6-DOF HIP Procedure, Constants for TrackerPointing Reprocessing, and CSC Investigations

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The situation:

- CMS needs a procedure to align all muon chambers with a precision of several hundred microns (in $r\phi$), both internally and relative to the tracker, using tens of pb^{-1}
- Only "tracker $\to$ muon" extrapolations have been shown to be able to reach that precision without external information in MC exercises
- The procedure must be robust against effects unsimulated in MC; must be thoroughly tested in data

In this talk, we

- Show how our HIP procedure satisfies this need, combining experience from CRAFT with a solid theoretical basis
- Highlight unsolved problems
- Present CRAFT alignment constants from this procedure, useable in TrackerPointing and SuperPointing re-processing
- Investigate CSC misalignments with the same procedure

- In the past few months, we have focused on CRAFT data to discover unsimulated effects, potential sources of bias
  - we found propagation errors from wrong $\vec{B}(\vec{x})$, and a way to correct for them ("two-bin method")
  - we found global z translations from tracks coming from the TEC
- Keeping these corrections, we should revisit parameter space
  - back in CSA08, we treated DT chambers as 2-D devices, measuring Δx and Δy residuals only
  - CSA08 HIP alignment limited to δ_x, δ_y, δ_{ϕ_z} parameters
  - by combining residuals within each chamber, DTs actually measure Δx, Δy, $\Delta\frac{dx}{dz}$, $\Delta\frac{dy}{dz}$
  - Ugo, Alicia, and Sara's magnetic field studies showed clear 4 mrad ϕ_y misalignments using $\Delta\frac{dx}{dz}$
  - should be incorporated into our alignment procedure!

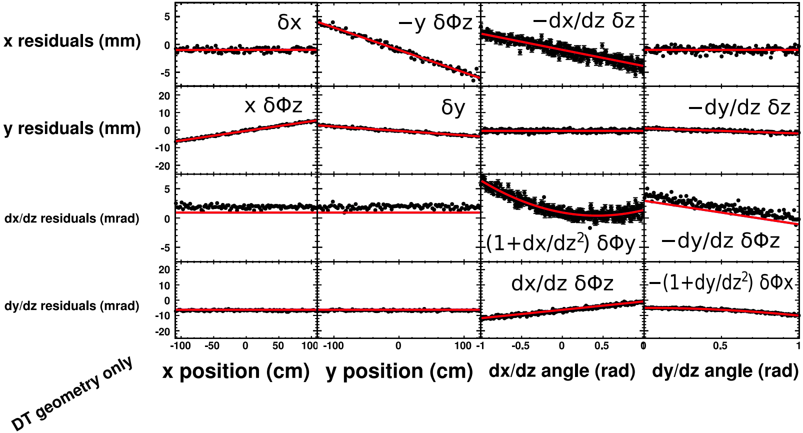
- 4 observables: $(\Delta x = \Delta x^{\text{geom}} \oplus \Delta x^{\text{meas}})$, Δy, $\Delta \frac{dx}{dz}$, $\Delta \frac{dy}{dz}$
  - small differences between track and hit (mm and mrad)
- 4 parameters: x, y, $\frac{dx}{dz}$, $\frac{dy}{dz}$
  - can be coarse (cm and rad), determined by track
- Related to 6 alignment parameters δ_x, δ_y, δ_z, δ_{ϕ_x}, δ_{ϕ_y}, δ_{ϕ_z}

$$\begin{pmatrix} \Delta x^{\text{geom}} \\ \Delta y^{\text{geom}} \\ \Delta \frac{dx}{dz}^{\text{geom}} \\ \Delta \frac{dy}{dz}^{\text{geom}} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{dx}{dz} & -y\,\frac{dx}{dz} & x\,\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\,\frac{dy}{dz} & x\,\frac{dy}{dz} & x \\ 0 & 0 & 0 & -\frac{dx}{dz}\frac{dy}{dz} & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}$$

- Top two rows are for 2-D devices like tracker (Karimaki derivatives)

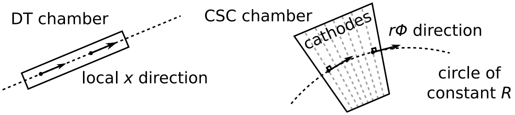
Geometry-only MC

- Thoroughly tested matrix by creating geometry-only residuals:
  - propagate track to chamber twice, before and after alignment
  - full CMSSW alignment geometry description, full propagator
  - fitter (red) always returned correct alignment in 1000's of trials



Differential geometry of CSCs

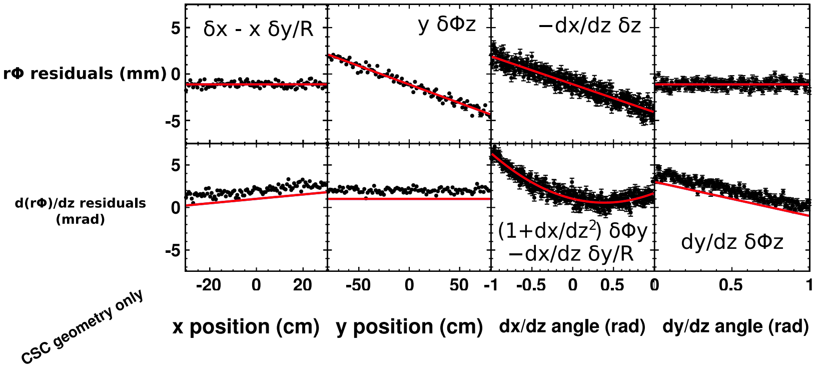
- We learned from beam-halo data that
  - CSC wires are too granular for use in alignment
  - CSC strips fan from beamline, actually measure $r\phi$, not x
- Two observables: $\Delta r\phi$ and $\Delta \frac{dr\phi}{dz}$ with sensitivity to 6 DOF because of strip angle (δ_y sensitivity is weak because it is suppressed by distance to beamline R)



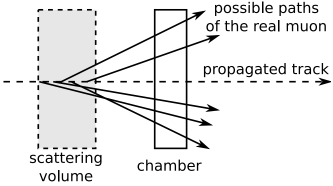
$$\begin{pmatrix} \Delta r\phi^{\text{geom}} \\ \\ \Delta \dfrac{dr\phi}{dz}^{\text{geom}} \end{pmatrix} =$$

$$\begin{pmatrix} 1 & \left[-\dfrac{x}{R} + 3\left(\dfrac{x}{R}\right)^3\right] & -\dfrac{dx}{dz} & -y\,\dfrac{dx}{dz} & x\,\dfrac{dx}{dz} & -y \\ 0 & -\dfrac{dx}{dz}/(2R) & 0 & \left[\dfrac{x}{R} - \dfrac{dx}{dz}\,\dfrac{dy}{dz}\right] & 1 + \left(\dfrac{dx}{dz}\right)^2 & -\dfrac{dy}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}$$

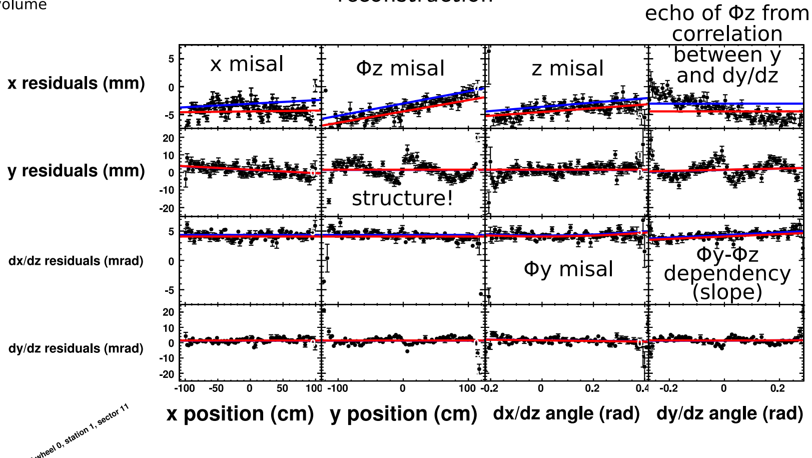
- Thoroughly tested this matrix, too (and DT station 4's 5-DOF matrix)
- Apparent gap between fit curve and data is a plotting artifact (projecting a non-linear distribution onto one axis)
- The fits converged on the true values of δ_x, δ_y, δ_z, δ_{ϕ_x}, δ_{ϕ_y}, δ_{ϕ_z}



Full MC studies

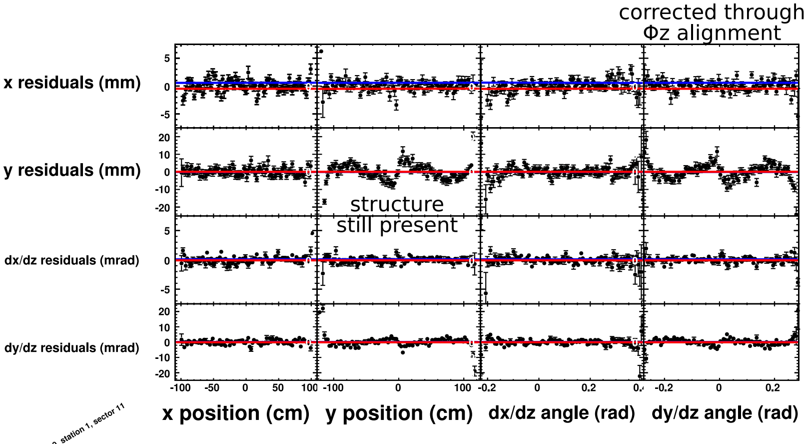


- Full MC includes known measurement effects
- Correlation between y and $\frac{dy}{dz}$ (fig on left) introduces plotting artifacts ("echo")
- Real structure in GEANT but not track reconstruction



