Status Report on the Geodetic and Alignment Results for the NuMI/MINOS Project at Fermilab

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INTRODUCTION

- Part of the neutrino research program at Fermilab is the search for non-zero neutrino mass
- Looks for neutrino oscillations ($\nu_\mu \rightarrow \nu_\tau$) or ($\nu_\mu \rightarrow \nu_e$)
- **NuMI** (Neutrinos at the Main Injector) has built a new particle beamline capable of directing a pure beam of muon neutrinos
- **MINOS** (Main Injector Neutrino Oscillation Search) experiment uses NuMI beam to search with significantly greater sensitivity for neutrino oscillations utilizing two detectors:
  - "near" detector - located close to the neutrino source (1 km away from the target)
  - "far" detector - 735 km away, in a deep underground mine in northern Minnesota, 710 m below the surface
NuMI Tunnels and Halls

NuMI Tunnel Project

Target Building
Target Hall
Beam absorber
Absorber Hall
Near detector for MINOS
MINOS Hall
Proton beam from Main Injector
NuMI beamline

- Recycler
- NuMI Extraction
- Main Injector
- Steep incline
- Pre-Target
- Target Hall
NuMI Beamline
From Fermilab to Soudan, MN

From Fermilab to Soudan, MN: 735 km
Alignment Tolerances

- primary proton pointed ±12 m at the far detector (±3.4 arc second)
- neutrino beam centered ±75 m at the far detector (±21 arc second)

<table>
<thead>
<tr>
<th>Component</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam position at target</td>
<td>±0.45 mm</td>
</tr>
<tr>
<td>Beam angle at target</td>
<td>±0.7 mrad</td>
</tr>
<tr>
<td>Target position - each end</td>
<td>±0.5 mm</td>
</tr>
<tr>
<td>Horn 1 position - each end</td>
<td>±0.5 mm</td>
</tr>
<tr>
<td>Horn 2 position - each end</td>
<td>±0.5 mm</td>
</tr>
<tr>
<td>Decay pipe position</td>
<td>±20 mm</td>
</tr>
<tr>
<td>Downstream Hadron monitor</td>
<td>±25 mm</td>
</tr>
<tr>
<td>Muon Monitors</td>
<td>±25 mm</td>
</tr>
<tr>
<td>Near Detector</td>
<td>±25 mm</td>
</tr>
<tr>
<td>Far Detector</td>
<td>±12 m</td>
</tr>
</tbody>
</table>

- NuMI is mainly sensitive to final primary beam trajectory
- beamline components, target, and horn alignment => relative positions to ±0.35 mm (1σ)
NuMI: Neutrino Beam
From Protons to Muon Neutrinos ($\nu_\mu$)

Focusing Horns misalignments have steering effect on secondary beam

Target Hall

Decay Pipe

Absorber

Muon Monitors

Hadron Monitor
Determination of the Global Positions

- **geodetic orientation parameters of the beam** => absolute & relative positions of target (Fermilab) and far detector (Soudan)
- GPS tied to national CORS network
- solution in ITRF96 reference system => transformed in national NAD 83 system
- NGS provided independent solution (excellent agreement)
- vector known to better than 1 cm horizontally and vertically
- inertial survey through 713 m shaft tied the the 27th level of the mine to surface geodetic control
GEOID CONSIDERATION
Models Comparison
(Local Geoid Model and NGS Geoid93)

- differences up to 5 mm (consistent with expected values)
- NuMI beamline in 1.5 mm range of differences
- Geoid93 - sufficient to cover tolerance requirements
Primary Geodetic Network at Fermilab

- existing Fermilab control network (accuracy < 2 mm @ 95% confidence level)
- NAD 83 horizontal geodetic datum (GRS-80 reference ellipsoid)
- NAVD 88 vertical datum
- Geoid93 NGS model
- included 3 monuments tied to CORS
- added 6 new geodetic monuments (densification around access shafts)
- 410 GPS, terrestrial, and astronomic observations
- error ellipses in millimeter range (@ 95% confidence level)
- precision levelling: ± 0.58 mm/km double-run
Primary Geodetic Network Results

Error ellipses @ 95% confidence level (bar scale tick = 1 mm)

Histogram of standardized residuals (bar scale tick = 1 $\sigma$)
Underground Control Networks

- Network simulations => 7 locations for transferring coordinates from the surface (3 vertical sight risers, 2 tunnel Access Shafts, 2 Exhaust Air Vent pipes)
Underground Control Networks
Target Hall and Near Detector Hall

