Advanced Optics Measurements at Tevatron

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ANL

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Talk overview

- Response matrix fit method description
- Program description
- Results of the fit for Tevatron
- Accuracy of the measurements
- Uniqueness of the fit results
- Comparison with tune shift measurements
- Example of beta function correction at APS

Orbit response matrix

- 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:

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

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

The method was first suggested by Corbett, Lee, and Ziemann at SLAC and refined by Safranek at BNL. A very careful analysis of the response matrix was done at the NSLS X-ray ring, ALS, and later at APS. A similar method was used at ESRF for characterization and correction of the linear coupling and to calibrate quadrupoles by families.

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

Main coupling parameters

- Energy shift associated with steering magnet changes
- BPM nonlinearity
- Steering magnet and BPM longitudinal positions
- etc.

First full-scale measurements

- Response and dispersion measurements are taken on 2004/08/05
- Measurements contain all corrector magnets: two 110×236 matrices
- Total response matrix derivative is more than 500 Mb – there is no way to analyze the entire set
- The measurement is split into 3 approx. equal subsets, and each subset is analyzed separately
- The comparison of the results gives us an estimate of the fit accuracy

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 40 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):

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

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

$$\boxed{130\ \text{Mb}}$$

Program organization chart

GUI: tcl/tk - unix, linux

↓

Fitting program
tcl/tk

↓

Response matrix derivative calculation

- `optim` or `elegant` calculate RM for different variables (can run in parallel)
- sddstoolkit is used to postprocess and build RM derivative
- Inverse RM derivative is computed with matlab of sddstoolkit

↓

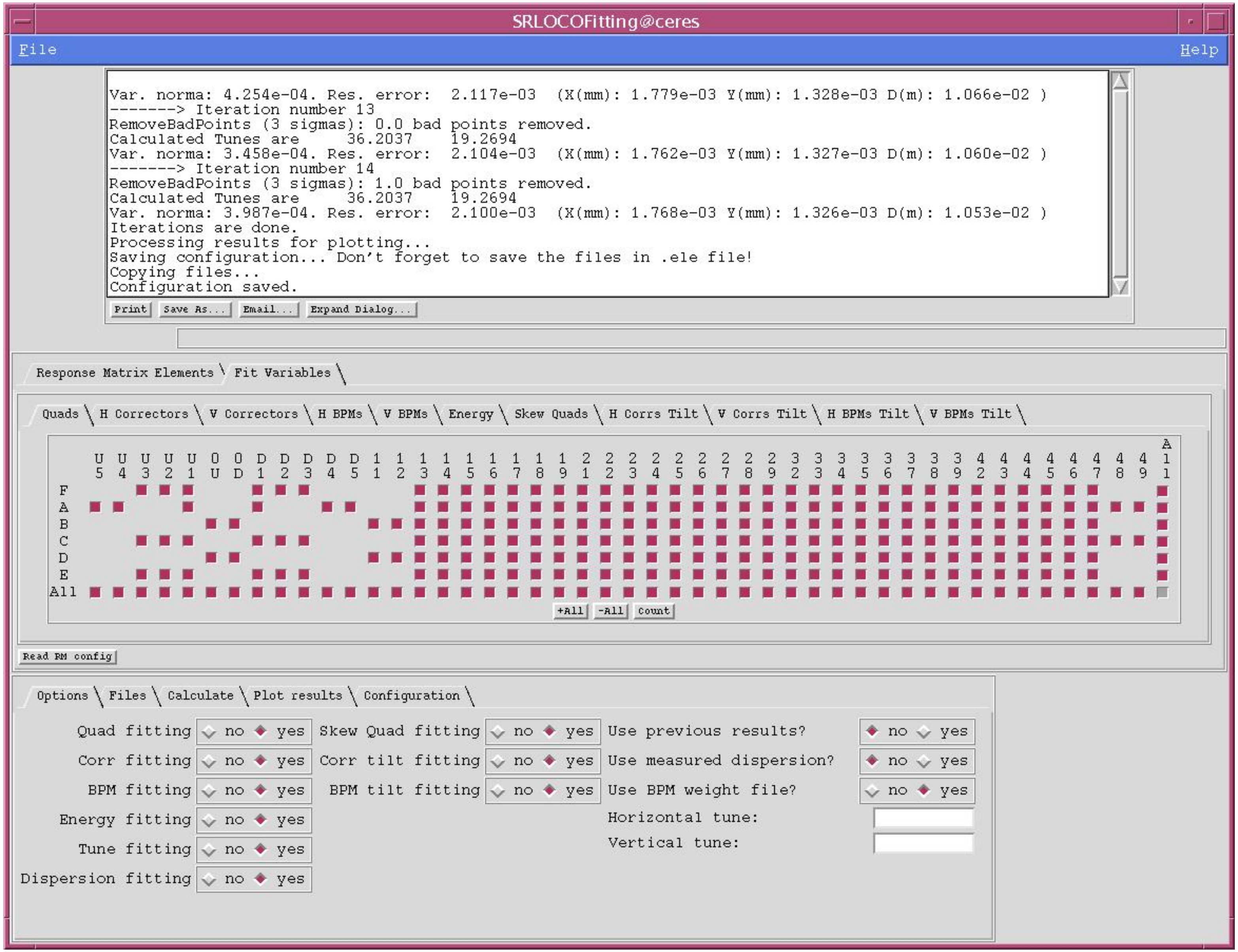
Iterations

- RM calculations – `elegant` or `optim`
- preprocessing, postprocessing - sddstoolkit

↓

Output

- all results are stored in sdds files
- `sddsplot` can be used for graphic output

