Beam Parameter Document

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Abstract

This note is an attempt to gather and calculate in one document the important parameters for the NOvA beam and detectors. These parameters are intended to be used consistently across the collaboration for simulations, calculations, and data analysis. However, they are the best we have so far. All point positions for the detectors refer to the center of the upstream (front) face of the detector.

Table 1: The Beam Parameter Sheet. All point locations for detector positions refer to the center of the upstream face of the detector.

Detector Locations (Table 2)

Detector	x	y	z
NDOS (NuMI System)	-0.29 m	92.21 m	841.76 m
NDOS (Booster System)	13.88 m	8.01 m	641.40 m
Near Underground 3×3	11.57 m	-3.64 m	993.35 m
Far	11.03746×10^3 m	-4.16264×10^3 m	810.42232×10^3 m

Detector Orientations as of Sep. 25, 2013 (Table 6)

Detector	Magnetic Declination	Δ(Declination)/Δt	True N Orientation
NDOS	$-3°14' \pm 30'$	$-5'$/ yr	$-23°48'39'' \pm 14'2''$
Near Underground	$°$	$°$	$°$
Far	$-0°29' \pm 30'$	$-6'$/ yr	$-27°51'26'' \pm 5'51''$

Target Information (Table 7)

Start of Target	$z = -143.3$ cm
Start of Target (Excl. Budal Monitors)	$z = -137.55$ cm
End of Target	$z = -20$ cm
Width	7.4 mm
Height	150.5 mm
ZXF-5Q graphite density	1.78 g/cm^3
Beam center dist from fin top	3.7 mm
Beam center dist from fin side	3.7 mm

Horn Information (Table 8)

	Horn 1	Horn 2
Start of idealized Horn	$z = 0.00$ m	$z = 19.1779$ m
Horn Insertion Point	$z = 0.03$ m	$z = 19.1779$ m
Current	200 kA	200 kA

Booster Beam Angles (Table 9)

NuMI Coord. Axis	Angle
x	111.50988°
y	89.284678°
z	21.50988°

1 Coordinate System Conventions

When the parameters in this sheet refer to a physical position, it will be in one of two beam coordinate systems: the NuMI Simulation System or the Booster Beam System.

1.1 NuMI Simulation System

The origin of the NuMI Simulation System (a.k.a. the beam Monte Carlo system [?]) is known as MCZERO, the idealized start of Horn 1, or the Horn 1 insertion point; it is 0.030000 m upstream of the beginning of the active part of horn one [?]. The NuMI Simulation System used in this document places the z axis parallel to the beam with positive being downstream, the y axis being vertical, and the x axis is perpendicular to those two with positive being westward. The Booster Beam System is defined similarly with respect to the Booster Neutrino beam rather than the NuMI beam.

1.2 Booster Beam System

The Booster Beam coordinate system has its origin at the MiniBooNE Target [?]. The axes are defined relative to the origin and MiniBooNE beam in the same was as the NuMI Simulation System is defined relative to the NuMI beam.

1.3 Numi Beamline System

Note that the coordinate system used by Alignment and Metrology group is different! It is known as the Numi Beamline System. The z axis is positive upward when looking downstream beamline (and orthogonal to the beam); the y axis is positive downstream beamline, and the x axis is positive beam right (Eastward) when looking downstream beamline [?]. So, to convert from this coordinate system to either the Booster Beam System or the NuMI Simulation System, interchange the y and z values, then multiply the x values by -1.

1.4 DUSAF and Local Tunnel Coordinate Systems

The DUSAF coordinate system is obsolete and no longer used at Fermilab. It has been replaced by the Fermilab Site Coordinate System (FSCS). Within Fermilab Main Injector Projects, two local tunnel coordinate systems (LTCS) are used. These systems and their relationship to one another are defined in Ref. [?].

1.5 How long is a foot?

While extremely confusing, this document must contend with two different definitions of the foot. The foot defined as 12 inches with 1 inch defined as exactly 2.54 centimeters (1 foot $\equiv$ 0.3048 meter) is the International Foot. The foot used by the Alignment and Metrology group is the U.S. Customary foot, which is defined such that 1 meter is exactly equal to 39.37 inches (1 foot = 0.30480061... meter) [?].

One must therefore be extremely careful about which definition of foot one is using when converting from feet to metric units over long distance scales. If the distances in question are less than 1.64 feet, the difference between U.S. Customary and International foot is less than 1 μm. If the distances in question are less than 164 feet, the difference between U.S. Customary and International foot is less than 0.1 mm.

