Status of Reference Network Simulations

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LET Beam Dynamics Simulation Meeting

19 March 2009

LiCAS

OXFORDphysics

Linear Collider Alignment & Survey

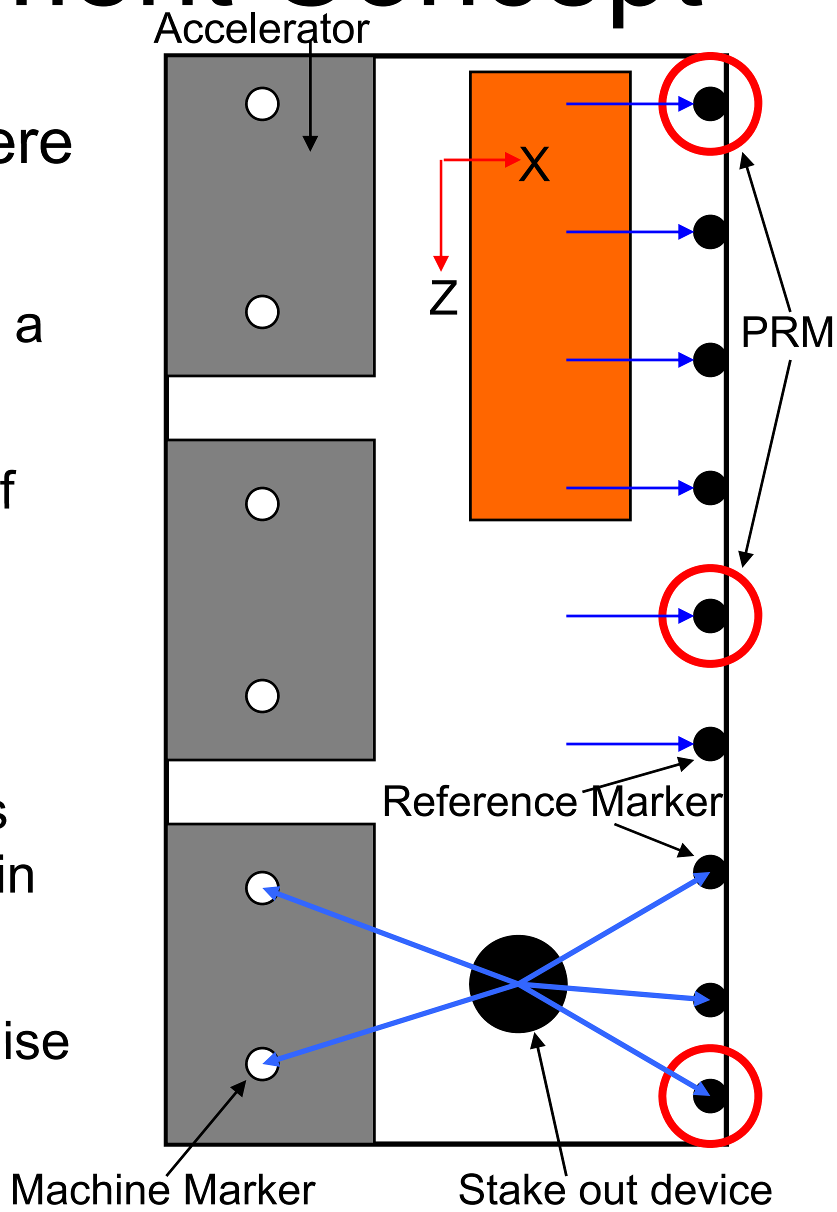
John Adams Institute J.A.I. for Accelerator Science

Introduction

- Accelerator Alignment Concept
- Reference Network Simulations Model
  - Concept
  - Linearised model
  - Free network constraint
- Reference Network Simulation Results
  - Error Curves
  - Dispersion Matched Steering (DMS) results

Accelerator Alignment Concept

- Many possible ways to Align an Accelerator, the concept used here is:
  - Over lapping measurements of a network of reference markers using a device such as a laser tracker, stretched wires or LiCAS RTRS
  - Measurements of a small number of Primary Reference Markers (PRM) using, for example GPS transferred from the surface.
  - Combining all measurements in a linearised mathematical model to determine network marker positions
  - Using adjusted network to align Main Linac
  - Using Dispersion Matched Steering (DMS) to adjust correctors to minimise emittance



Reference Network Simulation Aims

- Generate ILC reference network solutions which can be used for LET simulations
- Easy to use
- Quickly (minutes not days)
- Correct statistical properties
- Capable of simulating existing as well as novel network measurement techniques

Possible Approaches

- Commercial survey adjustment software
  - Expensive
  - Need to be survey expert to use
  - Usually only use laser tracker/tachometers
- Full simulation of a specific device
  - Slow to generate networks
  - Restricted to one measurement technique
- Simplified Model
  - If designed correctly can be quick
  - Can be used to model novel devices

Simplified Model

- Have a device model
  - measures small number of RMs E.G. 4
  - moves on one RM each stop and repeats measurement
  - rotates around the X and Y axis
  - determines vector difference between RMs
  - only the error on the vector difference determination is required as input
- PRM measurements are vector difference measurements between PRM's

The Linearised Model

- M device stops, N reference Markers Total, O PRMs Total, device measures 4 markers per stop
- Measurement Vector L
- Measurement Covariance Matrix P
  - Simple diagonal matrix assuming no cross dependency on measurements
- Variables Vector X
- Prediction Vector F(X)
- Difference Vector $W = F(X) - L$
- Design Matrix $A = \delta F(X)/\delta X$

