Precise Analysis of Beam Optics at the VEPP-4M by Turn-by-Turn Betatron Phase Advance Measurement

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VEPP-4M

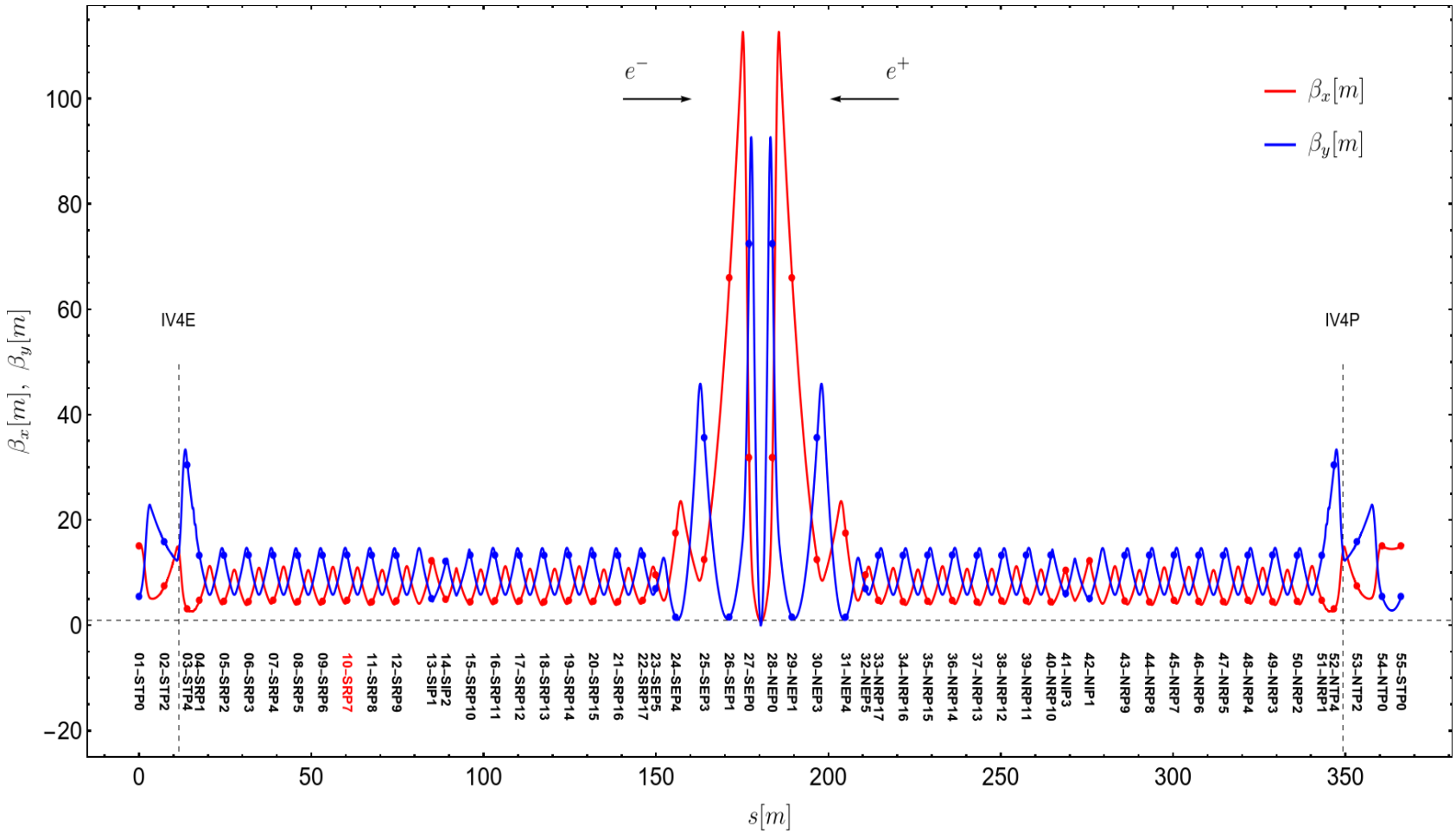
Motivation

- Improve current workflow for frequency and optics measurement
- Add TbT data processing, anomaly detection and noise estimation
- Accurate frequency measurement
- Amplitude and phase measurement with error propagation
- Optics measurement from amplitude and phase

Contents

VEPP-4M BPM System

Bekhtenev, E. A., Karpov, G. V. & Piminov, P. A.
A beam-position monitor system at the VEPP-4M electron-positron collider. Instrum Exp Tech 60, 679–685 (2017)



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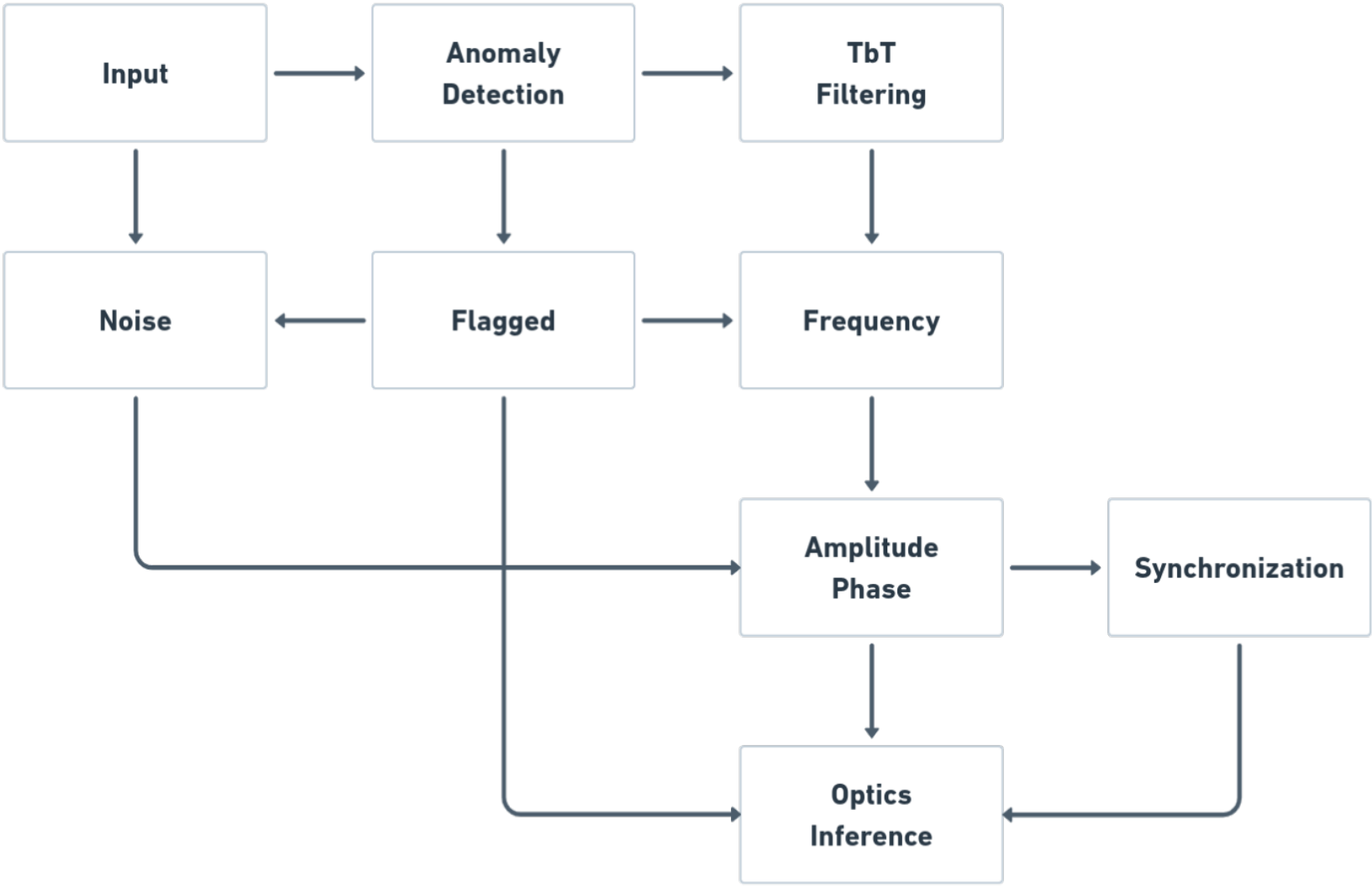
TbT Analysis Workflow



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TbT Processing

TbT cleaning with SVD

$M = U\Sigma V^T \rightarrow$ keep selected number of singular values

Signal representation in the matrix form (Hankel–Prony)

$$S = [s_1\ s_2\ s_3\ s_4\ s_5\ s_6\ s_7\ s_8] \rightarrow M_S = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2 & s_3 & s_4 & s_5 \\ s_3 & s_4 & s_5 & s_6 \\ s_4 & s_5 & s_6 & s_7 \\ s_5 & s_6 & s_7 & s_8 \end{bmatrix}$$

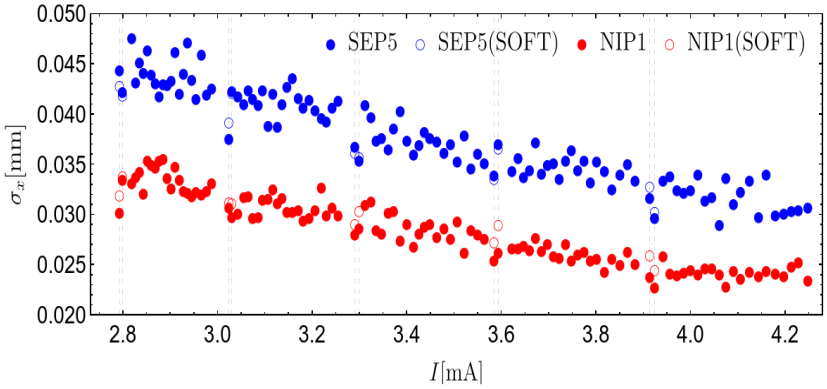
Individual signals filtering

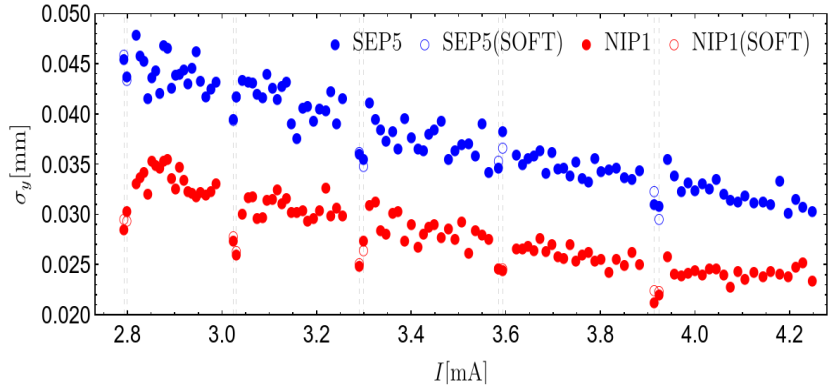
$S \rightarrow M_S = U\Sigma V^T \rightarrow \bar{M}_S \rightarrow \bar{S}$

