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Fermilab

SURVEY OF THE NOvA DETECTORS AT FERMILAB

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Abstract

The NOvA experiment is looking to answer fundamental questions about neutrinos and the role they play in the universe. NOvA will use two detectors, a near detector located underground at Fermilab and a far detector located 810 km from Fermilab near the US-Canada border in Ash River, Minnesota. The 14 kton far detector and the 0.3 kton near detector are composed of several cells of extruded PVC plastic in a cellular structure. This paper discusses the survey of the NOvA detectors using the Laser Tracker and the Laser Scanner.

INTRODUCTION

NOvA (NuMI Off-Axis ν_e Appearance) is a second generation experiment on the NuMI (Neutrino at Main Injector) beamline designed to search for oscillations of muon neutrinos to electron neutrinos ($\nu_\mu \rightarrow \nu_e$) by comparing electron neutrino rates at Fermilab with electron neutrino rates observed 810 km away from Fermilab at Ash River, Minnesota (Figure 1) [1].

THE NOvA EXPERIMENT

The NOvA experiment is an upgrade of the NuMI beam intensity from 400 kW to 700 kW. NOvA consists of a 0.3 kton near detector at Fermilab and a much larger 14 kton far detector in Ash River, Minnesota just south of the U.S.-Canada border (Figure 1 and Figure 2). The NOvA detectors are sited 14.6 mrad off the center of the NuMI beam axis. The NOvA far detector is located in a new building that is 20.4 m wide by 113.8 m long with the detector section sunk 16 m below the existing grade into granite rock (Figure 3). Figure 4 shows the detector hall inside of the building. The NOvA near detector is located on the Fermilab site about 1 km from the NuMI target. It is similar to the far detector and is located 105 m underground in a new cavern adjacent to the MINOS access tunnel, downstream of the MINOS shaft (Figure 5). The cavern is 6.0 m wide by 20.5 m long and 6.0 m high. Figure 6 shows the recently completed NOvA near detector cavern. An earlier prototype of the near detector on surface (NDOS) (Figure 7) exists as well at Fermilab [3]. The 0.22 kton detector is located on the surface in the NOvA Near Detector Surface Building at Fermilab (Figure 8). This prototype serves as a venue to test all the parts of the NOvA detectors together [2]. The NDOS is about 107 mrad off-axis to the NuMI neutrino beam and it has been operating since November 2010.

NOvA uses liquid scintillator contained in rigid, highly reflective PVC (Polyvinyl chloride) cells to detect neutrino interactions. The charged particles produced by the neutrino interaction inside the detector cause the liquid scintillator to produce light that is captured by optical fibers and carried to light-sensitive detectors. This paper will focus on how the detectors are assembled using the PVC cells to construct planes and blocks used to make the detectors, and how the detectors are surveyed.

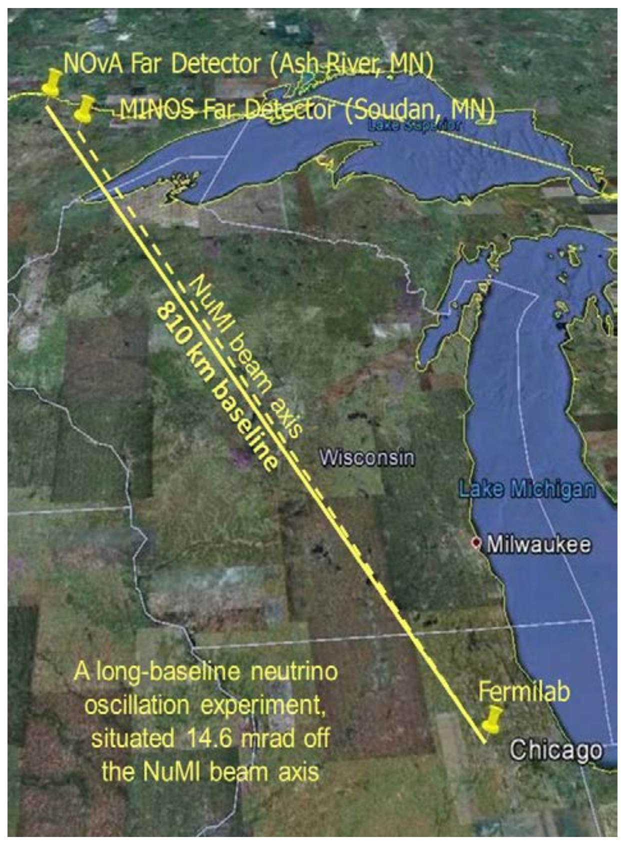


Figure 1: Beam trajectory 810 km from Fermilab to Ash River, Minnesota.

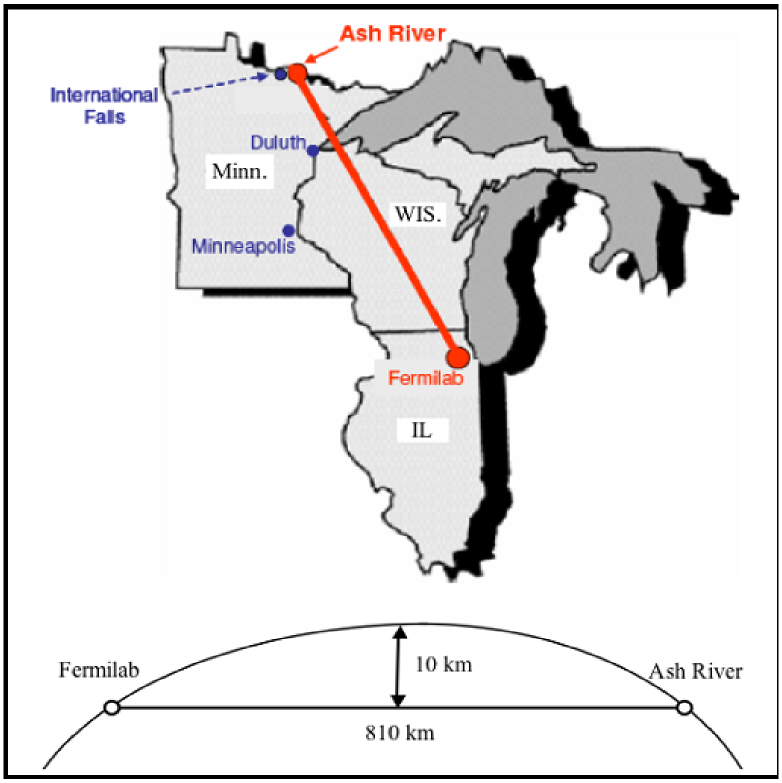
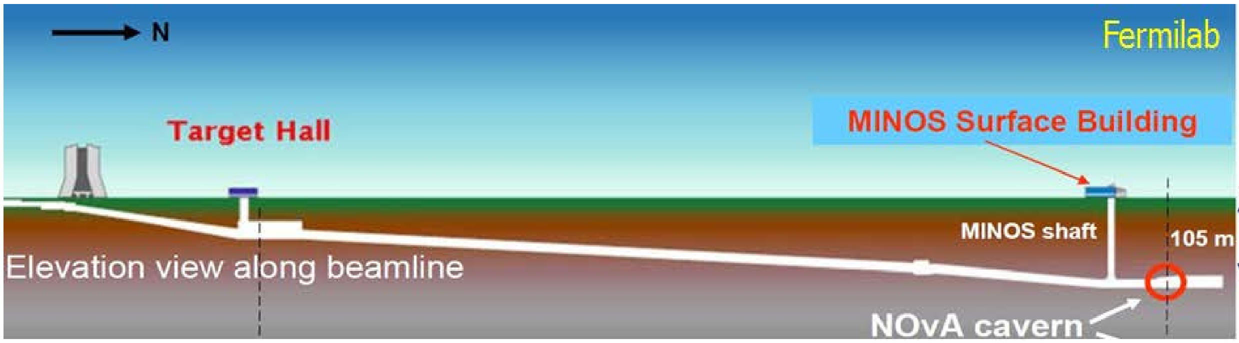


Figure 2: Ash River located 810 km from Fermilab.

Figure 3: Far Detector Building in Ash River.

Figure 4: Far Detector Hall in Ash River.



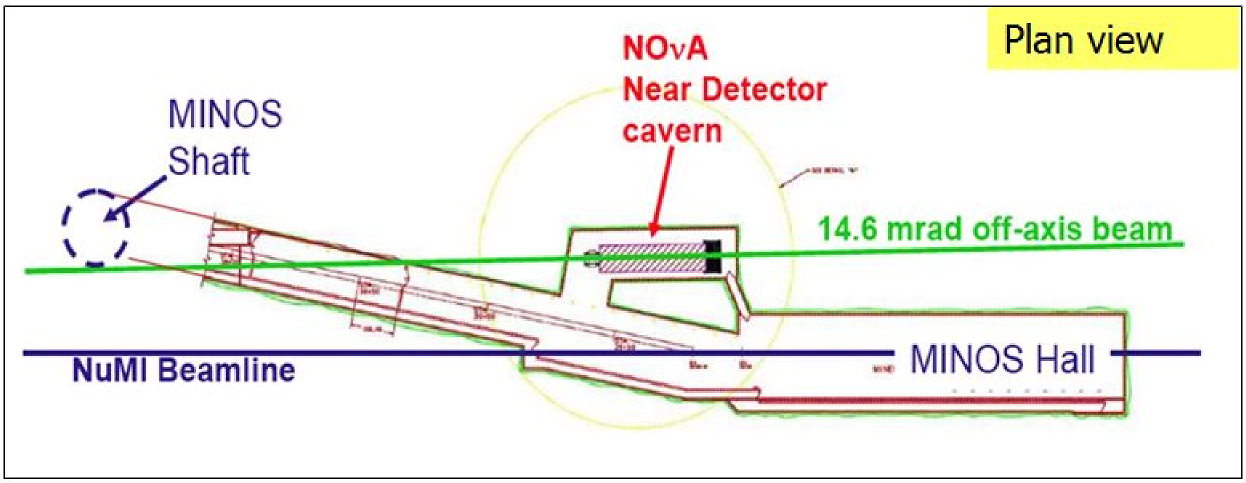


Figure 5: The NOvA Near Detector in a cavern adjacent to the MINOS access tunnel.

