

Status Report on the Survey and Alignment Activities at Fermilab

V. Bocean, G. Coppola, R. Ford, J. Kyle
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

1. INTRODUCTION

The Alignment and Metrology Group is responsible for all surveying and alignment activities at Fermilab, including the design, development, and implementation of geodesy and industrial alignment procedures to support the construction and installation of all experiments and achieve the required precise global and local positioning.

This report presents the projects and other major activities of the Alignment and Metrology Group at Fermilab during the period of 2004 to 2006, other than the projects specifically presented in more detail at this conference through independent talks - NuMI [1], E-Cool [2], TeVnet [3].

2. CURRENT PROJECTS

In the past two years, there have been several new experiments at Fermilab, which are currently taking data for physics, such as the NuMI/MINOS experiment, the Electron Cooling project, and the MIPP experiment. The Alignment and Metrology Group has supported these projects from the facility construction phase to the installation and final alignment of components in the beam line. Other group activities have been the upgrade of the horizontal and vertical survey networks for the Tevatron accelerator complex and associated beam lines, the ILC Test Area project as a part of Fermilab's R&D program for the ILC, and the development and implementation of the Alignment Data Management System.



Figure 1: Overview of Fermilab Accelerator Complex

2.1. Vertical Control Network Upgrade

The 2006 site wide vertical control upgrade responded to our needs to have a current homogeneous control network that incorporates surface and underground networks derived from observations during a common epoch. During the recent maintenance shutdown, we were able to survey a large portion of our surface and subsurface vertical networks along with their corresponding elevation transfers or vertical ties from the surface to subsurface control. The following tunnels were observed during this campaign: Fermi Main Injector (FMI), NuMI (Neutrinos at the Main Injector), MiniBooNe, Pbar (Antiproton), 8 GeV, and the Tevatron. In addition, D0 and CDF the experimental halls were also observed. At present, efforts are underway to incorporate some of the fixed target experimental beam lines and their Assembly/Detector buildings in the current campaign. In particular, Meson test beam area and the New Muon Building.

Within the past few years the AMG has designed and installed a site wide network of Deep Rod Monuments (DRM's) to monitor deformation at Fermilab. Though the DRM's are primarily located on the surface we have been systematically installing them in the tunnels as opportunities present themselves. The objective of the DRM's in the tunnels is to reduce or eliminate the amount of effort required in doing elevation transfers from surface to subsurface networks and to ultimately have stable subsurface control. Until recently many of the surface monuments were not referenced to our primary vertical control network. Currently, approximately 90 percent of this task is completed.

The procedures for First Order Class II accuracy (± 0.7 mm/km) for geodetic leveling specified by the 1984 FGCC Standards and Specifications for Geodetic Control Networks have been followed. The observations were performed using Leica DNA03 digital level as instrumentation. The site wide surface network consisted of over 37 km of double-run precise leveling, observing over 223 monuments. The minimally constraint adjustment yielded a precision of ± 0.5 mm/km double-run, consistent with the standard accuracy requirements. The deformation analysis, employing the Iterative Weighted Similarity Transformation (IWST) method [4], was performed using the DEFNAN Analysis Software [5].

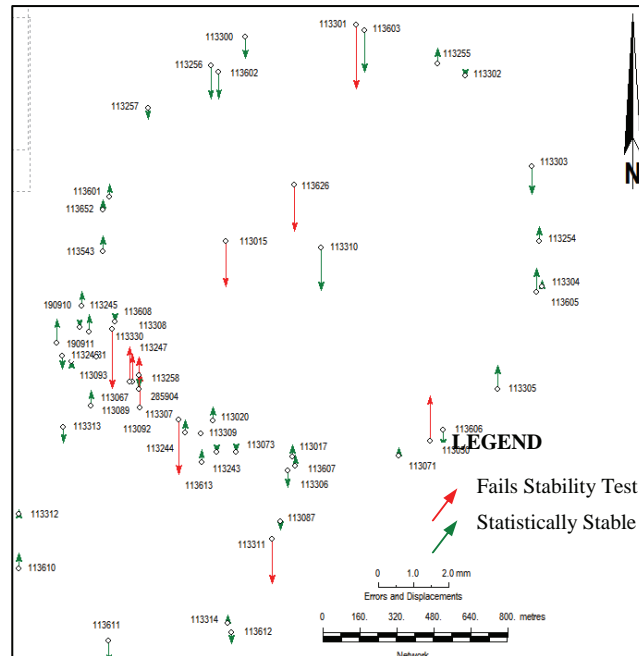


Figure 1: Plot of Displacements for Surface Network

The deformation analysis for the surface network encompassed primarily, in the first phase, the regions bounded by the FMI and the Tevatron. The deformation magnitude in these regions is shown graphically in Figure 1.