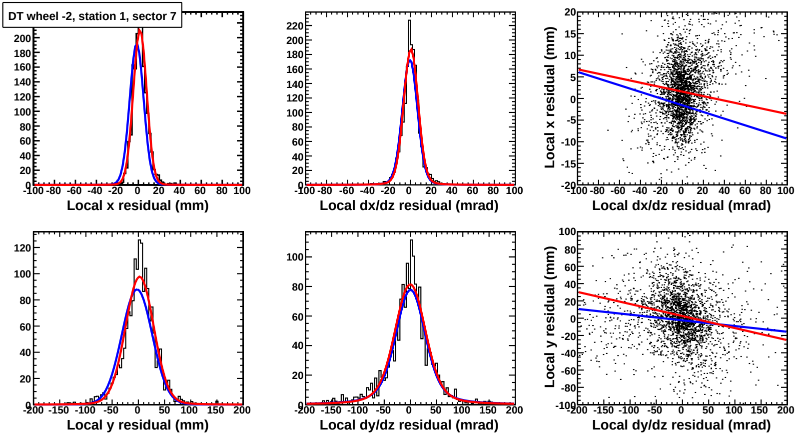
Same chamber, aligned

- "Echo" disappears because ϕ_z was corrected
- Internal DT structure is not alignable with rigid body parameters
- Red and blue are μ^+ and μ^- from two-bin method
  - corrects for dE/dx errors in addition to $\vec{B}(\vec{x})$;
    the propagator uses a different material description than GEANT



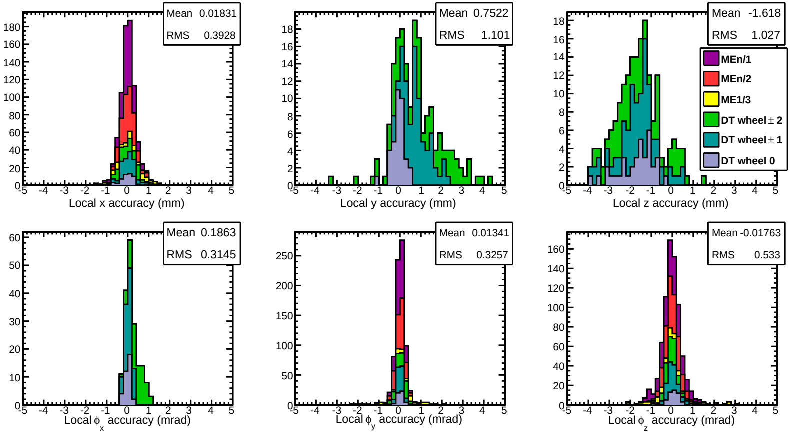
Highly descriptive fit function

- Non-Gaussian tails accounted for (red is fit to μ^+, shown in black, blue is for μ^-, not shown)
- Expected x, $\frac{dx}{dz}$ and y, $\frac{dy}{dz}$ correlations are included (semi-major axis of error ellipse shown as a line on the μ^+ scatter plot)
- This chamber is in the corner of the barrel (hardest to satisfy)

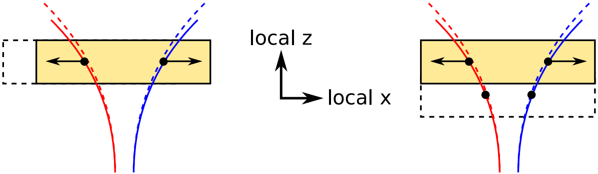


MC accuracy

- Workflow applied to 50 pb^{-1} inclusive μ MC as though it were data
- 400 μm $r\phi$ (local δ_x) resolution in *all* stations and endcap
- Radial alignment (local δ_z) biased by an effect described on next page
- Wrong radius implies wrong global z (local δ_y) except in wheel 0

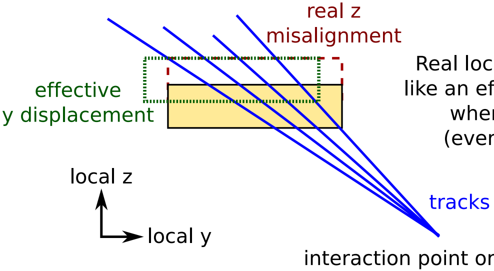


Why local δ_z is biased



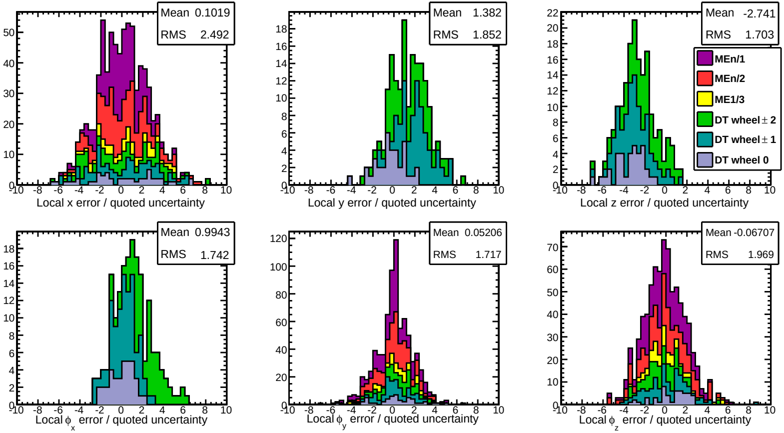
oppositely-charged tracks contribute to *x* residuals with opposite signs: two-bin method cancels their effect

oppositely-charged tracks contribute to "*z* residuals" with the same sign: two-bin method does not solve it



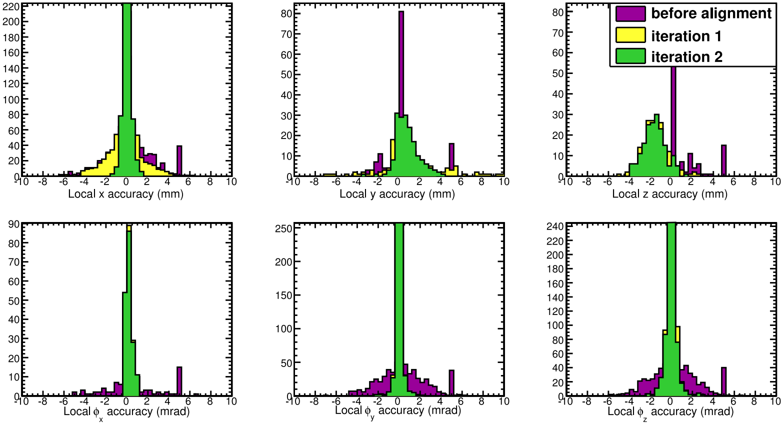
Real local z misalignment looks like an effective local y correction when tracks are inclined (everywhere but wheel 0)

- Uncertainties from Minuit's HESSE are 1.7–2.5 times too small
- Minuit's strategy=2 and MINOS yield differences in quoted uncertainties on this scale, but zero differences in the central value
  - both algorithms are also slow to compute



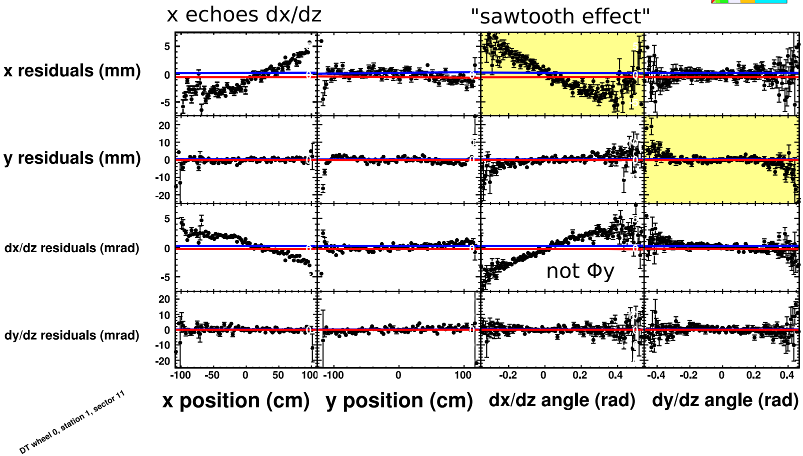
Convergence

- Most parameters converge in 1 iteration (purple to yellow)
- δ_x requires two iterations to reach final accuracy (green)
- Δx residuals are the most affected by dE/dx errors, largest $\dfrac{\delta_x(\mu^+) - \delta_x(\mu^-)}{2}$ (two-bin correction is applied outside of fitter)



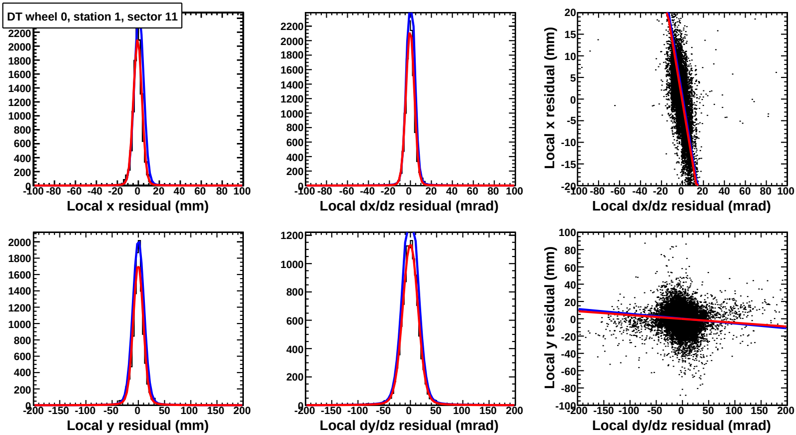
- From this point onward, all plots will show CRAFT data
- First we will consider a 6-DOF alignment of DTs
- Then we will restrict local δ_z and some δ_y to obtain a production-quality alignment for TrackerPointing and SuperPointing re-processing
- Then we will use the same framework to investigate CSC misalignments

A typical DT (after alignment)



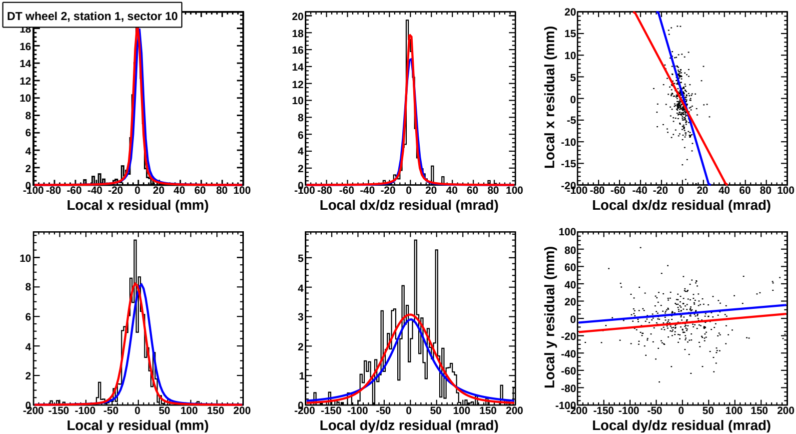
- Known "sawtooth effect" is linearly independent of δ_z (which affects both yellow plots) and δ_{ϕ_y} (which is symmetric in $\frac{dx}{dz}$)
- All correlations seen here agree with the single-chamber study
- All of these arguments were made before, but never in one plot

