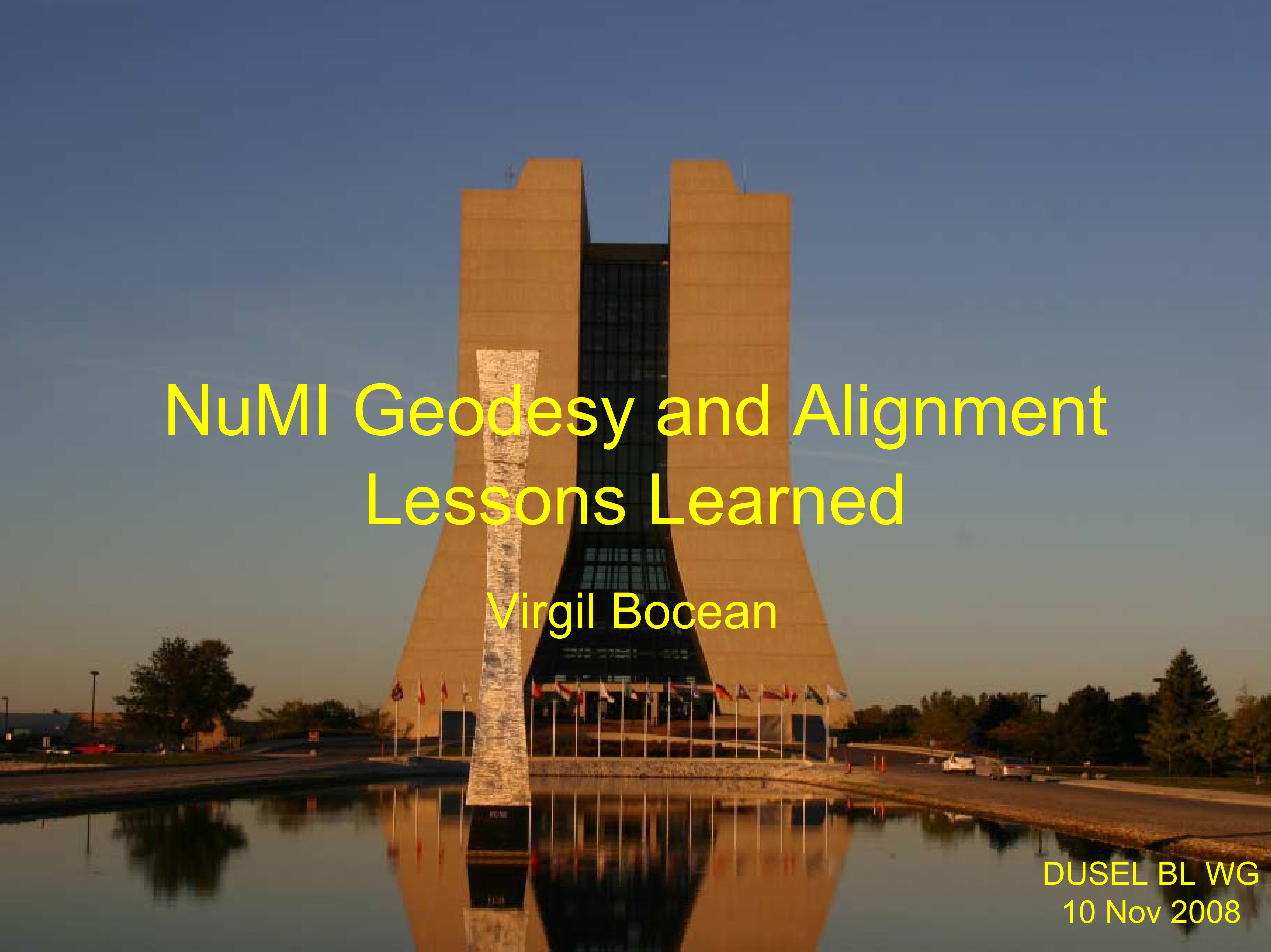


# NuMI Geodesy and Alignment Lessons Learned

Virgil Bocean

DUSEL BL WG
10 Nov 2008

# Introduction



- Assessments made in this presentation are based only on the many similarities of the DUSEL beam with NuMI and the information available regarding the current preliminary design of the DUSEL beam
- Only the aspects related to the NuMI beam as relevant to the DUSEL beam are presented (will not discuss about the MINOS detectors)

- Outline
  - Tolerances
  - Geodetic determination of global positions
  - Alignment during construction phase
  - Primary surface geodetic network and underground control network
  - Primary beam and Target station components alignment
  - Summary

# Alignment Tolerances



- Absolute tolerances:
  - Primary proton centered ± 12 m at the far detector (± 3.4 arcsecond = ± 0.016 mrad )
  - Neutrino beam centered ± 75 m at the far detector (± 21 arcsecond = ± 0.102 mrad)
- Relative tolerances:

| | |
|---|---|
| **Beam position at target** | **± 0.45 mm** |
| **Beam angle at target** | **± 0.7 mrad** |
| **Target position - each end** | **± 0.5 mm** |
| **Horn 1 position - each end** | **± 0.5 mm** |
| **Horn 2 position - each end** | **± 0.5 mm** |
| **Decay pipe position** | **± 20 mm** |
| **Downstream Hadron monior** | **± 25 mm** |
| **Muon Monitors** | **± 25 mm** |
| **Near Detector** | **± 25 mm** |
| **Far Detector** | **± 12 m** |

- NuMI is mainly sensitive to final primary beam trajectory : Beamline components, Target and Horn alignment => relative positions ±0.35 mm (1$\sigma$)

# Alignment Tolerances

- The correct aiming of the beam is of great importance for the experiment
- Absolute and relative tolerances for directing the beam are driven by physics requirements
  - For NuMI: the **neutrino energy spectrum test for oscillations** (predicting the far detector energy spectrum –w/o oscillations- from the measured energy spectrum in the near detector). The combined effect of all alignment errors must cause **less than 2% change in any 1 GeV energy interval.**
- The relative alignment tolerances of beamline components have been already achieved for other Fermilab projects
- Due to the uniqueness of the NuMI project, achieving the absolute global tolerances presented a challenge with respect to the detail and complexity of the geodetic aspects

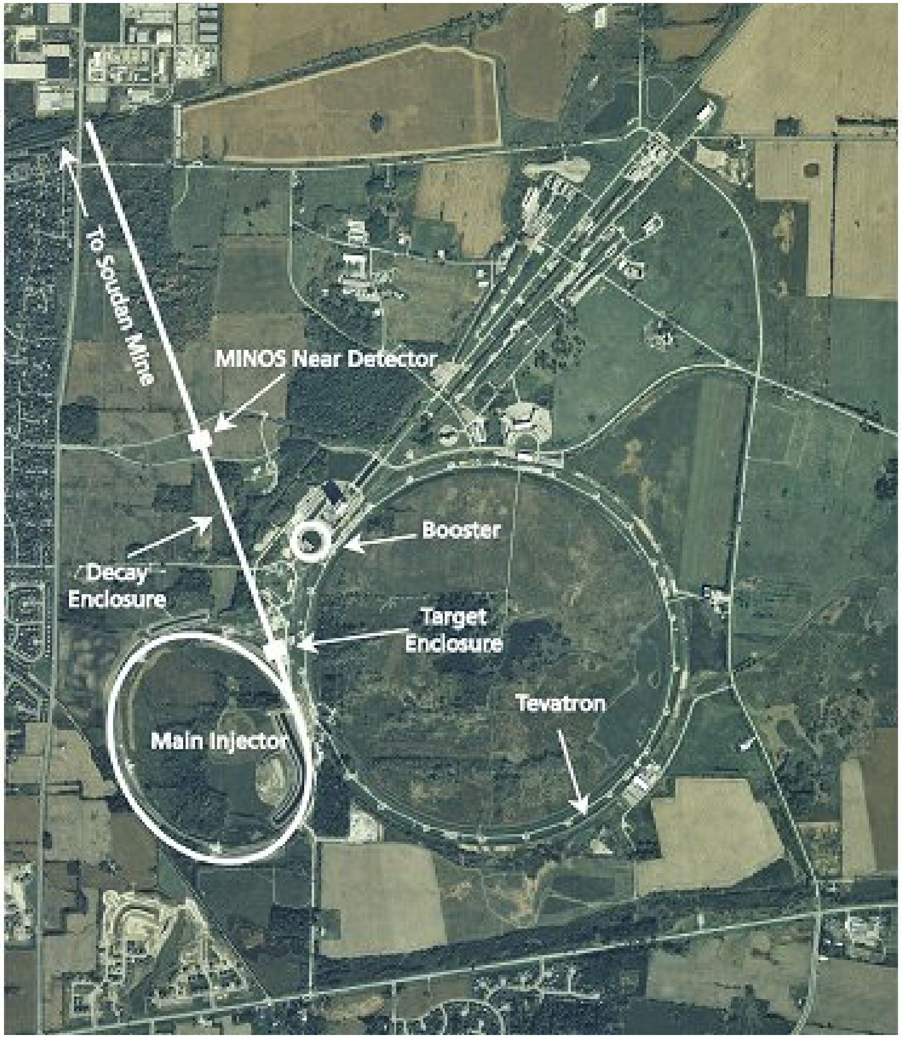
➢ *Lessons learned:*

- Alignment tolerances computed in an early phase of the design
- Early participation of Geodesy experts in the design
  - DUSEL beam will have comparable tolerances => requires a rather exact knowledge of the geometric parameters of the beam trajectory (the azimuth and the slope of the vector joining the two sites)
- Helped us develop a very comprehensive geodesy/alignment plan to achieve those tolerances and provide adequate and efficient support throughout the project

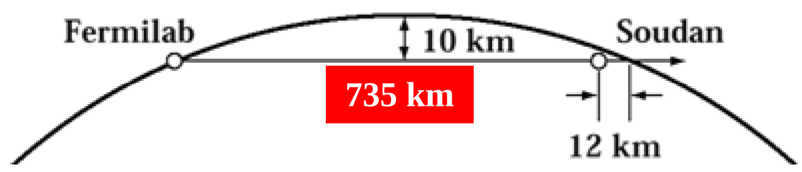
# Geodetic determination of global positions

