Recent Results of Optics Measurement at the Tevatron

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Differential Orbit Measurements

- The aim is to find gradient errors utilizing the fact that quadrupoles act as dipole correctors with off-center orbit

$$\theta = Kl \cdot x$$

- Initially, closed orbit is excited using a single dipole corrector

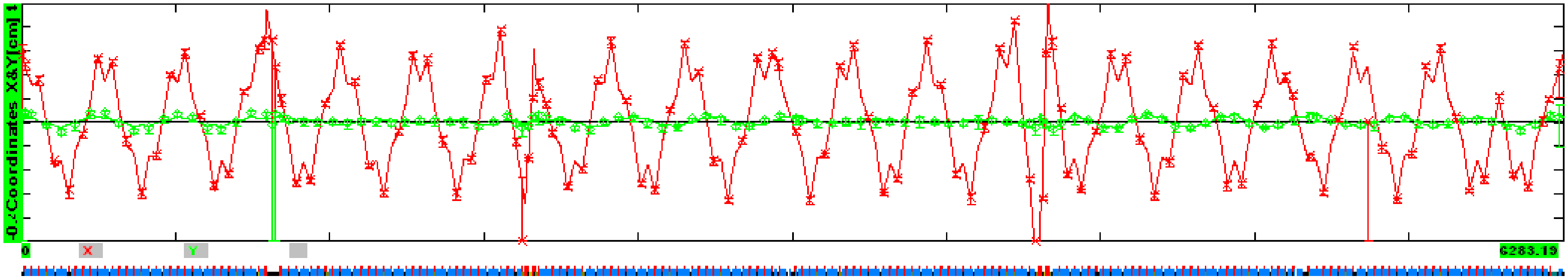
$$x_i(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi\nu)} \theta \sqrt{\beta(s_0)} \cos\left(\left|\varphi(s) - \varphi(s_0)\right| - \pi\nu\right)$$

- The orbit distortion due to quadrupoles is given by

$$x_q(s) = \frac{\sqrt{\beta_x(s)}}{2\sin(\pi\nu_x)} \sum_j Kl_j x_{ij} \sqrt{\beta_{xj}} \cos\left(\left|\varphi_x(s) - \varphi_{xj}\right| - \pi\nu_x\right)$$

$$y_q(s) = \frac{\sqrt{\beta_y(s)}}{2\sin(\pi\nu_y)} \sum_j SQ_j x_{ij} \sqrt{\beta_{yj}} \cos\left(\left|\varphi_y(s) - \varphi_{yj}\right| - \pi\nu_y\right)$$

- Dispersion measurement $x_d(s) = -\frac{D(s)}{\eta} \frac{\Delta f_{RF}}{f_{RF}}$
- Use BPM system to measure and record orbit differences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Y
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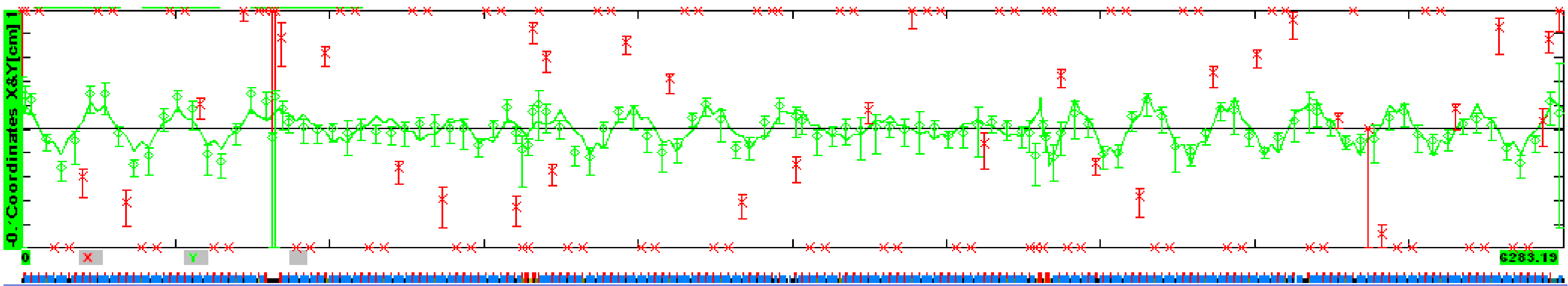
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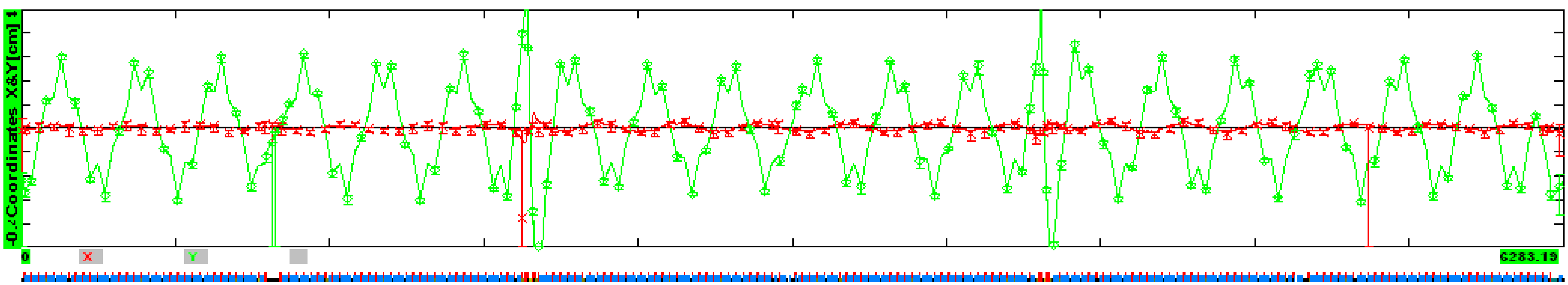
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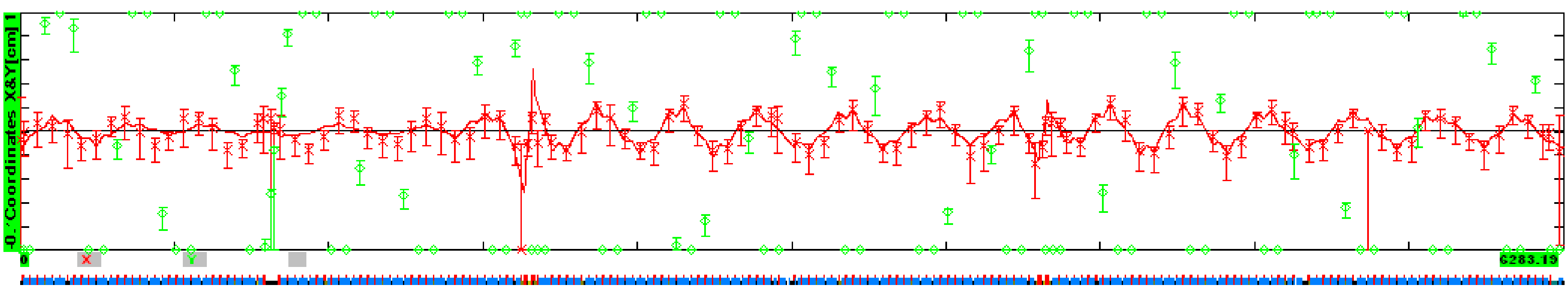
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X
Y
6283.19

Orbit response matrix fit
(LOCO, V.Sajaev, ANL)