The Linearised Model

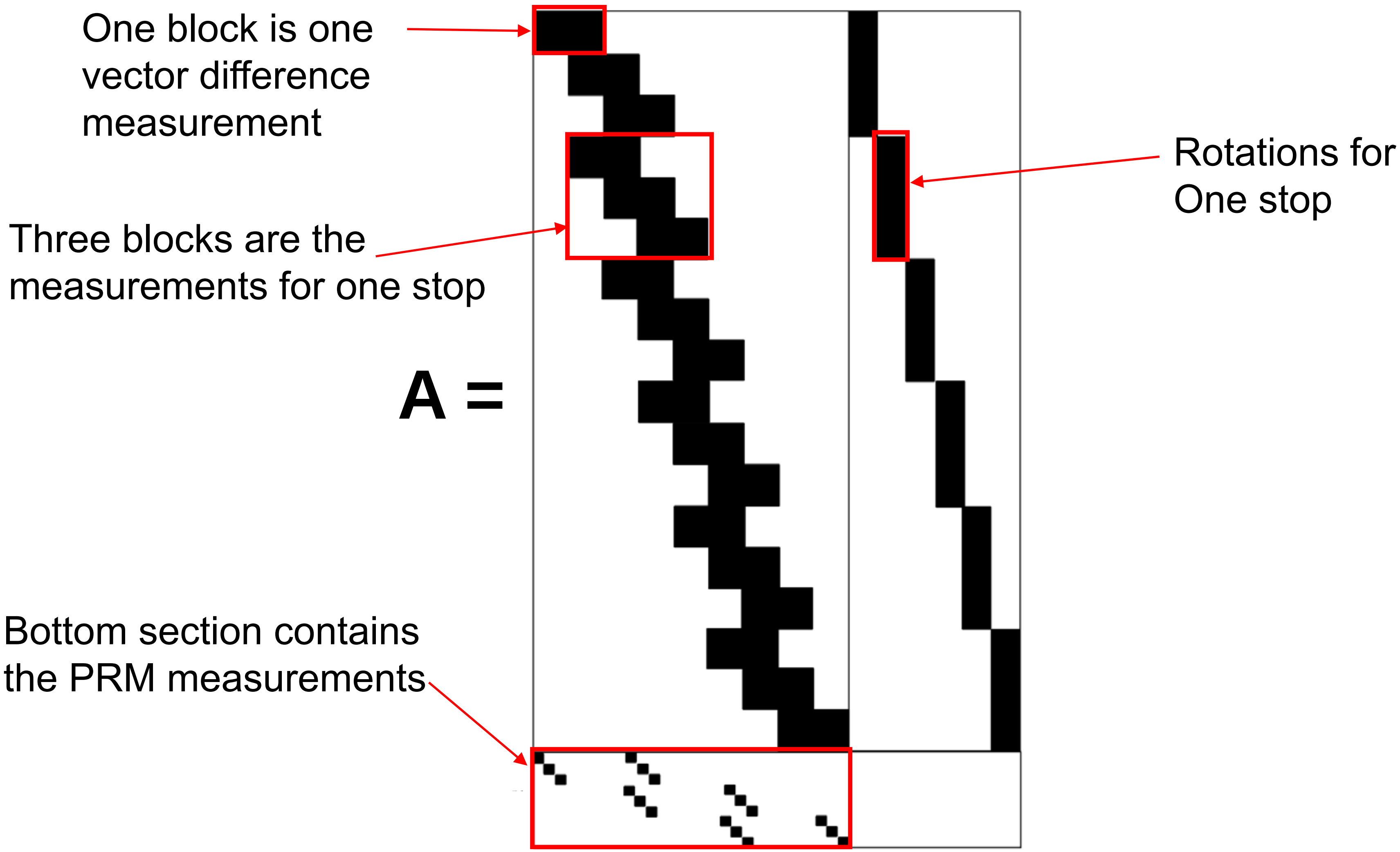
$$L = \begin{bmatrix} \Delta X'_{1,1\to 2} \\ \Delta Y'_{1,1\to 2} \\ \Delta Z'_{1,1\to 2} \\ \Delta X'_{1,2\to 3} \\ \Delta Y'_{1,2\to 3} \\ \Delta Z'_{1,2\to 3} \\ \Delta X'_{1,3\to 4} \\ \Delta Y'_{1,3\to 4} \\ \Delta Z'_{1,3\to 4} \\ \Delta X'_{2,2\to 3} \\ \Delta Y'_{2,2\to 3} \\ \Delta Z'_{2,2\to 3} \\ \vdots \\ \Delta X'_{2,4\to 5} \\ \Delta Y'_{2,4\to 5} \\ \Delta Z'_{2,4\to 5} \\ \vdots \\ \Delta X'_{m,m\to m+1} \\ \Delta Y'_{m,m\to m+1} \\ \Delta Z'_{m,m\to m+1} \\ \vdots \\ \Delta X'_{m,m+2\to m+3} \\ \Delta Y'_{m,m+2\to m+3} \\ \Delta Z'_{m,m+2\to m+3} \\ \Delta X_{GPS_1\to GPS_2} \\ \Delta Y_{GPS_1\to GPS_2} \\ \Delta Z_{GPS_1\to GPS_2} \\ \vdots \\ \Delta X_{GPS_O\to GPS_{O-1}} \\ \Delta Y_{GPS_O\to GPS_{O-1}} \\ \Delta Z_{GPS_O\to GPS_{O-1}} \end{bmatrix}$$

$$X = \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \\ \vdots \\ X_n \\ Y_n \\ Z_n \\ \theta_1 \\ \phi_1 \\ \vdots \\ \theta_m \\ \phi_m \end{bmatrix}$$

