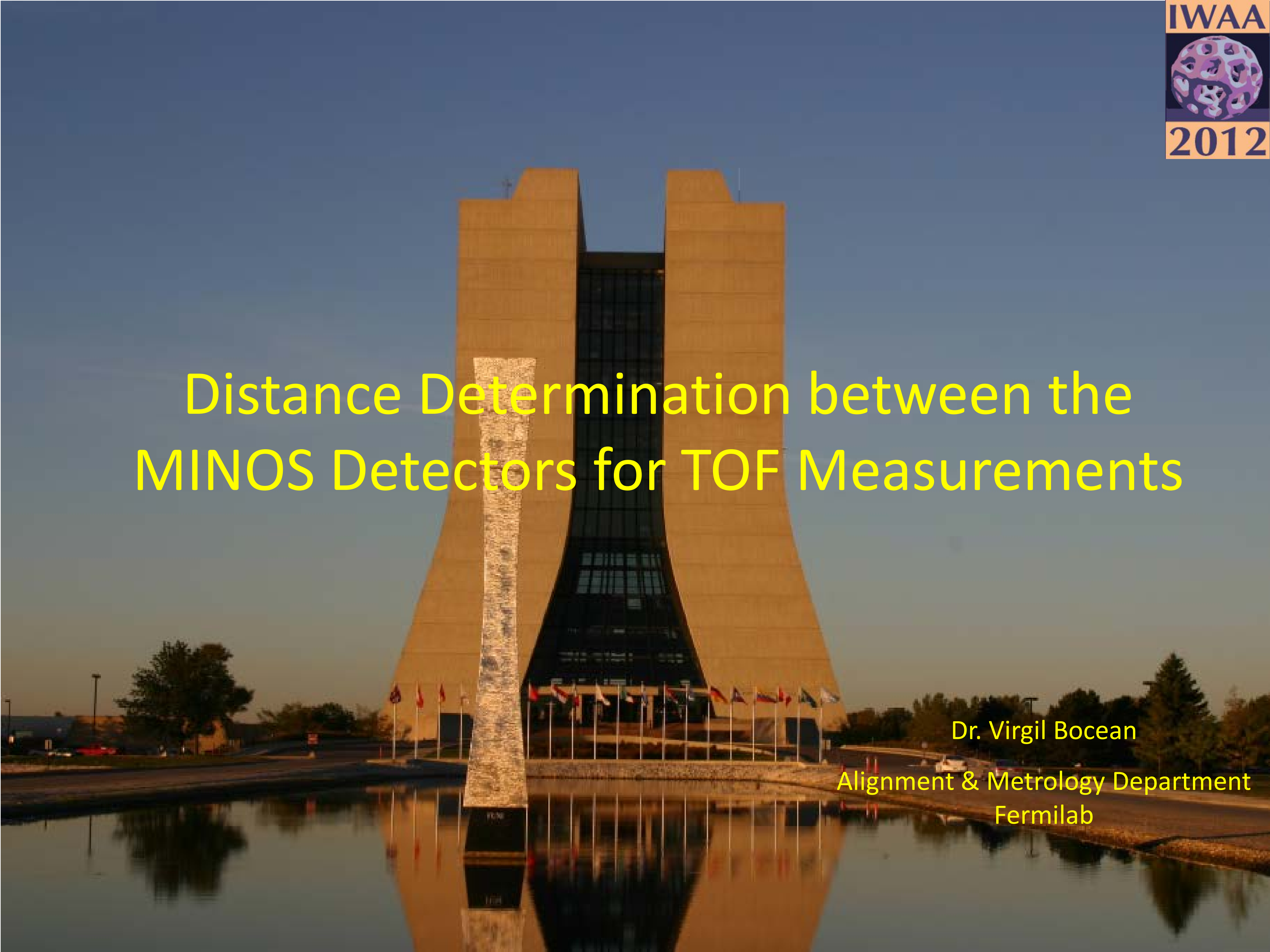
IWAA 2012



Distance Determination between the MINOS Detectors for TOF Measurements

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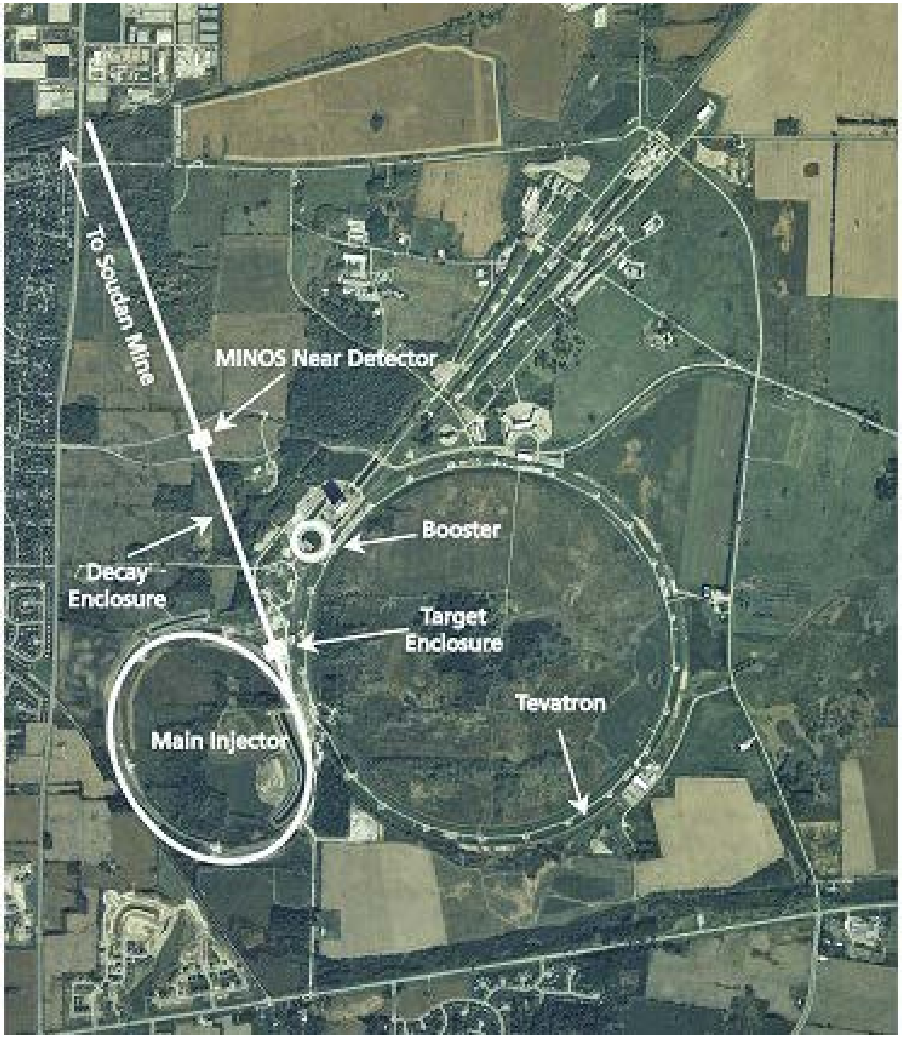
Introduction

