BaBar Si Tracker Alignment

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Representing the BaBar SVT alignment group

- The BaBar experiment
- The BaBar Si Tracker alignment procedure
- Alignment procedure validation
- Results
- Lessons learned
PEP-II and BaBar

- **DIRC (PID)**
  - 144 quartz bars
  - 11000 PMs

- **1.5T solenoid**

- **EMC**
  - 6580 CsI(Tl) crystals

- **e^+ (3.1GeV)**

- **e^- (9GeV)**

- **Instrumented Flux Return**
  - iron / RPCs (muon / neutral hadrons)

- **Drift Chamber**
  - 40 layers
    - 1/3 axial, 2/3u+v stereo

- **Silicon Vertex Tracker**
  - 5 layers, double sided strips
Track Momentum on the $\Upsilon(4S)$

$<P_t> \sim 500 \text{ MeV}$

- Scattering (material) largely dominates over point (hit) resolution in impact parameter resolution
BaBar Physics Goals

- Observe CP violation in B system
  - Time-dependent mixing (e.g. $\sin 2\beta$)
  - $\lambda_z \sim 260$ $\mu$m, $\sigma_z$ vertex $\sim 180$ $\mu$m, $\Rightarrow$ 20 $\mu$m point resolution

- PDG-competitive measurement of B, $\tau$ lifetimes
  - Control average alignment systematics to $\sim$ 1 $\mu$m (0.5%)

- No $B_\text{s}$ mixing, tertiary charm vertex separation, ...
  - Modest requirements on material, resolution

![Diagram showing B meson reconstruction and flavor tagging](image)
5 layers, 340 wafers
- Radii from 3.3 to 15 cm
- ‘Lampshades’ in layers 4 + 5

- Double sided readout
  - 90° strips
  - Kapton fanouts in active region

- ~2% $X_0$ total at normal
  - 1% $X_0$ Be beampipe

- No hardware alignment
Wafer Alignment Description

- Sensor local coordinates
  - $u \approx \phi$, $v \approx \text{beam}$, $w \approx \text{radial outward}$
- 6 alignment parameters
  - Deviation WRT nominal
  - 3 translations $\delta u \delta w \delta v$
  - 3 (small) rotations $\alpha u \alpha w \alpha v$
- Total system has 6 redundant Global alignment DOFs
- Internal DOFs
  - Charge drift asymmetry (=0)
  - Lorentz shift (estimated)
  - Non-planar distortions

Geometric midplane $\equiv w = 0$

Si Sensor

$u \approx \phi$, $v \approx \text{beam}$, $w \approx \text{radial outward}$

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$\approx 280 \mu m$
Residual ≡ min. distance from track to hit in space

Reduced residual (cm)

\[ \chi^2 = \sum_{\text{residuals}} \left( \frac{r}{\sigma_r} \right)^2 \]
BaBar Alignment History

- **BaBar design and construction: 1995→1999**
  - Alignment is considered (overlaps) but not studied
- **First data and commissioning in 1999**
  - Used Optical Survey wafer alignment + cosmics
- **1st Alignment procedure development 1999→2000**
  - Based on (primarily) $e^+e^-\rightarrow\mu^+\mu^-$ events
  - 1.5 FTE for development and operation
  - Procedure was manpower, cpu and data intensive
    - ~1 month turnaround time
  - Visible systematic errors remained
    - Early BaBar physics results were not compromised!
- **Complete rewrite of alignment procedure 2001→2002**
  - 3 FTE development effort over 1 year
  - Separate operations effort of 0.5 FTE
  - Designed coherently with a new BaBar Data Model
  - Deployed in 2002, we are still using this procedure today
BaBar $\tau$ lifetime in year 2000

Average $\tau$
1-3 decay distance

$\chi^2$/d.o.f. = 292.7 / 59, $P(\chi^2) = 0.0000$

variation is $\sim$10% of lifetime

Black=data, red=MC
Alignment Design Principles

● Combine complementary constraints
  ✔ Use lots of tracks to cover all wafer DOFs
  ✔ Use different event triggers and track geometries to balance systematic biases
  ✔ Relate wafers across the detector to control global distortions
  ✔ Incorporate lab-based optical survey information

● Select data to provide uniform constraints
  ✔ Make detector coverage more uniform
  ✔ Select events uniformly over (short) time period
  ✔ Equilibrate statistical errors
  ✔ Minimize statistical correlations between wafers
Global Distortions

- Small relative changes between adjacent wafers that add up coherently across the detector
  - Residuals work ‘locally’
- Can introduce significant physics bias
- Choose alignment constraints which control these

<table>
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David Brown
LHC Detector Alignment Workshop
Sept. 4, 2006
Overlaps

- Active Si overlap between adjacent wafers in the same layer
- Small gap between overlapping wafers
  - Constrains adjacent wafers
  - Not as effective in hex geometry
- Overlaps cumulatively provide a circumference constraint
  - Relies on precise knowledge of wafer size
  - Constrains radial expansion, clamshell distortions
- Small fraction of tracks
  - Between 1% and 3%
Cosmic Rays

