CMS Tracker Alignment Strategy with Cosmic Muons

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FOR

CMS Tracker Alignment Group

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3rd LHC Alignment Workshop, CERN, Switzerland
Tracker in the CMS Detector

CMS Tracker

1440 Si Pixel
15148 Si Strip modules
Input to CMS Tracker alignment algorithms:

- Laser Alignment System
- optical survey
- tracks from cosmic muon runs ⇒ ultimate precision

Tracker Integration Facility (TIF) with partial Tracker in 2007
CMS at Point-5 ("CRAFT" cosmic run) with full Tracker in 2008

Detailed results in the next talk (by E. Migliore)

Alignment is a big project, but only the final step in commissioning

part of the CMS tracker alignment team “on the ground”
CMS Tracker Alignment Goal

- Alignment goal: nail down (few $\mu$m) all 16,588 modules ($\times$ 6 dof)

- Minimize residuals

$$\chi^2(p_{\text{modules}}, q_{\text{tracks}}) = \sum_{i=1}^{N_{\text{residuals}}} r_i^T V_i^{-1} r_i$$

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Laser Alignment System (LAS)

- See talk at 2nd LHC alignment workshop (June 2007):
  B. Wittmer “The Laser Alignment System of the CMS Tracker”

- Connect large structures (8 sectors in $\phi$): TIB - TOB - TEC

- Cosmic runs for commissioning: standalone $\sim 100 \mu m$, relative $\sim 20 \mu m$

- Tracker geometry: note 2D (100 mrad strip angle) and 1D modules

- LAS vs. Track-based $\phi$ of TEC disks
• See talk at 2nd LHC alignment workshop (June 2007):
  A.G. “First CMS Alignment Geometry: Survey Data and Their Implementation”

Barrels:
  PXB - modules (2D only)
  TIB - modules and up
  TOB - barrel

Endcaps:
  PXF - modules and up
  TID - modules and up
  TEC - disks and endcap

• Tracks + Survey in “local algorithm”, to constrain all 6 dof:

\[
\chi^2_{\text{module}} = \sum_i r_i^T (p_m) V_i^{-1} r_i (p_m) + \sum_j r_{*j}^T (p_m) V_{*j}^{-1} r_{*j} (p_m)
\]

following BABAR implementation: arXiv:0809.3823
Statistical Methods in CMS Tracker Alignment

- **Local iterative method** ("Hits & Impact Points") CMS-NOTE-2006/018

\[
p_m = \left[ \sum_i J_i^T V_i^{-1} J_i \right]^{-1} \left[ \sum_i J_i^T V_i^{-1} r_i \right]
\]

<table>
<thead>
<tr>
<th>pros</th>
<th>full Kalman Filter track model</th>
<th>simple implementation, all dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>cons</td>
<td>ignore correlations in one iteration</td>
<td>large CPU with many iterations</td>
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- **Global method** ("Millepede II") NIM A 566, 5 (2006), talk by V. Blobel

\[
\chi^2(p, q) = \sum_j \sum_i \frac{(y_{ji} - f_{ji}(p, q_j))^2}{\sigma^2_{ji}}
\]

<table>
<thead>
<tr>
<th>pros</th>
<th>model module correlations</th>
<th>less CPU with one or few iterations</th>
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</thead>
<tbody>
<tr>
<td>cons</td>
<td>simple helix trajectory model</td>
<td>large matrix may limit N parameters</td>
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</tbody>
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- **Kalman filter algorithm** with MC and TIF data: see talk by E. Widl
Tracker Alignment at Integration Facility

- First integrated tracker: spring-summer 2007  
arXiv:0904.1220

$\sim 15\%$ of strip tracker only
no B-field, assume $p = 1$ GeV/c
$\Rightarrow$ multiple scattering
cannot be predicted per event

- Reach $\sim 50/80 \mu m$ in TOB/TIB

Design: mean = 78.4
Survey: mean = 63.7
Aligned: mean = 43.0

Data - no alignment  
Data - HIP alignment  
MC - ideal geometry  
MC - tuned misalignment (TIB = 80 $\mu m$, TOB = 50 $\mu m$)
Alignment at Point-5 without Magnetic Field

- First experience with full Tracker: summer 2008
  - \( \sim 600k \) cosmic tracks for Tracker alignment
  - still no B-field

- Achieved \( \sim 30-40 \mu \text{m} \) in TIB/TOB
  - low statistics in Pixels and Endcaps

- Measure of alignment precision
  - Distribution of mean of the Residuals ("DMR", more later)

\[
\text{Distribution of mean of residuals for TIB}
\]

\[
\text{Distribution of mean of residuals for TOB}
\]
Alignment at Point-5 with Magnetic Field

- Best data for alignment of CMS Tracker: **fall 2008** ("CRAFT")
  - \( \sim 4 \text{M cosmic tracks} \) for Tracker alignment
  - \( B\text{-field} = 3.8\text{T} \Rightarrow \text{account for multiple scattering}, \ p > 4 \text{ GeV/c} \)

- Require good quality tracks and hits:
  - clean hits, outlier hit rejection, \( \chi^2 \) cut, min hits, 2D hits
  - accept all good tracks (statistics limited): only 3\%+1.5\% in Pixels

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Alignment Strategy during “CRAFT”

- Multi-step approach by both algorithms to address CMS geometry:
  - large structure movement: coherent $v$ alignment of 1D modules
  - alignment of two sides of 2D strip modules (units): $u, w, \gamma$

- Global method: 3 steps from “design”
  1. large structures (6 dof) & units (3 dof)
  2. module alignment: add $\alpha, \beta$ for TIB; 6 dof for PXB
  3. repeat (1); note above: keep <46,300 parameters, use pre-sigma

- Local method: 5 steps from survey; ~50 iterations each
  1. large structures ($u, v, w, \gamma$)
  2),3 Strip: modules (6 dof) with survey; units (3 dof)
  4),5 Pixels: ladders (6 dof); modules (6 dof)
Alignment Strategy: Merging Algorithms

- Combined method
  1. run global method ⇒ solve global correlations efficiently
  2. run local method ⇒ solve locally to match track model in all dof
- All three results are compatible, but combined is the best
  also compare to “not aligned”

Alignment Position Errors (APE) set for combined
see next talk

- Reference system: center-of-gravity and rotation move to design
Example: Pixel Residuals (local, global, combined)

- Residuals $\leftarrow$ multiple scattering + hit errors + alignment errors
  (random) (random) (systematic)

$r\phi$ pixel hit errors $\sim 19\mu$m here
Median of the Residuals

- Again global + local → best combined
  for example: PXB better local transverse, global longitudinal

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Summary

• CMS Tracker alignment with first data:
  Tracker construction & survey in 2006-2008
  Tracker integration cosmic run in 2007
  global CMS cosmic runs in 2008

• Successful CMS Tracker alignment algorithms:
  several complementary statistical methods
  best combination of global & local
  combine track + survey (done) and LAS (in progress) data

• Result in successful CMS Tracker alignment with cosmics
  but far from being done: cosmic and beam runs in 2009-2010
  cosmics alone has limitations, see next talk...
BACKUP
• Track reco data: reduced skim “AlCaReco” for alignment
  see talk by G. Flucke about workflow tomorrow

• Result: 16,588 module Positions (6D) and Alignment Position Errors (APE, 3D)