The U.S. Customary foot is thus used for all dimensions on construction and civil engineering drawings, such as the drawings of the near detector cavern [**?**]. I think the International foot and inch are used on drawings of parts, such as extrusions, for the detectors themselves; however, for most such drawings the metric equivalents are given on the drawings, so there is no need to convert.

In remaining sections of this document, the traditional tick marks (’ and ”) will denote the international foot, and the abbreviations (ft. and in.) will denote the U.S. Customary foot.

2 Detector Locations

All point positions for the detectors refer to the center of the upstream (front) face of the detector.

Table 2: Unless otherwise noted, these are the positions of the NOvA detectors in the NuMI Beam Simulation coordinate system, with $z = 0$ at the horn 1 insertion point (MCZERO). The values in this table for the NDOS are calculated as detailed in §2.1; the other values do not have solid references yet. All dimensions in m.

Detector	x	y	z
NDOS in NuMI System (§2.1)	-0.29 m	92.21 m	841.76 m
NDOS in Booster System (§2.1)	13.88 m	8.01 m	641.40 m
Near Underground 3×3 (§2.2)	11.57 m	-3.64 m	993.35 m
Far [**?**]	11.03746×10^3 m	-4.16264×10^3 m	810.42232×10^3 m

Table 2 shows the currently best understood positions of the NOvA detectors in the relevant coordinate system. These values can be used for the present time, but they will be updated as new and better information becomes available.

2.1 NDOS

Table 3 shows the positions of the NDOS building corners in the NuMI Simulation System and the Booster Beam System. The event rates that Zelimir calculated [**?**] use the center of this building as the position of the detector, but our standard convention is to use the center of the front face of the detector.

Precise survey measurements of the NDOS position have been performed [**?**, **?**, **?**], and these are in the process of being converted into coordinates in the NuMI Simulation System.

For now, we combine the survey positions for the NDOS building corners (Table 3), the Corwin-Messier tape measure survey (Table 4), and the NDOS dimensions given

Table 3: Positions of the corners of the NDOS building. These positions are all at survey points 1.37 m above the floor [?]. All dimensions in m.

	NuMI Beam Simulation System			Booster Beam System		
Survey Point	x	y	z	x	y	z
SW	3.722390	91.102719	838.723274	16.370826	8.941392	636.992112
SE	-4.919480	91.100797	838.723640	8.411293	8.939806	640.357785
NW	3.730588	92.356373	860.171386	24.745261	8.944113	656.777512
NE	-4.941250	92.351116	860.150710	16.749870	8.940424	660.135329

in Table 5 to obtain the position of the center of the front face of the near detector in the two coordinate systems.

Originally, the method described in Appendix A was used to find the position of the NDOS in the NuMI coordinate system. This method failed to produce consistent results for the Booster coordinate system. A new method was implemented which is simpler to understand and produces good results quickly.

The system used relies on the invariance of distance regardless of coordinate system. From the tape measure survey and the building survey, we can calculated the distance from each of the four survey points to the center of the front face of the detector. In ROOT, a histogram is filled with three of these distances. We use a fitting function. The parameters of that function are the coordinates of the center of the front face of the detector in the desired coordinate system. The histogram is then fitted using this function. Since we have three parameters and three unknowns, this should produce a unique solution. When the parameters have been calculated by the ROOT fitting algorithm, we compare the distance between the location given by the parameters and the final of the four corners (the NW). In both coordinate systems, all four distances match to within 1 cm. The results are shown in Table 2.

2.2 Near Detector Underground

The underground near detector is currently planned to have a square face that is three modules high and wide (3×3). Virgil Bocean has calculated the planned location of the center of the upstream face of this design [?] based on preliminary drawings [?]. This calculation, which is reported in Table 2 assumes the same pallet height as the 3×2 detector. These values will be updated when the near detector is built and surveyed.

2.3 Far Detector

Until April of 2012, we had far detector positions only by word of e-mail and from the TDR (see Appendix B). More precise survey data became available in April of 2012.

Since the detector blocks will be deliberately tilted slightly toward the south, specifying a point on the front face of the detector would be problematic. Instead, the point calculated in this section and specified in Table 2 is the center of where the front face of the detector would be if it were placed perfectly vertical and flush against the metal bookend at the south (upstream) end of the detector. The Fermilab alignment and

Table 4: Luke Corwin and Mark Messier surveyed the position of the NDOS relative to the building walls using a tape measure on the afternoon of Dec. 7, 2010.

