Track based Alignment in CMS

Frank-Peter Schilling (CERN)
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- Data samples
- Alignment strategy
- Alignment algorithms
  - HIP
  - Kalman Filter
  - Millepede-II
- Muon alignment with tracks
Track based Alignment in CMS

- Large number of alignment parameters (~100,000 in tracker) requires novel techniques
- Three different alignment algorithms implemented in CMS reconstruction software (now transition from “ORCA” to “CMSSW”)
  - Kalman Filter, Millepede-II, HIP Algorithm
  - Cross check results using different algorithms with different approaches and systematics
  - Supported by common software infrastructure
- Alignment using different data sets (dedicated MC generators)
  - Muons from Z,W; Cosmics; beam halo; muons from J/ψ, B; high pt QCD tracks
- Reduced data format (AlCaReco)
  - Development of fast Alignment stream (Z,W) produced during prompt reconstruction at Tier-0
- Combine track based alignment with laser alignment and survey data
- Employ mass and vertex constraints; use of overlaps
- Develop observables sensitive to misalignment other than $\chi^2$
  - Monitoring, fix $\chi^2$ invariant mode
- CMS alignment group ~20 people from ~8 institutes
**Data Samples**

- **High $p_T$ muons from Z,W decays**
  - Rate: $20k \ Z \to \mu\mu$, $100k \ W \to \mu\nu$ per day at $L=2\times10^{33}$
  - Gold plated for tracker alignment (small multiple scattering)
  - Exploit $Z^0$ mass constraint

- **Cosmic Muons**
  - ~400Hz after L1 and s.a. muon reco.

- **Beam Halo Muons**
  - ~5 kHz per side after L1 and s.a. muon
  - Problem: Muon endcap trigger outside tracker acceptance in $R$!
  - Potentially install scintillators (for startup) or use TOTEM T1

- **Muons from $J/\psi$ and inclusive B decays**
  - $J/\psi$ mass constraint

- **Min. bias, high pt hadrons from QCD events**
  - Potentially useful for pixel alignment
Simulation of Cosmics and Beam halo muons in CMS

- Cosmic muons: 400 Hz
- Beam halo muons: 5 kHz per side

- Rates after L1 and standalone muon reconstruction
Alignment Strategy

Basic sketch:

- **2007: Before beams:**
  - Cosmics (+laser alignment and survey measurements)
- **2007: single beams**
  - Add beam halo muons
- **2007: Pilot run, pixel detector not installed (except few test modules)**
  - Cosmics, beam halo muons
  - Add available high pt muons, tracks
  - Initial alignment of high level strip tracker structures (layers, rods)?

- **2008: Two-step approach:**
  - Add larger statistics of muons from Z,W
  - 1. Standalone alignment of pixel detector
  - 2. Alignment of strip tracker, using pixel as reference

- To be layed out in more detail …

See next slides for rate estimates
Expected event rates

- **Pilot run 2007 @ 900 GeV, L~10^{29}**
  
  What data samples in 2007 ?

  - ATLAS preliminary
  
  $\sqrt{s} = 900$ GeV, $L = 10^{29} \text{ cm}^{-2} \text{s}^{-1}$

  - 30% data taking efficiency included (machine plus detector)
  - Trigger and analysis efficiencies included

  F. Gianotti (ICHEP 2006)

  - Loads of min. bias, QCD jets
  - Not much of anything else …

- **Physics Run 2008 @ 14 TeV, L~10^{32...33}**

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$10^{32} \text{ cm}^{-2} \text{s}^{-1}$</th>
<th>$2\times10^{33} \text{ cm}^{-2} \text{s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Int. Luminosity</td>
<td>few weeks 6 months</td>
<td>1 day few weeks one year</td>
</tr>
<tr>
<td></td>
<td>100 pb^{-1} 1 fb^{-1}</td>
<td>1 fb^{-1} 10 fb^{-1}</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \mu^\pm \nu$</td>
<td>700K 7M</td>
<td>100K 7M 70M</td>
</tr>
<tr>
<td>$Z^0 \rightarrow \mu^+ \mu^-$</td>
<td>100K 1M</td>
<td>20K 1M 10M</td>
</tr>
</tbody>
</table>

  - Large statistics of high pt muons within few weeks!
General Software Framework

• (MIs)alignment implemented at reconstruction level:
  - “Misalignment tools”, move and rotate modules or higher level structures
• Dedicated “Misalignment Scenarios”
  - Short term scenario
    - First data taking (few 100 pb⁻¹)
    - Pixel already aligned
    - Strip tracker misaligned, only survey and laser alignment
  - Long term scenario
    - Few fb⁻¹ accumulated
    - Full alignment performed, residual misalignments ~20μm
• Fast track refit (without redoing pattern recognition)
• Reduced data format containing only alignment tracks
  - Small file size, fast processing