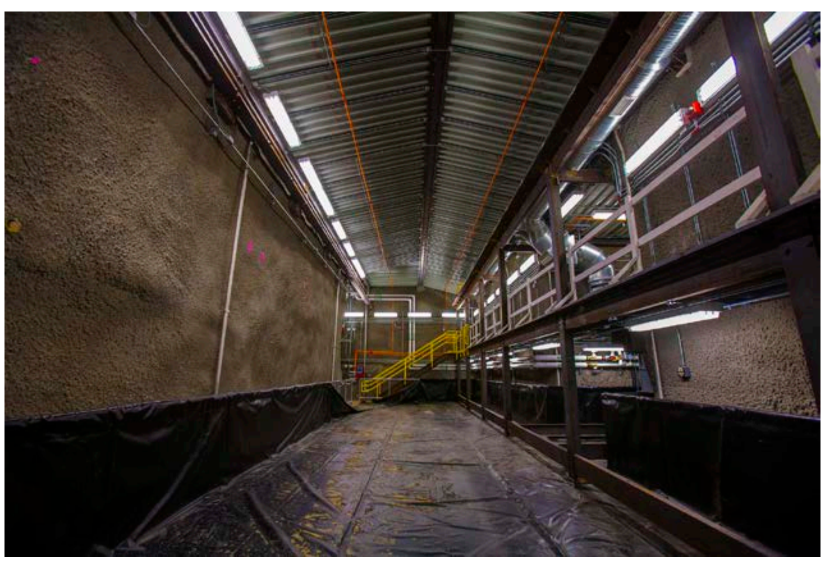


Figure 6: Recently completed NOvA Near Detector Cavern.

Figure 7: The NOvA Near Detector on Surface.

Figure 8: Near Detector Surface Building at Fermilab.

NOvA DETECTORS

Far Detector

The 14 kton far detector is 15.6 m wide, 15.6 m tall and 60 m long (Figure 9). This detector is composed of 344,064 cells of extruded PVC plastic in a cellular structure. Each cell is 3.9 cm wide by 6.6 cm deep and is 15.6 m long. The cells are filled with a total of 3.0 million gallons of liquid scintillator. The liquid scintillator comprises 63.5% of the total detector mass, making this a totally active tracking calorimeter detector optimized for identification of electron neutrino (ν_e) interactions. The detector is read out via 10,668 km of 0.7 mm diameter optical wave-shifting fiber into 344,064 avalanche photodiodes (APD) with associated electronics (Figure 10). The far detector consists of 28 blocks of 32 planes (16 vertical, 16 horizontal) for a total of 896 planes [4].

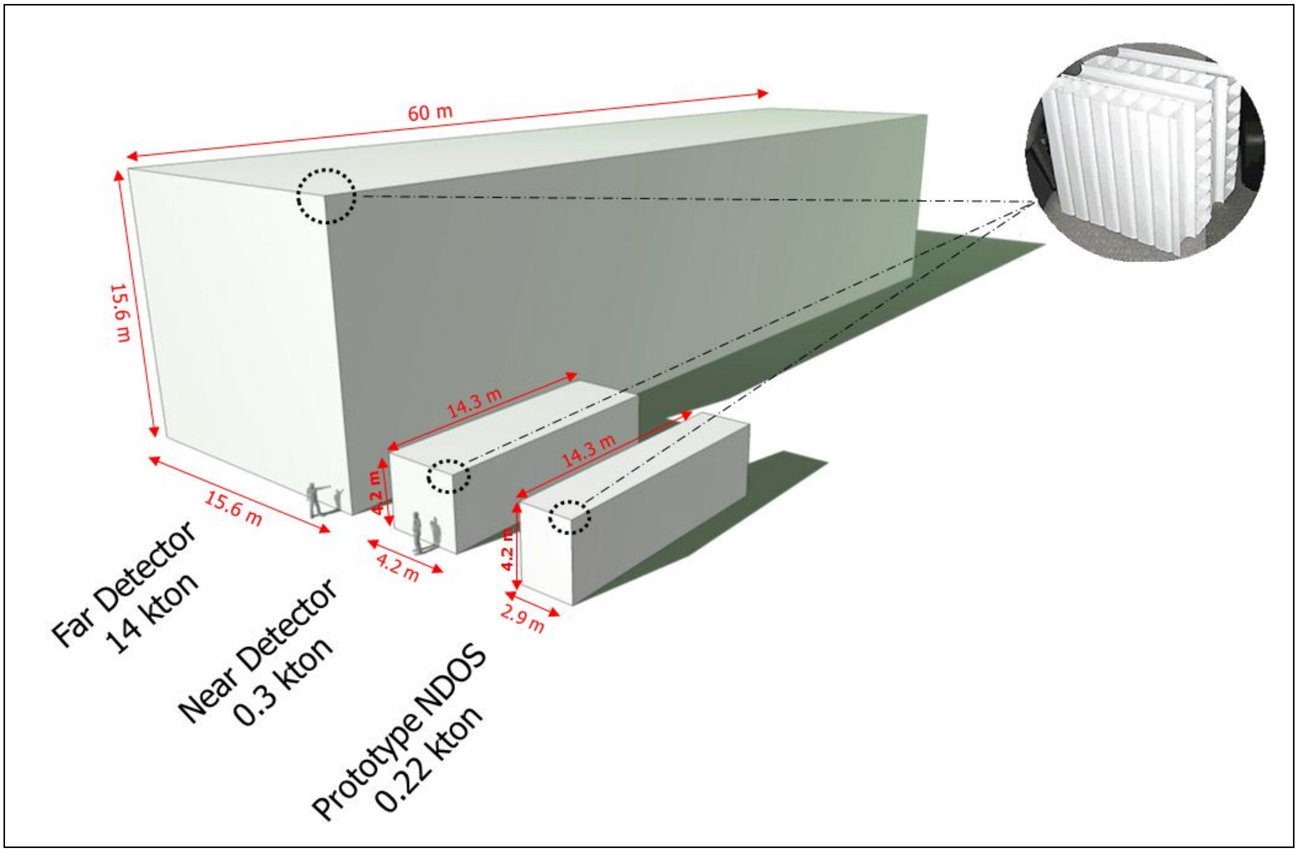


Figure 9: The NOvA Detectors.

Near Detector

The 0.3 kton near detector is 4.2 m wide, 4.2 m tall and 14.3 m long (Figure 9). This detector is an identical copy of the far detector except that the length of the extrusion modules is 4.2 m. The near detector consists of 8 blocks of 24 planes (12 vertical, 12 horizontal) for a total of 192 planes followed by a muon catcher unit that consists of 10 pieces of 4” steel plates sandwiched with PVC modules.

NOvA DETECTOR ASSEMBLY

NOvA PVC Extrusions

The rigid PVC extrusions are the basic building blocks of the NOvA detectors. They are the structural elements containing the liquid scintillator and light measuring fiber optics [1]. The total mass of PVC used to make the far detector is 5.0 kton, which is 36.5% of the total far detector mass. The extrusions have a cellular structure, with 16 isolated cells per extrusion. The cells have exterior PVC walls 4.8 mm thick with 3.3 mm thick interior webs between cells. The extrusion thickness is 6.6 cm. The length of the rigid PVC extrusions with 16 cells extruded together in a unit is 63.5 cm wide (Figure 10). All far detector extrusions are 15.544 m long. Extrusions for the near detector are 3.988 m long. The width of a module is 1.27 m.

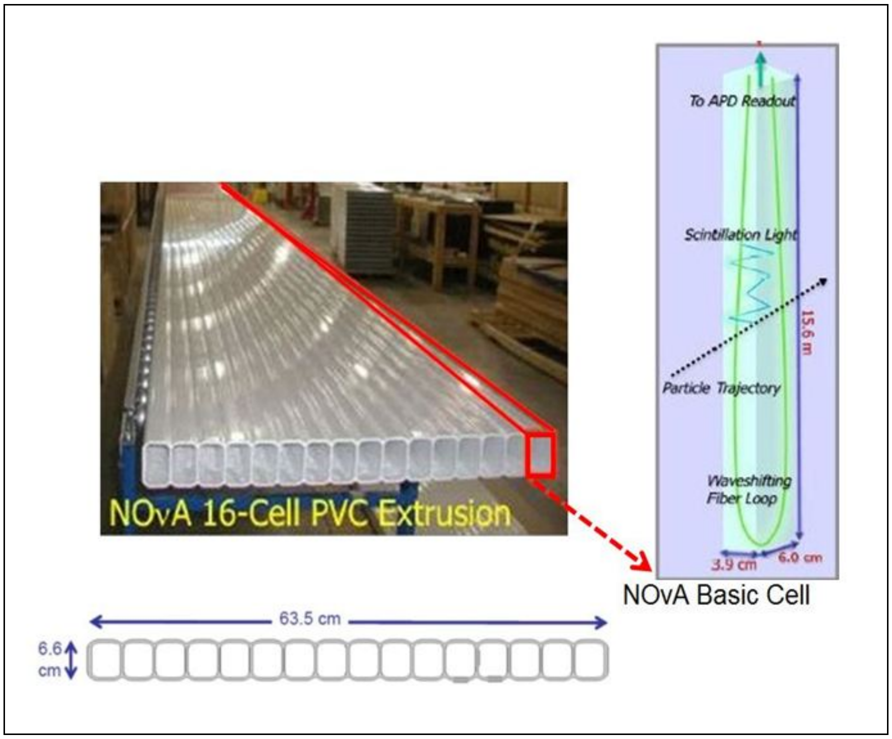


Figure 10: NOvA PVC Extrusions.

NOvA Extrusion Modules

The basic cell of the NOvA detector is a column or row of liquid scintillator encased in a PVC container. NOvA modules consist of two 16-cell PVC extrusions glued together to make a 32-cell extrusion assembly. Two 16 cell objects are attached with glue at the long sides and the extrusion module is cut to an exact length. The module assembly shown in Figure 11 defines a model plane. The extrusion modules are capped at one end by a simple PVC end cap to contain the liquid scintillator and are capped at the other end by a more complicated fiber manifold. The manifold routes the 64 fiber ends to 32 avalanche photodiode pixels. The assembled extrusion modules with fiber manifolds and end caps are 15.6 m long for the far detector. The end caps and fiber manifolds encase the entire 32 cells into a common sealed liquid volume. Thus the 1.27 m by 15.6 m extrusion module forms the primary containment vessel for the liquid scintillator. The length of the extrusion module for the near detector is 4.2 m. The assembly provides a leak-tight container for liquid scintillator [1].

