Laser Scan Analysis of the NOνA Far Detector Layer Surfaces

B.C. Mercurio, University of South Carolina, Columbia, SC
mercurio@barney.physics.sc.edu

Abstract

To determine how well the modules of the NOνA far detector are aligned, a laser scanner measures the positions of points on the upstream side of each layer. A C++ program has been developed to reduce the scanner data and display the shapes of the modules along their borders to the construction managers before construction of the next layer begins. In this paper, I present a summary of the program's algorithm and show a sample of its results.

INTRODUCTION

The NuMI Off-axis ν_{e} Appearance (NOνA) experiment is a long-baseline neutrino experiment designed to measure the probabilities of $\nu_\mu \to \nu_{\mathrm{e}}$, $\overline{\nu_\mu} \to \overline{\nu_{\mathrm{e}}}$, $\nu_\mu \to \nu_\mu$, and $\overline{\nu_\mu} \to \overline{\nu_\mu}$. The primary goals of NOνA are to reduce the uncertainty of Δm^2_{23} and the neutrino mixing angles θ_{13} and θ_{23}, to resolve the neutrino mass hierarchy, and to measure the CP-violating parameter of neutrino mixing. A beam of muon neutrinos will travel 810 km from Fermilab to a far detector in northern Minnesota. There will also be a near detector 1 km from the beam target to measure the ν_μ and ν_{e} rates before oscillation [1].

Both detectors use cells made of PVC extrusions and filled with liquid scintillator. The cells have widths of 6.6 cm parallel to the beam direction and 4.0 cm perpendicular to the beam direction. The cell lengths are 15.6 m in the Far Detector and 4 m in the Near Detector. 32 cells form a module, with 12 modules per layer in the Far Detector and 3 modules per layer in the Near Detector. The layers alternate between those with horizontally aligned cells and those with vertically aligned cells. The layers are assembled in groups of 32, called blocks [1][2].

In an ideal detector assembly, all cell axes in the same layer are coplanar. The vertical cell axes all point straight up. The horizontal cell axes all point at an elevation of exactly 1.25 mrad. The layers are separated by exactly 6.6 cm. Any significant deviation from the ideal detector alignments should be considered in the Monte Carlo simulations and track reconstruction algorithms.

After the Far Detector block assembly table (pivoter) has been set in place and after each layer has been added to the block, a Key Leica HDS6100 laser scanner measures the positions of points on the pivoter or on the upstream side of the layer [2]. A C++ program named NOνA Surface Analysis (NSA) has been developed to reduce the data from the laser scans and perform a quick analysis of how well adjacent modules are aligned within the layer.

COORDINATE SYSTEMS

When referring to relative positions inside the Far Detector building, "north" is a horizontal projection of the beam direction, and points close to northwest in geographic coordinates. "NOνA east" points close to northeast in geographic coordinates.

Monte Carlo Coordinates

The Monte Carlo coordinate system is used for detector simulation and track reconstruction. The origin is at the south (upstream) side of the detector. The z axis points north through the centers of the vertical layers. The y axis points up. The x axis points west.

Block Coordinates

The block coordinate system is used for block assembly and for the output of NSA. The origin is at the surface of the pivoter and directly below the expected center of the first layer to be assembled (Layer 31). The z axis points down. The y axis points north. The x axis points west.

After a block has been moved to its final position and orientation in the Far Detector, the x and y values of a point in block coordinates will be the same as in Monte Carlo coordinates. The correct offset in z will be measured at that time.

Scanner Coordinates

The scanner coordinate system is used for the output of the scanner software and the input of NSA. The origin is at the scanner, which hangs 17 m above the pivoter surface. The z axis points downward from the scanner to the pivoter. The x and y axes change whenever the scanner is reinstalled after maintenance.

Before Layer 31 is assembled, targets are placed at known positions on the surface of the pivoter. The pivoter is scanned and the positions of the targets are found in scanner coordinates. The position of the target placed at the origin of the block coordinate system defines the linear offset between scanner coordinates and block coordinates. The slope of a line connecting the target in the southeast corner to the target in the northeast corner defines the angular offset between the two coordinate systems.