The underground networks, comprising the tunnels associated with the projects listed above, consisted of over 22 km of double-run precise leveling, observing over 1500 monuments. The minimally constraint adjustments yielded, in average, a precision of ± 0.55 mm/km double-run, consistent with the projects accuracy requirements.

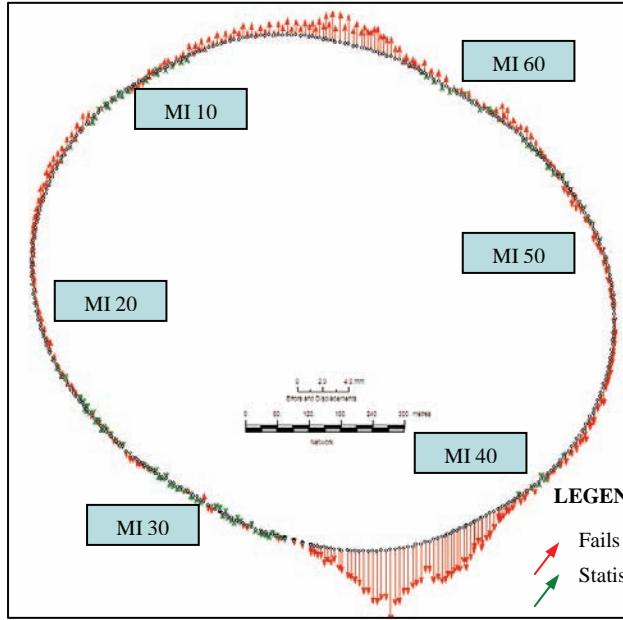


Figure 2: Plot of Displacements for FMI Tunnel

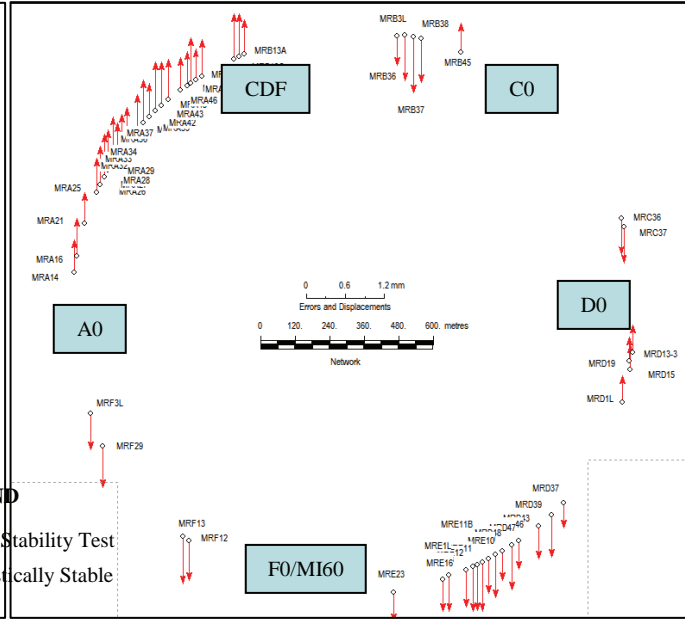


Figure 3: Plot of Displacements for Tevatron Tunnel

The deformation analyses for the FMI and Tevatron underground networks have been also completed and the results presented to the beam line physicists for correlation with beam analysis data. The magnitude of deformation in the FMI and Tevatron tunnel networks is shown graphically in Figure 1 and, respectively, Figure 2.

In addition, a comparison on common points between adjusted values based on the surface network and adjusted tunnel network, including elevation transfers from the surface, yielded agreement in 0.08-0.20 mm range.

Currently, the vertical network control analysis for upgrade is in final phase of completion and implementation.