The Linearised Model

$$
F(X) = \begin{bmatrix}
\Delta X'_{1,1\rightarrow 2} \\
\Delta Y'_{1,1\rightarrow 2} \\
\Delta Z'_{1,1\rightarrow 2} \\
\Delta X'_{1,2\rightarrow 3} \\
\Delta Y'_{1,2\rightarrow 3} \\
\Delta Z'_{1,2\rightarrow 3} \\
\Delta X'_{1,3\rightarrow 4} \\
\Delta Y'_{1,3\rightarrow 4} \\
\Delta Z'_{1,3\rightarrow 4} \\
\Delta X'_{2,2\rightarrow 3} \\
\Delta Y'_{2,2\rightarrow 3} \\
\Delta Z'_{2,2\rightarrow 3} \\
\vdots \\
\Delta X'_{2,4\rightarrow 5} \\
\Delta Y'_{2,4\rightarrow 5} \\
\Delta Z'_{2,4\rightarrow 5} \\
\vdots \\
\Delta X'_{m,m\rightarrow m+1} \\
\Delta Y'_{m,m\rightarrow m+1} \\
\Delta Z'_{m,m\rightarrow m+1} \\
\vdots \\
\Delta X'_{m,m+2\rightarrow m+3} \\
\Delta Y'_{m,m+2\rightarrow m+3} \\
\Delta Z'_{m,m+2\rightarrow m+3} \\
\Delta X_{GPS_1\rightarrow GPS_2} \\
\Delta Y_{GPS_1\rightarrow GPS_2} \\
\Delta Z_{GPS_1\rightarrow GPS_2} \\
\vdots \\
\Delta X_{GPS_O\rightarrow GPS_{O-1}} \\
\Delta Y_{GPS_O\rightarrow GPS_{O-1}} \\
\Delta Z_{GPS_O\rightarrow GPS_{O-1}}
\end{bmatrix}
=
\begin{bmatrix}
(X_2 - X_1)Cos(\phi_1) + (Z_2 - Z_1)Sin(\phi_1) \\
(Y_2 - Y_1)Cos(\theta_1) - (Z_2 - Z_1)Cos(\phi_1)Sin(\theta_1) + (X_2 - X_1)Sin(\theta_1)Sin(\phi_1) \\
(Z_2 - Z_1)Cos(\theta_1)Cos(\phi_1) + (Y_2 - Y_1)Sin(\theta_1) - (X_2 - X_1)Cos(\theta_1)Sin(\phi_1) \\
(X_3 - X_2)Cos(\phi_1) + (Z_3 - Z_2)Sin(\phi_1) \\
(Y_3 - Y_2)Cos(\theta_1) - (Z_3 - Z_2)Cos(\phi_1)Sin(\theta_1) + (X_3 - X_2)Sin(\theta_1)Sin(\phi_1) \\
(Z_3 - Z_2)Cos(\theta_1)Cos(\phi_1) + (Y_3 - Y_2)Sin(\theta_1) - (X_3 - X_2)Cos(\theta_1)Sin(\phi_1) \\
(X_4 - X_3)Cos(\phi_1) + (Z_4 - Z_3)Sin(\phi_1) \\
(Y_4 - Y_3)Cos(\theta_1) - (Z_4 - Z_3)Cos(\phi_1)Sin(\theta_1) + (X_4 - X_3)Sin(\theta_1)Sin(\phi_1) \\
(Z_4 - Z_3)Cos(\theta_1)Cos(\phi_1) + (Y_4 - Y_3)Sin(\theta_1) - (X_4 - X_3)Cos(\theta_1)Sin(\phi_1) \\
(X_3 - X_2)Cos(\phi_2) + (Z_3 - Z_2)Sin(\phi_2) \\
(Y_3 - Y_2)Cos(\theta_2) - (Z_3 - Z_2)Cos(\phi_2)Sin(\theta_2) + (X_3 - X_2)Sin(\theta_2)Sin(\phi_2) \\
(Z_3 - Z_2)Cos(\theta_2)Cos(\phi_2) + (Y_3 - Y_2)Sin(\theta_2) - (X_3 - X_2)Cos(\theta_2)Sin(\phi_2) \\
\vdots \\
(X_4 - X_3)Cos(\phi_2) + (Z_4 - Z_3)Sin(\phi_2) \\
(Y_4 - Y_3)Cos(\theta_2) - (Z_4 - Z_3)Cos(\phi_2)Sin(\theta_2) + (X_4 - X_3)Sin(\theta_2)Sin(\phi_2) \\
(Z_4 - Z_3)Cos(\theta_2)Cos(\phi_2) + (Y_4 - Y_3)Sin(\theta_2) - (X_4 - X_3)Cos(\theta_2)Sin(\phi_2) \\
\vdots \\
(X_m - X_{m+1})Cos(\phi_m) + (Z_m - Z_{m+1})Sin(\phi_m) \\
(Y_m - Y_{m+1})Cos(\theta_m) - (Z_m - Z_{m+1})Cos(\phi_m)Sin(\theta_m) + (X_m - X_{m+1})Sin(\theta_m)Sin(\phi_m) \\
(Z_m - Z_{m+1})Cos(\theta_m)Cos(\phi_m) + (Y_m - Y_{m+1})Sin(\theta_m) - (X_m - X_{m+1})Cos(\theta_m)Sin(\phi_m) \\
\vdots \\
(X_{m+2} - X_{m+3})Cos(\phi_m) + (Z_{m+2} - Z_{m+3})Sin(\phi_m) \\
(Y_{m+2} - Y_{m+3})Cos(\theta_m) - (Z_{m+2} - Z_{m+3})Cos(\phi_m)Sin(\theta_m) + (X_{m+2} - X_{m+3})Sin(\theta_m)Sin(\phi_m) \\
(Z_{m+2} - Z_{m+3})Cos(\theta_m)Cos(\phi_m) + (Y_{m+2} - Y_{m+3})Sin(\theta_m) - (X_{m+2} - X_{m+3})Cos(\theta_m)Sin(\phi_m) \\
X_{GPS_2} - X_{GPS_1} \\
Y_{GPS_2} - Y_{GPS_1} \\
Z_{GPS_2} - Z_{GPS_1} \\
\vdots \\
X_{GPS_O} - X_{GPS_{O-1}} \\
Y_{GPS_O} - Y_{GPS_{O-1}} \\
Z_{GPS_O} - Z_{GPS_{O-1}}
\end{bmatrix}
$$

