Survey and Alignment of the Fermilab MiniBooNE Horn and Target

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ABSTRACT

The first phase of the BooNE (Booster Neutrino Experiment) program at Fermilab is called MiniBooNE. One of the primary goals is to test for neutrino mass via a search for neutrino oscillations. The MiniBooNE consists of a Neutrino Beam and a 40-foot (12.2-meter) diameter Detector. The detector is located 500 m from the neutrino beam line fed by the 8 GeV protons Booster. The Neutrino Beam consists of four sections: the Target, the Horn (focusing system), the decay region, and the beam absorber. This paper discusses the alignment methodology employed to survey the MiniBooNE Horn and Target.

1. INTRODUCTION

The first phase of the **Boo**ster **N**eutrino **E**xperiment (**BooNE**) at the Fermi National Accelerator Laboratory is called "**MiniBooNE**." The major goal of the MiniBooNE experiment is to confirm or refute the LSND evidence for neutrino oscillations. LSND is the Liquid Scintillator Neutrino Detector experiment at the Los Alamos National Laboratory. In 1995, the LSND collaboration presented evidence for the oscillation of muon anti-neutrinos to electron anti-neutrinos. MiniBooNE is set out to confirm or refute the LSND evidence. It began its two-year data collection run in August 2002.

2. THE MINIBOONE EXPERIMENT

The MiniBooNE experiment consists of two geographically separated parts: the Neutrino Beam and the Detector [1]. The experiment is located in the southwest region of the Fermilab site (Figure 1). The BooNE neutrino beam originates at the MI-10 and points almost due north. The distance from the neutrino source to the detector is 500 m.

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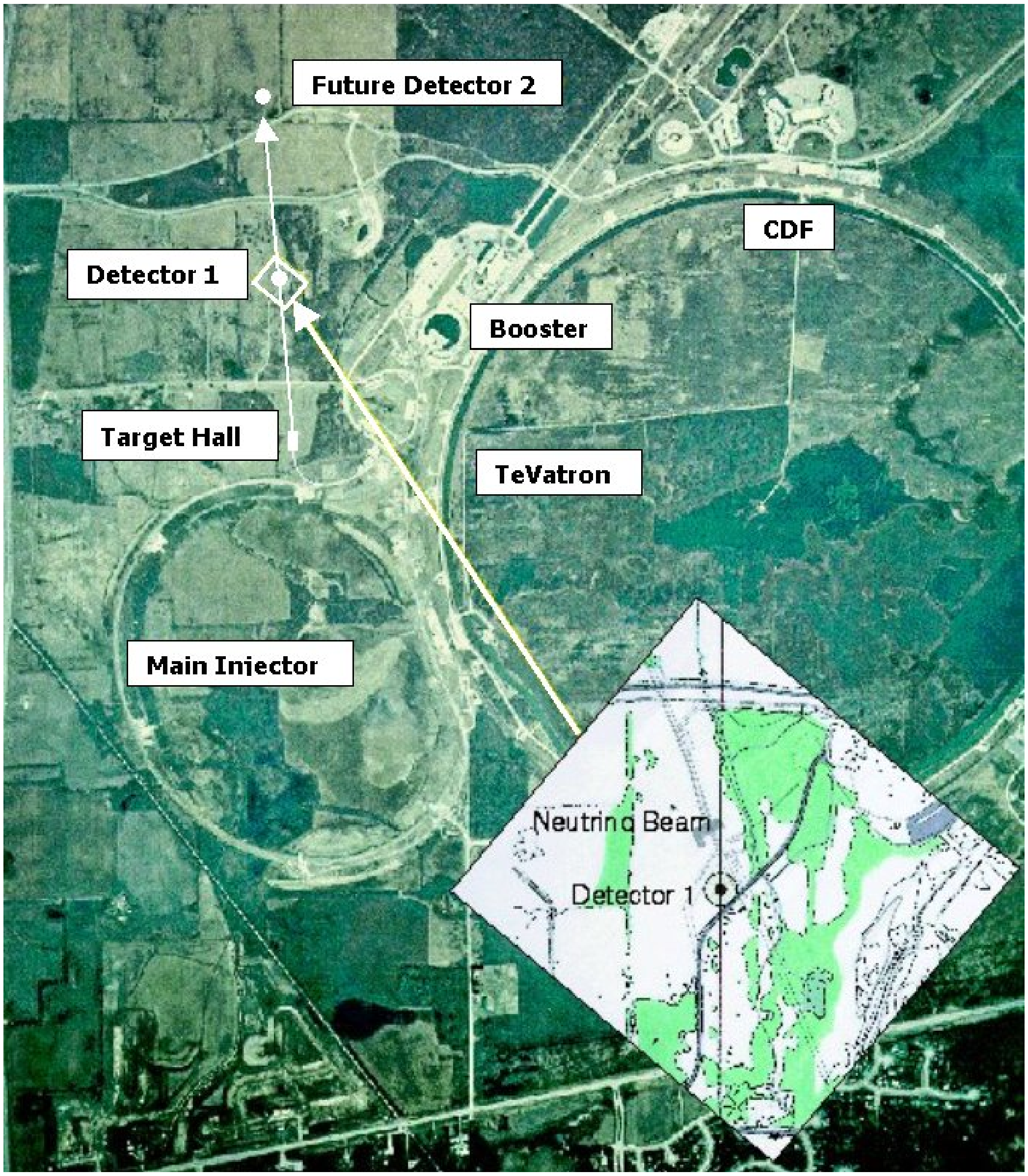

Figure 1. The MiniBooNE site location.

Neutrino Beam consists of four sections: the target, the focusing system, the decay region, and the beam absorber (Figure 2) [1]. These devices are enclosed in the Target Hall (MI-12), the Target Service Building, and the Decay Pipe, and consist of all the technical elements required to form a neutrino beam (Figure 3). These include the horn (focusing system) and power supply, the target and the target shielding, and the beam absorbers.