2.2. MIPP Experiment

The Main Injector Particle Production (MIPP) experiment (E907) measures hardronic particle production in the Meson area using primary and secondary beams from the Main Injector, focusing on the next generation of production models based on “minimum bias events” data. The objectives of the experiment are: to verify a general scaling law of hardronic fragmentation, to measure particle production off NuMi targets using 120 GeV/c protons with sufficient accuracy to predict the NuMi neutrino spectrum, and to collect a comprehensive dataset that would have a profound impact on related physics issues, such as atmospheric neutrino flux estimates, neutrino factory design, and simulations of hardronic showers for high energy colliders [6].

The primary beam particles hit a target located just upstream of the Time Projection Chamber (TPC), which resides

in the center of the Jolly Green Giant analysis magnet. Immediately downstream, and interspersed by a series of drift chambers, there is a Cerenkov counter, a Time of Flight detector array, a second analysis magnet (Rosie), a Ring Imaging Cerenkov (RICH) counter, an Electromagnetic Shower Detector and a Neutron Calorimeter. Figure 4 shows a view of the experiment with tracks from a simulated event.

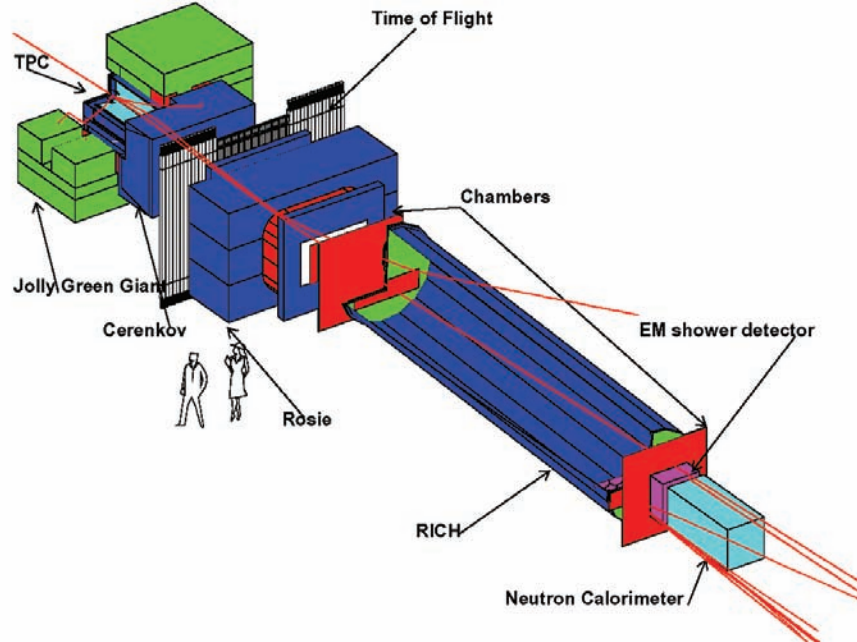


Figure 4: MIPP Experiment 3-D view

Table 1 lists alignment tolerance requirements at 95% confidence level.

Beam Components/Instrumentation	± 0.50 mm
Beam position at Targets	± 0.50 mm
Time Projection Chamber (TPC)	± 0.50 mm
Analysis Magnets (JGG and Rosie)	± 5 mm
Time of Flight counters (TOF)	± 1 mm
Drift Chambers (DC1-DC6)	± 1 mrad
RICH Counter	± 0.5 mm
EM Shower Detector	± 0.5 mm
Neutron Calorimeter	± 1 mm

Table I: Alignment Tolerances

Prior to the installation of the components, high-accuracy Laser Tracker control networks were established throughout the primary beam line enclosures and in the Experimental Hall. The networks were processed as three-dimensional trilateration (distances derived from Laser Tracker observations), supported by precision underground leveling. Mekometer distances, precision angles, and gyro-azimuths were also observed to control the scale and, respectively, to study the network behavior during the adjustment. We obtained relative errors between control points below ± 0.150 mm at 95% confidence level throughout the network. Figures 5 and 6 show the distribution of standardized observation residuals for the primary beam tunnel and for the Experimental Hall networks.