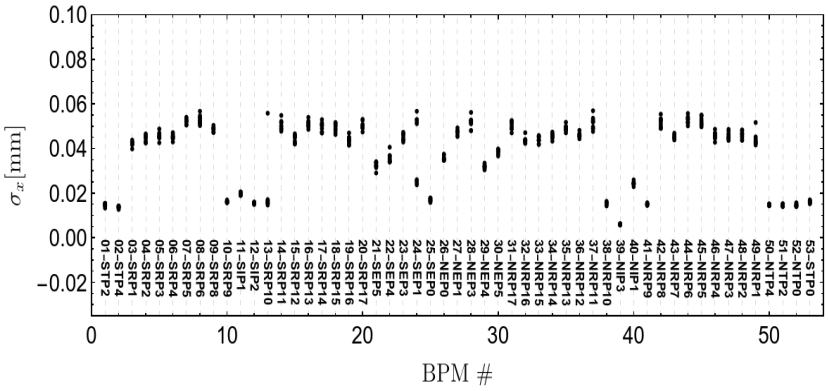
Optimal SVD truncation

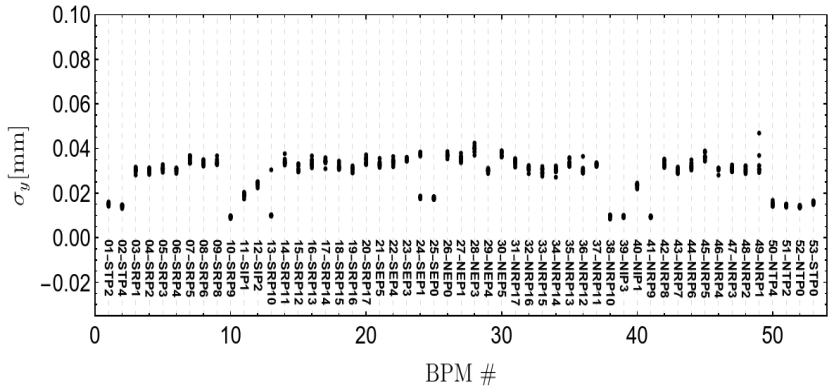
Matan Gavish and David L. Donoho, The Optimal Hard Threshold for Singular Values is $4/\sqrt{3}$, 2014

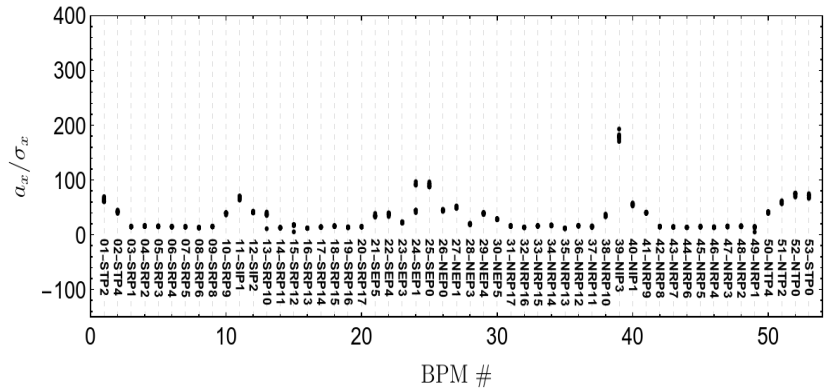
BPM Noise Estimation

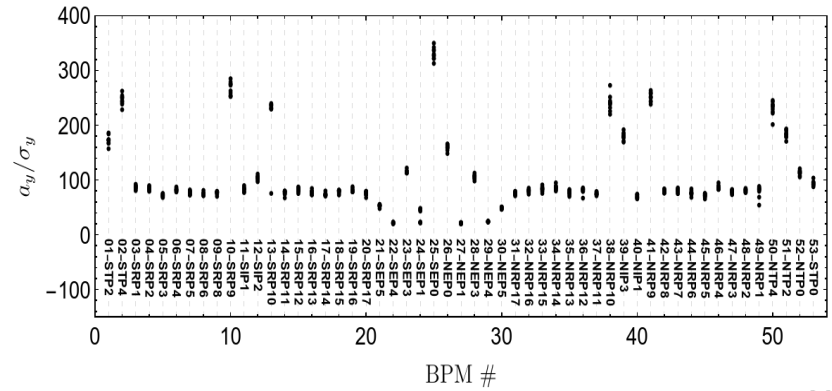












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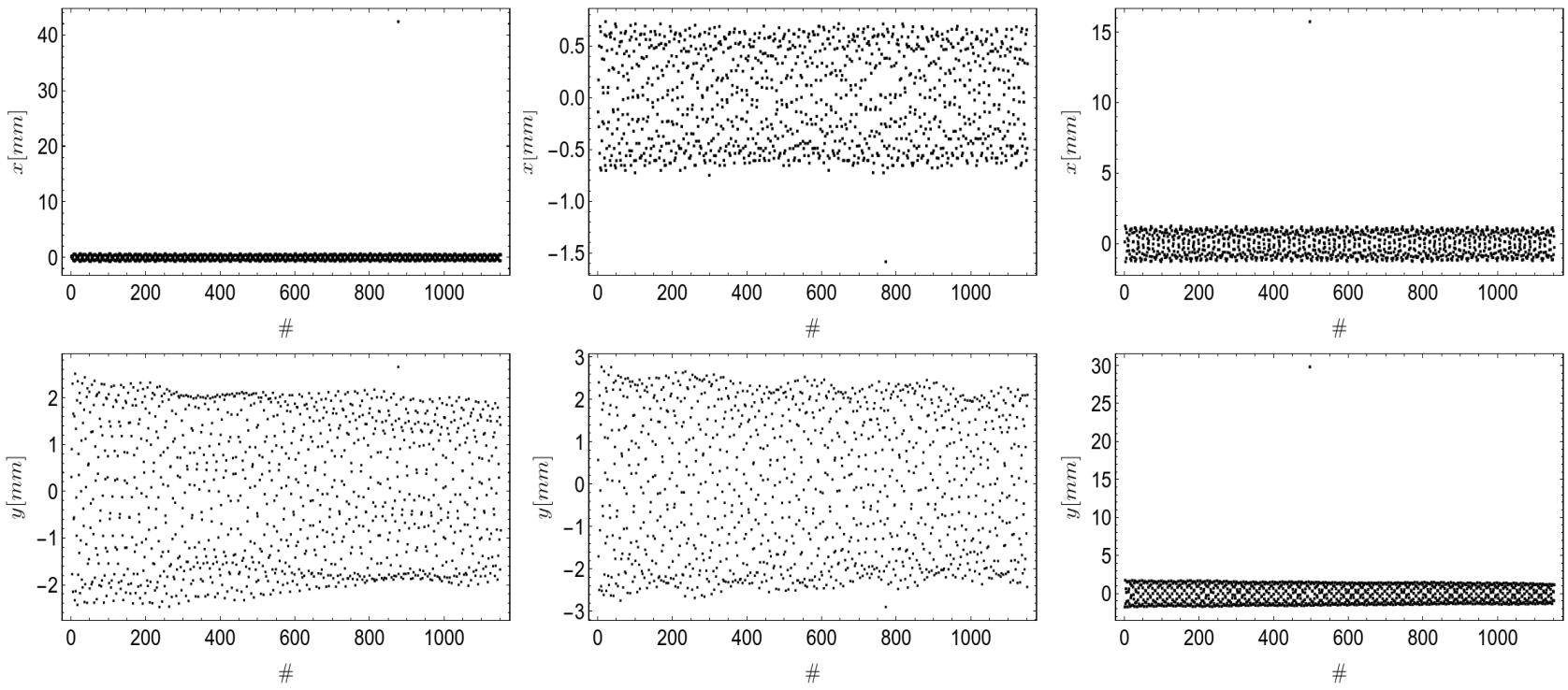
Anomaly Example

What is an anomaly?

Something that deviates from what is standard, normal, or expected.



How to take anomalies into account?

Remeasure, flag and exclude, use robust estimators.

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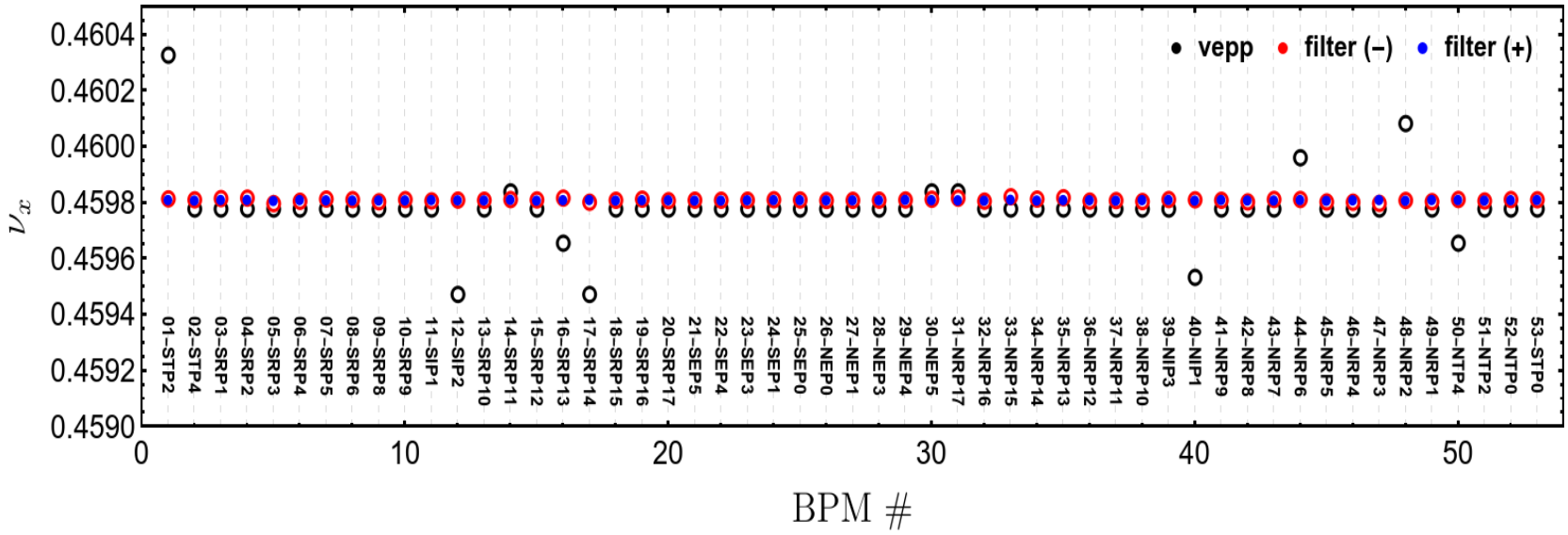
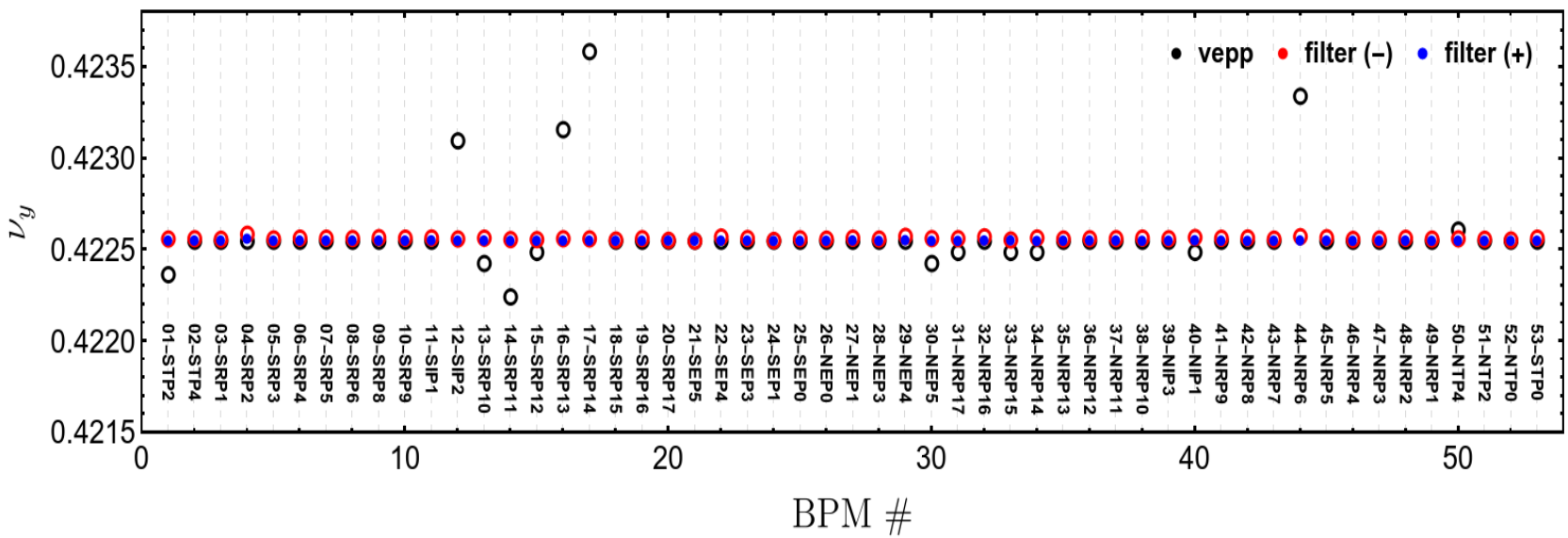
Frequency Measurement Example





