GEODETIC DETERMINATIONS FOR THE NuMI PROJECT AT FERMILAB

Virgil Bocean, Fermi National Accelerator Laboratory

ABSTRACT

As a part of the Neutrinos at the Main Injector (NuMI) project, the MINOS experiment will search for neutrino mass by looking for neutrino oscillations. The project plans to direct a beam of muon neutrinos from the Main Injector towards both nearby and far-off detectors capable of counting all three types of neutrinos.

The beam will travel 735 km through the Earth towards a remote iron mine in northern Minnesota where, 710 m below surface, a massive 5400 metric tons detector will be built. For the neutrino energy spectrum physics test to work properly, the primary proton beam must be within ± 12 m from its ideal position at Soudan, MN, corresponding to ± 1.63 x 10-5 radians, i.e. 3.4 arcseconds. Achieving this tolerance requires a rather exact knowledge of the geometry of the beam, expressed in terms of the azimuth and the slope of the vector joining the two sites.

This paper summarizes the concepts, the methodology, the implementation, and the results of the geodetic surveying efforts made up to date for determining the absolute positions of the Fermilab and the Soudan underground mine sites, from which the beam orientation parameters are computed.

1. Introduction

The Neutrinos at the Main Injector (NuMI) project is a very important part of the neutrino research program at Fermilab. Fermilab's new particle accelerator, the Main Injector, is able to provide high intensity and high duty cycle extracted beams for fixed target experiments. The Laboratory plans to construct a new particle beamline 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.

Scientists from Fermilab and many other U.S. and foreign institutions are searching for non-zero neutrino mass by looking for neutrino oscillations. 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. The experiment that will make use of the NuMI beam is called MINOS, which stands for Main Injector Neutrino Oscillation Search. MINOS 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 will be located close to the neutrino source, about 1 km away from the target. An aerial photograph of the Fermilab site with the proposed beamline superimposed is shown in Figure 1. The "far" detector will be 735 km away, in a deep underground mine in northern Minnesota where, 710 m below surface, a massive 5400 metric tons magnetized iron and scintillator calorimeter will be built in a new cavern at the Soudan Laboratory. The trajectory of the neutrino beam between Fermilab and Soudan is shown in Figure 2, while Figure 3 and 4 show a perspective view of the MINOS cavern at the 27th level of the Soudan mine, and respectively a sketch of the MINOS "far" detector.

Figure 1. Aerial view of Fermilab and the proposed NuMI beamline

Figure 2. Trajectory of the neutrino beam

In NuMI, the neutrino beam and its properties at the two widely separated locations will be carefully measured, using the same beam and detectors as similar as possible. If at the "far" detector is found a changed mixture of neutrino flavors some of the muon neutrinos in the beam must have oscillated to the other flavors, therefore neutrinos must have non-zero mass. The experimenters will measure the oscillation parameters with high precision and also determine the oscillation modes.

2. Geodetic Concepts

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

Although the divergence of the NuMI beam at this distance is several kilometers wide for low neutrino energies, the neutrino energy spectrum test, which has the potential to measure oscillation parameters, is much more demanding. The neutrino energy spectrum test for

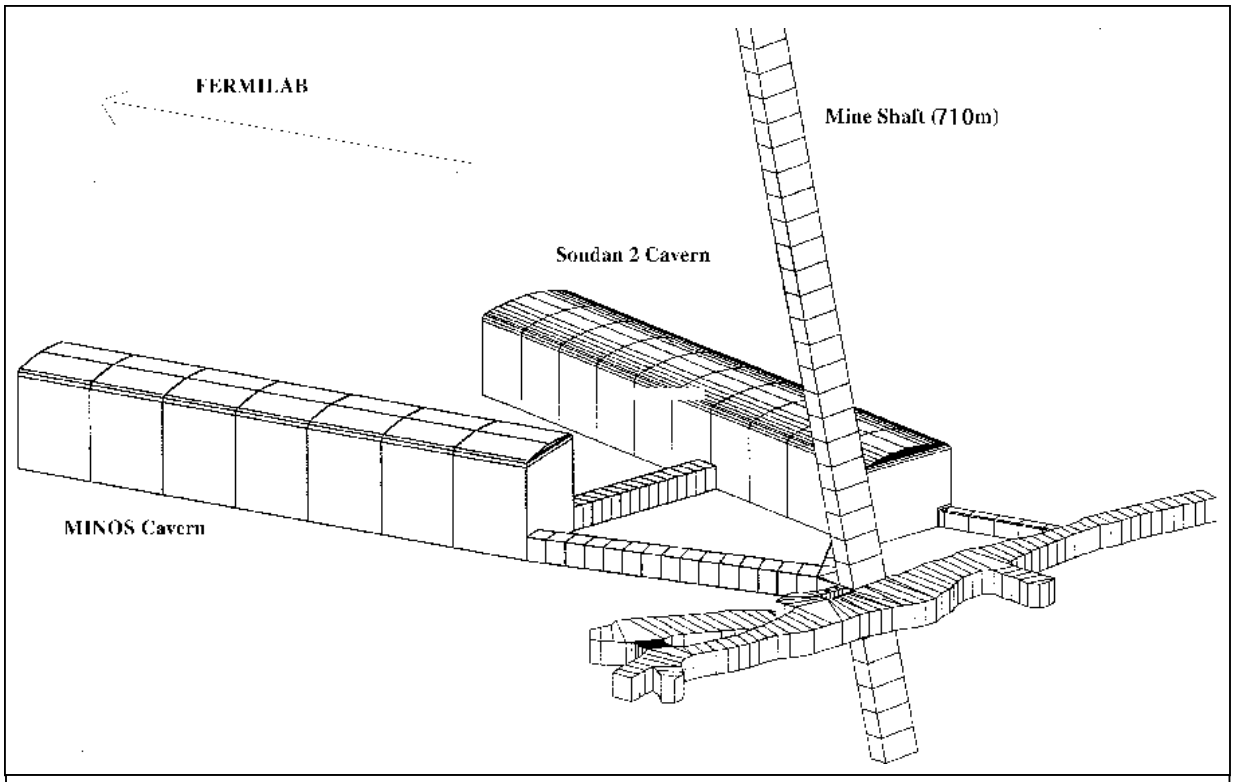

Figure 3. Perspective view of MINOS caverns at the 27th level of the Soudan mine.