- Reminder: red curves fit black μ^+ data,
  blue curves fit μ^- data, not shown
- Lines are the semi-major axes of error ellipses



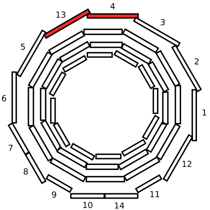
Extreme corner of barrel

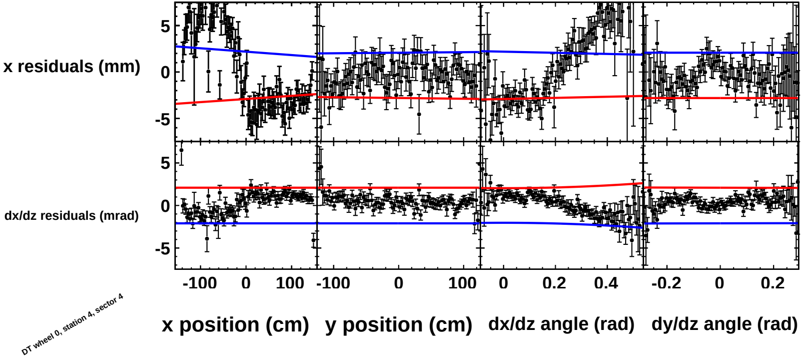
- Another example, this one is from wheel 2, station 1 where non-Gaussianess of residuals is most extreme
- Note μ^+/μ^- splitting in Δy residuals, rather than Δx: this is also the only part of the barrel with a radial $\vec{B}(\vec{x})$



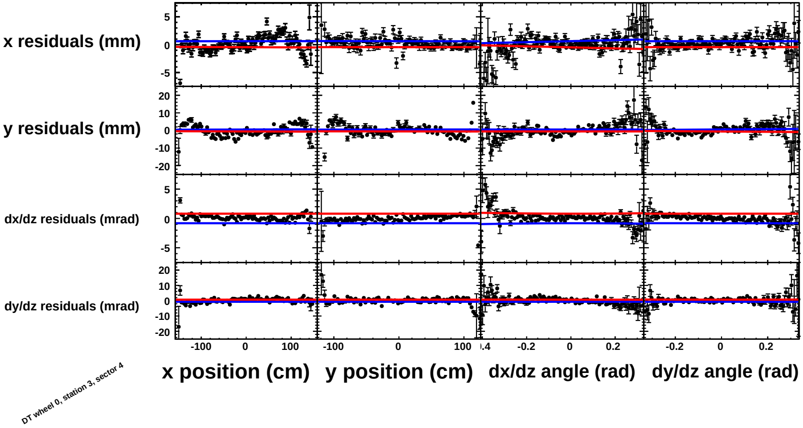
Station 4 structure

- Some station 4 chambers show the sawtooth effect
- But sectors 4 and 13 also have a sharp step laterally down the center ($x = 0$)
- Gap between μ^+ and μ^- is due to $\vec{B}(\vec{x})$ errors



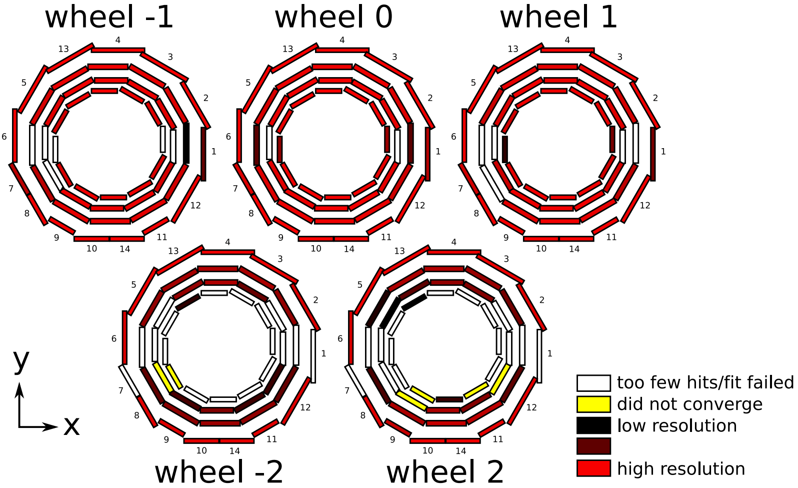


- The degree of sawtooth varies from chamber to chamber



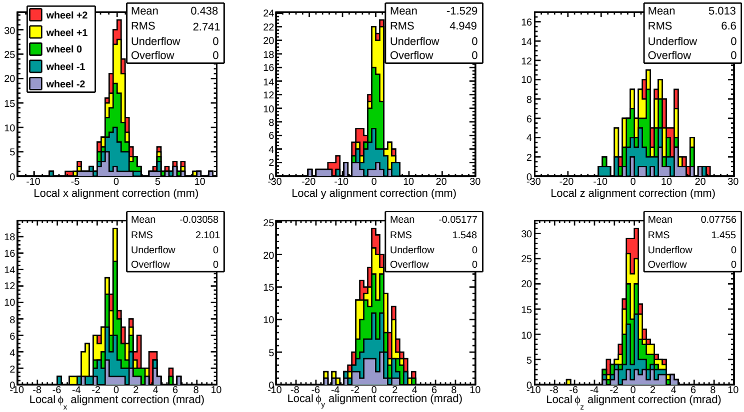
Which chambers were aligned

- Pattern of convergence and resolution follow cosmic ray statistics
- "Convergence" = no change in parameters after 4 iterations bigger than 0.1 mm, 0.1 mrad



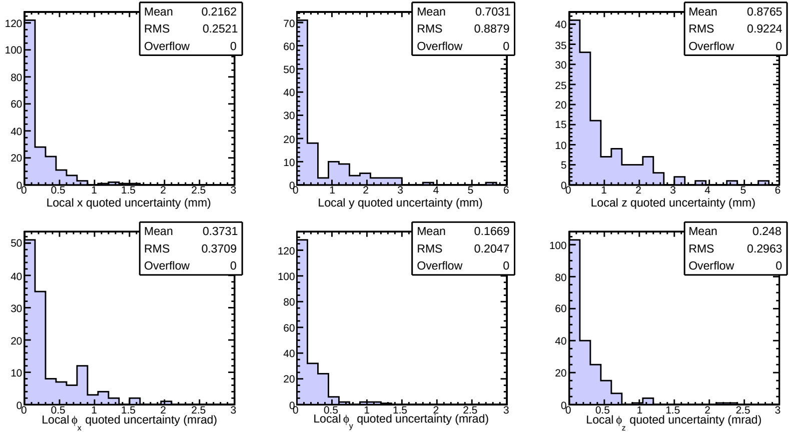
Alignment corrections

- Changes in parameters, with respect to the previous geometry
- Wide spread in local δ_z, and hence δ_y differences (will be fixed later)
- No evidence for a coherent rotation of any wheel, though individual chambers shifted by local $\delta_x = 2$ mm ($\delta_{\text{“}\phi\text{”}} = 0.5$ mrad)
- Note the large δ_{ϕ_x}, δ_{ϕ_y} corrections (new with this alignment)



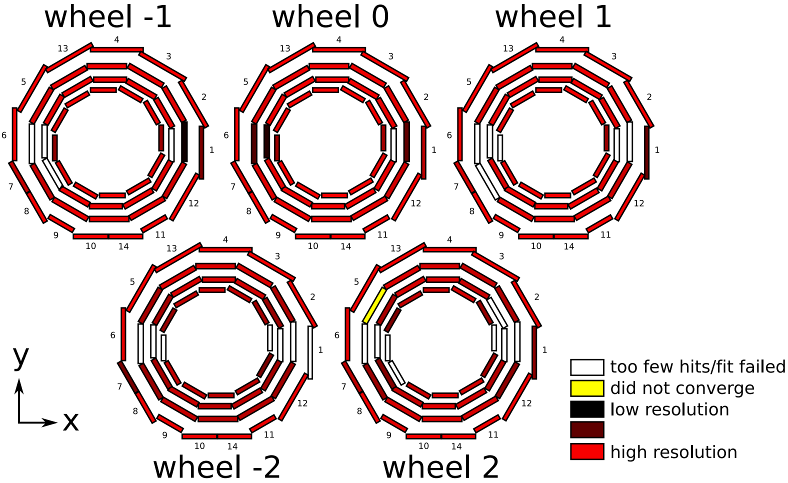
Quoted uncertainties

- Most are below 0.3 mm, 0.3 mrad
- But remember underestimation in MC by a factor of 2

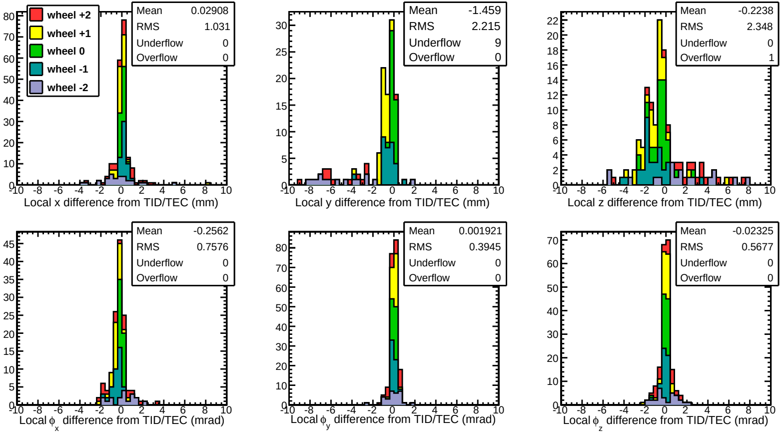


Study: allow TID/TEC

- Exclusion of TID/TEC tracker hits was based on a November study
- What changes if we repeat the analysis without excluding TID/TEC?
- For one thing, we reach more chambers in wheels ± 2...