NuMI beam from Fermilab to Soudan, MN



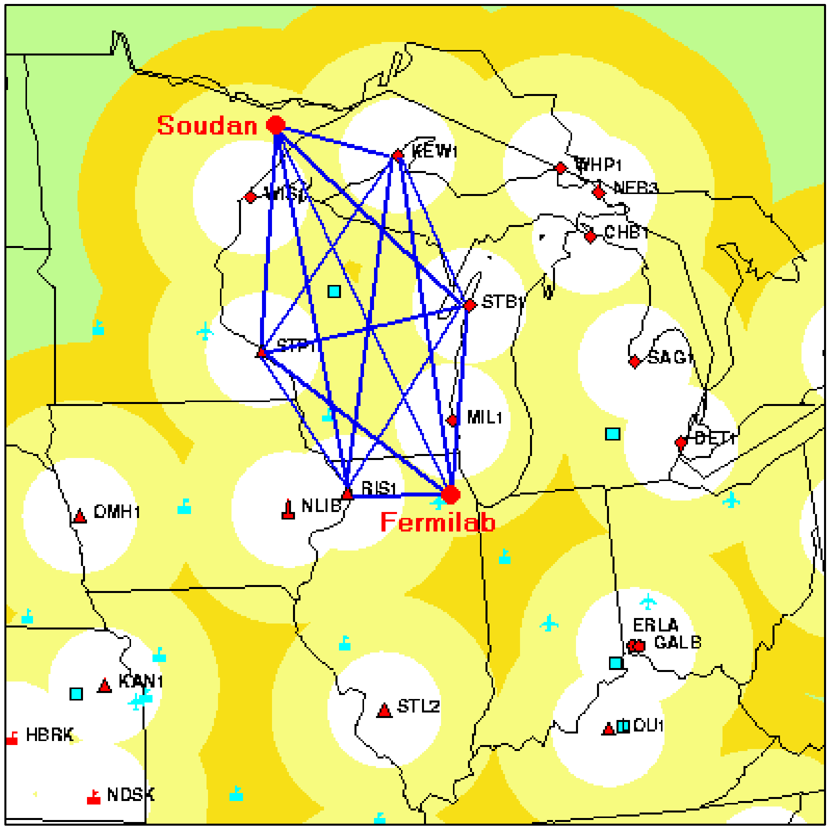






# Geodetic determination of global positions






- 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


# Geodetic coordinates and parameters

## Refinement phases of GPS determinations



### Coordinates in Local Geodetic System at Fermilab
### (as reference is NGS CORS determination 1999)

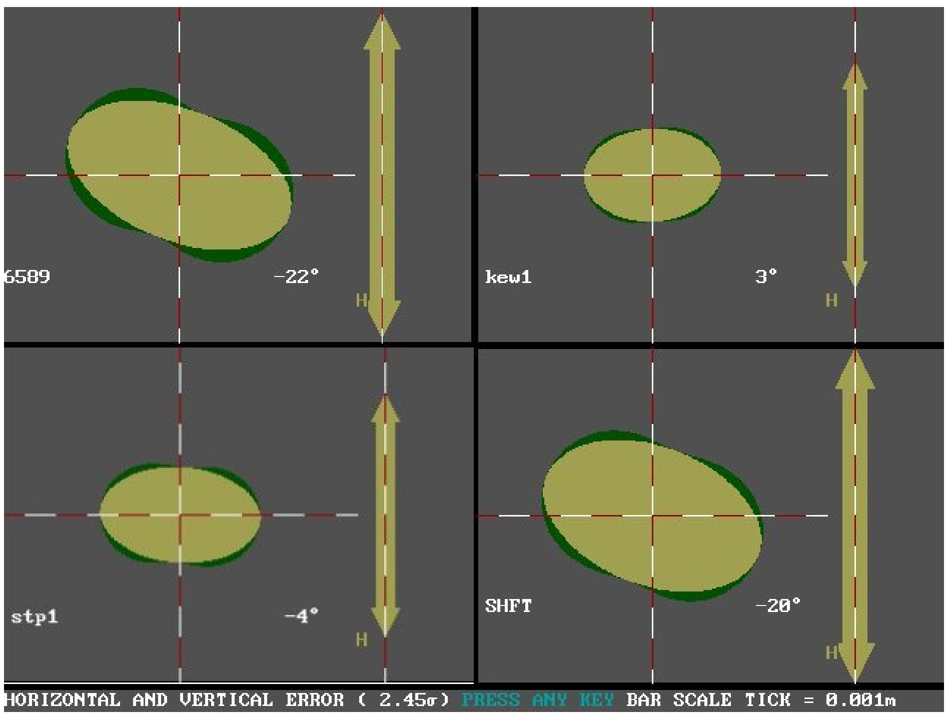
| FROM | TO | n | e | up | Δ n | Δ e | Δ up | Comment |
|---|---|---|---|---|---|---|---|---|
| | | (m) | (m) | (m) | ( m) | ( m) | ( m) | |
| 66589_93 | SHAFT_93 | 671107.806 | -297423.720 | -42175.340 | 0.725 | -0.296 | -0.050 | NGS NAD83 tie |
| 66589_93 | SHAFT_98 | 671108.303 | -297424.045 | -42175.408 | 0.229 | 0.029 | 0.018 | GPS differential |
| 66589_CORS Fermi | SHAFT_CORS Fermi | 671108.540 | -297424.003 | -42175.396 | -0.008 | -0.013 | 0.006 | CORS calc Fermi |
| 66589_CORS NGS | SHAFT_CORS NGS | 671108.532 | -297424.016 | -42175.390 | 0.000 | 0.000 | 0.000 | CORS calc NGS |

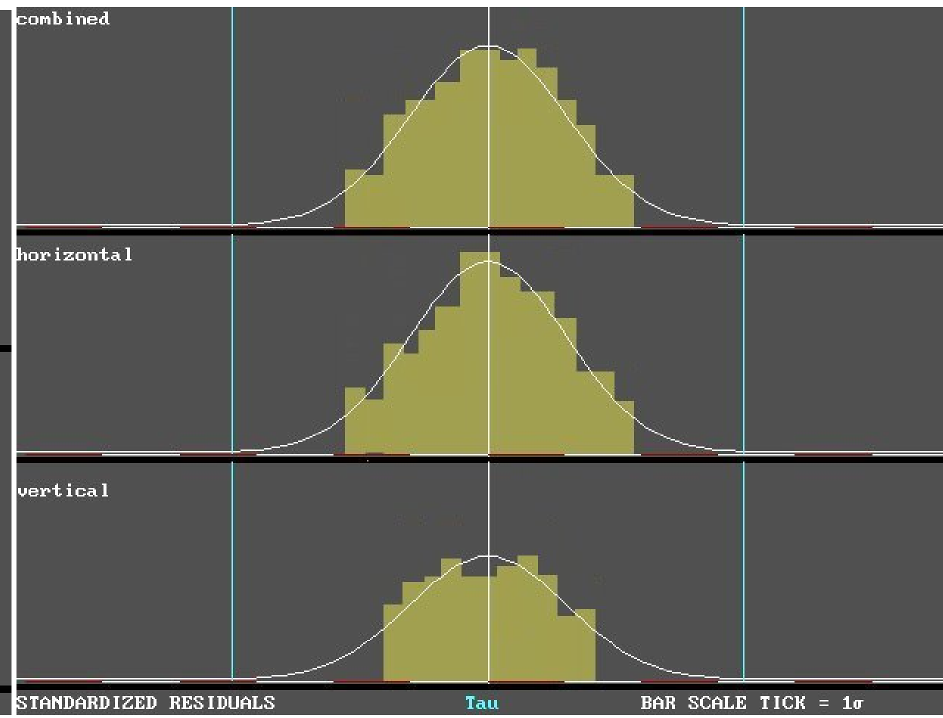
### Geodetic parameters for beam orientation
### (as reference is NGS CORS determination 1999)

| FROM | TO | Normal Sect Az | Δ Az | Vertical Angle | Δ VA | Distance | Δ D | |
|---|---|---|---|---|---|---|---|---|
| | | (d-m-s) | (sec) | (d-m-s) | (sec) | (m) | ( m) | |
| 66589_94 | SHAFT_94 | 336-05-52.35714 | 0.01079 | 3-17-17.88121 | 0.00122 | 735272.273 | 0.785 | |
| 66589_94 | SHAFT_98 | 336-05-52.33031 | 0.03762 | 3-17-17.89081 | -0.00838 | 735272.862 | 0.196 | |
| 66589_CORS Fermi | SHAFT_CORS Fermi | 336-05-52.36793 | -0.00335 | 3-17-17.88412 | -0.00169 | 735273.061 | -0.003 | |
| 66589_CORS NGS | SHAFT_CORS NGS | 336-05-52.36458 | 0 | 3-17-17.88243 | 0 | 735273.058 | 0.000 | |

# GPS tie to CORS network

## Ellipse of errors and histogram of residuals



# Geoid consideration

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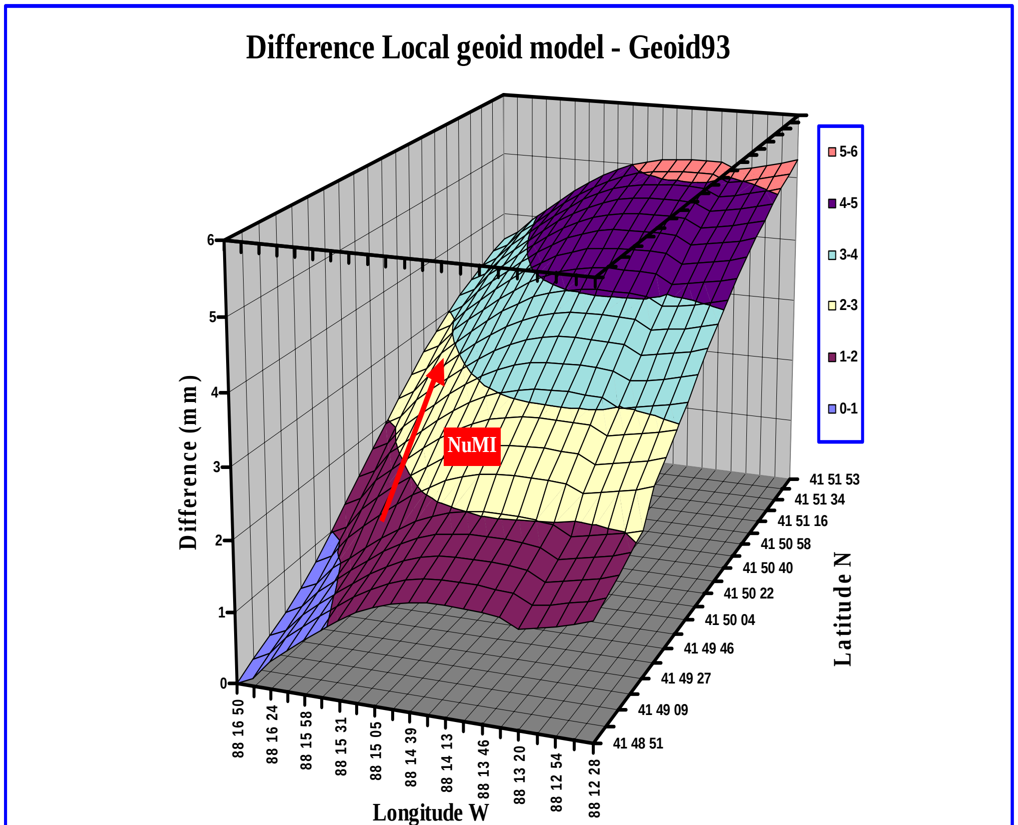
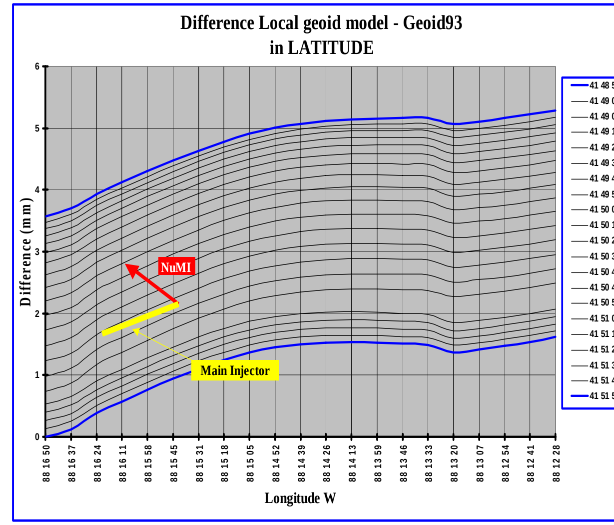
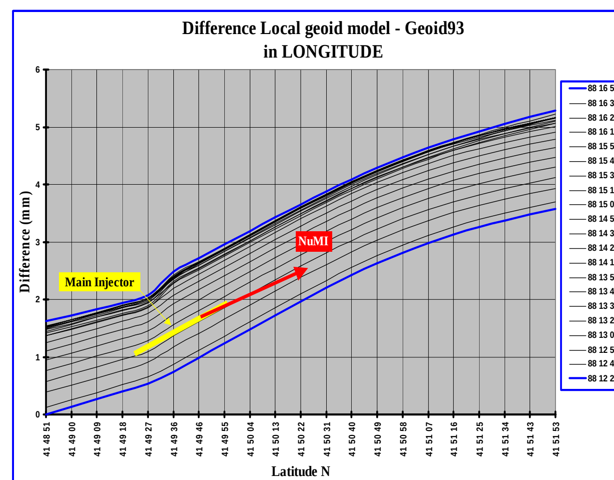
- Needed knowledge of the gravity vector at the origin (Fermilab)
- Study of a Local Geoid Model and NGS Geoid93
- Differences up to 5 mm (consistent with expected values)
- NuMI beam in 1.5 mm range of differences
- Geoid93 - sufficient to cover tolerance requirements