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Signal Decomposition & Parameter Estimation

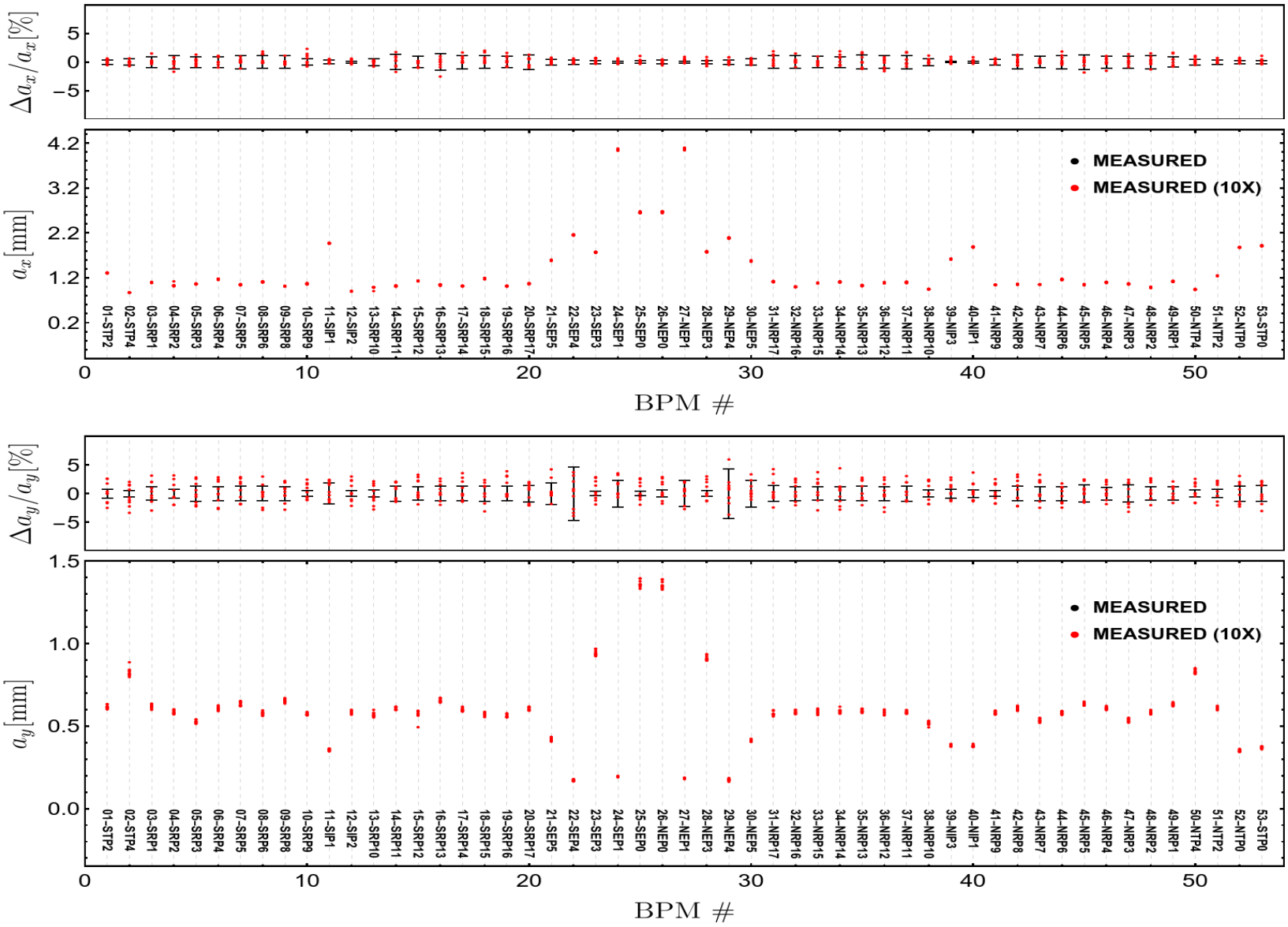
Quasiperiodic decomposition

$$x(n) = \sum_{m=1}^{M} \left(c_m \cos(2\pi\nu_m n) + s_m \sin(2\pi\nu_m n)\right) = \sum_{m=1}^{M} a_m \cos(2\pi\nu_m n + \phi_m)$$

Estimation of parameters

$$c_m = \frac{2}{N}\sum_{n=1}^{N} x(n)\cos(2\pi\nu_m n), \quad s_m = \frac{2}{N}\sum_{n=1}^{N} x(n)\sin(2\pi\nu_m n)$$

Amplitude Measurement



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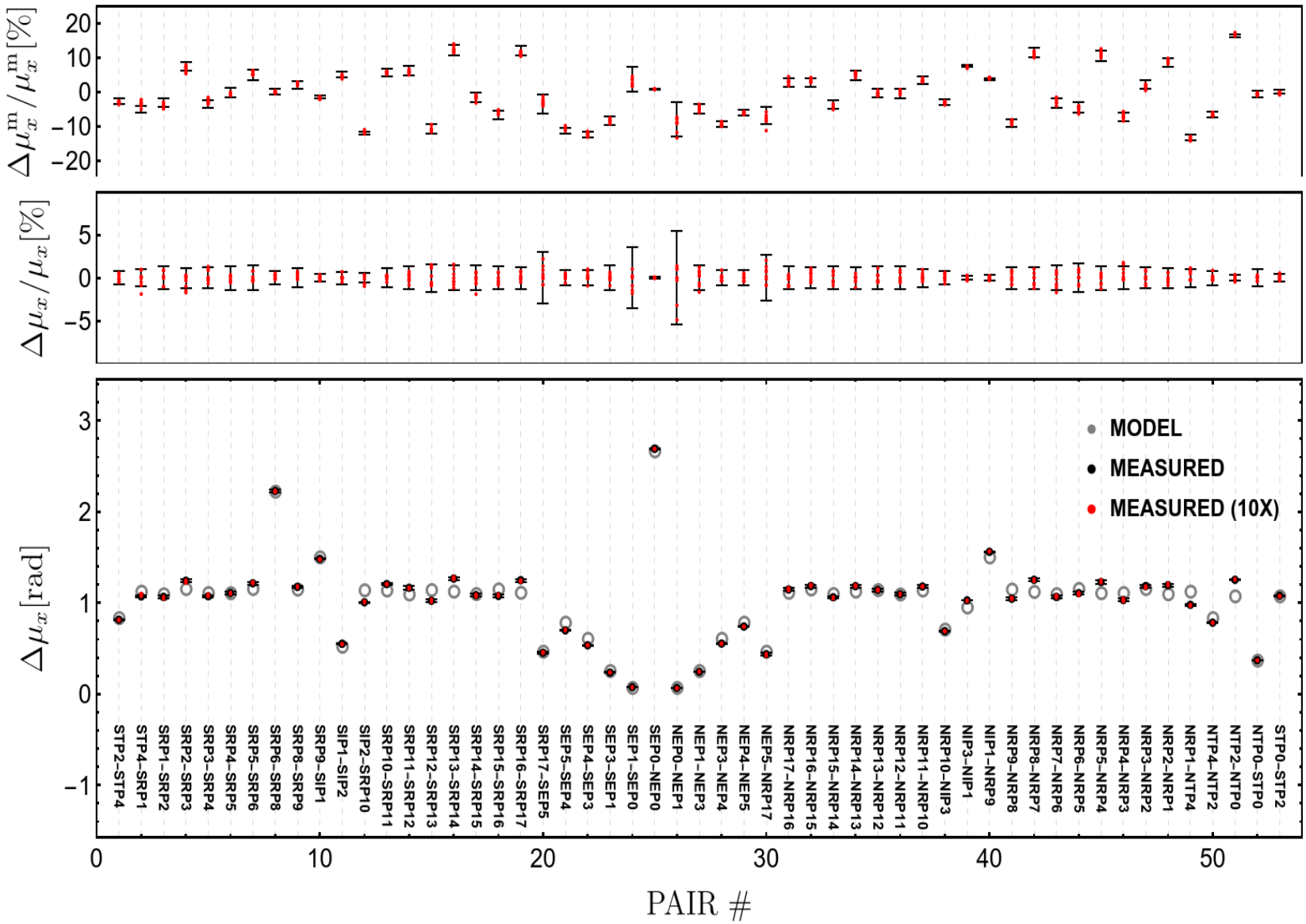
Phase Measurement