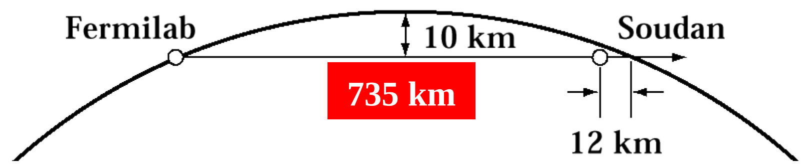
- Part of the neutrino research program at Fermilab is the search for non-zero neutrino mass
- Looks for neutrino oscillations ($\nu_\mu \rightarrow \nu_\tau$) or ($\nu_\mu \rightarrow \nu_e$)
- NuMI (Neutrinos at the Main Injector) has built a new particle beamline capable of directing a pure beam of 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

- Recent results on neutrino velocity measured with the Opera detector and CNGS beam raised questions about the neutrinos possibly traveling faster than light.
- As a result, this generated increased interest in determining the precise distance for verification of the neutrino time-of-flight (TOF)

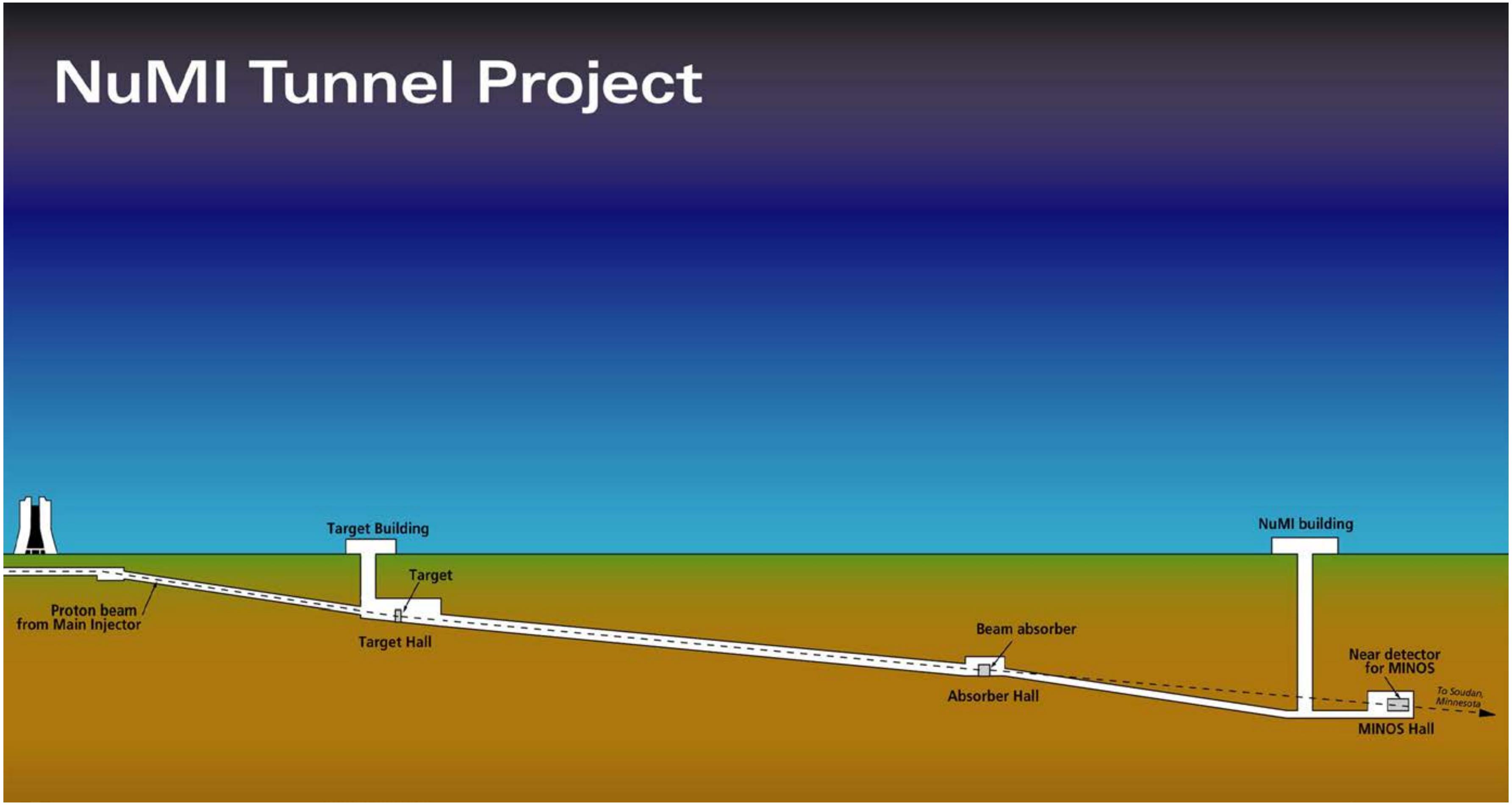
- The distance for NuMI TOF measurements was computed between the front (most upstream) planes of the Near and Far detectors (the events timestamp was reduced to those planes)
- A rigorous solution for computing the Euclidian distance between the two detectors along the beam path requires precise knowledge of the absolute positions of those detectors in space

NuMI Beamline
From Fermilab to Soudan, MN





NuMI Tunnels and Halls

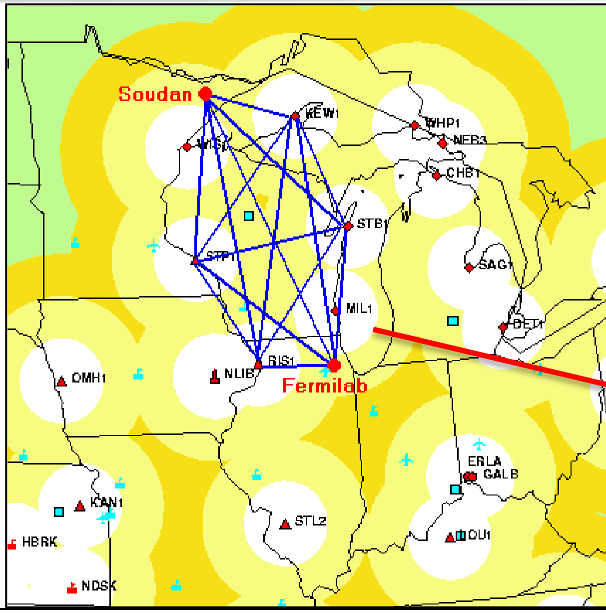


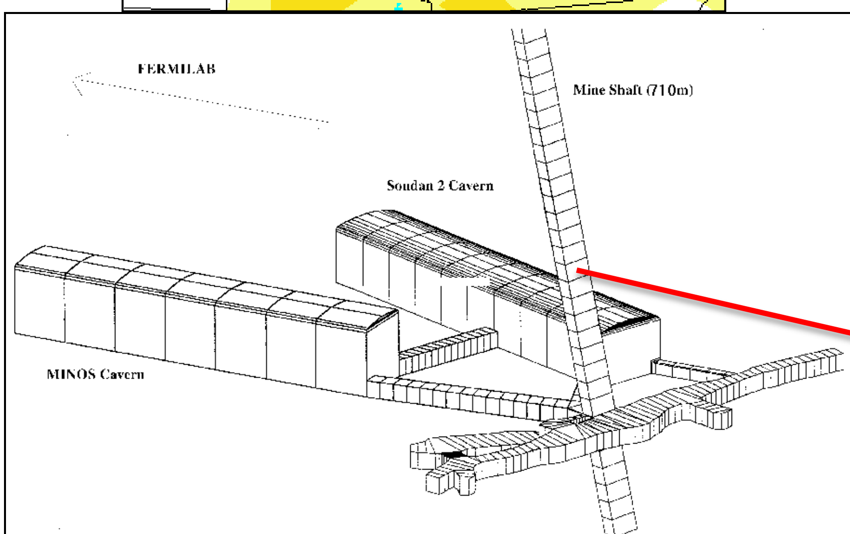
Alignment Tolerances (1σ)