- High-momentum tracks (> 1Gev)
- Relates opposite side wafers $\Rightarrow$ constrains "telescope distortion"
- Off-axis $\Rightarrow$ constrains "twist, elliptical distortions"
- Low rate, non-uniform illumination
Pair Fit

- Fit 2 tracks from $e^+e^-\rightarrow\mu^+\mu^-$ (and $e^+e^-\rightarrow e^+e^-$) simultaneously
  - Constrained to a common origin
  - Constrain $\Sigma$ momentum to ‘known’ CM 4-momentum
    - Scale errors for beam uncertainties
    - Implemented in the BaBar Kalman track fit
- Provides pair-constrained residuals
  - Not just a mass-constrained vertex fit!
- Constrains curl, bowing, and skew distortions
- Technique can work for other track pairs (ie $\psi\rightarrow\mu^+\mu^-$)
- Depends on initial beam parameter knowledge
Optical Survey

- Use combination of Module Survey (lab bench) + Assembly Survey
- Constraint of wafers within a module complementary to tracks
- Constrains $Z$ expansion distortion

Top ($\phi$-$z$) view

(side ($r$-$z$) view  
(distortions X 50)

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Survey Constraint

- Compute ‘survey to current’ transform using reference wafers
  - Minimize difference between position of fiducials on the wafers
- Predict position of ‘test’ wafer position in ‘current’ alignment
- Compute $\Delta \chi^2 = \text{difference between current and survey position}$
  - Multiply out-of-plane errors $\times 10$ to accommodate motion since survey
- Add survey $\Delta \chi^2$ to track residual $\chi^2$
Outer Tracking Constraint

- Tracks are split at boundary
  - Each half fit separately
- Outer track fit used to constrain the inner track fit
  - Can select which parameters to propagate
  - Improves precision while controlling propagation of outer tracker systematics
  - Standard feature of BaBar Kalman track fit
- \( \mu \)-pair + cosmic (high p)
  - Constrain only curvature
- Isolated high-P hadrons
  - Constrained to full outer track fit (5 parameters)
- Keeps relative (global) alignment from drifting
Alignment Data Reduction

Central reconstruction

BaBar Data
Calibration stream
1% of all events
Calib. Data
Alignment skim
0.1% of calib. data
Align Data

- A dedicated sample is selected during reconstruction
  - \( \mu \) pairs, cosmics, prescaled hadronic events with high \( P \) tracks, ...
  - Written to a dedicated stream (file)
- From ~ 2 days accumulation we extract an alignment sample
  - Events are prescaled by type and polar angle coverage
    - Timescale driven by cosmics
  - Only selected tracks are kept, all other data is removed
    - Outer tracker info is kept as a fit constraint, reduces track size by 1/3
  - Hits are prescaled for uniform coverage, selected hits are flagged
    - Defines fixed selection of hits used across iterations
    - Greatly reduces statistical correlation between wafers
- Customizations are built in to the BaBar Data Model
Alignment Iteration

- Iteration factorizes the alignment problem
  - No need for huge matrix inversion (6X6 vs 1440X1440)
  - No need to compute distant derivatives
- 1 iteration = loop over all wafers
- Minimize $\sum \chi^2$ (closed form) for each wafer
  - Sum $\Delta \chi^2$ + associated derivatives wrt alignment parameters
  - Solve for the change in this wafers alignment parameters
- Wafer positions are updated only after a full iteration
  - Parallelizable (if wall-clock time were an issue)
- Initialize using previous, survey, nominal, test configuration, …
- Tighten residual cuts after partial convergence
  - Reduces the effect of outliers without biasing alignment
  - Requires re-writing alignment dataset (reflagging hits)
- Convergence $\equiv$ when wafers stop moving
  - $\Delta \chi_p^2 \equiv (\Delta P/\sigma P)^2/6 < 0.01$ for every wafer in 1 iteration
  - $\sim 100$ iterations, <24 hours real-time (single processor)
Alignment Convergence

\[ \chi^2 / N_{\text{dof}} \]

- Tight residual cuts applied

- Convergence
  \[ \equiv \Delta \chi^2_{p} < 0.01 \text{ for every wafer} \]
  \[ (\sim 100 \text{ iterations}) \]
Alignment Operations

- Alignment computed every 2 weeks (or as necessary)
  - Fully automated (except validation!)
  - 2-day turnaround
  - Upload to database only if changes are significant (by a human)
- So far we have ~40 alignment periods, separated by
  - Detector interventions
  - Humidity effects
    - Carbon fiber is hygroscopic
- Detector has been stable for the past ~2 years

History of outer layer relative radial position vs Z for 2001→2003

http://dnbmac3.lbl.gov/~brownd/alignment/SvtChange_dr
Global Distortion Tests

- Validate the procedure against global distortions
  - Small, coherent relative wafer displacement
- Use undistorted MC sample composed as data
  - Cosmics, \( \mu \)-pairs, hadronic decays, …
- Align starting with a distorted initial condition
  - 50 \( \mu \)m scale, smooth dependence on either R, \( \phi \), or Z

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Example: Elliptical Distortion

Apply 0.1% elliptical distortion (~50μm amplitude in layer 5)

ΔR vs $\phi$ by layer

100 Iterations

Layer 1
Layer 2
Layer 3
Layer 4
Layer 5

before

~50μm amplitude

after

Residual amplitude <5μm
Tracks from material interactions agree with bench measurements to 0.03 ± 0.05 %
μ-pair miss distance

After alignment, we observed a strong 6-fold symmetry

Year 2002 data!
The Explanation: Wafer Bowing

- **Fit wafer sagitta**
  - Use both $u$ and $v$ residuals
  - Iterate with normal alignment
  - Mostly affects layers 1, 2 + 3

- **Correct in reconstruction**
  - Model $v$ strips as 3 linear pieces
Wafers are not planes (or cylinders)!