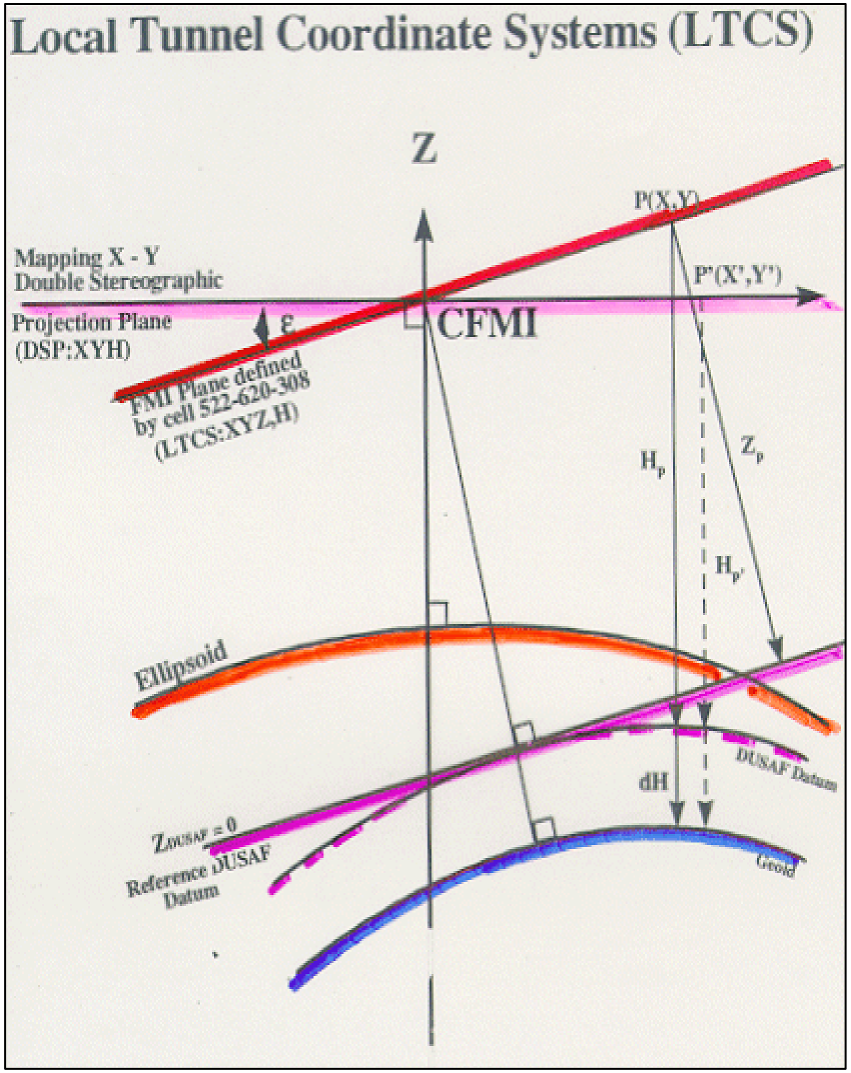



# The Local Tunnel Coordinate System



- Transformed geodetic coordinates and beam orientation parameters from the absolute geodetic system => in the Local Tunnel Coordinate System (LTCS) = beamline system for the Main Injector and NuMI

- Those coordinates constituted the basis for developing high accuracy local networks for supporting the civil construction phase and the alignment of the NuMI beam components in the same beamline system as designed by physicists



# Geodetic determination of global positions



## *Lessons learned:*

- Geodetic determination of global positions used for NuMI is adequate for DUSEL
- Precise differential GPS tied to national CORS network
- Involve National Geodetic Survey (NGS) to provide independent solution
- Use inertial survey techniques to determine the underground location and orientation of the far detector and tie it to the surface geodetic control
- Upgrade the Geoid93 currently used at Fermilab to the higher resolution Geoid03 model – proposed improvement
- Use the Local Tunnel Coordinate System to provide feedback to beamline physicists and civil engineers with respect to geodetic coordinates and beam orientation parameters

# Alignment during construction phase



- During the civil construction and outfitting phase the Fermilab surveyors were responsible for providing the Quality Control to ensure that construction tolerances of facilities are achieved

➢ *Lessons learned:*

- The construction Quality Control used for NuMI is adequate for DUSEL
- Safety is a paramount factor especially when working in an underground tunnel construction environment
- Make sure that the qualification and experience of contractor's surveyors is adequate for the complexity of the job (the NuMI contractor had a very good surveying team)
- Work closely with the Fermilab construction management team and provide them with feedback in a timely fashion throughout the construction schedule
- **What we would do different**:
  - ➢ If budget permits, do QC work on weekends rather than during the week (prevents conflicts with ongoing work and better safety environment)
  - ➢ Use modern and more efficient Laser Scanner technology for QC "as built" facilities => create a virtual 3D model (3-5 mm accuracy level) easily superimposed over civil engineering design models for comparison

# NuMI Primary surface geodetic network

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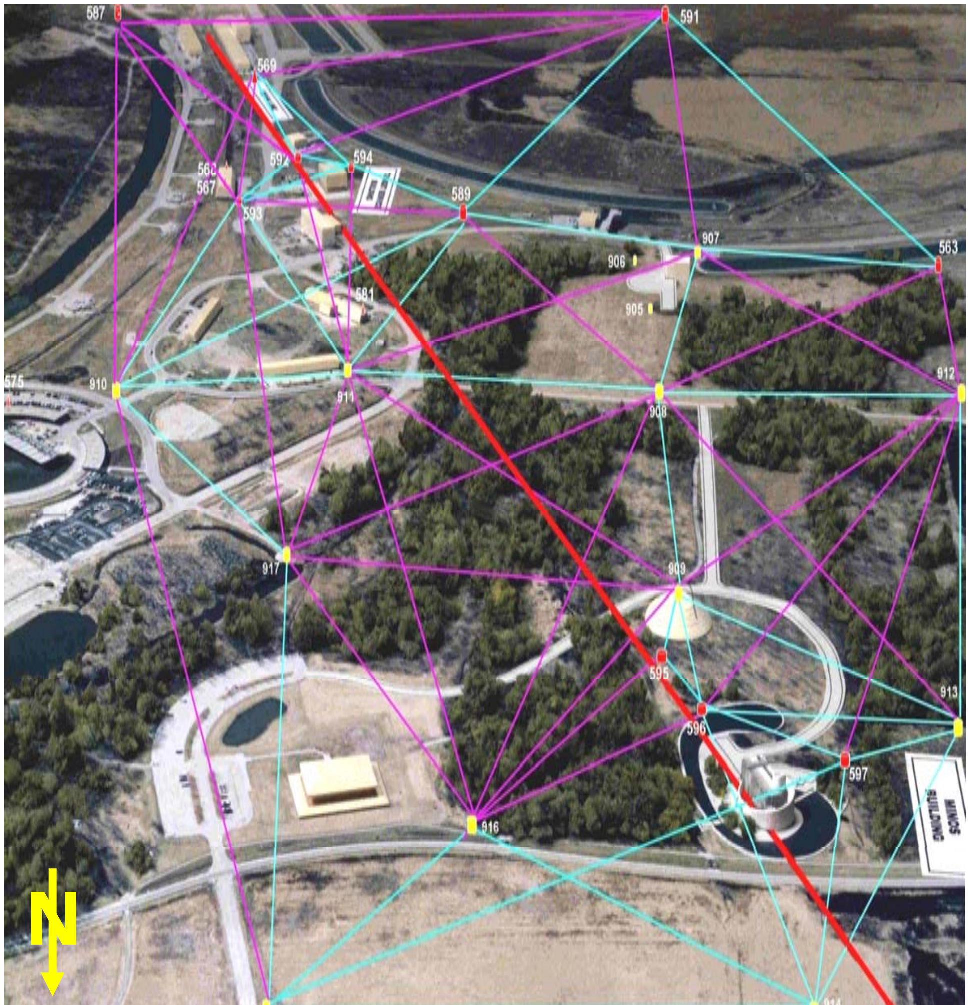
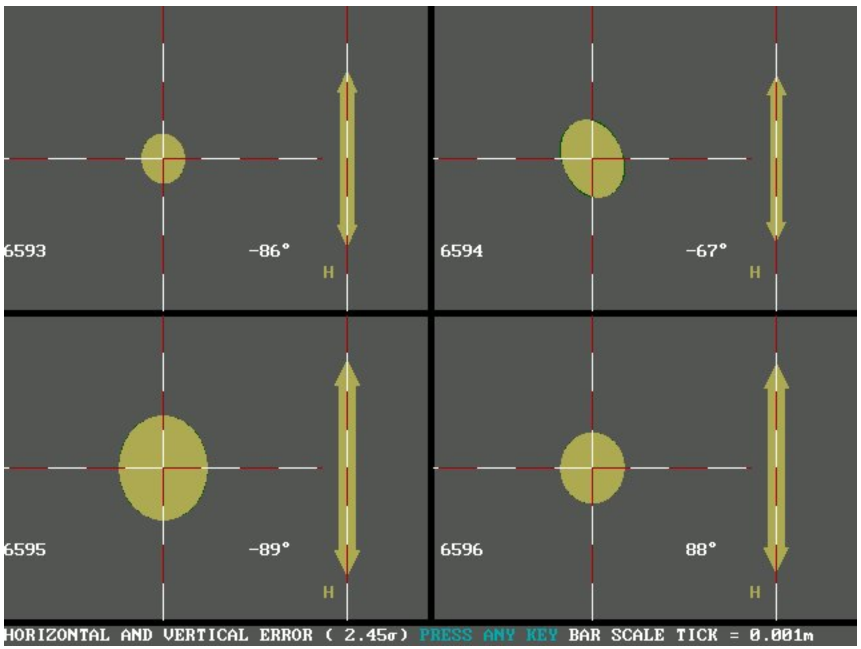


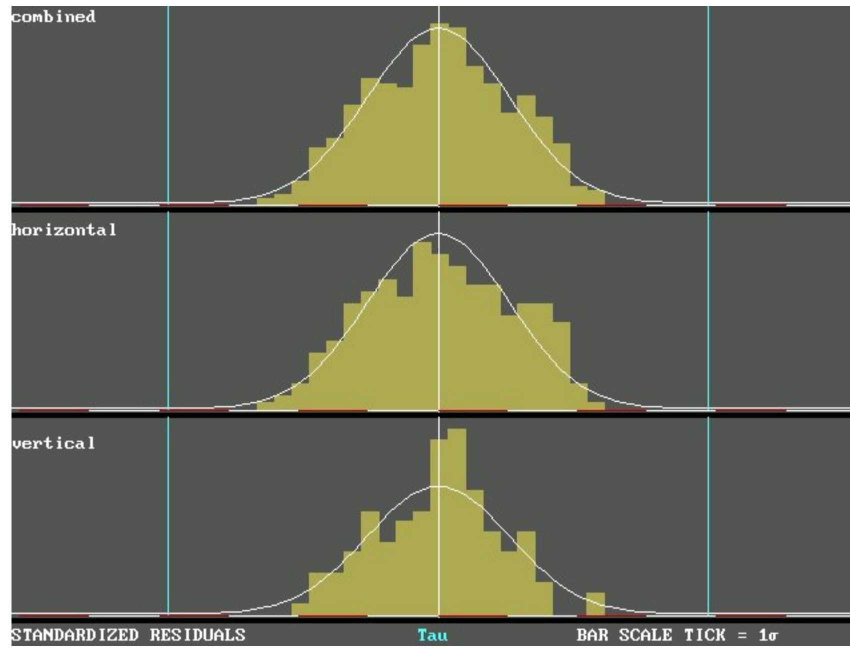

- Provides the basis for construction surveys and for the precision underground control networks
- existing Fermilab control network
  (accuracy < 2 mm @ 95% confidence level)
- NAD 83 horizontal geodetic datum
  (GRS-80 reference ellipsoid)
- NAVD 88 vertical datum
- Geoid93 NGS model
- included 3 monuments 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