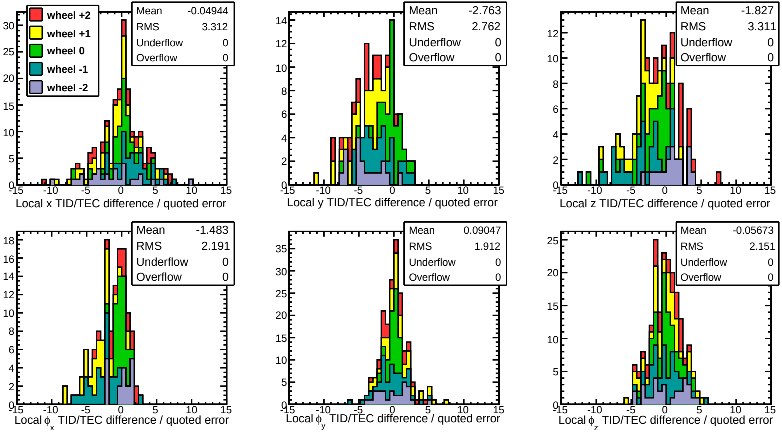


- How do individual parameters change for individual chambers? (database comparison: TID/TEC excluded minus TID/TEC allowed)
- Biggest differences in wheels ± 2, mostly in local δ_y/δ_z...

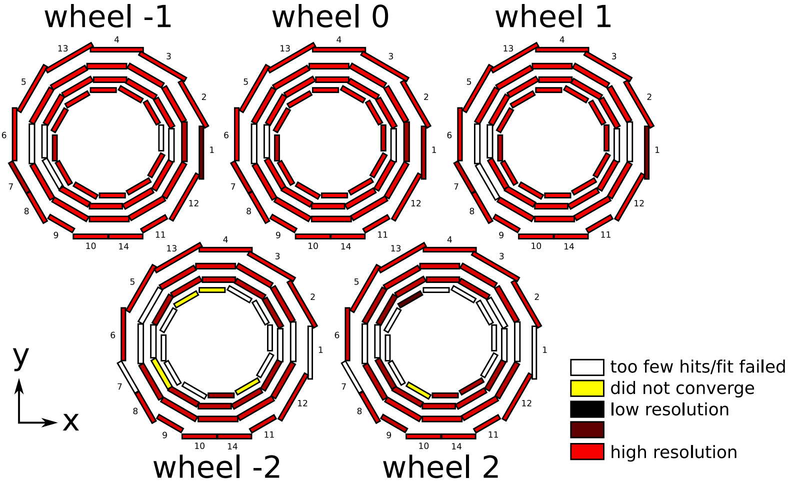


Study: allow TID/TEC

- What is the significance of those changes?
  (difference over quoted uncertainty)
- Large differences in wheel ± 2 local δ_y/δ_z was due to low statistics
- We will still exclude TID/TEC anyway
  (better for future studies of TID/TEC from the muon system)

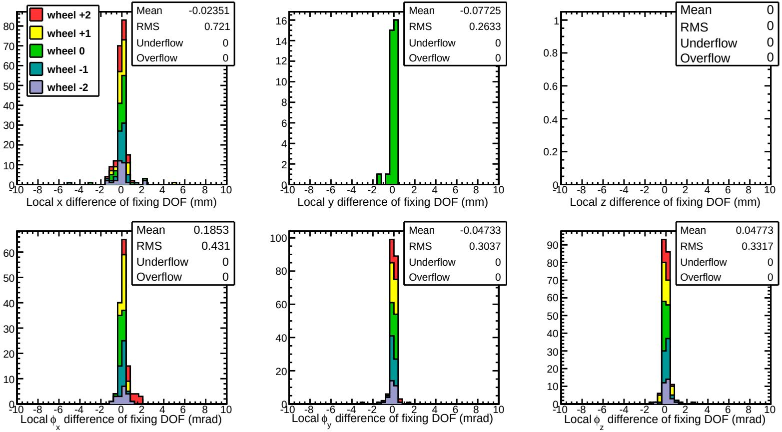


- Fix local $\delta_z = 0$ for all chambers
- Fix local $\delta_y = 0$ for all chambers except wheel 0
- Align only δ_x, δ_{ϕ_y}, δ_{ϕ_z} for station 4 because it's a 2-D device



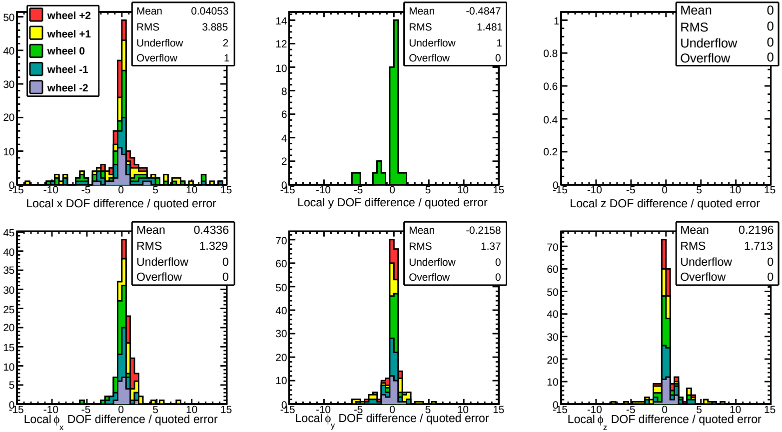
Effect of $\delta_y = \delta_z = 0$

- Does that adversely affect other alignment paramters? (database comparison: restricted DOF minus 6-DOF)
- No, within 0.7 mm and 0.4 mrad



Significance of $\delta_y = \delta_z = 0$

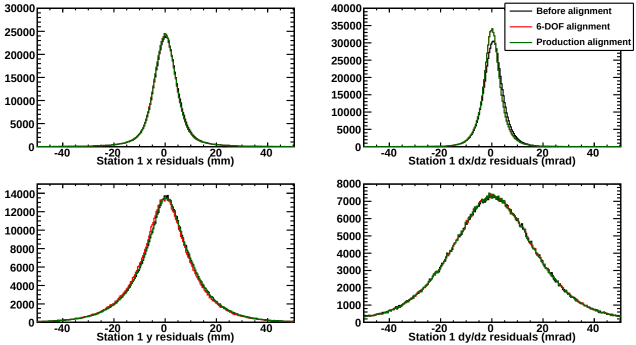
- Check the same difference divided by quoted uncertainties
- Most δ_x within one sigma, some differ by as much as 10 sigma
- By comparison with the previous page, those sigmas $\ll 1$ mm



Validation

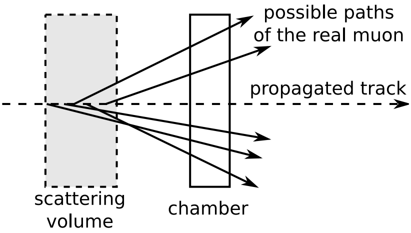
by which we mean checking that the procedure is valid: "sanity checks"

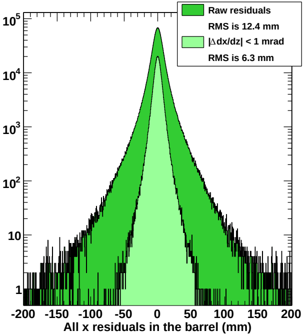
- Residuals distributions should get narrower, because we moved chambers to center their residuals distributions
- A summary must fit on 1–2 slides (unlike 100's of "map plots")
- But raw residuals are too wide to see the new corrections
  - e.g. δ_x corrections hidden under 7 mm Δx
  - exception: new δ_{ϕ_y} corrections can be seen in 5 mrad $\Delta \frac{dx}{dz}$



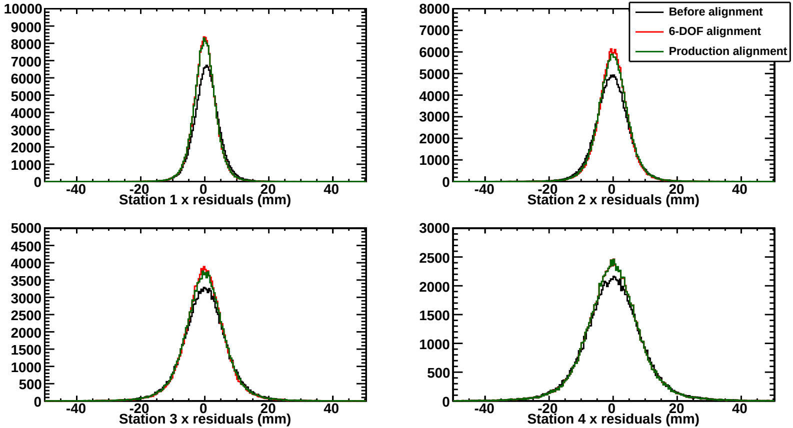
- To see systematic alignment effects on residuals, we need to reduce the track-by-track variance
- Cutting on p_T reduces tails, but not the core width
- Instead, note that Δx and $\Delta \frac{dx}{dz}$ are correlated by physics:
  - small $|\Delta \frac{dx}{dz}|$ indicates that a track was measured well and did not scatter, and its *measurement* is independent of Δx
  - Δx with $|\Delta \frac{dx}{dz}| < 1$ mrad is highly sensitive to δ_x misalignments

Using the familiar correlation between Δx and $\Delta \frac{dx}{dz}$:



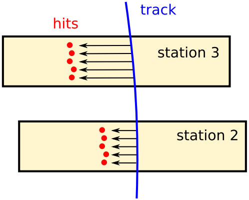


- With the track variance a factor of 2 narrower, we can now see the new δ_x corrections
- But this validation only checks that we got what we asked for: global residuals closer to 0



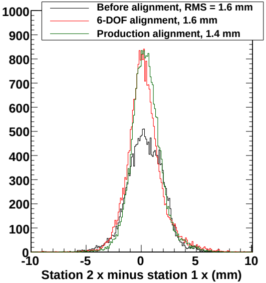
Verification

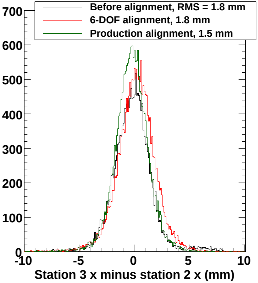
by which we mean making sure that the aligned positions are *true*

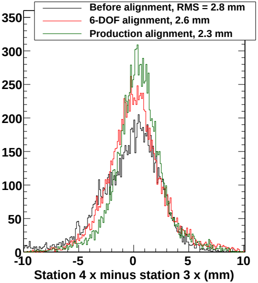


- We aligned the global position of each chamber individually
- If we look at differences in residuals, we will see relative alignment within sectors: new information that we did not use as a constraint (also higher precision)

- With $|\Delta \frac{dx}{dz}| < 1$ mrad cut, dramatic improvement in $\Delta x_{i+1} - \Delta x_i$
- Best results with Production, even though 6-DOF optimizes residuals!