3-D Interferometric survey of 1 module before installation
μ-pair Miss Distance

- Average variation of $< 2 \, \mu m$ in $\Sigma d_0$, $< 10 \, \mu m$ in $\Delta z_0$
- With 10X standard alignment sample, structure is seen
  - More general non-planar distortions
**τ Lifetime Revisited (2005)**

- "The peak to peak variation of the reconstructed decay length vs $\phi$ is consistent with just natural lifetime fluctuations."

Average $\tau$

1-3 decay distance

![Graph showing $\lambda$ vs. $\phi$ (rel-12)]

- Entries: 400350

[Diagram of $\lambda$ vs. $\phi$ (rel-12)]

- Final alignment
BaBar’s sin2$\beta$ History

BaBar's sin2Beta vs Luminosity

Alignment Development

Luminosity (fb$^{-1}$)
Si Alignment Lessons Learned

- **Detector Design**
  - Prioritize material, resolution, stability
  - Simulate alignment to optimize overlap, layer coverage, ...

- **Construction**
  - Make Lab-bench measurements of all components
    - Survey aggregate sensor units (module, ladder, ...) in 3-D
    - Measure material properties of all active-region components
      - Si thickness, material of hybrids, location of masking, ...
  - Assembly survey as a cross check (if practical)

- **Software Design**
  - Data model support for alignment
    - Custom event selection, hit flagging, parameter constraints
  - Kalman track fit alignment-specific features
    - Pair fit, parameter constraint
  - Allocate adequate manpower to alignment development

- **Operations**
  - Allocate dedicated processing and storage for alignment
Lessons Learned (continued)

- **Procedure**
  - Accurately represents the true DOFs
    - Consider non-planar distortions!
  - Use complementary event types and external constraints
  - Prescale events to create a uniform, consistent data sample
  - Prescale and flag hits
    - Reduce statistical correlations
    - Consistent and stable $\chi^2$ calculations
  - Validate against realistic distortion scenarios
  - Don’t get hung up on mathematical details
    - Any well-behaved, additive measure will probably work
    - Any minimization technique that converges will probably work

- **Physics Use**
  - Plan for providing an early (preliminary) alignment
  - Provide analysts with a misalignment estimate

- **Be prepared for the unexpected!**
Backup Slides
How Well To Align?

### Vertex resolution

\[ \delta L \approx \frac{\delta_x}{0.7 \sqrt{N}} \oplus \frac{R_{\text{min}} \cdot 14 \text{ MeV} \sqrt{\Delta / X_0}}{P \sin^{3/2} \theta} \]

### Momentum resolution

\[ \frac{\delta P_t}{P_t^2} \approx \frac{\delta_x \sqrt{720/(N+5)}}{0.3L \int \vec{B} \times dL} \oplus O(1/P) \]

#### Statistical (< 5% from alignment)

- $\delta_{\text{in-plane}} < \delta_x / 3$
- $\delta_{\text{out-of-plane}} \sim \delta_{\text{in-plane}} / \theta$

#### Systematic (no visible biases)

- Roughly 3-times better than statistical on average
Pair Fit Results

- Curvature resolution improves >2 orders of magnitude!
- Constrains relative dip angle (through boost)
Lab ↔ Assembly Survey Comparison

- Compare at fiducials
  - Remove global DOFs
- <3\,\mu m in plane
  - \sim 1\,\mu m statistical
- \sim 20\,\mu m out of plane
  - \sim 10\,\mu m statistical
- Average these when used in alignment

Lampshade wafers
Event and Hit Prescaling

- Prescale events by category
  - $\mu^+\mu^-$, cosmic, overlap track, ...

- Prescale hits on each track
  - Uniformly populate wafers
  - Sample data period uniformly
  - Balance different event types
  - Eliminate statistical correlation between wafers

- Flag selected hits
  - The exact same hits are used to calculate $\chi^2$ every iteration
  - Can (anti-)select hits when validating
  - Written into the data

- Overlaps are under-populated
  - 1.5% nominal overlap in layer 4
Iteration Control

- Iteration is controled by tcl scripts with tk window
  - Parameters can be adjusted
  - Job progress is monitored
- Typical job converges in ~100 iterations and takes ~ 24 hours
μ-pairs after Curvature Correction

- Average distortion reduced to ~2 μm in $\Sigma d_0$, ~10 μm in $\Delta z_0$
- With 10X data, structure is seen!
Aleph VDET bonding error

Track position on wafer (cm)