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CMS Tracker alignment with cosmic data at the Integration Facility

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The first results of the CMS silicon-strip tracker alignment analysis are presented using the data from cosmic tracks, optical survey information, and the laser alignment system at the Tracker Integration Facility at CERN. During several months of operation in the spring and summer of 2007, about five million cosmic events were collected with a partially active CMS Tracker. With these data, the first alignment of the active silicon modules has been performed using three different statistical approaches. Comparison with simulations show that the achieved alignment precision can be estimated as 50 (80) μm in the outer (inner) part of the tracker barrel. Within this statistical precision, no instabilities of Tracker structures were found under temperature changes ranging from $+15^\circ$ C to -15° C and under mechanical stress of the system.

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1. Introduction

The design of the CMS tracker poses new challenges in aligning a system with more than 15,000 independent silicon modules. Given the precision needed for physics studies, the most accurate way to determine the silicon detector positions is to use the data generated by the detectors themselves when they are traversed by charged particles. Additional information about the module positions is provided by the optical survey during construction and by the Laser Alignment System during the detector operation.

The first opportunity of large-scale alignment tests of the CMS silicon strip tracker, ahead of the installation at the underground cavern, has come from the data taken at the Tracker Integration Facility (TIF). During several months of operation in the spring and summer of 2007, about five million cosmic events were collected. In this note, we show alignment results primarily with the track-based approach using these cosmic data, where three statistical algorithms have been employed. Assembly precision and structure stability with time have also been studied.

2. The CMS Tracker and track samples at the Integration Facility

The structure of the CMS tracker is described in detail in Ref. [1]. The silicon strip part consists of four main sub-detectors referred to as: Tracker Inner Barrel (TIB), Tracker Outer Barrel (TOB), Tracker Inner Disks (TID), and Tracker EndCaps (TEC).

At the TIF a simple system consisting of four plastic scintillators, placed above and below the partially active tracker, has been used to trigger cosmic muon events. Lead plates were included above the lower trigger scintillators, which enforced a minimum energy of the cosmic rays of 200 MeV to be triggered. In addition to room temperature, data were collected at +10° C, -1° C, -10° C, and -15° C. The large cosmic data sample at -10° C (about 900,000 tracks) has been mainly analyzed for track-based alignment, the others being used only for temperature-dependence tests.

The performance of alignment algorithms was validated with simulated data. A sample of approximately three million cosmic events was generated, tuning the energy spectrum to data from CAPRICE [2] and retaining only cosmic muons within specific geometrical ranges, to reproduce the scintillator trigger configuration.

Charged track reconstruction includes three essential steps: seed finding, pattern recognition, and track fitting. Several pattern recognition algorithms are used in CMS [3]. For the alignment analysis we adopt the "Combinatorial Track Finder" (CTF): the track model used is a straight line parametrised by four parameters and the Kalman filter track fit takes into account both multiple scattering effects in each crossed layer and an estimate of the possible initial misalignment. Since no magnetic field was present during the data-taking, momentum of the tracks could not be measured and estimates of the energy loss and multiple scattering were done only approximately. A track momentum of 1 GeV/*c* is assumed in the estimates, which is close to the average cosmic track momentum observed in simulated spectra.

For alignment purposes, a selection is applied to the track samples:

- the number of reconstructed tracks in an event must be exactly one;
- the normalized track fit is required to be $\chi^2/\mathrm{ndof} < 4$;

- the number of associated hits in the tracker modules is required to be at least 5;
- the minimum total charge collected in the corresponding clusters is required to be 50 ADC counts;
- hit isolation is required (no other reconstructed hit within 8.0 mm);
- "outliers", i.e. single hits giving a contribution to the track χ^2 larger than 5, are rejected.

The combined efficiency for the cuts above (defined as the number of selected events over the total number of triggered events) is estimated to be 8.3% on TIF data and 20.5% on the TIF simulated sample, the discrepancy coming mostly from the absence of fake triggers and multi-track events in the simulation.