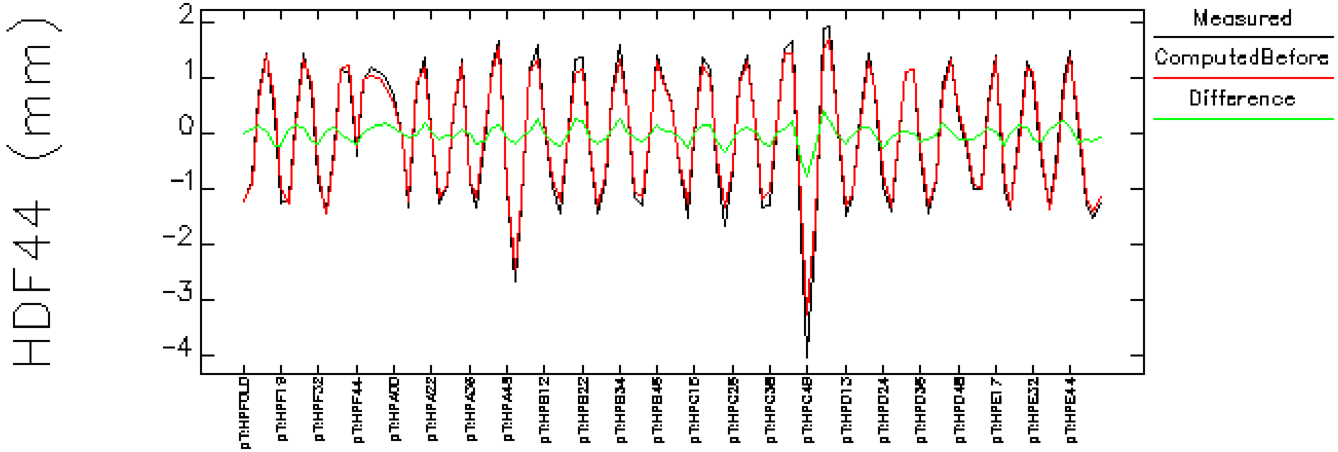

SRLOCOFitting@ceres
File
Help
Var. norma: 4.254e-04. Res. error: 2.117e-03 (X(mm): 1.779e-03 Y(mm): 1.328e-03 D(m): 1.066e-02)
-------> Iteration number 13
RemoveBadPoints (3 sigmas): 0.0 bad points removed.
Calculated Tunes are 36.2037 19.2694
Var. norma: 3.458e-04. Res. error: 2.104e-03 (X(mm): 1.762e-03 Y(mm): 1.327e-03 D(m): 1.060e-02)
-------> Iteration number 14
RemoveBadPoints (3 sigmas): 1.0 bad points removed.
Calculated Tunes are 36.2037 19.2694
Var. norma: 3.987e-04. Res. error: 2.100e-03 (X(mm): 1.768e-03 Y(mm): 1.326e-03 D(m): 1.053e-02)
Iterations are done.
Processing results for plotting...
Saving configuration... Don't forget to save the files in .ele file!
Copying files...
Configuration saved.
Print
Save As...
Email...
Expand Dialog...
Response Matrix Elements
Fit Variables
Quads
H Correctors
V Correctors
H BPMs
V BPMs
Energy
Skew Quads
H Corrs Tilt
V Corrs Tilt
H BPMs Tilt
V BPMs Tilt
F
A
B
C
D
E
All
+All
-All
Count
Read RM config
Options
Files
Calculate
Plot results
Configuration
Quad fitting no yes
Corr fitting no yes
BPM fitting no yes
Energy fitting no yes
Tune fitting no yes
Dispersion fitting no yes
Skew Quad fitting no yes
Corr tilt fitting no yes
BPM tilt fitting no yes
Use previous results? no yes
Use measured dispersion? no yes
Use BPM weight file? no yes
Horizontal tune:
Vertical tune:

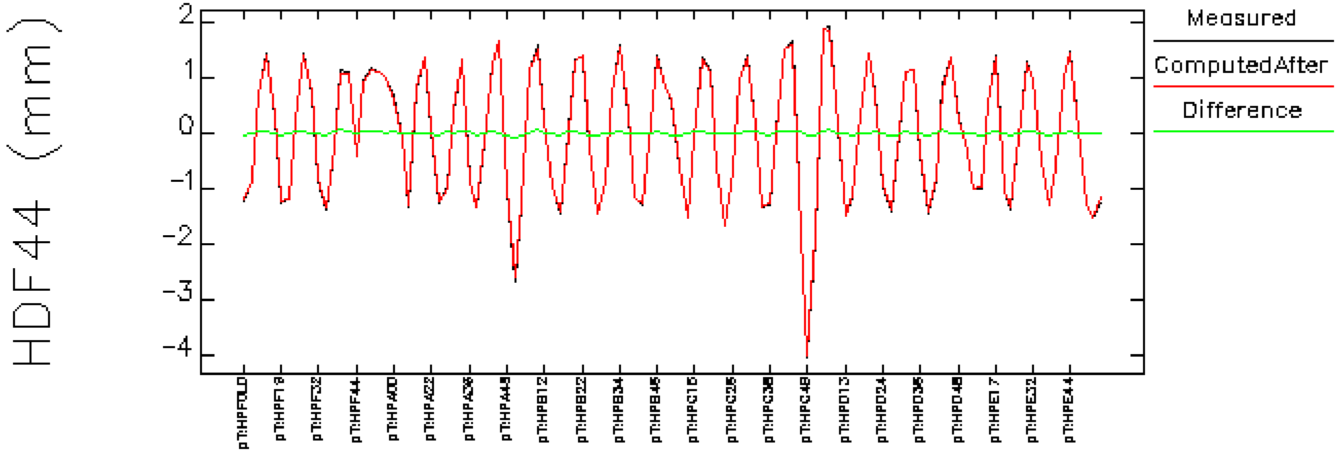
The starting point of the fit is the model resulted from differential orbit adjustment

The following variables are used:

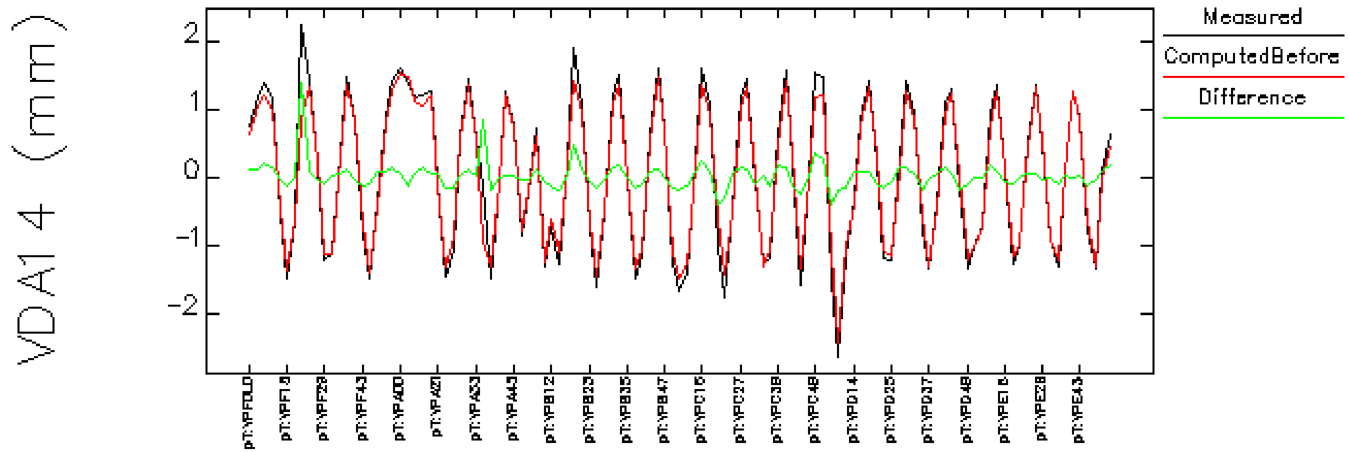
- Gradient errors in all quads
- Corrector calibration errors (≈1/3 of correctors)
- BPM gain errors in all BPMs
- Quadrupole tilts (½ of all quads)
- Corrector and BPM tilts
- Energy change due to horizontal correctors

