STATUS REPORT ON THE GEODETIC AND ALIGNMENT EFFORTS FOR THE NUMI PROJECT AT FERMILAB

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ABSTRACT

The discovery of neutrino oscillations was the first experimental proof that the Standard Model of particle physics is incomplete. The Neutrinos at the Main Injector (NuMI) and the MINOS experiment will perform the first high-precision measurements of the physics parameters, guiding and directing future research. The success of the experiment depends on precise, accurate surveying and alignment of the beamline, especially the production target, magnetic focusing elements, decay pipe, and the two detectors.

This paper reviews the concepts, methodology, implementation, and current results of the geodetic surveying and precise positioning efforts necessary for the construction, installation, and alignment of the NuMI particle beamline and the two MINOS detectors.

1. INTRODUCTION

Scientists from Fermilab and many other U.S. and foreign institutions are searching for non-zero neutrino mass by looking for neutrino oscillations. The Neutrinos at the Main Injector (NuMI) project, as an important part of the neutrino research program at Fermilab, has built a new particle beamline, Figure 1, to direct a nearly pure beam of muon neutrinos from the Main Injector toward both nearby and far-off particle detectors capable of recording all three types of neutrinos. The 120 GeV protons from the Main Injector will produce a neutrino beam of sufficient intensity and energy so that experiments capable of detecting muon neutrino to tau neutrino ($\nu_\mu \rightarrow \nu_\tau$) or electron neutrino ($\nu_\mu \rightarrow \nu_e$) oscillations are feasible.

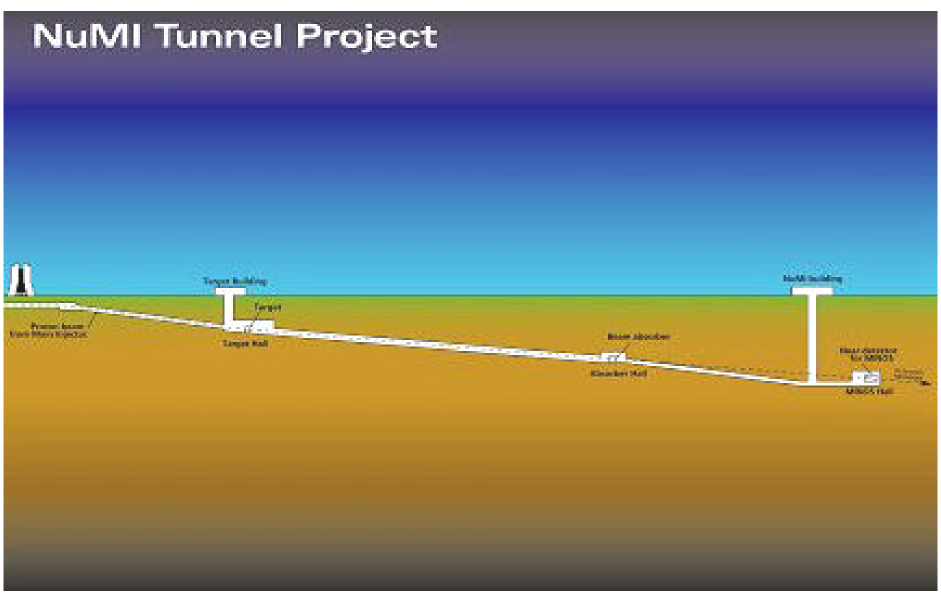


Figure 1

The 120 GeV primary proton beam is extracted from the Main Injector ring and, after being transferred through the MI-60 extraction enclosure, is focused and bent by 9^0 downward through a steeply inclined carrier pipe to the pre-target and target regions located deep underground in newly excavated caverns. In the pre-target another set of bend magnets brings the protons to the correct targeting angle directed toward the target and the experiment. As the targeting is at zero degrees, the proton beam at the target must be aimed precisely at the MINOS far detector. Figure 1 shows a diagram of the NuMI project tunnels and halls.

The primary proton beam from the Main Injector is transformed into a beam of neutrinos through a three-step process. Protons strike a target to produce short-lived hadrons which are focused by devices called horns, that produce intense magnetic fields towards the neutrino experimental areas. As the hadrons travel through a long evacuated pipe, a fraction of them decay to neutrinos and muons. At the end of the pipe the remaining hadrons are absorbed in a beam stop while neutrinos, which are weakly interacting particles, continue through the hadron absorber and the earth to the MINOS experimental areas.

As a part of the NuMI project, the MINOS (Main Injector Neutrino Oscillation Search) experiment is designed to search for neutrino oscillations with sensitivity significantly greater than has been achieved to date. The MINOS experiment utilizes two detectors: the "near" detector is located close to the neutrino source (1 km away from the target), and the "far" detector is 735 km away, in a deep underground mine in northern Minnesota where, 710 meters below the surface, a massive magnetized iron and scintillator calorimeter has been built in a new cavern at the Soudan Laboratory.

