SIMULATION OF THE ALIGNMENT OF LINEAR ACCELERATORS

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Figure 1: Reference Network Measurement Procedure.

Abstract

The alignment of the next generation of linear accelerators will be much more critical than that of currently existing machines. This is especially true for very long machines with ultra-low emittance beams; such as the ILC and CLIC. The design and study of such machines will require a large number of simulations. However, full simulation of misalignment currently requires computer programs which are very resource intensive, and cannot simulate novel reference network measurement devices. A model which can be used to rapidly generate reference networks with the required statistical properties will be presented.

INTRODUCTION

A model has been developed to simulate reference networks for linear accelerators. Here the model will be described and compared to a commercially available network adjustment package PANDA [2]. The model aims to produce reference networks quickly, with the correct statistical properties and have the ability to simulate novel as well as existing reference network measurement techniques.

THE MODEL DESIGN

The Network

The network simulated in the model is a single horizontal line of Reference Markers (RMs), with a marker placed every S meters. The ideal network is set up with $x_n = y_n = 0.0$ and $z_n = n * S$, where x is the horizontal plane, y is the vertical plane, z is along the tunnel and n is the index $1 \leq n \leq numberOfMarkers$

The Measurement Simulations

There are two types of measurements simulated in the model: 1) Primary Reference Marker (PRM) measurements. 2) Standard network measurements.

PRM measurements are long range measurements between PRMs. There are O RMs defined as PRMs in the network which are placed every T m, where T >> S. At the ILC these measurements may take the form of GPS measurements on the surface which are transfered to the tunnel via access shafts. PRM measurements are simulated as vector differences in the global frame, the measurements are smeared and no cross dependency is assumed.

Standard network measurements are made using a device such as a laser tracker or a LiCAS RTRS. The simulated device measures vector differences between adjacent markers. The device measures a small number of markers
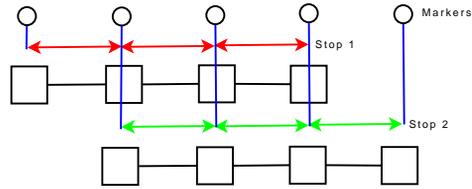
at one stop, moves on one marker position and measures the new set. This is repeated until all RMs are measured. For example the first device stop measures the differences between markers $1 \rightarrow 2$, $2 \rightarrow 3$ and $3 \rightarrow 4$; the second device stop measures between markers $2 \rightarrow 3$, $3 \rightarrow 4$ and $4 \rightarrow 5$ (see figure 1).

The vector differences are measured in the device's frame of reference. The device has two possible rotations: rotations around the x-axis (θ) and rotations around the y-axis (ϕ). The vector differences in the global frame is given by:

$$\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} X_{n+1} - X_n \\ Y_{n+1} - Y_n \\ Z_{n+1} - Z_n \end{bmatrix} \quad (1)$$

To get the measurements in the train frame we need to rotate using θ and ϕ. The rotation matrix for one train stop is R; leading to the difference measurements in the train frame, for one vector difference being:

$$\begin{bmatrix} \Delta X\prime \\ \Delta Y\prime \\ \Delta Z\prime \end{bmatrix} = R \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \quad (2)$$

The measurements simulated using the device are smeared and no correlations between measurements are assumed.

The Linearized Mathematical Model

The measurements simulated in the above section can now be used in a linearized mathematical model which will determine the best fit marker positions. The model has several matrices and vectors which need to be defined [6]: vector L contains the PRM measurements and the device measurements, vector X contains all of the current estimates for the positions of the RMs and the device stop rotations, function vector F(X) can predict all the values in L given X, the residual vector $W = F(X) - L$, the matrix of partial derivatives $A = \frac{\partial F(X)}{\partial X}$ and the covariance matrix P which is modeled as a single diagonal matrix.