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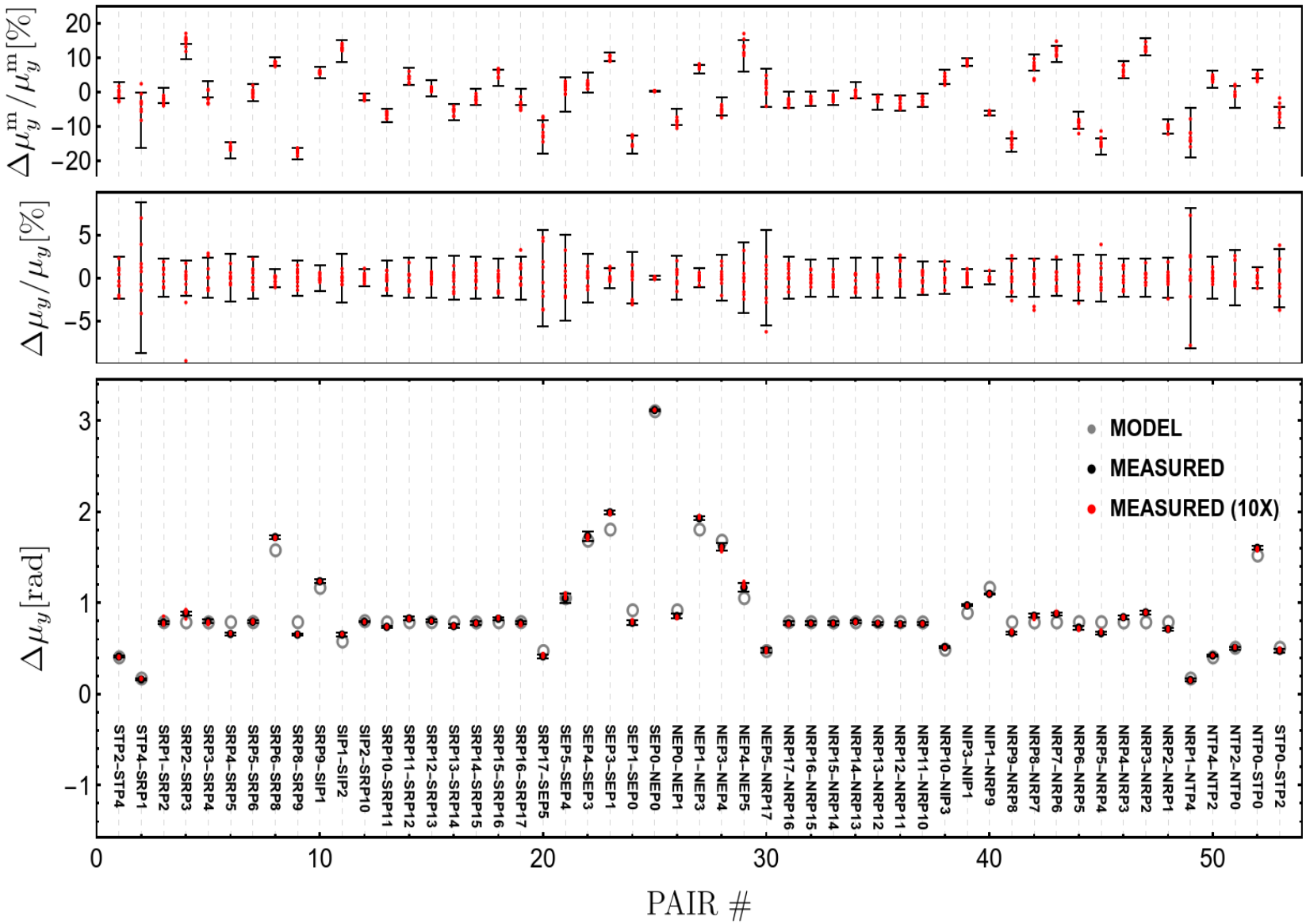
Phase Measurement



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Optics Measurement

β^a

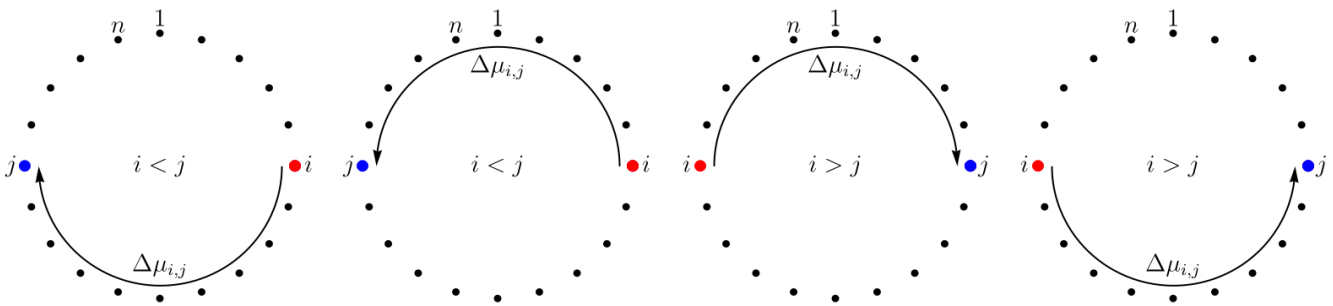
$$x^m(n) = a_x^m \cos(2\pi\nu_x n + \varphi_x^m) = \sqrt{2I_x\beta_x^m}\cos(2\pi\nu_x n + \varphi_x^m)$$

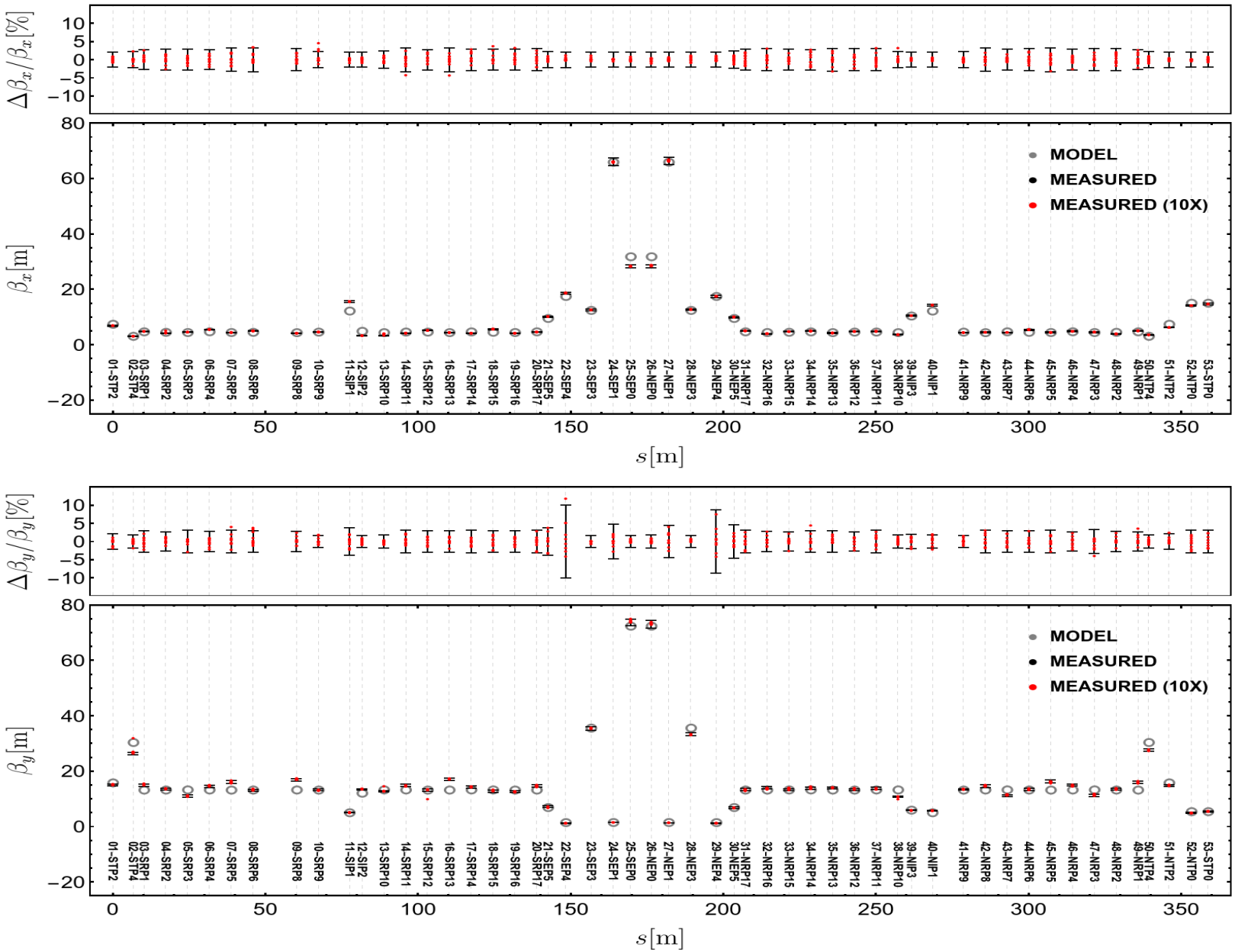
$$\hat{I}_x = \frac{1}{2}\left\langle \frac{a_x^m \cdot a_x^m}{\beta^m_{x,\ \mathrm{model}}} \right\rangle_m$$