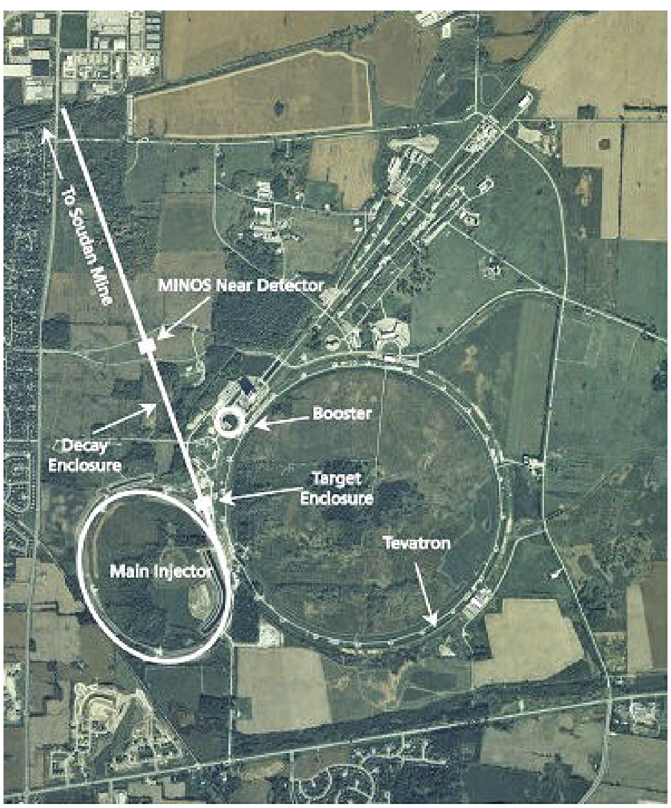


Figure 2

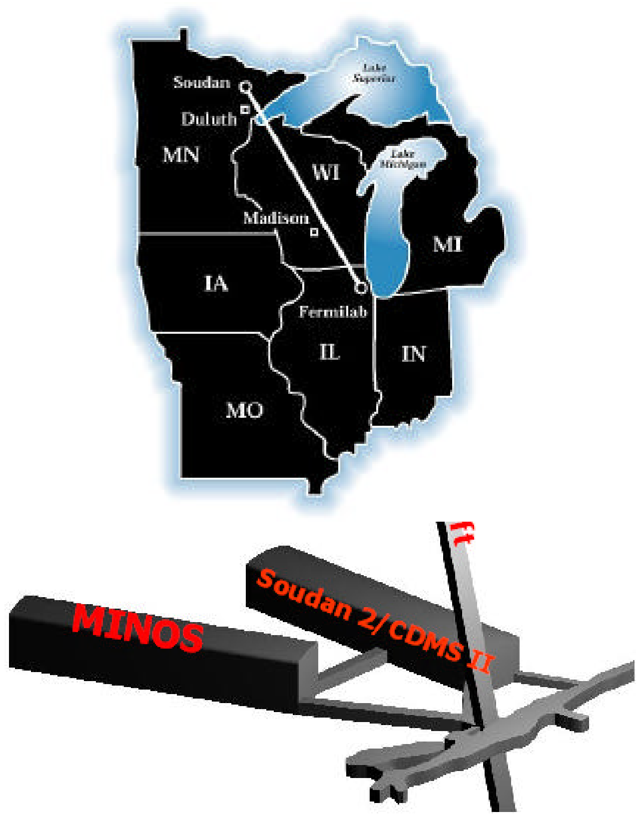


Figure 3

Figures 2 and 3 show an aerial photograph of the Fermilab site with the NuMI beamline superimposed, and the trajectory of the neutrino beam between Fermilab and Soudan and a perspective view of the MINOS cavern at the 27th level of the Soudan mine.

2. ALIGNMENT TOLERANCES

The correct aiming of the beam towards the underground detector located 735 km away in the northern Minnesota Laboratory is of vital importance for the MINOS experiment. Absolute and relative tolerances for directing the beam are driven by physics requirements.

Although the divergence of the neutrino beam at this distance is rather large (kilometers wide) for low energies, the neutrino energy spectrum test is much more demanding. It requires that the combined effect of all alignment errors must cause less than 2% change in any 1 GeV energy interval in predicting the far detector energy spectrum (without oscillations) from the measured energy spectrum in the near detector. To accomplish this, the neutrino beam center must be within ± 75 m from its ideal position at the far detector, corresponding to an angular error of $\pm 10^{-4}$ radians (21 arc seconds). The primary proton beam must be pointed within ± 12 m from the center of the far detector, corresponding to an angular error of $\pm 1.63 \times 10^{-5}$ radians (3.4 arc seconds). Achieving this tolerance requires knowledge of the geometry of the neutrino beam. Table 1 lists alignment tolerance requirements for the Low Energy beam. [1]

Table 1

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 monitor	± 25 mm
Muon Monitors	± 25 mm
Near Detector	± 25 mm
Far Detector	± 12 m

3. DETERMINATION OF THE GLOBAL POSITIONS

The geometric parameters of the beam trajectory, expressed in terms of the azimuth and the slope of the vector joining the two sites, are essential for the civil engineering work (NuMI tunnels and halls) and for the NuMI beam lattice design. They require precise knowledge of the absolute positions of the two ends of the vector.

Between 1992 and 1999, several geodetic determinations of the absolute and relative position of the Fermilab target and the Soudan, MN detector were carried out. This geodetic process was meant to ensure the refinement of the geodetic orientation parameters of the beam and to lead to a more rigorous solution.