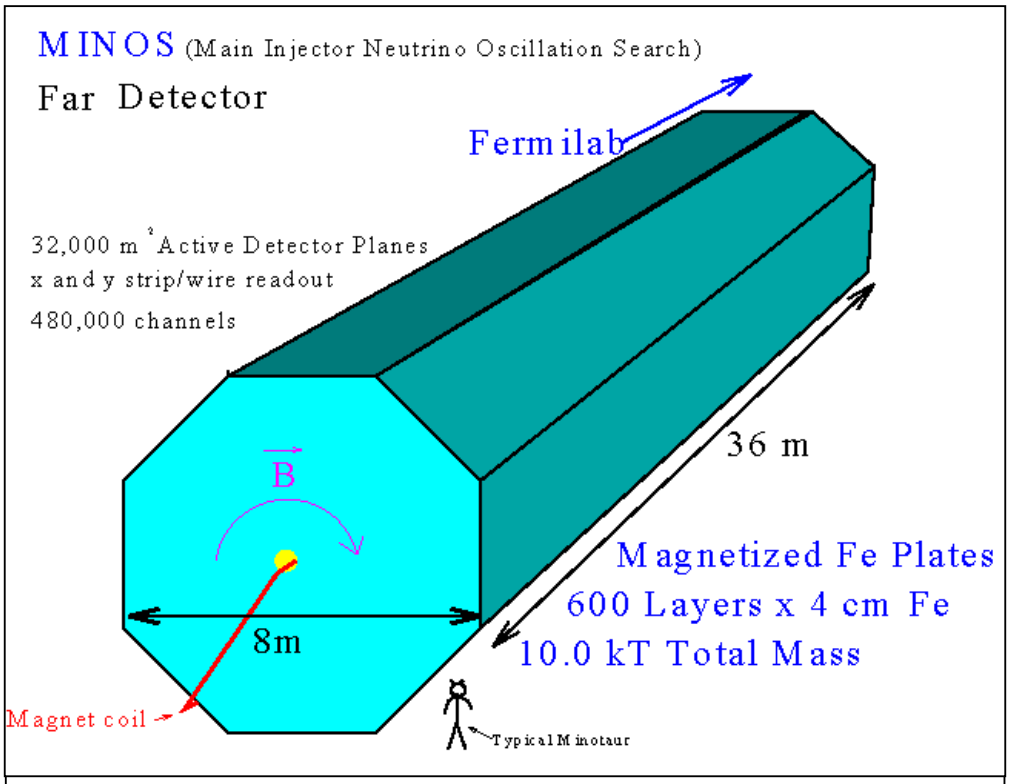

Figure 4. Sketch of the MINOS "far" detector.

oscillations requires predicting the far detector energy spectrum (without 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 in this prediction. To accomplish this, the neutrino beam center must be within ± 75 m from its ideal position at the far detector, corresponding to ± 10-4 radians, i.e. 21 arcseconds. As a vital component of the total error, the primary proton beam must be pointed within ± 12 m from the center of the far detector, corresponding to ± 1.63 • 10-5 radians, i.e. 3.4 arcseconds. [1]

Achieving this tolerance requires a rather exact knowledge of the geometry of the requisite neutrino beam. The computation of the geometric parameters of the beam trajectory, expressed in terms of the azimuth and the slope of the vector joining the two sites, requires precise knowledge of the absolute positions of the two ends of the vector, at Fermilab and respectively at the Soudan mine in Minnesota.

The purpose of this paper is limited to summarizing only our geodetic efforts to determine the beam orientation parameters for the NuMI project.

3. Geodetic Parameters

Starting in 1992, during the conceptual design process of the NuMI project, and up till now, months away from the January 2000 construction ground breaking, several geodetic determinations of the beam orientation parameters have been performed. This geodetic process, meant to ensure the refinement of the geodetic orientation parameters of the beam, took place in successive stages in accordance with the project design schedule.

3.1. Preliminary Determinations

Preliminary geodetic determinations, other than elementary interpolations from cartographic maps, took place after the tie of Fermilab and Soudan sites to the national geodetic datum.

At Fermilab, the tie took place in the fall of 1992 in preparation for the implementation of a map projection for defining the transformation algorithms/parameters between the surveying space and the Main Injector layout coordinate system. Simultaneously, it coincided with the need to tie to the global coordinate systems to support future experiments going off-site (i.e. NuMI, which originates at the Main Injector extraction point at MI-60). A GPS network comprising eleven Fermilab primary control monuments and five National Geodetic Survey (NGS) geodetic network points located around the laboratory between 5-25 km has been established. The Figures 5 a, b show diagrams of the Fermilab tie to the GPS network.

At the Soudan mine, the tie was performed in the spring of 1993, when a GPS network including four monuments located in the immediate vicinity around the access shaft and three NGS geodetic network points located between 18-29 km around the site had been established. The Figures 7 a, b show diagrams of the Soudan mine tie GPS network.

The 1989 Federal Geodetic Control Committee (FGCC) for GPS Positioning

specifications for Order B were followed. Throughout the project Trimble 4000SSE receivers were used, the occupation time ranging from one to two hours. The specific observation length took into consideration the number of satellites available, the satellite constellation, and the length of the baseline.

At Fermilab and Soudan sixty-eight and, respectively, seventeen independent baselines have been computed. The minimal constraint adjustments consisted of 204 observations, and respectively 51 observations, and yielded at 95% confidence level standard deviations of the adjusted coordinates in the millimeters range. The analysis of loop misclosures and the vector component (relative position) standard errors computed in the weighted minimally constraint adjustments conformed to the FGCC specifications for Order B three-dimensional GPS positioning (geometric relative accuracy at 95% confidence level 8 mm + 1:1,000,000D).

