



# MillePede-II short review

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### MP - Introduction

- \* Millepede is a software package for linear least squares fits with a large number of parameters
- \* Developed and implemented in FORTAN77 by Volker Blobel (Univ. Hamburg)
- \* Used by several experiments for track based alignment and calibration

**MP basics** 
$$\chi^{2}(\Delta \mathbf{p}, \Delta \mathbf{q}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{hits}} \frac{1}{\sigma_{ij}^{2}} \left( \mathbf{m}_{ij} - \mathbf{f}_{ij} \left( \mathbf{p}_{0}, \mathbf{q}_{j0} \right) - \frac{\partial \mathbf{f}_{ij}}{\partial \mathbf{p}} \Delta \mathbf{p} - \frac{\partial \mathbf{f}_{ij}}{\partial \mathbf{q}_{j}} \Delta \mathbf{q}_{j} \right)^{2}$$

- \* Track based alignment (and calibration)
  - Minimizing  $\chi^2$  sum
    - + for large number of global (alignment) parameters  $\Delta \mathbf{p}$
    - + from large number of local fits (tracks  $\Delta q_j$ )
    - + with model f linearized at initial parameters ( $\mathbf{p}_0, \mathbf{q}_0$ )
  - Linear equation system with bordered band matrix
    - + Border populated due to global derivatives  $\partial f/\partial p$
    - + Block diagonal by (independent) local derivatives  $\partial f/\partial q_i$
  - Local fits  $(\partial \chi^2/\partial \Delta q_i=0)$  done with  $p=p_0$ 
    - + Size of lin. eqn. system reduced to number of global par.
    - + Correlations of global trough local parameters maintained

### Millepede basics (II)

#### \* Procedure

- Local (track) fits
  - + For all tracks 'j' solve linear equation system  $A_j \cdot \Delta q_j = b_j$
  - + With solution and  $A_j^{-1}$  fill global matrix  $A_g$  and vector  $\mathbf{b}_g$

#### Global fit

- + Optionally add constraints ( $C \cdot \Delta p = c$ , e.g. implement hierarchy)
- + Solve linear equation system  $A_g \cdot \Delta p = b_g$
- + Update alignment parameters:  $p=p+\Delta p$

#### Iteration

- + For outlier rejection repeat previous steps
- \*  $\chi^2$  cut for local fit changed from soft to hard

### Millepede history (I)

#### \* Millepede-I

- Development started 1996
- One set of (FORTRAN) subroutines
- Since 1997 main user has been H1 for calibration and alignment of the central drift chambers
  - + Online calibration: mean drift velocity, Lorentz angle vs t
  - + Offline calibration: vd, alor vs R, φ, B(Z,R), E, P, ...
- Applicable for up to several thousand parameters
  - + Matrix inversion as only solution method, CPU time  $\sim n_{par}^3$

### MillePede history (II)

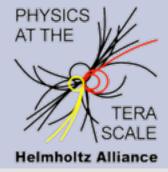
#### \* MillePede-II

- Development started 2005 for LHC experiments
  - + Allow for 100 000 parameters
- Split into two parts
  - \* Mille: create binary files with measurements, errors and derivatives from user code (C/C++ or FORTRAN)
  - \* Pede: standalone FORTRAN executable, steering text file and binary files as input
- Main user is CMS for alignment of the Si tracker
  - + 25k (curved) Si sensors

### MillePede history (III)

- \* New features with MillePede-II
  - Matrix storage
    - + Sparse: only nonzero matrix elements Mij stored
      - In alignment typically only 10-30% of  $M_{ij}$ <>0 (i,j connected by track(s))
  - Solution method
    - + MINRES: stepwise minimize  $|A_g \cdot \Delta p b_g|$  to obtain  $\Delta p$ 
      - $A_g^{-1}$  is not calculated  $\rightarrow$  no errors for results
      - CPU time dominated by product 'matrix times vector': ~npar2·nstep

V. Blobel: Track based alignment, Nuclear Instruments and Methods A, 566 (2006), pp. 5-13)



## MillePede today

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- Maintenance and development by Statistics Tools group of Analysis Center in Helmholtz Terascale Alliance
- \* Moved to FORTRAN90, 64bit (doxygen documentation)
- \* Optimization of (Pede) resource usage
  - Memory: matrix compression
  - ▶ CPU: parallelization with <u>OpenMP<sup>TM</sup></u>
  - Fit 200k parameters from 10<sup>7</sup> tracks in 32GB in 10h