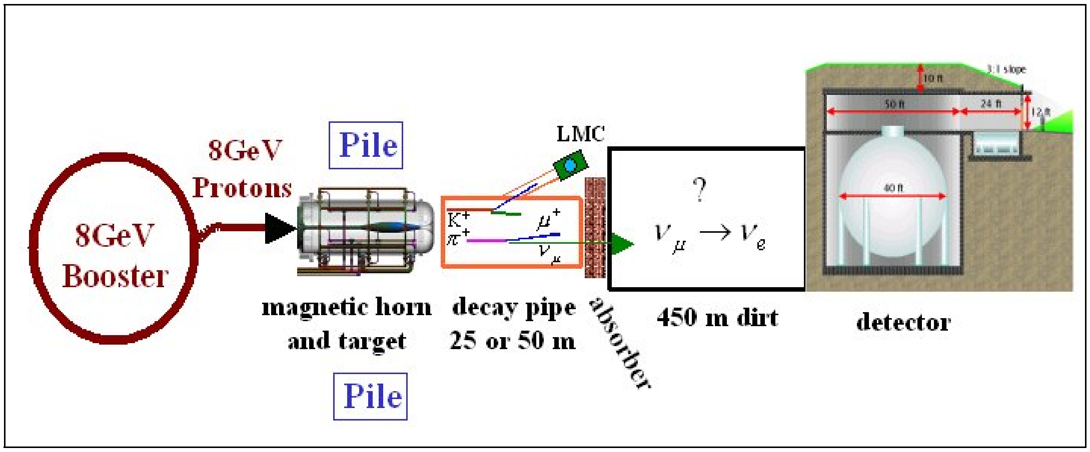

Figure 2. An overview of the MiniBooNE Experiment.

The MiniBooNE neutrino beam is initiated by a primary beam of 8 GeV protons from the Fermilab Booster. A secondary beam is produced when the 8 GeV protons strikes a 71-cm (180.340-in) beryllium target positioned inside a magnetic horn. Protons from the Booster are extracted near MI-10 and transported through a long string of components to the Target Hall which contains the beryllium target within the magnetic horn, followed by an approximately 50 m long pion decay volume. The resulting neutrino beam points to the MiniBooNE detector. Figure 2 gives an overview of MiniBooNE experiment. The purpose of this paper is to discuss the survey and alignment of the MiniBooNE horn and target.

2.1 Target Hall

Located at the end of the Target Hall is the Target Pile (Figure 3). The Target Pile provides a cavity into which the horn is inserted from the upstream end. The Target Pile consists of approximately 160 steel “blue block” (1600 tons), 60 concrete shielding blocks (300 tons) and special custom sized steel (40 tons) above and below the horn module. The target and the horn are located in a cavity within the Target Pile, and the top of the Target Pile is covered with 24-foot (7.3 m) long shielding blocks. The horn power supply is installed on top of the shielding blocks. The lower portion of the Pile, which provides a stable platform, has been aligned.

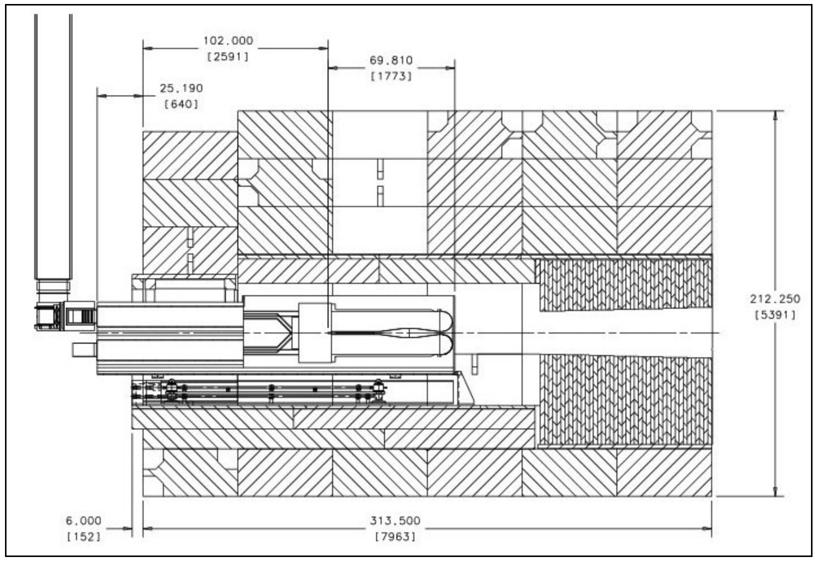

Figure 3. The Horn cavity inside the Target Pile.

Figure 3a. Elevation view of the Target Pile.

2.2 The Horn

When protons from the Booster hit the beryllium target, short-lived hadrons are produced. The hadrons are focused by the magnetic fields generated from a high-current-carrying device called a "horn" (Figure 4). The MiniBooNE horn contains a toroidal magnetic field in the volume between two coaxial conductors. Current flows along the inner (small diameter) conductor and back along the outer (large diameter) conductor. There is no field inside the inner conductor, or outside the outer conductor. The horn has a total length of 73.000 inches (185.420 cm). It consists of an inner conductor and outer conductor. The inner conductor consists of a small diameter tube and a large diameter tube welded together. A rendering of the horn model is shown in Figure 5. The outer conductor has water ports and spider ports welded on it. The spiders are the lateral bracing between the outer and inner conductors. The inner conductor varies in diameter from 1.732 inches (4.399 cm) for the small tube to 5.150 inches (13.081 cm) for the large tube. The outer conductor is 25.622 inches (65.080 cm) outside diameter.

The inner and outer conductors were built separately. The inner conductor was later inserted and installed into the outer conductor. Two end flanges, upstream and downstream end-cap, held the inner conductor inside the outer conductor. The outside diameter for the upstream flange is 16.000 inches (40.640 cm) and the downstream end-cap flange is 13.065 inches (33.185 cm). Figure 6 shows the inner conductor attached to the flanges on the welding machine. The inner conductor was measured with respect to the outer conductor after the inner conductor had been inserted into the outer conductor. The outer conductor was later assembled onto the horn box.

Figure 4. MiniBooNE Horn.