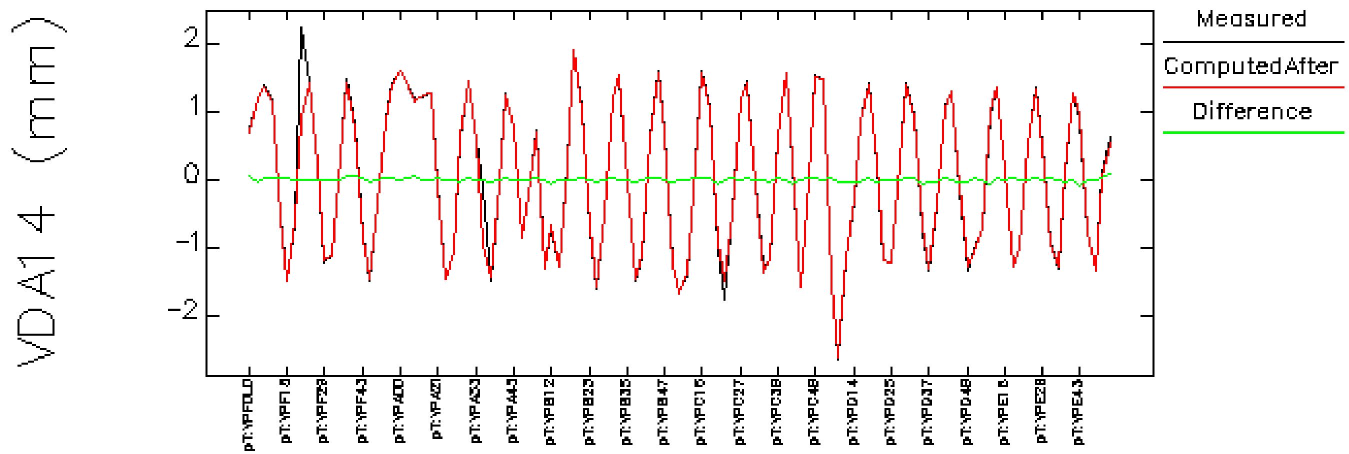
Measurements and fitting: X-X orbit



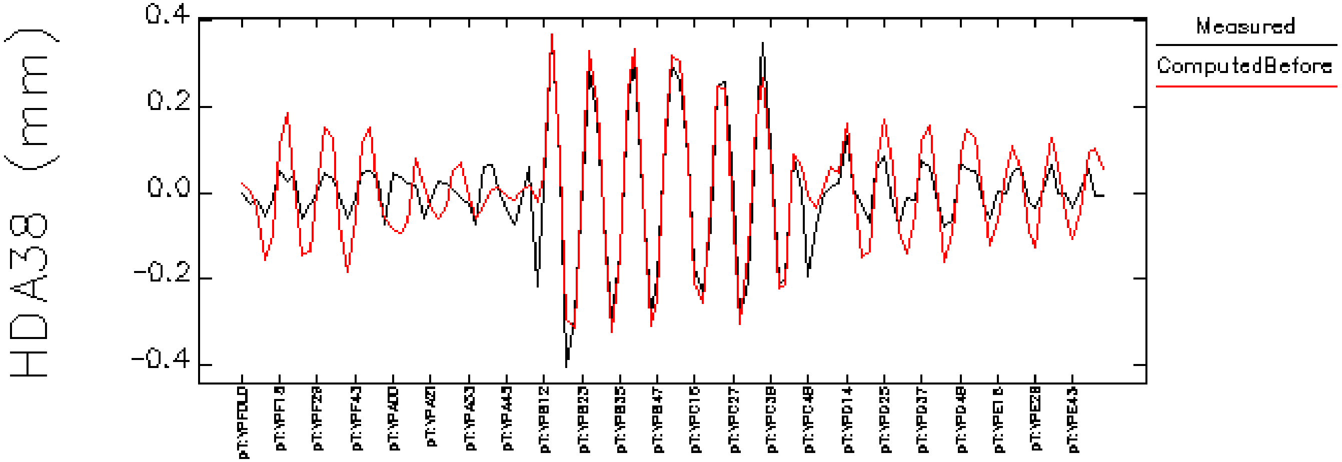


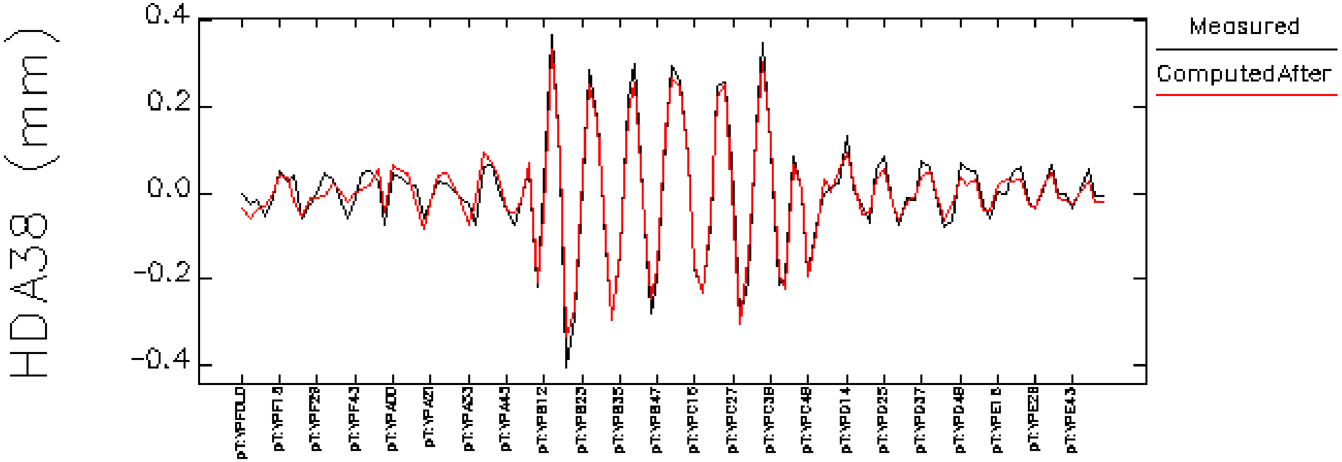
Measurements and fitting: Y-Y orbit



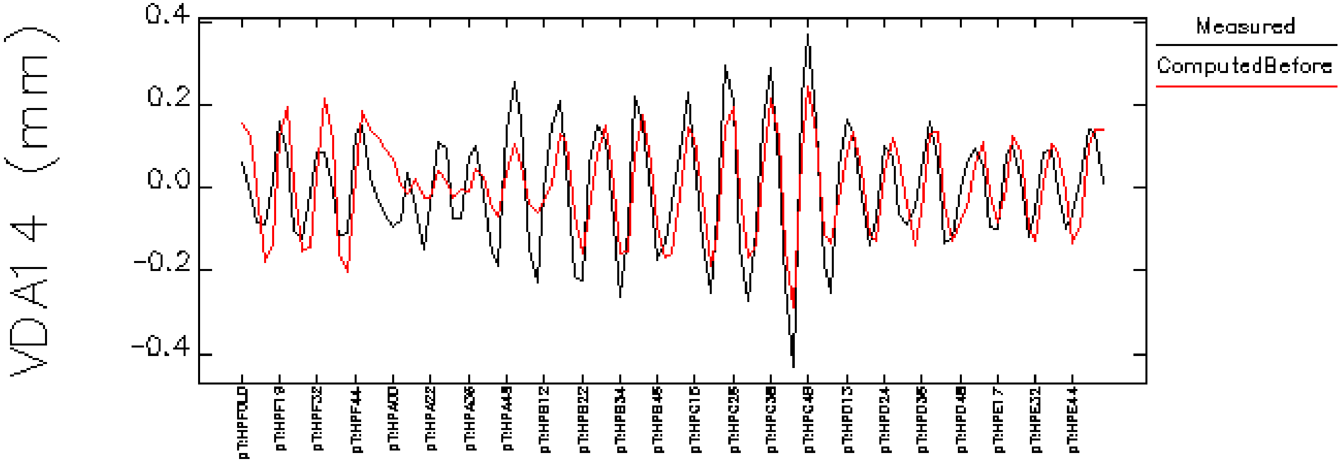


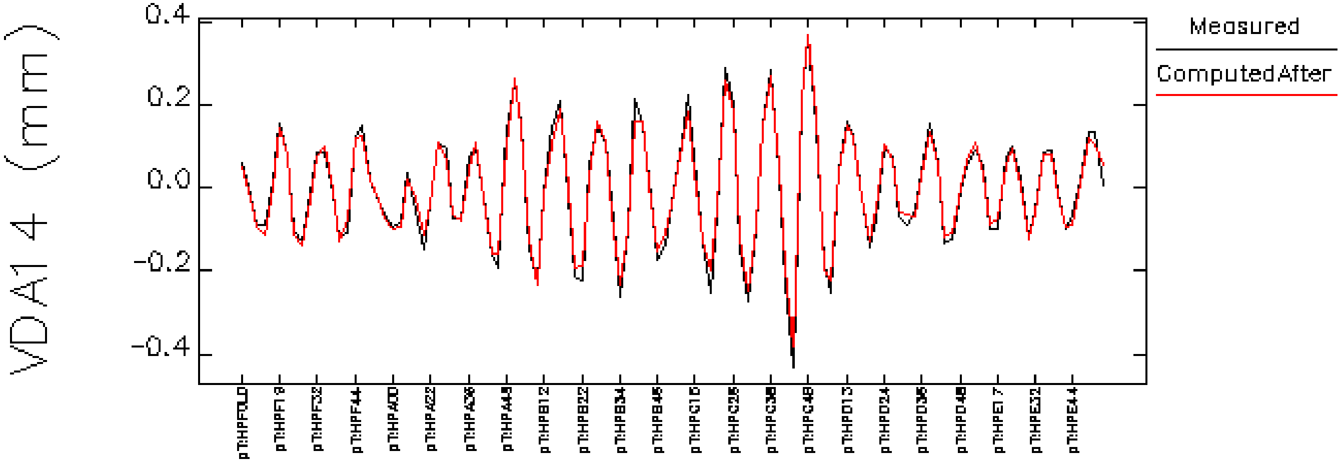