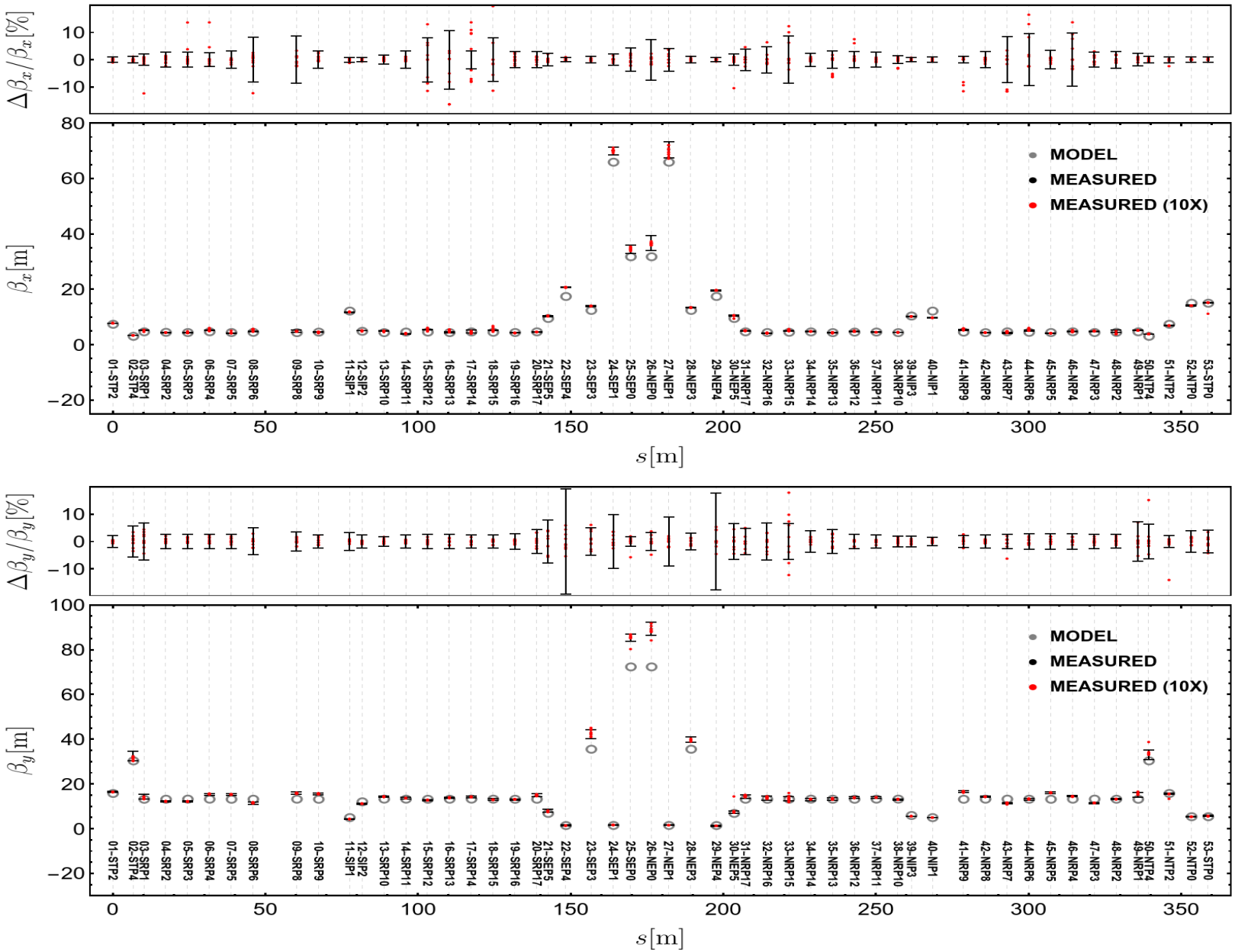
β^φ

$$M_{i,j} = N_j R_{i,j} N_i^{-1}$$

$$\begin{bmatrix} \sqrt{\beta_j} & 0 \\ -\frac{\alpha_j}{\sqrt{\beta_j}} & \frac{1}{\sqrt{\beta_j}} \end{bmatrix} = \begin{bmatrix} m_{1,1}^{(i,j)} & m_{1,2}^{(i,j)} \\ m_{2,1}^{(i,j)} & m_{2,2}^{(i,j)} \end{bmatrix} \begin{bmatrix} \sqrt{\beta_i} & 0 \\ -\frac{\alpha_i}{\sqrt{\beta_i}} & \frac{1}{\sqrt{\beta_i}} \end{bmatrix} R_{i,j}^{-1}(\Delta\mu_{i,j})$$

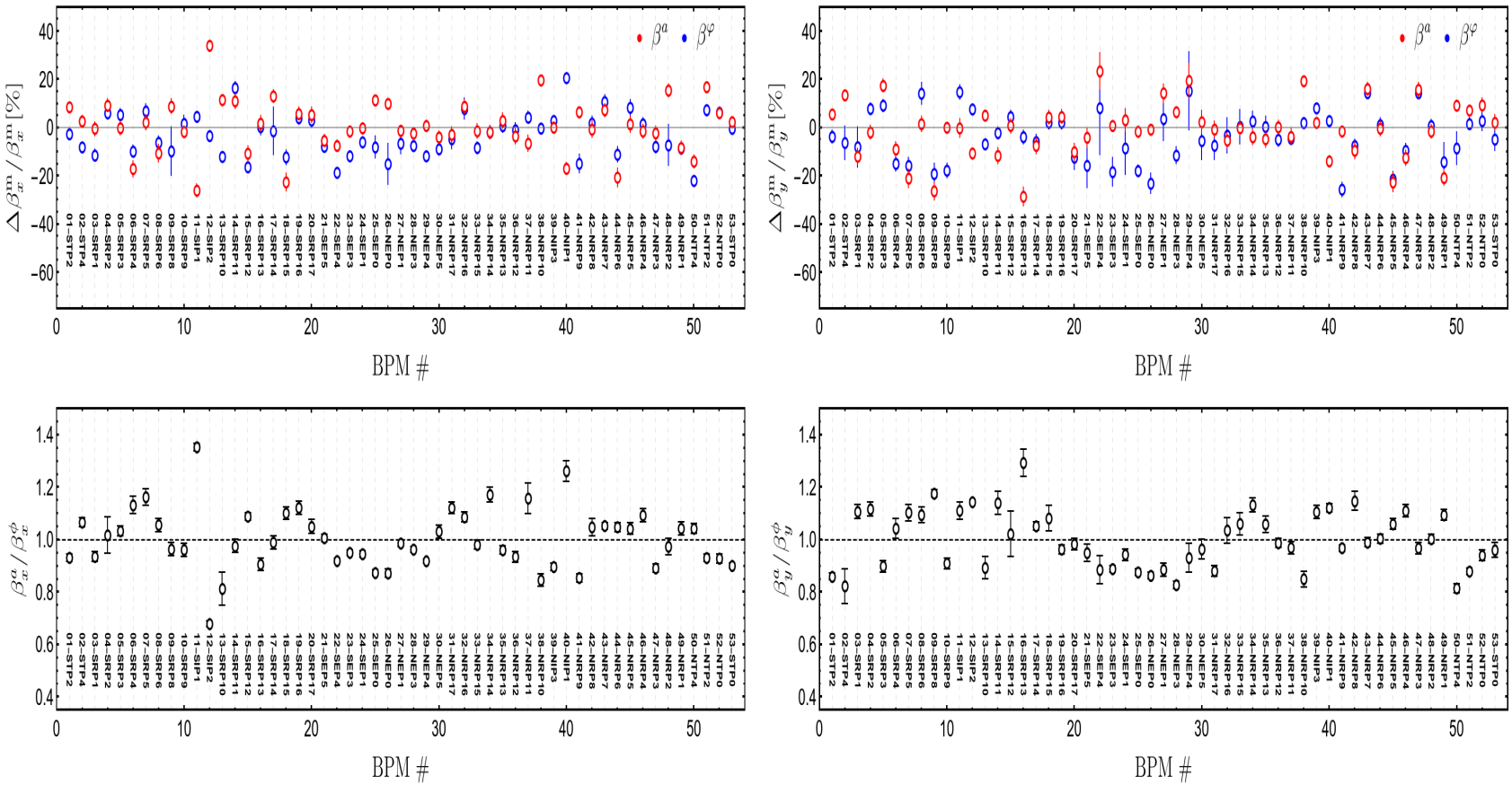



$\Delta\beta_x/\beta_x$ [%]
β_x [m]
MODEL
MEASURED
MEASURED (10X)
s [m]
$\Delta\beta_y/\beta_y$ [%]
β_y [m]
MODEL
MEASURED
MEASURED (10X)
s [m]


$\Delta\beta_x/\beta_x$ [%]
β_x [m]
$\Delta\beta_y/\beta_y$ [%]
β_y [m]
s [m]
MODEL
MEASURED
MEASURED (10X)
01-STP2
02-STP4
03-SRP1
04-SRP2
05-SRP3
06-SRP4
07-SRP5
08-SRP6
09-SRP8
10-SRP9
11-SIP1
12-SIP2
13-SRP10
14-SRP11
15-SRP12
16-SRP13
17-SRP14
18-SRP15
19-SRP16
20-SRP17
21-SEP5
22-SEP4
23-SEP3
24-SEP1
25-SEP0
26-NEP0
27-NEP1
28-NEP3
29-NEP4
30-NEP5
31-NRP17
32-NRP16
33-NRP15
34-NRP14
35-NRP13
36-NRP12
37-NRP11
38-NRP10
39-NIP3
40-NIP1
41-NRP9
42-NRP8
43-NRP7
44-NRP6
45-NRP5
46-NRP4
47-NRP3
48-NRP2
49-NRP1
50-NTP4
51-NTP2
52-NTP0
53-STP0

β^a vs β^φ

- β^a and $\beta^\varphi \approx 20\%$ deviation from model
- β^a and β^φ ratio $\approx 15\%$



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Conclusion

- Data processing and noise estimation
- Accurate and robust frequency measurement $\sigma_\nu \approx 10^{-6}$
- Amplitude ($< 5\%$) and phase ($\approx 5\%$) measument with error propagation
- Robust action estimation
- β^a accuracy $\approx 5\%$ @ $\approx 20\%$ deviation from model
- β^φ accuracy $\approx 10\%$ @ $\approx 20\%$ deviation from model
- β^a vs β^φ ratio $\approx 15\%$

Thank you for your attention

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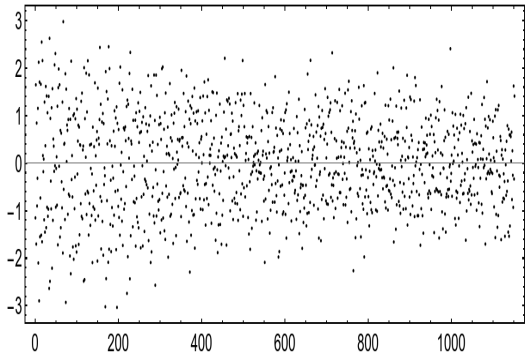
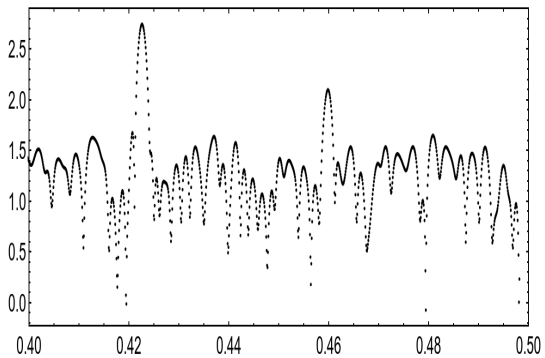
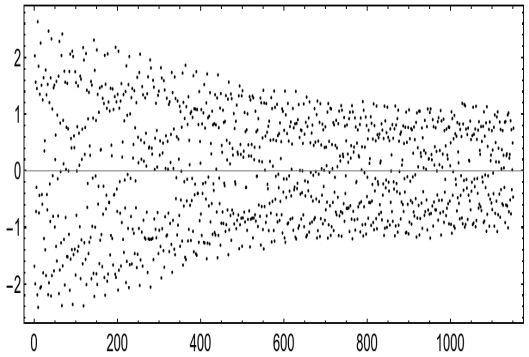
Signal Processing Example