- The orbit response matrix is the change in the orbit at the BPMs as a function of changes in steering magnets:

$$\begin{pmatrix} x \\ y \end{pmatrix} = M_{\substack{measured \\ model}} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}$$

- Modern storage rings have a large number of steering magnets and precise BPMs, so measurement of the response matrix provides a very large array of precisely measured data
- The response matrix is defined by the linear lattice of the machine; therefore it can be used to calibrate the linear optics in a storage ring

Orbit response matrix fit

The main idea of the analysis is to adjust all the variables that the response matrix depends on in order to solve the following equation:

$$M_{measured} - M_{model}(z) = 0 \quad ,$$

$$\Delta z = \left(\frac{\partial M_{model}}{\partial z} \right)^{-1} \cdot \left(M_{measured} - M_{model}(z_0) \right)$$

Computer Model of Tevatron

- We use OptiM accelerator optics code, the model contains regular optics elements (similar to MAD).
- Differences from MAD:
  - Strengths of individual quadrupoles (measured), power supply currents are taken directly from the control system
  - A1 component in dipoles (correct pattern of re-shimmed magnets)

Orbit response matrix fit

The response matrix depends on the following parameters:

- Quadrupole gradient errors
- Steering magnet calibrations
- BPM gains

} Main parameters

- Quadrupole tilts
- Steering magnet tilts
- BPM tilts
- Energy shift associated with steering magnet changes

} Main coupling parameters

- BPM nonlinearity
- Steering magnet and BPM longitudinal positions
- etc.

Orbit response matrix fit for Tevatron

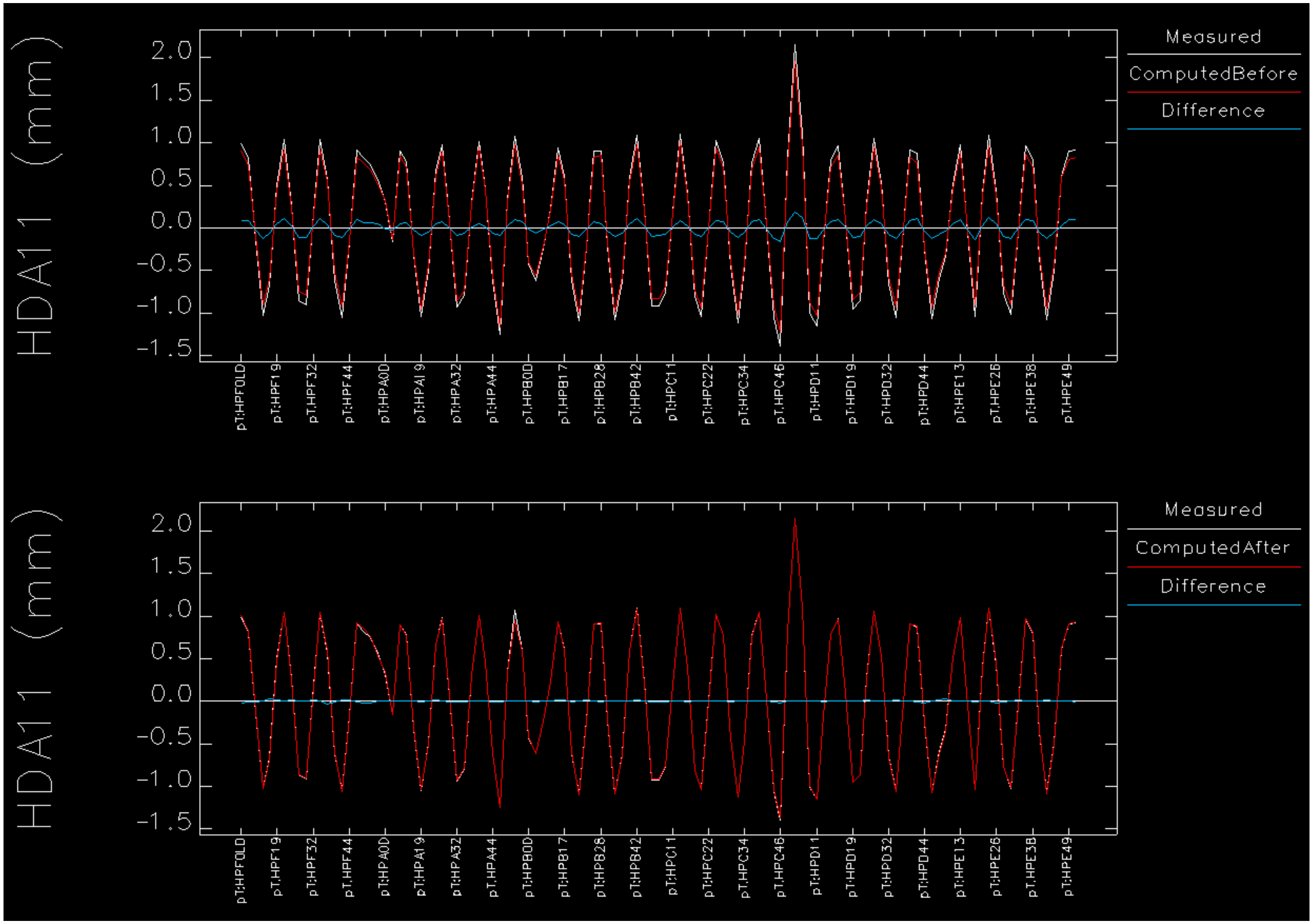
- Tevatron has 110 steering magnets and 120 BPMs in each plane and 216 quadrupoles
- For our analysis we use about 30 steering magnets in each plane, all BPMs, all quadrupoles, and tilts of one half of quadrupoles. The resulting response matrix has about 16,500 elements, and the number of variables is 980.
- Finally we solve the following equation (by iterations):