Measurements and fitting: Y-X orbit



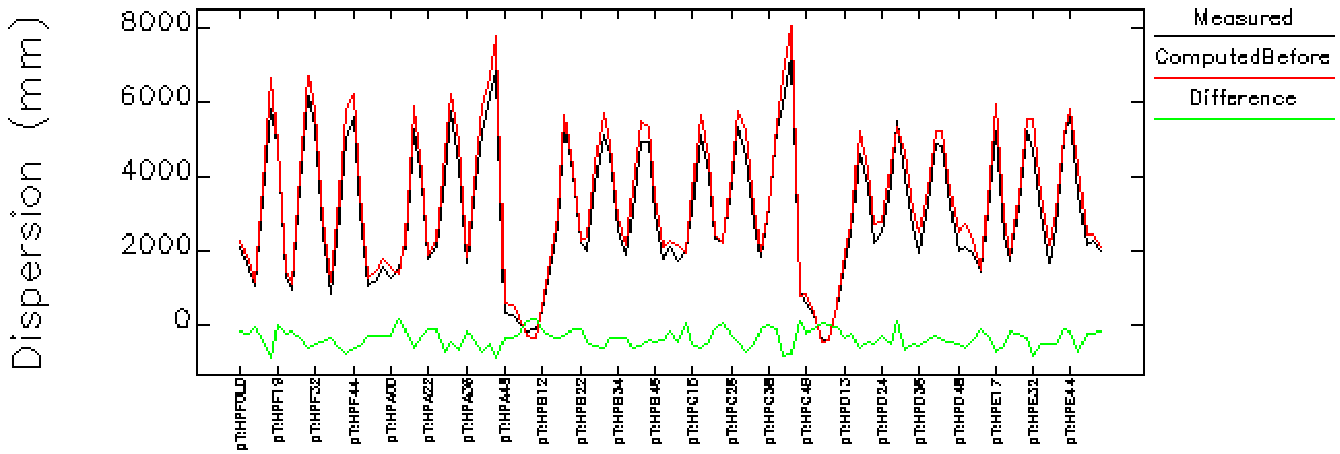


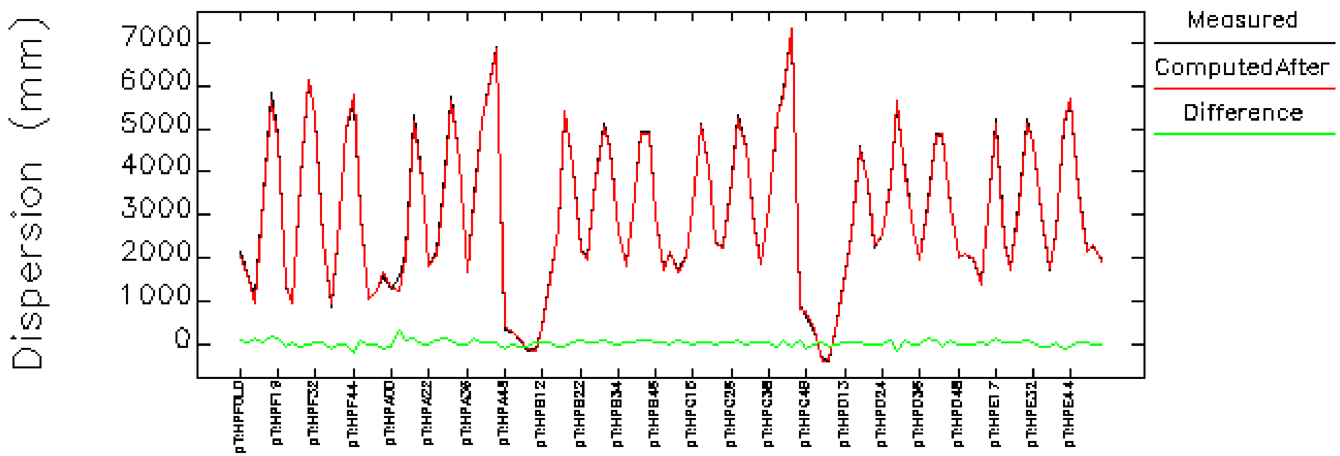
Measurements and fitting: X-Y orbit



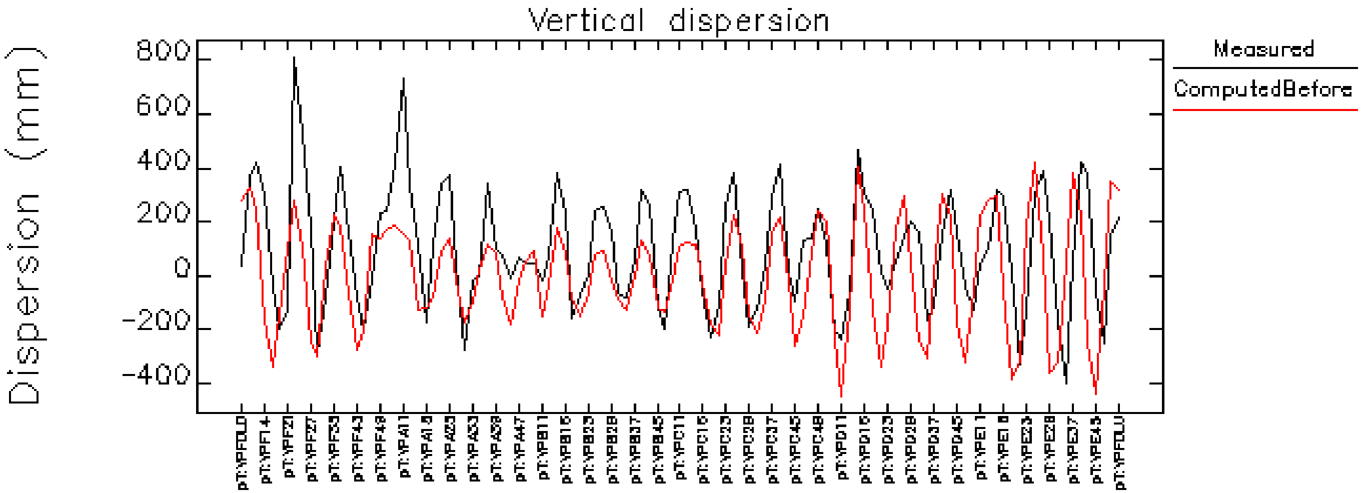


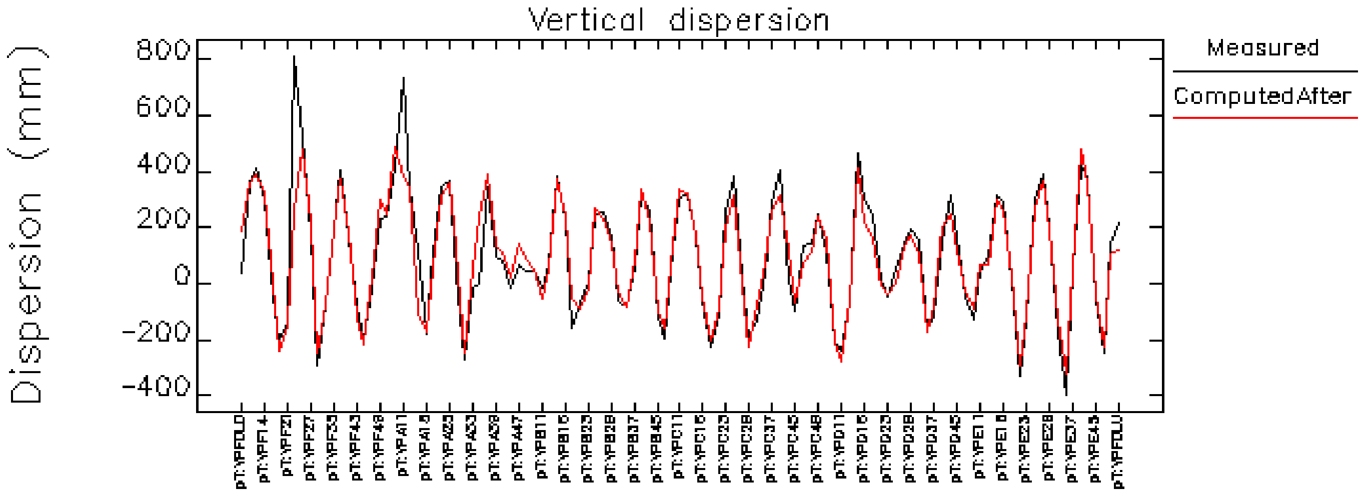
Horizontal dispersion





Vertical dispersion



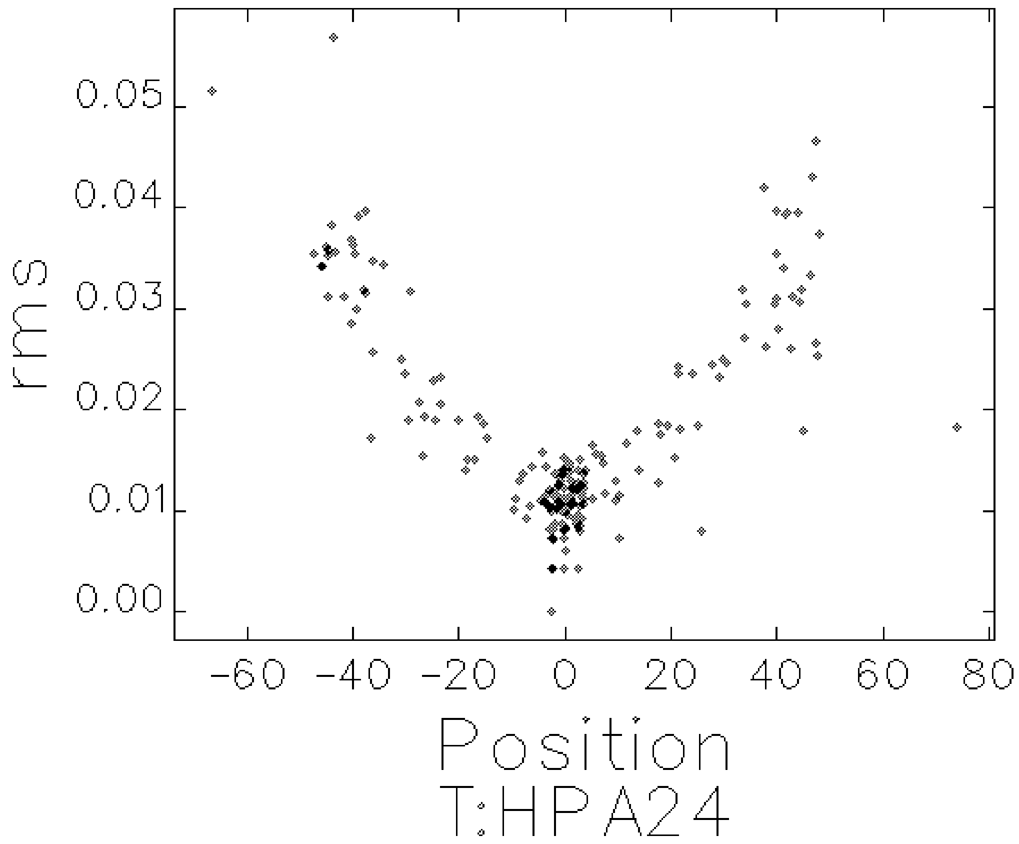