The Linearised Model



The Linearised Model

- Normal Non-linear least squares minimises W^TW leading to an improvement of estimates given by

$$\Delta X = -(A^TPA)^{-1}A^TPW$$

- Problem A^TPA is singular and not invertible

- Model Requires Constraints.

Free Network Constraints

- Five constraints required
- Could constrain first point to be at (0,0,0) and both the rotations of first stop to be 0.
  - Gives zero error at one end and large error at other. Not the desired form

- Use a free network constraint
  - Technique developed in Geodesy
  - The free network constraint is that X^TX is minimised.
  - If X^TX = min the trace of the output covariance matrix is also minimised
  - Equivalent to a generalised inverse
  - The least squares minimises W^TW and X^TX to give a unique solution

Free Network Constraint

- Break Up A^TPA into sub-matrices
  - N11 Must be non-singular
  - N22 size 5*5

$$A^T P A = \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix}$$

- Break X into sub-vectors
  - X2 length 5

$$X = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$$

- Gives constraint Equation

$$((N_{11}^{-1} N_{12})^T - I) \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = 0$$

Free Network Constraint

- Leading to constraint Matrix A2

$$A_2 = ((N_{11}^{-1} N_{12})^T - I)$$

- Improvement given by

$$\Delta X = -\begin{bmatrix} A^T P A & A_2^T \\ A_2 & 0 \end{bmatrix}^{-1} \begin{bmatrix} A^T P W \\ 0 \end{bmatrix}$$

- Output Covariance matrix given by
  - Contains the errors on the RM positions

$$\Sigma_X = \begin{bmatrix} A^T P A & A_2^T \\ A_2 & 0 \end{bmatrix}^{-1}$$

- Note ΔX and Σ_X are longer than X, but extra elements are zero.

Model Summary

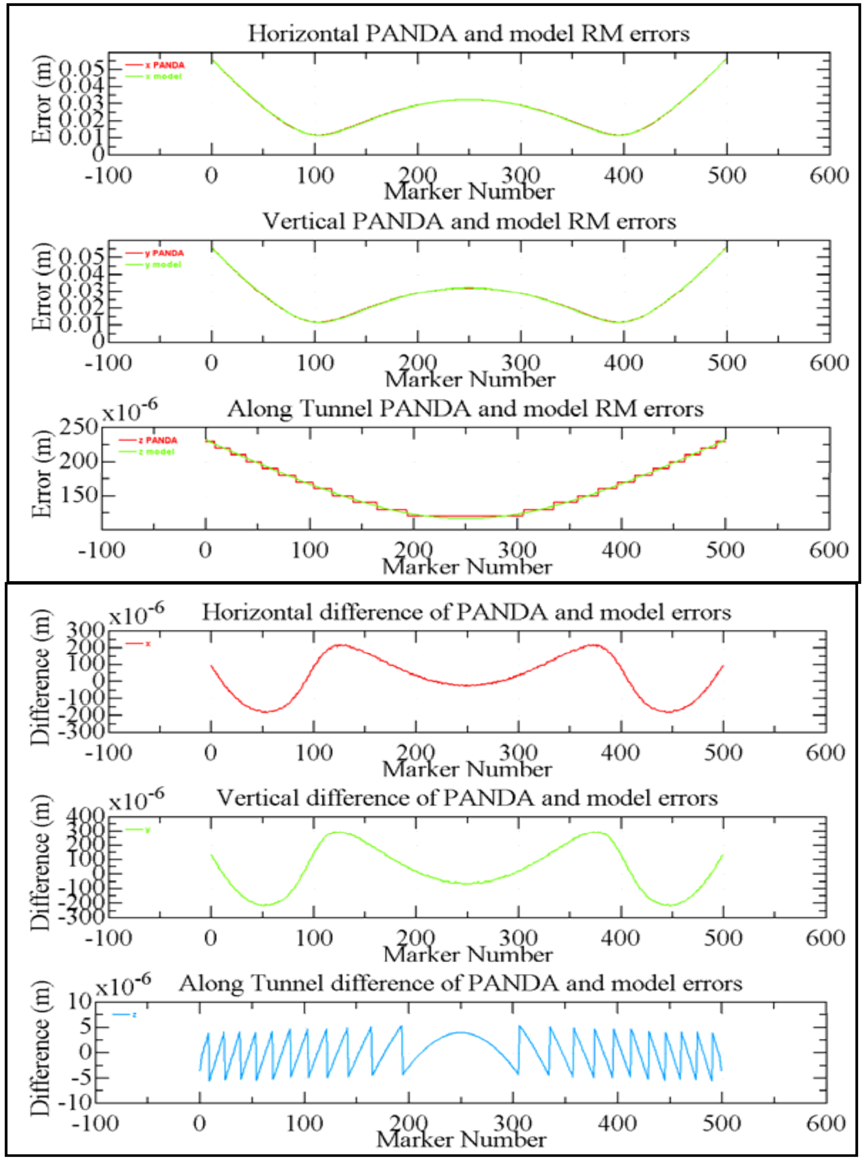
- Input
  - Device Measurement Errors
  - Number RMs measured by device in one stop
  - PRM Measurement Errors
  - Network Parameters
    - Number RMs, Number PRMS, RM spaceing, PRM spacing
- Output
  - Reference marker position difference from truth
  - Reference marker position statistical error