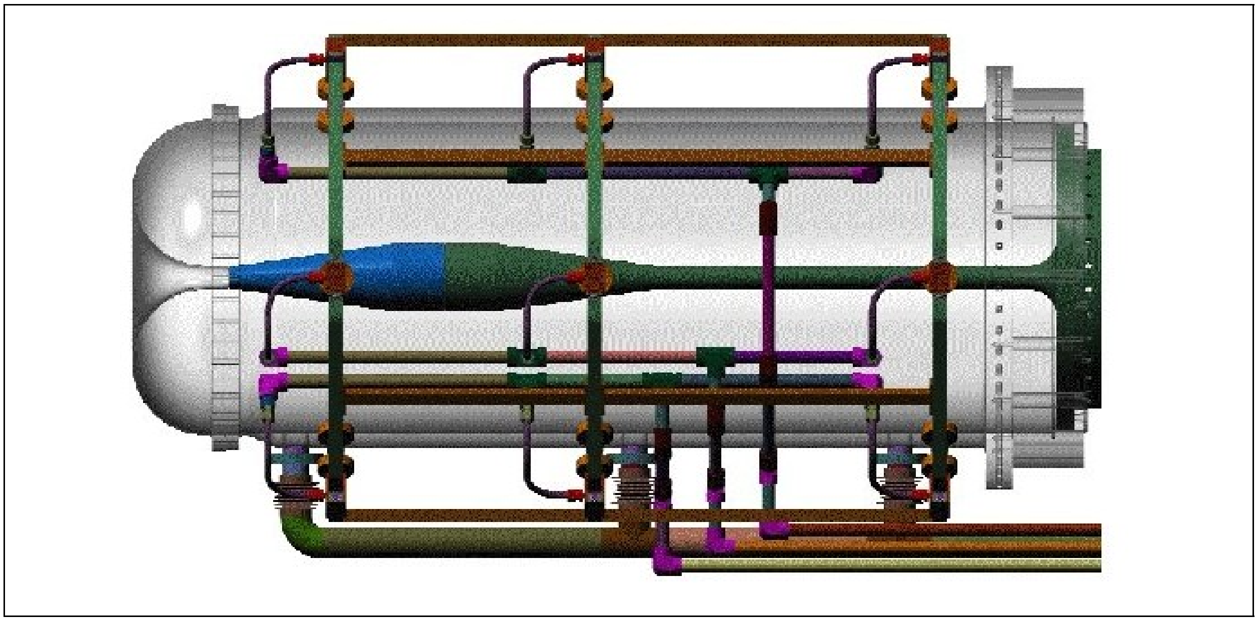

Figure 5. MiniBooNE Horn. The outer conductor is rendered transparent

to see the inner conductor.

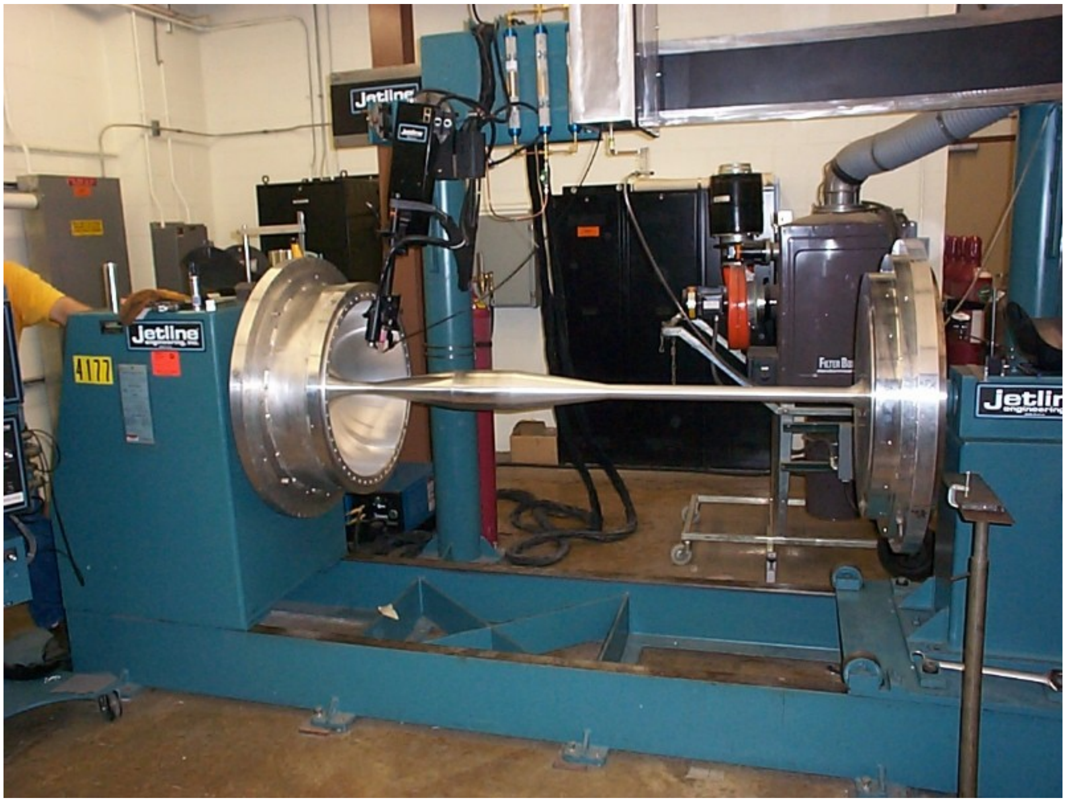

Figure 6. The inner conductor on the welding machine.

The horn is contained in an airtight box, called the horn box (Figure 7), with following connections:

i) Two horn striplines each consisting of five aluminum plates separated by ceramic spacers, cooled by a closed loop air cooling system.
ii) Water supply and return for the horn system.
iii) The target module, consisting of the beampipe, four beam position monitors (BPM), a titanium vacuum window, and the beryllium target assembly.

The horn box has alignment fiducials and mounting feet. The mounting feet mate with the appropriate features on the "adjuster module." The adjuster module has jackscrews for elevation adjustment, and rack and pinion drives for horizontal adjustment. The striplines and the target support channels go inside the horn box. Figure 8 shows horn, stripline and target with the horn box rendered transparent. The material used for the horn and its support structure and stripline is aluminum.