The ultimate geodetic coordinates resulted in 1999 from precise GPS determinations of several stations belonging to the Fermilab and Soudan networks in conjunction with the national CORS (Continuously Operating Reference Station) system, Figure 4. [2] The NGS provided an independent solution in the ITRF96 reference system, which was then transformed in the NAD 83 system. [3] The agreement between the NGS result and the method of analysis at Fermilab was excellent. The Fermilab to Soudan surface vector, averaged over the period of three days 9-10 hours observations sessions, is known to better than 1 cm horizontally and vertically, well within requirements. The position of the 27th level at the bottom of the Soudan mine relative to the surface geodetic frame was determined through an extensive inertial survey. Together they provide a robust solution for the end points of the vector for computing the final beam orientation parameters for the NuMI project. The final geodetic coordinates, and the beam orientation parameters computed in the absolute geodetic system, were then transformed in the Fermilab Main Injector Local Tunnel Coordinate System (LTCS), Figure 5. Those coordinates constituted the basis for developing a high accuracy local network for supporting the construction and installation of the NuMI beam.

Figure 4

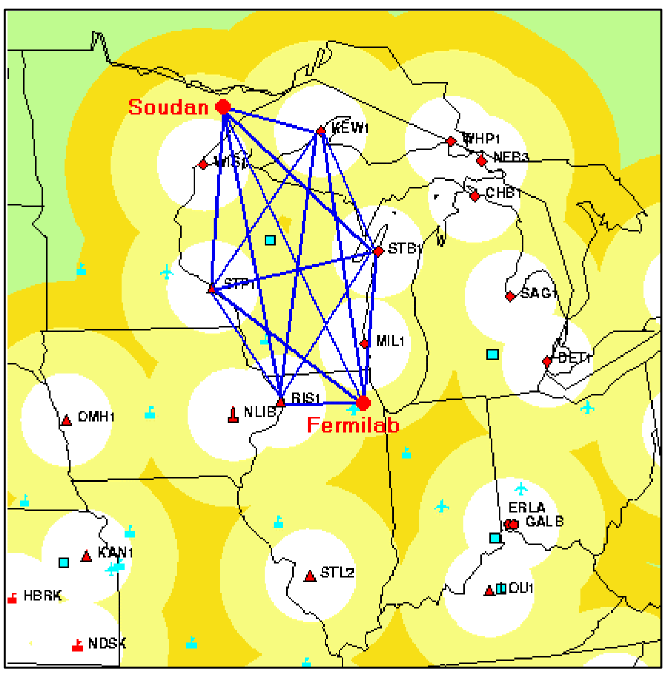
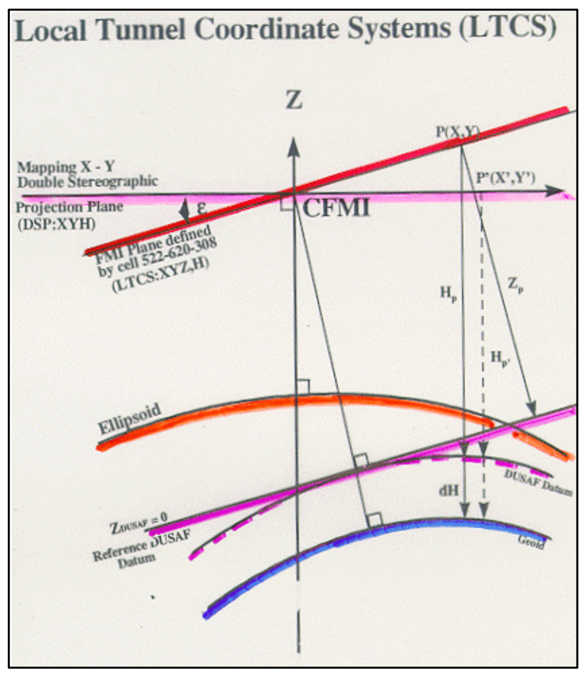


Figure 5



4. PRIMARY GEODETIC NETWORK FOR NUMI AT FERMILAB

The geodetic reference for the supporting the construction and positioning of the NuMI project derived from a high accuracy local surface network. The existing Fermilab/ Main Injector master control network, which has a relative positional accuracy better than 2 mm, included the monuments surveyed during the CORS ties campaign, and was supplemented with six geodetic monuments, providing densification around the tunnel access shafts. Figure 6 shows a simplified version of the network geometry.