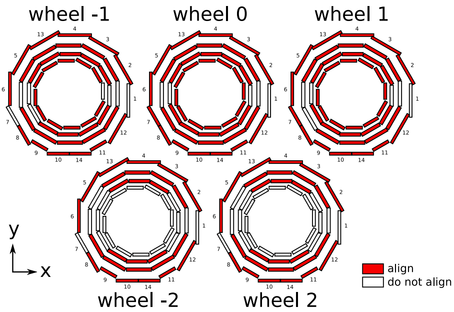






Proposal for TrackerPointing

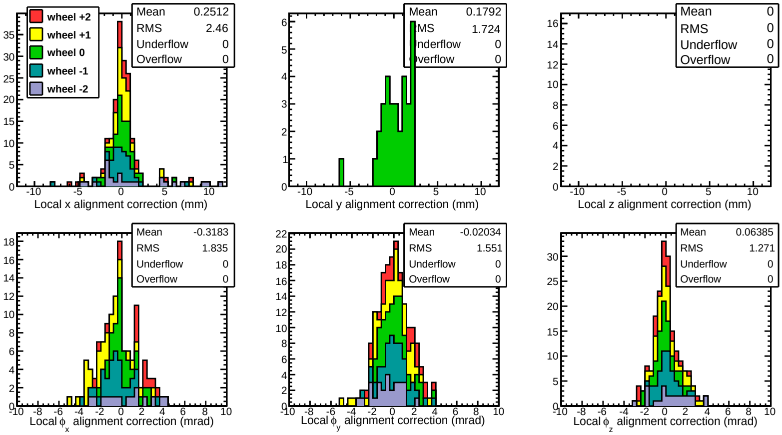
- From the Production alignment ($\delta_z = 0$ for all chambers, $\delta_y = 0$ in all wheels except 0, $\delta_y = \delta_{\phi_x} = 0$ for station 4),
- Align only converged chambers with quoted uncertainties σ_x and $\sigma_y < 1$ mm, σ_{ϕ_x}, σ_{ϕ_y}, and $\sigma_{\phi_z} < 1$ mrad
- Uses latest tracker alignment, APEs; independent of TID/TEC
- Contains track-based internal DT alignment (negotiable)



- Chambers selected by the above shown at left
- APE $= 0$ for aligned, 1000 cm for not aligned for TrackerPointing + SuperPointing reprocessing *only*
- Distributions of aligned positions on next page

Proposal for TrackerPointing

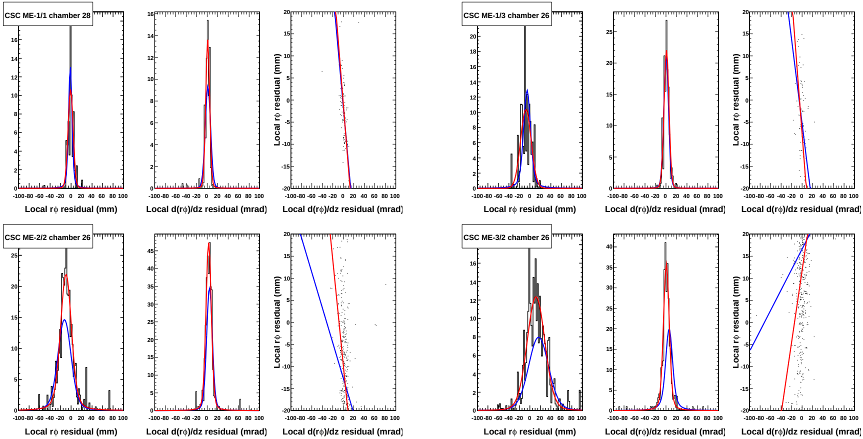
- Changes in parameter values between CRAFT_ALL_V11 and proposal for TrackerPointing + SuperPointing skim reprocessing



/afs/cern.ch/cms/CAF/CMSALCA/ALCA_MUONALIGN/SWAlignment/MuonAlignmentFromReference/

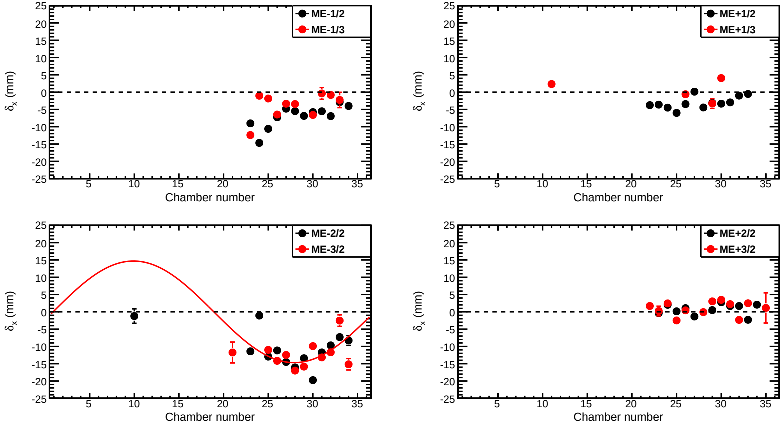
CMSSW_2_2_7/src/final_production_alignment.db

- Use same alignment framework to look for large CSC displacements using globalMuons
- Fix all parameters except δ_x due to low statistics



Measured CSC $r\phi$ offsets

- Temporarily missing data from tops of rings (probably using wrong globalMuon collection: 1-leg rather than 2-leg)
- Large (10 mm) collective misalignments on minus endcap
- ME−2/2 agrees with ME−3/2, indicating disk misalignment



Conclusions

- Techniques learned from first CRAFT alignment incorporated into a highly-constrained fit for 6 DOF
  - Matrix thoroughly tested, with and without measurement error
  - "Sawtooth" is linearly independent of alignment parameters
  - $\vec{B}(\vec{x})$ and dE/dx uncertainty is degenerate with local δ_z
- More detailed plotting reveals internal DT structures in residuals
- Fixing $\delta_z = 0$ yields a more true alignment, independently verified by residuals differences
  - residuals differences indicate agreement between global and local-within-sectors alignments
  - it would be very interesting to see a local-within-stations cross-check! (DT analogy of CSC Overlaps procedure)
- Proposed constants for TrackerPointing + SuperPointing reprocessing
  - important updates in some parameters (especially ϕ_y)
- Started investigations into CSC disk misalignment

local parameters relative to ideal in mm and mrad

Wheel -2 station 2 sector 3 x -0.858923 y -0.0720215 z 2.80667 ϕ_x 3.96011 ϕ_y -5.33354 ϕ_z 2.23048
Wheel -2 station 2 sector 4 x 1.07277 y -0.0067139 z 5.97687 ϕ_x -0.73094 ϕ_y -2.1354 ϕ_z -0.22626
Wheel -2 station 2 sector 5 x 1.24524 y -0.907593 z 2.79189 ϕ_x -0.85864 ϕ_y 1.42262 ϕ_z -0.04094
Wheel -2 station 2 sector 9 x 2.99256 y -1.89636 z 1.76863 ϕ_x 0.54153 ϕ_y -0.9352 ϕ_z -1.05429
Wheel -2 station 2 sector 10 x 6.99802 y -1.06567 z 3.29407 ϕ_x -0.34119 ϕ_y 0.16928 ϕ_z 0.87478
Wheel -2 station 2 sector 11 x 11.3105 y -1.88721 z 2.62662 ϕ_x -2.30027 ϕ_y 0.23883 ϕ_z 1.08601
Wheel -2 station 3 sector 2 x 6.46888 y -1.74744 z -2.80803 ϕ_x 1.16527 ϕ_y -4.82761 ϕ_z 1.73633
Wheel -2 station 3 sector 3 x 3.75496 y -1.37756 z 1.95508 ϕ_x 1.6912 ϕ_y -3.45107 ϕ_z 2.58493
Wheel -2 station 3 sector 4 x 1.68022 y 3.79272 z 4.63501 ϕ_x 3.05403 ϕ_y -0.94105 ϕ_z 1.89042
Wheel -2 station 3 sector 5 x 0.54414 y 1.81335 z 2.62827 ϕ_x 4.73392 ϕ_y 1.37383 ϕ_z 0.64016
Wheel -2 station 3 sector 8 x 3.61984 y -2.89368 z -2.41129 ϕ_x -1.65342 ϕ_y -3.91324 ϕ_z -0.02912
Wheel -2 station 3 sector 9 x 5.68894 y -1.99646 z 3.0322 ϕ_x -2.74787 ϕ_y -1.26053 ϕ_z -1.43302
Wheel -2 station 3 sector 10 x 6.74927 y 4.88831 z 4.22668 ϕ_x 2.00942 ϕ_y -0.69467 ϕ_z 0.95828
Wheel -2 station 3 sector 11 x 8.60024 y -1.57837 z 1.75396 ϕ_x 0.3483 ϕ_y 1.73684 ϕ_z -0.28396
Wheel -2 station 3 sector 12 x 8.05289 y -1.49963 z -4.65297 ϕ_x 2.11138 ϕ_y 3.22851 ϕ_z 0.13574
Wheel -2 station 4 sector 2 x 9.72444 y -0.511475 z -5.18802 ϕ_x 0.51305 ϕ_y -3.40401 ϕ_z 2.43357
Wheel -2 station 4 sector 3 x 6.2483 y -1.19995 z -0.0136648 ϕ_x 0.41225 ϕ_y -3.34996 ϕ_z 1.30165
Wheel -2 station 4 sector 4 x 7.0369 y -3.94897 z 4.81384 ϕ_x 0.6729 ϕ_y -2.31353 ϕ_z 0.74123
Wheel -2 station 4 sector 5 x -0.524401 y -0.548096 z 0.5297 ϕ_x 0.04806 ϕ_y 1.22018 ϕ_z -0.61708
Wheel -2 station 4 sector 6 x -0.894128 y -1.74072 z -4.65677 ϕ_x 0.19692 ϕ_y 1.44744 ϕ_z -0.85629
Wheel -2 station 4 sector 8 x 3.43594 y -2.00562 z -2.39533 ϕ_x -0.66752 ϕ_y -1.73741 ϕ_z -2.39205
Wheel -2 station 4 sector 9 x 2.57994 y -2.99194 z 3.18522 ϕ_x -0.67428 ϕ_y -2.53263 ϕ_z -0.14228
Wheel -2 station 4 sector 10 x 6.97891 y -3.17749 z 5.5719 ϕ_x -0.42322 ϕ_y 1.23173 ϕ_z -1.87454
Wheel -2 station 4 sector 11 x 6.34256 y -1.29089 z 2.13981 ϕ_x 0.98053 ϕ_y 1.26424 ϕ_z 1.2012
Wheel -2 station 4 sector 12 x 6.41509 y -0.737305 z -3.53497 ϕ_x 0.32122 ϕ_y 1.88682 ϕ_z 1.25792
Wheel -2 station 4 sector 13 x 1.78986 y -2.51648 z 4.39148 ϕ_x -0.15294 ϕ_y 1.69593 ϕ_z -2.43774
Wheel -2 station 4 sector 14 x 7.5322 y -1.58081 z 4.97314 ϕ_x 0.32806 ϕ_y 0.92582 ϕ_z 0.93819
Wheel -1 station 1 sector 2 x 0.851181 y -1.26953 z -3.52266 ϕ_x 2.13109 ϕ_y -4.03852 ϕ_z -0.18744
Wheel -1 station 1 sector 3 x 1.69849 y -0.015564 z 2.10756 ϕ_x -0.15521 ϕ_y -3.26974 ϕ_z -0.33618
Wheel -1 station 1 sector 4 x 1.23409 y 1.93726 z 4.89441 ϕ_x 2.22465 ϕ_y 0.14531 ϕ_z -0.13689
Wheel -1 station 1 sector 5 x 3.94354 y 1.77826 z 1.78128 ϕ_x -0.7791 ϕ_y 3.34266 ϕ_z -2.14837
Wheel -1 station 1 sector 6 x 1.06901 y -1.24908 z -2.93099 ϕ_x -0.02112 ϕ_y 5.47121 ϕ_z 0.09473