NOvA Block

The NOvA detector is constructed from alternating planes (layers) of vertical and horizontal PVC extrusion modules, connected together by glue between planes. The basic structural unit of the NOvA detector is an assembly of 32 planes of PVC extrusion modules called a block for the far detector. The near detector consists of 24 planes. The modules in each block are glued together in a horizontal orientation on a block assembly table. The block configuration for the far detector is defined as:

$$\mathbf{B = h_0v_1h_2v_3h_4v_5h_6v_7h_8v_9h_{10}v_{11}h_{12}v_{13}h_{14}v_{15}\ldots}$$
$$\mathbf{\ldots h_{16}v_{17}h_{18}v_{19}h_{20}v_{21}h_{22}v_{23}h_{24}v_{25}h_{26}v_{27}h_{28}v_{29}h_{30}\ v_{31}}$$

where **v** represents is the vertical plane and **h** the horizontal plane. The number of planes is counted from 0 through 31. Similarly, the block configuration for the near detector is defined as:

$$\mathbf{B = h_0v_1h_2v_3h_4v_5h_6v_7h_8v_9h_{10}v_{11}h_{12}v_{13}h_{14}v_{15}\ldots}$$
$$\mathbf{\ldots h_{16}v_{17}h_{18}v_{19}h_{20}v_{21}h_{22}v_{23}}$$

where the number of planes is counted from 0 through 23.

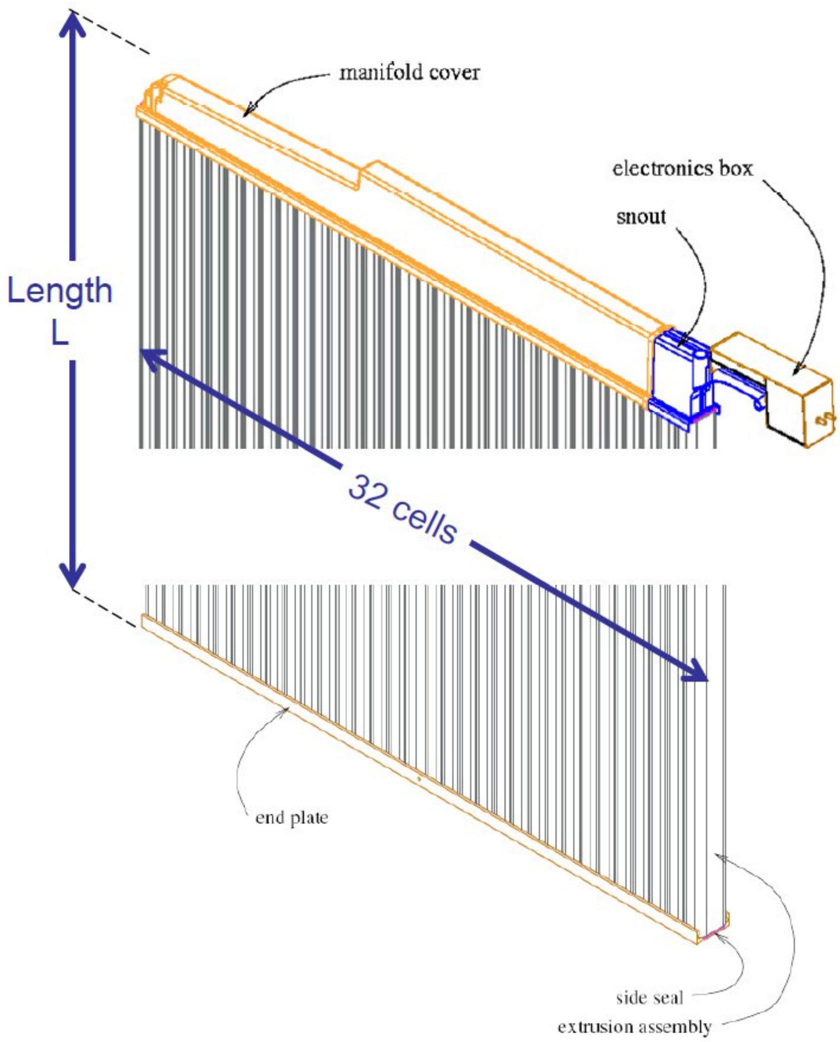


Figure 11: PVC extrusion modules (Two 16 cells).
L = 15.6 m for Far Detector; L = 4.2 m for Near Detector.

Far Detector Assembly

The far detector (**FD**) consists of 28 blocks. Each block is 15.6 m wide by 15.6 m high by 2.141 m thick. The PVC in a 32-plane block weighs 177.7 metric tons and when filled with liquid scintillator, the weight of a 32-plane block is 487.5 metric tons [4]. The far detector block configuration starting from the upstream end is:

FD → $B_0B_1B_2B_3B_4B_5$.........B_{22} $B_{23}B_{24}$ $B_{25}B_{26}B_{27}$

where the number of blocks is counted from 0 through 27. The total number of planes or layers in the far detector is 896. Twelve extrusion modules are placed side by side on a flat Pivoter assembly table to form one plane of the far detector. The total number of modules per block is 384 and the total number of modules in the far detector is 10,752.

The installation of the NOvA far detector is currently underway. The block assembly area houses the NOvA block Pivoter machine and the Pivoter assembly table that is used to build all the blocks (Figure 12).

Each of the 28 blocks in the detector is assembled on the assembly table while it is in its horizontal position. Each block is rotated to a vertical orientation after completion. Block assembly starts from plane-31 ($\mathbf{v_{31}}$) on the assembly table and ends with plane-0 ($\mathbf{h_0}$). The block assembly procedure starts at the glue machine (Figure 13) where glue is applied to the extrusion modules. The modules are then transported to the assembly table by the vacuum lifting fixture to be glued to the next modules to form planes or layers (Figure 14). Alignment posts attached to the assembly table are used as guides for the module installation. The block is assembled in its horizontal position starting first with the downstream end. Once a block has been finished (Figure 15), the block Pivoter is used to move the block into place within the detector building starting from the south wall (Figure 16). The Pivoter then pivots 90° to set the block upright to the ideal location.

Figure 12: Pivoter Assembly Table in vertical (left) and horizontal (right) positions.

Figure 13: The Glue Machine.

Figure 14: NOvA Far Detector Assembly.

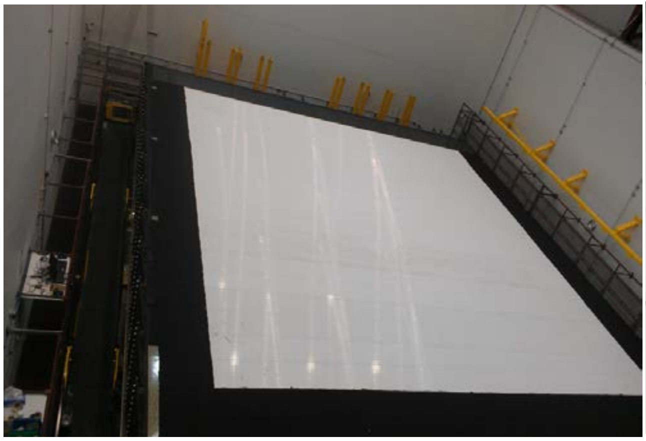


Figure 15: Completed Block on Pivoter Assembly Table.

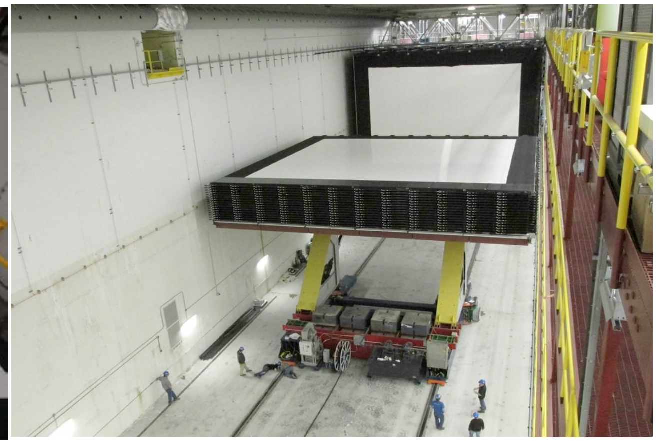


Figure 16: Block Transported To Location by Pivoter.

Near Detector Assembly

The near detector consists of 8 blocks of 24 planes and a 22-plane muon catcher. Each block is 4.2 m wide by 4.2 m high by 2.136 m thick. The PVC in a 24-plane block weighs 5 metric tons and when filled with liquid scintillator, the weight of a 24-plane block is 13.75 metric tons. The block configuration starting from the upstream end is:

$$\mathbf{ND} \rightarrow \mathbf{B_0B_1B_2B_3B_4B_5\ B_6B_7}$$

where the number of blocks is counted from 0 through 7.

The blocks are currently being constructed at Fermilab CDF (Figure 19). Block assembly starts from plane-23 ($\mathbf{v_{23}}$) on the assembly table and ends with plane-0 ($\mathbf{h_0}$). The total number of planes in the near detector is 192. Three extrusion modules get placed side by side on a flat assembly table to form one plane of the near detector. Total number of modules per block is 72. The block assembly procedure is similar to that of the far detector.