# NuMI Primary surface geodetic network

## Results




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

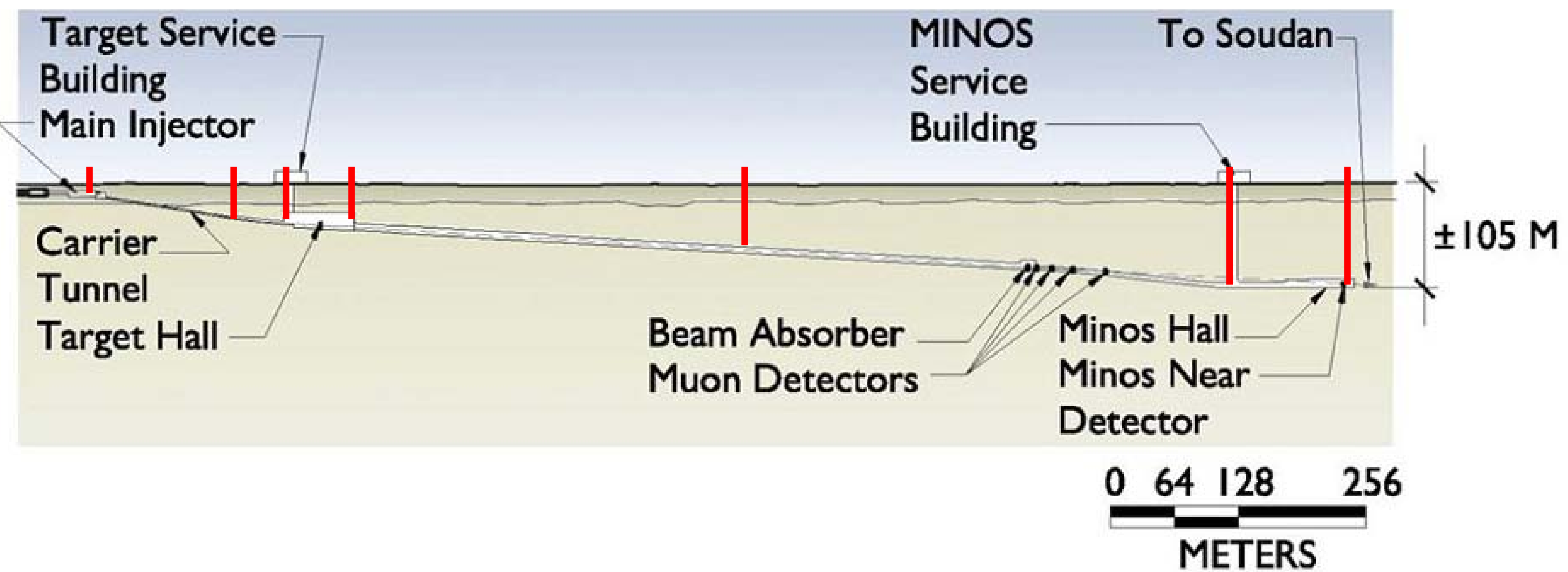



Histogram of standardized residuals
(bar scale tick = 1 σ)

# NuMI Underground Control Network

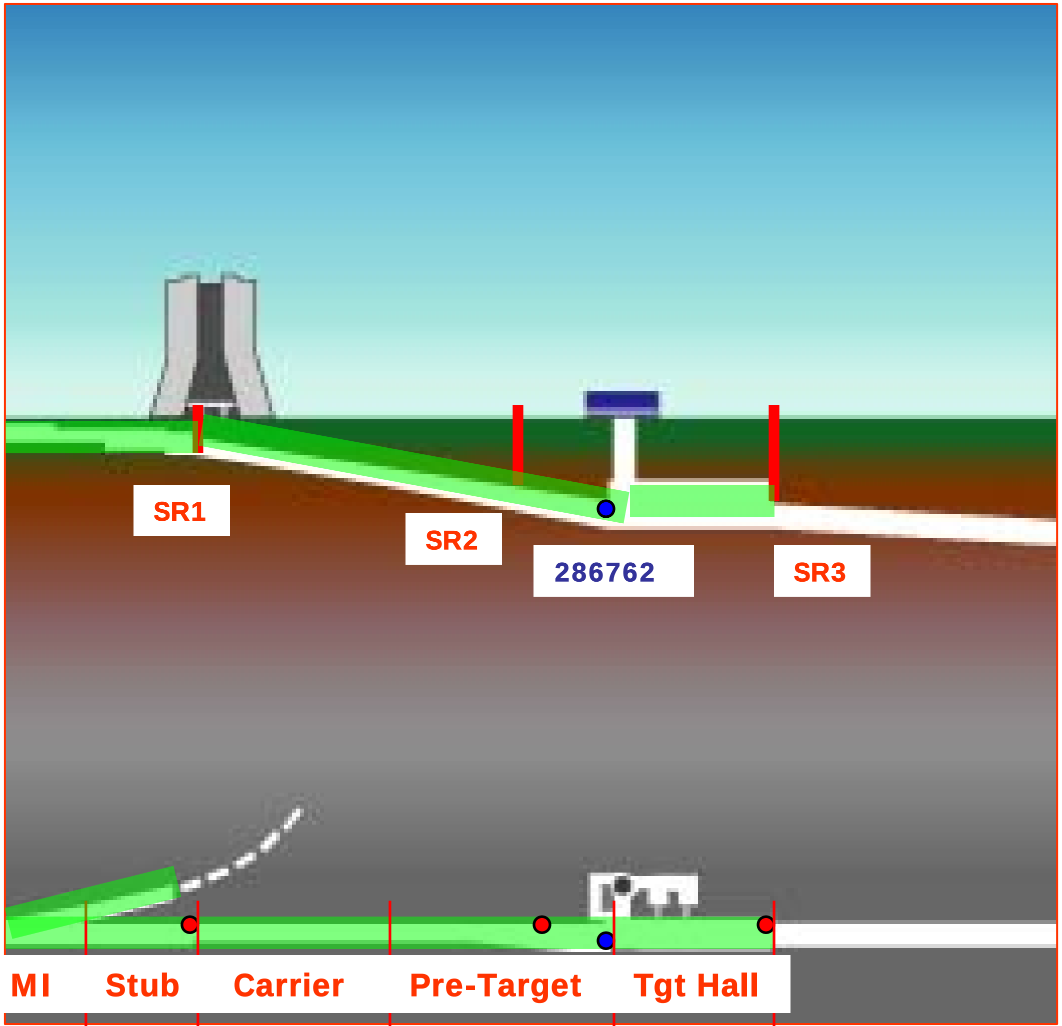


- Network simulations => **7** locations for transferring coordinates from the surface (3 vertical sight risers, 2 tunnel Access Shafts, 2 Exhaust Air Vent pipes)
  - we initially proposed 6 vertical sight risers but because of budget constraints we were asked to cut their number in half and temporarily used the Exhaust Air Vent pipes



# NuMI Underground Control Network





# NuMI Underground Control Network

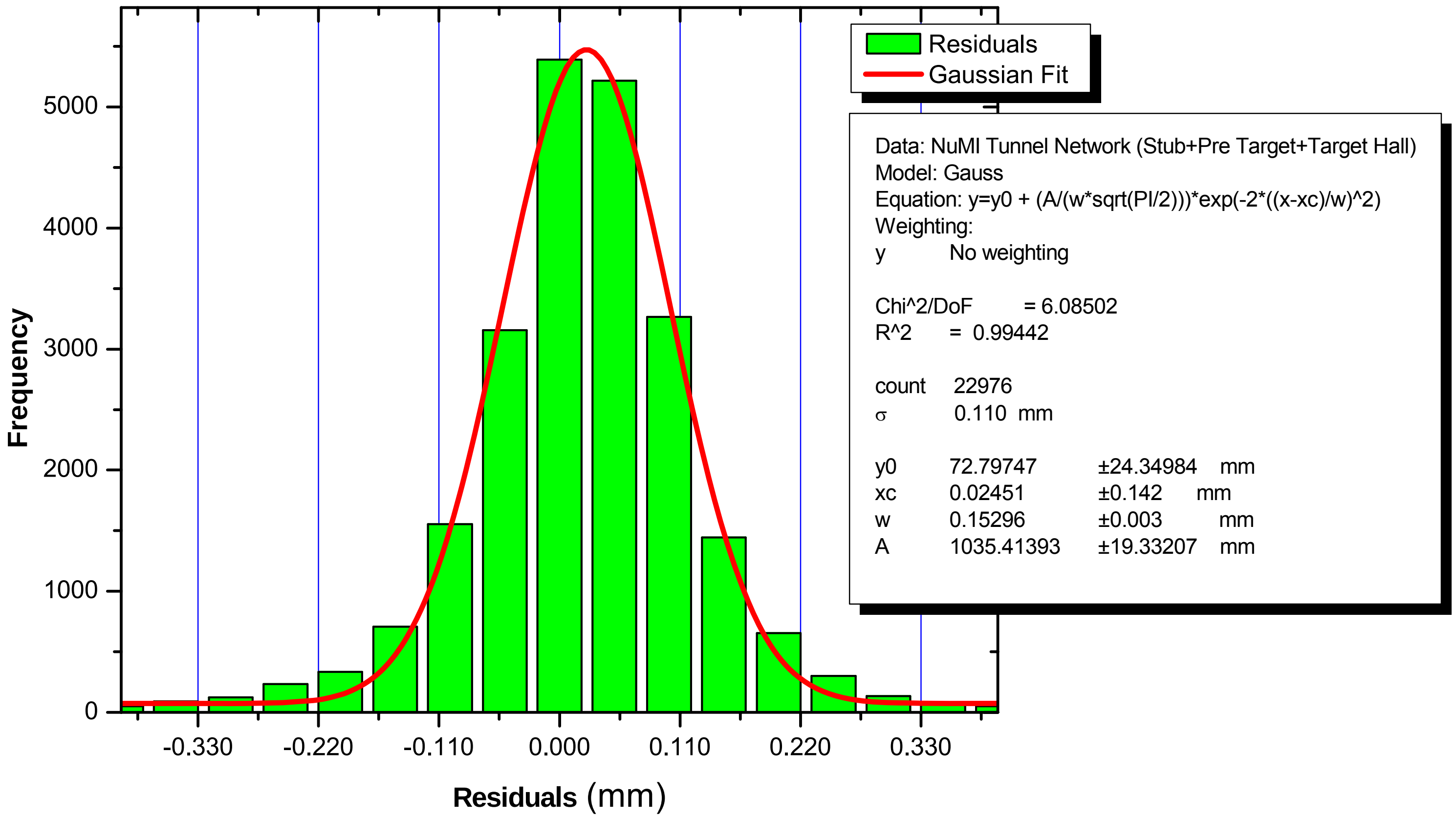


- Supports the alignment of Primary Beam components, the Target and focusing Horns = > relative alignment accuracy requirement ±0.35 mm (1$\sigma$)
- Least-Squares adjustment (fit) with constraints at MI-60, SR-1, SR-2, and SR-3
- Network type: Laser Tracker processed as trilateration **+** additional many other precision measurements to study and control error propagation behaviour =>23,000 Observations
- Network results: errors below ± 0.45 mm at 95% confidence level
- The azimuth of the final primary beam trajectory and Target Hall **confirmed** by first order Astronomical Azimuth => agreement at 0.74 arcsecond = 0.004 mrad (s=± 0.21 arcsecond = ± 0.001 mrad)

# NuMI Underground Control Network

## Results: histogram of standardized residuals






(bar scale tick = 1 $\sigma$)