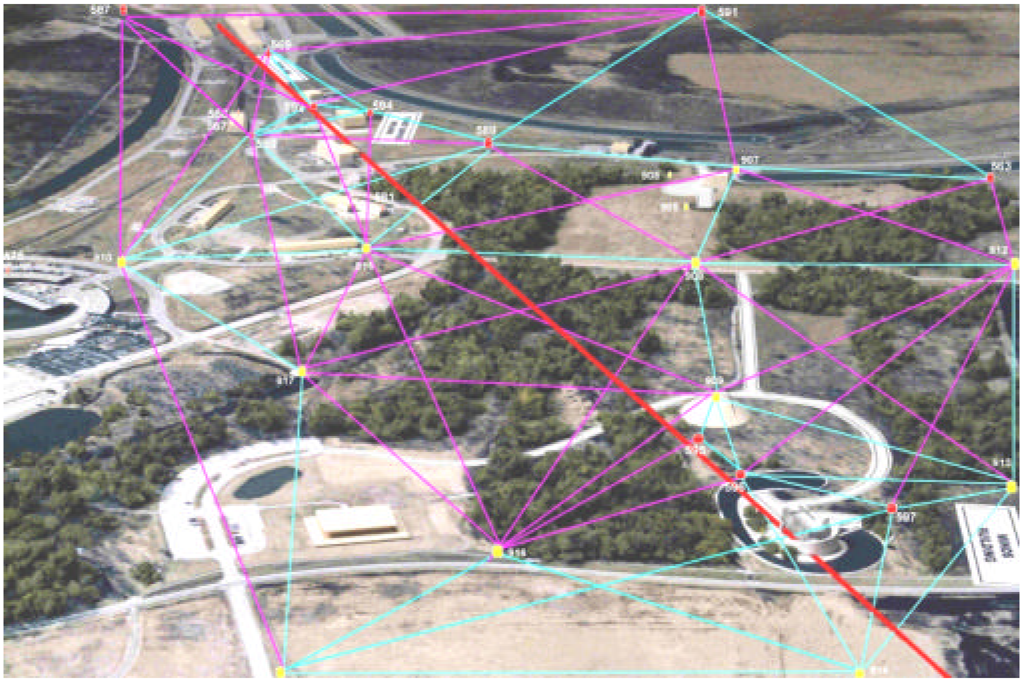


Figure 6

The NuMI absolute positioning tolerance requirements called for extensive combined GPS, terrestrial, and astronomic surveys, which took place in 2001-2002. The computations were performed in North American Datum 1983 (NAD 83) horizontal geodetic datum, which uses GRS-80 as the reference ellipsoid. The minimal constraint adjustment consisted of 410 observations and yielded absolute error ellipses in millimeter range at the 95% confidence level, Figure 7. A histogram of the standardized observation residuals is shown in Figure 8.

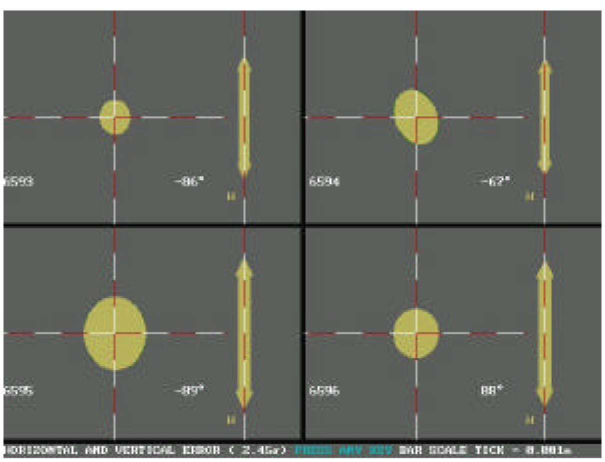


Figure 7 (bar scale tick = 0.001 m)

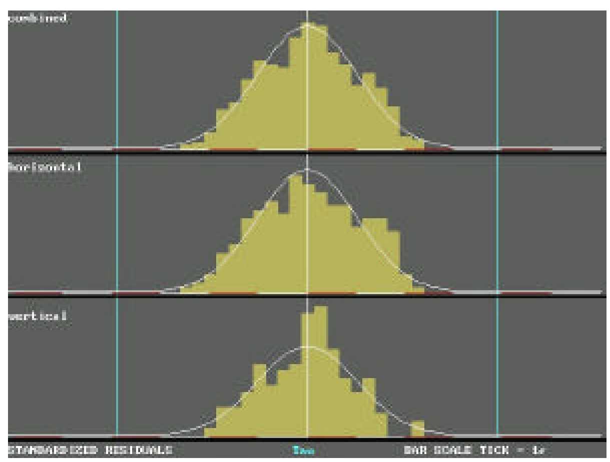


Figure 8 (bar scale tick = 1 σ)

A constraint adjustment was performed holding fixed the horizontal coordinates of the monuments determined during the ties to Soudan mine through CORS, including the ellipsoidal and orthometric height of three vertical points. The NGS Geoid-93 model was used in the adjustment. The levelling campaign adjustment yielded a precision of ± 0.58 mm/km double-run and had ties to the National Geodetic Vertical Datum 1988 (NAVD 88) through a ± 0.96 mm/km double-run survey to three Second Order Class I NGS vertical benchmarks.

Precise astronomical azimuth determinations were performed in April 2001 on two FMI geodetic monuments surveyed during the CORS campaign. Those monuments, with wide visibility over the NuMI upstream area covering the entire beamline, were used extensively during the project as reference control, among others, for transferring absolute coordinates from the surface into the underground tunnels and halls. They also served as a calibration baseline for the DMT-Gyromat2000 precision gyro-theodolite. The standard deviation of the azimuth over three nights of observations was 0.66 arc seconds. The difference between the geodetic azimuth of the line and reduced geodetic azimuth from astronomic azimuth and Laplace correction provided by Deflec93 was 0.86 arc seconds. As an additional check, the difference between the direct and reverse astronomic azimuths verifies Clairaut's equation ($dA = d\lambda \cdot \sin\phi_m$).

5. GEOID CONSIDERATION

The vertical alignment of the beamline components along the vector joining the two sites relies on levelling measurements, which use as vertical reference surface the geoid (the equipotential surface of the Earth's gravity field at the mean sea level). Parameters describing the earth's gravity field are most commonly used to determine the general shape of the geoid over a large area. Even if the non-homogeneity of the earth and the surrounding the Fermilab topography do not change dramatically enough to raise major concerns for distortions of the gravity equipotential surfaces, for the purpose of aiming the neutrino beam correctly, it is important to have rather exact knowledge of the gravity vector at the origin and local variations in the gravity field have to be considered. Another reason is to determine precisely the magnitude of corrections that will compensate for deflections from the vertical.