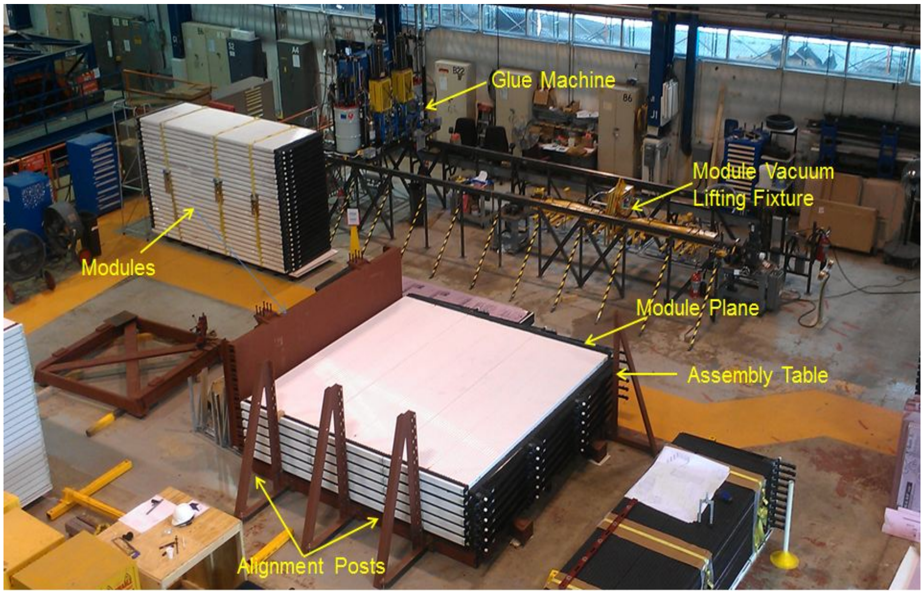


Figure 19: The NOvA Near Detector Assembly Area at Fermilab CDF.

SURVEY OF THE NOvA DETECTORS

The goal is to determine the relative positions of the modules within each detector block and the relative positions of the detector blocks with respect to each other. The relative position and orientation of the full detector with respect to the beamline also has to be determined.

Survey Methodology

The survey instrumentation that is being used for the detector survey is as follows:

i) An API T3 Laser Tracker and Spatial Analyzer™ software are used to establish control4 points in the entire NOvA far and near detector halls. It is used for the module plane measurements of the near detector; and flatness measurements of the detector floors and block assembly tables. It is also used for the block survey of the near detector.

ii) A Leica AT401 Absolute Tracker and Spatial Analyzer™ software are used to establish additional control points in the NOvA far detector hall. It is also used for the block survey of the far detector.

iii) A Trimble S6 Total Station is used for the block survey of the far detector. It is also used for the flatness measurements of the far detector block assembly table.

iv) A Leica HDS6100 Laser Scanner system and its associated software are being used for mapping every far detector plane.

v) A newly purchased Romer Arm will be used for the near detector plane measurements.

vi) A Geodimeter Total Station is used for connecting surface control network to the detector hall network.

vii) A Leica DNA03 Digital level is used for the vertical control network measurements.

viii) Trimble GPS receivers are used to establish a common control network at Ash River and Fermilab.

Surface Geodetic Network

There already exists a well-established surface geodetic network on the Fermilab site. A GPS surface geodetic control network is established that connects points at Fermilab to Ash River. The network is tied to the National Geodetic Survey's Continuously Operating Reference Stations (CORS) precision geodetic network (Figure 20). The network is based on NAD83 (North American Datum 1983) for the horizontal datum and NAVD88 (North American Vertical Datum 1983) for the vertical datum.

Detector Hall Control Network

A precision control network is established to bring horizontal and vertical controls into the near and far detector halls for positioning the detectors using the API Laser Tracker. This control network is extended to the higher levels of the west wall of the far detector hall using the Leica AT401 Tracker. The detector hall control network is tied to the surface network using the Geodimeter Total Station (Figure 21).

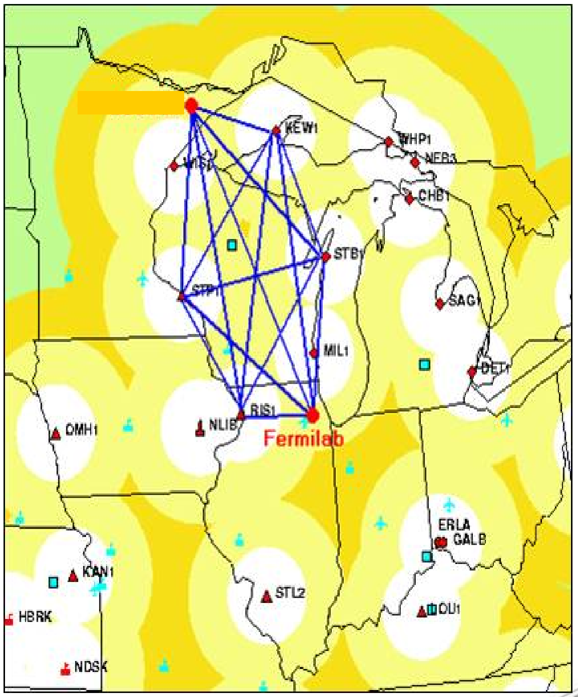


Figure 20: GPS Surface Geodetic Network.

Tolerances of the NOvA Module and Block Survey

The NOvA module and block survey tolerances are specified as follows [5]:

Overall Tolerance:

i) Relative 2 mm (Horizontal) edge to edge;

ii) Relative 0.75 mm or better (Vertical) between adjacent module pieces;

iii) Angular tolerance of ± 2 mm/15.6 m = ± 0.13 mrad.

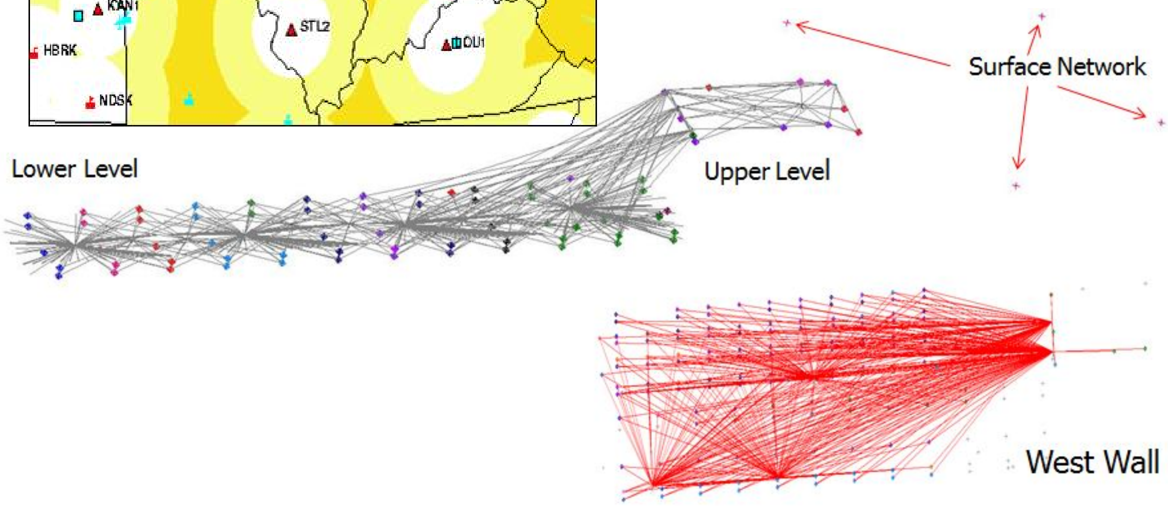


Figure 21: Far Detector Hall Control Network.

Block Fiducialization

Near Detector

Several survey fiducials are mounted at suitable locations on the outside edges of each block for the near detector. Magnet rings are used as fiducials (Figure 22). The magnet rings are glued to the points of interest with a 24-hour epoxy. The location of each fiducial is defined by the center of the SMR (Spherically Mounted Retroreflector) as it precisely sits on the fiducial. A total of 24 fiducials are used for each block, 9 on the module

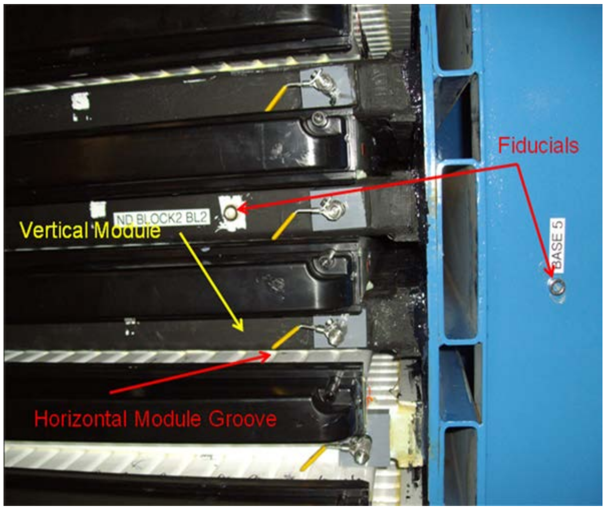


Figure 22: Fiducials on Near Detector Module.

extrusions and 6 on the blue steel base plate. There are 9 fiducials on the extrusions at about the first, middle and last planes and 3 on the base plate on the east side of the block. The same number of fiducials is used on the west side.

Far Detector

There are 44 targets used for Block0 and Block1 [6]. There are two targets each on the top horizontal surfaces of Layer-2 and Layer-28. There are 10 targets each on west and east vertical faces of Layer-1 and Layer-29. Figure 23 shows the upstream view of the target locations. The locations marked by red-colored heart symbols are fiducials for the block survey and those marked with red/blue-colored stars are for the block shape monitoring. The targets on the top east corners, marked by blue-colored stars on Layer-1 and Layer-29, are fitted permanently with prism reflectors in the assembly hall before blocks are rotated to the upright position. There are only 8 targets mounted on Block2 through Block27, locations marked by red-colored heart symbols on Layer-2 and Layer-26 in Figure 23.

All the target holders are glued to the detector during module stacking in the assembly hall. For each location, the target is held in place by a 2.5" x 1.75" x 1.0" PVC block with a 0.625" threaded hole in the middle. These target mounting blocks are glued to the midpoint of a module (Figure 24). Different types of targets can be screwed to the rectangular mounting block for use with the HDS6100 Laser Scanner paddle target, S6 Total Station prism reflector or AT401 Tracker SMR retroreflector. Figure 25 shows the 6" black & white circular paddle target mounted on the module before scanning the layer. The length of the paddle target center to the base of the target base is 6.5” (16.5 cm). The length of the prism center to the base of the prism adapter is 18.3 cm (7.20"). A 1-inch diameter carbon fiber extension rod is used to hold the target prism (Figure 26) or SMR (Figure 27). Three extension rod lengths are used: 25 cm (9.84"), 50 cm (19.68") and 75 cm (29.53").

The 8 targets marked by the heart-shaped symbols are fitted with laser scanner paddle targets in the assembly area so that the scanner can record their locations along with the module location during scanning in the horizontal position. These targets are later used for the block survey with the block in the upright position.