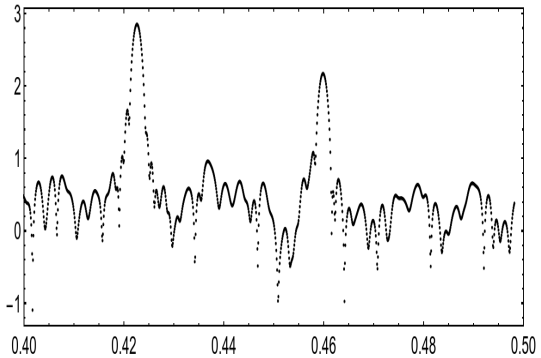
INPUT



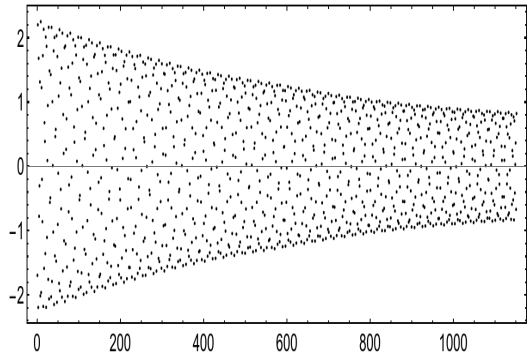


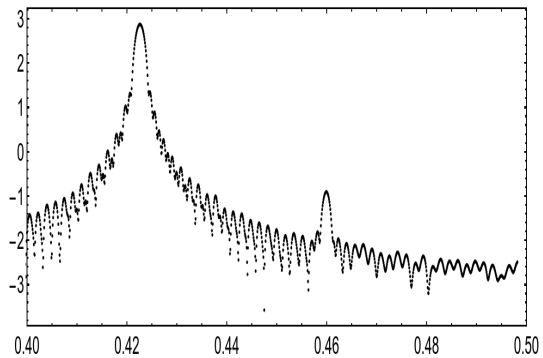
SVD





HANKEL





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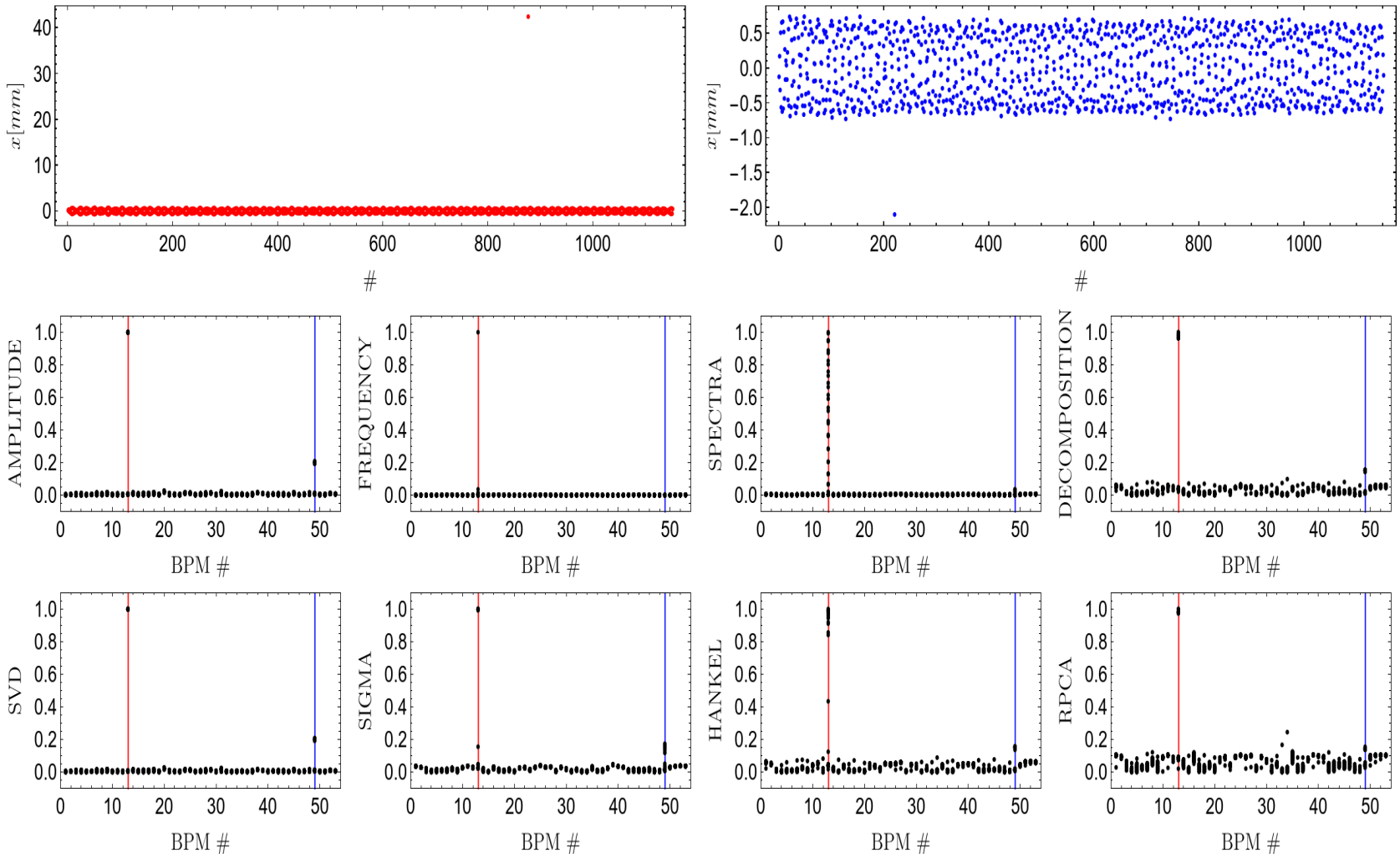
Spike Anomalies



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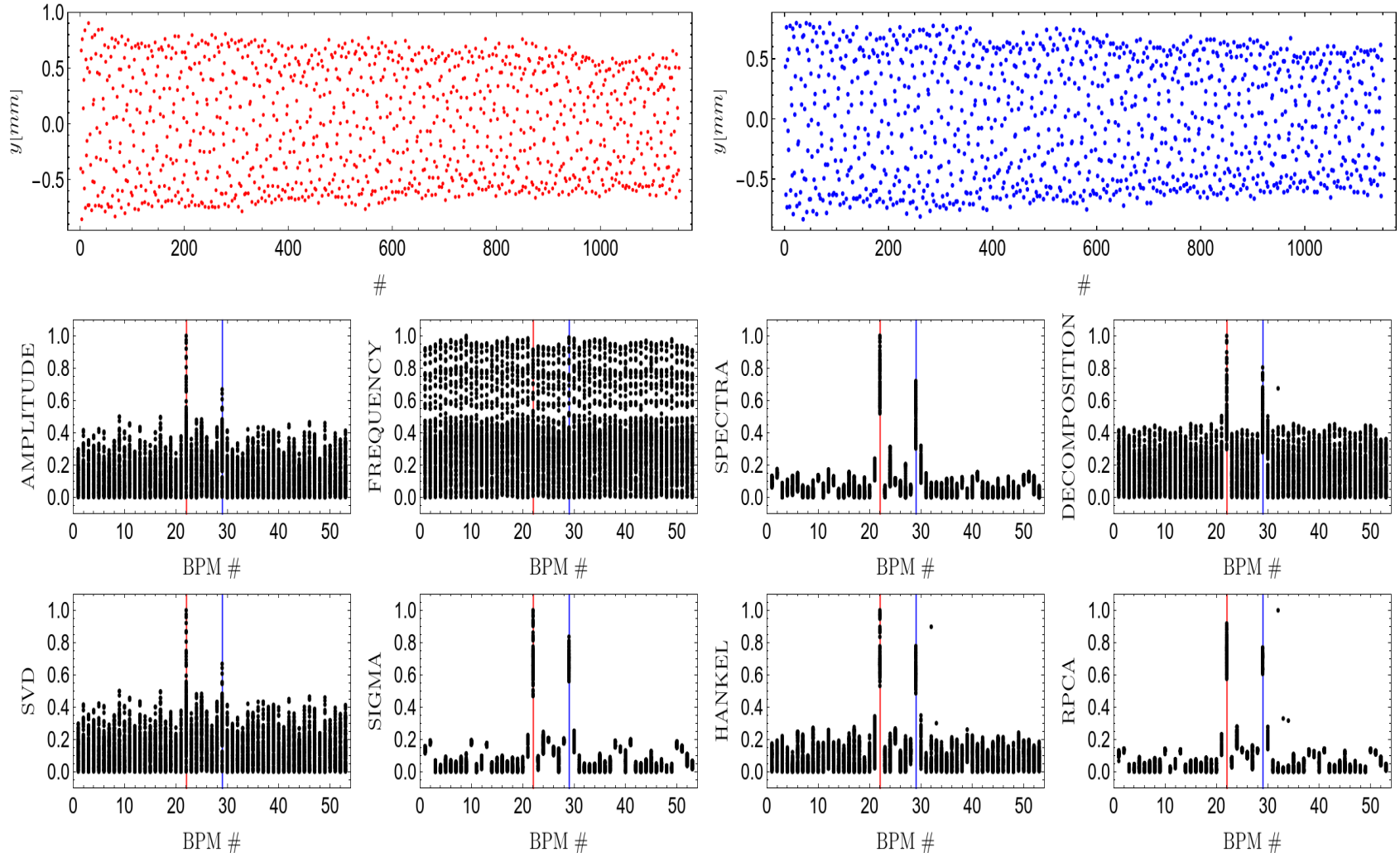
Systematic Anomalies