$$X = M^{-1} \cdot V$$

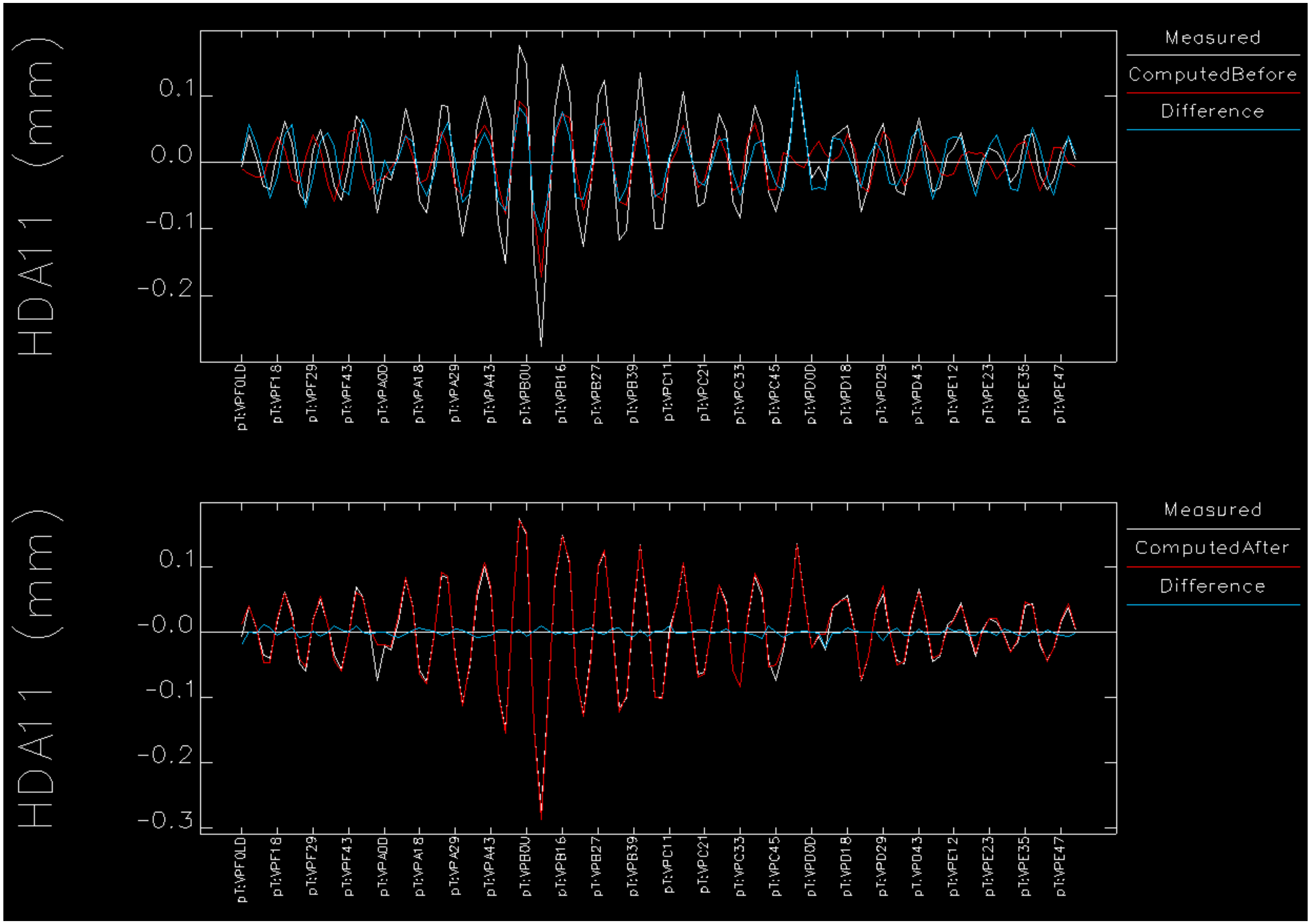
$$\begin{pmatrix} 1 \\ \times \\ 980 \end{pmatrix} = \begin{pmatrix} 980 \\ \times \\ 16500 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \times \\ 16500 \end{pmatrix}$$