As a starting point, because the NuMI beamline originates from the Main Injector, we used the study of the local geoid model covering the Fermilab area developed in the mid-1990s, when we determined the exact spatial geometric interrelationship between the Tevatron and the new Main Injector accelerators. With both high precision GPS and geodetic levelling measurements available for a rather large number of monuments covering the site, the geoid height at those points was calculated differentiating between GPS ellipsoidal height and the orthometric height from geodetic levelling. The local geoid model then used a best fitting surface employing a second order polynomial and a spline function to compute heights at other points where surveying data was not available. The results show that the accuracy for computing relative geoid heights and the two components of the deflection from the vertical were in the range of ± 3 mm, and respectively ± 0.1- 0.2 arc seconds with respect to the local origin.

The local geoid model was compared with the Geoid93 model provided by the National Geodetic Survey (NGS). Based on over 1.8 million terrestrial and ship gravity values, the model uses a Fast Fourier Transform (FFT) method to compute the detailed geoid structure which, combined with an underlying OSU91A geopotential model, produces a geoid height grid with a 3' X 3' spacing in latitude and longitude referred to the Geodetic Reference System 1980 (GRS 80) normal ellipsoid. The values for the intermediary points are then interpolated by using a locally fit biquadratic function. NGS estimates that the comparison of Geoid93 model with combined GPS and levelling yields roughly a 10-cm accuracy (one sigma) over length scales of 100 km, but better accuracy is expected over shorter lengths.

The comparison between the two models shows differences up to 5 mm, consistent with the expected values. Furthermore, this is also an indication that are no local gravity anomalies (local variations in the gravity field) un-modelled by the national model for this area, at least at this sensitivity level.[4] The NuMI beamline finds itself in the 1.5 mm range of those differences, well within the estimated accuracy for the local or the national geoid models. The national geoid model was considered sufficient to cover the tolerance requirements for the project. As a result, the Geoid93 and Deflec93 provided by NGS were used in our geodetic computations. A 3-D plot of the difference between the two models is presented if Figure. 9, and the differences in latitude and longitude are shown in Figures 10 and respectively 11.

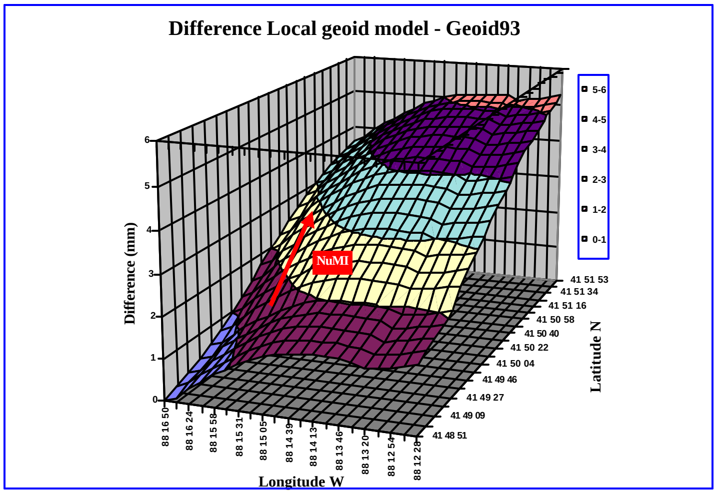


Figure 9

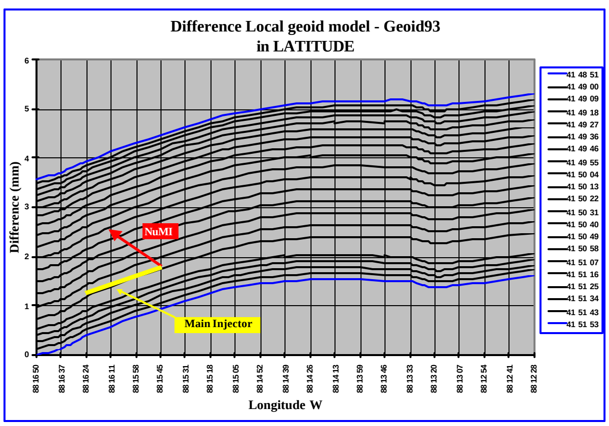


Figure 10

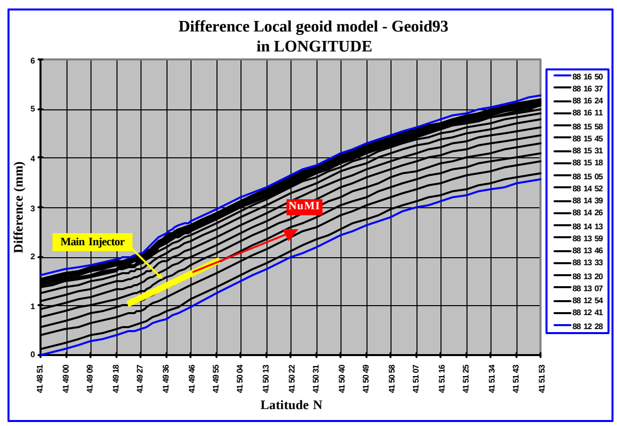


Figure 11

6. HIGH ACCURACY UNDERGROUND CONTROL NETWORK

NuMI is mainly sensitive to the final primary beam trajectory. Therefore a major requirement for the beamline components, target, and horn alignment is to minimize the relative errors. This called for a high accuracy underground control network with strict tolerances, which makes it possible to establish relative component positions to ±0.35 mm (1σ) throughout the extraction enclosure, transfer tunnels, and Target Hall. It is also the basis for a dynamic monitoring system for relative position checks on components.