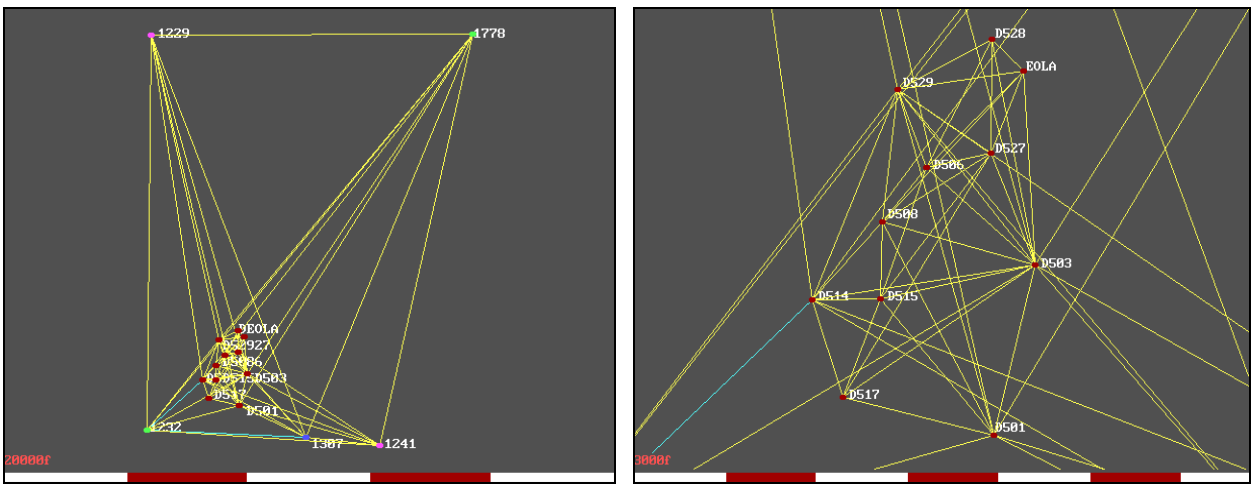

Figure 5 a, b. GPS network for tying Fermilab to the NGS NAD-83 control

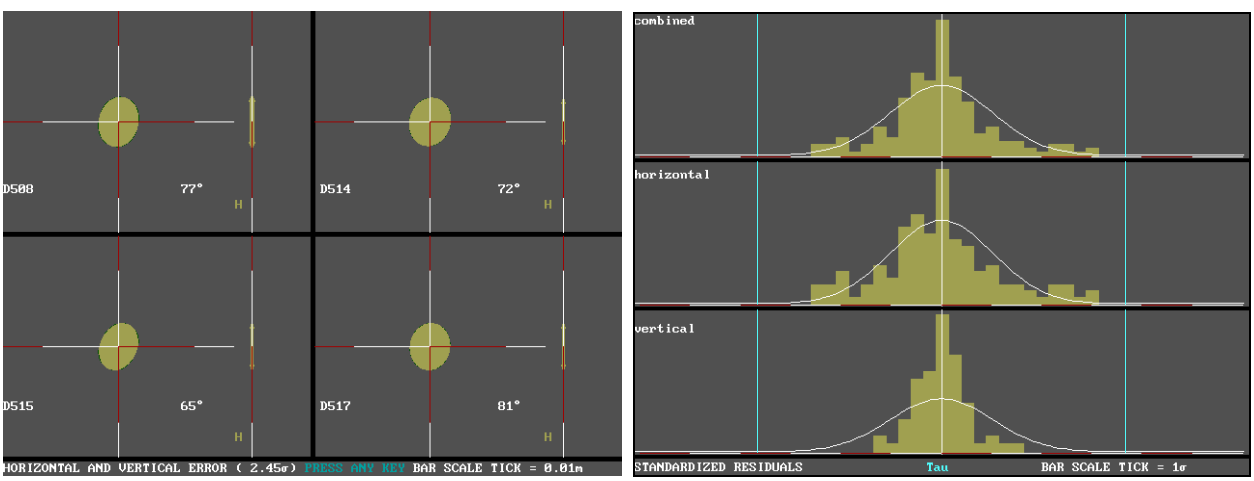

Figure 6 a, b. Fermilab GPS tie to the NGS NAD-83: ellipse of errors and histogram of residuals.

Constraint adjustments were then performed holding fixed the horizontal coordinates of the NGS geodetic control points, including the ellipsoidal and orthometric height of three vertical points. The NGS Geoid-90 and Geoid-93 models were used in the adjustments. This solution solved for rotations and scale, also obtained a more precise estimation of orthometric heights The

Figures 6 a, b and 8 a, b show ellipse of errors and histograms of residuals plots of the Fermilab and Soudan GPS ties to the national geodetic reference systems.