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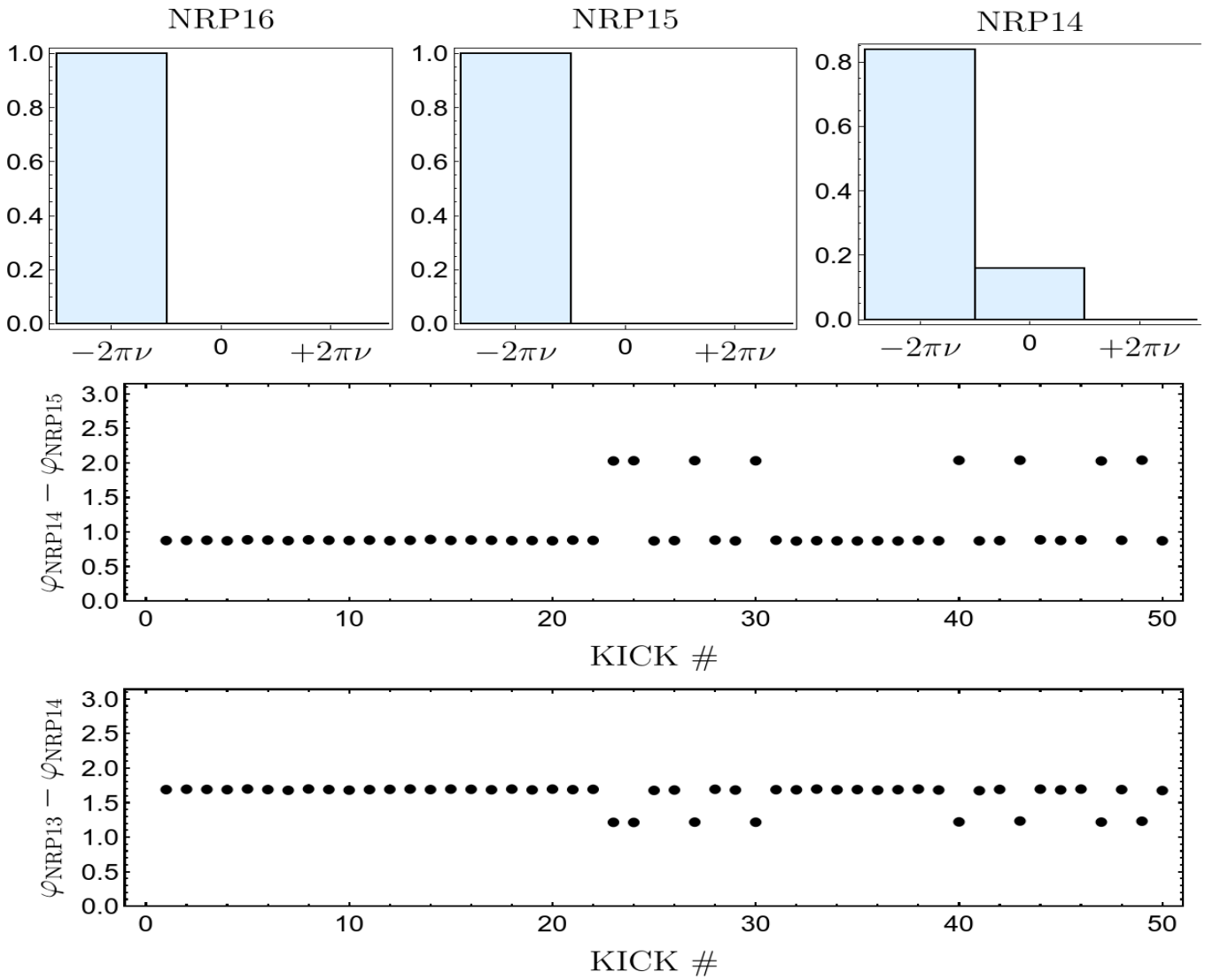
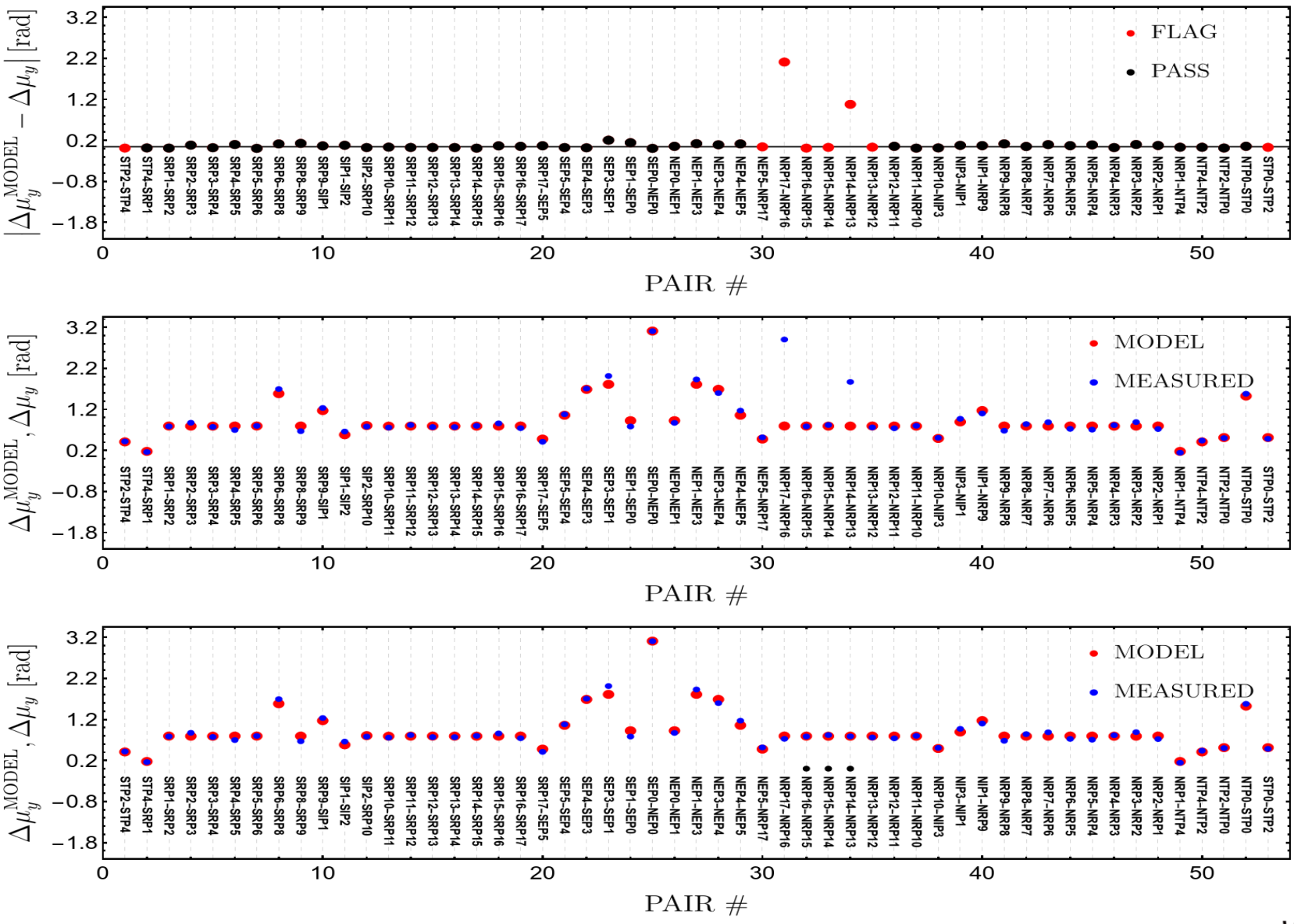
BPM Synchronization