Summary of the residual rms errors after the fit:

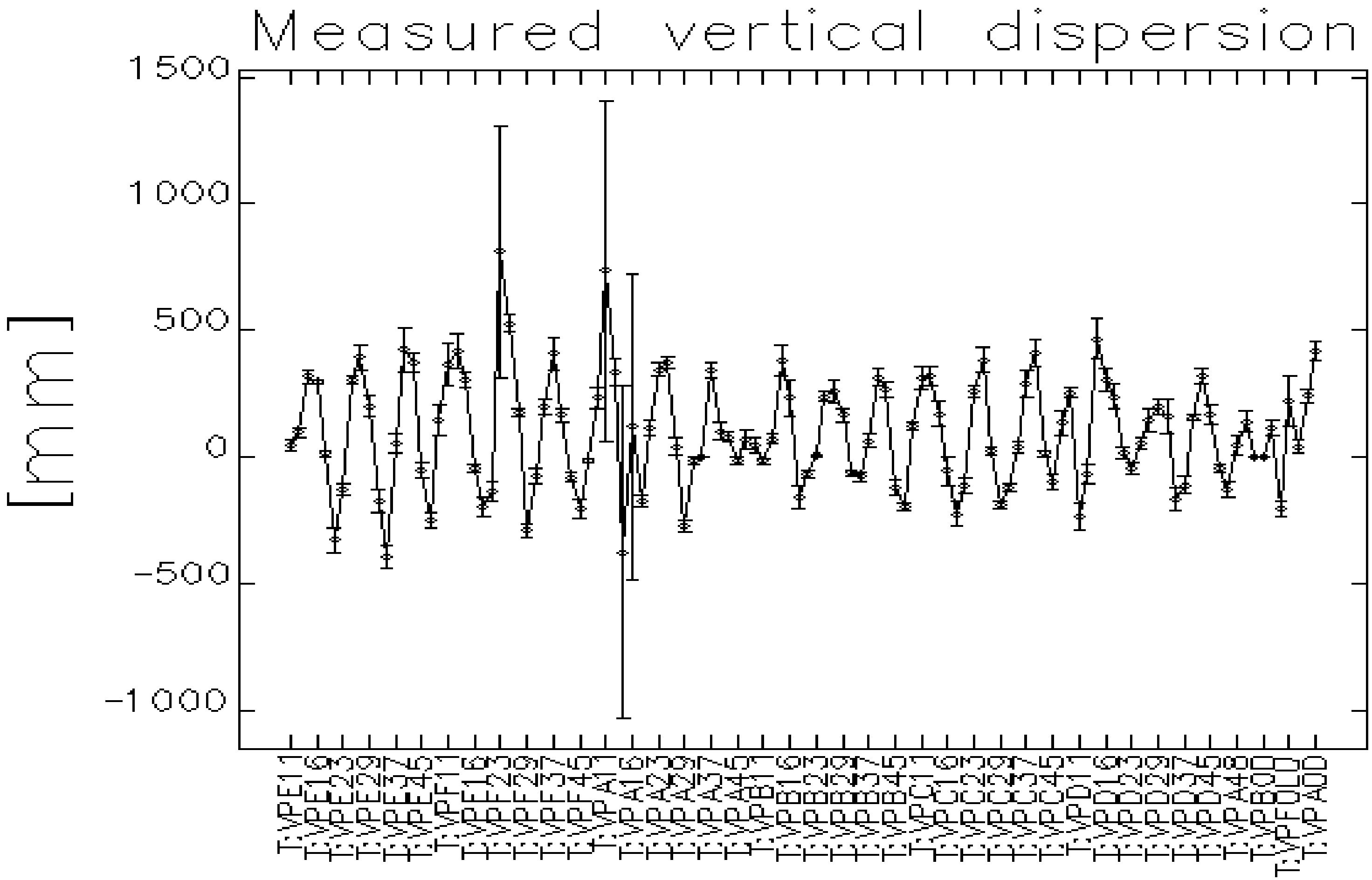
	x-x (μm)	y-x (μm)	x-y (μm)	y-y (μm)	h disp (mm)	v disp (mm)
Before	160	120	100	200	240	190
Set 1	21	19	19	24	60	52
Set 2	23	19	17	22	60	58
Set 3	24	20	19	26	68	57

Measurement accuracy (response)