ALGORITHM

NSA performs two tasks. The first is data reduction. It converts the points to block coordinates and removes points that are not needed in the surface analysis, for example points outside the layer surface. The second is a preliminary analysis of the shape of the surface to alert the technicians at the Far Detector construction site of emerging problems.

Box Cut

The laser scans include unwanted points that are outside the surface of the new layer. During the scan, a target is at each of the four corners of the layer, centered between the first and second (or last and second-to-last) cells and pressed against the end cap [2], as shown in Figure 1.

NSA uses the minimum and maximum values of x, y, and z from the positions of the targets to define a virtual box. The edges of this virtual box are shifted 212 mm inward parallel to the cells in order to exclude the black area of the surface. Then they are shifted 33 mm outward perpendicular to the cells in order to include the first and last cells. Then they are shifted 30 mm outward perpendicular to the surface in case the layer contains any major bumps or dips. For horizontal layers, the north and south sides of the virtual box are rotated 1.25 mrad to match the expected rotational offset of the horizontal layers. All scanned points outside that virtual box are removed from the analysis.

Figure 1: Northwest corner target for a horizontal layer. Photograph by Bill Miller.

Nadir Thinning

The points in the scan are separated by 0.009° in nadir angle and 0.009° in azimuth. Projected on a flat surface at the same height as the new layer, the points would have a radial separation of about 3 mm and a lateral separation that becomes extremely small near the pole. The point density near the scanner's nadir is much higher than needed for this analysis.

All points within 5 mm of the z axis in scanner coordinates are removed. 99% of all remaining points within 3 cm of the z axis are removed. 96% of the points between 3 cm and 10 cm away from the z axis are removed.

Spike Removal

If a part of the surface is perpendicular to the laser beam, the reflected signal is too bright for the scanner to correctly measure the distance to the point of reflection. As a result, some small clusters of points will be measured as too close or too far from the scanner. When viewing projections of the raw data, these clusters look like spikes pointing into or out of the layer like in Figure 2. They can prevent NSA from finding the positions of the cells.

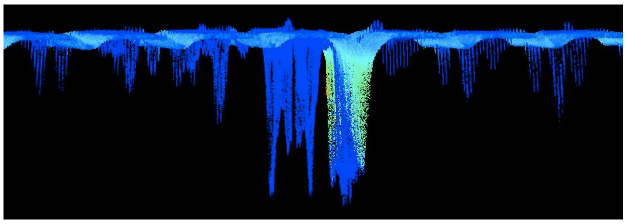

Figure 2: Edge view of a section of the surface, as interpreted by the laser scanner. Several clusters of points were given incorrect distances from the scanner.

NSA divides the surface into 2400 sections of size $\sim$25 cm perpendicular to the cells and $\sim$37 cm parallel to the cells. The mean value of z is calculated for each section. All points with z value $>$ 9 mm away from the mean are removed. The mean value of z is recalculated for the remaining points. All points $>$ 6 mm away from the new mean are removed. The mean value of z is calculated a third time.

All points that have survived the cuts so far are output using the fprintf text format "%-9.5f %-9.5f %-9.5f\n",X,Y,Z. Other programs can then read in the reduced data at a later time and perform more precise calculations of the cell positions.

Groove Finder

The module surfaces as designed are not actually flat, instead containing grooves, or scallops, between the cells and at the module borders. The points inside the grooves should not be included in a calculation of how close all cells in the same layer are to being coplanar. Figure 3 illustrates this problem.

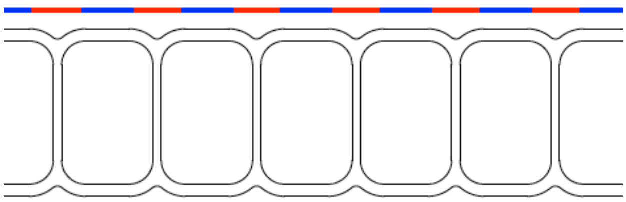

Figure 3: Drawing of an edge view of part of a module. The surface under the blue is what should be flat. Points on the surface under the red are in the grooves. Based on a drawing in [3].