Laser Tracker Network Simulation

- Test model by comparing to laser tracker network
- Can simulate laser tracker networks using PANDA
- Use PANDA output to determine model parameters
  - minimising the difference between the PANDA statistical errors and the model statistical errors
  - Minimiser can adjust the model input parameters
  - minisation using JMinuit
- minisation done for networks with and without PRMs

Error Curve Comparison

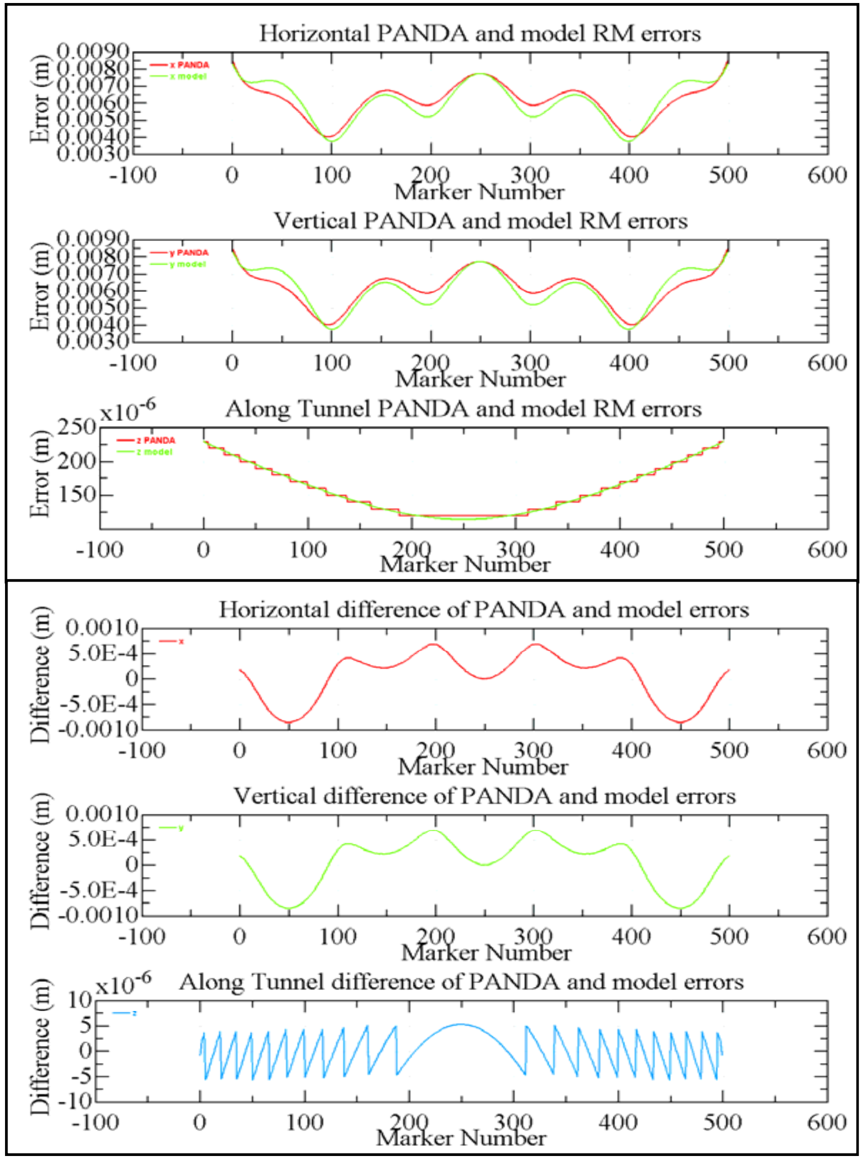
- Use Model to generate laser tracker measured network without PRM's
- Model used to produce network with the following parameters
  - No markers = 500
  - Space between markers = 25m
  - σx = 7.3046818E-05
  - σy = 7.2511348E-05
  - σz = 3.1150023E-05