3. Alignment methods

3.1 Survey and laser alignment

The first detailed information about the relative position of modules within detector components and of the larger-level structures within the Tracker is available from the optical survey analysis prior to or during the Tracker integration. This includes Coordinate Measuring Machine data and photogrammetry, the former usually used for the active element measurements and the latter for the larger object alignment.

Additionally, the CMS Tracker is equipped with a Laser Alignment System (LAS), using infrared laser beams with fixed wavelength to monitor the position of selected tracker modules. It operates globally on tracker substructures (TIB, TOB and TEC disks) and cannot determine the position of individual modules. The goal of the system is to generate alignment information on a continuous basis, providing geometry reconstruction of the tracker substructures at the level of $\sim 100\,\mu$m.

3.2 Track-based alignment

The alignment analysis with tracks uses the fact that the hit positions and the measured trajectory impact points of a track are systematically displaced if the module position is not known correctly. The difference in local module coordinates between these two quantities are the *track-hit residuals* $\mathbf{r}_i$, which are 1- (2-dimensional) vectors in the case of a single (double) sided module and which are computed using all other measurements in the track trajectory except the hit itself, in order to make these quantities unbiased. One can minimise the χ^2 function which includes the covariance matrix $\mathbf{V}$ of the measurement uncertainties:

$$\chi^2 = \sum_i^{\text{tracks}} \mathbf{r}_i^T(\mathbf{p},\mathbf{q})\mathbf{V}_i^{-1}\mathbf{r}_i(\mathbf{p},\mathbf{q}) \tag{3.1}$$

where $\mathbf{p} = \{x, y, z, \theta_x, \theta_y, \theta_z\}$ represents the position and orientation of the modules and $\mathbf{q}$ represents the track parameters.

In CMS, three statistical methods are used to minimise Eq. (3.1):

- Hits and Impact Points (HIP): an iterative procedure to find a local analytical solution for **p** only [4];

- Kalman filter fit method: a sequential procedure updating alignment parameters after adding every track [5];

- MillePede minimisation: a method to find a global solution for **p** and **q**, taking into account all possible correlations [6].

which have all been used successfully in TIF Tracker alignment.

According to the statistics available in the Tracker sub-detectors, different choices are made for the maximal structure level for which a reliable track-based alignment can be achieved. A minimum of 100 hits per aligned object is required, which leads to the following choices:

- tracker barrels (TIB and TOB) are aligned at the level of the single sensor in the coordinate orthogonal to the strip positioning and in the stereo coordinate, for layers where this measurement is available. In TIB modules only, also the radial coordinate is left free.

- due to the cosmics rate decreasing rapidly vs. the angle w.r.t. the zenith, the vertical endcap structures receive much less hits useful for alignment. For this reasons TEC has only been aligned on a per-disk basis, while TID has not been aligned at all.

4. Alignment validation

4.1 Validation techniques

Validation of alignment performances at TIF is done in two different ways.

In the first methods track quantities are employed coming from a statistically independent data sample than those used in track-based alignment, in order to avoid biased estimates. This is achieved at TIF using cosmics taken at the same conditions but with much looser cuts than those listed in Sec. 3.2. Residual and track fit χ^2 distributions for these track samples are used to estimate improvements after alignment. In this method simulated data is used to estimate the average remanining misalignment. The simulated data is reconstructed first using an ideal CMS Tracker geometry, then adding artificially a random misalignment to sensors and higher structures, with increasing values. The estimate corresponds to the value of the applied misalignment when the residual and track fit χ^2 distributions match those observed in data after alignment.

A second method, which is used to estimate the level of consistency between the alignment techniques, is the direct geometrical comparison of the positions of objects determined by different methods. It must be noticed that there is a well-known weakness in this comparison that comes from the χ^2-invariant movements and deformations, which alignment is not sensitive to, due to the principles stated in Sec. 3.2. Such weakness will be overcome when tracks coming from different sources will traverse the detector (collision tracks, beam-halo, cosmics... etc.) while it remains in tests where tracks present a single, well-defined pattern, like cosmics.