130 Mb

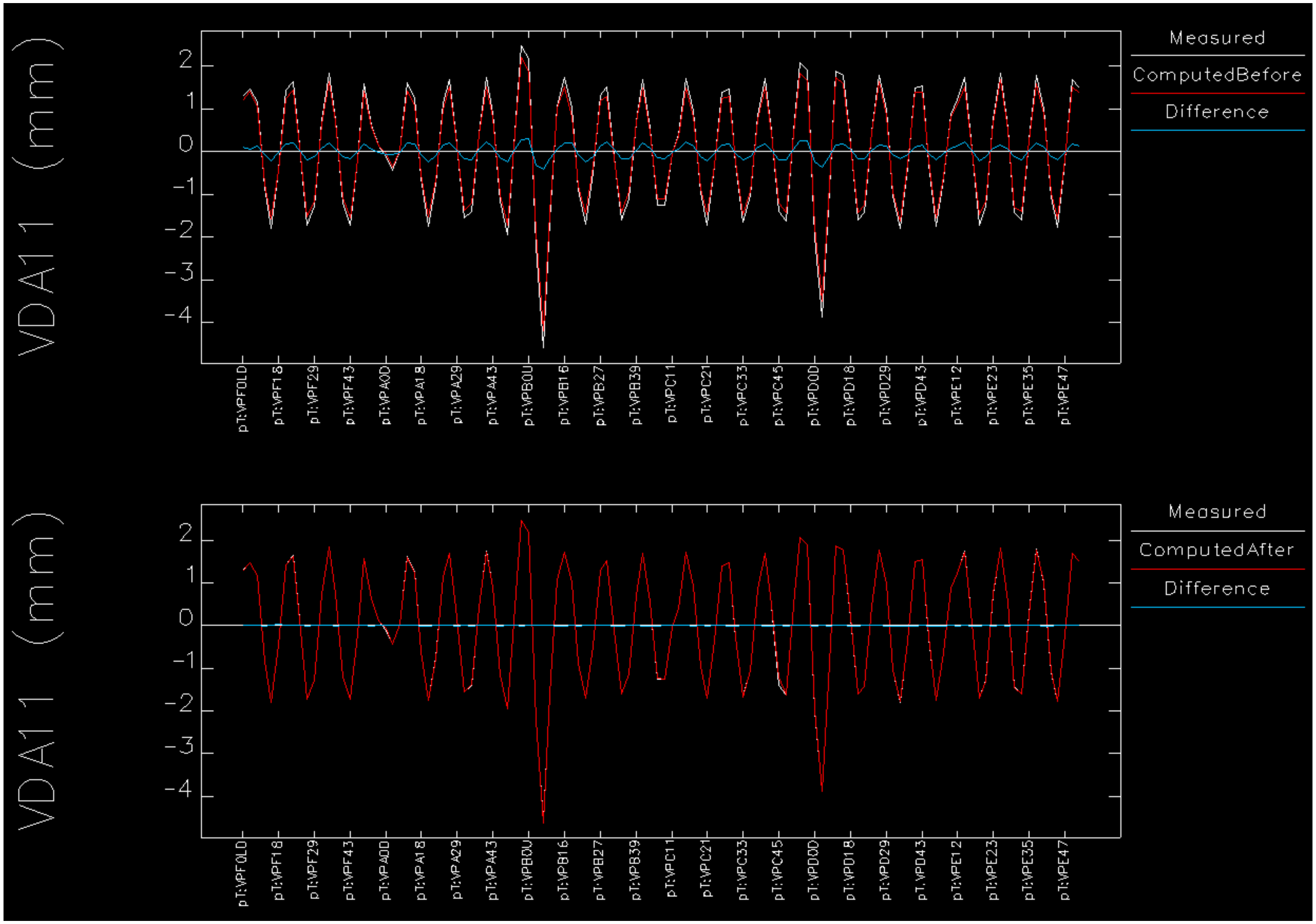
Differential Orbit. X Corr. - X plane



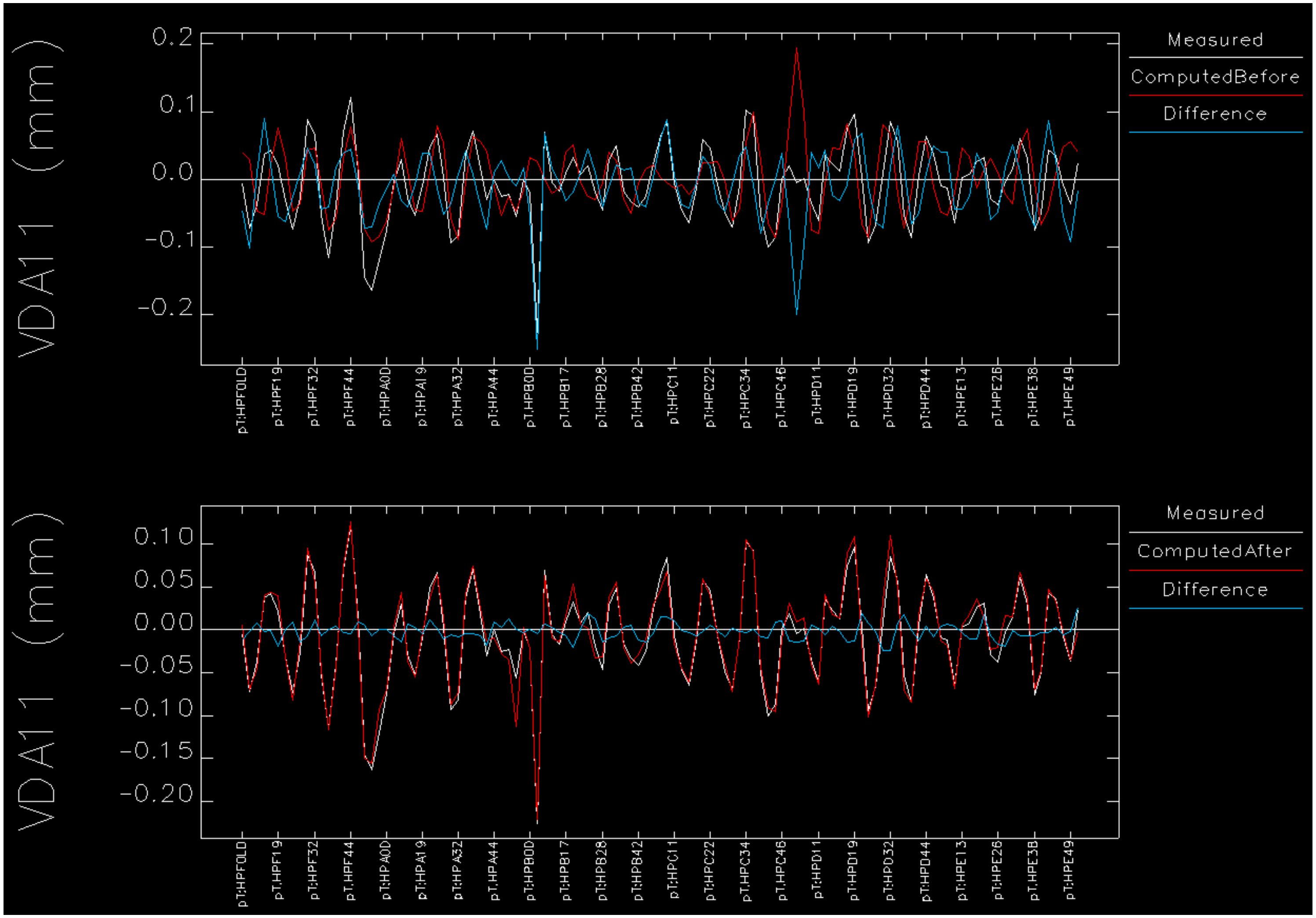
Differential Orbit. X Corr. - Y plane



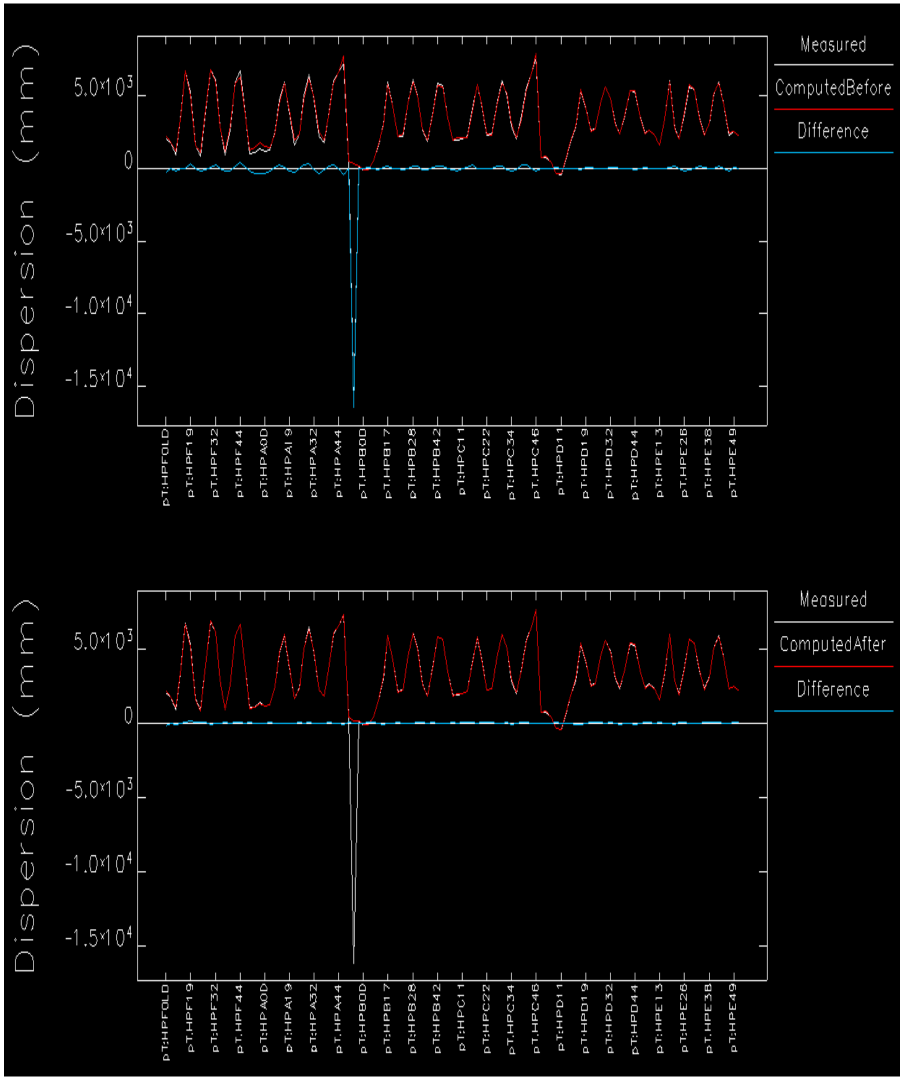
Differential Orbit. Y Corr. – Y plane