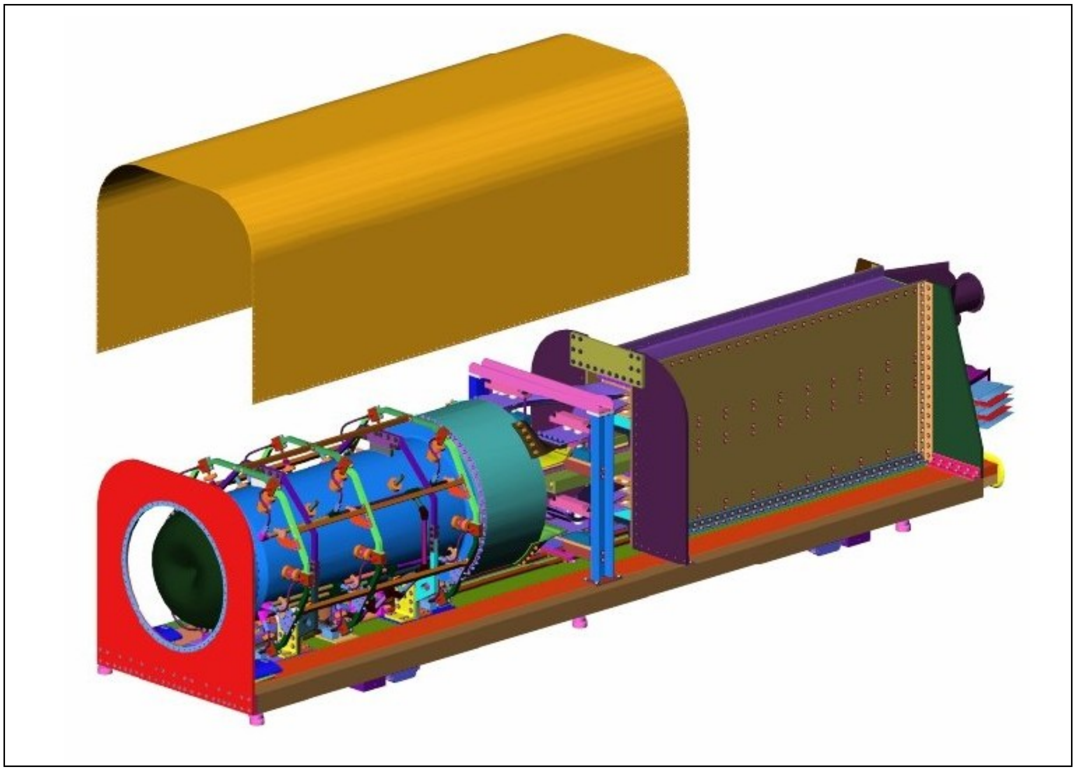

Figure 7. MiniBooNE Horn in Box with air-tightening cover suspended above.

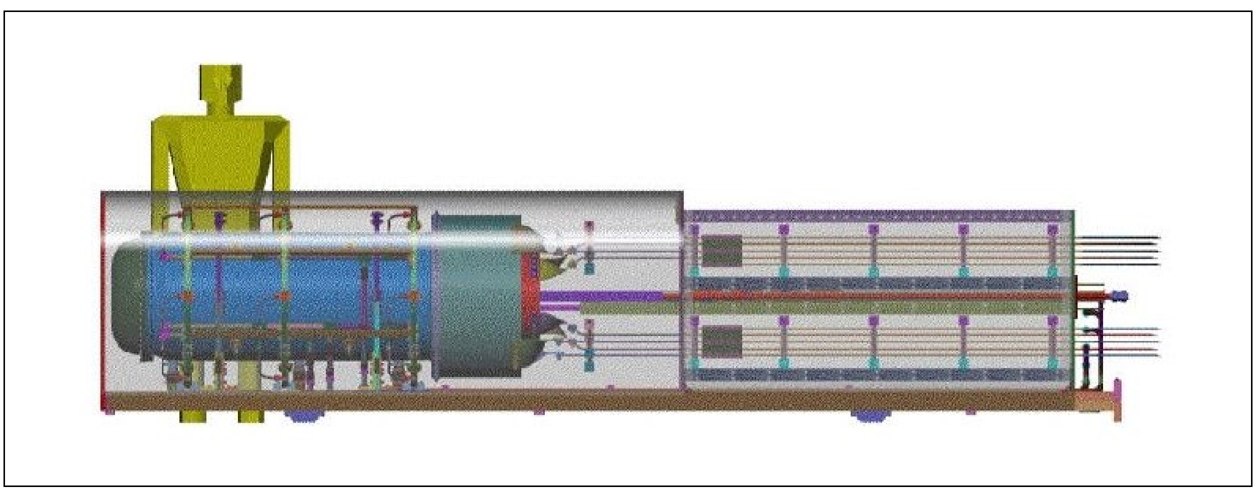

Figure 8. MiniBooNE Horn, stripline and target with the horn box rendered transparent.

An adjuster module is used to support and adjust the position of the horn box. Figure 9 shows the overall view of horn sitting on the adjuster module. The adjuster module rests within the Target Pile and supports the Horn Box at three points. These three supports points are independently adjustable to provide movement vertically, horizontally, pitch and yaw. Two horns were assembled in total for the MiniBooNE experiment.

Figure 9. Overall view of Horn sitting on the Adjuster Module.

2.3 Target and Target Module

The target has a length of 180.340 inches (71 cm) and is located within the magnetic focusing horn. The target is entirely independent of the horn assembly and it is physically separated from the horn. In the event of a target failure, the target can be extracted without removing the horn itself. The target consists of the primary beryllium target elements, two concentric beryllium tubes, an aluminum manifold piece, and a stainless steel bellows that makes electrical contact with the horn inner conductor. The primary beryllium target is a set of beryllium slugs encased in tubes of beryllium, which route cooling air around the slugs. Figure 10 shows the beryllium target assembly for the MiniBooNE. The right photo shows the target slug with its cooling fins at the downstream end of the beryllium tube. The cooling air is directed to the target through a gas distribution flange at the upstream end of the target. This flange also mechanically supports the target from a structure that allows the target to slide along rails inside the upstream end of the horn box, in between the upper and lower striplines. The target is inserted unto the upstream end of the horn and fills most of the length of the upstream tube of the inner conductor.