Proposed constants

local parameters relative to ideal in mm and mrad

Wheel -1 station 1 sector 7 x 2.58514 y 1.96991 z -4.85504 ϕ_x -1.14318 ϕ_y 1.7261 ϕ_z -0.6607
Wheel -1 station 1 sector 8 x 1.14522 y 1.38611 z -3.36188 ϕ_x 0.41927 ϕ_y -1.93849 ϕ_z -2.0445
Wheel -1 station 1 sector 9 x 0.684911 y 0.18158 z 1.8441 ϕ_x 0.10399 ϕ_y -1.81308 ϕ_z -1.31284
Wheel -1 station 1 sector 10 x 2.42973 y 0.242615 z 5.30792 ϕ_x 1.67733 ϕ_y 1.11036 ϕ_z 0.23085
Wheel -1 station 1 sector 11 x 6.65886 y -2.7948 z 0.944794 ϕ_x -0.93816 ϕ_y 2.54819 ϕ_z 0.53715
Wheel -1 station 1 sector 12 x 6.07349 y 0.561218 z -3.90522 ϕ_x 0.98034 ϕ_y 1.33822 ϕ_z 1.40098
Wheel -1 station 2 sector 2 x 1.27805 y 0.910645 z -4.53837 ϕ_x -1.33999 ϕ_y -4.87714 ϕ_z 2.26321
Wheel -1 station 2 sector 3 x 2.00527 y -0.811462 z 0.78703 ϕ_x -4.21608 ϕ_y -3.29525 ϕ_z -0.1112
Wheel -1 station 2 sector 4 x 0.812187 y 1.0321 z 3.75244 ϕ_x -1.88002 ϕ_y -1.2377 ϕ_z -0.03208
Wheel -1 station 2 sector 5 x 0.984457 y -0.551148 z 1.61113 ϕ_x -1.91649 ϕ_y 2.71483 ϕ_z 0.40509
Wheel -1 station 2 sector 6 x -0.0057912 y -4.08295 z -3.85105 ϕ_x -2.83985 ϕ_y 4.13584 ϕ_z -1.16917
Wheel -1 station 2 sector 9 x 0.232805 y -1.28174 z 0.813811 ϕ_x -2.69568 ϕ_y -1.32692 ϕ_z -0.30736
Wheel -1 station 2 sector 10 x 2.01275 y -0.827332 z 4.96704 ϕ_x -1.04391 ϕ_y 1.34498 ϕ_z -0.16109
Wheel -1 station 2 sector 11 x 5.8136 y -4.02344 z 1.29748 ϕ_x -2.6418 ϕ_y 2.68797 ϕ_z -0.19522
Wheel -1 station 2 sector 12 x 4.37855 y -1.26282 z -4.59131 ϕ_x -2.01649 ϕ_y 2.35011 ϕ_z 0.83574
Wheel -1 station 3 sector 2 x 5.14254 y 0.671692 z -4.35886 ϕ_x -0.05725 ϕ_y -2.38851 ϕ_z -0.65212
Wheel -1 station 3 sector 3 x 3.83586 y -1.32812 z 1.21315 ϕ_x -0.47087 ϕ_y -2.42001 ϕ_z -0.02429
Wheel -1 station 3 sector 4 x 1.80733 y 2.37885 z 2.8186 ϕ_x 3.57361 ϕ_y -0.78949 ϕ_z 0.019
Wheel -1 station 3 sector 5 x -0.630927 y 0.423889 z 1.61594 ϕ_x -0.39316 ϕ_y 1.69806 ϕ_z 1.55537
Wheel -1 station 3 sector 6 x 1.29171 y -2.85614 z -3.89869 ϕ_x -0.32836 ϕ_y 3.4787 ϕ_z 0.21418
Wheel -1 station 3 sector 8 x 2.07733 y -0.0100708 z -3.71398 ϕ_x 0.80849 ϕ_y -2.47492 ϕ_z -1.88791
Wheel -1 station 3 sector 9 x 1.00799 y -1.3443 z 2.31782 ϕ_x -0.75375 ϕ_y -2.88205 ϕ_z -1.00432
Wheel -1 station 3 sector 10 x 1.24508 y 2.82745 z 5.31433 ϕ_x 0.89432 ϕ_y 0.09742 ϕ_z 0.38588
Wheel -1 station 3 sector 11 x 3.80897 y -2.79053 z 1.81034 ϕ_x -0.80268 ϕ_y 1.85814 ϕ_z -0.45142
Wheel -1 station 3 sector 12 x 3.38981 y -1.48163 z -4.60363 ϕ_x -0.12083 ϕ_y 2.18909 ϕ_z 1.23862
Wheel -1 station 4 sector 2 x 6.8624 y -0.81543 z -5.06709 ϕ_x -0.34134 ϕ_y -0.74481 ϕ_z -1.7839
Wheel -1 station 4 sector 3 x 7.76991 y -0.256043 z -1.25512 ϕ_x -0.39782 ϕ_y -2.53869 ϕ_z 1.02988
Wheel -1 station 4 sector 4 x 4.2952 y 0.0436401 z 1.88538 ϕ_x 0.19289 ϕ_y -0.54105 ϕ_z 2.08803
Wheel -1 station 4 sector 5 x -1.02414 y -0.666199 z 1.04657 ϕ_x 1.0394 ϕ_y 1.99977 ϕ_z -1.31932
Wheel -1 station 4 sector 6 x -4.2617 y -1.4621 z -4.54662 ϕ_x -0.08118 ϕ_y 2.46445 ϕ_z -2.27855
Wheel -1 station 4 sector 8 x -0.0615974 y -2.54364 z -3.70044 ϕ_x -1.0352 ϕ_y -0.18402 ϕ_z -1.04923
Wheel -1 station 4 sector 9 x 0.331674 y 0.214539 z 1.68138 ϕ_x -1.04893 ϕ_y -1.34946 ϕ_z -0.92164