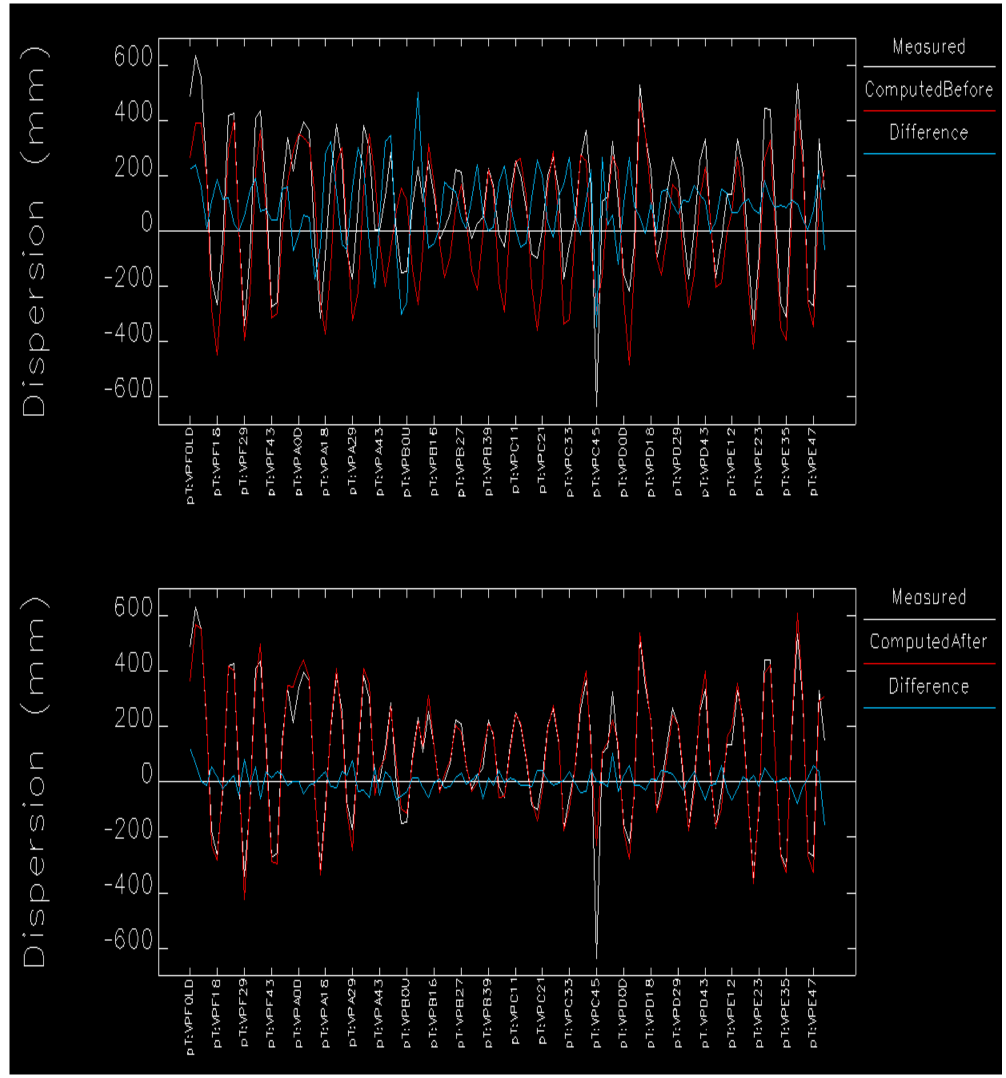


Differential Orbit. Y Corr. - X plane

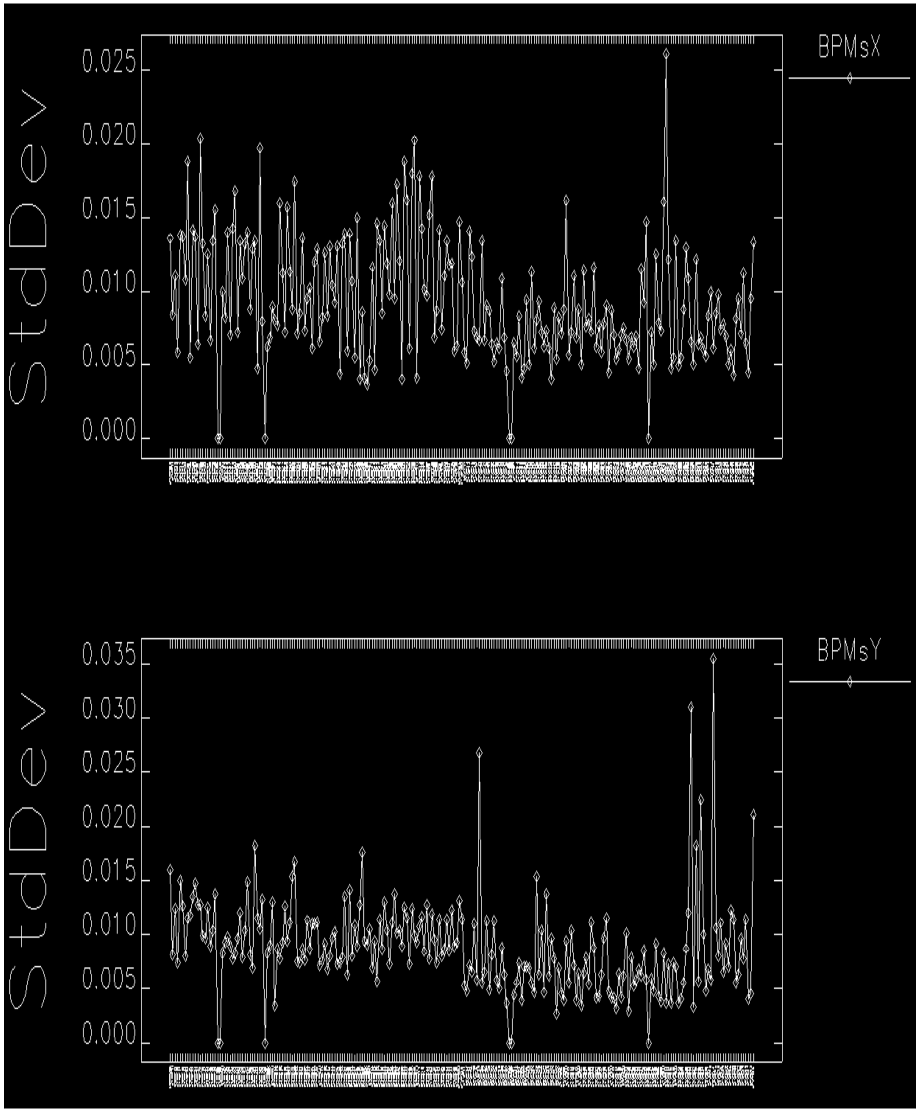


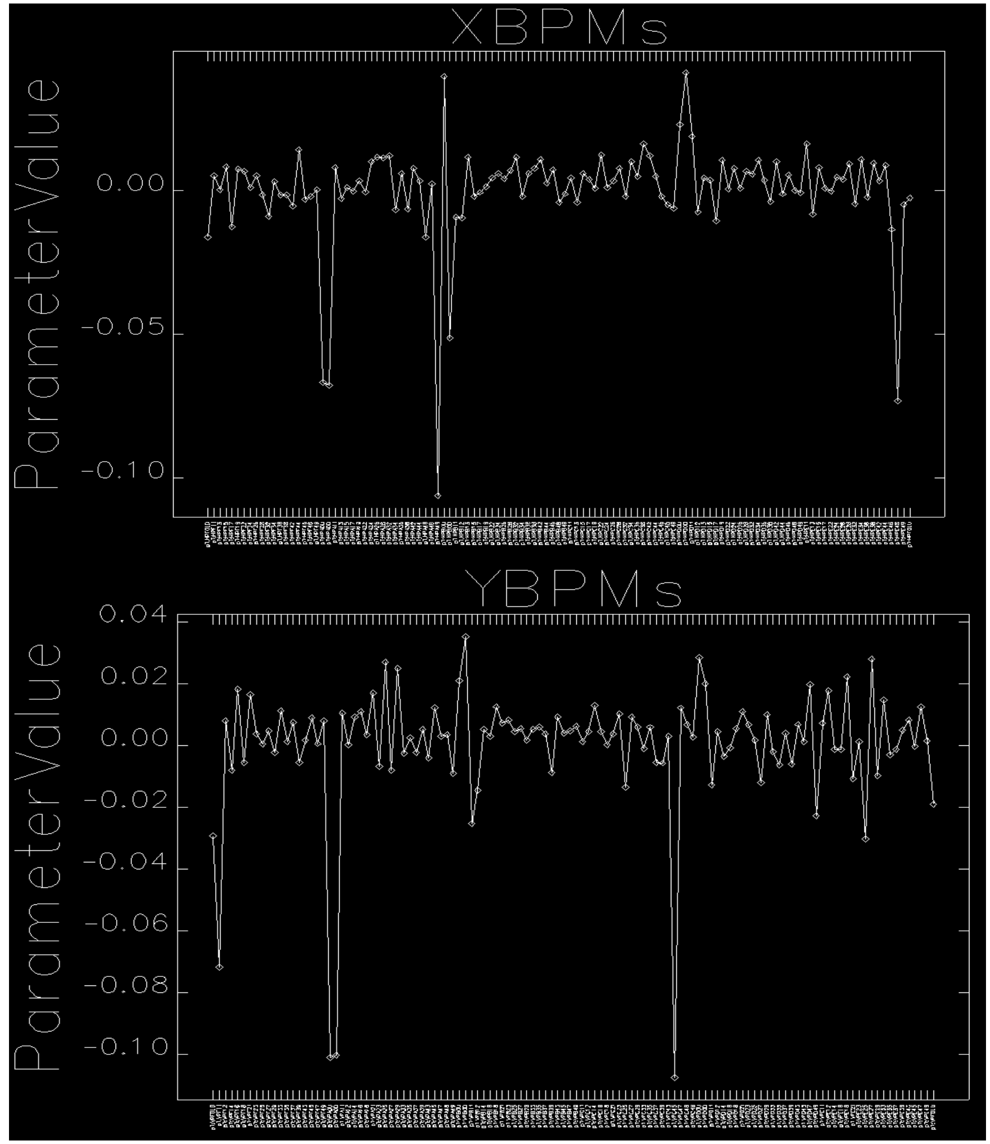
Dispersion


Dispersion (mm)
5.0×10³
0
-5.0×10³
-1.0×10⁴
-1.5×10⁴
Measured
ComputedBefore
Difference
Dispersion (mm)
5.0×10³