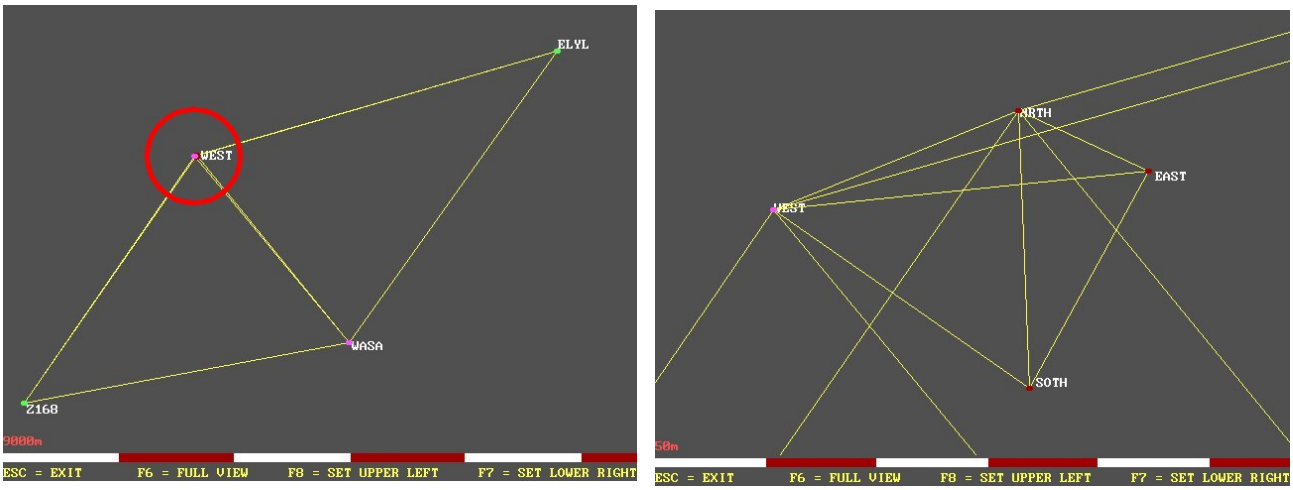

Figure 7 a, b. GPS network for tying Soudan to the NGS NAD-83 control

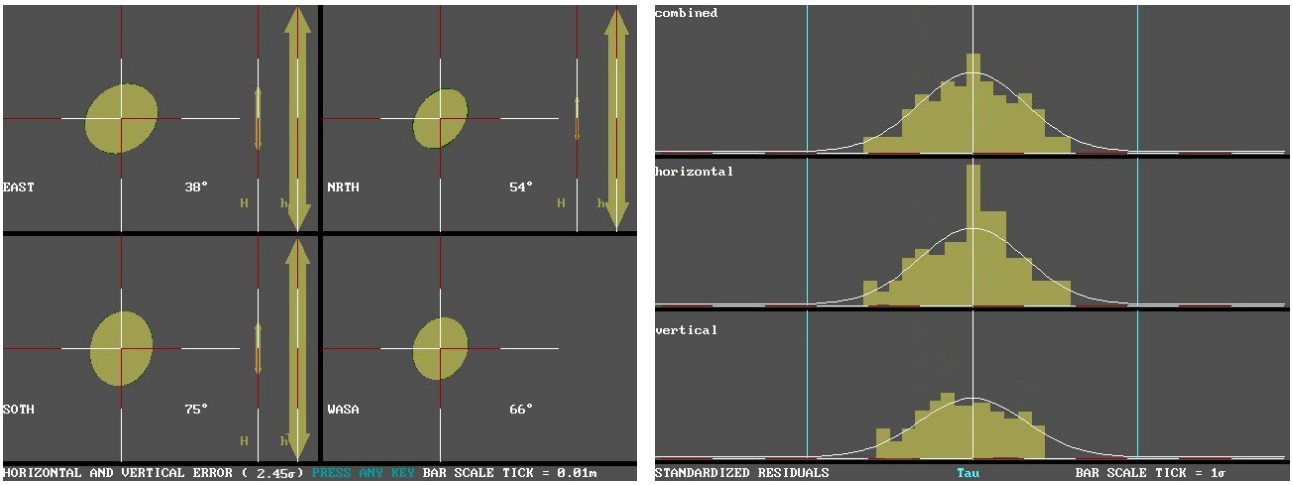

Figure 8 a, b. Soudan GPS tie to the NGS NAD-83: ellipse of errors and histogram of residuals.

The NGS control points used to tie the Fermilab and Soudan local networks pertained to the North American Datum of 1983 (NAD-83) national reference frame, which was established through "classical" geodetic methods. Regarding the NGS relative positioning accuracy classification, these control points ranged from the First Order (10 mm + 1:100,000D) to the Third Order (50 mm + 1:10,000D). The classification of the two adjustments into the national geodetic reference system can not exceed the lowest order of the control points used in the combined network. Therefore, even if superior accuracy was achieved internally in the two network ties to NGS, the overall accuracy would be classified as Third Order.

The accuracy of the NAD 83 network compared against GPS derived coordinates, as described in Chapter 19 of North American Datum of 1983 [2], has been estimated by the National Geodetic Survey as:

$$e = aK^b$$

where e denotes the rms value of the vector component in meters, K denotes the interstation distance in kilometers, and a and b are quantities whose values depend upon the line order classification as shown in Table 1:

Table 1. Values for accuracy parameters

Line Order	Collinear Component	Transverse Component
First	a = 0.008	a = 0.020
	b = 0.7	b = 0.5
Second	a = 0.010	a = 0.025
	b = 0.7	b = 0.5
Third	a = 0.010	a = 0.030
	b = 0.7	b = 0.5

Accordingly, the expected accuracy of the vector between Fermilab and Soudan reference networks computed from NAD 83 Third Order accuracy geodetic coordinates would be:

- the magnitude of collinear component $e_c = \pm 1.015$ m
- the magnitude of transverse component $e_t = \pm 0.813$ m.

Defining the geodetic parameters of the neutrino beam line implies, besides the global aspect of determining the absolute positions of the Fermilab and Soudan sites, connecting the Underground Soudan Laboratory, which is located the 27th level of the mine, to the geodetic coordinates system established at the surface.

In this initial phase of the project design the coordinates of the MINOS detector at the bottom of the Soudan mine have been computed mostly theoretically, and we did not perform a direct tie to the 27th level with respect to the surface geodetic reference system. In stead, various historical sources gathered during construction of the Soudan Underground Laboratory were relied on. These documents provided information with regards to the depth and vertical angle of the access shaft, the local coordinate system established at the 27th level, and the orientation of this system with respect to North determined by previous gyro-theodolite observations. Thus the beam orientation parameters could be determined with sufficient accuracy to cover for the moment the NuMI project design necessities,

The first refinement of the geodetic parameters of the neutrino beam took place during the April 1998 campaign at the Soudan site. Four sessions of 4-5 hours and one session of 7 hours of differential GPS measurements were performed between two points at Fermilab and Soudan, following the FGCC specifications for High Accuracy Reference Network (HARN) observation. The HARN procedures were also used for processing the long GPS baselines, employing precise orbits and improved atmospheric refraction modeling. Holding fixed the coordinates of the Fermilab monument determined during the NGS tie, improved coordinates for the Soudan monument were obtained, which yielded differences with respect the previously computed coordinates from the NGS tie in the range of 0.5 m in both latitude and longitude.

During the same campaign, an investigation of the possibility (methodology and instrumentation) of tying the surface control points to the underground local network located at the 27th level of the mine by surveying through the 710 m deep elevator shaft took place. The shaft has an 3.5 m x 2.5 m wide opening at the top and is inclined at an angle of 12.2^0 with respect to the vertical (see Fig. 3). Despite our efforts, this investigation was unsuccessful in making direct measurements using classical surveying instrumentation all the way to the 27th level, mainly because adverse atmospheric conditions encountered through the shaft. Based on the most recent determinations, it was concluded that the direct line of sight top/bottom is mostly obscured because of the inclination of the shaft angle part way down.

Gyro-theodolite observations were also performed using a DMT Gyromat-2000 instrument between points from the underground local network in order to verify the "historic" rotation of this reference system with respect to North. The results indicated a difference of 18' 15" from the previously determined gyro azimuth.

3.2. Final Determinations

The spectacular development in recent years of the GPS Continuously Operating Reference Station (CORS) System led to the conclusion that direct GPS observations of long baselines between monuments located at Fermilab and Soudan mine sites, combined with CORS data, would provide the most precise and reliable results. Currently, the CORS network has achieved the highest accuracy regarding positioning standards. In addition to supplying GPS observational data needed for relative positioning, the CORS stations contribute to a variety of efforts such as precise geodetic positioning, the generation of precise satellite ephemerides and clock correction data, crustal motion monitoring, and atmospheric and earth rotation studies. Connections derived from two or more CORS stations will ensure unprecedented positional integrity without the expense of sending additional receivers and personnel into the field.

In 1998/99, as a result of the ongoing collaboration, we established a Cooperative Agreement with the National Geodetic Survey for determining the coordinates of several stations belonging to the Fermilab and Soudan networks in conjunction with the CORS system. NGS agreed to establish the procedures and provide high accuracy geodetic coordinates for the two sites using the adjacent CORS network.

The GPS CORS System has been implemented by NGS in an effort to meet post-processing requirements of positioning (including precise positioning) of a broad range of surveying, mapping and related disciplines by providing GPS code range and carrier phase observational data from a nationwide network of stations. CORS facilities, established at precisely known locations and equipped with high quality dual frequency geodetic receivers, collect and record, in an automated manner, the GPS data required for relative positioning. This data, in RINEX format and 30 seconds sampling rate, is made accessible to the public for use and can be retrieved over the Internet. Currently, the network comprises over 150 stations in the coterminous United States, as shown in Figure 9.