local parameters relative to ideal in mm and mrad

Wheel -1 station 4 sector 10 x -1.40884 y 1.0553 z 4.22424 ϕ_x -0.9327 ϕ_y 0.3924 ϕ_z 0.43537
Wheel -1 station 4 sector 11 x 3.61883 y -0.733948 z 2.13226 ϕ_x 0.27058 ϕ_y 2.7407 ϕ_z 0.24152
Wheel -1 station 4 sector 12 x 2.03445 y -1.96838 z -2.3232 ϕ_x -0.03391 ϕ_y -0.02276 ϕ_z 2.8036
Wheel -1 station 4 sector 13 x 1.65863 y -1.06781 z 2.9071 ϕ_x -0.22036 ϕ_y 1.35953 ϕ_z 0.87837
Wheel -1 station 4 sector 14 x 1.1969 y 1.59119 z 5.27954 ϕ_x 0.18895 ϕ_y -0.24893 ϕ_z 1.64755
Wheel 0 station 1 sector 1 x 4.31149 y -0.244357 z -8.48053 ϕ_x 0.99252 ϕ_y 0.91948 ϕ_z -0.65497
Wheel 0 station 1 sector 2 x 1.11441 y 3.33206 z -2.19542 ϕ_x 1.28161 ϕ_y 6.25448 ϕ_z 1.59838
Wheel 0 station 1 sector 3 x 0.79053 y 2.52988 z 5.85166 ϕ_x -0.44511 ϕ_y 4.41379 ϕ_z -0.9004
Wheel 0 station 1 sector 4 x 0.852737 y -5.83083 z 8.48877 ϕ_x 0.563 ϕ_y 1.04017 ϕ_z 0.13207
Wheel 0 station 1 sector 5 x 2.21733 y 1.29413 z 5.03072 ϕ_x 0.81484 ϕ_y 4.1282 ϕ_z -0.56564
Wheel 0 station 1 sector 6 x -1.11174 y 0.996257 z -4.33983 ϕ_x -0.72122 ϕ_y -4.44425 ϕ_z -1.24608
Wheel 0 station 1 sector 7 x -0.7127 y -1.87665 z -8.55133 ϕ_x -1.14117 ϕ_y -0.93658 ϕ_z -2.47521
Wheel 0 station 1 sector 8 x -3.43098 y -2.5747 z -6.654 ϕ_x 0.03518 ϕ_y -3.81879 ϕ_z -2.29433
Wheel 0 station 1 sector 9 x -2.2637 y -1.40539 z 3.211 ϕ_x 0.44219 ϕ_y -4.0168 ϕ_z -0.92233
Wheel 0 station 1 sector 10 x -3.33191 y 3.90959 z 5.45807 ϕ_x 1.33823 ϕ_y 1.06359 ϕ_z -1.20489
Wheel 0 station 1 sector 11 x -6.04528 y 2.21034 z 3.50357 ϕ_x 0.37176 ϕ_y -4.15583 ϕ_z -0.38046
Wheel 0 station 1 sector 12 x 10.62 y -1.01235 z -7.82866 ϕ_x -0.69138 ϕ_y 3.98762 ϕ_z -1.12286
Wheel 0 station 2 sector 2 x 1.62126 y 2.28219 z -4.72858 ϕ_x -0.56968 ϕ_y 1.23423 ϕ_z -0.29783
Wheel 0 station 2 sector 3 x -0.806553 y -0.295698 z 4.61924 ϕ_x -1.34884 ϕ_y 3.50955 ϕ_z 2.13239
Wheel 0 station 2 sector 4 x 2.30427 y -8.14645 z 8.60016 ϕ_x -0.29633 ϕ_y -2.72441 ϕ_z 0.60622
Wheel 0 station 2 sector 5 x 1.57191 y 1.3299 z 5.73776 ϕ_x 0.2668 ϕ_y 3.14588 ϕ_z 1.18292
Wheel 0 station 2 sector 6 x 0.545702 y 0.507466 z -1.7306 ϕ_x -2.77717 ϕ_y -4.33322 ϕ_z 0.45867
Wheel 0 station 2 sector 8 x -2.44087 y -2.09158 z -5.63427 ϕ_x -0.00477 ϕ_y -3.31363 ϕ_z -1.63931
Wheel 0 station 2 sector 9 x -2.11484 y 0.31826 z 2.36418 ϕ_x 0.31905 ϕ_y -3.04983 ϕ_z -0.22975
Wheel 0 station 2 sector 10 x 0.617771 y 4.44215 z 6.6571 ϕ_x -1.39624 ϕ_y -0.30562 ϕ_z 0.08301
Wheel 0 station 2 sector 11 x -3.27321 y 3.59291 z 3.29205 ϕ_x -0.61194 ϕ_y -5.16856 ϕ_z 1.2275
Wheel 0 station 2 sector 12 x 9.83251 y -1.23156 z -6.55066 ϕ_x -0.29319 ϕ_y 3.39463 ϕ_z 1.20365
Wheel 0 station 3 sector 2 x -1.58877 y 1.71524 z -4.20434 ϕ_x 0.96071 ϕ_y 4.64165 ϕ_z 0.86643
Wheel 0 station 3 sector 3 x -3.78264 y 0.422799 z 5.03824 ϕ_x 2.61095 ϕ_y 4.18387 ϕ_z 0.26061
Wheel 0 station 3 sector 4 x 2.31722 y -4.15166 z 10.249 ϕ_x -1.54944 ϕ_y 0.00255 ϕ_z -0.13908
Wheel 0 station 3 sector 5 x -0.571674 y 3.78601 z 6.31147 ϕ_x -0.53773 ϕ_y 3.35972 ϕ_z 0.28602
Wheel 0 station 3 sector 6 x 2.56187 y -1.83215 z -3.42709 ϕ_x -0.3067 ϕ_y -4.04527 ϕ_z -0.8713

local parameters relative to ideal in mm and mrad

Wheel 0 station 3 sector 8 x -2.60014 y -1.15745 z -4.88687 ϕ_x 0.32136 ϕ_y -3.32985 ϕ_z -1.43223
Wheel 0 station 3 sector 9 x -1.30916 y -0.481679 z 3.21908 ϕ_x 0.21335 ϕ_y -2.136 ϕ_z -0.00664
Wheel 0 station 3 sector 10 x -1.49691 y 4.14856 z 7.38953 ϕ_x 2.56641 ϕ_y -0.00575 ϕ_z -0.39747
Wheel 0 station 3 sector 11 x -5.05493 y 3.50028 z 4.06302 ϕ_x -0.19602 ϕ_y -3.61992 ϕ_z -0.65023
Wheel 0 station 3 sector 12 x 9.75095 y -3.44321 z -5.95042 ϕ_x 1.1613 ϕ_y 2.58857 ϕ_z 0.40561
Wheel 0 station 4 sector 2 x -2.79989 y -0.482284 z -6.35894 ϕ_x -0.53711 ϕ_y 1.71273 ϕ_z -1.06504
Wheel 0 station 4 sector 3 x -6.40613 y 1.36144 z 1.52083 ϕ_x -0.1756 ϕ_y 3.65436 ϕ_z -0.52607
Wheel 0 station 4 sector 4 x 6.8457 y 0.153022 z 6.59851 ϕ_x 0.07554 ϕ_y -1.62017 ϕ_z 1.00673
Wheel 0 station 4 sector 5 x -2.47676 y 0.612476 z 4.85868 ϕ_x -0.08818 ϕ_y 3.87655 ϕ_z 0.03601
Wheel 0 station 4 sector 6 x 3.40954 y 1.25147 z -4.89895 ϕ_x -0.69604 ϕ_y -2.47187 ϕ_z -1.23236
Wheel 0 station 4 sector 7 x 1.40625 y 0.402119 z -8.11646 ϕ_x -0.18864 ϕ_y -0.28251 ϕ_z -0.13526
Wheel 0 station 4 sector 8 x -2.55356 y 1.1972 z -9.71891 ϕ_x -0.14007 ϕ_y 2.22931 ϕ_z -2.11928
Wheel 0 station 4 sector 9 x -2.20721 y -2.96517 z 4.94177 ϕ_x 0.05375 ϕ_y -2.93942 ϕ_z -0.99161
Wheel 0 station 4 sector 10 x 0.687561 y 1.21544 z 7.98645 ϕ_x -0.73872 ϕ_y 0.96927 ϕ_z 0.00373
Wheel 0 station 4 sector 11 x -2.70243 y 1.25618 z 4.84614 ϕ_x 0.61865 ϕ_y -3.79912 ϕ_z -0.6001
Wheel 0 station 4 sector 12 x 8.84109 y -0.139828 z -5.10142 ϕ_x 1.3117 ϕ_y 0.2933 ϕ_z -1.47789
Wheel 0 station 4 sector 13 x 1.96198 y 1.15505 z 6.87988 ϕ_x -0.15212 ϕ_y 0.57321 ϕ_z -0.69774
Wheel 0 station 4 sector 14 x -1.85883 y -0.614842 z 3.33862 ϕ_x -0.2608 ϕ_y -4.84295 ϕ_z -2.39709
Wheel 1 station 1 sector 1 x -2.58495 y -1.6925 z -5.99884 ϕ_x -1.9484 ϕ_y -0.56512 ϕ_z -0.05504
Wheel 1 station 1 sector 2 x 0.130108 y -0.216064 z -3.40223 ϕ_x 1.62371 ϕ_y 4.87149 ϕ_z -2.1568
Wheel 1 station 1 sector 3 x 1.24372 y -1.65558 z 2.94429 ϕ_x -2.3927 ϕ_y 2.98929 ϕ_z -1.49108
Wheel 1 station 1 sector 4 x -0.840034 y -0.657349 z 5.87891 ϕ_x -1.87183 ϕ_y 0.26802 ϕ_z -0.59566
Wheel 1 station 1 sector 5 x -1.01297 y -4.39575 z 2.43018 ϕ_x -0.40417 ϕ_y -2.51583 ϕ_z 0.45195
Wheel 1 station 1 sector 6 x 1.83001 y -2.36725 z -3.0486 ϕ_x 0.08558 ϕ_y -3.33404 ϕ_z -0.26003
Wheel 1 station 1 sector 7 x 4.69452 y -2.276 z -6.70288 ϕ_x 1.17097 ϕ_y -3.28029 ϕ_z 0.83038
Wheel 1 station 1 sector 8 x 5.45029 y -0.971375 z -3.36291 ϕ_x -0.21555 ϕ_y 1.48713 ϕ_z 0.22603
Wheel 1 station 1 sector 9 x 2.87232 y 0.239258 z 2.76553 ϕ_x -0.74411 ϕ_y 3.85255 ϕ_z -0.03942
Wheel 1 station 1 sector 10 x -0.614929 y 1.82465 z 4.61243 ϕ_x -0.92573 ϕ_y 0.68658 ϕ_z 1.38139
Wheel 1 station 1 sector 11 x -5.79432 y 1.41632 z 2.28367 ϕ_x -1.76968 ϕ_y -1.41843 ϕ_z -0.1892
Wheel 1 station 1 sector 12 x -8.20031 y -1.75873 z -4.34373 ϕ_x 0.12695 ϕ_y -1.34722 ϕ_z 0.04941
Wheel 1 station 2 sector 2 x -0.770293 y -3.03314 z -3.3646 ϕ_x -3.42128 ϕ_y 2.04586 ϕ_z 1.27777
Wheel 1 station 2 sector 3 x -0.736401 y -1.51642 z 2.02042 ϕ_x -3.47135 ϕ_y 1.7259 ϕ_z 1.26397