- Primary proton beam centered ± 12 m at the far detector (± 0.016 mrad = 3.4 arc sec)
- Neutrino beam centered ± 75 m at the far detector ± 0.102 mrad = 21 arc sec)
- NuMI is mainly sensitive to final primary beam trajectory : primary beamline components, Target and Horn alignment => relative positions ±0.35 mm

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**

Geodetic determination of global positions





- The correct aiming of the beam is of great importance for the experiment
- Requires a rather exact knowledge of the geodetic orientation parameters of the beam => absolute & relative positions of the target (Fermilab) and the far detector (Soudan) at the global level
- Two steps procedure:

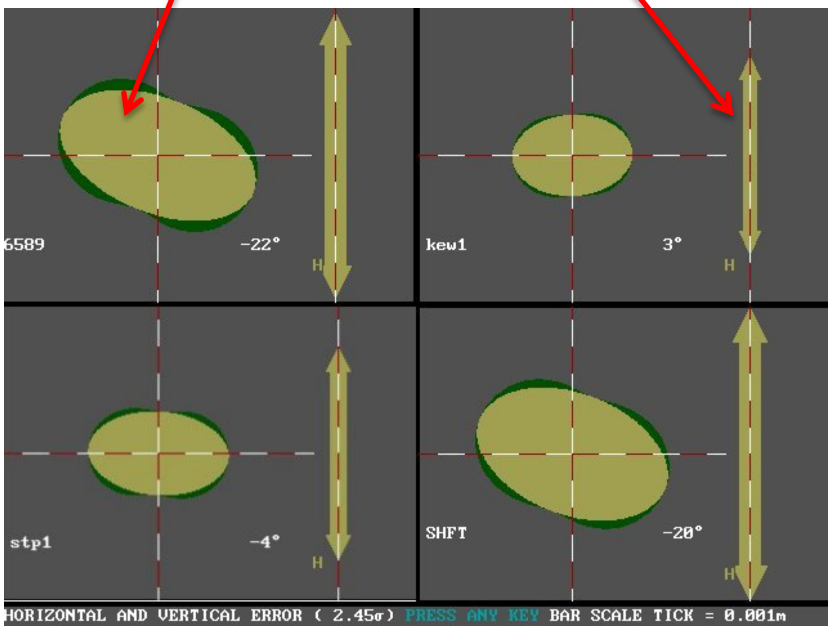
1. FNAL/Soudan long GPS baseline measurements tie the surface control to the National Geodetic Survey's Continuously Operating Reference Station (CORS) precision GPS geodetic network
   - vector known to better than 1 cm horizontally and vertically
   - solution in International Terrestrial Reference Frame of 2000 (ITRF00) reference system => then transformed in the national North American Datum of 1983 (NAD 83) system
   - NGS will provide an independent solution (excellent agreement within 1 cm)
2. Inertial system survey through 713 m shaft tied the the 27th level of the mine to surface geodetic control
   - University of Calgary Department of Geomatics Engineering contracted to perform the survey with an rms be below 1 meter
   - A posteriori coordinates transfer accuracies : latitude 0.48 m, longitude 0.20 m and height 0.23 m

Geodetic determination of global positions

Results

Ellipses of Error in x, y plane

Errors in Height

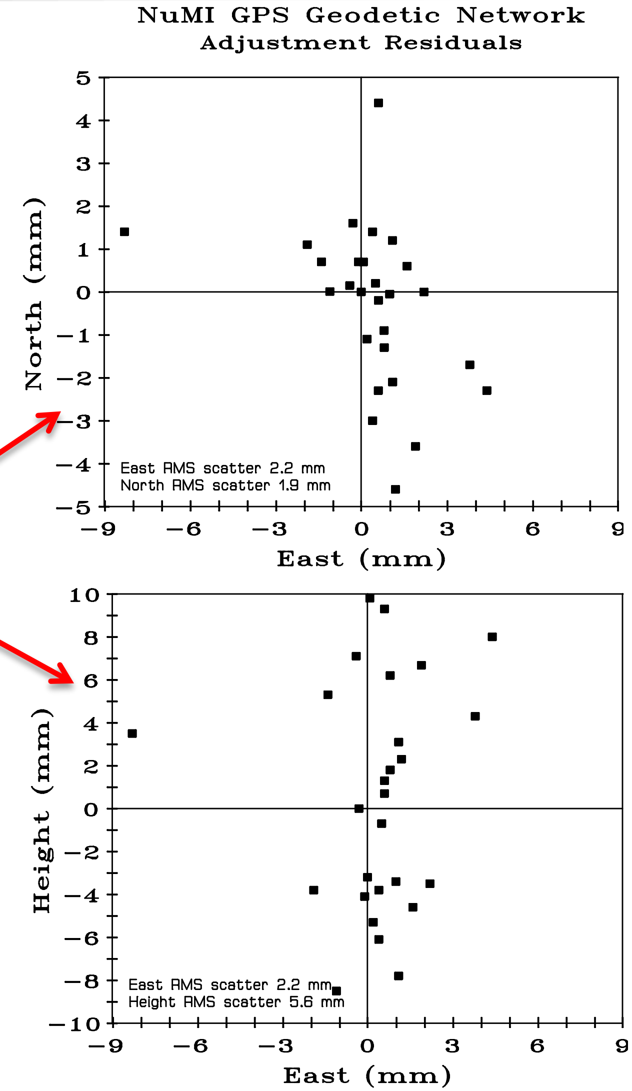


Ellipses of Error @ 95% confidence level
(bar scale tick = 1 mm)

Rms of residuals @ 95% confidence level

Long/Lat = 2 mm

Height = 6 mm



- NuMI global position accuracy is shown

Comparison between coordinates and geodetic parameters

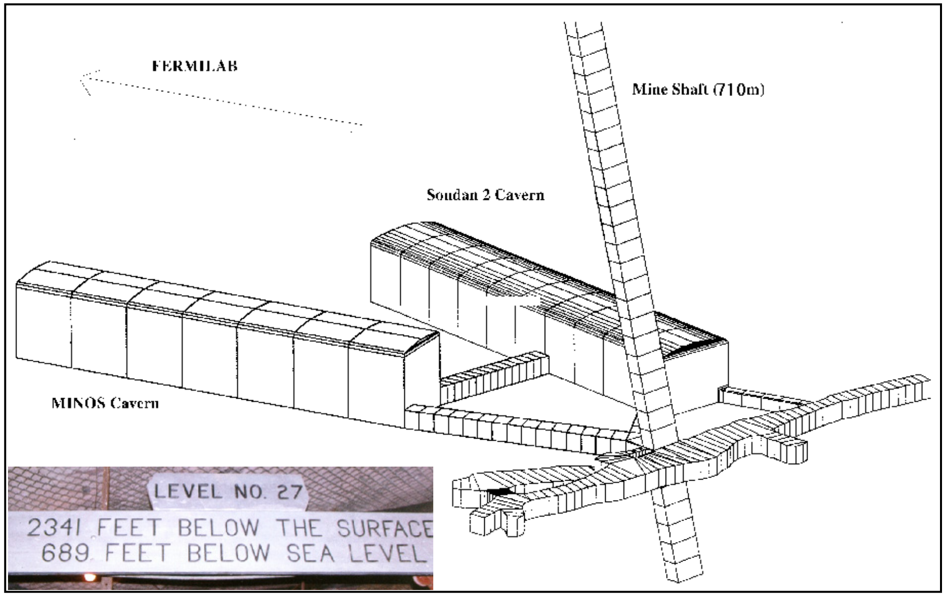
Coordinates in Local Geodetic System at 66589