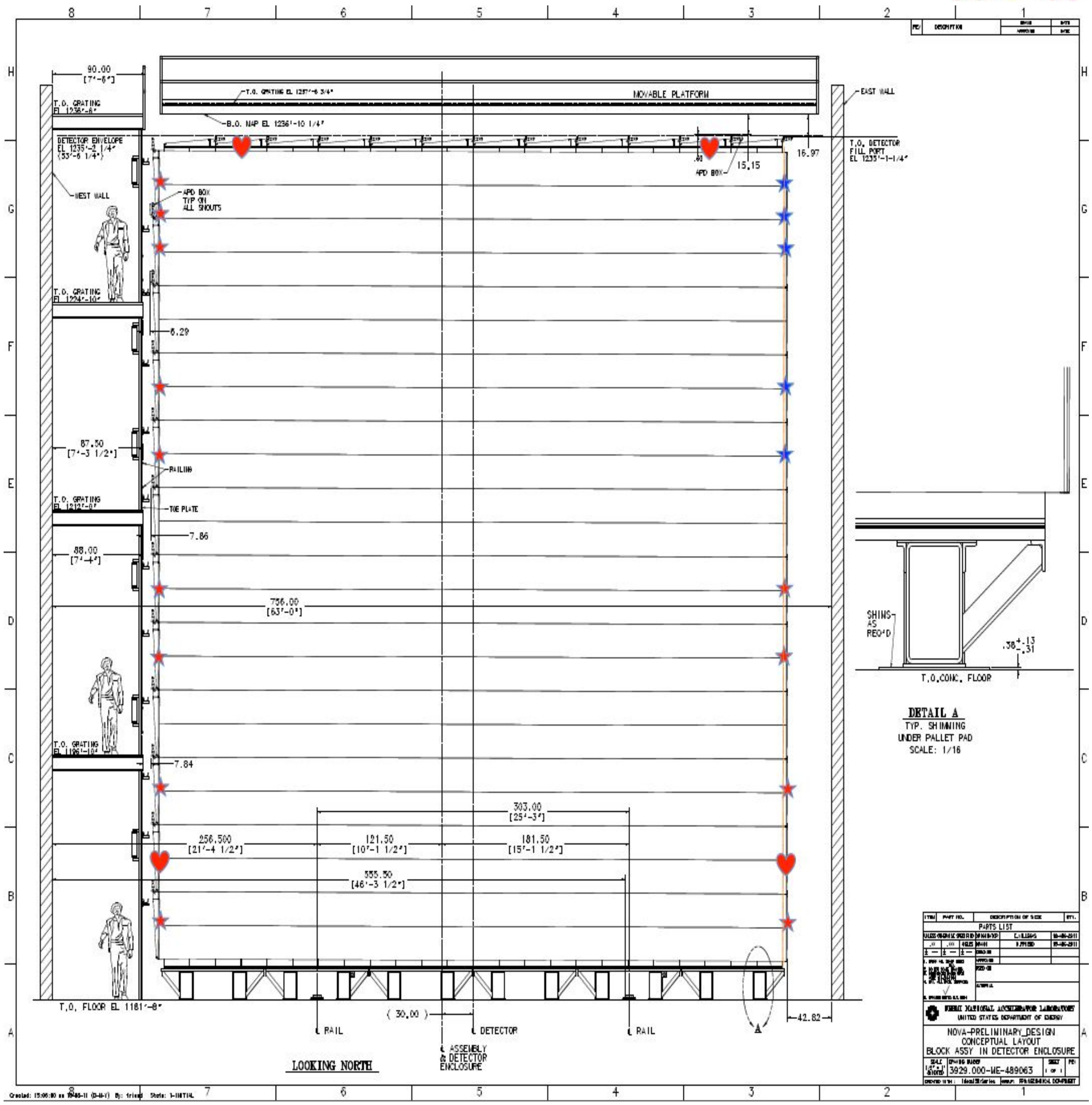


Figure 23: Upstream view of Targets on Far Detector Module for Block0 and Block1 in Upright Position.

Figure 24: Target Mounting Block on Far Detector Module.

Figure 25: Paddle Targets on Mounting Block.

Figure 26: Prism and Extension Rod on Mounting Block.

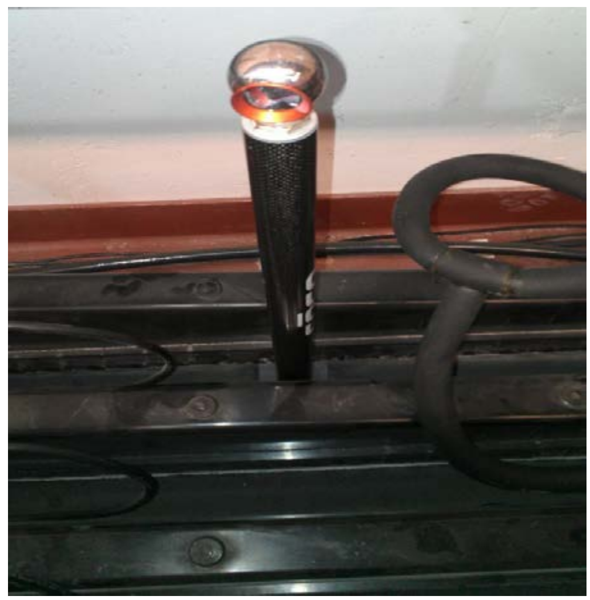


Figure 27: SMR and Extension Rod on Mounting Block.

Detector Floor Measurements

Floor measurements are made with the Laser Tracker in the far and near detector halls to determine the flatness. These measurement results are used for shimming the pallets that the blocks sit on. Figure 28 shows the results of using a 720 grid point of 24” x 24” (61 cm x 61 cm) in the far detector hall. The maximum surface elevation difference is 1.1” (2.8 cm).

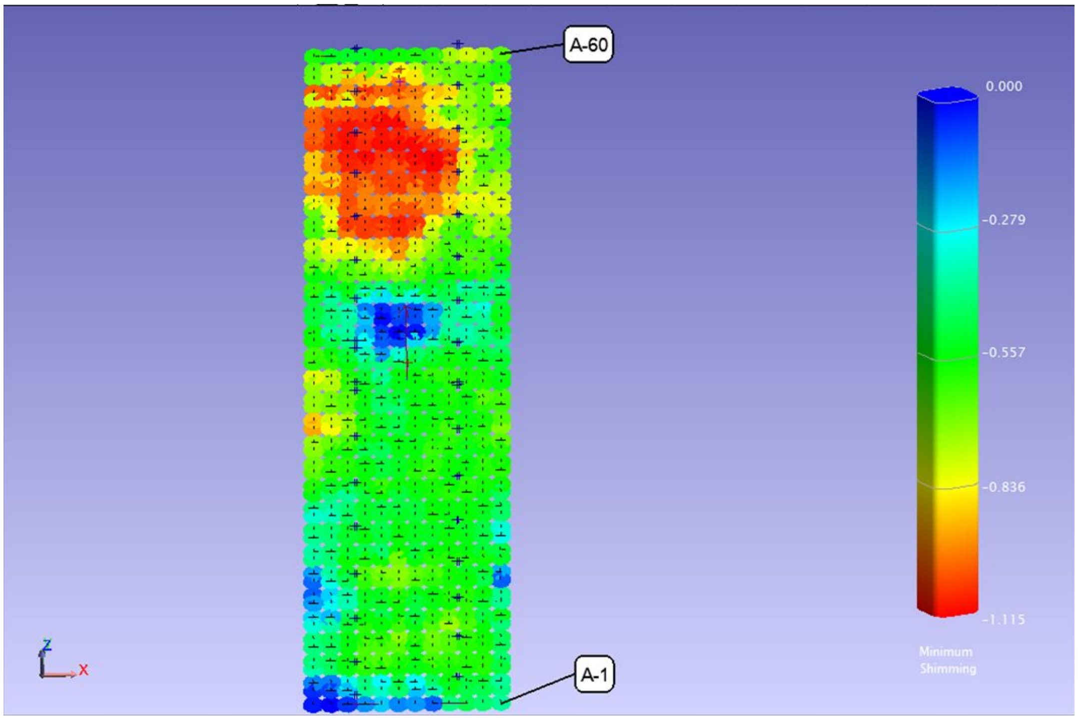


Figure 28**:** Far Detector Floor Flatness.

Pivoter Table Measurements

Before each block is assembled, the block assembly table must be leveled. To determine the flatness, the surface of the near detector assembly table is measured with the API Tracker. The surface of the far detector Pivoter Table is first measured with the S6 Total Station using 24” x 24” (61 cm x 61 cm) grids with the table in the vertical position (Figure 29). The API Tracker is then used to measure the surface with the table in the horizontal position (Figure 30). These measurement results are used for shimming the assembly table surface before the first plane is assembled. Figures 31 and 32 show the results for the far detector assembly table surface. The surface elevation differences range from -0.8” (-2.0 cm) to 1.2” (3.0 cm).

Figure 29: Table Surface Measurements in Vertical Position.

Figure 30: Table Surface Measurements in Horizontal Position.