The target module consists of the beampipe, four beam position monitors (BPM), a titanium vacuum window, and the beryllium target assembly (Figure 11). The target module is supported by two parallel Thomson rails (Figure 12). The rails are hidden inside the middle C-channel that supports the target module in Figure 9. The Thomson rails guide the target into the center of the horn. This system maintains the aligned relationship between the target and its beam position monitors. The same parallel Thomson rails that support the target module also support the vacuum pipe and the BPM module.

Figure 10. The MiniBooNE Target. Left: Side view. Right: Downstream view.

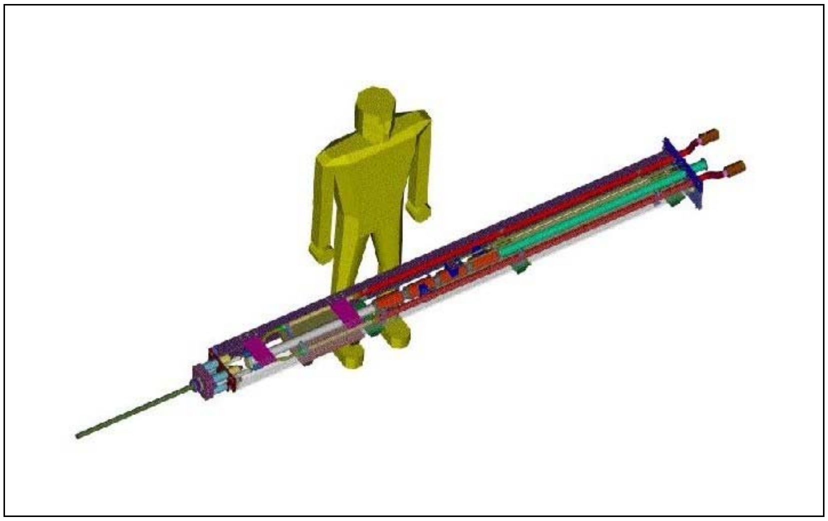

Figure 11. Overall view of the Target Module with man for scale.

Figure 12. Left: Assembled Target Rail for inside Horn Box.
Right: Target Rail inside C-channel.

3. SURVEY AND ALIGNMENT OF THE MINIBOONE HORN AND TARGET

The purpose of this paper is to discuss the:

i) Survey of the horn assembly to measure how concentric the inner conductor is to the outer conductor. This is done by measuring the radius of the inner and outer conductors after the whole horn assembly has been completed, using the photogrammetric system.

ii) Survey of the target and the target module using the Laser Tracker and optical techniques. This survey is independent of the horn survey.

iii) Survey the target and the target module relative to the horn assembly using the photogrammetric system and optical techniques.

The alignment tolerance for the target and horn is 0.5mm (0.020in).

3.1 Survey and Alignment Methodology

The survey instrumentation used for the entire MiniBooNE experiment were as follows:

i) The V-Stars system was used for referencing and for most of the surveys. It is a portable non-contact, three-dimensional digital photogrammetric system. The system consists of one or two digital cameras and software. To measure an object, the camera(s) are used to photograph the object from various directions. The digital images are processed immediately by the software to provide three-dimensional coordinates and statistical information. The software is based on photogrammetric-bundle- triangulation methods.

ii) The Laser Tracker, SMX Tracker 4500 and its associated software Insight™, were used for mapping the target rails. The Laser Tracker is a device that makes three-dimensional measurements. It uses a laser distance meter, two precision angle encoders and proprietary software to calculate, store and display the real-time three-dimensional position of a mirrored target positioned on the desired point or feature. The mirrored target is a spherically mounted retro-reflector (SMR).

iii) Optical Tooling (Brunson) techniques were used for surveying the target and the target module, and for making offset measurements from the completed horn assembly to the control points in the Target hall. Optical (Wild N3) and electronic (Leica NA3000) levels were used for elevations.

3.2 Fiducialization and Referencing

The goal of the horn or target fiducialization is to relate all its physical measurements and the physical center to the survey fiducials mounted on the component. Several survey fiducials are mounted at the corners of each component. Construction plates are used as fiducials. At the center of each fiducial is a 0.250 in. hole that precisely fits a Laser Tracker SMR pin nest or photogrammetric retro-reflective targets. The center of this hole defines the location of the fiducial point. Each component is referenced in a local component coordinate system defined such that its origin is at the physical center, y is positive downstream, x is positive right and perpendicular to y, and z is positive up. The components were placed in the beam line such that Y is longitudinal along the beamline, X is transverse to the beamline, and Z is the vertical positive above the beamline. Beam right is positive.

There were six fiducials welded to the stable feet of the adjuster module. These six points were used as control points for the entire survey. The horn was referenced to these control points. After the final assembly of the horn and the horn box, the horn was referenced to fiducials outside the box, which would be visible through channels in the bottom of the box. The horn box fiducialization done with scales. These points were used to place the entire horn system on the beamline and into its final location in the Target Pile.

Four fiducials welded to the four outside corners of the target module. The beryllium target and other components in the target module were referenced to these four points. These four points were later used for the optical alignment of the target module to the beam line in the Target Hall. The external target support frame were fiducialized for two purposes:

i) to be able to align the frame with respect to the horn box when they were both in the tunnel so that new targets could be transferred into the horn box.

ii) After the target was aligned to the horn, to put this target module on the external target support and measure where it was with respect to the rails on the external target support.

This would allow the alignment of a new target at some point in the future to the external support rails, so that a new target would end up in the correct place inside the horn box (where the rails will be radioactive and not accessible to survey in future.)

The MiniBooNE horn and target were both referenced and surveyed in MI-8 service building.

3.3 Horn Survey

Since the smaller diameter tube of the inner conductor was welded onto the larger diameter tube, the entire tube was aligned by checking the concentricity of the small and large tubes. The inner conductor was measured with respect to the outer conductor after the inner conductor had been inserted into the outer conductor. The upstream flange and the downstream end-cap flange were also measured. These measurements were used as a check on the Runout measurements that were made while the inner conductor was in the welding machine. Runout = $(X^2+Y^2)^{1/2}$, where X and Y are the center point of the circle.