NGS computes a ITRF96 daily national solution for all operational CORS stations by performing a network adjustment applied to baselines observed 24 hours with 30-second

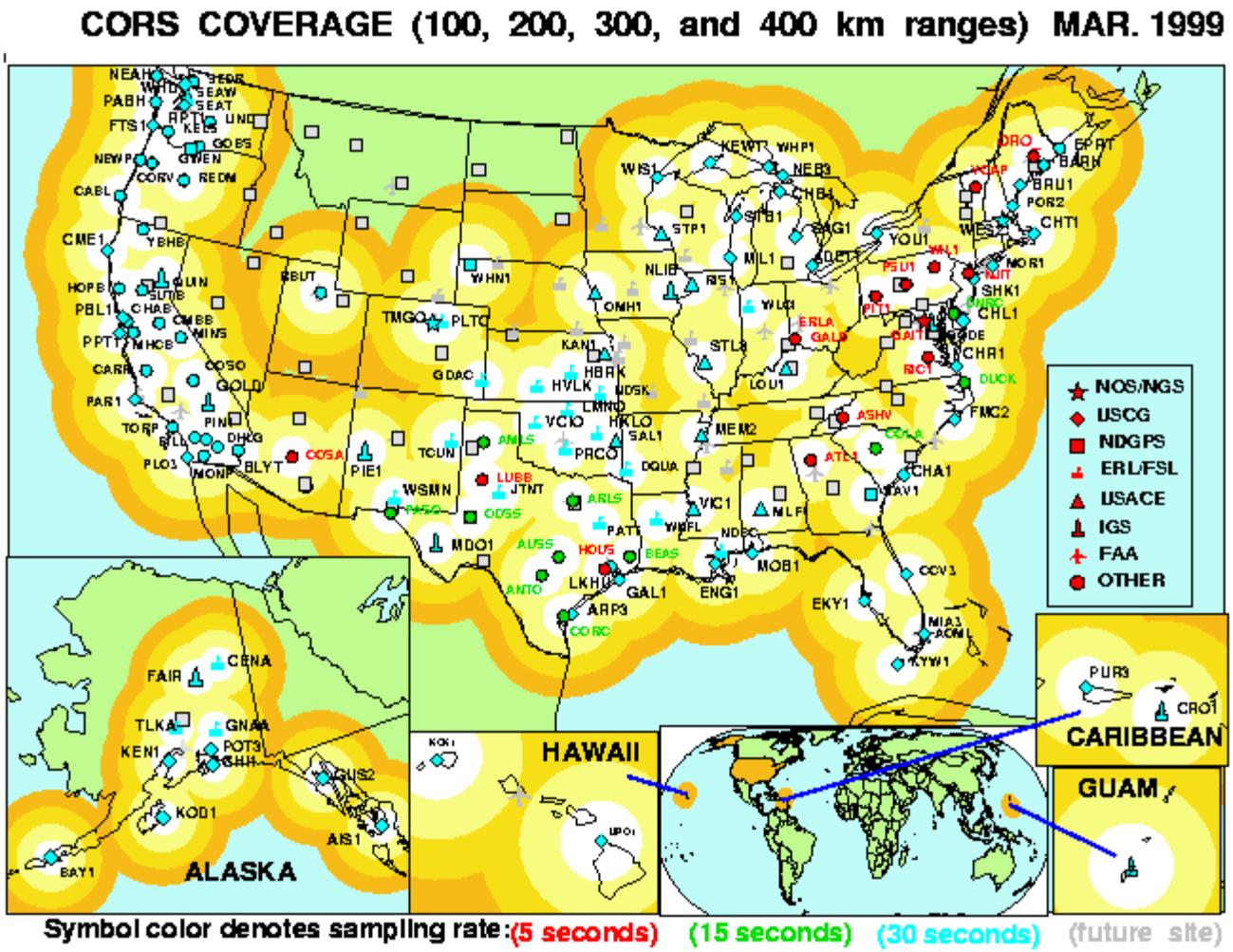

Figure 9. CORS coverage

sampling interval. It takes into account various forms of crustal motion including plate tectonics, subsurface fluid withdrawal, and crustal loading/unloading, and also temporal tidal variations. Also, these high accuracy coordinates of the CORS stations are monitored on a daily basis.

The GPS observation campaign took place in April 1999 and followed the NGS specifications. Except for station occupation time, these specifications were similar to the High Accuracy Reference Network procedures regarding equipment setup, GPS receiver controls, weather data collection, and documentation. During three days of observations and using four dual frequency Trimble 4000SSE receivers, three sessions of 9-10 hours of data were at each site, staggering the observations start times in order to observe the complete satellite constellation orbital period of 12 hours. Figure 10 shows the three points from the Fermilab control network that were observed during this campaign.

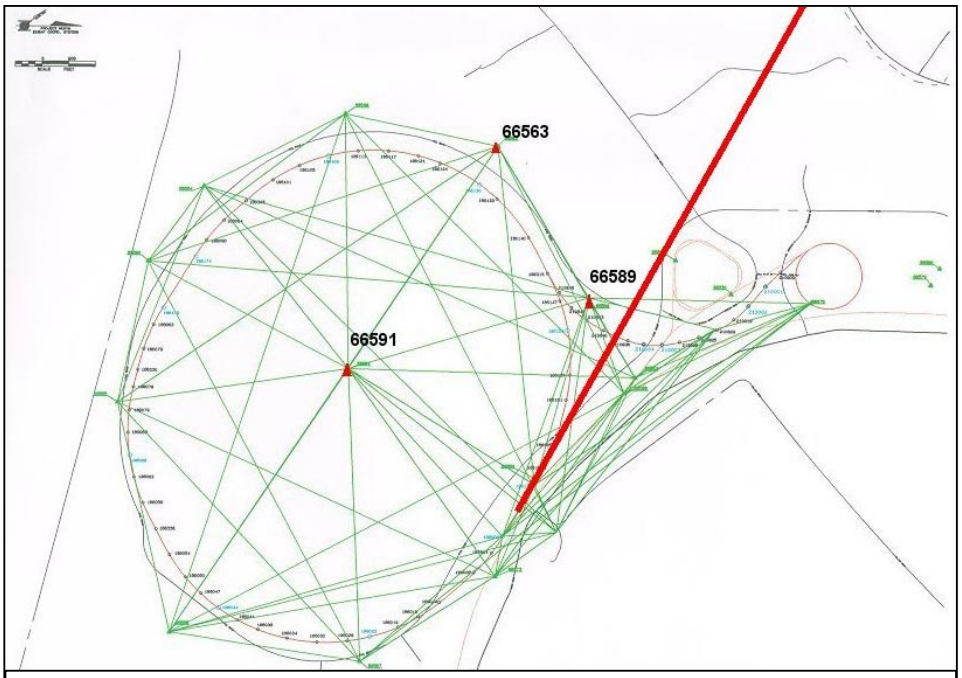

Figure 10. Points from the Fermilab network computed from CORS

Although the NGS analysis and results will constitute the official coordinates set for computing the geometric parameters of the NuMI beam trajectory, Fermilab also processed the data and computed a preliminary independent solution. The network for determining accurately the coordinates for the Fermilab-Soudan baseline was formed by four CORS stations and the two primary monuments 66589 at Fermilab and Shaft at Soudan, for which the most GPS observation data has been collected. Moreover, they are also the nearest to the designed target hall and the mine access shaft. From the CORS stations adjacent to the Fermilab-Soudan baseline we selected four, two on each side of the vector in a balanced manner. Figure 11 show a map of the Midwest CORS stations with the proposed network superimposed.