- First phase: to support components installation in the Target Hall and the construction and alignment of the Near Detector in the MINOS Hall
- Measured with the Laser Tracker and processed as trilateration
- Additional measurements to study/control network behaviour: Mekometer distances, precision angles, and gyro-azimuths
- Network results: errors below ±0.35 mm at 95% confidence level

Initial Target Hall Network
Histogram of standardized residuals
(bar scale tick = 1 \( \sigma \))

Count = 13187
\( \sigma \) = 0.120 mm
Center = 0.022 mm

MINOS detector Hall Network
Histogram of standardized residuals
(bar scale tick = 1 \( \sigma \))

Count = 1688
\( \sigma \) = 0.077 mm
Center = 0.010 mm
Underground Network for the Primary Beam

- **Second Phase:** to support the alignment of Primary Beam components and the Target and focusing Horns
- **Network:** from MI-60 to the downstream end of the Target Hall
- **Least-Squares Adjustment:** constraints at MI-60, SR-1, SR-2, and SR-3
- **Network type:** Laser Tracker processed as trilateration
- **Additional measurements** to study and control network behaviour and for confirmation
  - 23,000 Observations => Laser Tracker ($\sigma=0.050-0.15$ mm), Mekometer Distances ($\sigma=0.2$ mm +/- 0.2 ppm), Precision Angles ($\sigma=0.3''$), Optical offsets ($\sigma=0.2-0.5$ mm), Gyro Azimuths ($\sigma=3''$)
- **Azimuth SR2-SR3** confirmed by first order Astronomical Azimuth: agreement at 0.74 arc second ($\sigma=\pm 0.21$ arc second)

- **Alignment results:**
  - **Primary beam magnets and instrumentation aligned to ±0.25 mm**
  - **Target station components aligned to ±0.5 mm**
Underground Network for the Primary Beam

SR1  SR2  286762  SR3
MI  Stub  Carrier  Pre-Target  Tgt Hall
Underground Network for the Primary Beam
Results: Histogram of Standardized Residuals

Data: NuMI Tunnel Network (Stub+Pre Target+Target Hall)
Model: Gauss
Equation: \( y = y_0 + \frac{A}{(w\sqrt{\pi/2})} \exp\left(-2\left((x-x_c)/w\right)^2\right) \)
Weighting: \( y \) No weighting

\( \text{Chi}^2/\text{DoF} = 6.08502 \)
\( R^2 = 0.99442 \)

- count: 22976
- \( \sigma = 0.110 \text{ mm} \)
- \( y_0 = 72.79747 \pm 24.34984 \text{ mm} \)
- \( x_c = 0.02451 \pm 0.142 \text{ mm} \)
- \( w = 0.15296 \pm 0.003 \text{ mm} \)
- \( A = 1035.41393 \pm 19.33207 \text{ mm} \)

(\( \text{bar scale tick} = 1 \sigma \))
Underground Network for the Primary Beam
Results: Error Ellipses XY Axes

- Errors Ellipses below ±0.45 mm at 95% confidence level
- Error budget network requirements ±0.50 mm at 95% confidence level
Errors Ellipses below $\pm 0.46$ mm at 95% confidence level

Error budget network requirements $\pm 0.50$ mm at 95% confidence level
NuMI Beam Commissioning
Commissioning the Primary Proton Beam

**NuMI starts December 3, 2004:**
- target OUT of the beam, horns turned OFF
- small number of low intensity pulses carefully planned
- beam extracted out of Main Injector on the 1st pulse, per design parameters – no tuning required
- beam centered on the Hadron Absorber, 725 m away from target, in 10 pulses - very minimal tuning
- beam points in the right direction to < 2 arc second
Beam Extraction in 10 Pulses
Centered on Hadron Absorber at 725 m Distance

10th pulse: SEMs and Hadron Monitor readings
**MINOS starts January 21, 2005:**
- target at $Z=-1m$ (Medium Energy Beam)
- horns turned ON
- on the 4th horn pulse - first neutrino in the Near Detector
- after fine tuning the proton line, on February 18, 2005, NuMI turn to high intensity beam, operating on 6 multi-batch mode
- March 07, 2005 - first confirmed neutrino in the Far Detector
First Neutrino in the Near Detector
First Neutrino in the Far Detector
The relative alignment of the primary proton beam, target, and focusing horns affects the neutrino energy spectrum delivered to experiments.