Network simulations of different models led to the design of an optimum number and location of three vertical sight risers which, together with two tunnel Access Shafts (at Target

Hall and near detector MIINOS Hall) and two Exhaust Air Vent pipes, raise the number of points used for transferring coordinates from the surface geodetic control network to seven. Those points provided azimuth constraints, concurrently controlling the scale of the network.

The configuration of the underground network is of longitudinal type, limited by the shape and the geometry of the tunnels and halls. Studies carried out led to a framework system based on chains of polygons. To improve the isotropy of the network and compensate the weaknesses caused by the poor ratio between the sides of polygons, additional measurements spanning adjacent polygons were added. Redundant observations were needed to ensure quality and uniformity of accuracy. The network was materialized by monuments permanently imbedded in the enclosures floor, alternating with monuments rigidly attached to walls for improving the overall spatial geometry.

The underground control networks were measured with the Laser Tracker and processed as three-dimensional trilateration networks (distances derived from Laser Tracker observations) "sitting" on the vertical datum provided by precision underground levelling. Other types of observations included Mekometer distances, precision angles, and gyro-azimuths measured over long underground baselines, which provided additional information to: control the scale in the unstable underground environment, and respectively to study the behaviour (tendency to bow) of the network during adjustment, and to check the azimuth of the adjusted coordinates.

Between 2001-2004, based on the installation schedule, the underground networks for the MINOS far detector in the Soudan mine, and the MINOS near detector and the NuMI beamline at Fermilab were measured several times for maintenance and monitoring purposes. We obtained consistently throughout the network relative errors between control points below ±0.35 mm, at 95% confidence level. Figures 12 and 13 show the distribution of the standardized observation residuals for the Target Hall/Pre-Target tunnel and for the MINOS near detector networks.

Figure 12

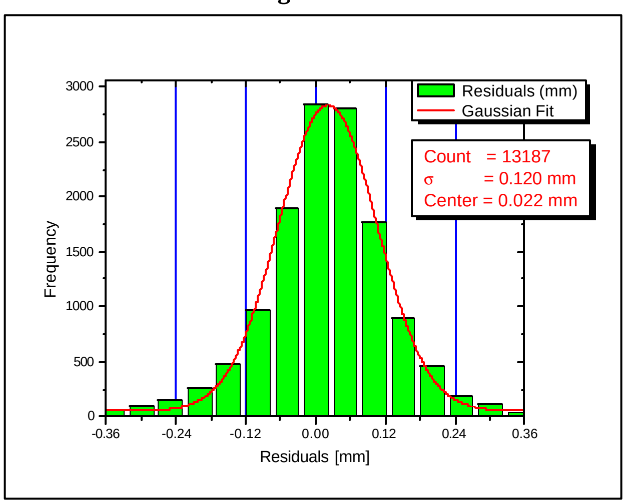
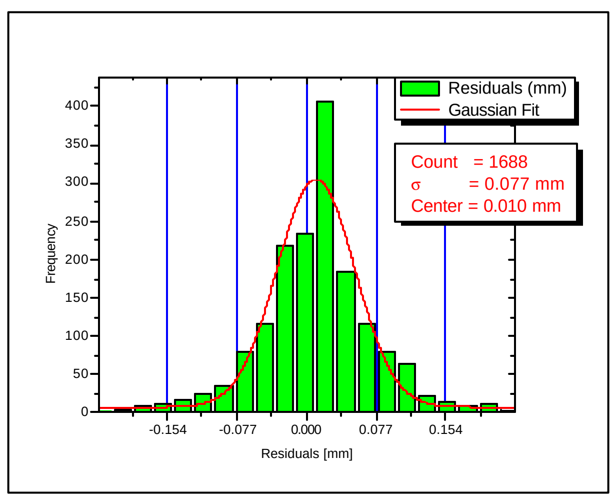


Figure 13



Currently, the last determination of the entire underground network for the NuMI project before the final alignment of all beamline components ands instrumentation, the target and two focusing horns is close to completion.

7. MINOS DETECTORS INSTALLATION AND INDOOR GPS

The MINOS far detector, installed in a new underground laboratory in the Soudan mine, is a massive 5.4 kton tracking calorimeter, assembled in two supermodules, built from 486 steel and scintillator octagonal planes, 8 m wide, Figure 14. The MINOS near detector, installed in the new underground hall at Fermilab, serves a reference/calibration for the far detector and has the same basic construction, sampling and response. Built a smaller version one of the far detector supremodule, it weights 980 tons and was assembled from 282 steel and scintillator planes shaped as a "squashed octagon", 3.8x4.8 m, Figure 15. While horizontally the axes of both detectors are collinear with the beam, the planes are suspended vertically in large arrays, therefore they follow the local gravity vectors of each of the two sites.

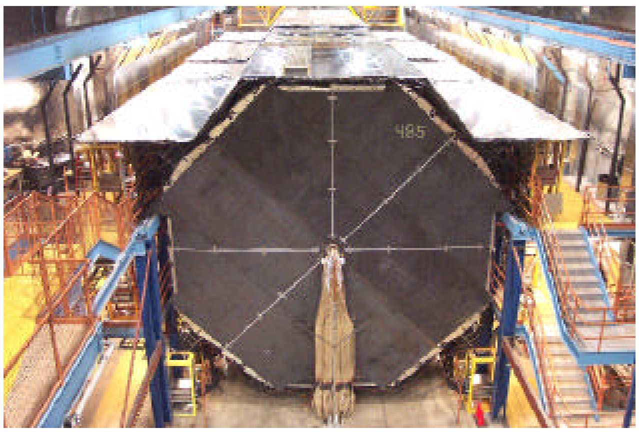


Figure 14

Figure 15

Underground control networks, established in both near and far experiment halls, provided the local reference frames in which the detectors were constructed and supported the installation and alignment of the detectors components. The networks where tied to the surface geodetic control, then additional precision gyro-azimuth measurements were performed for confirming the orientation of the detectors axes with the NuMI beam.