Each 25 cm $\times$ 37 cm section is divided into narrow bins of size $\sim$1.5 mm perpendicular to the cells and 37 cm parallel to the cells. If the mean value of z for the points inside a bin is more than 1 mm greater than the mean value of z for that 25 cm $\times$ 37 cm section, the bin is considered to be inside a groove. If a bin is inside a groove and is lower than the the four bins closest to it, its position is output for comparison in other surface analysis programs. Figure 4 displays this process.

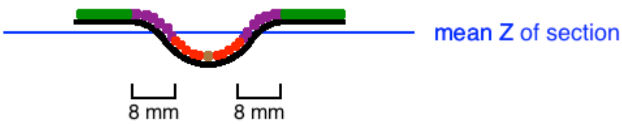

Figure 4: Example of groove removal. Red: Bins > 1 mm below the mean are considered to be in the groove, Orange: A local minimum inside a groove is recorded as the center of the groove, Purple: Bins < 8 mm from the red are also removed.

If a point is less than 8 mm from the center of any bin that's inside a groove, the point is removed. The points that remain form what is ideally the flat surface of the layer.

Surface Flatness at Module Borders

The surface is redivided into sections of size 15 m perpendicular to the cells and 2.54 cm parallel to the cells. Each section is divided into bins of size 2.54 cm $\times$ 4 mm. If a bin does not contain any points, it is assumed to be inside a groove between cells. Starting from the edge of a section, NSA counts the cells based on the number of times a bin that contains points is found right after a bin that does not contain points.

The mean and the standard deviation of the z values of the points inside the 32nd cell (last cell of the first module) of a section are output. Then the mean and standard deviation of the mean of z for the 33rd cell (first cell of the second module) are output. The same is done for other module borders until it reaches the 192nd and 193rd cells, which cross the center of the layer.

The process of counting cells begins again with the 384th cell at the opposite edge of the section. The mean and standard error of z for the 352nd and 353rd cells are output and the process continues until NSA again reaches the 192nd and 193rd cells.

A Root script inputs the results and plots z with respect to y (in vertical layers) or x (in horizontal layers) for the cells at each module border. It also plots the difference in z across the module borders. The technician who runs NSA can consider $|\Delta z| > 1$ mm across a border or $|\Delta z| > 1$ cm along a cell to be a sign of emerging trouble in module alignment.

If NSA does not correctly find the grooves in a section of the surface, it will miscount them and record the mean value of z for the wrong cells. If the x or y position of a pair of cells is more than 3 cm away from the expected position of a module border, Root will skip that 2.54 cm section of the cell border when plotting z and $|\Delta z|$.

SAMPLE RESULT

Figure 5 shows z and Δz with respect to x along the border between two modules of the horizontal Layer 14 of Block 0. $|\Delta z|$ remains less than 1 mm, as desired. z changes 2.8 cm along the length of the cells for a reason that has not been found.

CONCLUSION

The upstream sides of the layers of the NOνA Far Detector are scanned to measure the surface flatness. A new program reduces the data from the scanner output and performs a preliminary analysis of the surface shape. The program worked correctly during construction of the first Far Detector block.

REFERENCES

[1] The NOνA Collaboration, "Proposal to Build a 30 Kiloton Off-Axis Detector to Study $\nu_\mu \rightarrow \nu_e$ Oscillations in the NuMI Beamline," NOVA Document 593, (2005)

[2] P. Lukens, "Far Detector Assembly Procedure," NOVA Document 7541-v2 (2012).