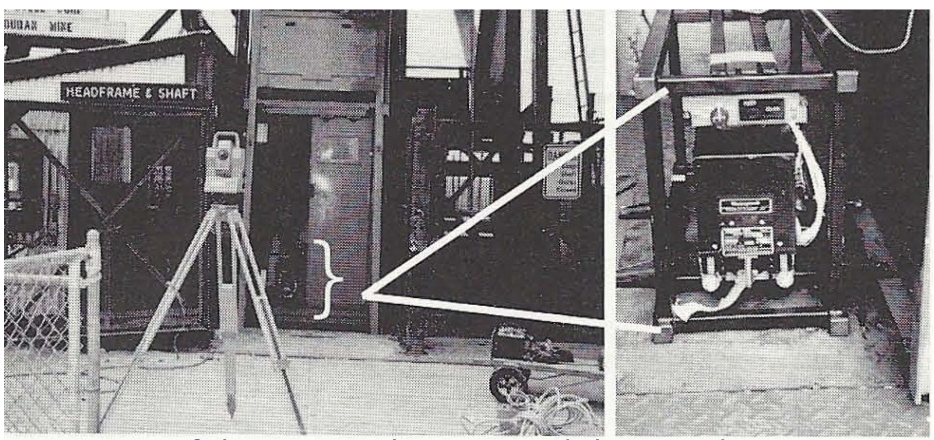
FROM	TO	n (m)	e (m)	up (m)	Δ n (m)	Δ e (m)	Δ up (m)	Comment
66589_93	SHAFT_93	671107.806	-297423.720	-42175.340	0.725	-0.296	-0.050	NGS NAD83 tie
66589_93	SHAFT_98	671108.303	-297424.045	-42175.408	0.229	0.029	0.018	GPS differential
66589_CORS Fermi	SHAFT_CORS Fermi	671108.540	-297424.003	-42175.396	-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

FROM	TO	Normal Sect Az (d-m-s)	Δ Az (sec)	Vertical Angle (d-m-s)	Δ VA (sec)	Distance (m)	Δ D (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	

Underground coordinate transfer at Soudan
The weakest link!





Setup of the IMU in the cage and the coordinate transfer performed by a total station at the surface

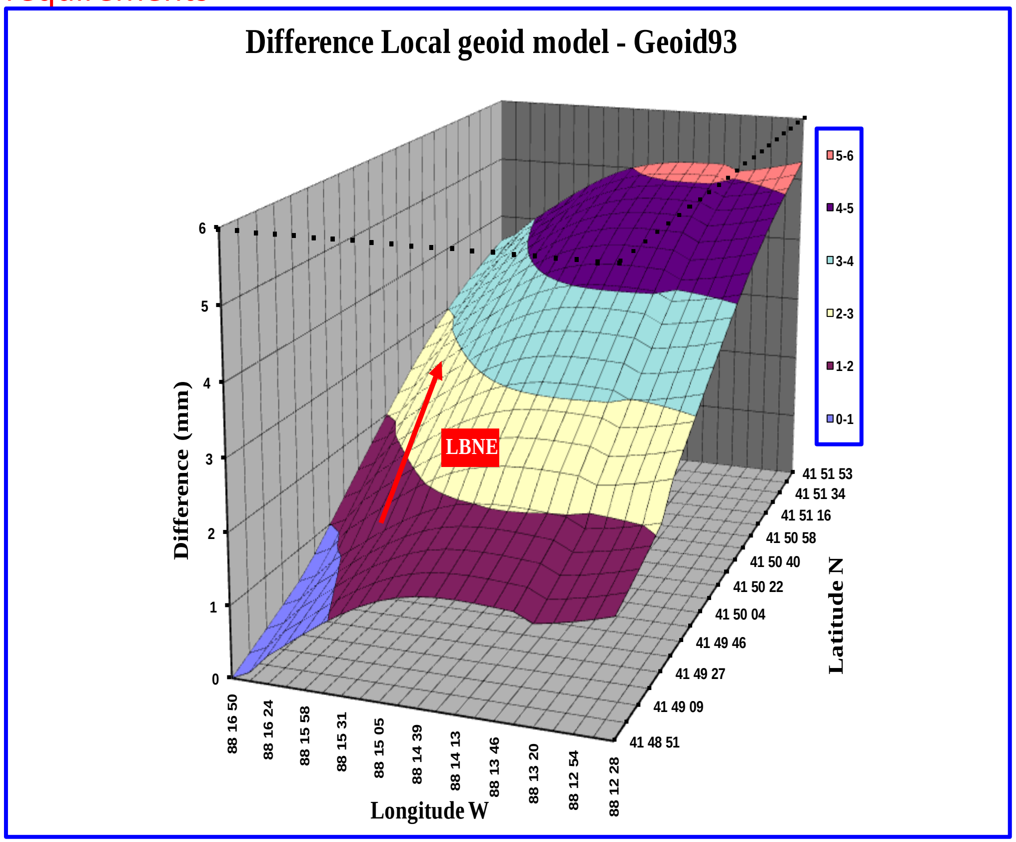
- HG Honeywell 2001 Inertial Navigation System (INS) unit:
  - o composed of 3 accelerometers and 3 gyroscopes
  - o output specific forces and respective angular velocities from the orthogonal sensor triads
  - o outputs used in a dead-reckoning method which after initialization provides three dimensional geodetic coordinates at a high data rate

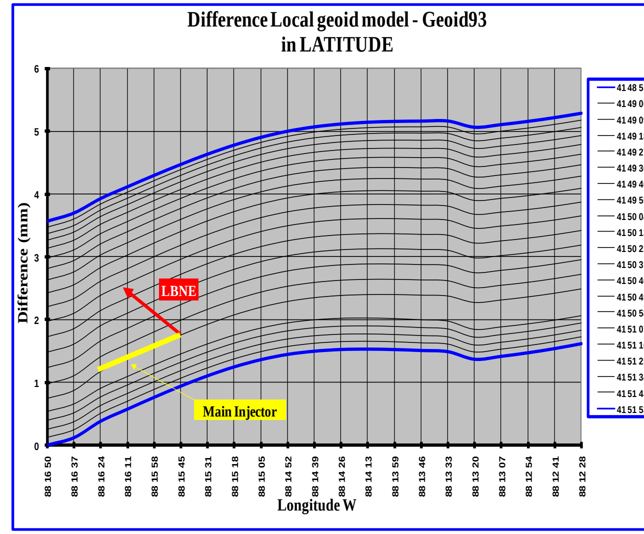
Performance Parameter	Class II 1.0 nmi./h
gyro bias uncertainty (deg/h)	0.003
gyro random noise (deg/ √h)	0.001
gyro scale-factor uncertainty (ppm)	1
gyro alignment uncertainty (arc sec)	?
accelerometer bias uncertainty (mGal)	10-25
accel. scale-factor uncertainty (ppm)	50
accelerometer alignment uncertainty (sec)	5
accelerometer bias trending (mGal/sec)	?
σ_{pos}	0.5 m at ZUPTs every 3 min
$\sigma_{acceleration}$	net bias < 50 mGal short term bias < 3 mGal