Because of personnel constraints and budget limitations the Fermilab Alignment Group could not support the construction of the MINOS far detector in Soudan, Minnesota on a daily basis. As a result, we proposed that physicist collaborators present on site survey the components of the detector using a fairly new technology, the indoor GPS Vulcan 3D Measurement System.

The indoor GPS Vulcan system, Figure 16, measures the position of an optical receiver by means of a pair of internal photodiodes, which sense laser light diffused from a pair of transmitters (in 2001 the system supported only two transmitters). Each transmitter generates three signals: two infrared laser rotating fanned beams, tilted –30 deg and +30 deg with respect to vertical, and an infrared LED strobe, Figure 17. These optical signals are converted into timing pulses by the photo detectors. The speed of rotation of the head, which is set independently at each transmitter, is continuously tracked and is used to convert the timing intervals into angles, Figure 18. [5]

As in satellite-based GPS, a one-way signal path is created continuously from each transmitter to the receiver, allowing to calculate a point positioning solution whenever two or

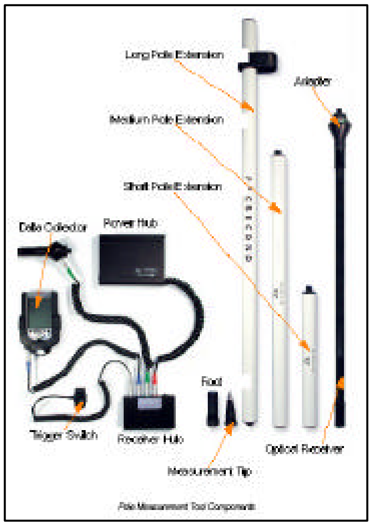


Figure 16

more transmitters are in view. A transmitter creates one-way position information: the relative azimuth and elevation from the transmitter to the receiver. With the addition of a second transmitter of known location and orientation, the 3D position of the receiver in the local coordinate system can be calculated by triangulating the position of the optical detectors relative to the transmitters.

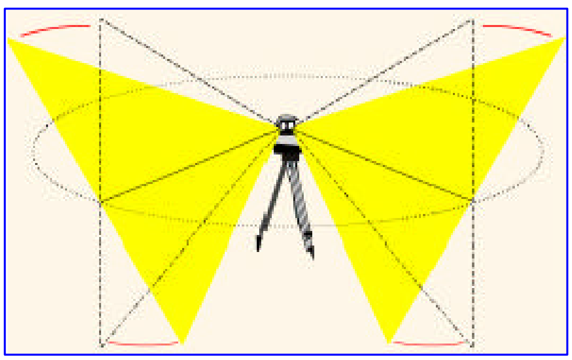


Figure 17

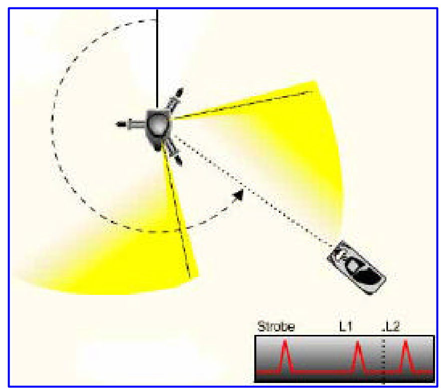


Figure 18

Optimum system performance is obtained by positioning the transmitters to ensure good triangulation geometry to the desired observation point in the work area. The transmitters have to be positioned in an approximately 90° convergence angle at the center of the measurement area, and also to ensure that all measurements lie within the work volume for which the system calibration was performed. The nominal precision of the Vulcan system was 1–2 mm, depending on the distance and orientation of the receiver to the transmitters.

The Vulcan system defines its own local 3D Cartesian coordinate reference frame but, if during calibration measurements are collected on at least four known control points, it employs a least-squares algorithm to best fit the transmitters into the control reference frame. Since the system performance relies on the accuracy of the control points, as well as the location and geometry of those points relative to the transmitters and work area, we established our network points within a local accuracy was ± 0.2–0.3 mm on each axis, and distributed homogenously throughout the experiment hall (in the floor, walls and, for the purpose monitoring the structure, on the support columns). Figure 19 and 20 shows a conceptual setup of the Vulcan system.