# NuMI Underground Control Network

## Results: error ellipses XY axis

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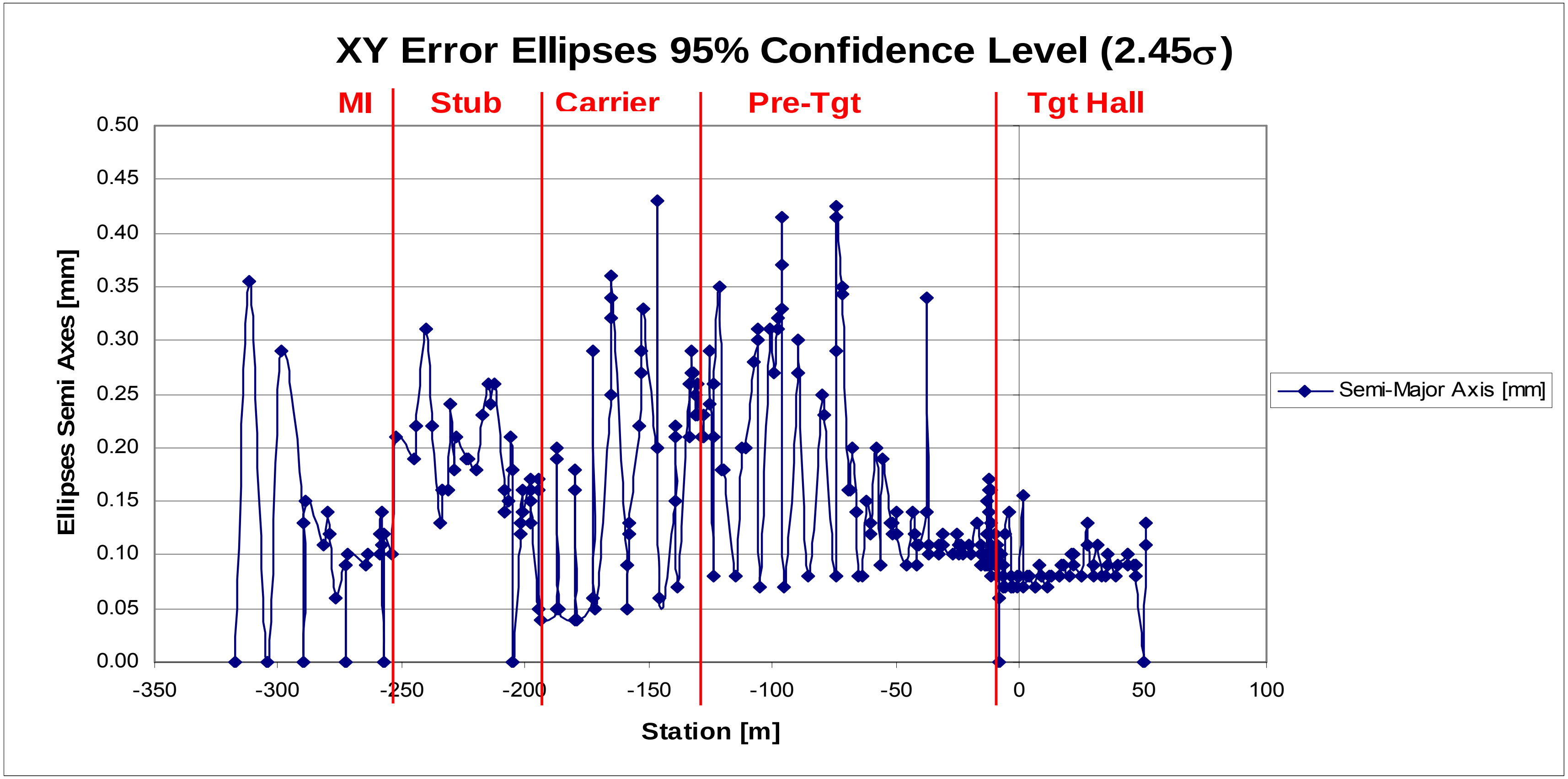
- Errors Ellipses below ±0.45 mm at 95% confidence level
- Error budget network requirements ±0.50 mm at 95% confidence level

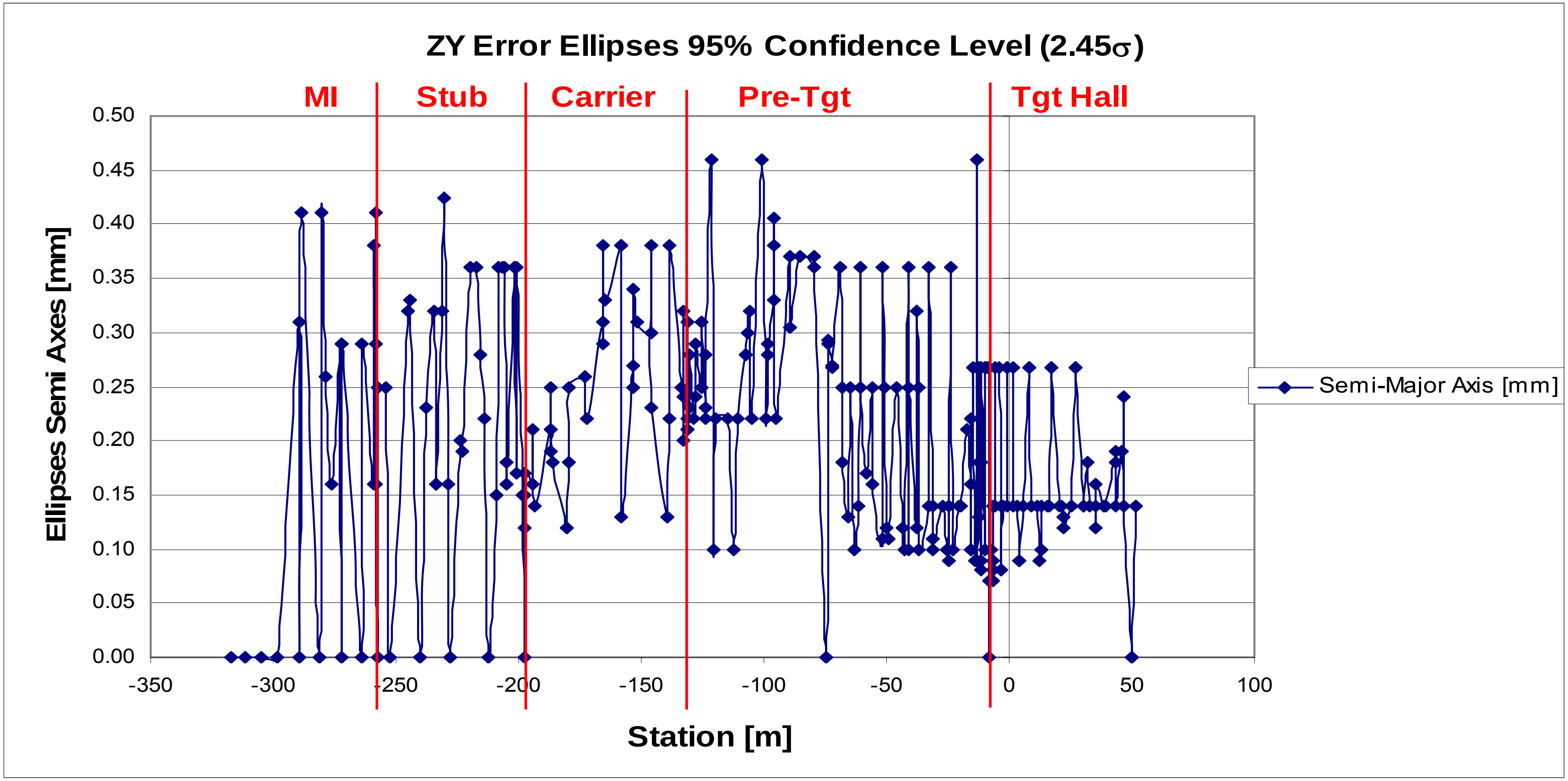


# NuMI Underground Control Network

## Results: error ellipses ZY axis



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



# NuMI Underground Control Network



- ***Lessons learned:***
- The surface geodetic network and the precision underground control network used for NuMI are adequate for DUSEL
- **What we would do different**:
  - Provide more vertical sight risers for transferring coordinates from the surface to the underground (better and more efficient for controlling error propagation in a weak geometry tunnel network)
  - Due to the increased depth of the tunnel, design adequate procedure for precision transfer of surface coordinates underground

# Primary beam alignment



- Primary beam alignment results: magnets and instrumentation aligned to ±0.25 mm
- **Successful Commissioning** the Primary Proton Beam (December 3-4, 2004) :
  - Target out of the beam, horns turned off and 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 (correctors were not used in beam steering because the precise alignment was sufficient)
  - Beam pointed in the right direction to < 0.010 mrad
- **Successful Commissioning** the Neutrino Beam (*January 21-23, 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

➢ *Lessons learned:*

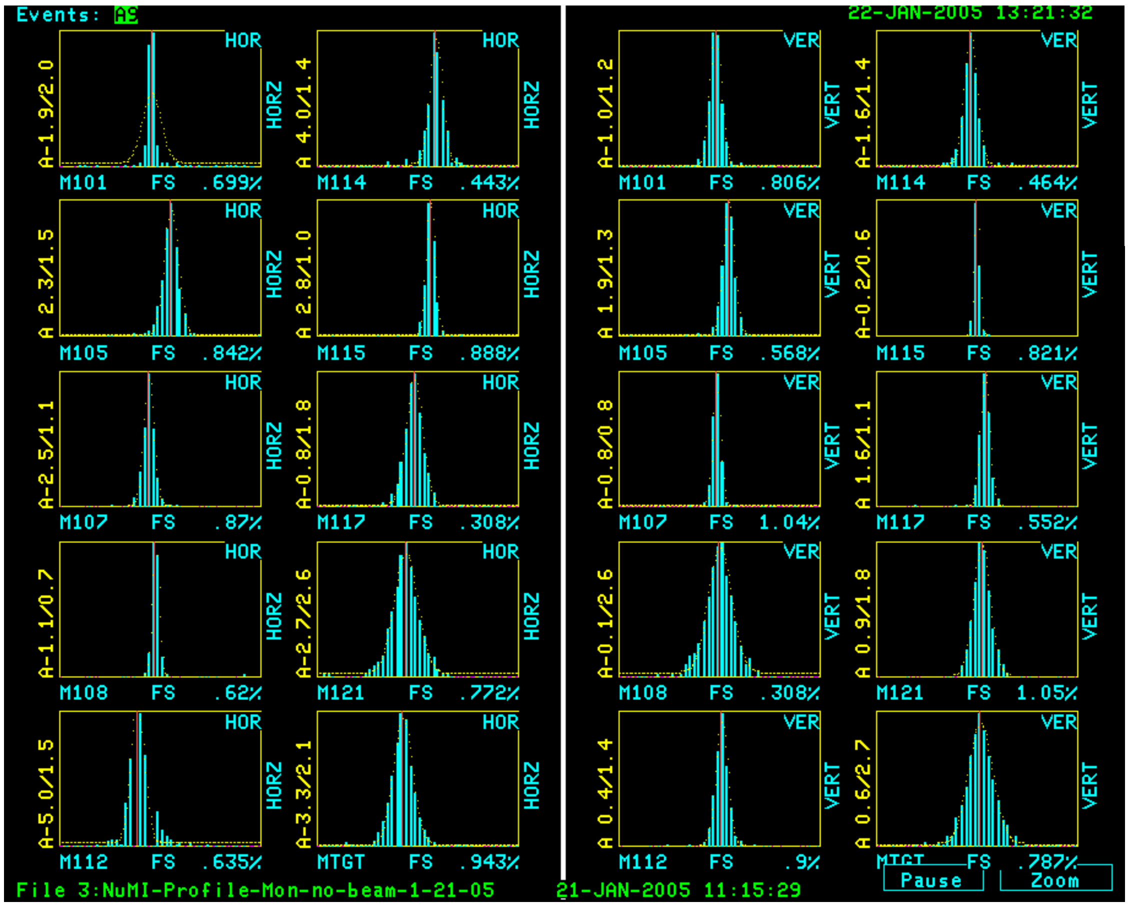
- The primary beam alignment used for NuMI is adequate for DUSEL