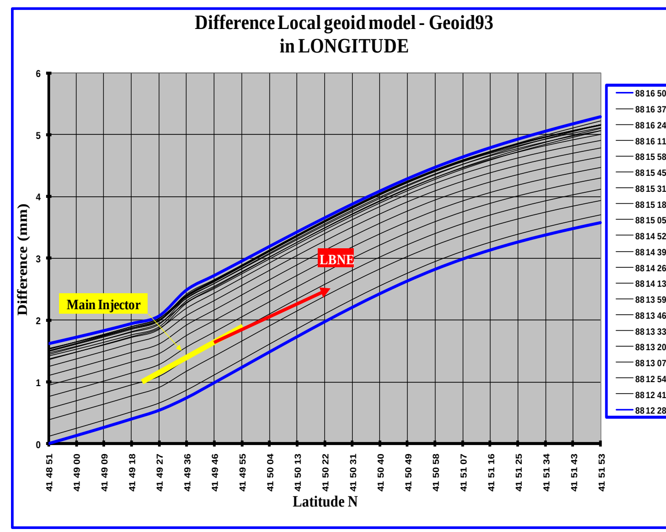
- The accuracy of the results depends of:
  - o the quality of the hardware, on the
  - o the method used to estimate systematic errors inherently present in the sensors
- Multiple determinations running the unit rigidly attached in the center of the elevator car
- Mapped the 710 m deep access shaft by setting the inertial system at 1 second data collecting rate
- A posteriori coordinates transfer accuracies : latitude 0.48 m, longitude 0.20 m and height 0.23 m

Geodetic determination of global positions
Geoid consideration

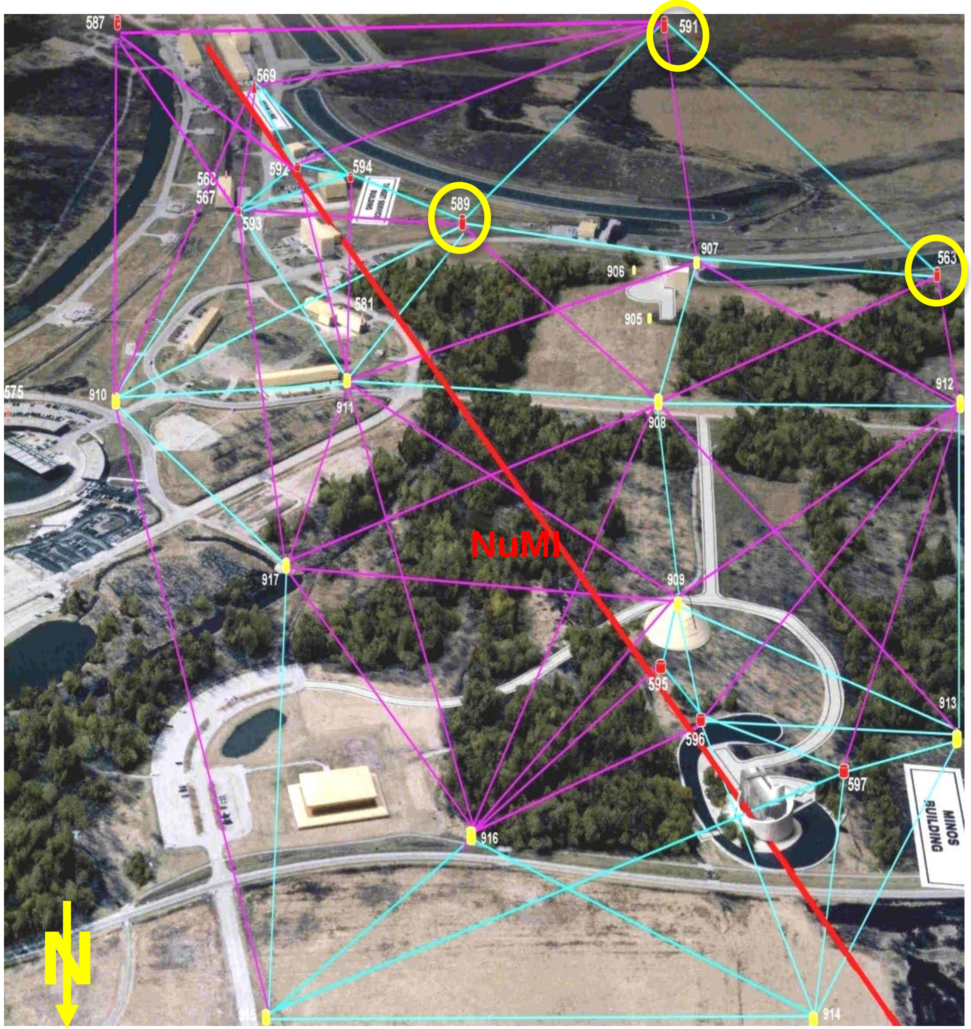
- Needed knowledge of the gravity vector at the origin (Fermilab)
- Previous study comparing a Local Geoid Model and NGS Geoid93 model
- Differences up to 5 mm (consistent with expected values)
- LBNE beam within 1.5 mm range of differences
- Geoid93 model (presently used) - sufficient to cover tolerance requirements







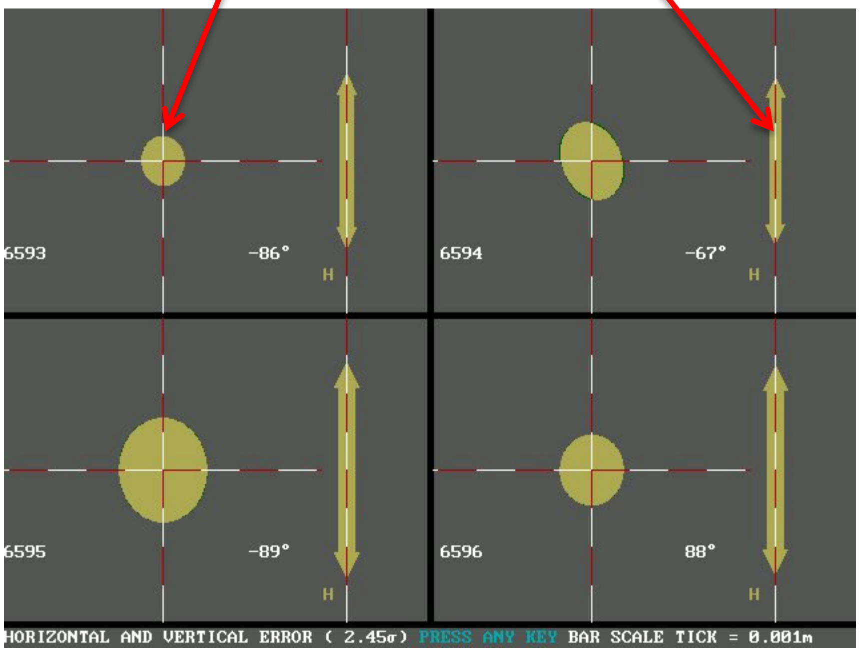
Primary geodetic network at Fermilab



- Provides the basis for construction surveys and for the precision underground control networks
- existing Fermilab control network (accuracy < 2 mm @ 95% confidence level)
  - horizontal geodetic datum = North American Datum of 1983 (NAD 83) based on the reference ellipsoid Geodetic Reference System 1980 (GRS-80)
  - vertical datum = North American Vertical Datum of 1988 (NAVD 88)
  - geoid model = NGS model Geoid93
- includes 3 monuments tied through CORS to Soudan
- add 6 new geodetic monuments (densification around access shafts)
- ~400 GPS, terrestrial and astronomic observations
- error ellipses in millimeter range (@ 95% confidence level)