The V-Stars photogrammetric system was used to measure the location of the inner conductor inside the outer conductor (Figures 13 and 15). To reach the inner conductor from the outside, a target stalk with a 0.25-in hole at one end was used. The stalks were exactly 16.00 inches long and were passed through the water and spider ports on the outer conductor to touch the inner conductor. Attached to the other end of the stalks were 45° double retro-reflective vector targets with 6-mm dots. Figure 14 shows the target stalks and holders with the retro-reflective vector targets attached. The coordinates of the double vector targets and the vector distance were used to construct the corresponding coordinates on the surface of the inner conductor. The vector distance is the distance from the top vector point to the surface of the inner conductor. Vector distance = 16.00 + 1.25 = 17.25 inches (43.815 cm). Corresponding standard deviations were also generated from the V-Star software. The standard deviations usually degenerated as the vector distance increased. Single adhesive 6-mm retro-reflective targets were used for the outer conductor surface and the flanges. These allowed the cylinder of the outer conductor to be reconstructed.

Table 1 shows the results of the photogrammetric measurements for the MiniBooNE horn. Similar results are shown in Table 2 for the spare horn. Figures 16 shows the graphical display of the same results from the V-Star software. Despite the target extension of 16.00 inches, the maximum radial deviation from ideal cylinder or circle is 0.004 inches for both inner and outer conductors. This is well within the tolerance specified. Table 3 shows the results of the Runout of the inner conductor with respect to the axis defined by the downstream end-cap flange. The maximum deviation of the Runout is 0.009 inches, which is no problem for the designers.

Figure 13. Photogrammetric survey of Horn.

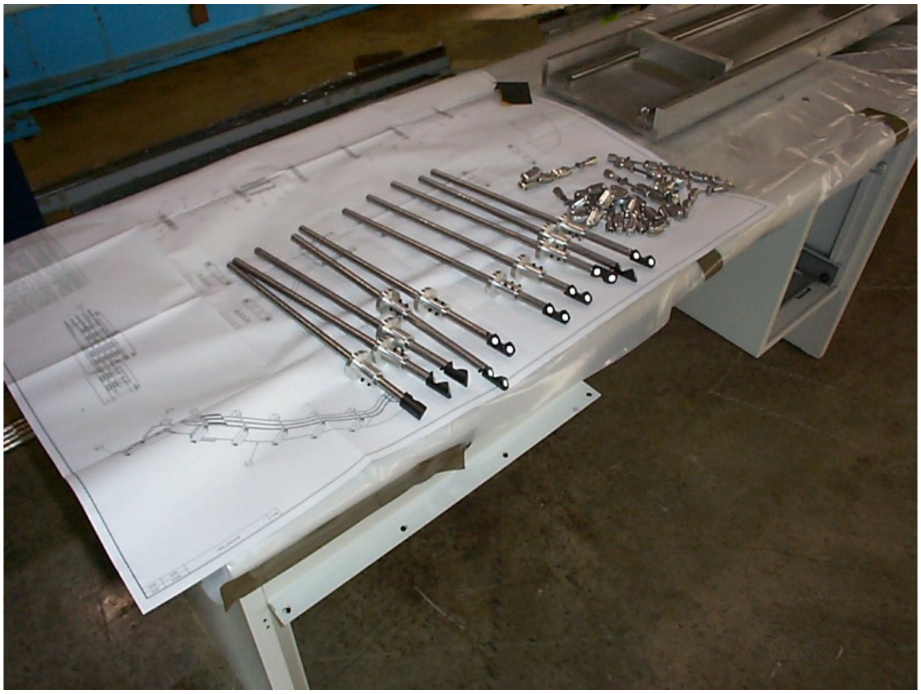

Figure 14. Target Stalk and holders with 45° double Vector Targets attached to one end.

Table 1. Horn Measurements.

Horn Part	Measurement Type	Points	Target Type	Radius Actual in	Radius Nominal in	Radius Act-Nom in	Total RMS in
Upstream Flange	Circle	20	Point	16.000	16.000	0.000	0.016
Inner Conductor - Small tube	Circle	6	Vector	0.866	0.866	0.000	0.013
Inner Conductor - Small tube	Circle	4	Vector	0.869	0.866	0.003	0.007
Inner Conductor - Small tube	Cylinder	10	Vector	0.867	0.866	0.001	0.001
Inner Conductor - Large tube	Circle	4	Vector	2.575	2.575	0.000	0.002
Downstream End-Cap Flange	Circle	16	Point	13.065	13.065	0.000	0.019
Outer Conductor - Horn Surface	Cylinder	89	Point	12.815	12.811	0.004	0.001

Table 2. Spare Horn Measurements.

Horn Part	Measurement Type	Points	Target Type	Radius Actual in	Radius Nominal in	Radius Act-Nom in	Total RMS in
Upstream Flange	Circle		Point	Not Measured			
Inner Conductor - Small tube	Circle	6	Vector	0.868	0.866	0.002	0.037
Inner Conductor - Small tube	Circle	4	Vector	0.868	0.866	0.002	0.043
Inner Conductor - Small tube	Cylinder	10	Vector	0.867	0.866	0.001	0.002
Inner Conductor - Large tube	Circle		Point	Not Measured			
Downstream End-Cap Flange	Circle		Point	Not Measured			
Outer Conductor - Horn Surface	Cylinder	24	Point	12.812	12.811	0.001	0.002

Table 3. Runout Measurements of the Inner Conductor.

Horn Part	Measurement Type	Center Point X in	Center Point Y in	Actual Runout $(X^2+Y^2)^{1/2}$ in	Nominal Runout in	Runout Act-Nom in
Upstream Flange	Circle	0.0001	0.0000	0.0001	0.0002	-0.0001
Inner Conductor - Small tube	Circle	0.0017	-0.0010	0.0020	0.0040	-0.0020
Inner Conductor - Small tube	Circle	0.0064	-0.0048	0.0080	0.0160	-0.0080
Inner Conductor - Large tube	Circle	-0.0083	0.0034	0.0090	0.0180	-0.0090

Downstream End-Cap Flange	Circle	0.0000	0.0000	0.0000	0.0000	0.0000
Outer Conductor - Horn Surface	Cylinder	0.0001	0.0003	0.0003	0.0006	-0.0003

