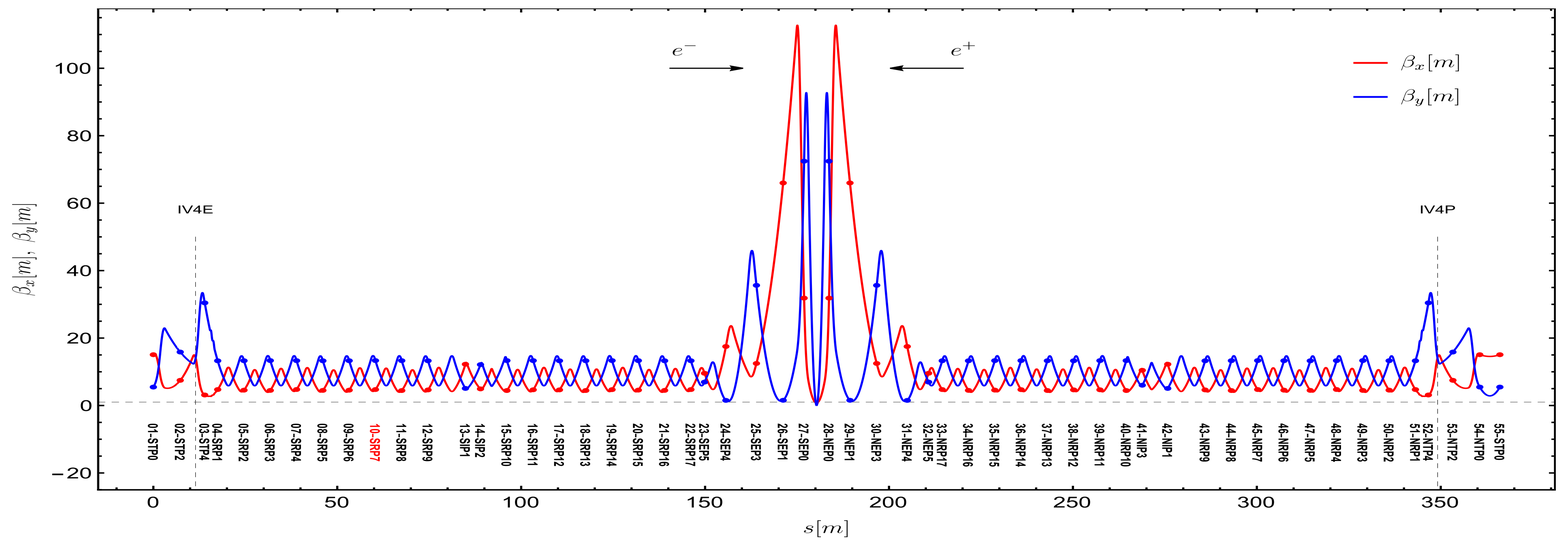

Fig. 4: VEPP-4M optics and BPM locations.

Threshold detector

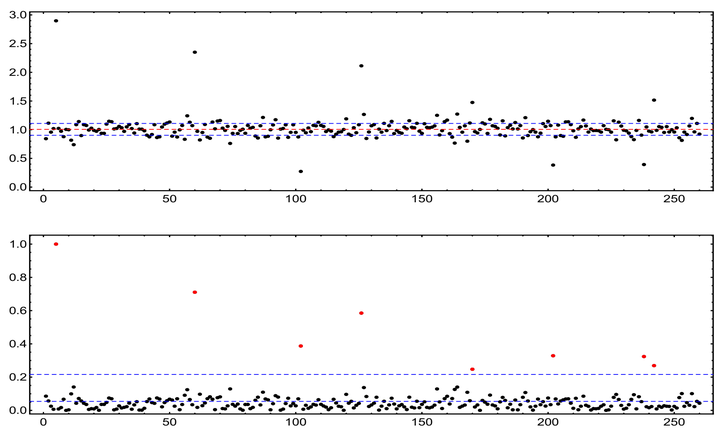

Fig. 5: Threshold detector in normalized feature space.

Spike anomalies

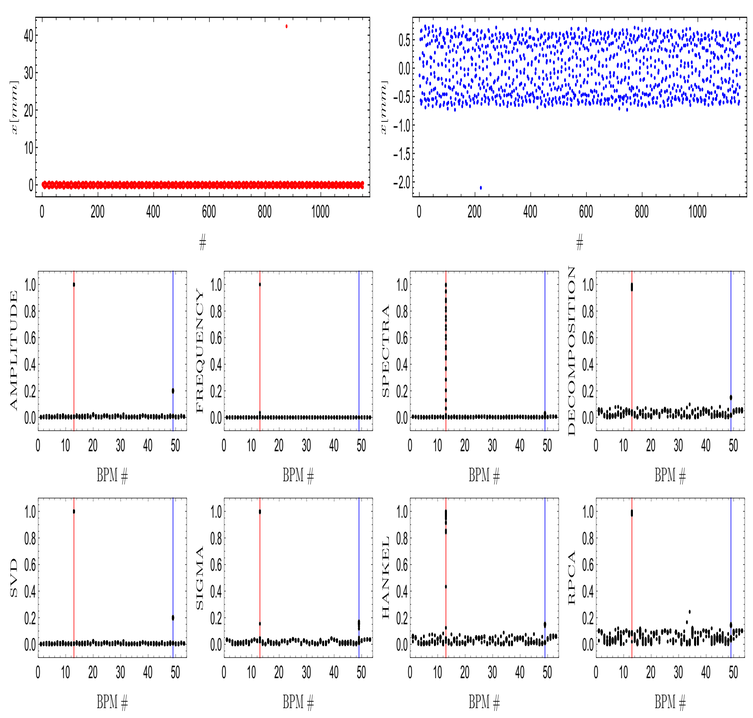

Fig. 6: Example of detected spike anomalies from single measurement (top plots). Normalized features for all BPMs (bottom plots). Positions of signals with anomalies indicated with lines.