Error Curve Comparison

- Use Model to generate laser tracker measured network with PRM's

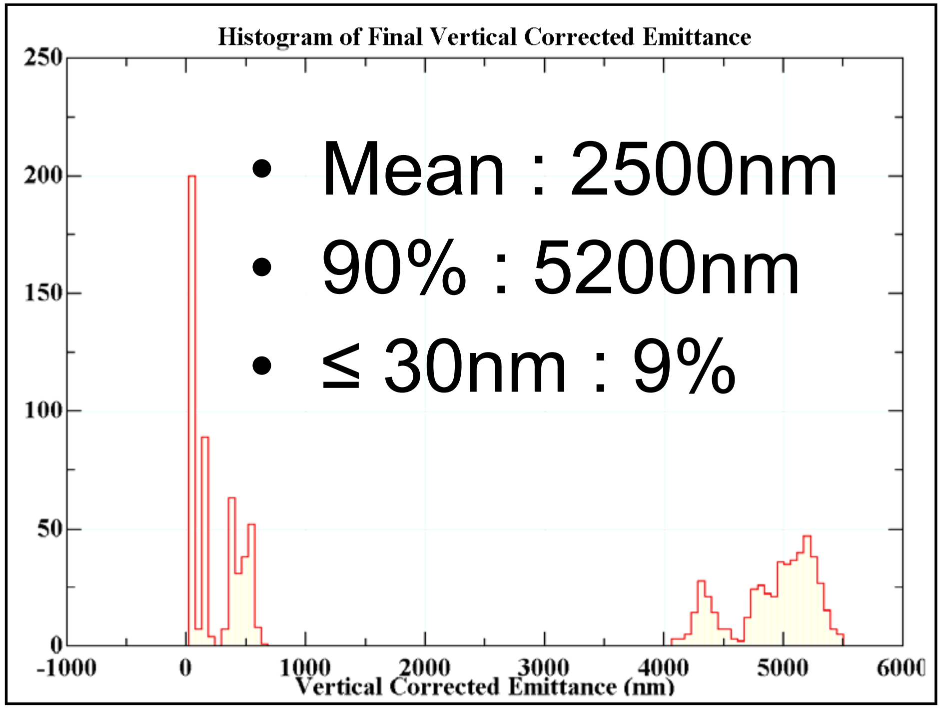
- Model used to produce network using the following parameters
  - No markers = 500
  - Space between markers = 25m
  - No PRM's = 6
  - Space between PRM's = 2500m
  - σx = 8.0917375E-05
  - σy = 8.0882151E-05
  - σz = 3.078411E-05
  - σGPS = 9.3804604E-03



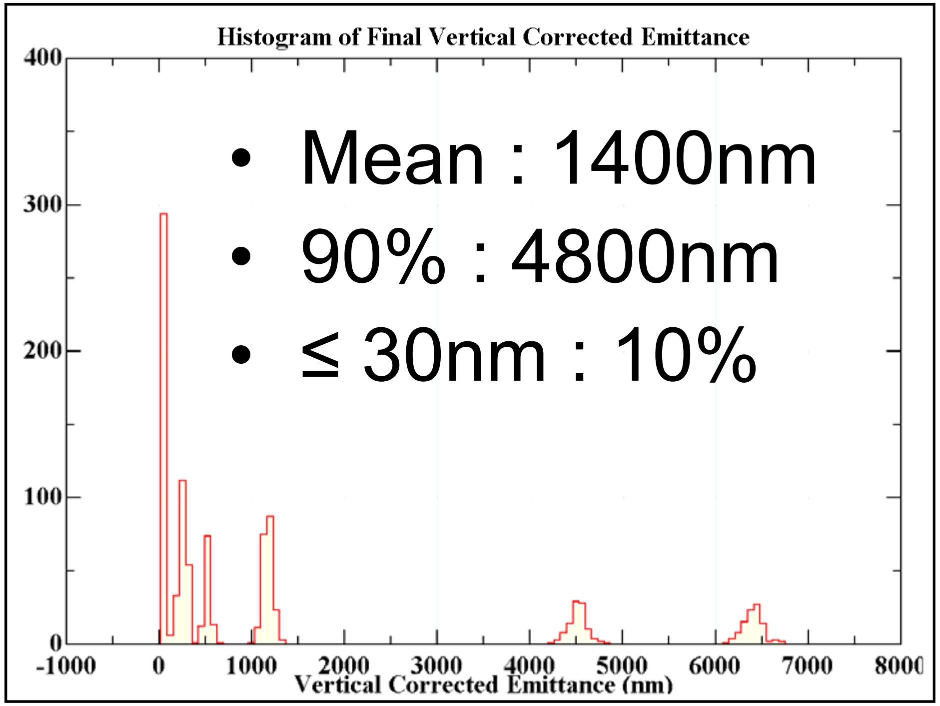
DMS Simulations for Laser trackers

- 10 networks generated without GPS using PANDA and the model
- 100 DMS simulations performed on each network using Merlin
- Note: PANDA results are revised compared to LCWS 2008