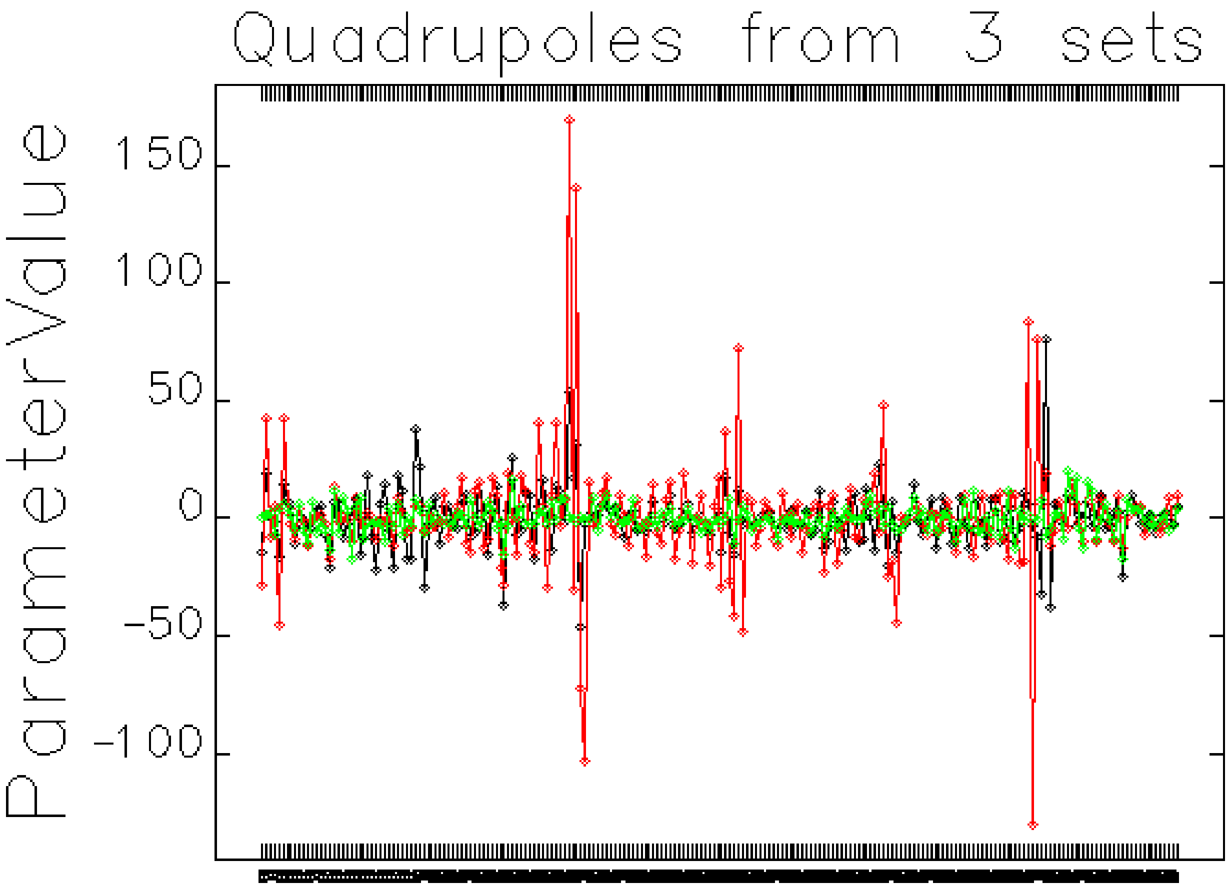
- 25 measurements on +δ and 25 measurements on -δ
- rms of the measured values are also recorded



Measurement accuracy (dispersion)