East wall to east edge of PVC		
At 8th horizontal plane (Mod1 br5 survey label)	128 5/8 ”	3.27 m
At 1st horizontal plane (Mod1 br4 survey label)	128 ”	3.25 m
South wall to south edge of PVC		
At cell #4 counting from east	121 11/16 ”	3.09 m
At cell #4 counting from west	121 1/16 ”	3.07 m
At east-west center	121 5/8 ”	3.09 m
Wall to strong back center + strong back center to PVC	121 11/16 ”	3.09 m
Ave.	121 33/64 ”	3.09 m
South wall to south edge of strong back posts		
East	111 13/16 ”	2.84 m
West	111 9/16 ”	2.83 m
Center	111 13/16 ”	2.84 m
S edge of center strong back post to PVC	9 7/8 ”	0.25 m
Width of 1st vertical plane	102 3/4 ”	2.61 m
West edge of detector to west wall		
From vertical plane #7 PVC to wall	106 3/8 ”	2.70 m

Table 5: Surveyed and Drawn dimensions of the NDOS detector.

Width of V plane	102.85 ± 0.05” [?]	2.6124 ± 0.0013 m
Height of V module	$160.0^{+0.5”}_{-0.0}$ [?]	$4.064^{+0.013}_{-0.000}$ m
Length of H module	$108.0^{+0.5”}_{-0.0}$ [?]	$2.743^{+0.013}_{-0.000}$ m
Distance from floor to detector bottom		0.288 m [?]

metrology group has surveyed the far detector building. Using the results of this survey, they have calculated this point [?] in the NuMI Beamline System (§1.3). Transforming into the NuMI Simulation System yields the results in Table 2.

3 Detecor Orientations

For cosmic ray studies, we wish to know the orientations of the detectors with respect to true and magnetic north. The positions of center of the north and south walls of the NDOS and Far detector building have been surveyed [?] with precision, and we can use this information to calculate the two orientations.

3.1 True North

The calculations of the orientations with respect to true north are preformed assuming Earth is a sphere with constant radius from the detectors to the north pole. Earth is not a perfect sphere; it can be better approximated as an ellipsoid with equatorial radius (semi-major axis) of $r_{eq} = 6378137.0$ meters and polar radius (semi-minor axis) of $r_p = 6356752.3142$ m [**?**]. The difference between these two is

$$\frac{|r_{\mathrm{eq}} - r_p|}{r_p} = 0.34\%, \tag{1}$$

which is taken as an uncertainty on our final result.

To calculate the orientation of the detector buildings (and hence the detectors) with respect to true north, we define a spherical triangle with points at the center of the north wall of the building, the center of the south wall of the detector building, and the north pole. The geodesic between the center of the two walls is called side a; between the center of the north wall and the north pole is called side b; between the center of the south wall and the north pole is called side c. The orientation angle B is defined as the angle between sides a and c, with east being positive. a, b, and c represent the angles subtended by each side at the center of the earth, approximated as a sphere. With these definitions and positions, we can then calculate the orientation angle [**?**].

From survey data, we have the latitudes and longitudes of centers of the north and south walls of the NDOS and far detector buildings [**?**], and the north pole is defined as exactly $90°N$. The angles subtended by two points on a sphere is given by

$$(a, b,\ or\ c) = \cos^{-1}\left[\cos(\phi_1)\cos(\phi_2)\cos(\theta_1 - \theta_2) + \sin(\phi_1)\sin(\phi_2)\right], \tag{2}$$

where (ϕ, θ) are the latitude and longitude of the points in question. Once these subtended angles are calculated, we can calculate the orientation angle

$$B = 2\tan^{-1}\left[\frac{k}{\sin(s-b)}\right], \tag{3}$$

where

$$k^2 = \frac{\sin(s-a)\sin(s-b)\sin(s-c)}{\sin(s)} \tag{4}$$

and

$$s = (a+b+c)/2. \tag{5}$$

We determine if B is positive or negative based on whether the longitude of the center of the north wall is east or west of the center of the south wall. Our sign convention is that positive values denotes East of true north and negative values denote West of true north; the results are shown in Table 6.

Several cross-checks are performed to ensure that this calculation gives reasonable results and give some idea of our uncertainties. We check that the geodesic between the two walls of the NDOS building is in agreement with the length of the building determined from Table 3. From the table, the west side of the NDOS building is 21.4847207 m long, and the east side is 21.4635295 m long; we compare the geodesic with the average 21.4741251 m. The geodesic length is given by $R_{♁}a$; the result is 21.51 m and 21.44 m when we use Earth's semi-major and semi-minor axis respectively.