Model



PANDA



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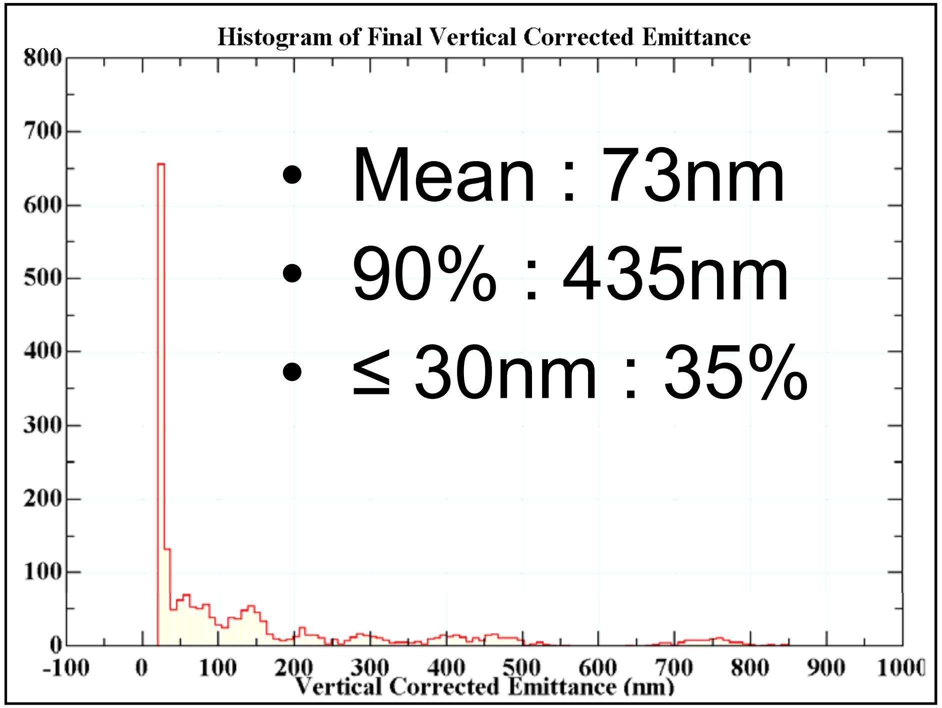
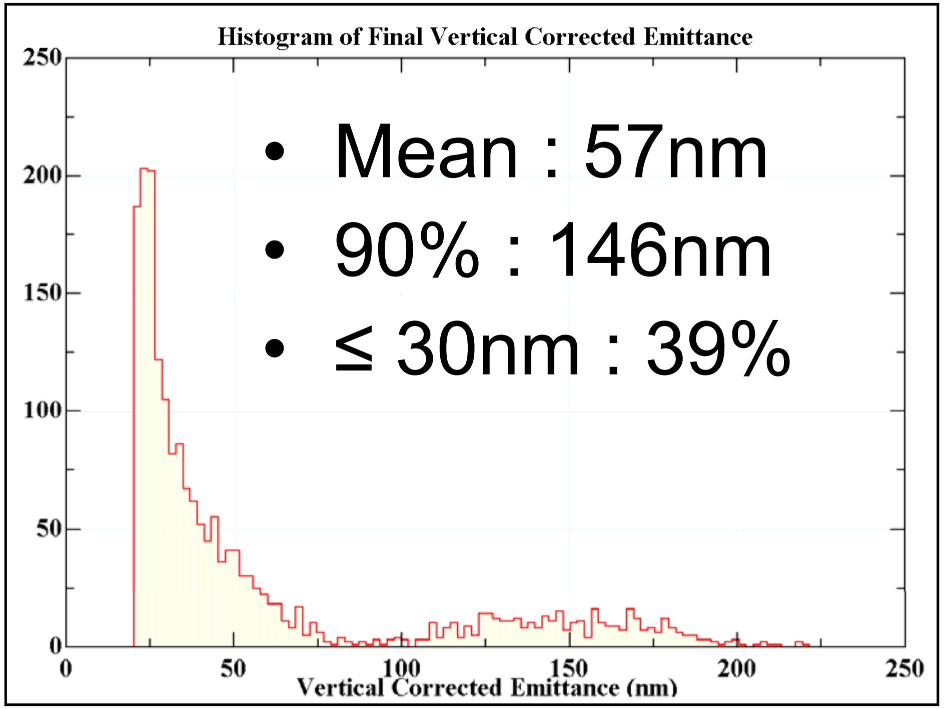
Model