The vector solutions for the network were processed by combining the GPS data collected by Fermilab with the data collected by the CORS stations which was made available

for retrieving via Internet. During the GPS vectors processing the satellites' precise orbits made available by NGS have been used in the baseline computations for improving their accuracy. Observed meteorological data for modeling the tropospheric effect on the GPS signal propagation were also employed.

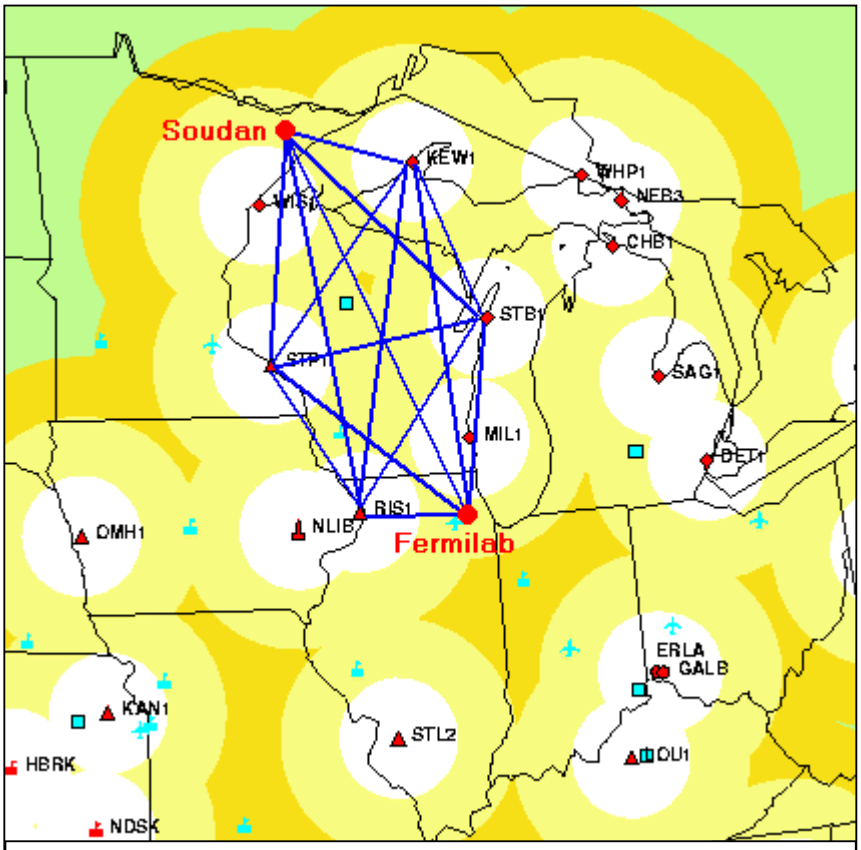

Figure 11. Map of Midwest CORS stations and the proposed network.

A minimal constraint adjustments consisting of 72 observations (24 vectors) was performed and yielded standard deviations of the adjusted coordinates in the millimeters range in all three coordinates (longitude/latitude 1-3 mm, ellipsoid height 7-10 mm) at 95% confidence level. The high quality of this network was further confirmed by computing standard deviations for the spatial distances and height differences for all adjusted vectors using variance-covariance propagation. It was found that the standard deviations for the spatial distances are less than 5mm (this includes lines across the network). The height differences have standard deviations of 10-15 mm. The Figures 12 and 13 a, b show diagrams of the GPS network, and respectively ellipse of errors and histograms of residuals plots.

NGS database provides 3-dimensional positions and velocities for the L1 phase center of each CORS antenna. They are expressed in two different reference frames: IERS Terrestrial Reference Frame 1996 (ITRF96) instituted by the International Earth Rotation Service (IERS), and the North American Datum of 1983 (NAD 83), both with an epoch date of 1997.0, and both

referring to the GRS80 ellipsoid. In the preliminary solution, the coordinates of the two primary NuMI monuments were obtained from a least square constraint adjustment holding fixed the four CORS station to their NAD-83 coordinates.