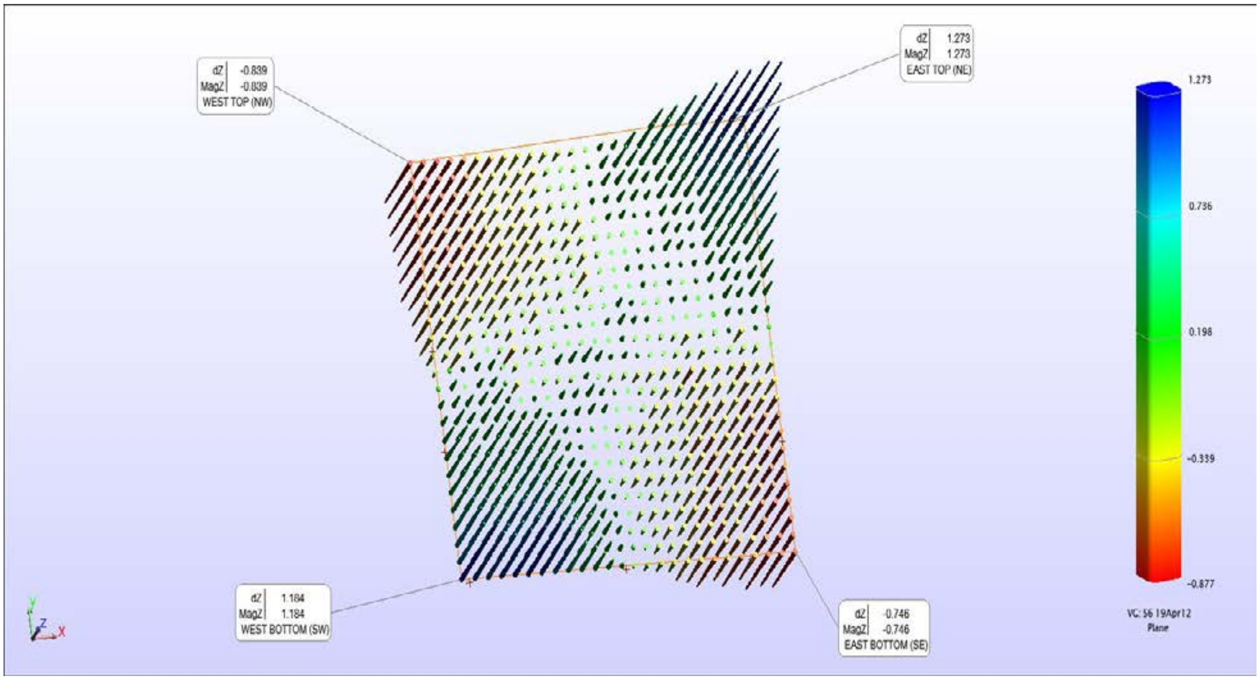


Figure 31: Far Detector Pivoter Table Flatness – API Laser Tracker.

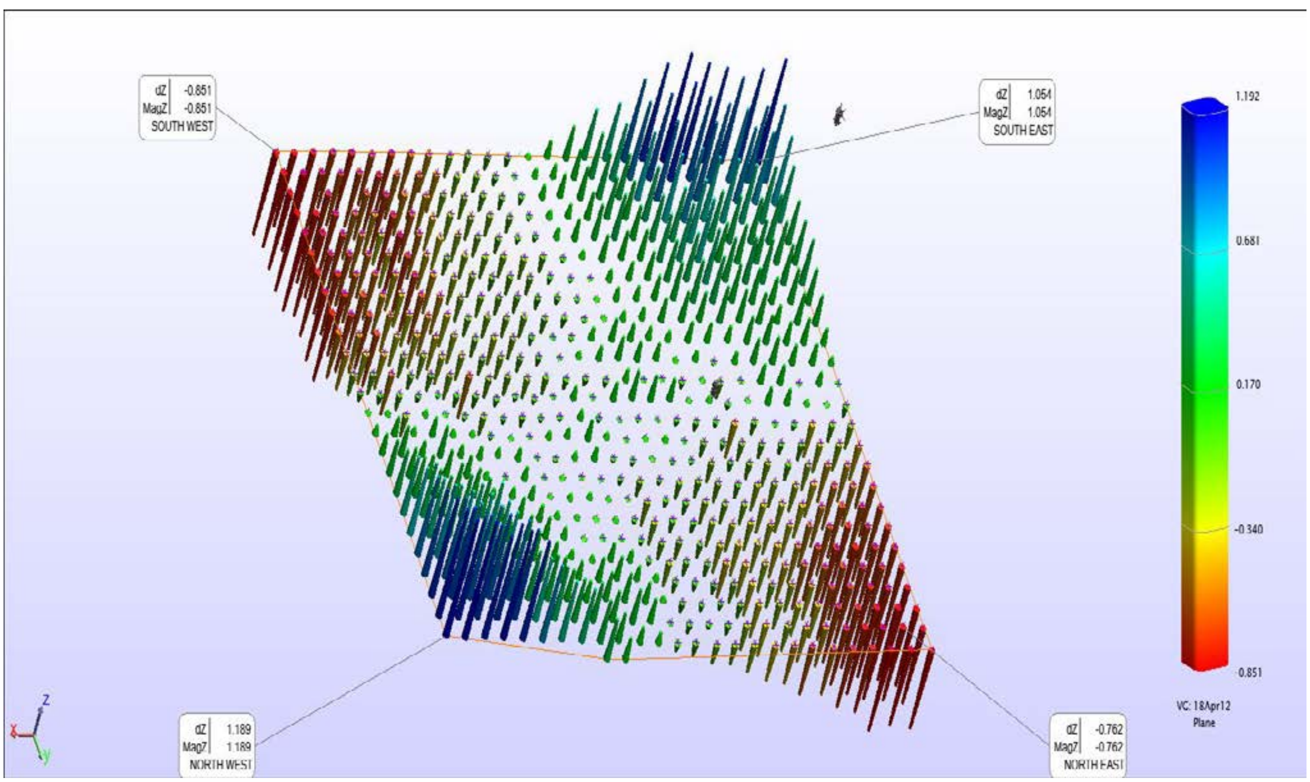


Figure 32: Far Detector Pivoter Table Flatness – Trimble S6.Total Station.

Block Measurements in Horizontal Position

Far Detector

To measure the surface flatness, the upstream surface of each of the 32 planes of the NOvA far detector block is scanned with the HDS6100 Laser Scanner located on the ceiling inverted directly above the Pivoter assembly table in the assembly area (Figures 33 and 34). Prior to scanning the planes, the surface of the Pivoter assembly table is also scanned. After each plane (or layer) is scanned, a program developed at Fermilab [7] is used to reduce the large scanner data and display the surface shapes of the modules along their borders (Figure 35). This graphic display is given to the construction supervisor to check if the plane meets the tolerance specified before the construction of the next layer begins.

Eight laser scanner paddle targets with known coordinates on the walls of the assembly area are always part of each scan. Also eight laser scanner targets are always fitted to the target mounting blocks on each block (Layer-2 and Layer-26) as part of each scanning procedure.

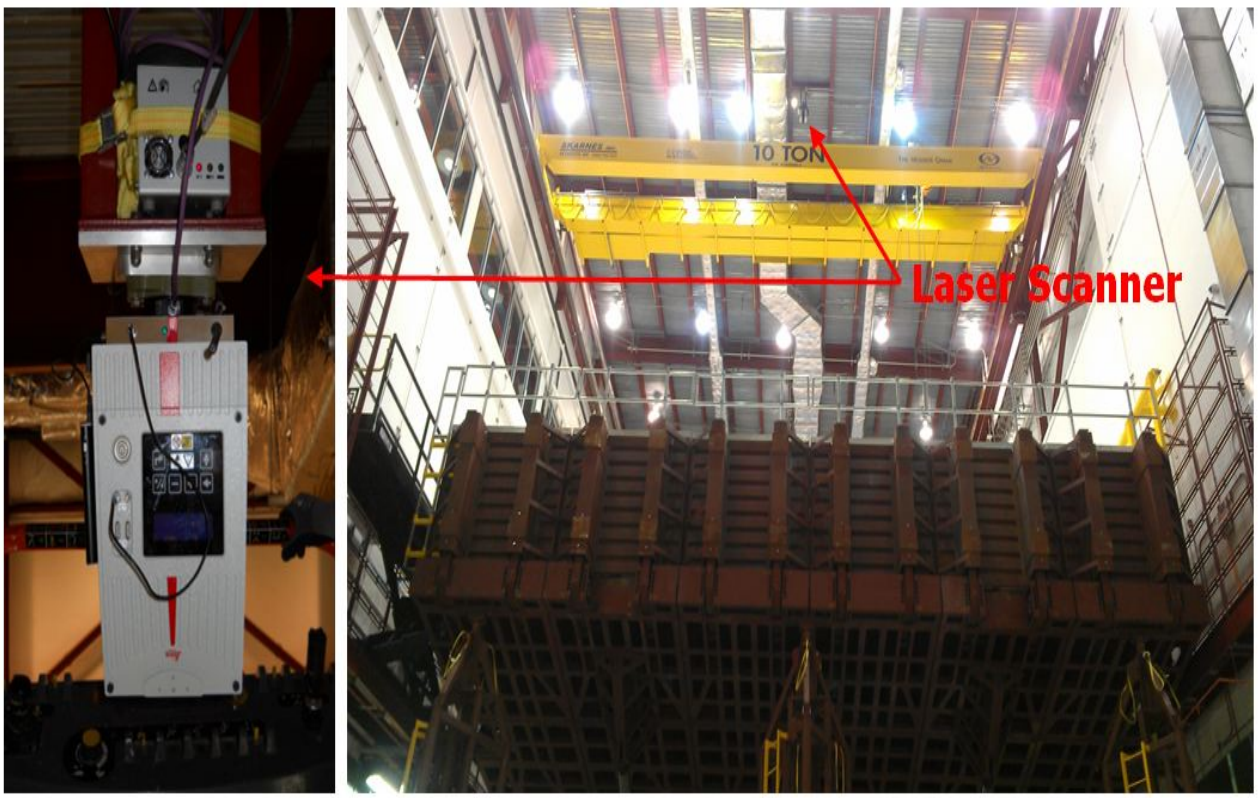


Figure 33: Laser Scanner on the Detector Hall Ceiling above the Block.

Figure 34: Block Directly below Laser Scanner.