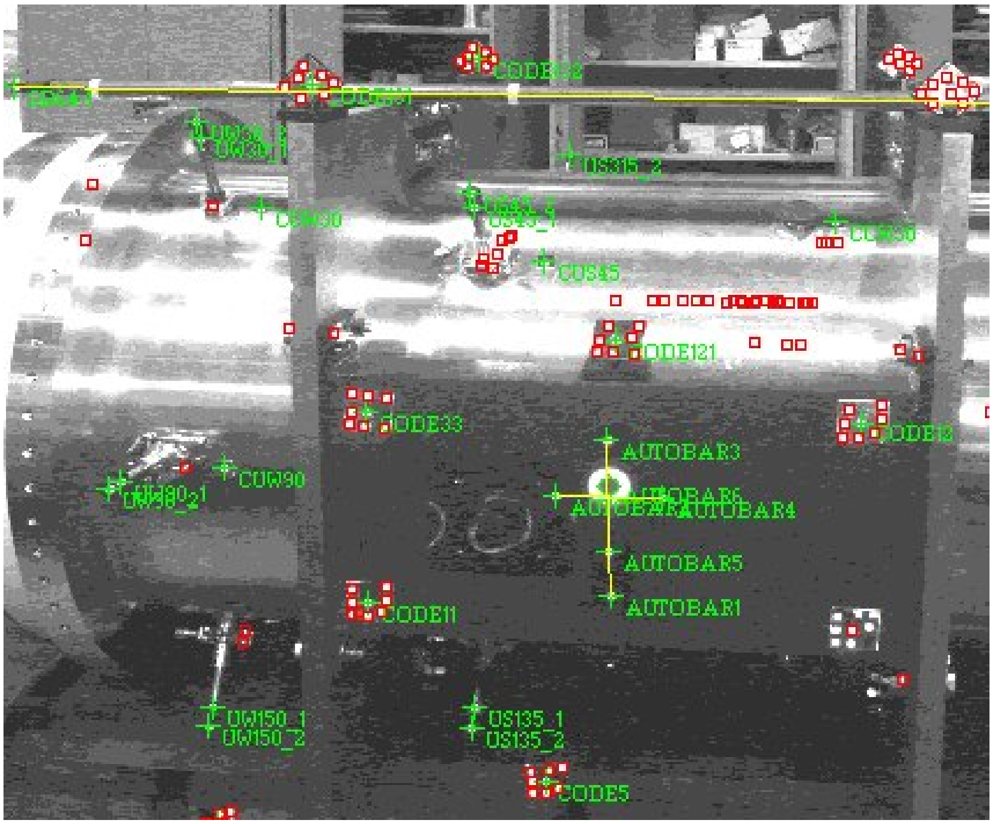

Figure 15. Photogrammetric survey of Horn showing target stalks with vector targets.

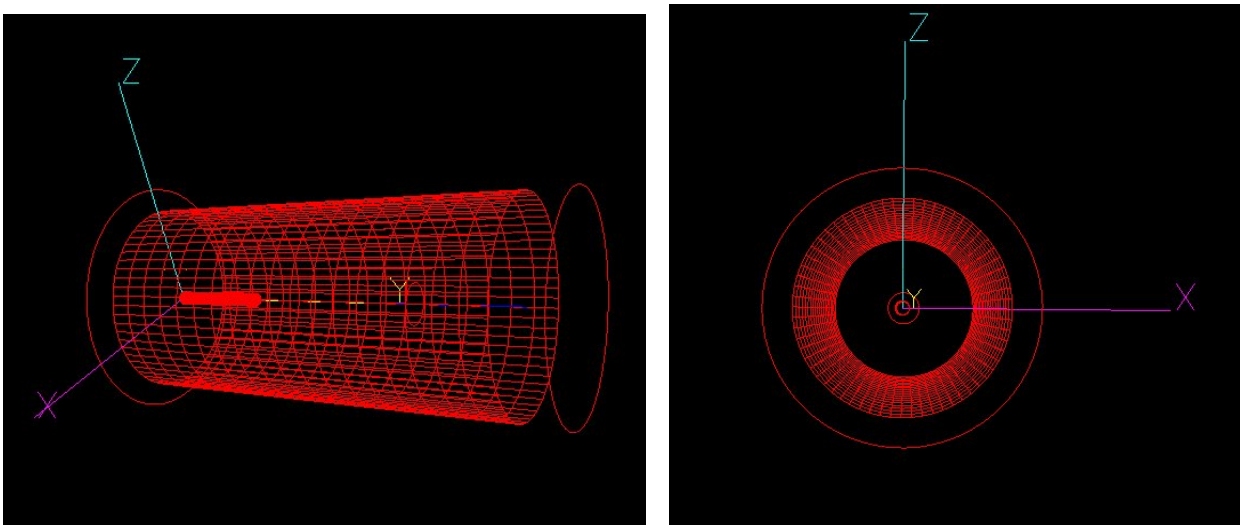

Figure 16. Graphical display of the inner and outer conductors.
Left: Side view. Right: View from the downstream.

3.4 Target Survey

The Laser Tracker was first used to map the two Thompson target rails. This was done by measuring the cylindrical surfaces at different intervals along the rails. Table 4 shows the results of the mapped rails. The parallelism between the two Thompson rails was measured with the Laser Tracker. The rails were good through most of their lengths to about 0.004 inches and deviated in one place by about 0.008 inches, which was no problem for the designers.

Table 3. Target Rail Measurements.