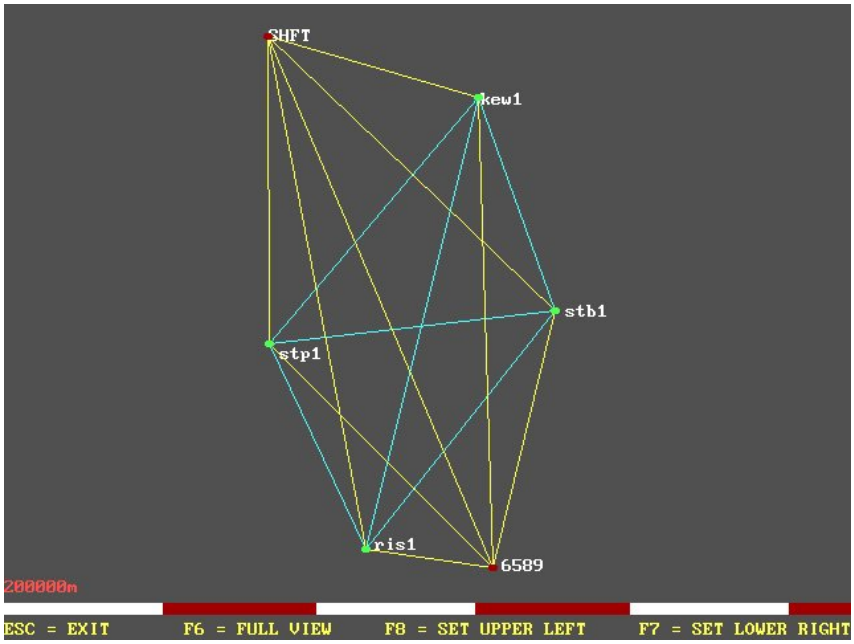

Figure 12. GPS network for tying Fermilab and Soudan to the CORS system

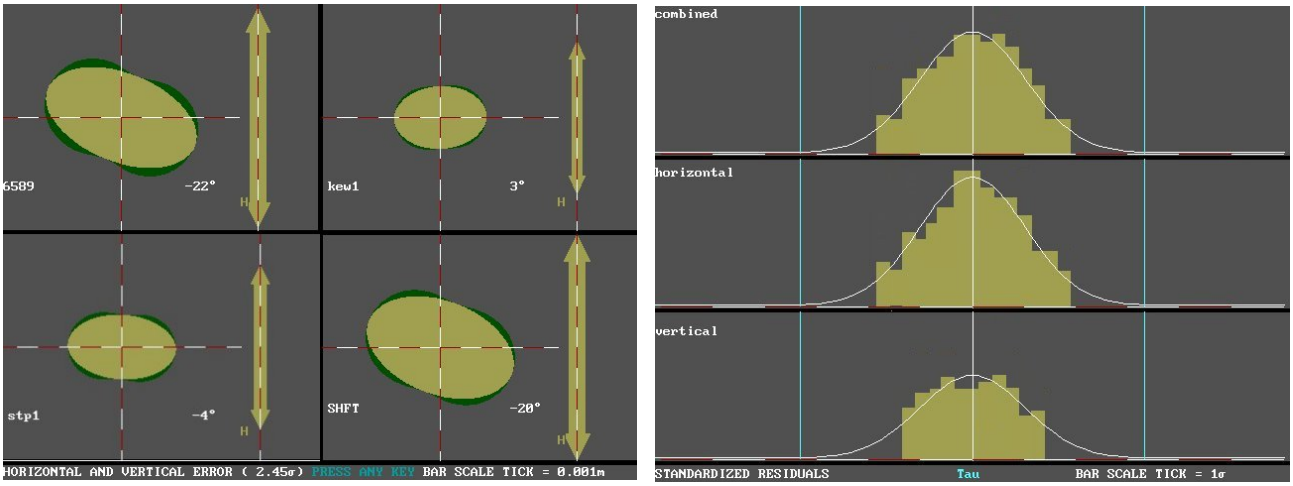

Figure 13 a, b. GPS tie to the CORS network: ellipse of errors and histogram of residuals.

The NGS performed the computations in the ITRF96 reference frame at the epoch date 1999.2968 (19 April 1999, the date of the GPS observations). The coordinates of the points were obtained from a least-squares adjustment holding fixed the CORS station STP1, which is located approximately equidistant from the station 66589 and Shaft. As a measure of internal consistency, the rms of the residuals of the adjustment only amounted to 2 mm in latitude and longitude and 6 mm in height.[3]

The comparison between Fermilab's independent solution and the NGS final results, after performing the transformation of the NGS coordinates from the ITRF96 to the NAD-83

reference system, indicated differences in the mm level for the longitude and latitude, amounting especially in height up to 10 mm. These small differences can be easily explained by several factors: different selection for the CORS stations, the computations were performed independently in two reference frames (ITRF96 and NAD 83), NGS used more updated coordinates for the CORS stations, also Fermilab did not account for temporal tidal variations. As an example, the NAD 83 reference frame is defined so that the North American tectonic plate does not move as a whole relative to it. On the other hand, relative to the ITRF, even points located on the rigid part of the North American tectonic plate move continuously at rates ranging from 9 to 21 mm/year in the coterminous United States.

As an alternate method for determining the location of the 27th level of the Soudan mine with respect to the geodetic coordinates system established at the surface employed inertial techniques. The Department of Geomatics Engineering from the University of Calgary was contracted to perform a survey through the 710 m deep mine shaft using a HG Honeywell 2001 Inertial Navigation System (INS) unit. Considering that errors in meter range would not be significant with respect to the physics requirements for the neutrino beam, the contract required that the rms be below 1 meter.

The inertial survey technique makes use of an Inertial Measuring Unit (IMU) composed of three accelerometers and three gyroscopes to output specific forces and respective angular velocities from the orthogonal sensor triads. The outputs are used in a dead-reckoning method which after initialization provides three dimensional geodetic coordinates at a high data rate. The accuracy of the results depends, besides on the quality of the hardware, on the method used to estimate systematic errors inherently present in the sensors. Table 2 presents the HG Honeywell 2001 sensors performance specifications.[4]

Table 2. HG Honeywell 2001 INS sensor performance specifications

Performance Parameter	Class II 1.0 nmi./h
gyro bias uncertainty (deg/h)	0.003
gyro random noise (deg/ $\sqrt{h}$)	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

After the calibration of the inertial system, multiple determinations were performed by running the unit, which was rigidly attached in the elevator car, through the access shaft between the surface and the 27th level of the mine. The comparison between the runs showed an agreement 0.040 m in height and longitude and about 1 m in latitude. Although it met the given

requirements, the latitude discrepancy was most likely caused by an initial azimuth misalignment between the IMU system and the surface geodetic control system, and is still under investigation.

Since the inertial system data collecting rate of 50 Hz was used during the elevator runs a fairly precise mapping of the 710 m deep access shaft was obtained. Moreover, the inertial system was used as a redundant method to check the rotation of the 27th level local reference system with respect to North. Latest results indicate an agreement with our 1998 Gyro determinations to 4 arcminutes, compared to an INS estimated error of 5 arcminutes.

For the final computation of the geometric parameters of the beam trajectory the NGS high accuracy geodetic coordinates provided by the tie to the CORS national network and the updated location of the 27th level of the Soudan mine provided by the inertial system survey were used. As a detail, the updated coordinates of the "far" MINOS detector differs by the ones previously determined by 3.6 m in longitude and latitude and 9.8 m in ellipsoid height. This indicates that the critical, and the least accurate, information in the preliminary determinations was the depth of the 27th level of the Soudan mine.

4. Conclusions

The tolerance for directing the neutrino beam from Fermilab to the "far" MINOS detector in Soudan Minnesota requires exact knowledge of the geometry of the beam. Precise knowledge of the absolute positions of the two ends of the vector leads to a more rigorous solution for computing the geometric parameters of the beam trajectory.

Table 3 presents a comparison between the coordinates of the Fermilab 66589 and Soudan SHAFT control points determined at different stages of the project showing the refinement of these coordinates. For simplification, the coordinates are shown in the Local Geodetic System at 66589. Table 4 presents a comparison of the geodetic parameters computed between the two points.

The preceding presentation and Tables 3 and 4 show that throughout the design phase the beam orientation parameters for the NuMI project have been determined with sufficient precision to cover the civil engineering requirements.