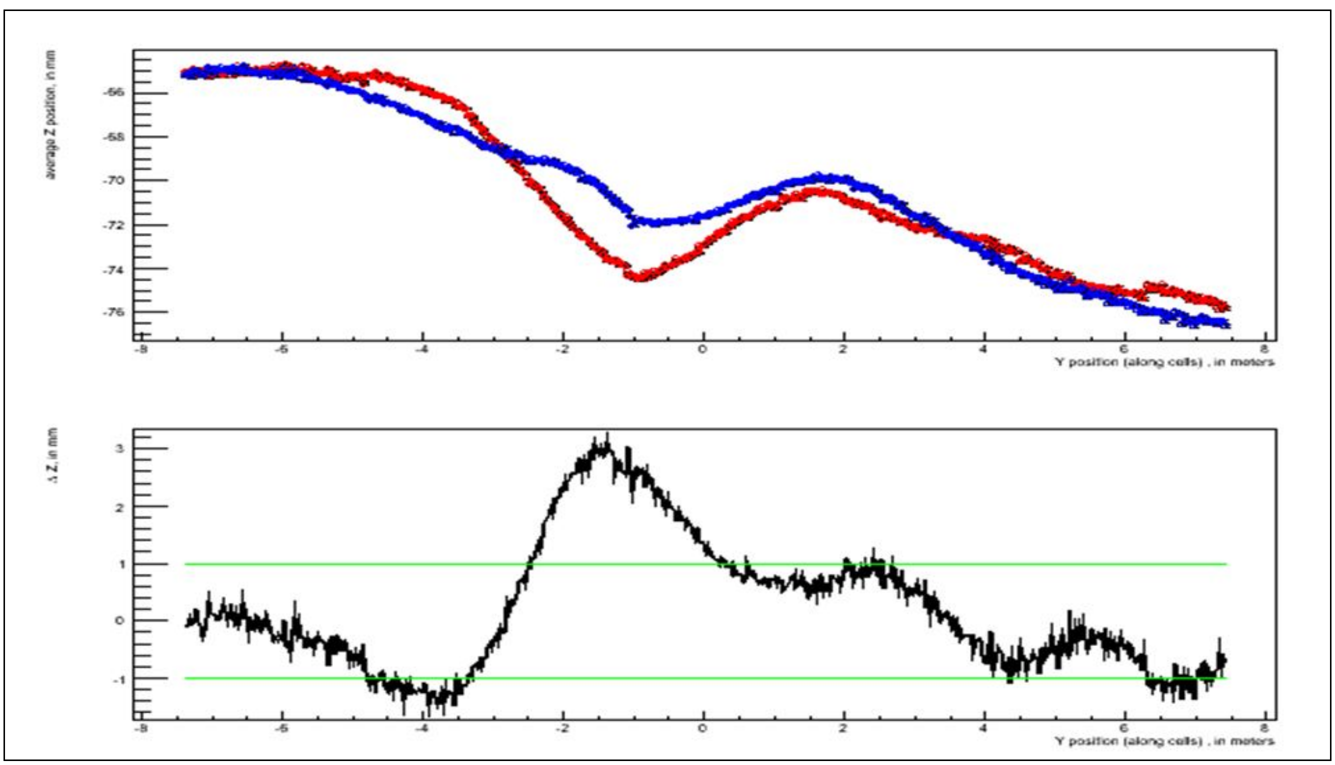


Figure 35: Result of the Surface Analysis at a Module Boundary for First Layer of Block 0 [8].

Near Detector

After all 32 planes have been assembled, several API Tracker measurements will be made to the 24 block fiducials while the block is in the horizontal position in the assembly area. To determine the module positions, groove measurements will be made at specified locations by placing the SMR where the horizontal module grooves intersect the extreme end of the vertical plane (Figure 22). The SMR will be placed on every third groove from the left (-13) and right (+13) edges of the module, and on the middle groove (0) as shown in Figure 36. Measurement will also be made on top of the block along the groove of the vertical modules.

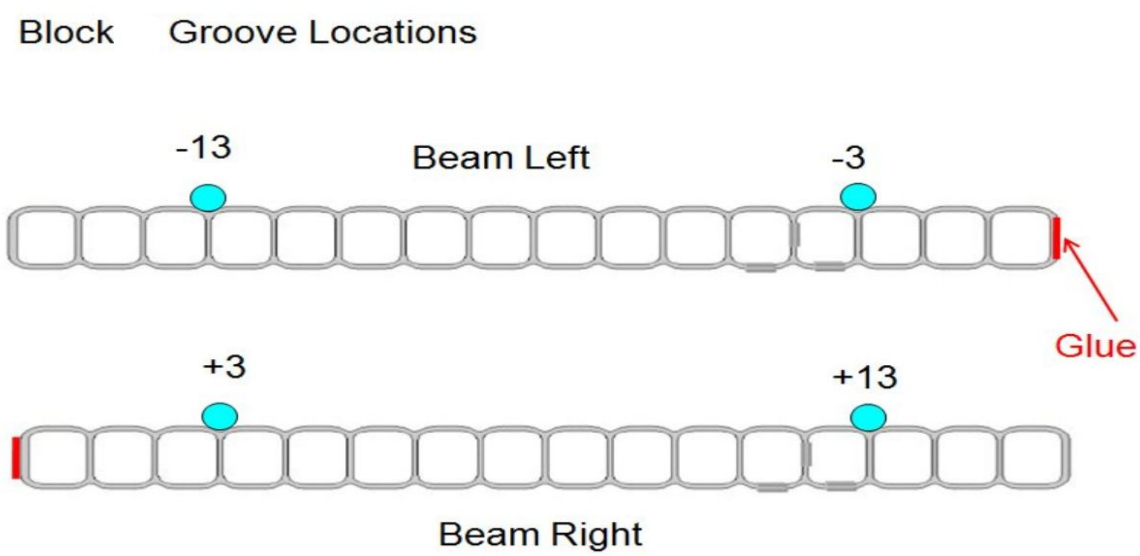


Figure 36: Groove Locations for Near Detector Blocks.

Block Measurements in Upright Position

The blocks are transported to from the assemble hall to the detector hall in their upright positions one block after the other. Figure 37 shows Block12 of the far detector in the upright position

Far Detector

With the blocks in the upright position, measurements are made to targets on the east and west sides of the blocks (Figures 38 and 39) and on the top of the blocks (Figure 40). As of May 2013, the following measurements have been completed for Block0 through Block12:

i) The top of Block0 through Block12 is measured with the 75-cm rods and SMR retroreflectors using the AT401Tracker on a wall bracket mounted up near the ceiling of the detector hall. In the process, one of the MAP platforms is used as a work platform. The same measurements are repeated for Block0 and Block1 using 50-cm rods. The two targets with different lengths are used as vector targets at each point. This will allow any desired location to be computed along the vector.

ii) Measurements on the east (beam-right) sides of Block0 through Block12 are made with prism reflectors without any rod extensions using the S6 Total Station.

iii) Measurements on the west (beam-left) side of Block0 through Block12 are made with prism reflectors and the 25-cm rods using the S6 Total Station. The same measurements are repeated for Block0 and Block1 with the prisms without extension rods.

A transformation is performed to transform all the horizontal position measurements [x_{HORIZ} , y_{HORIZ} , z_{HORIZ}] into the upright position measurements [$x_{UPRIGHT}$, $y_{UPRIGHT}$, $z_{UPRIGHT}$] as follows:

$$\begin{pmatrix} x_{UPRIGHT} \\ y_{UPRIGHT} \\ z_{UPRIGHT} \end{pmatrix} = \begin{pmatrix} x_{TRANS} \\ y_{TRANS} \\ z_{TRANS} \end{pmatrix} + S * \mathbf{R}(\varepsilon_X,\varepsilon_Y,\varepsilon_Z) * \begin{pmatrix} x_{HORIZ} \\ y_{HORIZ} \\ z_{HORIZ} \end{pmatrix}$$

where [x_{TRANS} , y_{TRANS} , z_{TRANS}] is the vector containing the translation parameters in XYZ; $\mathbf{R}(\varepsilon_X,\varepsilon_Y,\varepsilon_Z)$ is the rotation matrix; and S is the scale. For this survey the scale is fixed at S = 1.0. The measurements of the blocks in the detector hall require a survey crew to travel from Fermilab in Batavia, Illinois to Ash River, Minnesota for one week at a time. Two trips have been made so far with more trips planned for the future as more blocks are installed.

Near Detector

Blocks in the upright positions will be measured with the API Tracker inside the cavern. Similar transformation is performed as above to transform all the horizontal position measurements into the upright position measurements.

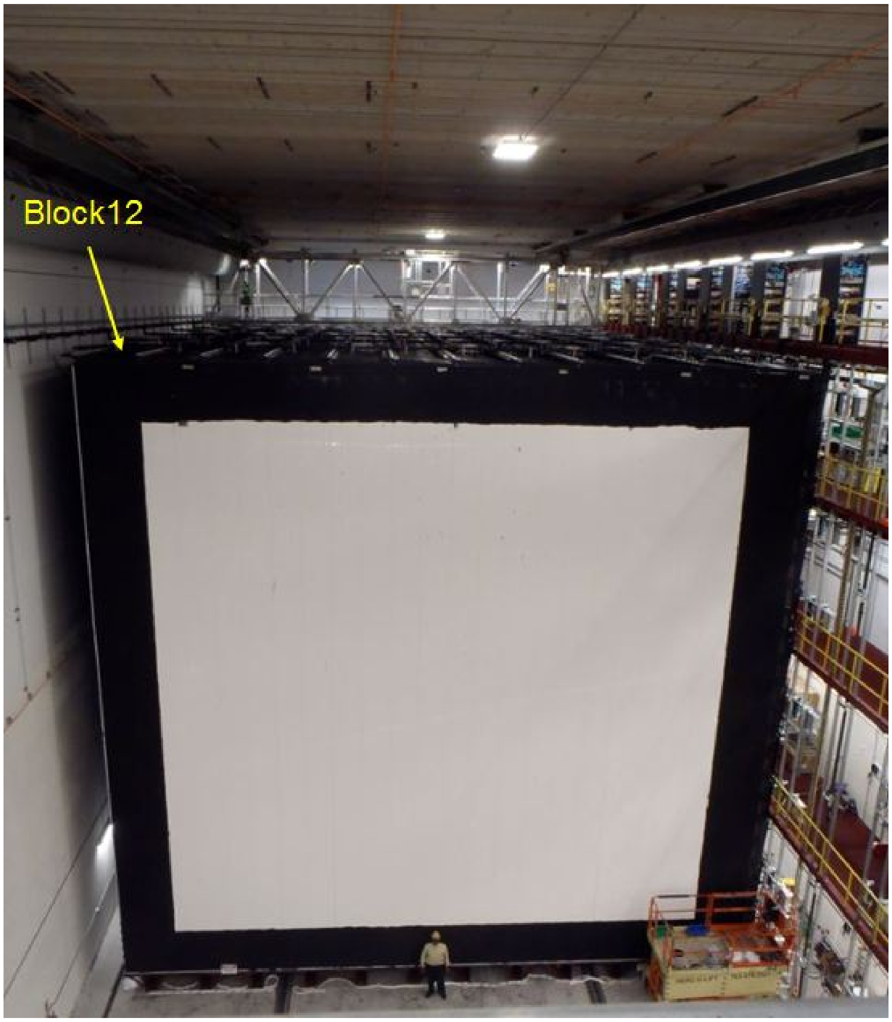


Figure 37: Block12 in the Upright Position.