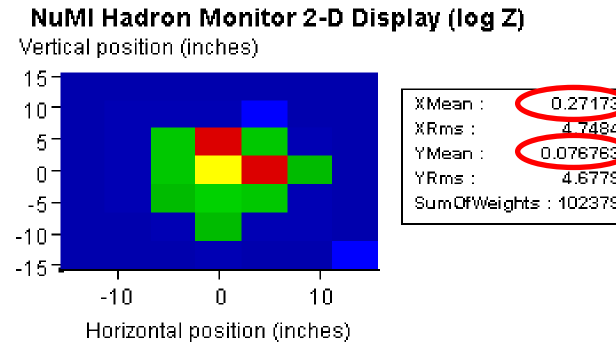
# Commissioning the Primary Proton Beam

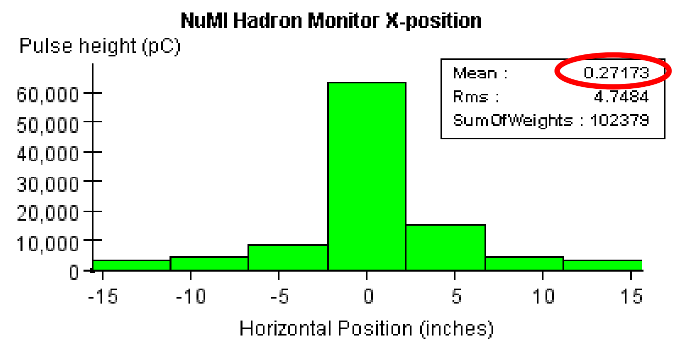
## Beam Extraction in 10 Pulses
## Centered on Hadron Absorber at 725 m Distance

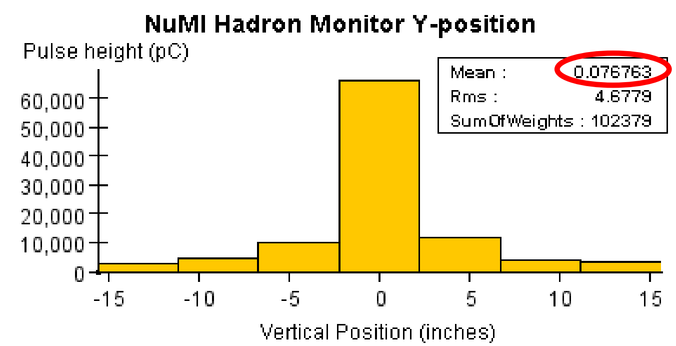


10th pulse: SEMs and Hadron Monitor readings



# Target station components alignment



- The relative alignment of the primary proton beam, Target, and focusing Horns affects the neutrino energy spectrum delivered to experiments
- Alignment results: Target station components aligned to ±0.5 mm

| DEVICE | Horizontal dX (mm) | Vertical dY (mm) |
|---|---|---|
| Target | -0.122 | -0.151 |
| Horn 1 | -0.285 | 0.303 |
| Horn 2 | -0.344 | -0.650 |

- Beam-based alignment of Target and Horns
- Proton beam used to locate the relative positions and angles of those components
- Procedure:
  - Scan proton beam ($\sigma$ = 1 mm) across known features of components (Target & Baffle and Horns cross-hairs)
  - Use instrumentation (BPMs and Profile Monitors) to correlate with measured proton beam position

# NuMI Beam and Monitoring Instrumentation

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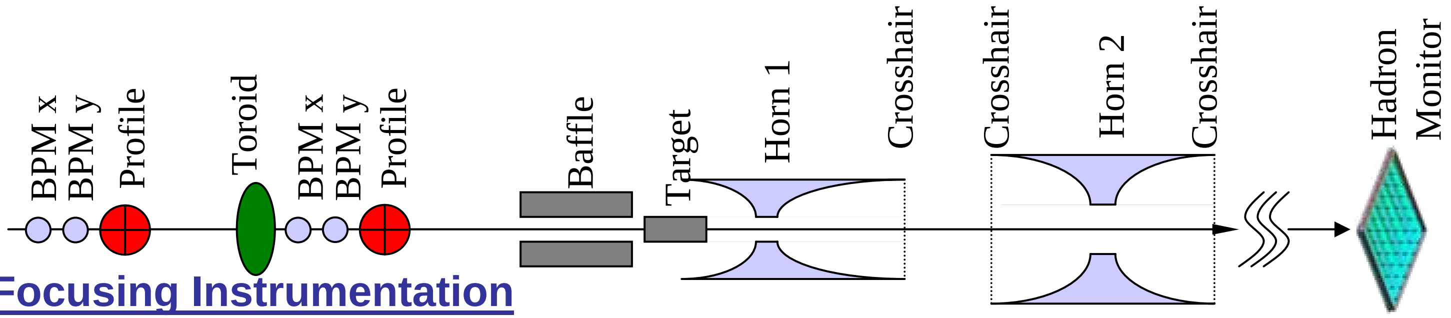
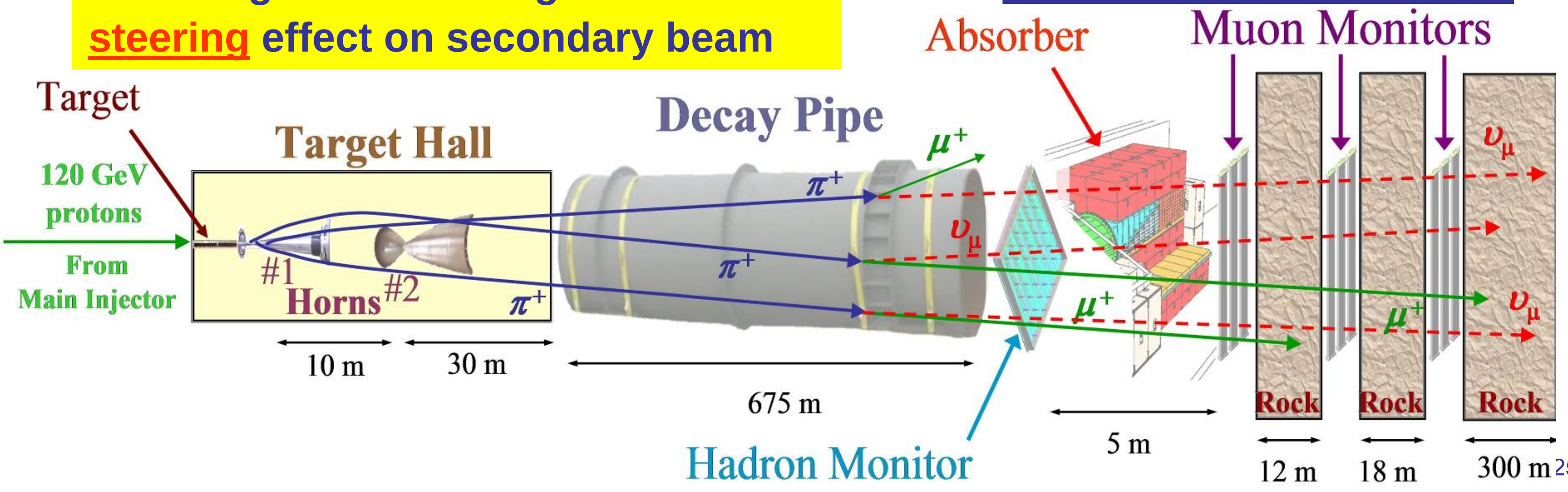



**Final Focusing Instrumentation**

**Focusing Horns misalignments have steering effect on secondary beam**

**Downstream Instrumentation**



# Summary of Target/Horns Sans on BPM Measurements

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



**Horizontal**

| DEVICE | Offset (mm) | Effect % | Angle (mrad) | Effect % |
|---|---|---|---|---|
| Baffle | -1.21 | 2.5 | -0.14 | <0.1 |
| Target | -1.41 | 2.5 | -0.14 | <0.1 |
| Horn 1 | -1.24 | 1.1 | -0.18 | 0.3 |
| Horn 2 | -1.82 | 1.2 | -0.18 | <0.1 |

**Vertical**

| DEVICE | Offset (mm) | Effect % | Angle (mrad) | Effect % |
|---|---|---|---|---|
| Baffle | 1.12 | 2.2 | -0.7 | <0.1 |
| Target | 0.13 | <0.1 | -0.7 | 0.26 |
| Horn 1 | 0.81 | 1.4 | 0.26 | 0.43 |
| Horn 2 | 0.08 | <0.1 | -0.43 | <0.1 |

- components are consistently to the westward , and usually down (exception: the 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



**Horizontal**

| DEVICE | Offset (mm) | Effect % | Angle (mrad) | Effect % |
|---|---|---|---|---|
| Baffle | 0.01 | <0.1 | -0.14 | <0.1 |
| Target | -0.21 | 0.37 | -0.14 | 0.1 |
| Horn 1 | 0.03 | <0.1 | -0.18 | 0.32 |
| Horn 2 | -0.62 | 0.23 | -0.18 | <0.1 |

**Vertical**

| DEVICE | Offset (mm) | Effect % | Angle (mrad) | Effect % |
|---|---|---|---|---|
| Baffle | 0.12 | <0.1 | -0.7 | <0.1 |
| Target | -0.87 | <0.1 | -0.7 | 0.26 |
| Horn 1 | -0.19 | <0.1 | 0.26 | 0.35 |
| Horn 2 | -0.92 | 0.42 | -0.43 | <0.1 |

- 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

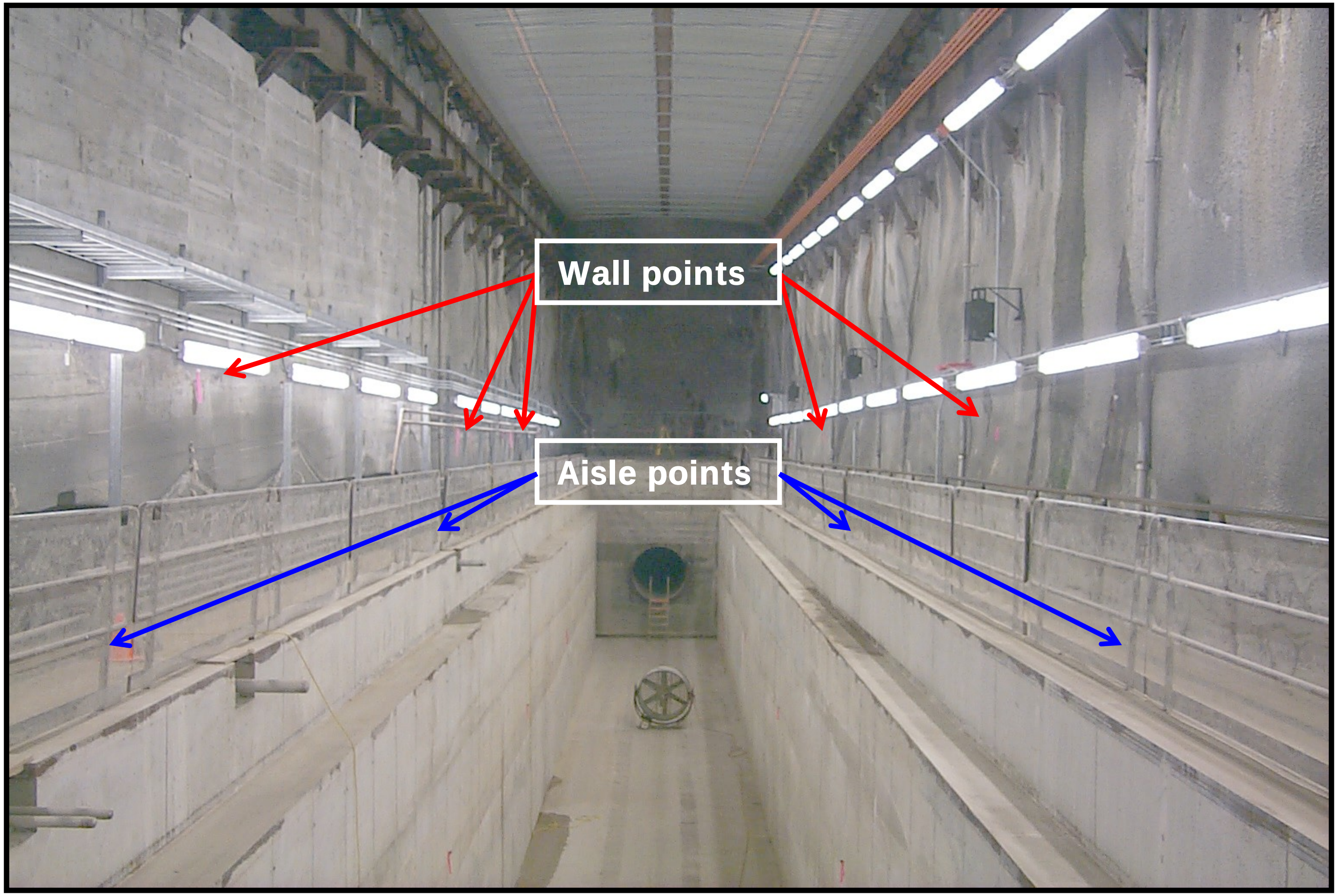
# Pre-Target and Target Hall
## Deformation Analysis