Beam Dynamics and Electromagnetic Fields

FREE NETWORK SOLUTION

In standard linearized models an improvement to the variable's vector X is usually found by the equation[6]:

$$\hat{X} = -(A^T P A)^{-1} A^T P W \qquad (3)$$

However, in the model defined above, $A^T P A$ is singular and therefore not invertible, implying that constraints are required. There are five constraints required; a single marker position (x,y,z) and a pair of device rotations (θ,ϕ). If these variables are fixed the model will solve, however the errors at the fixed positions will be zero and the errors will increase away from these points, which is not ideal. Instead of using fixed points, a free network constraint can be used. The free network constraint matrix used in the model is [5]:

$$A_2 = ((N_{11}^{-1} N_{12})^T - I) \qquad (4)$$

Where:

$$A^T P A = \left[\begin{array}{cc} N_{11} & N_{12} \\ N_{21} & N_{22} \end{array} \right] \qquad (5)$$

Where N_{11} must be non-singular and invertible. The constraint matrix A_2 can be used to determine an improvement to the X by using the augmented vector:

$$\hat{X} = - \left[\begin{array}{cc} A^T P A & A_2^T \\ A_2 & 0 \end{array} \right]^{-1} \left[\begin{array}{c} A^T P W \\ 0 \end{array} \right] \qquad (6)$$

and the augmented covariance matrix for the variables is given by:

$$\Sigma_X = \left[\begin{array}{cc} A^T P A & A_2^T \\ A_2 & 0 \end{array} \right]^{-1} \qquad (7)$$

FULL SIMULATION OF REFERENCE NETWORKS USING PANDA

To test the model it was compared with a commercially available network adjustment program PANDA. PANDA is a software package which can design, optimize, adjust (solve for positions) and assess 3D networks. It is a commercial package used by, for example, the DESY geodesy group [1]. The package can only use laser trackers or tachometers along with GPS measurements. Details of how to perform full network simulations and the design of the full simulation reference network is described in reference [4].

ACCELERATOR SIMULATION AND MISALIGNMENT

To study the effect that a reference network has on an accelerators, beam dynamics simulations are performed. The simulations are performed using the Merlin particle tracking code, in particular its ILCDFS package [3], which can perform Dispersion Matched Steering (DMS). An accelerator is simulated which follows the earths curvature and
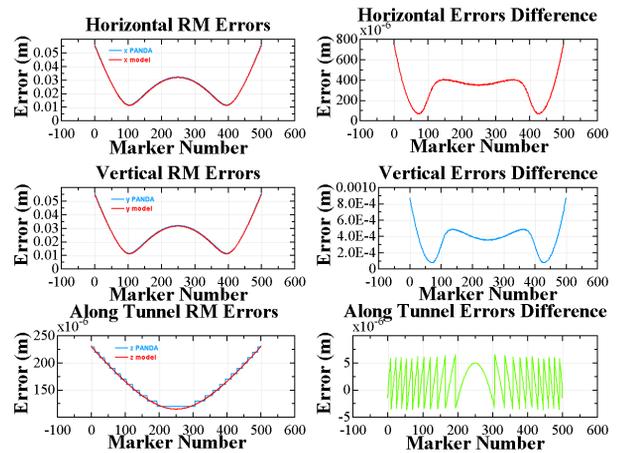

Figure 2: Laser Tracker Network Errors generated by the model and Panda Without PRMs.

misaligned by moving the components with respect to the reference network. The process of misaligning a simulated accelerator is described in reference [4].

COMPARISON TO LASER TRACKER NETWORK WITH AND WITHOUT PRIMARY REFERENCE MARKERS

To see how well the model performs; comparisons are made to PANDA using a laser tracker measured network. PANDA simulations, with and without PRMs, using a network setup of 500 RM rings, each spaced every 25m and PRMs spaced every 2500m. The model had 500 markers placed every 25m and PRMs every 2500m. The input parameters for the models were adjusted until the error curves generated by both the model and PANDA agreed. The adjustment of the parameters was performed by JMinuit. Table 1 shows model parameters determined by the fit.

Table 1: Laser Tracker Network Parameters without GPS.

Parameter	Without PRM	With PRM
$\sigma_X Device$	$7.3046818 * 10^{-05}$	$8.0917375 * 10^{-05}$
$\sigma_Y Device$	$7.2511348 * 10^{-05}$	$8.0882151 * 10^{-05}$
$\sigma_Z Device$	$3.1150023 * 10^{-05}$	$3.078411 * 10^{-05}$
σ_{PRM}	-	$9.3804604 * 10^{-03}$

Figure 2 left shows the error curves produced by PANDA and the model without PRMs, the differences between the curves is shown on the right. The differences show that the error curves disagree by less than 1.5%.