The refinement of the geodetic coordinates resulted from precise GPS determinations in conjunction with the CORS national system. The NGS provided an independent solution in the ITRF96 reference system, which was then transformed in the NAD 83. This was supplemented with coherent data between the surface geodetic frame and the27th level of the Soudan mine provided by the inertial system 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 updated geodetic coordinates, and the beam orientation parameters computed in the absolute geodetic system, will be transformed in the Fermilab Main Injector Local Tunnel Coordinate System (LTCS), Figure 14. These coordinates will also constitute the basis for developing a high accuracy local network for supporting the construction and installation of the NuMI beam.

5. Acknowledgements

In the spirit of scientific cooperation, we would like to thank our colleagues geodesists from the National Geodetic Survey, the director Charles Chalstrom, and especially to Tom Soler, Stepen Frakes, Dixon Hoyle, Richard Foote, and David Doyle for their enthusiastic and competent collaboration during the design phase of the geodetic aspect of this project.

6. References

[1] The Fermilab NuMI Group, "The NuMI Facility technical Design Report", September 1998
[2] National Oceanic and Atmospheric Administration, "North American Datum of 1983", 1989
[3] Soler, T., Foote, R., Bocean, V., "Accurate GPS Orientation of a Long Baseline for Neutrino Oscillation Experiments at Fermilab", submitted to Geophysical Research Letters, 1999
[4] Department of Geomatics Engineering, University if Calgary, Ca, "Inertial Survey of the 27th Level of Soudan Mine", 1999

Table 3. Comparison between coordinates (Local Geodetic System at 66589)

FROM	TO	n (m)	e (m)	up (m)	Δu (m)	Δe (m)	Δup (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 tie computed by Fermilab
66589_CORS NGS	SHAFT_CORS NGS	671108.532	-297424.016	-42175.390	0.000	0.000	0.000	CORS tie computed by NGS

Table 4. Comparison between geodetic parameters

FROM	TO	Normal Sect Azimuth (d-m-s)	ΔAzimuth (sec)	Vertical Angle (d-m-s)	ΔVAngle (sec)	Distance (m)	ΔDist (m)
66589_93	SHAFT_93	336-05-52.35784	0.00674	3-17-17.88121	0.00141	735272.273	0.785
66589_93	SHAFT_98	336-05-52.33101	0.03357	3-17-17.89081	-0.00819	735272.862	0.196
66589_CORS Fermi	SHAFT_CORS Fermi	336-05-52.36866	-0.00408	3-17-17.88412	-0.00150	735273.061	-0.003
66589_CORS NGS	SHAFT_CORS NGS	336-05-52.36458	0.00000	3-17-17.88262	0.00000	735273.058	0.000

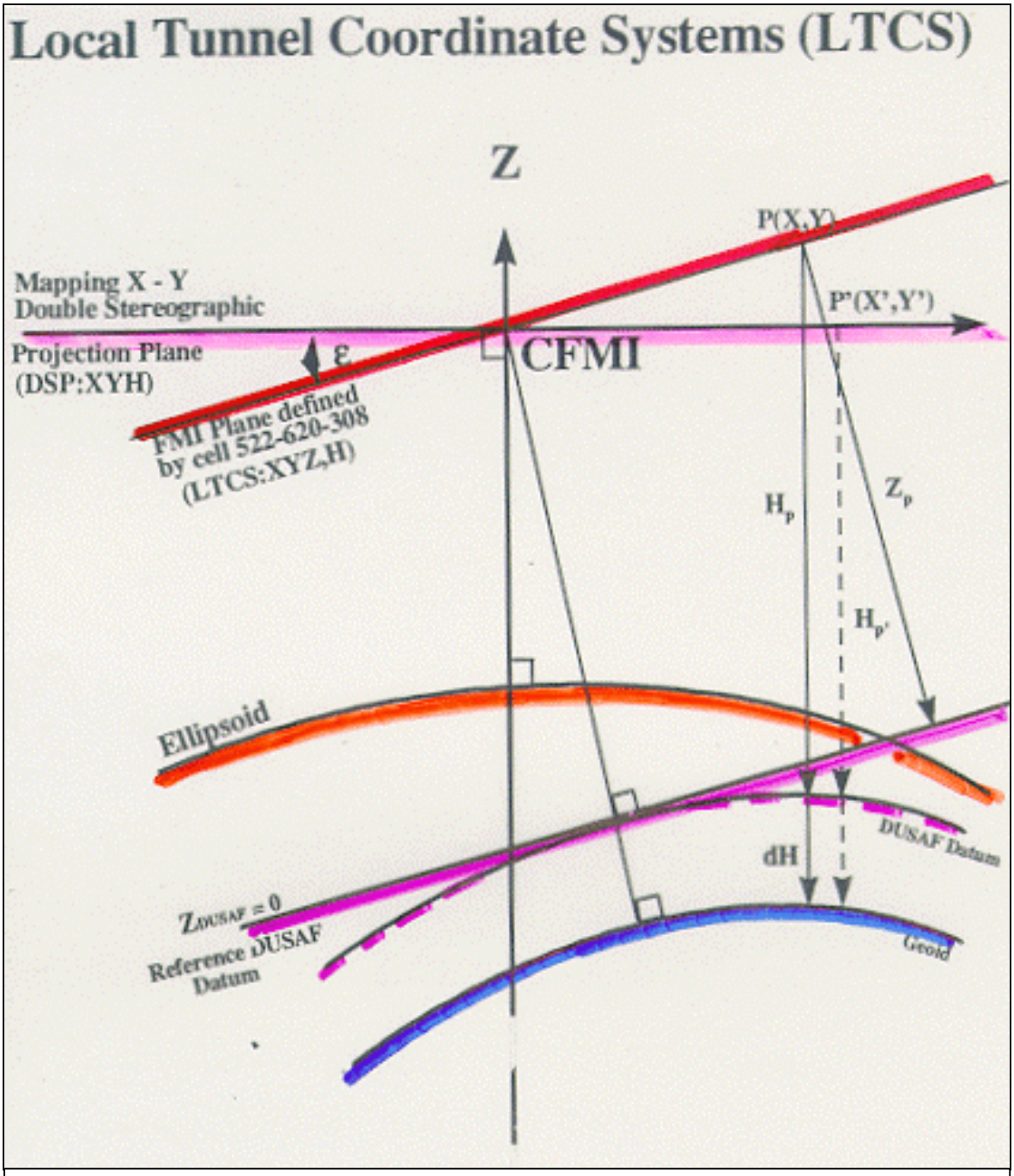

Figure 14. The Local Tunnel Coordinate System