Figure 38: Block Measurements on the Lower (left) and Upper (right) East Side of Far Detector.

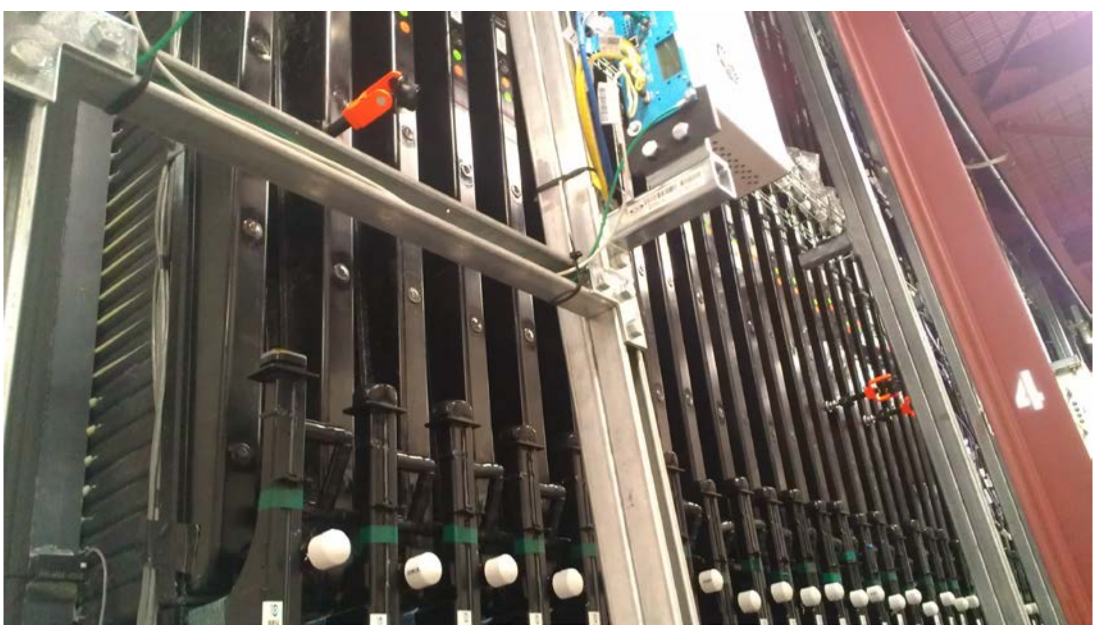


Figure 39: Block Measurements on the West Side of Far Detector.

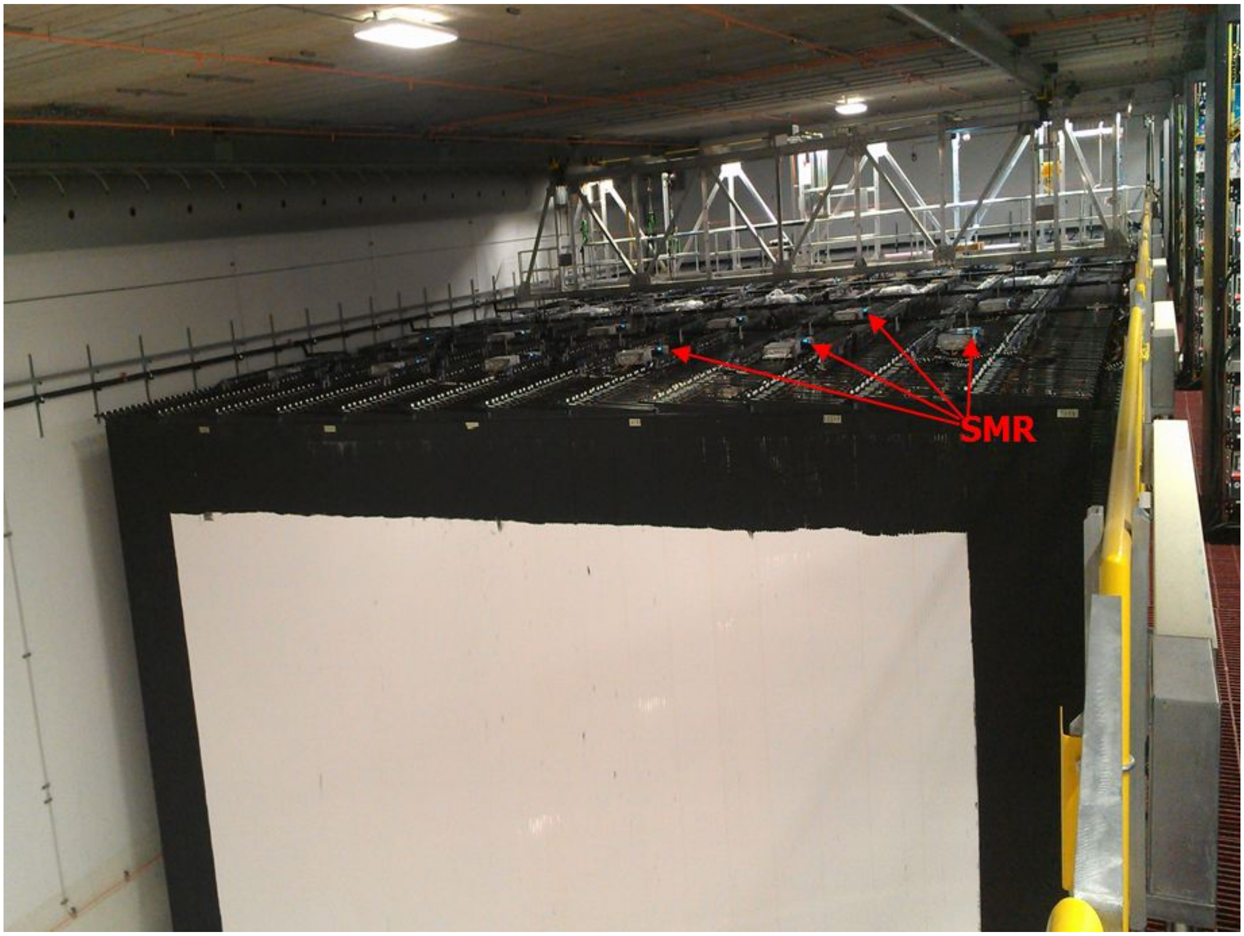


Figure 40: Block Measurements on the Top of Detector.

STATUS OF THE NOvA DETECTORS

The NOvA far detector construction is well underway. More than half of the modules have been installed (Figure 41). First beam data is expected in the summer of 2013. NOvA will finish module assembly by early 2014. It is on schedule to be fully instrumented by August 2014.

The NOvA far detector block survey is still in progress. As of May 2013, the following survey has been accomplished:

i) Block0 and Block1 surveyed with and without liquid scintillator.

ii) Block2 through Block6 surveyed only with filled liquid scintillator.

iii) Block7 through Block12 surveyed without liquid scintillator

Installation of the NOvA near detector will start in July 2013 with the block assembly. The near detector cavern is now ready for the block installation.

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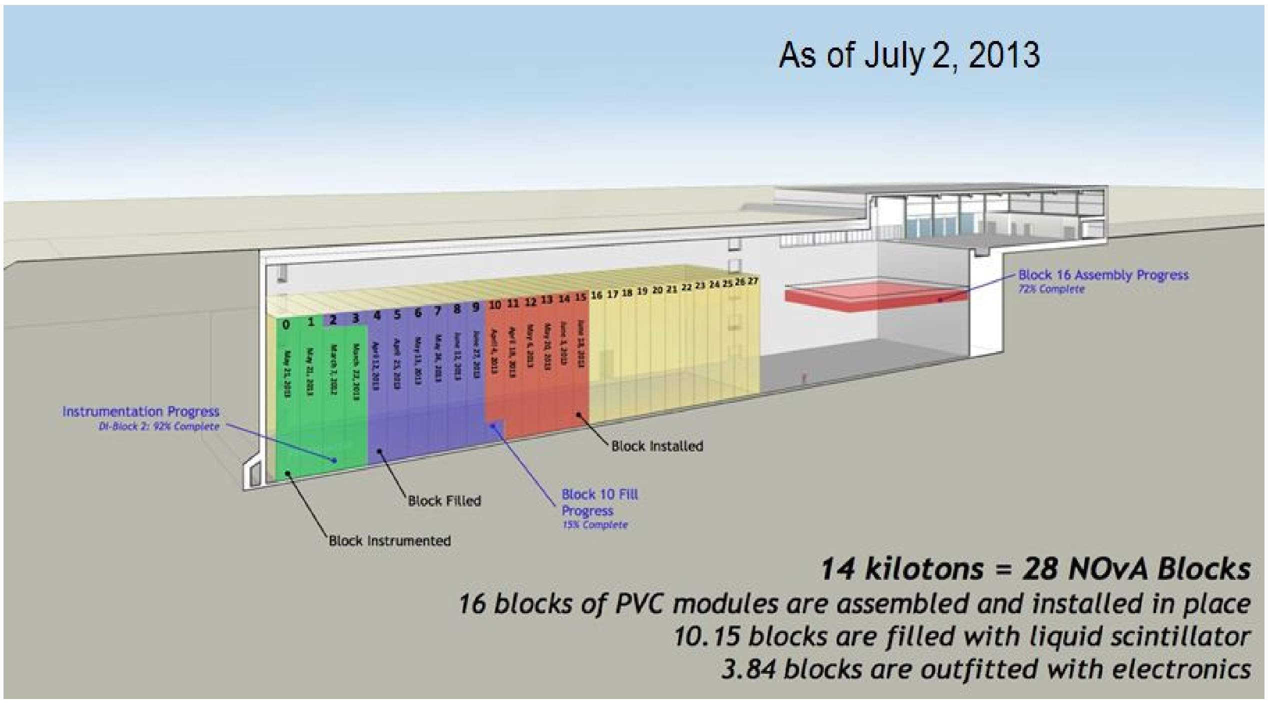

Figure 41: Status of the NOvA Far Detector. Updated weekly at
https://www.facebook.com/novaexperiment?fref=ts

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