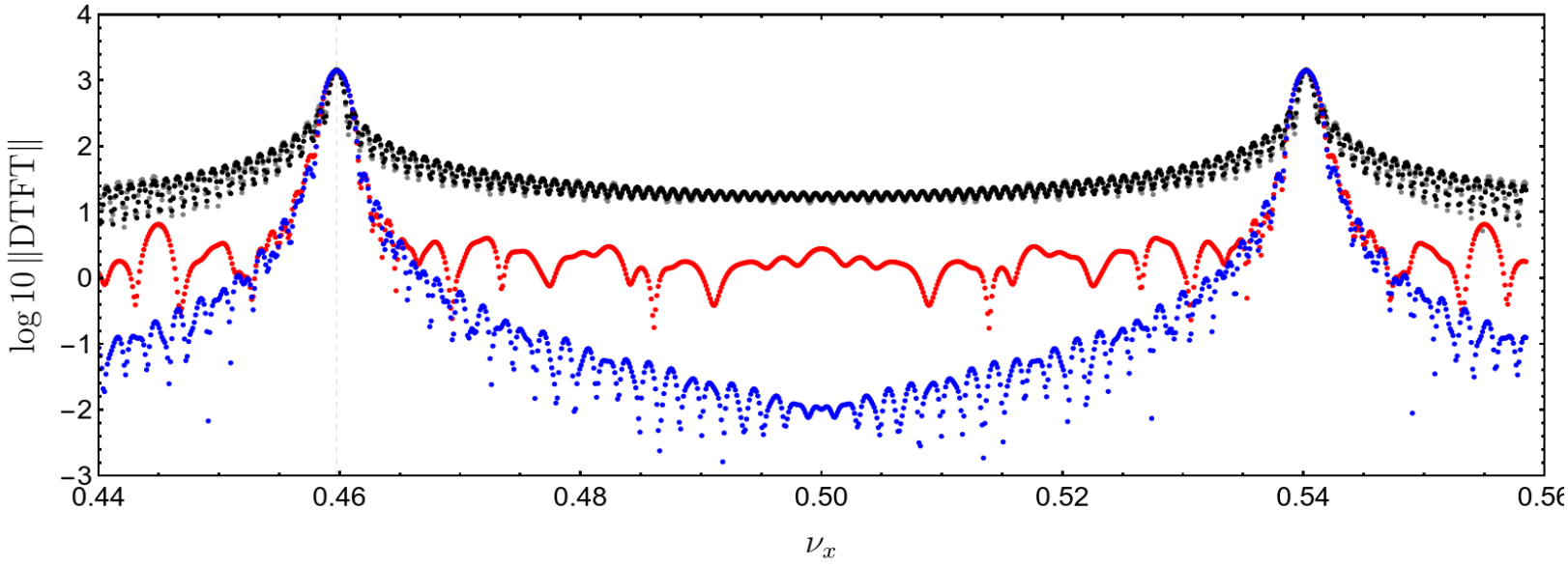


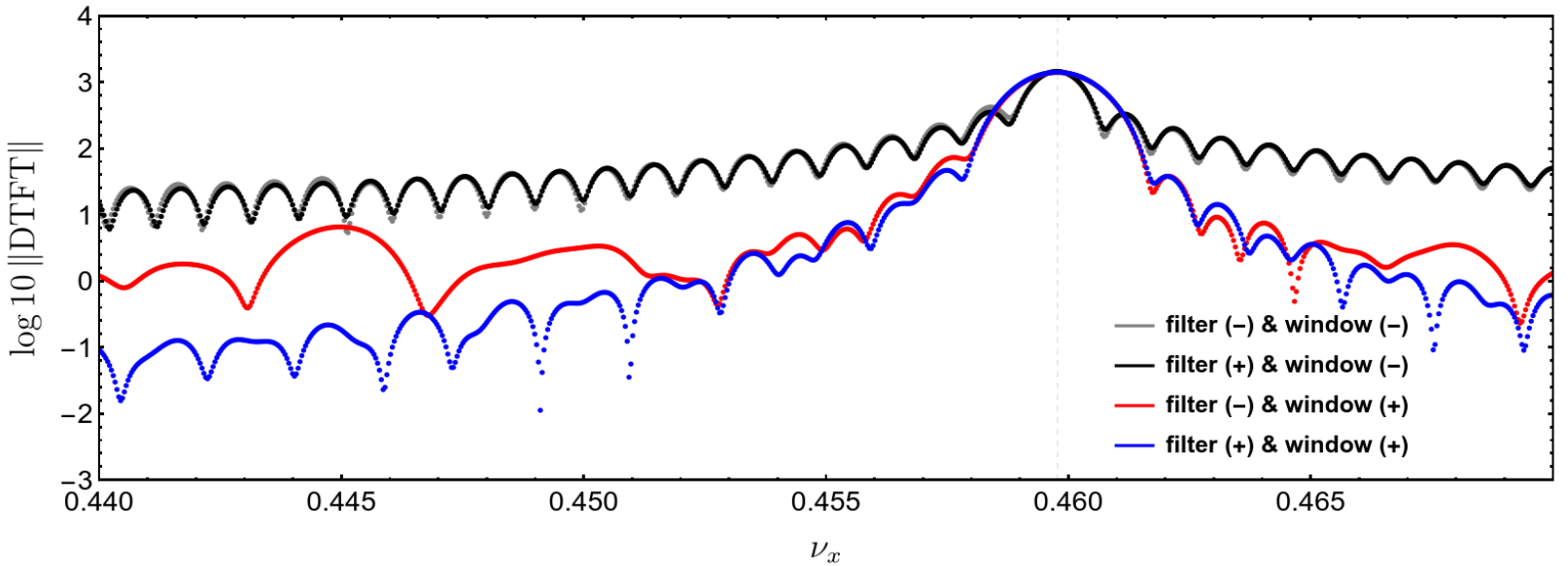
Synchronization Example



Frequency Estimation

Tunes $(8.54, 7.58) \rightarrow (0.46, 0.42)$





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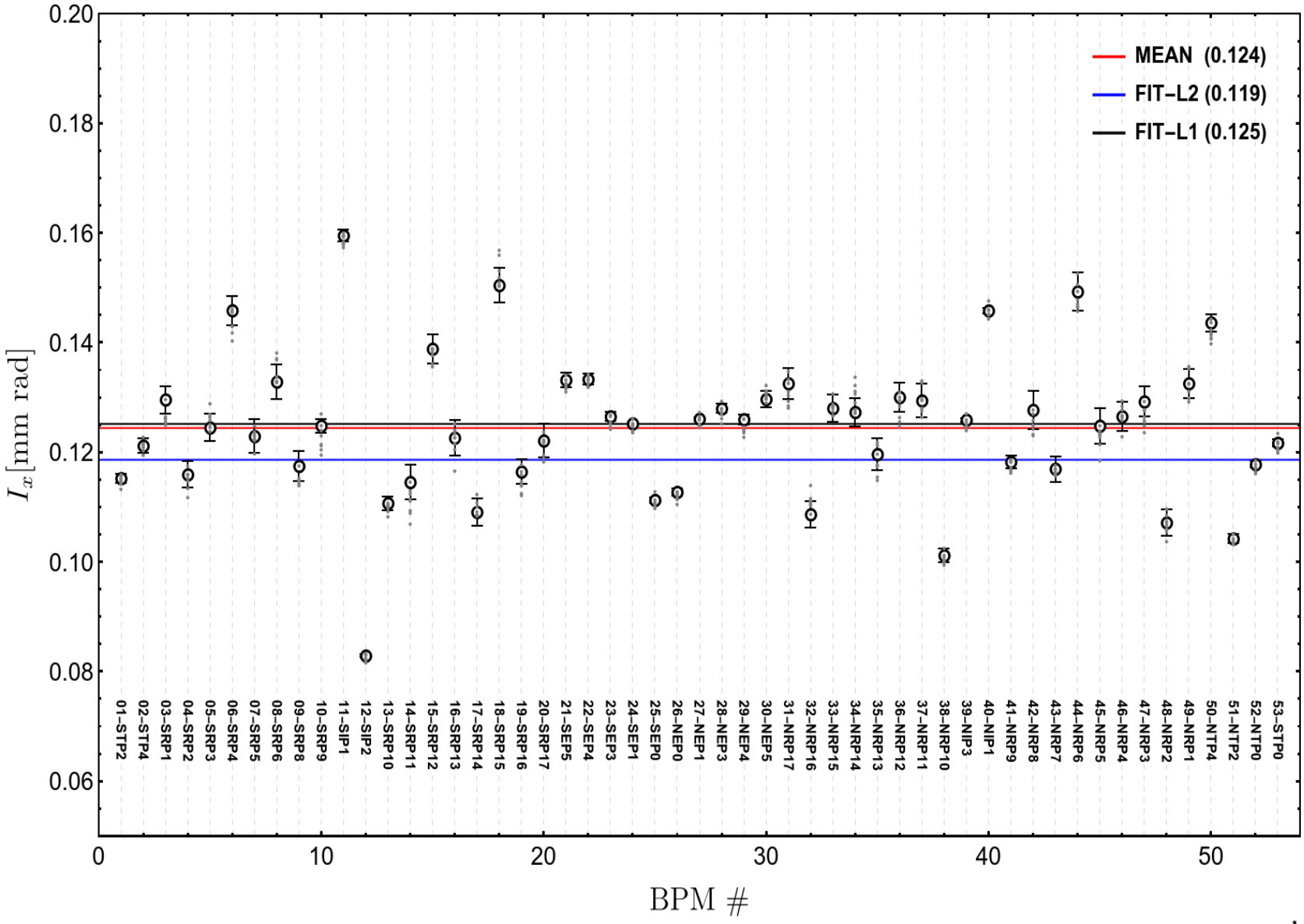
Action Estimation



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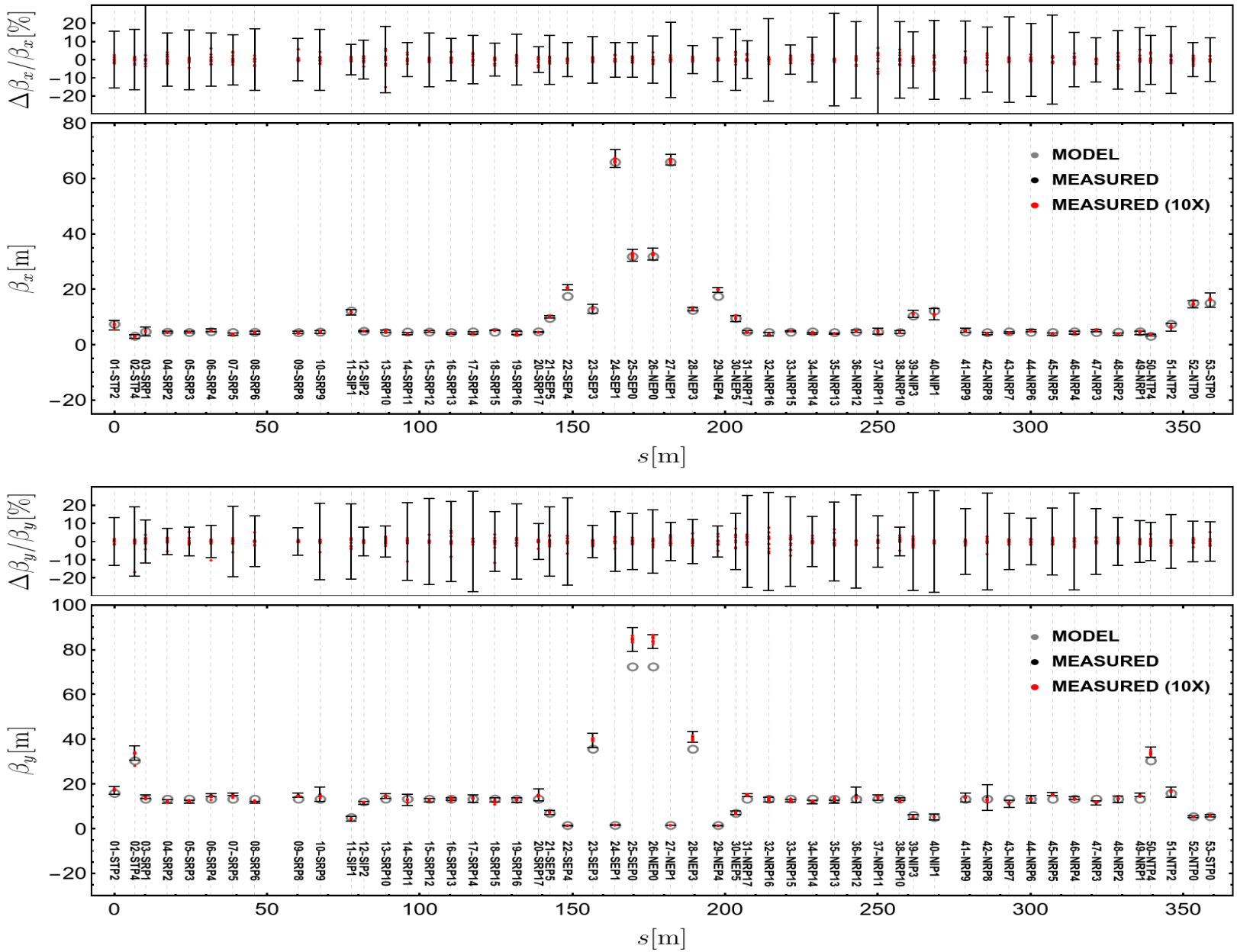
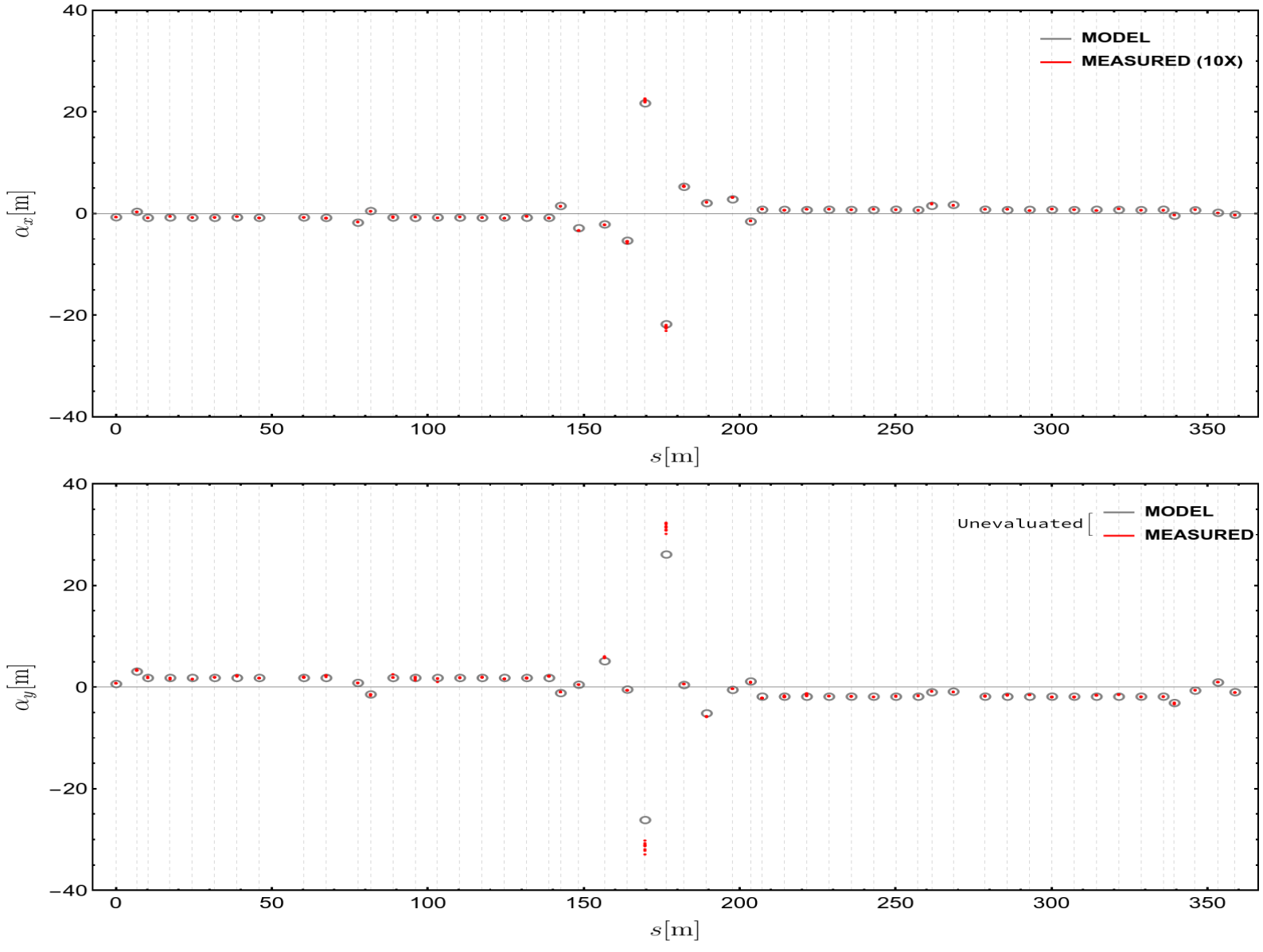
β^{φ} (combinations)



α


MODEL
MEASURED (10X)
α_x[m]
s[m]
Unevaluated [
MODEL
MEASURED
α_y[m]
s[m]