Figure 3 left shows the error curves produced by PANDA and the model with PRMs, the differences between the error curves are shown on the right. The differences with PRMs is only slightly worse than without PRMs, but the error curves produced by the model with PRMs is not as smooth as the error curves produced by PANDA.
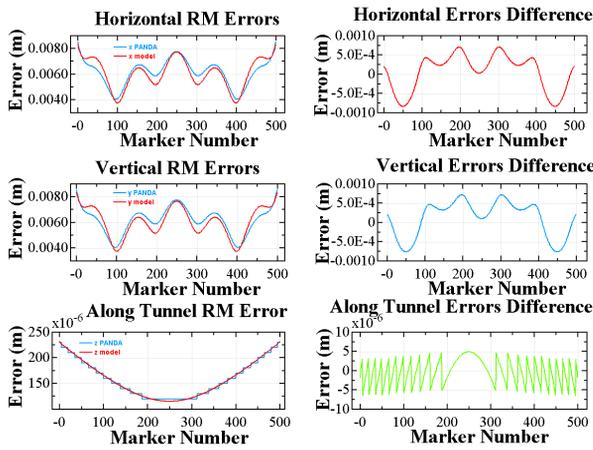
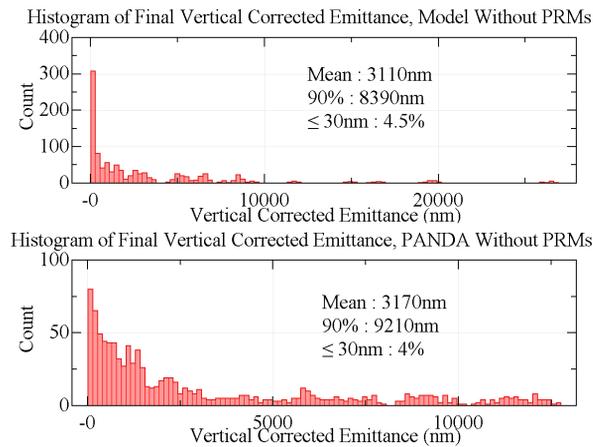Figure 3: Laser Tracker Network Errors generated by the model and Panda With PRMs.

Figure 4: Histograms showing DMS results using the Model and PANDA generated laser tracker network without PRMs.

Dispersion Matched Steering (DMS)

To compare the outputs of the model and PANDA, 100 network simulations were performed with PANDA and the model, with and without PRMs, using an ILC setup. For each network 10 misalignment and DMS simulations were performed and the results shown in figures 4 and 5.

CONCLUSION

Comparison of the histograms in figure 4 show that without PRMs there is good agreement between the model and PANDA. The model has a few events which have larger final corrected emittance, but this is expected as the model is simpler and the differences shown in figure 2 right are larger at the ends.

Comparison of the histograms in figures 5 show that with PRMs there is weak agreement between the model and PANDA, with the model causing higher final corrected
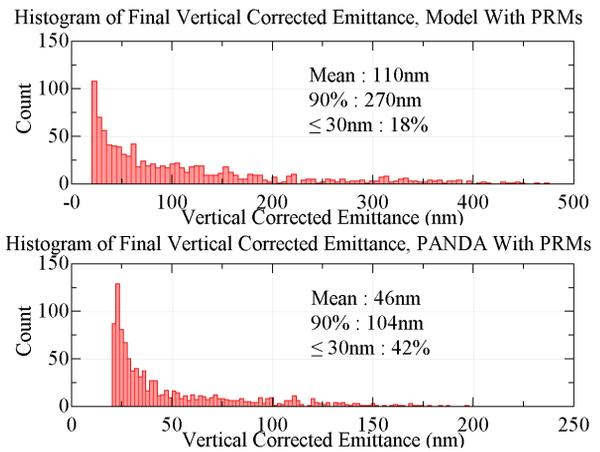

Figure 5: Histograms showing DMS results using the Model and PANDA generated laser tracker network with PRMs.

emittances. This is expected because the error curves in figure 3 generated by the model are not as smooth as those generated by PANDA, causing a higher final corrected emittance.

The histograms in figure 5 show that currently available laser trackers will not be capable of measuring the reference network of the ILC to a high enough precision as only 42% achieve the required corrected vertical emittance of < 30nm, the required vertical emmittance for the ILC.

FUTURE WORK

The model needs to be improved to deal with PRMs correctly. The model can then be used to study the effect of systematic as well as statistical errors in the measurement of reference networks. The DMS results have to be verified using a different simulation code.

REFERENCES

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