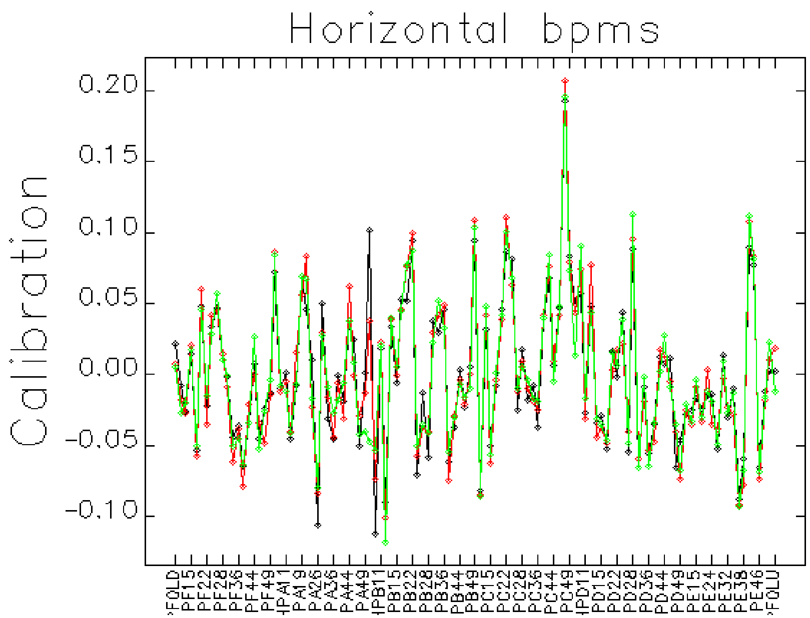
Fit variables: Quads

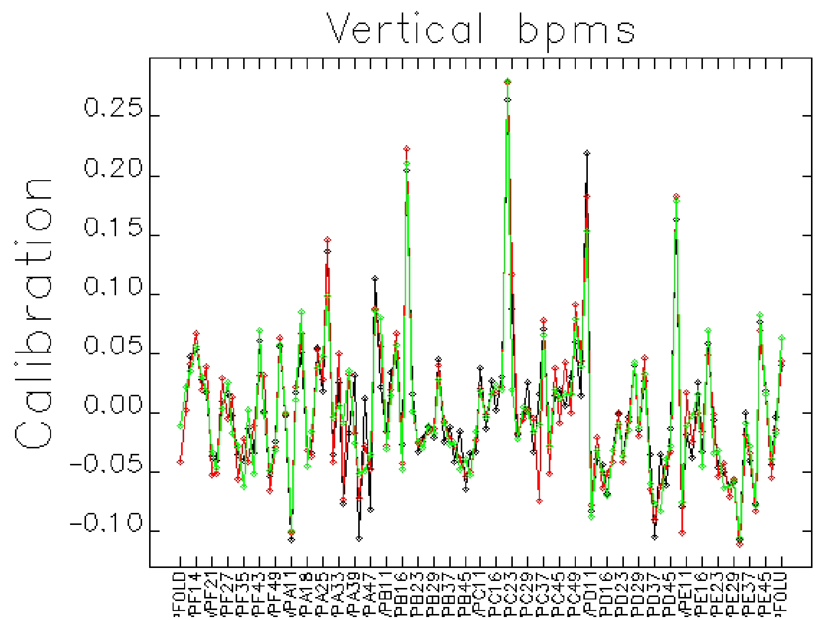


- No unique solution – too many variables

Fit variables: BPMs

- BPMs have to have the same gains

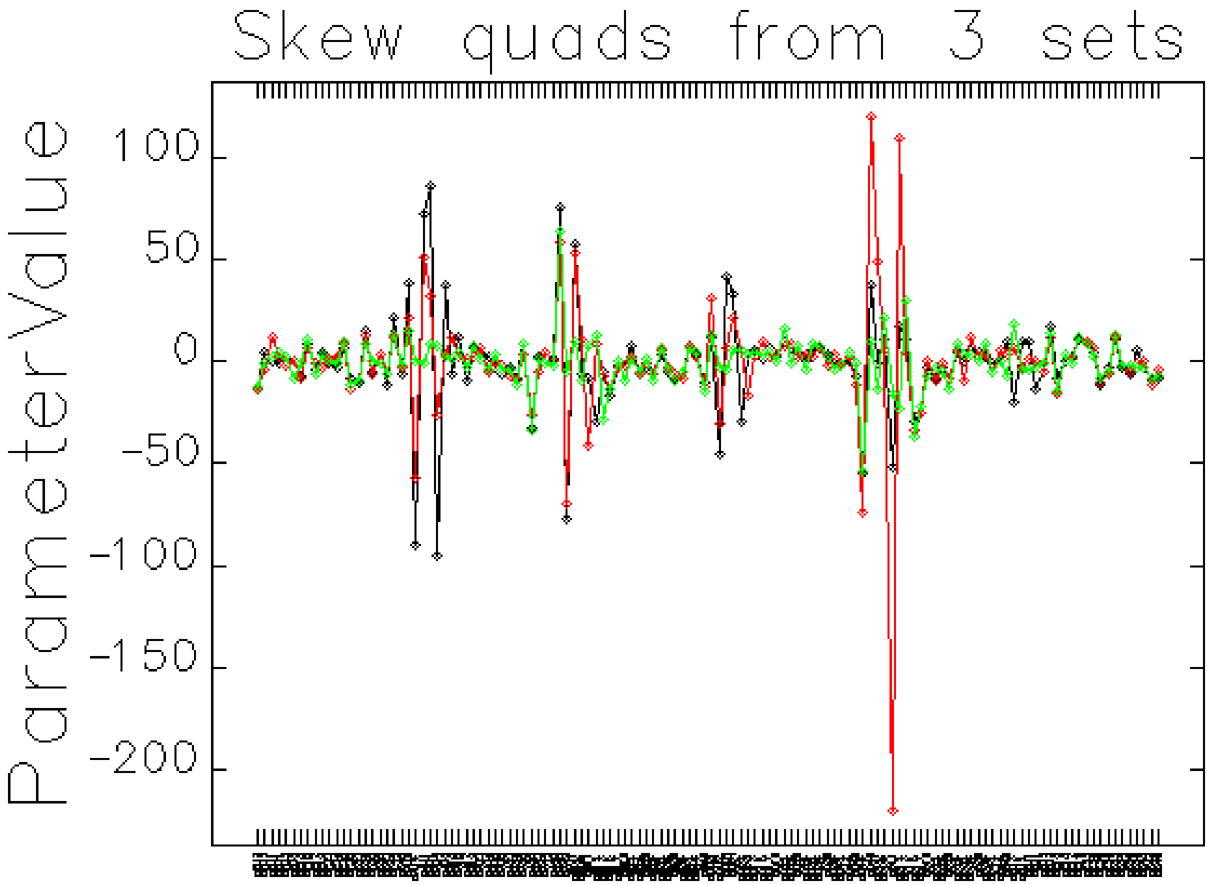




- rms gain difference is 1.7% in X and 2.1% in Y

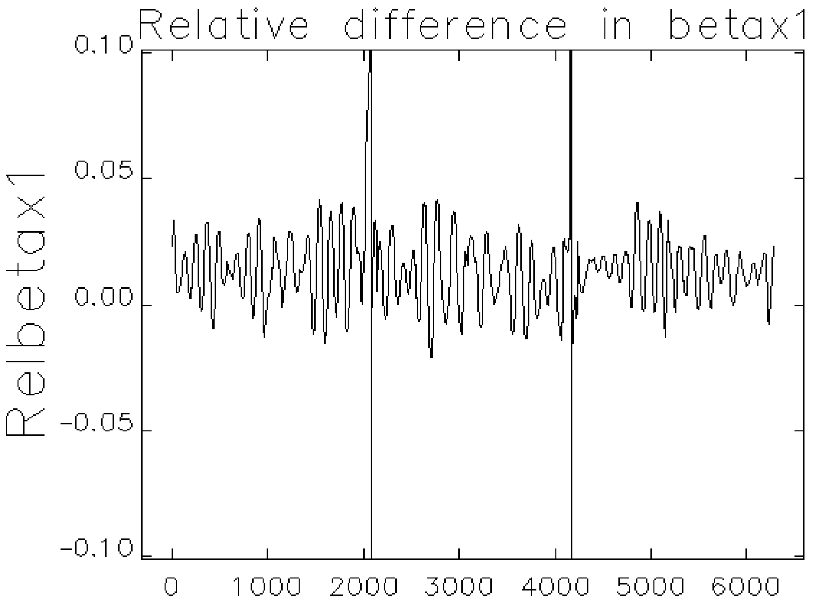
Fit variables: Skew quads

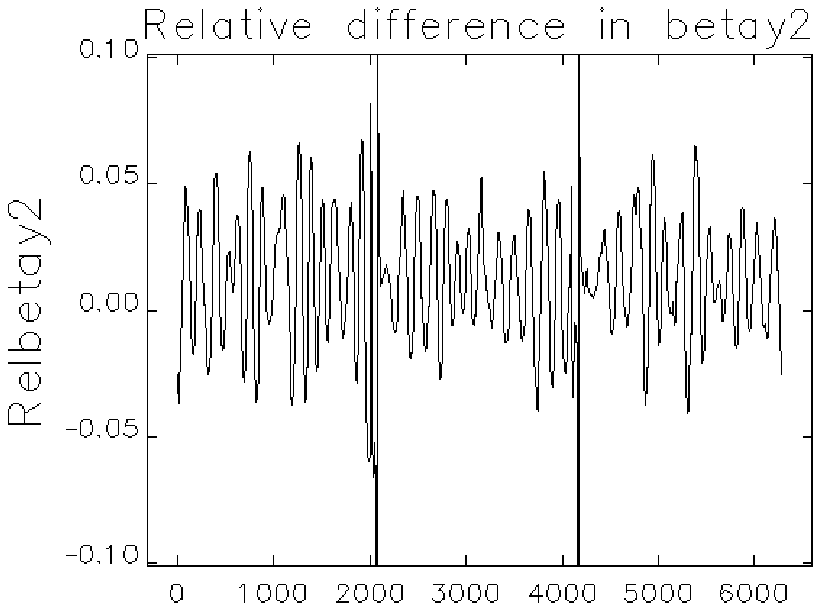
- Only ½ of all quads are used



Beta function accuracy

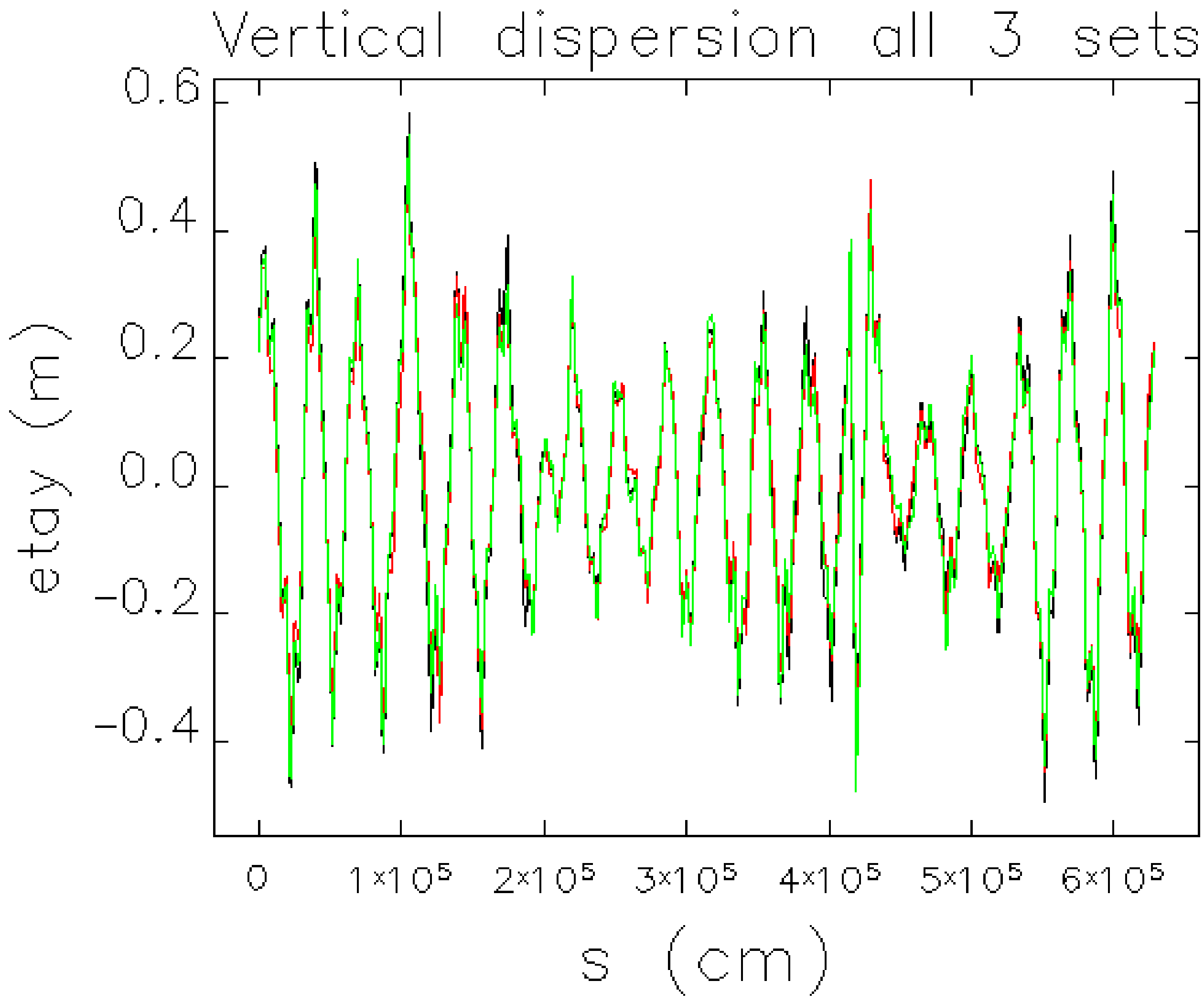
- Beta functions are computed based on each set of variables, then average beta functions are calculated
- Difference between the average beta function and one of data sets:





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

Vertical dispersion accuracy



Is the solution unique?

- **No – in terms of quadrupoles**

  (more accurate response measurements will result in less quadrupole ambiguity)

- **Yes – in terms of beta functions**

  (more accurate response measurements will result in better accuracy in beta function determination)

The best proof of correct beta function determination is the ability to make predictable changes

Measured and Computed Tuneshifts LOCO Fit

Element	dQx Meas.	dQx Model.	Difference %			dQy Meas.	dQy Model.	Difference %		
T:QE17H	0.0067	0.0070	**-4**	±	3	-0.0015	-0.0020	**-25**	±	10
T:QE19H	0.0053	0.0060	**-11**	±	3	-0.0022	-0.0025	**-13**	±	8
T:QE26H	0.0055	0.0066	**-16**	±	3	-0.0018	-0.0022	**-17**	±	9
T:QE28F	0.0071	0.0073	**-3**	±	3	-0.0015	-0.0018	**-16**	±	11
T:QF28F	0.0057	0.0059	**-3**	±	3	-0.0023	-0.0025	**-7**	±	8
T:QF32F	0.0073	0.0077	**-5**	±	3	-0.002	-0.0017	**15**	±	12
T:QE47F	0.0022	0.0024	**-8**	±	8	-0.0052	-0.0058	**-11**	±	3
T:QF33F	0.002	0.0024	**-18**	±	8	-0.0062	-0.0067	**-8**	±	3
C:B0Q2H	0.0114	0.0119	-4	±	2	0.0111	0.0112	-1	±	2
C:B0Q3H	0.0123	0.0138	-11	±	1	0.0127	0.0125	2	±	2
C:B0QT2H	0.0081	0.0091	-11	±	2	-0.0153	-0.0167	-8	±	1
C:B0QT3H	0.0075	0.0083	-9	±	2	-0.002	-0.0025	-20	±	8
C:D0Q2H	0.0117	0.0119	**-2**	±	2	0.0109	0.0108	**1**	±	2
C:D0Q3H	0.0128	0.0134	**-5**	±	1	0.0129	0.0125	**3**	±	2
C:D0QT2H	0.0085	0.0091	**-6**	±	2	-0.016	-0.0164	**-2**	±	1
C:D0QT3H	0.0078	0.0082	**-5**	±	2	-0.0025	-0.0026	**-3**	±	8

Conclusion

- Response matrix fit works and gives good results for Tevatron too
- It improves the accuracy of the existing beta function measurements
- Improving orbit measurement accuracy should further improve the fit and make the solution more unique
- APS experience shows, that over time our fit accuracy is improved by about factor of 2
- Real validation of the fit results is ability to predict consequences of lattice changes

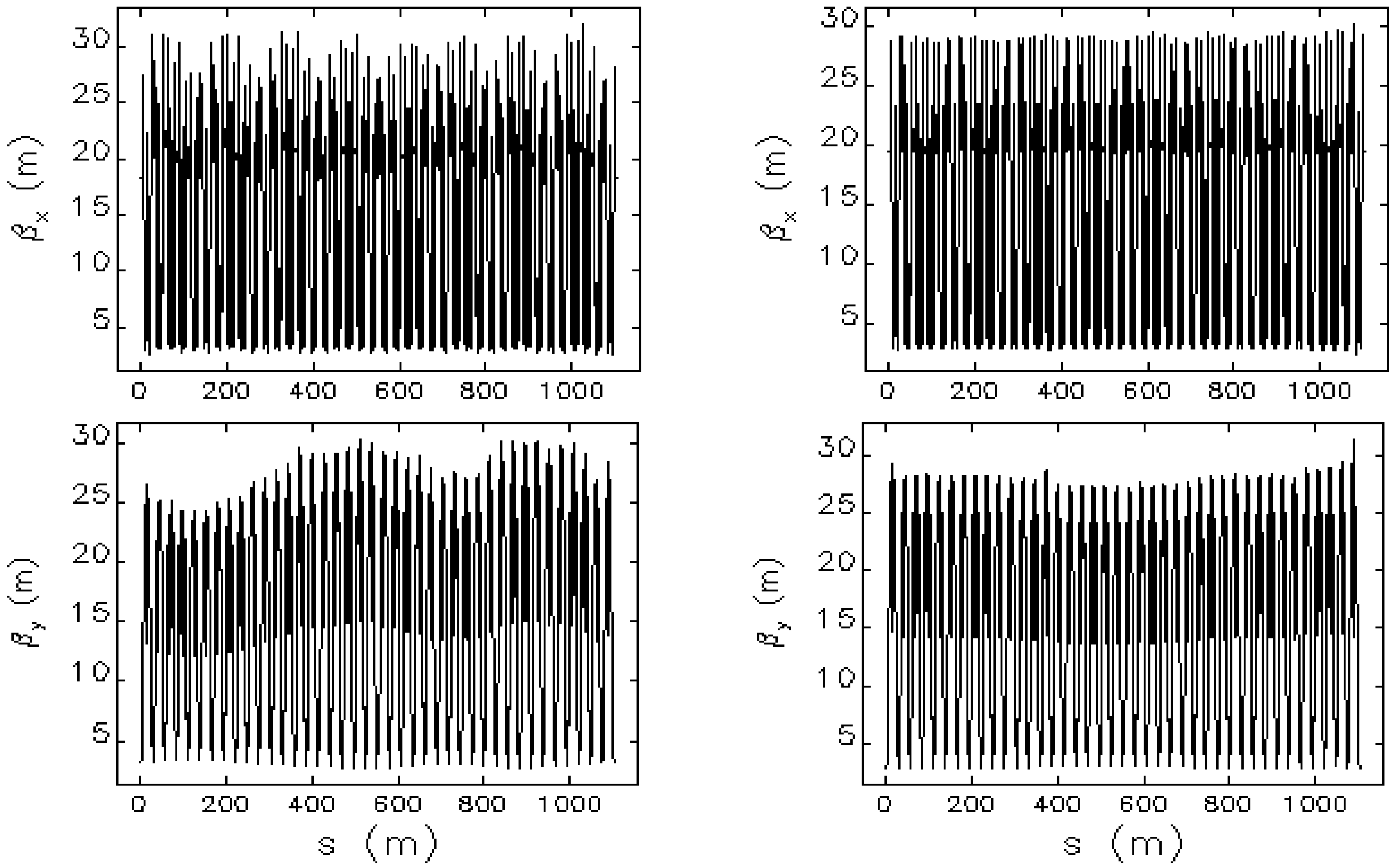
What is next?

- Beta function correction and control
- At APS we developed a program for beta function correction which looks very similar to the response matrix fit program – it minimizes the difference between measured and designed beta functions by varying all available quadrupole corrections
- Successful beta function control requires the ability to
  - Calculate correct quadrupole gradient corrections (good lattice model)
  - Transform quadrupole gradient changes into quadrupole current changes

APS beta function correction example

Before correction

After correction



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