Proposed constants

local parameters relative to ideal in mm and mrad

Wheel 1 station 2 sector 4 x -0.475597 y -0.696411 z 3.55835 ϕ_x -3.58408 ϕ_y 1.32851 ϕ_z -1.27913
Wheel 1 station 2 sector 5 x 1.12813 y -4.36157 z 2.97919 ϕ_x -4.69689 ϕ_y -2.94099 ϕ_z -0.58364
Wheel 1 station 2 sector 6 x 3.32585 y -1.10901 z -3.24092 ϕ_x -3.06812 ϕ_y -2.00568 ϕ_z -0.6916
Wheel 1 station 2 sector 8 x 6.28076 y -0.549927 z -3.94835 ϕ_x -2.5398 ϕ_y 2.80519 ϕ_z -0.67311
Wheel 1 station 2 sector 9 x 4.15433 y -1.16394 z 1.51863 ϕ_x -3.07832 ϕ_y 3.30244 ϕ_z -0.64401
Wheel 1 station 2 sector 10 x 1.90104 y 3.04199 z 3.81348 ϕ_x -2.15084 ϕ_y -1.7609 ϕ_z 1.07329
Wheel 1 station 2 sector 11 x -1.05188 y 1.19049 z 1.38368 ϕ_x -2.24672 ϕ_y -4.21742 ϕ_z 1.93762
Wheel 1 station 2 sector 12 x -2.11825 y -1.88141 z -3.77634 ϕ_x -2.70206 ϕ_y -2.26316 ϕ_z -1.71282
Wheel 1 station 3 sector 2 x -2.50617 y -3.79852 z -2.50551 ϕ_x 1.48432 ϕ_y 3.84227 ϕ_z -0.8706
Wheel 1 station 3 sector 3 x -3.35564 y -2.3111 z 1.38695 ϕ_x -1.09511 ϕ_y 2.81492 ϕ_z -0.57986
Wheel 1 station 3 sector 4 x -1.41115 y -2.5943 z 3.84949 ϕ_x -2.87057 ϕ_y -0.06575 ϕ_z -0.59622
Wheel 1 station 3 sector 5 x 1.45182 y -6.70563 z 2.43593 ϕ_x -0.18765 ϕ_y -2.96575 ϕ_z -0.47754
Wheel 1 station 3 sector 6 x 2.9947 y -2.23541 z -3.16814 ϕ_x -3.07041 ϕ_y -3.07103 ϕ_z 0.04104
Wheel 1 station 3 sector 9 x 0.734221 y -0.279541 z 2.12315 ϕ_x 1.29739 ϕ_y 2.8712 ϕ_z -0.41936
Wheel 1 station 3 sector 10 x 0.470944 y 1.49139 z 4.15344 ϕ_x -2.81304 ϕ_y -1.24358 ϕ_z -1.18247
Wheel 1 station 3 sector 11 x -2.80713 y 1.00037 z 1.70231 ϕ_x 0.45172 ϕ_y -2.48584 ϕ_z 0.71634
Wheel 1 station 3 sector 12 x -4.60759 y -3.09906 z -4.96545 ϕ_x 2.3272 ϕ_y -1.18845 ϕ_z -1.37861
Wheel 1 station 4 sector 2 x -6.18658 y -2.71881 z -4.72765 ϕ_x 0.00111 ϕ_y 0.75999 ϕ_z -0.5485
Wheel 1 station 4 sector 3 x -6.06843 y -1.77429 z 0.55484 ϕ_x 0.06375 ϕ_y 2.65 ϕ_z -1.32278
Wheel 1 station 4 sector 4 x -6.27701 y 0.368652 z 3.6377 ϕ_x -0.19802 ϕ_y 2.70494 ϕ_z -1.29406
Wheel 1 station 4 sector 5 x 2.03402 y -0.114441 z 2.05742 ϕ_x 0.40045 ϕ_y -5.33465 ϕ_z 1.69095
Wheel 1 station 4 sector 6 x 5.26769 y -1.16974 z -3.85461 ϕ_x 0.48044 ϕ_y -2.78904 ϕ_z 0.95017
Wheel 1 station 4 sector 7 x 6.99043 y 1.56982 z -5.60974 ϕ_x -0.78598 ϕ_y -2.27688 ϕ_z -3.01322
Wheel 1 station 4 sector 8 x 1.44745 y -0.147095 z -3.9011 ϕ_x 0.08251 ϕ_y -3.02992 ϕ_z 2.45753
Wheel 1 station 4 sector 9 x 0.459919 y -1.43768 z 1.74448 ϕ_x -0.29222 ϕ_y 1.93971 ϕ_z 3.44841
Wheel 1 station 4 sector 10 x 2.84683 y -1.67023 z 3.56689 ϕ_x 0.63226 ϕ_y -2.0471 ϕ_z 1.29825
Wheel 1 station 4 sector 11 x -5.24411 y -0.617065 z 1.69782 ϕ_x -0.61558 ϕ_y -2.06206 ϕ_z -0.15784
Wheel 1 station 4 sector 12 x -7.00754 y -1.36566 z -3.98861 ϕ_x 0.31415 ϕ_y -0.28497 ϕ_z -2.40785
Wheel 1 station 4 sector 13 x 0.69809 y -0.318604 z 3.31604 ϕ_x -0.00848 ϕ_y -2.49281 ϕ_z 2.49594
Wheel 1 station 4 sector 14 x 0.564728 y -1.04828 z 2.14722 ϕ_x -1.91697 ϕ_y 1.22462 ϕ_z -0.18523
Wheel 2 station 2 sector 3 x 5.24698 y -2.75879 z 2.30825 ϕ_x 1.17079 ϕ_y 4.12174 ϕ_z 0.42959
Wheel 2 station 2 sector 4 x 1.00798 y -1.7804 z 4.68079 ϕ_x -2.90444 ϕ_y 1.15071 ϕ_z 0.66689

Proposed constants

local parameters relative to ideal in mm and mrad

Wheel 2 station 2 sector 5 x 2.0299 y -0.755615 z 3.67497 ϕ_x 1.75317 ϕ_y -4.03868 ϕ_z 1.67154
Wheel 2 station 2 sector 9 x 3.284 y -2.90466 z 2.20294 ϕ_x -1.95323 ϕ_y 1.46048 ϕ_z -0.99145
Wheel 2 station 2 sector 10 x -0.684071 y 2.48657 z 3.90747 ϕ_x -0.56463 ϕ_y -0.64621 ϕ_z -0.49226
Wheel 2 station 2 sector 11 x -3.16977 y -3.23608 z 2.34994 ϕ_x 0.15366 ϕ_y -3.35436 ϕ_z 0.0875
Wheel 2 station 3 sector 2 x 0.579107 y -3.59985 z -2.92382 ϕ_x 1.3318 ϕ_y 3.24523 ϕ_z 0.27176
Wheel 2 station 3 sector 3 x 3.37728 y -2.23938 z 3.25135 ϕ_x 3.5841 ϕ_y 4.79966 ϕ_z -1.93466
Wheel 2 station 3 sector 4 x 1.77855 y -0.819092 z 4.20715 ϕ_x 1.63512 ϕ_y 1.7499 ϕ_z -1.60651
Wheel 2 station 3 sector 5 x 1.21149 y -1.43494 z 3.08229 ϕ_x 1.38582 ϕ_y -2.38098 ϕ_z 0.74591
Wheel 2 station 3 sector 8 x 0.167648 y -2.44812 z -3.98666 ϕ_x 1.11855 ϕ_y 1.99135 ϕ_z -0.84366
Wheel 2 station 3 sector 9 x -1.25018 y 1.47522 z 2.54715 ϕ_x -0.94766 ϕ_y 4.04735 ϕ_z -2.21441
Wheel 2 station 3 sector 10 x -3.17488 y 1.56067 z 4.34326 ϕ_x 0.91802 ϕ_y 0.41268 ϕ_z -1.18032
Wheel 2 station 3 sector 11 x -4.28959 y -0.0323486 z 1.95432 ϕ_x 3.54051 ϕ_y -2.31831 ϕ_z 0.26132
Wheel 2 station 3 sector 12 x -2.15165 y -0.165405 z -7.32356 ϕ_x 2.53826 ϕ_y -2.8025 ϕ_z -0.08573
Wheel 2 station 4 sector 2 x -2.87389 y -4.74854 z -4.69329 ϕ_x 0.01605 ϕ_y 1.89796 ϕ_z -0.29742
Wheel 2 station 4 sector 3 x -1.04335 y -2.7417 z 0.498776 ϕ_x 0.07462 ϕ_y 4.65125 ϕ_z -0.47567
Wheel 2 station 4 sector 4 x -1.80206 y -0.649414 z 3.51868 ϕ_x -0.22077 ϕ_y 3.00374 ϕ_z -2.56937
Wheel 2 station 4 sector 5 x 4.16278 y 4.38843 z 1.02837 ϕ_x -0.14998 ϕ_y -2.16139 ϕ_z -0.13496
Wheel 2 station 4 sector 6 x 5.56035 y -1.62903 z -3.61199 ϕ_x 0.16338 ϕ_y -3.39147 ϕ_z 1.95492
Wheel 2 station 4 sector 8 x -1.24406 y -0.480347 z -3.43727 ϕ_x -1.01309 ϕ_y 3.22395 ϕ_z -2.89316
Wheel 2 station 4 sector 9 x -1.74482 y -2.48291 z 2.54307 ϕ_x 0.31624 ϕ_y 3.14586 ϕ_z -1.43362
Wheel 2 station 4 sector 10 x -1.69113 y -2.69409 z 2.83447 ϕ_x -1.96386 ϕ_y 0.98601 ϕ_z -0.21197
Wheel 2 station 4 sector 11 x -4.18356 y -1.40564 z 2.31083 ϕ_x -0.32915 ϕ_y -2.07022 ϕ_z -1.18524
Wheel 2 station 4 sector 12 x -3.64197 y -2.30103 z -3.57919 ϕ_x 0.13262 ϕ_y 1.72587 ϕ_z -2.85656
Wheel 2 station 4 sector 13 x 2.8508 y -1.93542 z 3.60291 ϕ_x -0.34184 ϕ_y -2.66018 ϕ_z 3.1899
Wheel 2 station 4 sector 14 x -4.01169 y -3.54126 z 3.11951 ϕ_x -1.38171 ϕ_y -0.03555 ϕ_z -0.39379