We also verify that altering the longitude of the north pole does not change our results. If the latitudes of a building are equal, we should calculate $B = 90°$. When we slightly alter the latitudes of the NDOS and far detector buildings to make the north and south walls at equal latitude, the result is within $1''$ of $B = 90°$. Similarly, if the longitudes of a building are equal, we should calculate $B = 0°$. We check this by altering the coordinates so that the north and south walls are at the same longitude. Since our numerical precision is not perfect, k^2 can be slightly negative, so we take the absolute value of k^2 before taking the square root. When we perform the calculation, the deviation from zero in this case is on the order of several arc minutes.

Our uncertainty on the orientations with respect to true north is the sum in quadrature of the calculated value of B at equal longitude and 0.34% (from Equation 1) times our central value.

3.2 Magnetic North

Once we know the orientation of a detector with respect to true north, we can calculate its orientation with respect to magnetic north if we know the difference between true and magnetic north, which is called the magnetic declination. These values, their uncertainties, and variability with time are calculated by the U.S. National Oceanic and Atmospheric Administration and are available online [**?**]. They are also shown in Table 6.

Table 6: Orientations of the long axes of the detectors with respect to true and magnetic north. Declination is the angle of difference between true North and magnetic North. For instance, if the declination at a certain point were 10° W, then a compass at that location pointing north (magnetic) would actually align 10° W of true North. True North would be 10° E relative to the magnetic North direction given by the compass. Declination varies with location and slowly changes in time. These values are calculated on Sep. 25, 2013. In this table, positive values denotes East of true north and negative values denote West of true north. The latitudes and longitudes of the detectors are taken from Virgil Bocean [**?**], and the magnetic declinations are taken from NOAA [**?**].

Detector	Magnetic Declination	$\Delta(\text{Declination})/\Delta t$	True N Orientation
NDOS	$-3°14' \pm 30'$	$-5'/$ yr	$-23°48'39'' \pm 14'2''$
Near Underground	$\circ$	$\circ$	$\circ$
Far	$-0°29' \pm 30'$	$-6'/$ yr	$-27°51'26'' \pm 5'51''$

4 Beam Information

4.1 NuMI Beam Parameters

Most of the target design parameters are established in a memo [**?**], and a set of drawings [**?**, **?**] reviewed on Feb. 25, 2010. Table 7 includes those parameters as modified by suggestions in response to the review [**?**] that are also documented in a talk by Mike Martens [?]. The response was given to the manufacturer of the targets (IHEP); the set of final drawings is due back from them in January 2011.

Table 7: This table shows NuMI target information with coordinates in NuMI Simulation system (origin is MCZERO) [?].

Start of Target	$z = -143.3$ cm[?]
Start of Target (Excl. Budal Monitors)	$z = -137.55$ cm[?, ?]
End of Target	$z = -20$ cm[?]
Width	7.4 mm[?]
Height	150 mm [?] + 0.5 mm [?] = 150.5 mm
ZXF-5Q graphite density	1.78 g/cm^3[?, ?]
Beam center dist from fin top	3.2 mm [?] + 0.5 mm [?] = 3.7 mm
Beam center dist from fin side	3.7 mm(on center [?])

4.2 Booster Beam

Table 8: The positions of the horns are recorded as their idealized starting points, which is MCZERO for Horn 1 and ACTRN2 for Horn 2, and their insertion points, which is ACTRN1 for Horn 1 and ACTRN2 for Horn 2 [?]. The insertion points are the coordinates used in the FLUGG simulations. For all horn positions, $x = y = 0$.

	Horn 1	Horn 2
Start of idealized Horn	$z = 0.00$ m	$z = 19.1779$ m[?]
Horn Insertion Point	$z = 0.03$ m	$z = 19.1779$ m[?]
Current	200 kA	200 kA

Table 9: The directions of the Booster Neutrino Beam with respect to the axis of the NuMI Cooridante System.

NuMI Coordinate Axis	Angle
x	111.50988°
y	89.284678°
z	21.50988°

5 Acknowledgements

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A Transforming from Building to Beam Coordinates

This method is no longer used because it did not produce consistent results for the NDOS location in the Booster coordinate system. It has since been superseded by a simpler method that does produce consistent results, which is described in §2.1.

The measurements from the tape measure survey are, in effect, the position of the NDOS in a coordinate system relative to the building. To be close to the beam coordinate system, we choose x to be parallel with the south wall of the building with positive being westward, y to be vertical, and z to be parallel with the floor with positive being northward. The southwest corner of the building on the floor is the origin.