0
-5.0×10³
-1.0×10⁴
-1.5×10⁴
Measured
ComputedAfter
Difference

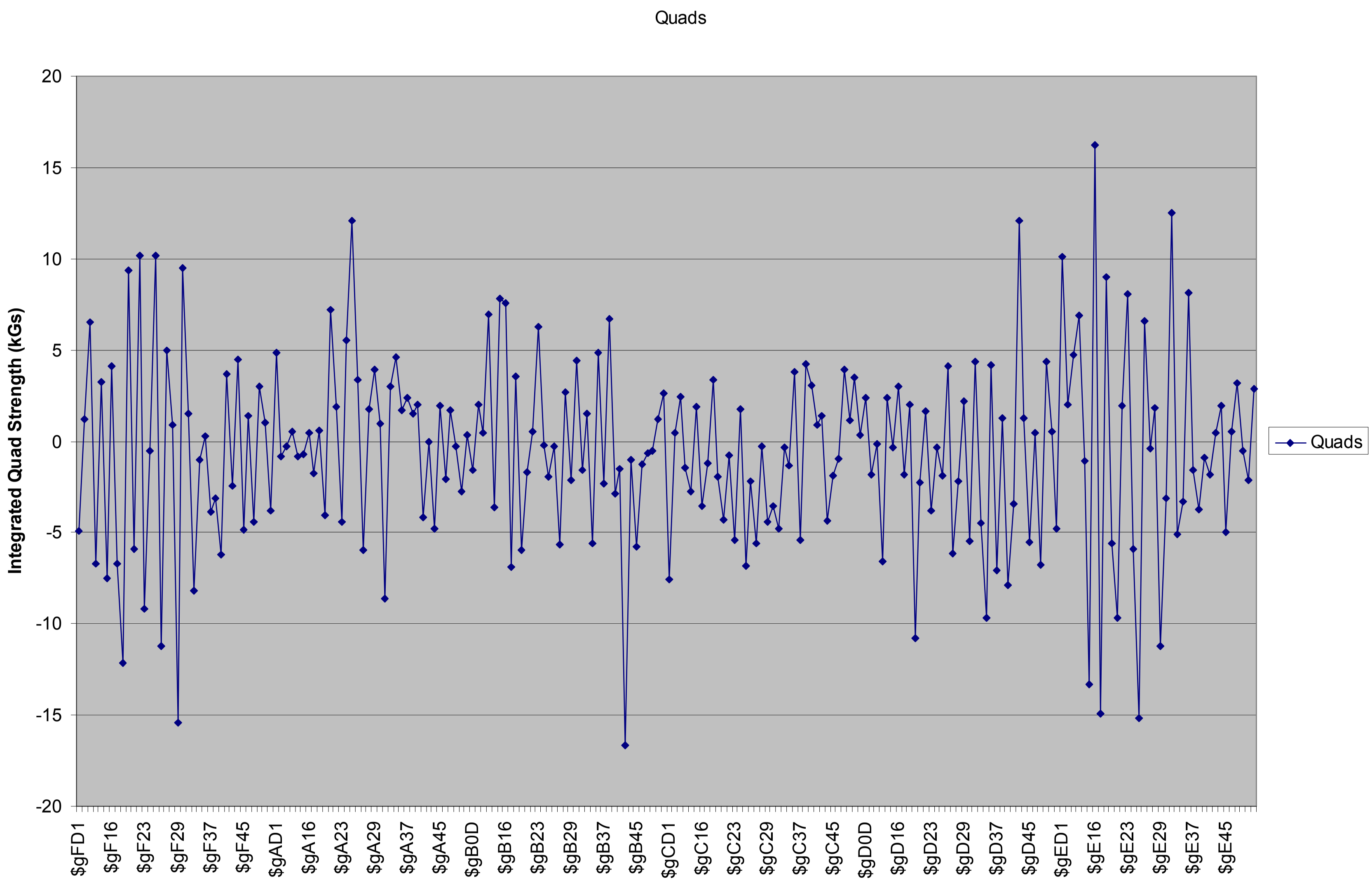

Dispersion (mm)
600
400
200
0
-200
-400
-600
Measured
ComputedBefore
Difference
Dispersion (mm)
600
400
200
0
-200
-400
-600
Measured
ComputedAfter
Difference

