Alignment of the ATLAS Inner Detector Tracking System

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on behalf of the ATLAS Collaboration
The ATLAS Detector at the LHC

Inner Detector

- Muon chambers
- Toroid magnets
- Solenoid magnet
- Semiconductor tracker
- Transition radiation tracker
- Pixel detector
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters
The Inner Detector

Magnetic Field $B=2T$
Tracking coverage up to $|\eta|=2.5$

<table>
<thead>
<tr>
<th>module type</th>
<th>modules</th>
<th>resolutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRT</td>
<td>straw drift tubes</td>
<td>176</td>
</tr>
<tr>
<td>SCT</td>
<td>silicon micro strip modules</td>
<td>4088</td>
</tr>
<tr>
<td>Pixel</td>
<td>silicon pixel modules</td>
<td>1744</td>
</tr>
</tbody>
</table>
Inner Detector Alignment

In order not to degrade track resolution by more than 20%, module positions should be known at the level of ~10μm; using the “as built” geometry (precision O(100μm±1mm)) causes:

- apparent ≠ real track
- biased track parameters
- degradation of tracking performances

Track based alignment algorithms minimize track-to-hit residuals $r$ via $\chi^2$

$$\chi^2 = \sum_{tracks} r^T V^{-1} r \quad \rightarrow \quad \frac{d\chi^2}{da} = 0$$

where $r=r(\pi,a)$ and:
- $\pi =$ track parameters
- $a =$ alignment parameters (6 x module)
- $V =$ residual covariance matrix
Alignment Levels

**Level 1: (4 structures)**
- Big structures come first:
  - Largest misalignments and hit statistics
  - Relative sub-systems alignment: (PIX-SCT barrels, SCT/TRT endcaps)
- Mounting structures: layers/disks
- Up to module by module alignment

**Level 2: (31 structures)**
- Example of stave bow track residuals

**Level 3: (5832 structures)**
- Example of stave bow
Cosmic ‘08: Track Residuals

<table>
<thead>
<tr>
<th></th>
<th>field off</th>
<th>field on</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>all tracks</td>
<td>4.9M</td>
<td>2.7M</td>
<td>7.6M</td>
</tr>
<tr>
<td>with SCT hits</td>
<td>1.2M</td>
<td>880k</td>
<td>2.0M</td>
</tr>
<tr>
<td>with Pixel hits</td>
<td>230k</td>
<td>190k</td>
<td>420k</td>
</tr>
</tbody>
</table>

After alignment:
- significant residuals improvements
- widths approaching MC with perfect alignment
Cosmic tracks cross the entire ID tracks can be split near the interaction point and fit separately providing two collision-like tracks to compare

**After alignment:**
- significant resolution improvements

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\[ \text{resolution} \approx \frac{\sigma}{\sqrt{2}} \]
Some detector deformations, may preserve the track $\chi^2$, while altering the track parameters. (**Weak Modes**)

Weak modes constitute a potential danger to ATLAS physics performances.

**Example: Curl systematic deformation**

- **Ideal Alignment**
- **Curl Large** = before alignment
- **Curl Small** = after alignment

With simulated collision data
Systematic Mis-alignments

- Some detector deformations, may preserve the track $\chi^2$, while altering the track parameters. *(Weak Modes)*

- Weak modes constitute a potential danger to ATLAS physics performances

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**Example: Curl systematic deformation**

- Degradation of the resolution on Z mass peak

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**Fighting weak modes:**

- by applying external constraints, using information from other subdetectors, calorimeter, muon spectrometer
- Using standard candles like $J/\Psi \rightarrow \mu^+\mu^-$
- and...

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*do, Florida, USA*  
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... and: by using different track topologies: from collision, cosmics, and beam-halo/gas events. 

i.e. introducing different correlations between modules.

Alignment algorithms ready to incorporate beam halo/gas events to complement cosmic alignment before first collisions.

SCT endcap residuals improvement after alignment with simulated beam gas events.
Conclusions

- An alignment precision of $\approx 10\mu m$ is needed in order not to degrade the tracking/physics performances more than 20%. This can be achieved using track-based alignment algorithms.

- Cosmic Ray data from 2008 provided a good testing ground for alignment algorithms commissioning and development.

- The width difference of residual distribution obtained by the aligned geometry and with MC perfect geometry, indicates that alignment performances on cosmic ray data are consistent with a residual random misalignment of $\approx 20\mu m$ (for the barrel part).

- Endcap alignment is very difficult, (single) beam data is needed.

- Different event and track topologies are needed to understand alignment systematics, develop ways to cope with weak mode deformations, and reach the ultimate alignment precision.

- Looking forward for beam-data, ATLAS Inner Detector alignment is in very good shape!
Alignment Flow

Alignment step:
- ID alignment stream data
- express stream data

Validation step:
- DB alignment constants
- alignment algorithms
- alignment validation

Physics stream data
- bulk reconstruction
- track reconstruction
- new alignment constants

24-hour alignment loop
weekly shifters

Physics analysis
Interplay Between Cosmic/Single-Beam
Alignment Consistency / Stability

- **Consistency:**
  Three alignment approaches, Global and Local $\chi^2$, and Robust alignment, provide consistent results.