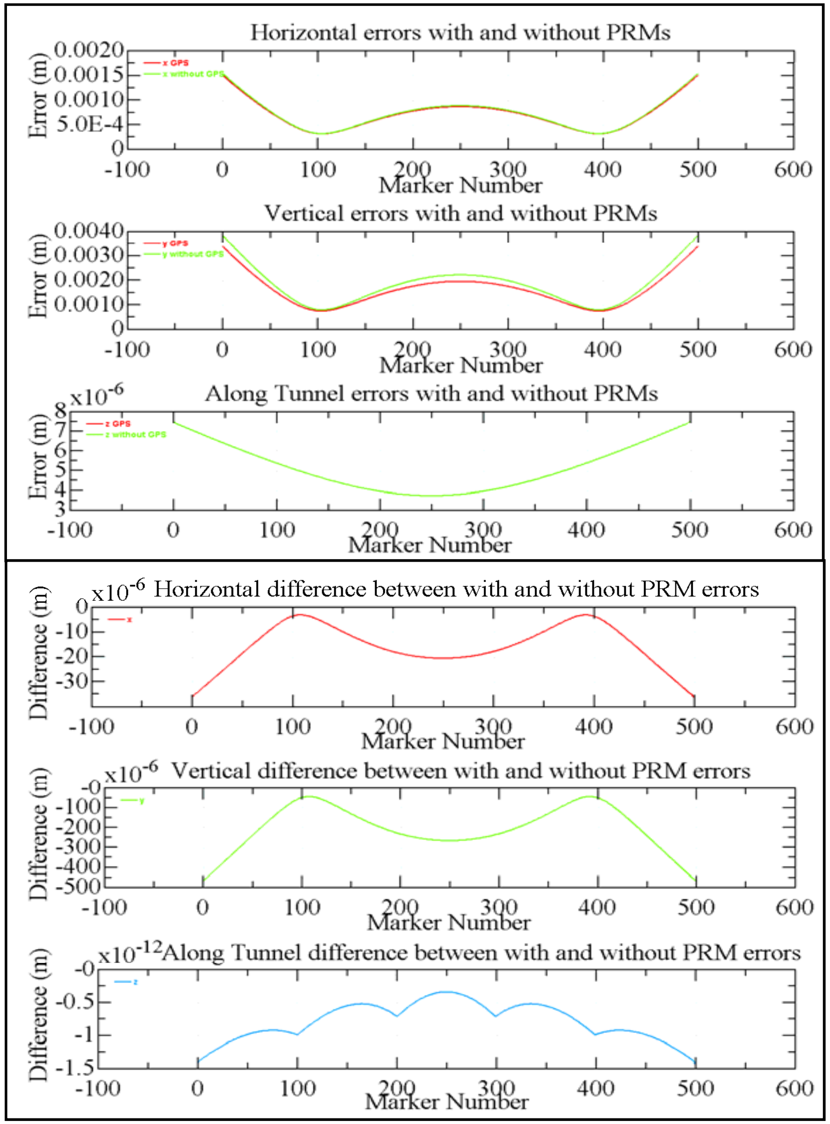


PANDA



First Statistical LiCAS RTRS Simulations

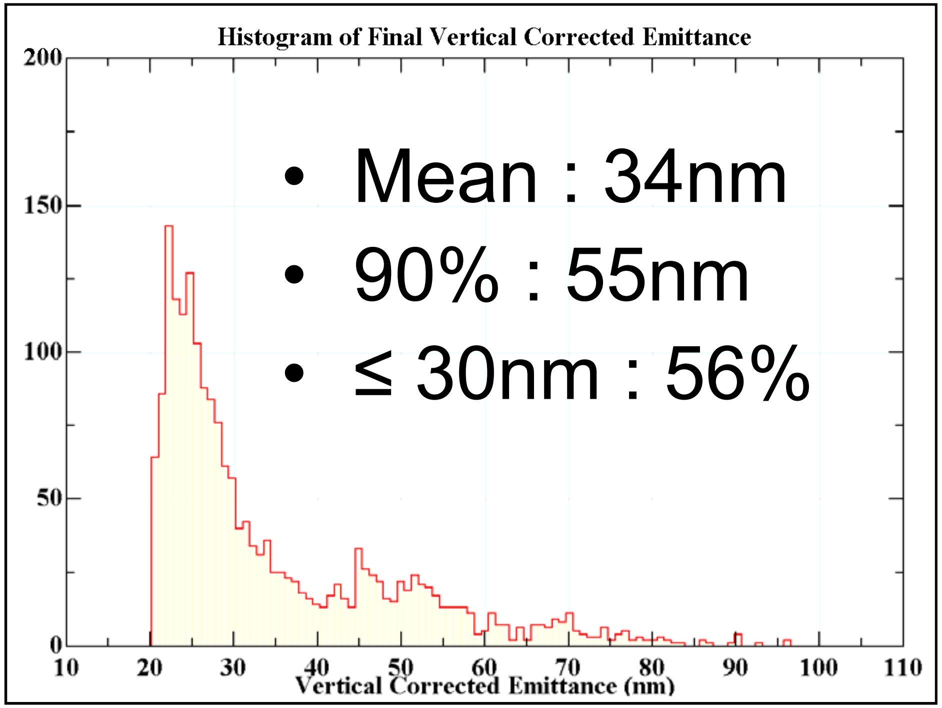
- Simulations performed with parameters to represent the LiCAS RTRS
  - σx = σz = 2.0E-06
  - σy = 5.0E-06
  - σGPS = 9.3804604E-03
  - Ball park figures, need to calculate actual
- No Systematics (systematcis are expected to dominate)
- Performed with and without PRMS



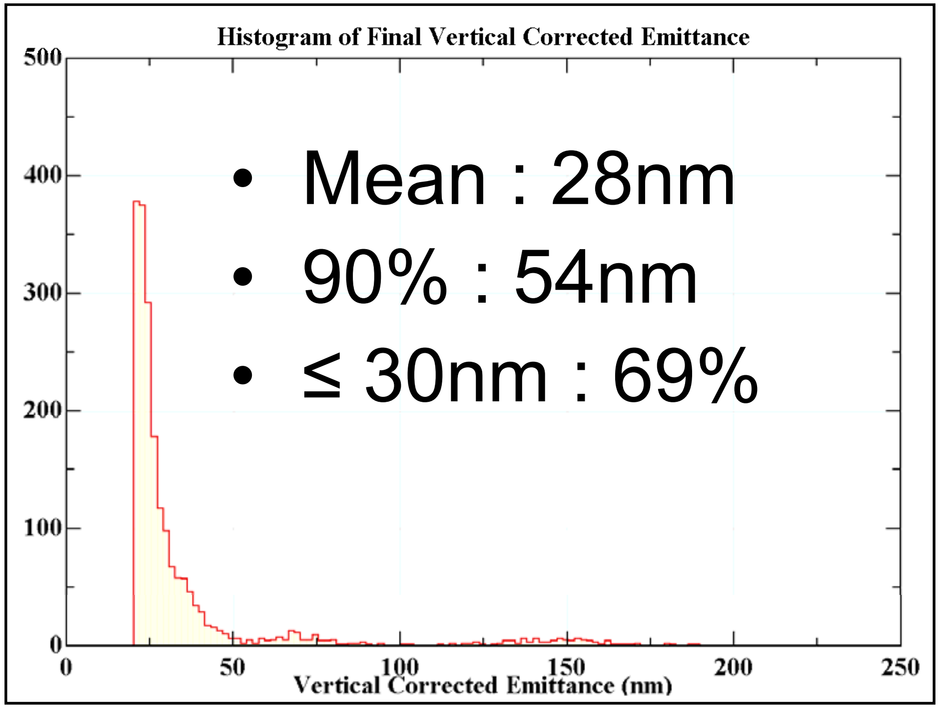
First Statistical LiCAS RTRS Simulations

- 20 networks generated with and without GPS
- 100 DMS simulations performed on each network using Merlin

With PRMs



Without PRMs



Future Work

- Find parameters to match laser tracker more closely
- Improve LiCAS Model Parameters
- Introduce systematics
- Generate more LiCAS networks to populate histograms further
- Verify DMS results using different code
- Release the Code