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4.2 Validation results

Fig. 1 shows the value of the normalized track χ^2 in the validation sample discussed above, when different sets of module positions are considered in reconstruction. They come respectively frome the Tracker design geometry, from survey information and as calculated by one alignment algorithm (HIP). As can be inferred from the mean χ^2, already a visible improvement is achieved going from the design to the surveyed detector geometry, while the improvement becomes much more significant after track-based alignment. Only the last step of track reconstruction (i.e. track fitting) is repeated when considering different geometries, so neither the number the degrees of freedom per track, nor the total number of tracks can change when comparing results.

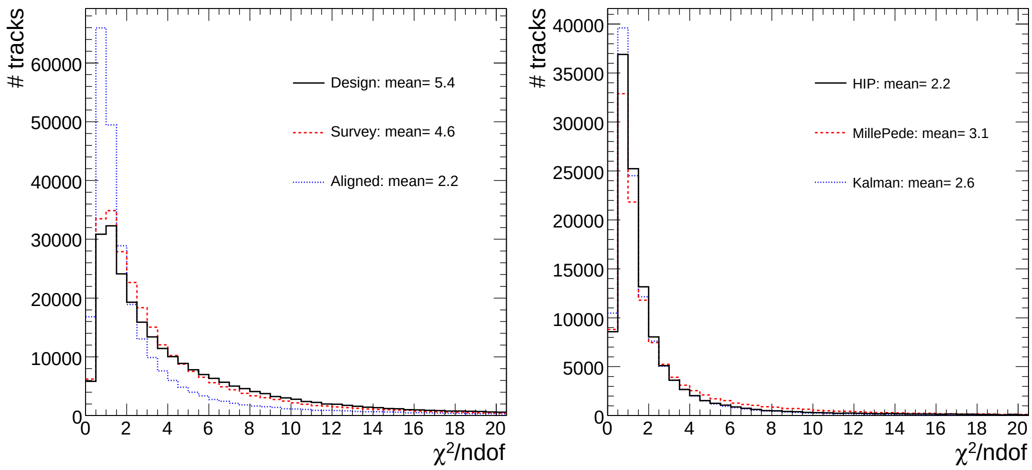

Figure 1: *Distributions of the normalized χ^2-values of the track fits for: design geometry, geometry updated after survey measurements and after HIP track-based alignment at TIF (left); geometries after HIP, Kalman filter and MillePede alignment (right).*

Fig. 2 shows the RMS value of the hit residual distributions per layer of the Tracker barrel. Comparison between data before and after alignment shows the large improvement reached, while comparison between aligned data and simulation with “tuned” misalignment is used to estimate the remaining misalignment in the detectors. A resonable match of RMS values is shown in the figures, corresponding to an average remaining misalignment of 50 (80) μm in the TOB (TIB) sensors. The limiting factor in the attained precision comes mainly from some track information which is missing using cosmic data, like the momentum measurement for the estimate of the multiple scattering contibution to the hit-residual uncertainties.

The most remarkable results of geometry comparisons are shown in the following.

Fig. 3 shows the differences in cylindrical coordinates (r and $r\phi$) between the non-aligned and HIP-aligned module positions in barrel. There is a clear coherent movement of the four layers of the TIB in both radial and azimuthal directions, compatible with the mounting technique of the TIB, in which modules are arranged on half-cylindrical concentric structures. On the other hand the scale of the effect (1-2 mm) is rather large with respect to expected mechanical precisions. The clear similarities in the r and $r\phi$ displacement patterns (leading to a correlation of $\rho_{r-r\phi}$ =