[3] D.F. Friend, "32 Plane Block Assembly for Far Detector," NOVA Document 5813-v25 (2012)

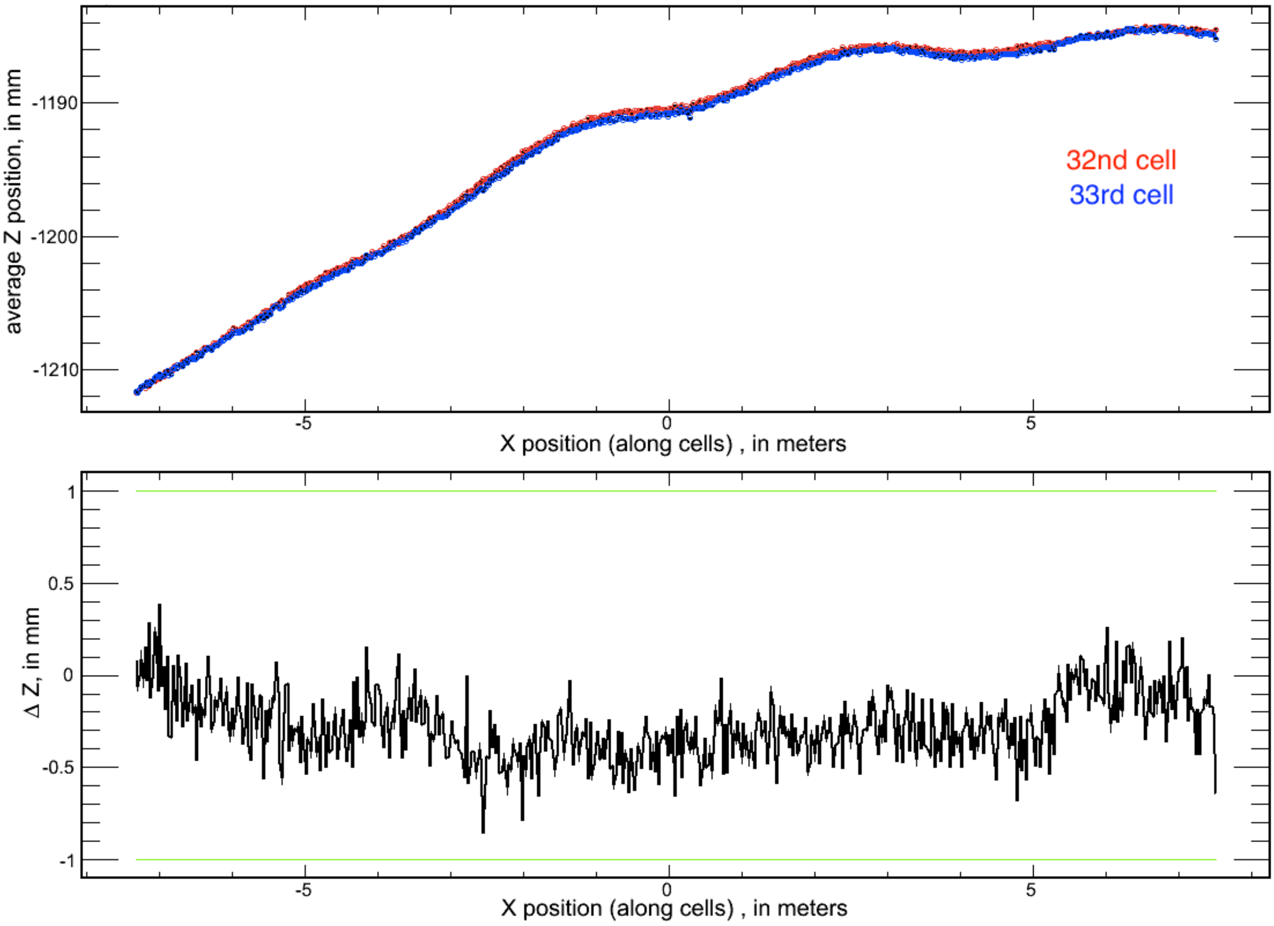

Figure 5: Sample result of the analysis of the scan of Block 0 Layer 14.