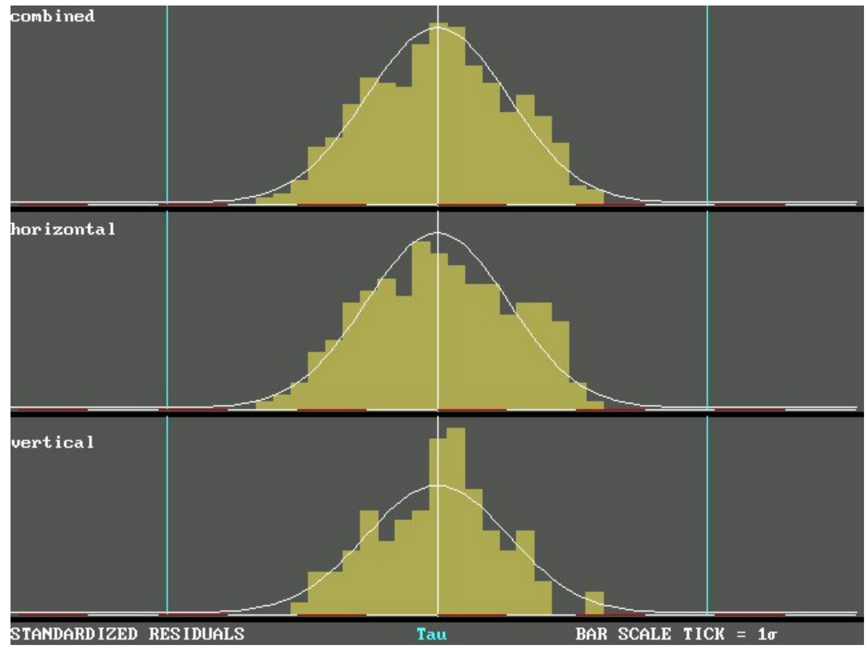
Primary surface geodetic network at Fermilab
Results

Ellipses of Error in x, y plane   Errors in Height



Ellipses of Error @ 95% confidence level

(bar scale tick = 1 mm)



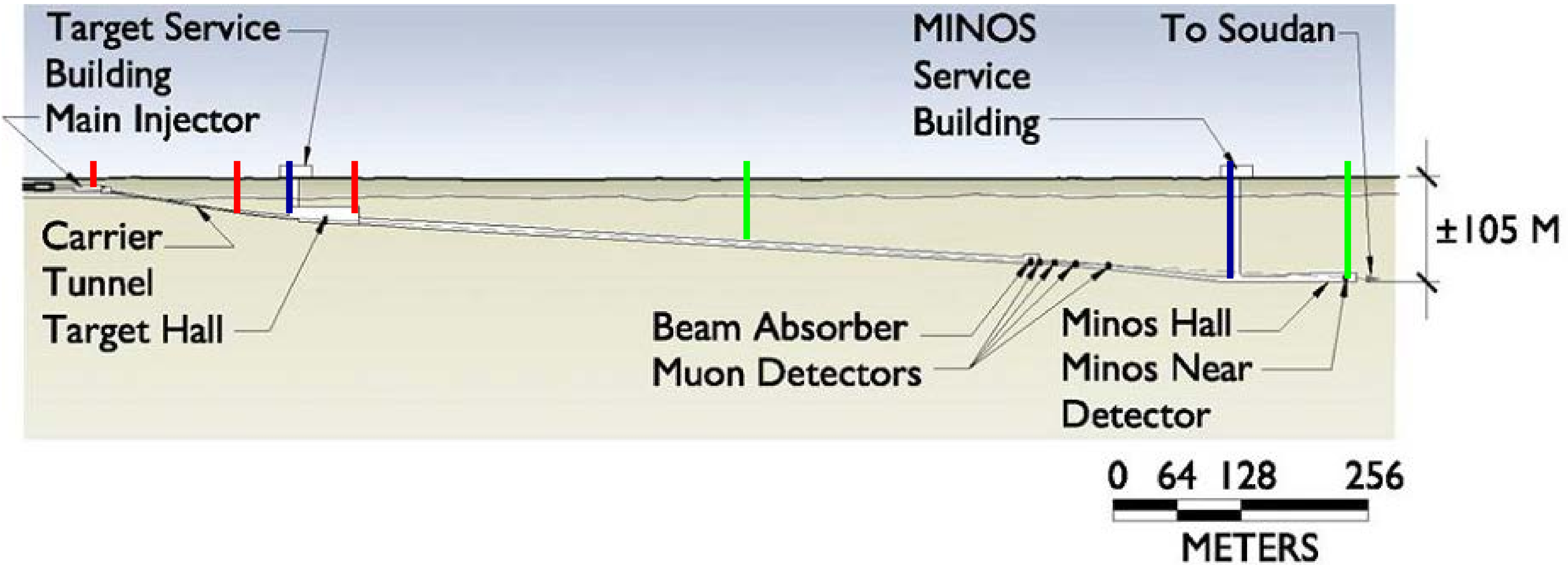
Histogram of standardized residuals

(bar scale tick = 1 σ)

- NuMI surface geodetic network accuracy is shown

Precision underground control networks

- Provided 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)
- Network simulations => 7 locations for transferring coordinates from the surface (3 vertical sight risers, 2 tunnel Access Shafts and 2 Exhaust Air Vent pipes)
- Due to the increased depth of the tunnel, designed adequate procedure for precision transfer of surface coordinates underground