Systematic anomalies

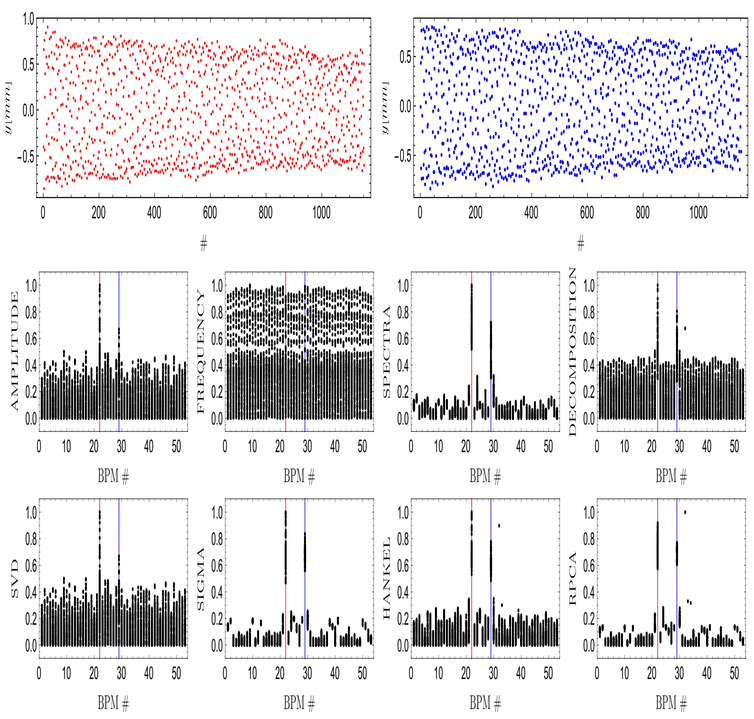

Fig. 7: Example of detected systematic anomalies from single measurement (top plots). Normalized features for all BPMs (bottom plots). Positions of signals with anomalies indicated with lines.

Anomaly summary

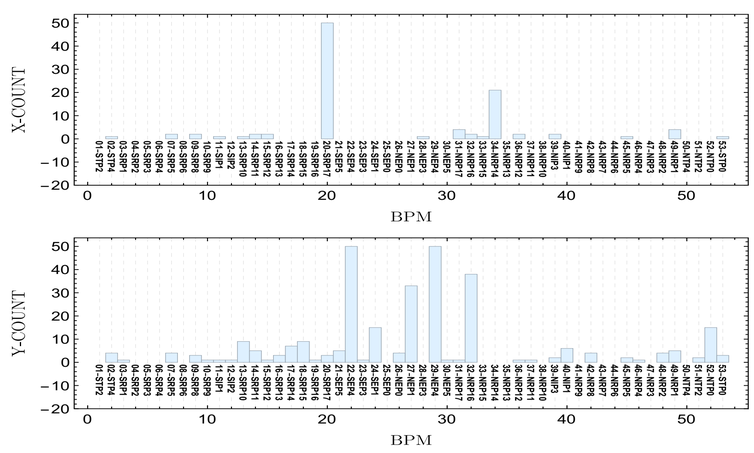

Fig. 8: Flagged BPM for 50 successive measurements.

BPM synchronization

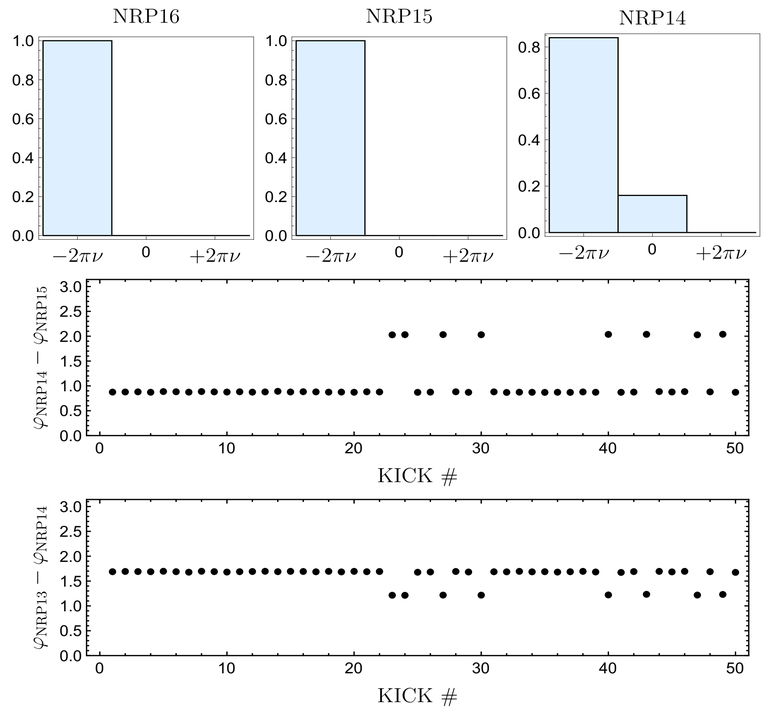

Fig. 9: BPM synchronization. Phase measurement requires synchronization of the first turn between BPMs. Measured phase advance can be compared with model to check the first turn synchronization.

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