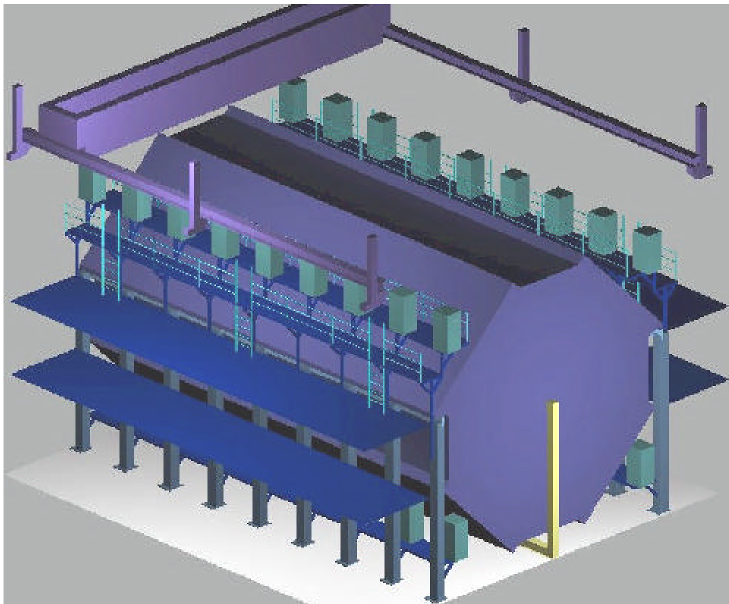
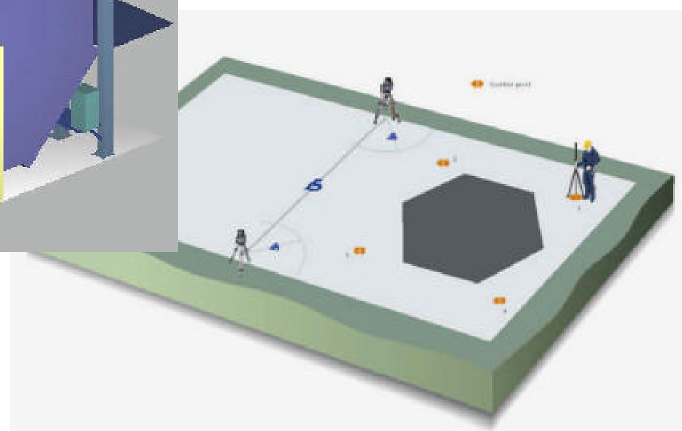


Figure 19



The survey of the far detector was originally envisioned to determine the position of the scintillator modules with respect to each other and the structure of the detector within a tolerance of 5 mm. A second reason was to monitor the positioning of the detector components as they are installed, providing continuing feedback on the erection of detector planes. After erecting the first few planes, it became apparent that the Vulcan system could also be used to provide feedback on plane-to-plane movements; in particular information was sought on the lateral drifts and warping of the planes. Comparing collars, axial bolts, and support "ears" data a detailed assessment could me made about the drift, pitch, and the warping of the planes. Feedback was provided weekly in the form of collar and axial bolt position plots, which allowed the mine crew to successfully shim and grind the collar and axial bolts to keep the detector growing straight.

Figure 20

The uncertainty due to the survey in the module data was investigated using cosmic ray muon tracks. An analysis of the scintillator strips measured any offsets in the real placement of scintilator modules from their assumed locations and estimated a 3-4 mm error per point in the x-y plane (transversal). [6]

A comparison of the Vulcan measurements with the Laser Tracker was made in December 2001 during a quality control campaign to Soudan Laboratory. While the residuals of fitting to the Laser Tracker control were 1 mm or below, the r.m.s errors in x, y, z were 2.0 mm, 3.5 mm, and 6.8 mm respectively for the points surveyed on the detector. Because of the placement and orientation of the transmitters, the z coordinate (along the detector) is expected to have the greatest uncertainty. The precision of the Vulcan was found to be in the range required for the construction of the MINOS detector. All assessments of the Vulcan indoor GPS indicated a good overall performance and that it was an appropriate system for measurements on the MINOS detectors during their construction. [7]

The construction, installation and alignment of the MINOS near detector were fully supported by the Fermilab surveyors. Building upon the experience gained from the far detector, we developed a surveying strategy based on a combination of the Vulcan indoor GPS system, a fixed laser targeting system, and the Laser Tracker, which proved to be very efficient. The Vulcan and the fixed laser targeting systems were used to survey the planes and scintillator modules, and the collars (which alignment requirements were more stringent this time) respectively as they were installed. The Laser Tracker was used for quality assurance, performing an overall survey weekly, with overlap into the previous week survey. This allowed making continuous assessments on the deformation of the supporting structure as it became loaded with more detector planes. Feedback was also provided weekly in the form of position plots, which provided the installation crew with minor corrections to keep the detector growing straight.

8. CONCLUSIONS

Since 1992, from the conceptual design for the NuMI project, and up till now, only months away from commissioning, the Fermilab Alignment and Metrology Group has put a considerable amount of effort and expertise into designing, developing and implementing geodesy and industrial alignment procedures to support the construction and installation of the project and achieve the precise global and local positioning requirements.

The geodetic orientation parameters of the beam, based on the absolute and relative positions of the target at Fermilab and the far detector at Soudan, MN, have been determined with GPS to a high level of accuracy in conjunction with the national CORS network. All other geodetic aspects related to the project (i.e. local geoid modelling, deflection from the vertical, differential tidal variations, plate tectonics and point velocities, precise azimuth determination) have been resolved and confirmed. Between 2000-2003, during the of civil construction phase of the underground tunnels and halls, the group ensured the surveying quality control aspect for the project. High accuracy local geodetic networks and underground networks have been established to support the installation and alignment of the NuMI beamline, neutrino beam devices and the two detectors.

At present, all the beam components, the target module and two horns have been installed and “pre-aligned”, the construction of both detectors is completed, and the installation of the neutrino beam monitoring system is underway. The final alignment of the NuMI beamline will take place during the current shutdown and the NuMI project will enter the commissioning phase in December 2004 and will be delivered to experimenters in March 2005.

9. REFERENCES

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