- Primary beam magnets and instrumentation aligned to $\pm 0.25$ mm.
- Target station components aligned to $\pm 0.5$ mm.

### Procedure:

- **Scan proton beam** ($\sigma = 1$ mm) across known features of beamline components (Target & Baffle and Horns cross-hairs).
- **Use instrumentation** (BPMs and Profile Monitors) to correlate with measured proton beam position.

### Table

<table>
<thead>
<tr>
<th>DEVICE</th>
<th>Horizontal dX (mm)</th>
<th>Vertical dY (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>-0.122</td>
<td>-0.151</td>
</tr>
<tr>
<td>Horn 1</td>
<td>-0.285</td>
<td>0.303</td>
</tr>
<tr>
<td>Horn 2</td>
<td>-0.344</td>
<td>-0.650</td>
</tr>
</tbody>
</table>
NuMI Beam and Monitoring Instrumentation

Final Focusing Instrumentation

Downstream Instrumentation

Target Hall

Decay Pipe

Target

Muon Monitors

Absorber

Hadron Monitor

120 GeV protons from Main Injector

Horns #1 #2

10 m 30 m 675 m

\( \pi^+ \)

\( \mu^+ \)

Hadron Monitor

Rock

12 m 18 m 300 m
Baffle & Target System

- Graphite fin core segments:
  \[(20 \text{ mm} \times 15 \text{ mm} \times 6.4 \text{ mm}) \times 47\]
- Target length = 95.4 cm
- Baffle length = 150 cm
NuMI Target
NuMI Target

View from inside the chase - for Low Energy (LE) beam configuration Target slides into Horn 1 without touching
NuMI Horns

- For scanning Horns, the Target must be OUT.
- Cross-hairs intercept primary proton beam:
  - One on the downstream end of Horn 1
  - One on each end of Horn 2
Horns Cross-hairs

- Beam narrow horizontally, wide vertically
NuMI Horn
Inside the Chase
The peaks are the gaps between baffle and target
Different peak heights => offsets target/baffle or a common angle
Target & Baffle
Vertical Positions

Measured: RMS

Measured: central pixel intensity

Hadron Monitor RMS (mm)

Hadron Monitor Central Pixel (nC)

Vertical Beam Position (mm)
- Scans at LE (0 cm), ME (100 cm), and HE (250 cm)
- Target parallel with primary beam better than 0.5mm across 2.5m of travel
Horn 1 Horizontal Position

Measured: integrated intensity

Loss Monitor Signal (V/1E12)

Horizontal Beam Position
Horn 2 Horizontal Positions

Measured: integrated intensity

Horn 2 Loss Monitor Signal (V/1E12)

Horizontal Beam Position (mm)

Scan at y = −1.5
Scan at y = −5.7
Summary of Target/Horns Sans on BPM Measurements

Beam Not Steered \((x,y) = (0,0) \) mm

<table>
<thead>
<tr>
<th>DEVICE</th>
<th>Offset (mm)</th>
<th>Effect %</th>
<th>Angle (mrad)</th>
<th>Effect %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baffle</td>
<td>-1.21</td>
<td>2.5</td>
<td>-0.14</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Target</td>
<td>-1.41</td>
<td>2.5</td>
<td>-0.14</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Horn 1</td>
<td>-1.24</td>
<td>1.1</td>
<td>-0.18</td>
<td>0.3</td>
</tr>
<tr>
<td>Horn 2</td>
<td>-1.82</td>
<td>1.2</td>
<td>-0.18</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baffle</td>
<td>1.12</td>
<td>2.2</td>
<td>-0.7</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Target</td>
<td>0.13</td>
<td>&lt;0.1</td>
<td>-0.7</td>
<td>0.26</td>
</tr>
<tr>
<td>Horn 1</td>
<td>0.81</td>
<td>1.4</td>
<td>0.26</td>
<td>0.43</td>
</tr>
<tr>
<td>Horn 2</td>
<td>0.08</td>
<td>&lt;0.1</td>
<td>-0.43</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

- components are consistently to the left, and usually down (exception is that baffle is about 1 mm high w.r.t. target)
- the “effects” represent the Far-to-Near ratio of neutrino fluxes as a result of the measured offsets – **tolerance required is < 2 %**
Summary of Target/Horns Scans on BPM Measurements