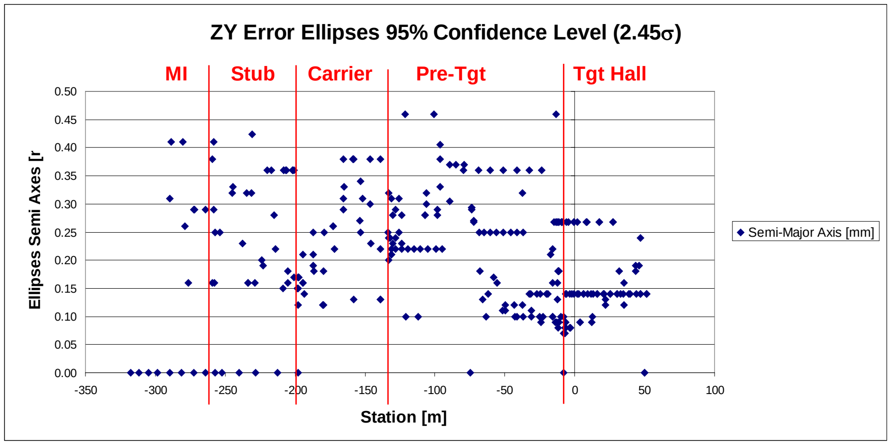


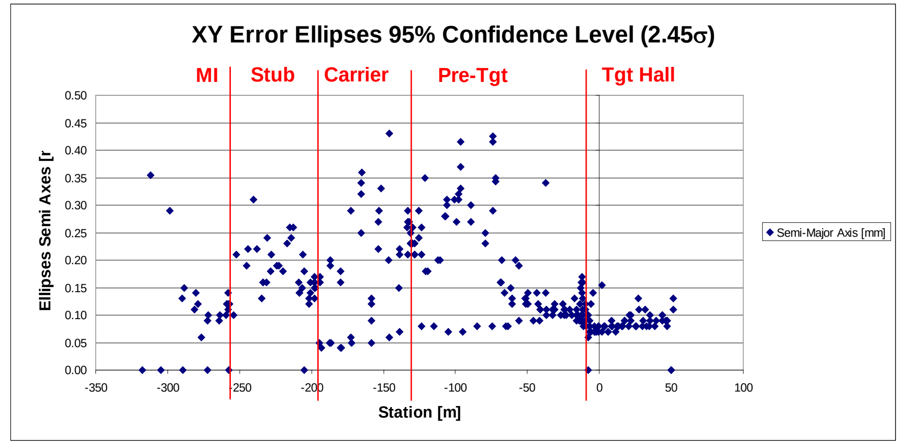
Precision underground control networks

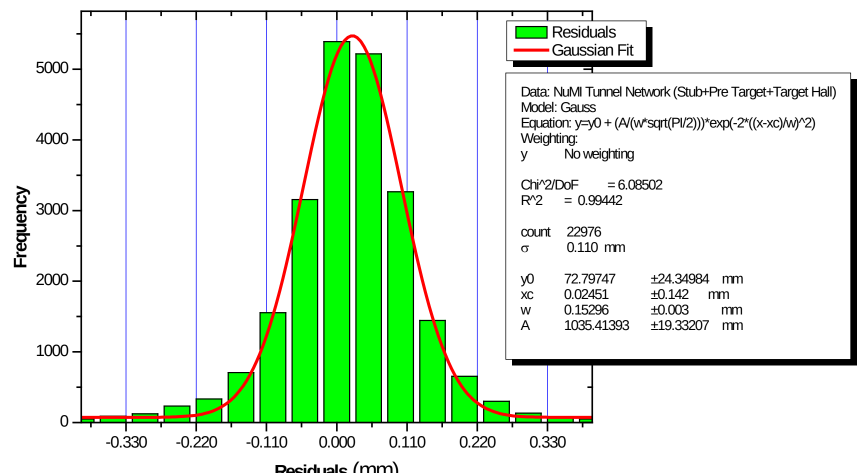
- Built to support the alignment of Primary Beam components, the Target and focusing Horns and the installation of the two Near and Far detectors
- Components alignment scope:
  - Primary beam magnets and instrumentation aligned to ±0.25 mm
  - Target station components aligned to ±0.5 mm
  - Detectors :
    - ➢ determine the relative position of the scintillator modules with respect to each other and the detector structure within ±5 mm
    - ➢ additionally: provided feedback on plane-to-plane movements (lateral drifts, pitch, and warping of the planes)
- Error budget networks requirements ±0.50 mm at 95% confidence level
- Primary Beam network => continuous from MI-60 to the downstream end of the Target Hall + two separate Near and Far detector networks
- Constraints at underground transfer points: sight risers, access shafts and aer exhaust vents
- Network type: Laser Tracker processed as trilateration
- Additional measurements to study and control network behaviour
- Final primary beam trajectory azimuth confirmed by first order Astronomical Azimuth at 0.004 mrad (0.74 arc sec) with s=±0.001 mrad (0.21 arc sec)
- Detectors azimuth confirmed through precision Gyro azimuth to < 0.010 mrad (2 src sec)

NuMI primary beam underground control network
Results

- Errors Ellipses ±0.45 mm and histogram of residuals σ=±0.110 mm at 95% confidence level







(bar scale tick = 1 σ)

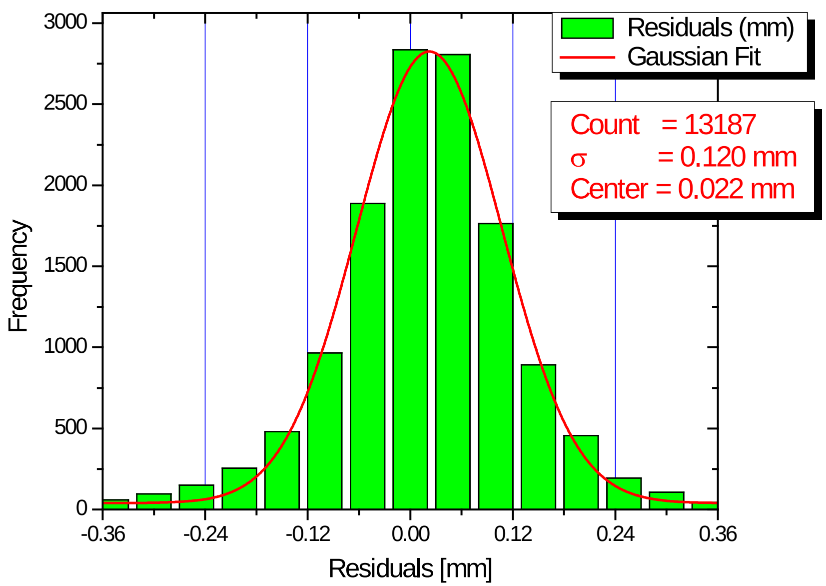
- NuMI underground network accuracy is shown

MINOS detectors underground control networks
Results

- measured with the Laser Tracker and processed as trilateration
- additional measurements to study/control network behaviour and for confirmation:
  Mekometer distances, angles, gyro-azimuths and precision levelling
- network results: relative errors below ±0.35 mm at 95% confidence level