• Algorithms implemented in standard CMS reconstruction software using a common layer of general functionality
  - Management of parameters and covariances
  - Derivatives wrt track and alignment parameters
  - I/O, Database connection
HIP Algorithm: Formalism

- Minimization of track impact point \( (x) \)
  - hit \( (m) \) residuals in local sensor plane as function of alignment parameters

\[ \mathbf{ε} = \begin{pmatrix} \epsilon_u \\ \epsilon_v \end{pmatrix} = \begin{pmatrix} u_x - u_m \\ v_x - v_m \end{pmatrix} \]

- \( \chi^2 \) function to be minimized on each sensor (after many tracks per sensor accumulated)
  - \( V \): covariance matrix of measurement

- Linearized \( \chi^2 \) solution:
  - \( \delta p \): vector of alignment parameters
    \( \delta p = (\delta u, \delta v, \delta w, \delta α, \delta β, δγ) \)
  - \( J_i \): derivative of residuals w.r.t. alignment parameters

\[ \delta p = \left[ \sum_i J_i V_i^{-1} J_i^T \right]^{-1} \left[ \sum_i J_i V_i^{-1} \epsilon_i \right] \]

- Local solution on each “alignable object”
  - Only inversion of small (6x6) matrices, computationally light

CMS Note 2006/018
HIP Algorithm: Formalism (cont.)

- Formalism extended to alignment of composite detector structures (ladders, disks, layers etc.)
  - Minimize $\chi^2$ using all tracks crossing sensors of composite object with respect to alignment parameters of composite object
  - Implemented using chain rule
  - Correlations between modules not included explicitly
    - Implicitly included through iterations
  - Large statistics $\rightarrow$ parallel processing:
    - Run on N cpu’s processing 1/N of the full sample each
    - Combine results from all CPUs, compute alignment corrections
    - Start next iteration on N cpu’s

$$\frac{\delta \epsilon_i^S}{\delta p_{i}^C} = \frac{\delta \epsilon_i^S}{\delta p_{i}^S} \times \frac{\delta p_{i}^S}{\delta p_{i}^C}$$

- Example: 1M $Z\rightarrow\mu\mu$ events:
  - reduced DST format keeps only muon tracks
  - Refit track, don’t re-reconstruct
  - With 20 CPUs in parallel, one iteration: $\sim 45'$
HIP Algorithm studies

- Alignment of 720 CMS Pixel Barrel modules

- “First data taking” misalignment scenario
  - Includes correlated misalignments

- 200K $Z^0 \rightarrow \mu^+\mu^-$ events, 10 iterations

- Good convergence: RMS $\sim 7\mu m$ in x,y, $\sim 23\mu m$ in z

- Caveat: Alignment w.r.t ideal strip tracker

CMS Note 2006/018
HIP Algorithm studies

- Standalone alignment of pixel modules
- Minimize influence of misaligned strip detector:
  - refitting only pixel hits of the tracks
  - use momentum constraint from full track (significantly improves convergence)
- Two muons from $Z^0 \rightarrow \mu^+\mu^-$ are fitted to common vertex
- Flat misalignment $\pm 300\mu m$ in $x,y,z$
- 500k events, 19 iterations
- Reasonable convergence, RMS $\sim 25\mu m$ in all coordinates

CMS Note 2006/018
Kalman Filter Alignment

• Method for global alignment derived from Kalman Filter

• Ansatz:
  - measurements \( m \) depend via track model \( f \) not only on track parameters \( x \), but also on alignment parameters \( d \):
    \[
    m = f(x, d) + \epsilon \quad \text{COV}(\epsilon) = V
    \]
  - Update equation of Kalman Filter:
    \[
    \begin{pmatrix}
      \dot{d} \\
      \dot{x}
    \end{pmatrix} = \begin{pmatrix}
      d \\
      x
    \end{pmatrix} + K \left( m - c - Ad - Bx \right)
    \]
  - For details, see talk by R. Fruehwirth!

• Iterative: Alignment Parameters updated after each track
• Global: Update not restricted to modules crossed by track
  - Update can be limited to those modules having significant correlations with the ones in current trajectory
  - Requires some bookkeeping
  - No large matrices to be inverted!

• Possibility to use prior information (e.g. survey data, laser al.)
• Can add mass / vertex constraints

CMS Note 2006/022
Kalman Filter Alignment (cont.)