We assume that the transformation from the building coordinate system to the beam coordinate systems can be accomplished by a linear translation and a rotation about the origin. The complete transformation is

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\phi\cos\theta\cos\psi - \sin\phi\sin\psi & -\sin\phi\cos\theta\cos\psi - \cos\phi\sin\psi & \sin\theta\cos\psi \\ \cos\phi\cos\theta\sin\psi + \sin\phi\cos\psi & -\sin\phi\cos\theta\sin\psi + \cos\phi\cos\psi & \sin\theta\sin\psi \\ -\cos\phi\sin\theta & \sin\phi\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x' + x_0 \\ y' + y_0 \\ z' + z_0 \end{pmatrix} \tag{6}$$

where (x, y, z) is the position in beam coordinates, the 3×3 matrix parameterizes the rotation about the origin [**?**], (x_0, y_0, z_0) is the translation vector, and (x', y', z') is the position in building coordinates.

We have the four corners of the building in the two beam coordinate systems (Table 3) and calculate them in the building coordinate system (Table 10). Using the SE and NE corners and the distance from the SW corner to the front face of the detector (5.45 m), we fit the six unknown parameters in Equation 6 simultaneously, obtaining the results in Table 11. Using the distance means that we over-constrain the six parameters by fitting them to seven known values.

B Far Detector Position Extracted from the TDR

The total distance to the detector is given as 810.54 km and the Distance from the beam axis is 11.81 km, given in Table 5.1 [**?**]. Elsewhere (§5.3.1) the beam is stated to be 4.2 km above the surface of the far detector site. I interpret these values to mean

$$x^2 + y^2 + z^2 = 810.54\ km \tag{7}$$

$$x^2 + y^2 = 11.81\ km \tag{8}$$

$$y = -4.2\ km \Rightarrow x = 11.04\ km,\ z = 810.45\ km \tag{9}$$

We can calculate the angle off-axis given by this postion:

$$\theta = \sin^{-1}\left(\frac{\sqrt{x^2 + y^2}}{\sqrt{x^2 + y^2 + z^2}}\right) = 0.01457, \tag{10}$$

which is identical to the value given in Table 5.1 of the TDR. However, since the y position is only given to two significant figures, all of the numbers I have calculated are also only trustworthy to two significant figures.

Table 10: Positions of the corners of the NDOS building in a coordinate system with the origin at the SW corner and the axes parallel to the building walls. The distance between the SE to NE corners is not equal to the distance between the SW and NW corners; this indicates that the building is not a perfect rectangle and is reflected in the difference in z position for the NW and NE corners. The final row is the position of the center of the front face of the NDOS calculated using the measurements in Table 4. Since the origin is at the SW corner on the floor, the y values reflect the fact that the survey point was taken 1.37 m above the floor. All dimensions are in m.
[htb]

Building Corner	x	y	z
SW	0	1.37	0
SE	-8.64187	1.37	0
NW	0	1.37	21.48472
NE	-8.64187	1.37	21.46353
NDOS FF	-4.01	2.32	3.09

Table 11: The fitted values of the parameters used for transforming the building coordinate system into the two beam coordinate systems. The values for the angles are in radians, and the values for the translational distances are in meters.

Parameter	Fitted Value (NuMI)	Fitted Value (Booster)
ϕ	1.65137	
θ	0.0584754	
ψ	-1.58814	
x_0	7.25829	
y_0	41.1723	
z_0	837.789	

C Location of the 3×2 Near Detector Underground

The NOνA Near Detector (ND) should have the same off-axis angle as the far detector. However, seen from an off-axis position so close longitudinally to the decay region, the neutrinos come from a line source, unlike the effective point source of the Far Detector. The decision has been made to have the correct off-axis angle for the part of the decay region from which comes the highest flux of muon neutrinos [?]. This part of the decay region (known as point S) is 184.45 m downstream of **center** of the target. The center of the target (from Table 7) is at $z = -0.8165$ m; therefor, Point S is at $z_S = 183.6335$ m. The off-axis angle is 14.572 mr, which is defined as the angle between the beam line and a line passing through point S and point C, which is the center of the ND [?].

The only real reference I have for the planned position for the near detector underground is an e-mail exchange with P. Vahle [**?**] in which she says the numbers were obtained "numbers from an email from Zarko [Pavlovic], or in an email from Brian, which originally came from Alysia."

Currently, the planned length of the detector is 50 ft. 3³/₄ in. (15.34 m) [**?**]. The current ND position in Table 2 does not have a solid reference; however, if we add half the length of the detector to the z position this should give a good approximation of the center of the detector. The resulting angle should be 14.572 mr. The resulting angle is

$$\theta = \sin^{-1}\left(\frac{\sqrt{x^2+y^2}}{\sqrt{x^2+y^2+(z-z_S+7.67\text{m})^2}}\right) = 14.566\text{ mr}, \tag{11}$$

where x, y, and z are taken from Table 2.