BPMs

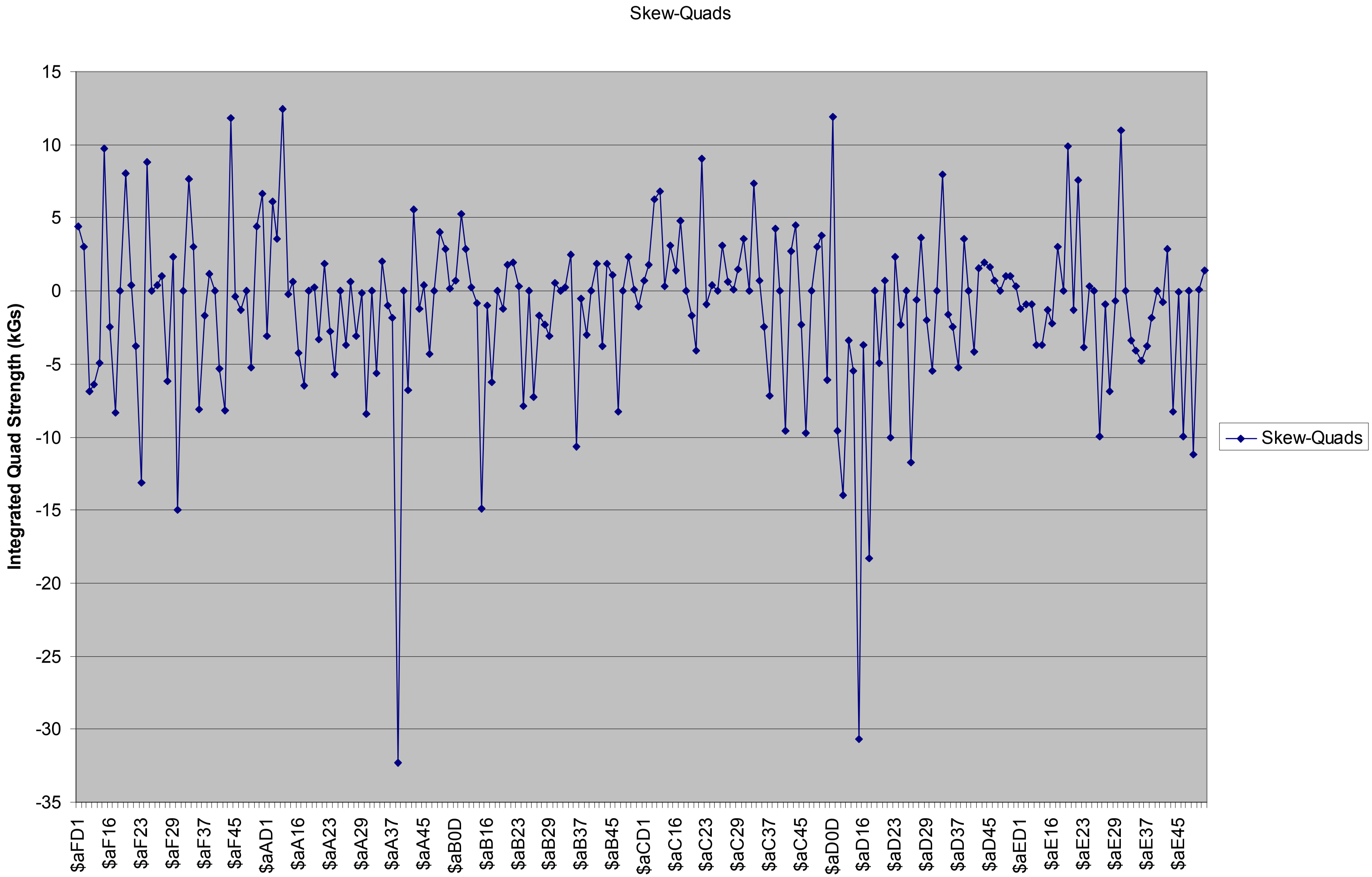

BPMsX
StdDev
0.025
0.020
0.015
0.010
0.005
0.000
BPMsY
StdDev
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000


XBPMs
Parameter Value
0.00
-0.05
-0.10
YBPMs
Parameter Value
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10

Fitted Quadrupole Errors



Fitted Skew-Quadrupole Errors

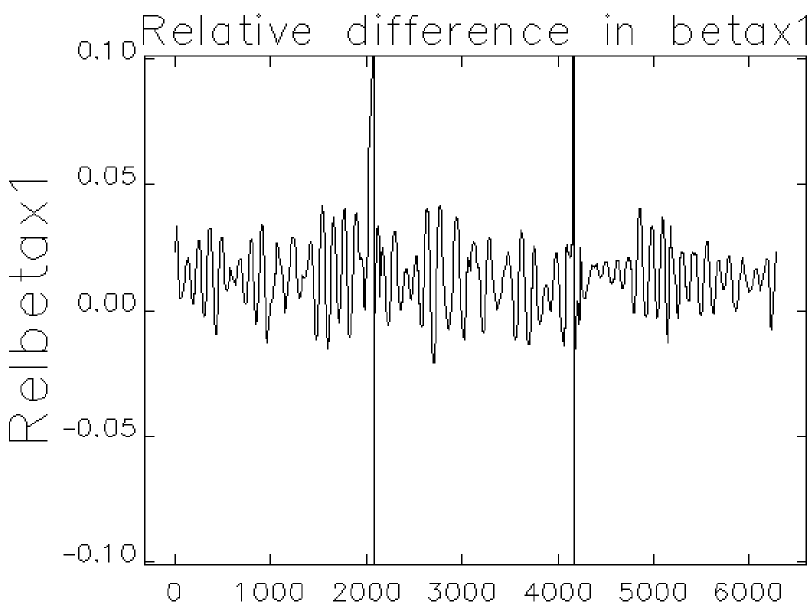


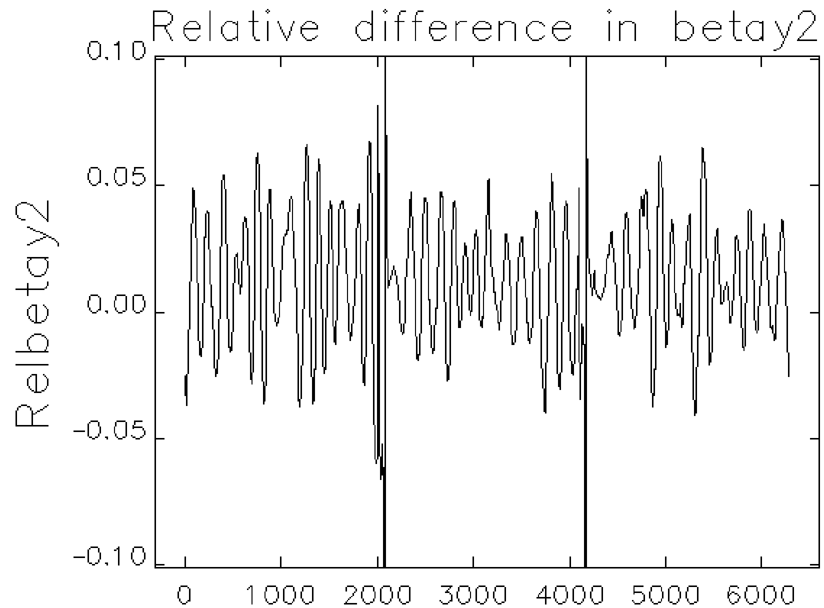
Summary of the residual rms errors after the fit:

	x-x (μm)	y-x (μm)	x-y (μm)	y-y (μm)	h disp (mm)	v disp (mm)
Before	140	42	44	123	139	120
Set 1	13	8	11	9	50	39
Set 2	14	8	9	9	49	36

Beta function accuracy

- Beta functions are computed based on each set of variables, then average beta functions are calculated
- Difference between the average beta function and one of data sets:





- BetaX1 rms error – 2.2%
- BetaY2 rms error – 3.1%
- DispX rms error – 2.9%

Direct Beta-function Measurement

- Vary current in quadrupoles which have separate power supplies and measure corresponding betatron tune shift