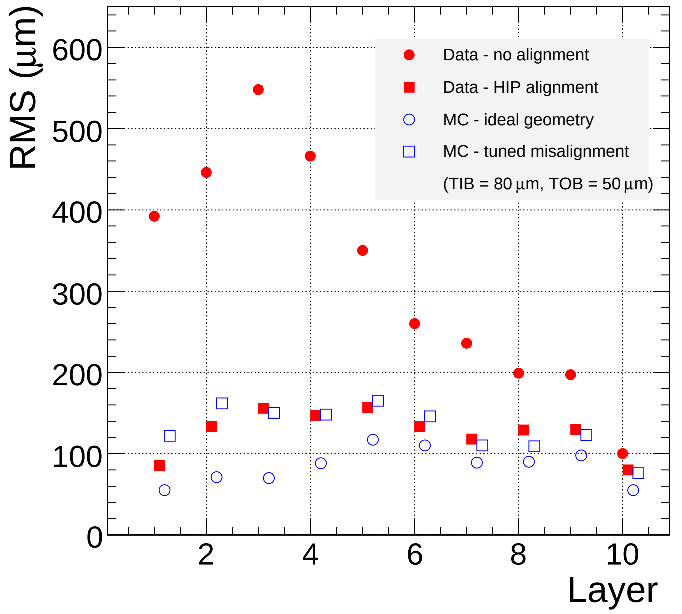

Figure 2: *Hit residual RMS in local x coordinate in ten layers of the barrel tracker, i.e. four layers of TIB and six layers of TOB, shown in data before track-based alignment (red full circles), after track-based alignment (HIP, red full squares), in simulation with ideal geometry (blue open circles) and in simulation after tuning of misalignment according to data (blue open squares).*

0.913) suggests the presence of possible weak modes, i.e. combination of coordinates with large uncertainty that cannot be solved using just the cosmic data sample.

For TOB, which was assembled with a different technique, the effect is much smaller for both layers within the TOB and for modules within layers. No obvious systematic deviations are observed apart from statistical scatter.

In order to check further the possibility of weak modes, Table 1 reports the RMS of the distributions of module positions as aligned by the three algorithms. Here an approximate decoupling of the possible weak modes is performed by the simple consideration that, transforming the results from the polar coordinates r and $r\phi$, used beforehand, into cartesian coordinates, the global x should be the most sensitive coordinate with a vertical track pattern, while y should appear as the main weak mode. The effect is mostly clear in HIP-Kalman comparison where values of the order of the expected misalignment are obtained for the Δx RMS while the Δy RMS is much larger. The absence of this discrepancy in TOB is due to the fact that the radial coordinate is constrained for these modules. The larger difference with the MillePede approach is partly due to the fact that this algorithm is capable to align a larger set of modules in TIB than the others, while only a common set is considered in this comparison.

Finally Fig. 4 shows the comparison between the positions of the nine positive-side endcap disks aligned alternatively with tracks or with the Laser Alignment System. The agreement in the alignment parameter $\Delta\phi$ (rotation about the global CMS z-axis) reaches the level of 0.1 mrad, which, considering an average disk radius of 0.6 m, is compatible with the LAS intrinsic resolution