- Wheel-like setup: (part of CMS tracker: 156 TIB modules)
- Pixel detector as reference
- Misalignment:
  - local $x,y \sigma = 100 \mu m$
- Update restricted to distance $d_{\text{max}} \leq 6$
- Single muons $p_T = 100$ GeV

- Convergence slower in outer layers (distance from reference system, less track statistics)

CMS Note 2006/022
Kalman Filter Alignment (cont.)

- Overall RMS $\sim 21\mu m$ after alignment

- Dependence of RMS and CPU time on $d_{\text{max}}$

<table>
<thead>
<tr>
<th>$d_{\text{max}}$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma [\mu m]$</td>
<td>24.75</td>
<td>21.38</td>
<td>20.97</td>
<td>20.95</td>
<td>20.94</td>
<td>20.94</td>
</tr>
<tr>
<td>$T [s]$</td>
<td>472</td>
<td>604</td>
<td>723</td>
<td>936</td>
<td>1152</td>
<td>1319</td>
</tr>
</tbody>
</table>

- $d_{\text{max}}=6$ does not exclude modules with relevant correlations
Millepede II Algorithm

- For formalism, see talk of V. Blobel
- Original Millepede method solves matrix eqn. $Ax = B$, by inverting huge matrix A. Can only be done for <12000 alignment parameters
- New Millepede II method instead minimises $|Ax - B|$. Expected to work for ~100000 alignment parameters (i.e. for full CMS at sensor level)
- Both successfully aligned ~12% of tracker modules using 2M $Z \rightarrow \mu\mu$ events. Results identical, but new method 1500 times faster!

Matrix Inversion (12000x12000)  
(t=13h)

MinRes  
(t=30s, 1500x faster!)

CMS Note 2006/011
Millepede-II in CMS

- Alignment of the strip tracker at sensor level
- Barrel region, $|\eta|<0.9$, 12015 alignment parameters
- (Mis)alignment in $r\phi$, r, z, $\gamma$ at half-barrel / layer / rod / module levels
CPU Requirements (Millepede-II)

CPU time in hours as a function of number of parameters

- New Millepede-II (iterative method) scaleable to full CMS problem
- Alternative: massively parallel algorithm (difficult to implement)
- Memory needs (dep. on sparseness of matrix) under study...

CPU Time for CMS (100k parameters):
- Diagonalization
  ~10 year at one CPU
- Inversion:
  ~1 year at one CPU
- Iteration:
  ~1 h at one CPU
Importance of using “complete” datasets

- Collision tracks and cosmics populate different parts of global covariance matrix → reduce global correlations!

- Example: Alignment of CMS strip barrel rods and layers
  - Only one layer fixed
  - 500k $Z^0 \rightarrow \mu\mu$ with vertex constraint
  - 100k Cosmics

- Use $Z^0$ tracks only:
  - No solution
  - Matrix singular

- Use $Z^0$ and Cosmics:
  - Problem solvable
  - Reasonable correlations

Simplified simulation and scenario, Now look at realistic study …
Global correlations: Realistic scenario

- Realistic alignment scenario of the CMS pixel and strip barrel studied
- Datasets and prior information:
  - 250k $Z^0 \rightarrow \mu\mu$ with vertex constraint
  - 500k Cosmics
  - Survey information
- Global correlations of alignment parameters high (can be >99%)
  - Independent of alignment algorithm!
- Cosmics (and beam halo, shifted vertex?!) very important to decrease global correlations!

M. Stoye (Hamburg)
Muon system Alignment with tracks

- 790 chambers ⇒ ”only” ~5000 alignment parameters

- Main differences w.r.t. Tracker Alignment:
  - Large amount of material for tracks crossing barrel-endcap
  - Chambers assumed as rigid body: provide vector information useable for alignment

- Two approaches
  - Alignment using tracks extrapolated from tracker
  - Standalone muon alignment

- Standalone muon alignment using $W \rightarrow \mu \nu$ events corresponding to 50h of data taking at $10^{34}$

CMS Note 2006/016
Conclusions

• Alignment of the CMS tracker and muon system is a challenge
  • Large number of parameters (~100,000 in tracker)
  • High intrinsic resolution of devices

• A lot of ongoing work on track based alignment already now
  • Implementation and further development of algorithms
    o Initial results promising
    o Not yet demonstrated realistic alignment of full tracker at sensor level
  • Alignment studies using various MC data sets
  • Dedicated HLT alignment stream
  • Use of overlaps, mass and vertex constraints
  • How to combine with Laser Alignment and Survey?
  • Define monitoring observables other than $\chi^2$ (“global modes”)
  • Condition Database infrastructure

• Alignment of test beam and cosmics data
  • Tracker “Cosmic Rack” test structure
  • Magnet Test & Cosmic Challenge (MTCC) data

• Aim for having all ingredients in place when data will arrive!