  - **Global $\chi^2$:** accounts for all module correlations, default algorithm
  - **Local $\chi^2$:** neglects module correlations when solving the linear system, but restores them via iterations
  - **Robust:** (silicon-only) translational alignment parameters calculated directly from residual size (no $\chi^2$)

- **Stability:**
  Residuals distributions from cosmic 2009 using alignment from 2008 show limited width degradation:

<table>
<thead>
<tr>
<th>residuals x</th>
<th>PIX</th>
<th>SCT</th>
<th>TRT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>cosmic 2008</strong></td>
<td>$\mu = 2 \mu m$</td>
<td>$\mu = 1 \mu m$</td>
<td>$\mu = 3 \mu m$</td>
</tr>
<tr>
<td></td>
<td>$\sigma = 24 \mu m$</td>
<td>$\sigma = 30 \mu m$</td>
<td>$\sigma = 160 \mu m$</td>
</tr>
<tr>
<td><strong>cosmic 2009</strong></td>
<td>$\mu = 2 \mu m$</td>
<td>$\mu = 0 \mu m$</td>
<td>$\mu = 2 \mu m$</td>
</tr>
<tr>
<td></td>
<td>$\sigma = 26 \mu m$</td>
<td>$\sigma = 36 \mu m$</td>
<td>$\sigma = 187 \mu m$</td>
</tr>
<tr>
<td><strong>difference '08/'09</strong></td>
<td>$\sim 10 \mu m$</td>
<td>$\sim 20 \mu m$</td>
<td>$\sim 98 \mu m$</td>
</tr>
</tbody>
</table>

*The detector is pretty stable!*
Pixel Residuals $y$

- Aligned geometry: $\mu=1\mu m$, $\sigma=131\mu m$
- MC perfect geometry: $\mu=2\mu m$, $\sigma=127\mu m$
- Nominal geometry: $\mu=5\mu m$, $\sigma=282\mu m$
Split Tracks: More Details

**ATLAS Preliminary SiUp-SiLow Tracks**

- **Aligned geometry** $\mu=-1\mu m$, $\sigma=49\mu m$
- **MC perfect geometry** $\mu=-1\mu m$, $\sigma=32\mu m$
- **Nominal geometry**

**ATLAS Preliminary SiUp-SiLow Tracks**

- **Aligned geometry** $\mu=9\mu m$, $\sigma=166\mu m$
- **MC perfect geometry** $\mu=4\mu m$, $\sigma=151\mu m$
- **Nominal geometry** $\mu=85\mu m$, $\sigma=396\mu m$

**ATLAS Preliminary SiUp-SiLow Tracks**

- **Aligned geometry** $\mu=0\times10^{-4}$, $\sigma=4\times10^{-4}$
- **MC perfect geometry** $\mu=0\times10^{-4}$, $\sigma=3\times10^{-4}$
- **Nominal geometry**

**ATLAS Preliminary SiUp-SiLow Tracks**

- **Aligned geometry** $\mu=0\text{ TeV}^{-1}$, $\sigma=5\text{ TeV}^{-1}$
- **MC perfect geometry** $\mu=0\text{ TeV}^{-1}$, $\sigma=4\text{ TeV}^{-1}$
- **Nominal geometry** $\mu=-13\text{ TeV}^{-1}$, $\sigma=14\text{ TeV}^{-1}$
Cosmic 2009 Residuals

- **2008 Aligned Geometry**
  - Pixel Barrel
  - SCT Barrel

- **2009 Cosmic Ray Data**
  - ATLAS Preliminary

- **Alignment Parameters**
  - $\mu=2\,\mu m$, $\sigma=26\,\mu m$
  - $\mu=0\,\mu m$, $\sigma=35\,\mu m$
  - $\mu=0\,\mu m$, $\sigma=36\,\mu m$
  - $\mu=2\,\mu m$, $\sigma=187\,\mu m$

- **Axes**
  - x residual [mm]
  - y residual [mm]
  - residual [mm]
Cosmic Track Distributions

ATLAS preliminary 2008 cosmic data

normalized rate

$\delta_0$ (mm)

$z_0$ (mm)

$\phi_0$ (rad)

normalized rate

$\theta_0$ (rad)

$q/p$ (c/GeV)
### Impact of Random Mis-alignment

**Residuals distributions consistent with a random misalignment ~20μm (barrel)**

**Random smeared module position during reconstruction:**

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<th>TRT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day-1 barrel</strong></td>
<td>20μm</td>
<td>20μm</td>
<td>100μm</td>
</tr>
<tr>
<td><strong>Day-1 endcaps</strong></td>
<td>50μm</td>
<td>50μm</td>
<td>100μm</td>
</tr>
<tr>
<td><strong>Day-100 barrel</strong></td>
<td>10μm</td>
<td>10μm</td>
<td>50μm</td>
</tr>
<tr>
<td><strong>Day-100 endcaps</strong></td>
<td>10μm</td>
<td>10μm</td>
<td>50μm</td>
</tr>
</tbody>
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