Name	Cylinder Center Point X in	Y in	Z in	Obs	Radius Actual in	Radius Nominal in	Radius Act-Nom in
RIGHT_Cylinder001	3.880	4.435	0.934	56	0.375	0.375	0.000
RIGHT_Cylinder002	3.881	10.484	0.931	53	0.375	0.375	0.000
RIGHT_Cylinder003	3.882	16.512	0.936	60	0.374	0.375	-0.001
RIGHT_Cylinder004	3.883	22.521	0.938	58	0.375	0.375	0.000
RIGHT_Cylinder005	3.885	28.572	0.937	55	0.375	0.375	0.000
RIGHT_Cylinder006	3.887	34.642	0.933	54	0.375	0.375	0.000
RIGHT_Cylinder007	3.886	40.439	0.930	53	0.374	0.375	-0.001
RIGHT_Cylinder008	3.886	46.540	0.933	53	0.374	0.375	-0.001
RIGHT_Cylinder009	3.884	52.267	0.937	54	0.375	0.375	0.000
RIGHT_Cylinder010	3.884	58.593	0.941	51	0.375	0.375	0.000
RIGHT_Cylinder011	3.884	64.719	0.943	54	0.374	0.375	-0.001
RIGHT_Cylinder012	3.885	70.632	0.941	54	0.375	0.375	0.000
RIGHT_Cylinder013	3.884	76.656	0.937	50	0.375	0.375	0.000

RIGHT_Cylinder014	3.882	82.737	0.937	48	0.375	0.375	0.000
RIGHT_Cylinder015	3.880	88.557	0.937	51	0.374	0.375	-0.001
RIGHT_Cylinder016	3.878	94.442	0.935	52	0.374	0.375	-0.001
LEFT_Cylinder001	-3.871	4.626	0.940	57	0.374	0.375	-0.001
LEFT_Cylinder002	-3.871	10.606	0.936	57	0.374	0.375	-0.001
LEFT_Cylinder003	-3.871	16.347	0.933	61	0.374	0.375	-0.001
LEFT_Cylinder004	-3.871	22.320	0.931	60	0.375	0.375	0.000
LEFT_Cylinder005	-3.872	28.345	0.930	63	0.375	0.375	0.000
LEFT_Cylinder006	-3.871	34.177	0.929	62	0.374	0.375	-0.001
LEFT_Cylinder007	-3.869	40.374	0.928	61	0.374	0.375	-0.001
LEFT_Cylinder008	-3.867	46.484	0.927	61	0.375	0.375	0.000
LEFT_Cylinder009	-3.866	52.168	0.931	62	0.375	0.375	0.000
LEFT_Cylinder010	-3.864	58.147	0.933	62	0.374	0.375	-0.001
LEFT_Cylinder011	-3.863	64.111	0.934	61	0.375	0.375	0.000
LEFT_Cylinder012	-3.863	70.303	0.935	62	0.374	0.375	-0.001
LEFT_Cylinder013	-3.865	76.182	0.934	61	0.374	0.375	-0.001
LEFT_Cylinder014	-3.869	82.372	0.930	61	0.374	0.375	-0.001
LEFT_Cylinder015	-3.873	88.467	0.925	60	0.374	0.375	-0.001
LEFT_Cylinder016	-3.875	94.375	0.922	58	0.374	0.375	-0.001

Optical tooling techniques were used to reference the beryllium target to the fiducials mounted at the four corners of the Target module. The target axis was determined. The target module and the BPM module and all the other components in the target module were surveyed with reference to these four points. The BPMs were placed on the same axis as the target. This survey was repeated several times with the target outside the horn, since the target could only be inserted once.

3.5 Final Survey of Horn and Target

A final survey was done to check where the beryllium target was with respect to the target rail and the horn. The target was aligned to the centerline of the horn. The target itself could not be surveyed once inserted into the horn. Therefore, target rail channel was surveyed because the experimenters needed to know where the rail axis was with respect to the horn axis. They also needed to know if the axes were parallel. Otherwise there was a risk of damaging either the target or the inner conductor when the target was inserted into the horn. This survey was done using the photogrammetric system. An alignment fixture was built to move along the rails. The center of the fixture coincided with the centers of the rails (Figure 12). A vector target was fitted into the 0.25-inch hole on top of the fixture. An 18-inch target extension could also be used with the fixture. The short fixture was 3.563 inches above the rail center and the tall fixture was 21.563 inches above the rail center. The tall fixtures were used where the rails were hidden inside the middle C-channel. Measurements were made every 12 inches along the rail. Before the target could be aligned to the horn, the horn had to be re-leveled and a new ideal line was created for the horn axis. The target was also leveled because the horn axis must be on the same line as the target axis.

Analysis of the results of the photogrammetric measurements of the target rails by the experimenter revealed that the angular variations between the rail axes and the horn axes were relatively small and correct. The data also revealed a vertical offset between the position of the rails and their ideal dimensions. With an optical survey, necessary adjustments were made to remove this vertical offset and to insure that there were no significant angular misalignments between the rails and horn axis. The channels were positioned with optical survey. This included leveling the horn box and the horn with respect to the horn platform. The horn platform was also leveled with the adjuster module. Horizontal and vertical measurements were made to correct for yaw, pitch, horizontal and vertical translations.

Once the target and horn were aligned, the target was placed on the external target support. At this point, the target and external support was completely characterized so that a new target could be assembled to exactly the same position as the original target on the external support frame. This was critical and must be done right because there would be no way to check the relationship between a radioactive horn and a new target. The new target installation would be completely blind and would rely on having made the new target as identical to the old as practical.

Figure 17. Left: Transferring Target into the Horn.
Right: Portion of Target inside the Horn.

Figure 18. Downstream view of Target completely inside the Horn.

The target was transferred between the external target support frame and the horn box. Figure 17 shows the target module being transferred, while Figure 18 shows a portion of the target inside the horn. To get ready for the installation of the horn in the tunnel at MI-12, an optical survey was performed to transfer the fiducialization of the horn to the new fiducials on the horn box, including the scales at the downstream end in the air ducts, so that the horn could be final aligned in the tunnel vault at MI-12. This was critical and must be done right because once the cover on the horn box was put on, the horn would never be seen again.

Alignment was fully completed once the target was able to move in and out of the horn without any problem.

3.6 Beamline Alignment

Once the referencing and alignment were completed in MI-8, the horn and the target were boxed up in a horn coffin, which was then transferred to the Target Hall in MI-12 where it was placed in the beamline inside the horn cavity in the Target Pile using the optical tooling techniques.

4. CONCLUSION

The MiniBooNE horn and target were both referenced and surveyed in the MI-8 service building. The survey results had been presented. The alignment methodology used had also been presented. The horn and target are currently in the beamline inside the horn cavity inside the Target Pile in the tunnel at MI-12. Fermilab began collecting neutrino event data in August 2002.

5. ACKNOWLEDGMENT

I would like to thank the Alignment and Metrology Group members who participated in the MiniBooNE experiment. A special thanks goes to Larry Bartoszek of Bartoszek Engineering for his help and for providing most of the images.

6. REFERENCES

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