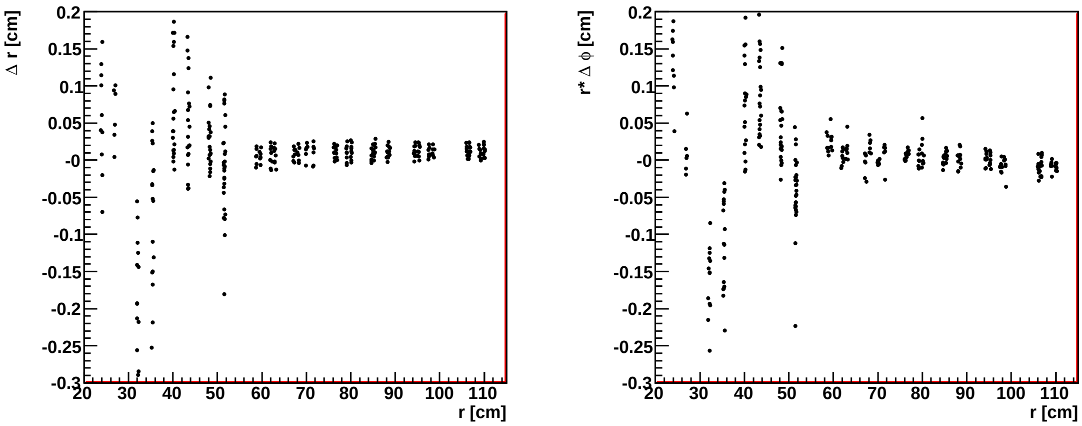

Figure 3: *Difference of the module positions between the measured (in HIP track-based alignment) and design geometries for TIB (radius $r < 55$ cm) and TOB ($r > 55$ cm). Projection on the r (left) and $r\phi$ (right) directions are shown.*

Algorithm 1	Algorithm 2	difference	TIB	TOB
Kalman	HIP	Δx	160	160
MillePede	HIP	Δx	340	160
Kalman	MillePede	Δx	300	120
Kalman	HIP	Δy	850	90
MillePede	HIP	Δy	1200	100
Kalman	MillePede	Δy	1320	60

Table 1: *Comparison of the global x and y RMS difference (in μm) of module positions between different geometries indicated in the first two columns for TOB and TIB.*

($\sim 100\mu$m).

Other comparison tests have been performed, both in barrels and endcap, e.g. between the data sets taken at different Tracker temperatures or before and after mechanical insertion of certain parts of it. Consistency has been observed between all of them, showing that the resolution of the alignment methods is not enough to highlight movements as small as those expected from deformations due to temperature changes.

5. Conclusions

First results of the CMS tracker alignment at the Integration Facility at CERN have been presented, coming from the analysis of cosmic data taken in spring-summer 2007, and compared to results of optical survey and the Laser Alignment System. Track-based alignment relies on a sample of about 900,000 cosmic muon tracks and is performed with three different statistical approaches.

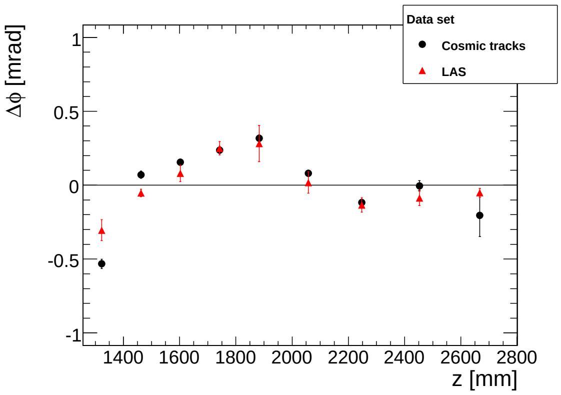

Figure 4: *Corrections $\Delta\phi$ for the nine TEC disks determined with track based alignment and LAS residuals.*

Overall, significant improvements in track χ^2 and hit residuals are achieved after track-based alignment of the Tracker at TIF, when compared either to design or survey geometry. Detailed studies have been performed of the Tracker Inner and Outer Barrel alignment with tracks. The typical achieved precision on module position measurement in the local x coordinate is estimated to be about 50 μm and 80 μm in the Tracker Outer and Inner Barrels, respectively. The above alignment precision estimates are based on prediction from MonteCarlo simulations of cosmic events.

Consistent alignment results have been obtained with the three different statistical methods. Direct comparison of obtained geometries indicate $\sim$150 μm consistency in the precisely measured coordinate, consistent with the indirect interpretation of track residuals. However, certain χ^2-invariant deformations appear in the alignment procedure when using only cosmic tracks and cannot be disentangled exactly from the intrinsic resolution of the method.

Alignment of the Tracker Endcap was performed at the disk level, both with tracks and by operating the CMS Laser Alignment System and showed good agreement between the two results. No significant deformations of the tracker have been observed under stress and with variation of temperature, within the resolution of the alignment methods.

Finally, experience gained in alignment analysis of the silicon modules at the Tracker Integration Facility is valuable in preparation for the full CMS tracker alignment, which is crucial to high precision to achieve the design physics goals of the CMS detector.

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