Beam Steered at \( (x,y) = (-1.2, +1.0) \) mm

<table>
<thead>
<tr>
<th>DEVICE</th>
<th>Offset (mm)</th>
<th>Effect %</th>
<th>Angle (mrad)</th>
<th>Effect %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baffle</td>
<td>0.01</td>
<td>&lt;0.1</td>
<td>-0.14</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Target</td>
<td>-0.21</td>
<td>0.37</td>
<td>-0.14</td>
<td>0.1</td>
</tr>
<tr>
<td>Horn 1</td>
<td>0.03</td>
<td>&lt;0.1</td>
<td>-0.18</td>
<td>0.32</td>
</tr>
<tr>
<td>Horn 2</td>
<td>-0.62</td>
<td>0.23</td>
<td>-0.18</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td><strong>Vertical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baffle</td>
<td>0.12</td>
<td>&lt;0.1</td>
<td>-0.7</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Target</td>
<td>-0.87</td>
<td>&lt;0.1</td>
<td>-0.7</td>
<td>0.26</td>
</tr>
<tr>
<td>Horn 1</td>
<td>-0.19</td>
<td>&lt;0.1</td>
<td>0.26</td>
<td>0.35</td>
</tr>
<tr>
<td>Horn 2</td>
<td>-0.92</td>
<td>0.42</td>
<td>-0.43</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

- beam is pointed on: Target center horizontally and Baffle center vertically
  - => established as beam RUN PARAMETERS
- all effects Far-to-Near ratio of neutrino fluxes as a result of measured offsets from beam scans are well below the 2% tolerance required
Pre-Target and Target Hall Deformation Analysis

- The beam-based alignment of the Target Hall components indicated that the Target Hall moved with loading of 6400 tons of steel/concrete
- A deformation survey campaign was performed in April 2005 covering the Pre-Target tunnel and Target Hall
- Three scenarios considered and analyzed:
  1. Target Hall empty (un-loaded)
  2. Target and Horns modules loaded into the chase and R-blocks unloaded (partial load)
  3. Target and Horns modules loaded into the chase and R-blocks loaded (full load)
- Methodology used: local Laser Tracker network supplemented by precision leveling
Target Hall During Network Observations

Wall points

Aisle points
Target Hall During Target and Horns Alignment

Wall points

Aisle points
Target Hall During Commissioning and Experiment Run

Wall points

Aisle points
Horizontal Stability Results

- The horizontal stability analysis results showed:
  - no deformations in the Target Hall (walls or aisles points) until loading of the R-blocks (February 2005)
  - the trend analysis showed no movement tendency on the Target Hall wall points across all three scenarios
  - deformations up to 0.9 mm due to the load on both aisles after the installation of the R-blocks (February 2005) => both E and W Target chase ledges/aisles moved inwards (towards the beam)
  - plastic deformation => very little (0.2 mm) or no rebound when the R-blocks were removed
- The Pre Target tunnel: no horizontal (or vertical) deformations
Target Hall Horizontal Deformation

R-blocks loaded (as during run)

rms fit wall points = 0.182 mm
Target Hall Vertical Deformation

R-blocks loaded (as during run)

West Aisle $\approx -0.7$ mm

East Aisle $\approx -0.4$ mm
Support/Capture Fixtures for Target and Horns

Components are captured in cups on the East side and sit freely on plates on the West side; because of deformation they moved westward.
Estimation on Effect of Deformation on Target and Horns

- **Horizontal beam on Target and Horns:**
  - Aisles (horizontal) deformation due to load = -0.9 mm
  - Displacement due to thermal expansion (\(\Delta T = 4^\circ C\)) = -0.1 mm
  - Target misalignment = -0.1 mm
  - **Total Horizontal estimated displacement = -1.1 mm**

- **Vertical beam on Target and Horns:**
  - Aisles (vertical) deformation due to load = -0.5 mm
  - Displacement due to thermal expansion (\(DT = 4^\circ C\)) = -0.1 mm
  - Target misalignment = -0.1 mm
  - **Total Vertical estimated displacement = -0.7 mm** (the baffle was found 2 mm higher than the target at referencing)

- The deformation analysis confirms the beam-based alignment results
June 24, 2005 Beam Profile at MTGT
CONCLUSIONS

- NuMI/MINOS commissioning and transition to Operations (May 12, 2005) successfully concluded, with excellent performance at each step.

- NuMI/MINOS delivered to experimenters and running for physics.
ACKNOWLEDGEMENTS

I would like to extend our sincere thanks to all the many people and organizations who contributed to the realization and success of the NuMI/MINOS project.