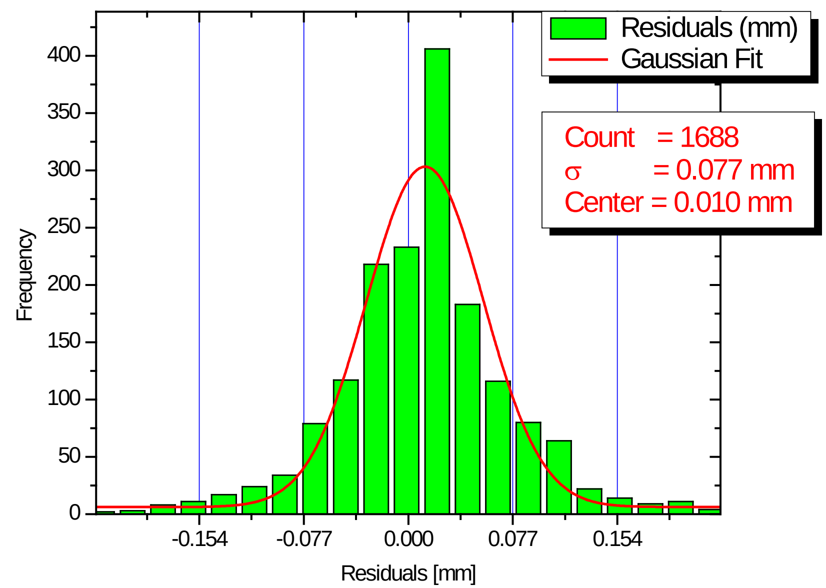
MINOS Far Detector Hall Network

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



MINOS Near Detector Hall Network

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



- MINOS underground network accuracy is shown

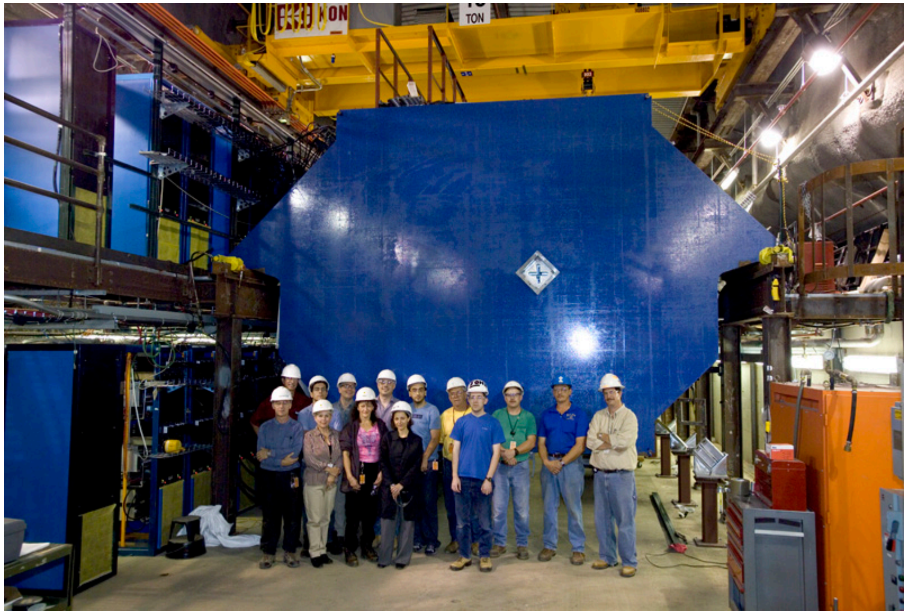
MINOS detectors installation

MINOS far detector:

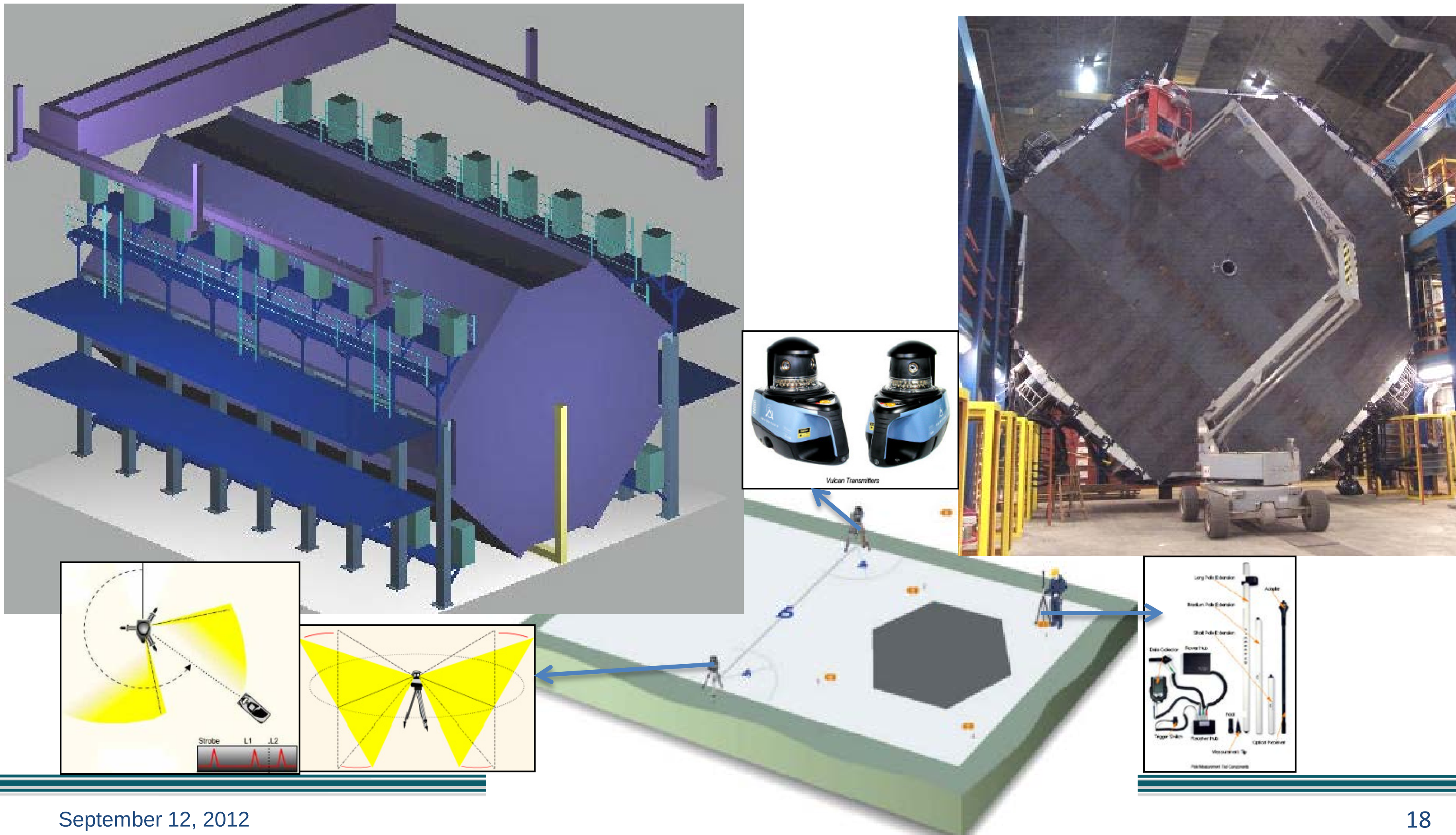
- at Soudan mine
- 5.4 kton tracking calorimeter
- 486 planes (steel and scintillator)
- 8 m wide, octagonal shape
- two super modules
- surveyed with the indoor GPS system: a posteriori accuracy sX =±2 mm, sY =±3.5 mm, **σZ (along the detector) =±6.8 mm**

MINOS near detector:

- at Fermilab
- 980 tons (smaller version)
- 282 planes (steel and scintillator)
- 3.8x4.8 m, "squashed octagon"
- reference for the far detector
- surveyed with the Laser Tracker: a posteriori accuracy σX, Y, **Z (along the detector) =±1 mm**



Surveying MINOS Far Detector with Indoor GPS (conceptual setup)



MINOS TOF distance summary

- The MINOS TOF distance from the front plane of the Near Detector to the front plane of the Far Detector:

$$D = 734286.898 \text{ m} \pm 0.5 \text{ m}$$

- In the error budget analysis, the accuracy of determining this distance is preponderantly being driven by the uncertainty of the Inertial Measurement System instrument used to tie the precise geodetic network on the surface and the underground control used to support the installation of the Far Detector.

- As reported by the contractor who performed the survey (The Department of Geomatics Engineering from the University of Calgary), the computed accuracies were 0.48 m, 0.20 m and 0.23 m in latitude, longitude and height, respectively, where the 0.48 m on latitude is dominant since the beam points almost North.

Backup slides