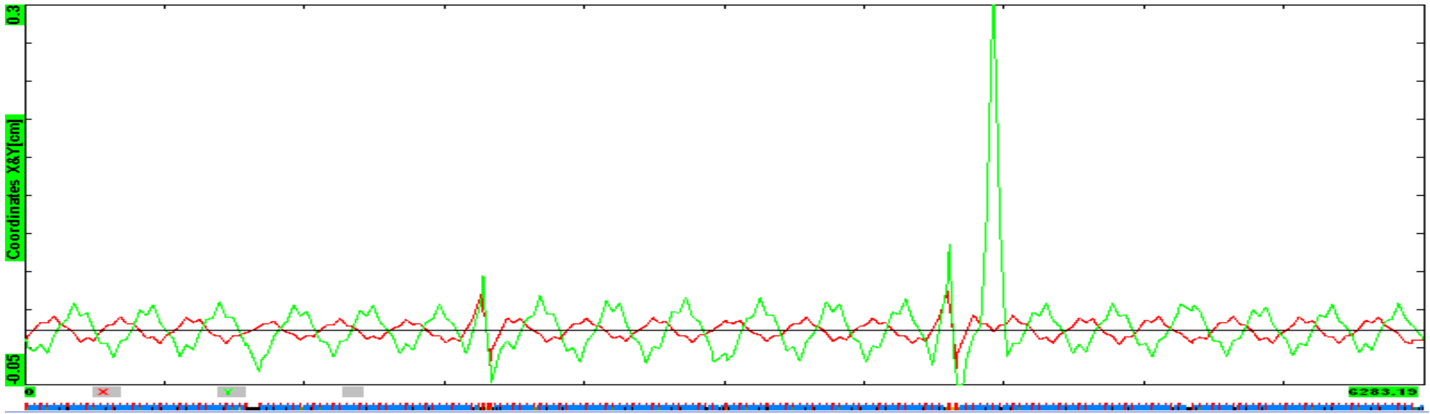
$$\Delta\nu = \frac{\Delta K \beta}{4\pi}$$

- Compare to the calculated tuneshift
- Accuracy of this method is determined by the accuracy of tune measurement (~1e-4 absolute error)

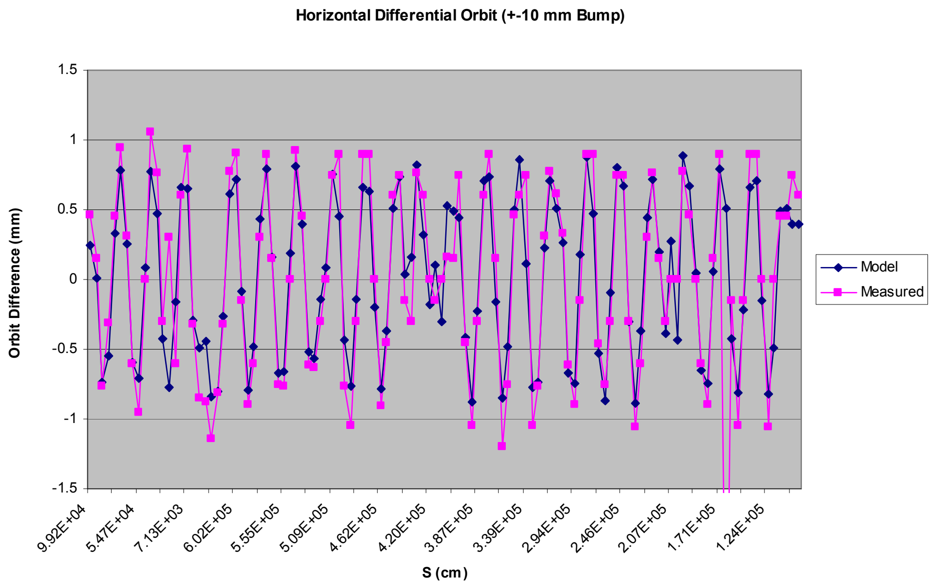
Measured (6-23-05) and Computed Tuneshifts

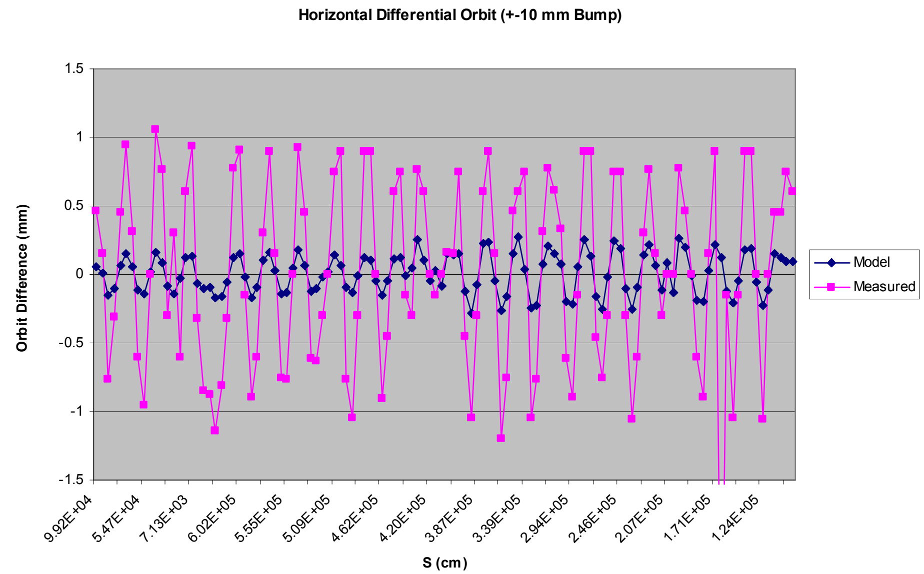
Element	dQx Meas.	dQx Model.	Difference %			dQy Meas.	dQy Model.	Difference %		
T:QE17H	0.071	0.0072	**-1.7**	±	3	-0.002	-0.00177	**13**	±	11
T:QE19H	0.0050	0.0058	**-13**	±	3	-0.00194	-0.0025	**-23**	±	8
T:QE26H	0.0063	0.0064	**-2**	±	3	-0.002	-0.0021	**-4**	±	9
T:QE28H	0.0077	0.0076	**1.3**	±	3	-0.0018	-0.0016	**10**	±	12
T:QF28H	0.0058	0.0057	**2.2**	±	3	-0.0024	-0.0025	**-3.5**	±	8
T:QF32H	0.0078	0.0079	**-1.4**	±	3	-0.00205	-0.0017	**21**	±	12
T:QE47H	0.0027	0.00255	**6**	±	8	-0.0056	-0.0059	**-5.6**	±	3
T:QF33H	0.00245	0.00256	**-4.4**	±	8	-0.0069	-0.0067	**3.2**	±	3

Skew Quadrupole Errors at D16 and A38



Closed Orbit Bump at D16 (calculation)





Skew Quadrupole Errors at D16 and A38

Based on Tech data:

- At D-16, quadrupole TQ184D has the lugs set incorrectly for the roll angle. If we call the correct orientation straight up, when the lugs are set level the field is pointing 12 mr toward the aisle.

- At A-39, quadrupole TQ096D has the lugs set incorrectly for the roll angle. If we call the correct orientation straight up, when the lugs are set level the field is pointing 10 mr toward the aisle.

Beta Functions at IPs

	β_x^* (cm)	β_y^* (cm)	D_x (cm)	D_y (cm)
CDF	32.8	37.1	1.9	-1.7
	32.0	37.2	1.7	-1.6
D0	35.8	40.0	-0.7	-2.0
	35.7	40.1	-1.2	-2.0

$\pm 5\%$

Conclusion

- The response matrix fit method with the new BPM system allows to pinpoint gradient errors in the Tevatron of the order of 2e-3
- The error in beta function measurement is ~ 5%
- Based on the fitted model the optics modification is proposed in order to:
  - Correct beta-beating in the arcs
  - Eliminate the difference between the two IPs
  - Decrease the beta* from 35 to 28 cm
- First optics correction was done during Tev study on July, 19th.