- 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

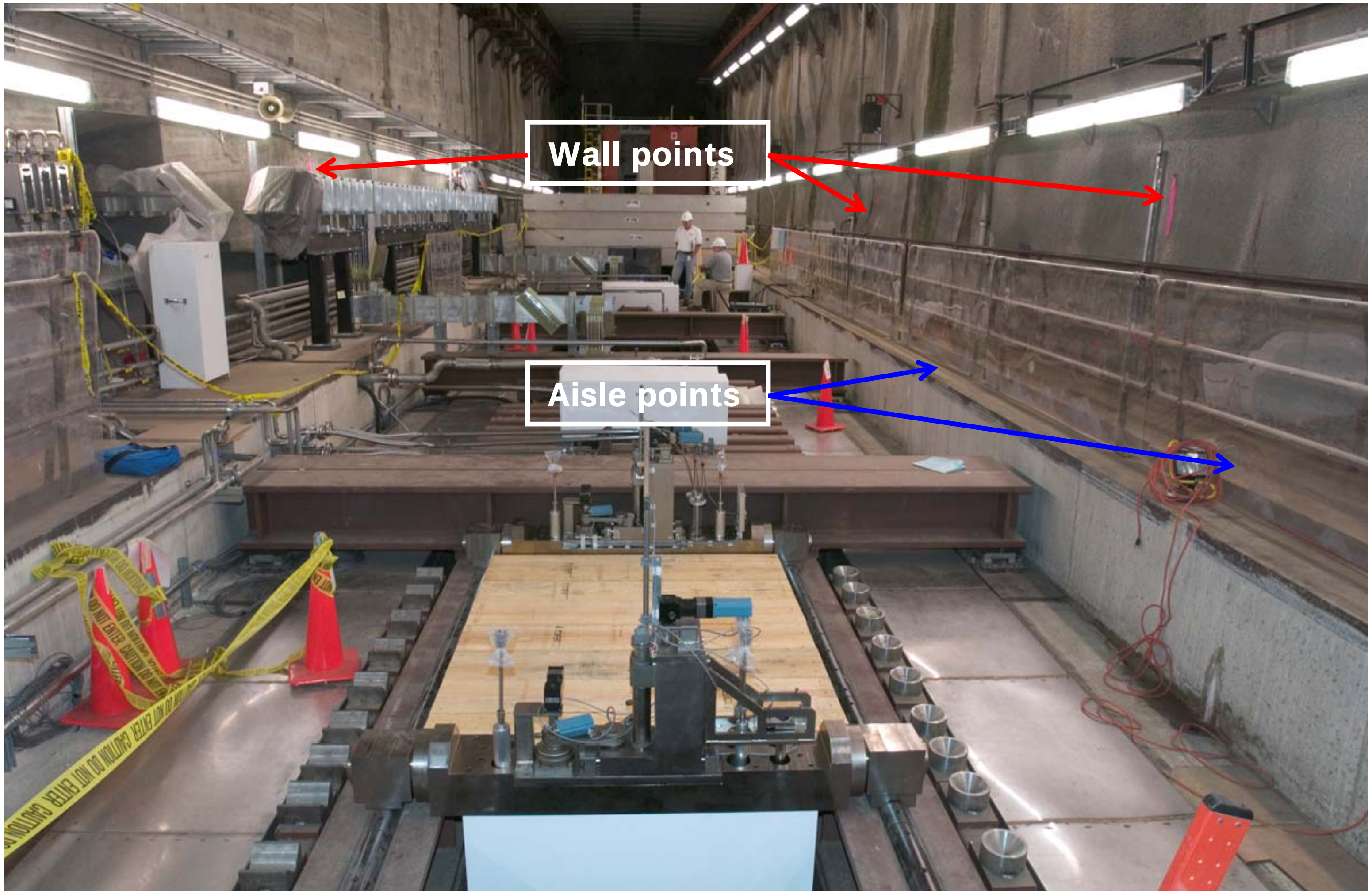
# Target Hall During Network Observations





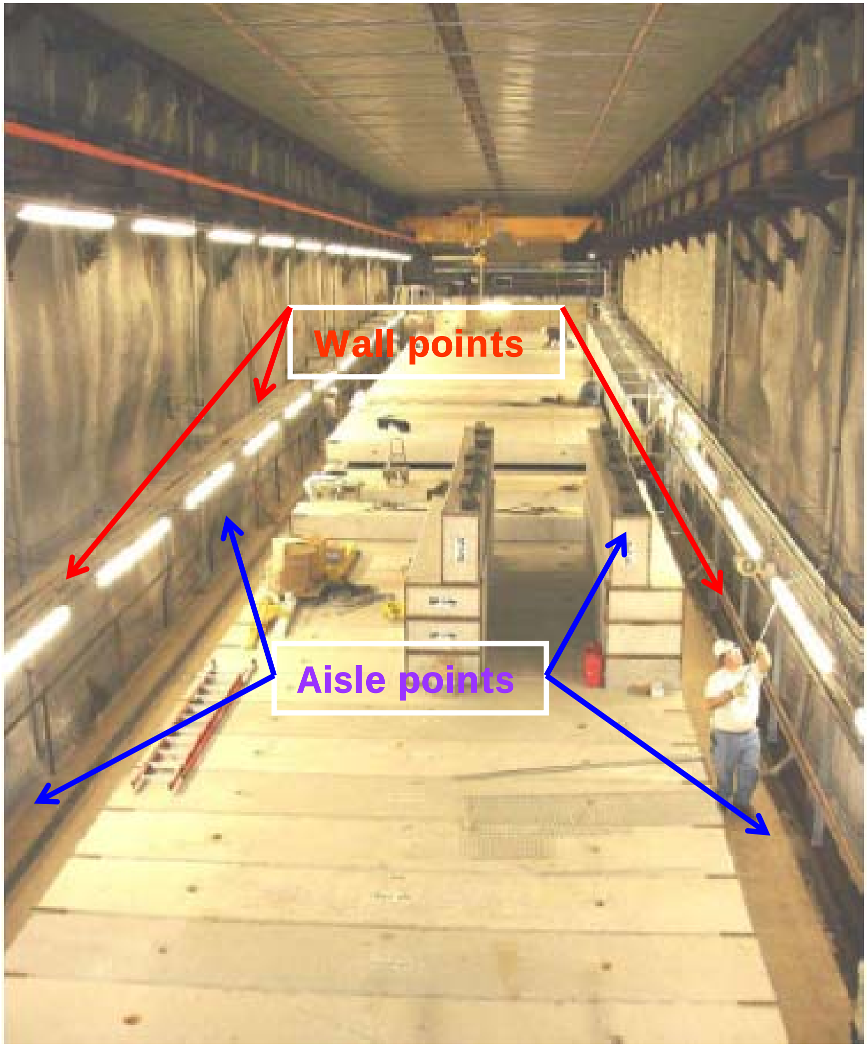
# Target Hall During Target and Horns Alignment





# Target Hall During Commissioning and Experiment Run





# 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 where removed
- The Pre Target tunnel: no horizontal (or vertical) deformations

# Target Hall Horizontal Deformation

## R-blocks loaded (as during run)

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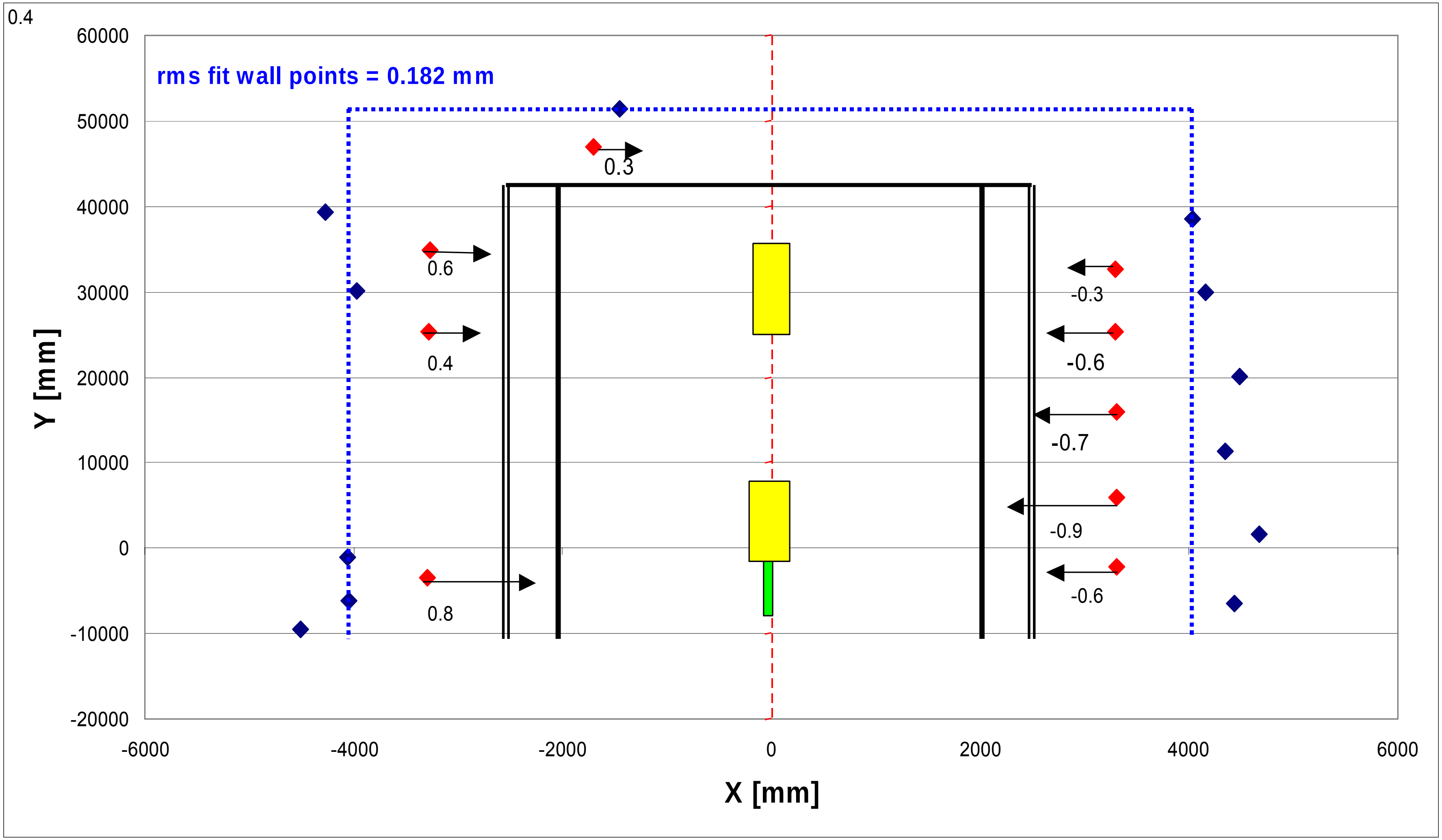


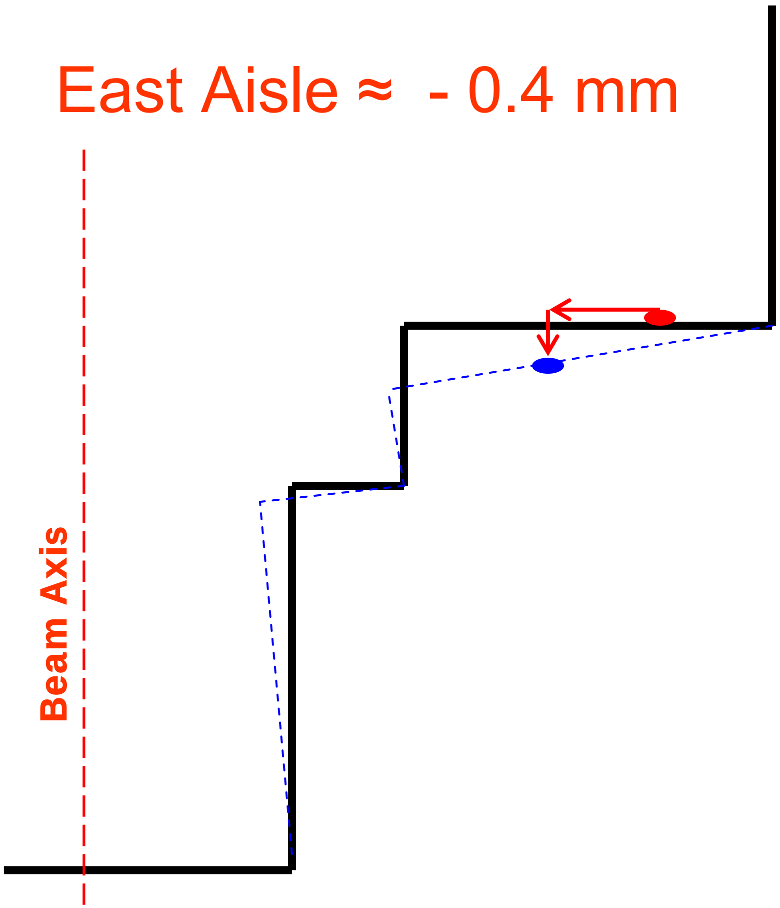
# Target Hall Vertical Deformation

## R-blocks loaded (as during run)



West Aisle ≈ - 0.7 mm

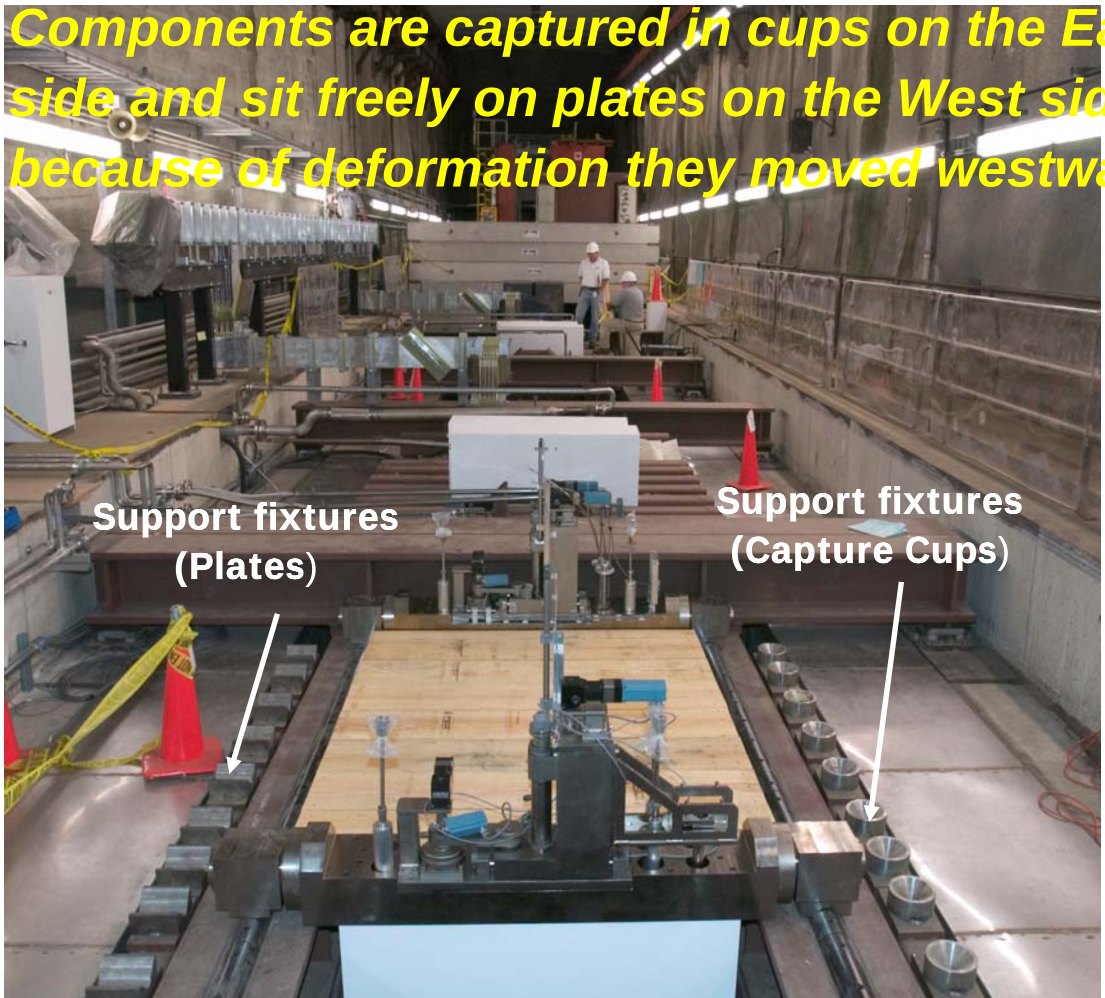
East Aisle ≈ - 0.4 mm



# 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***



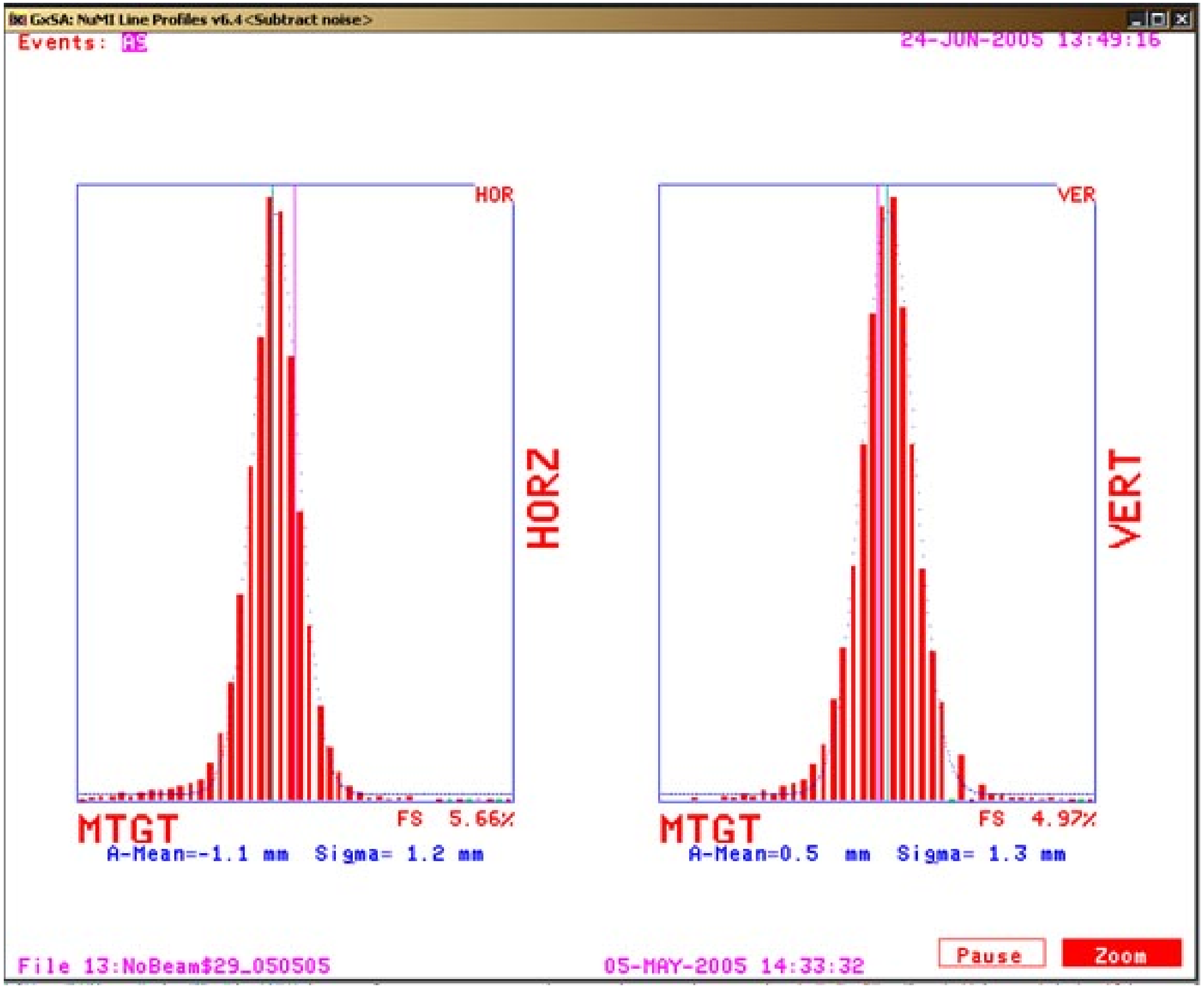

# Estimation on Effect of Deformation on Target and Horns



- Horizontal beam on Target and Horns:
  - Aisles (horizontal) deformation due to load = -0.9 mm
  - Displacement due to thermal expansion (DT = $4^0$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 = $4^0$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





# Target station components alignment



## ➢ *Lessons learned:*

- The Target station components alignment used for NuMI is only partially adequate for DUSEL
- The alignment running positions will be determined by the beam-based alignment of Target and Horns
- Deformation of the aisle ledges due to the loading of the R-blocks causes the components to move from their initial alignment up to 1-1.5 mm
- The current alignment procedure (of sighting down the fiducials with a precision scope through a vertical porthole) creates safety concerns due to high radiation levels (increased exposure potential for surveyors)
- **What we would do different**:
  - ➢ Develop a precise referencing and alignment procedure in which direct access to fiducials located inside the pit is unnecessary
    - ➢ A possibility is to reference the component to fiducials located on the top of the module (R&D to correlate the referencing with the deformation of the module when sitting on the chasse and in the work cell)
  - ➢ Better documentation on what the referencing of the components was done to and ask for clearer specifications (eliminate ambiguities)

# Summary



- For NuMI, we developed and executed well a very comprehensive and complex geodesy and alignment plan
- We achieved all the required tolerances and provided expert and efficient support throughout the project
- **The vast majority of geodesy and alignment methodology used for NuMI is adequate and applicable for DUSEL**

# NuMI Geodesy and Alignment Lessons Learned



How not to do it!