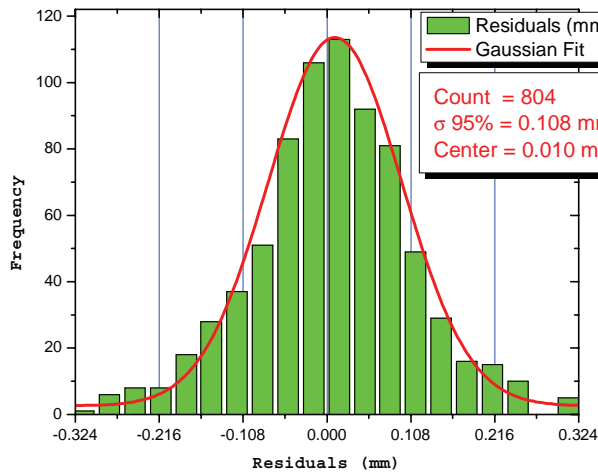


Figure 5: Primary beam tunnel network
Histogram of residuals (bar scale tick = 1 σ)

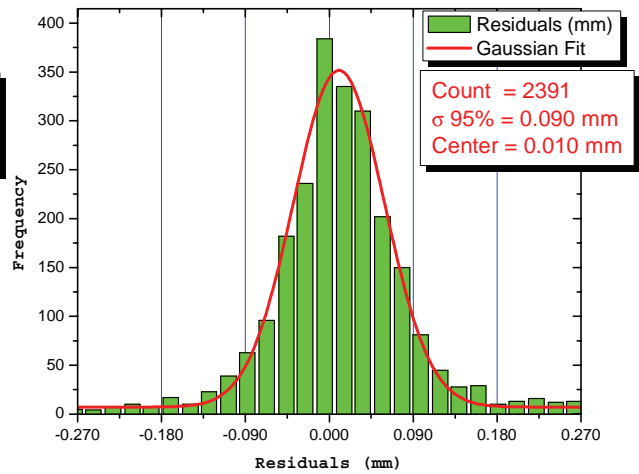


Figure 6: Primary beam tunnel network
Histogram of residuals (bar scale tick = 1 σ)

All the beam and experiment components, as well as the instrumentation, were individually referenced, by relating their effective beam centerlines to external mechanical points. The Laser Tracker, optical tooling, Coordinate Measuring Machines, or a combination of them has been utilized for fiducialization.

The final alignment of all beam line and experiment components was done using the Laser Tracker. The primary beam components alignment results indicated that, since horizontal and vertical residuals within ± 0.150 mm at 95% confidence level were obtained and the relative positioning requirements were satisfied, no smoothing correction was necessary. Figure 6 shows component residuals to the weighted linear regression computed in the horizontal and vertical plane.

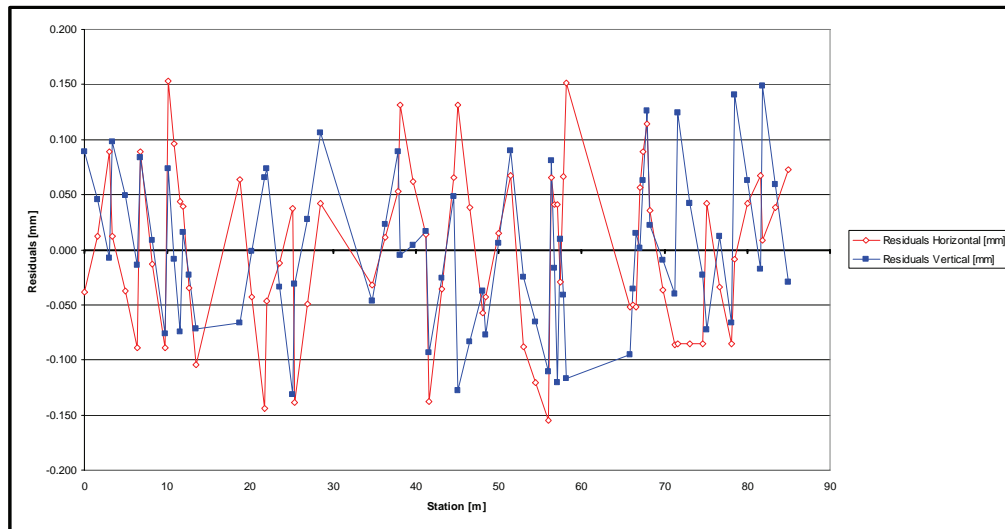


Figure 6: Primary beam components alignment results

The MIPP experiment was commissioned in the fall of 2004 and has run successfully for 14 months, finishing taking data in February 2006. During the run, three alternate target configurations were used: nuclear targets installed on a remotely controlled target wheel (Figure 7), a cryogenic target (Figure 8), and the NuMI spare target (Figure 9). Also,

since different beam energies were used for different runs, the primary beam configuration changed between runs (pinhole collimator in/out, primary target in/out).

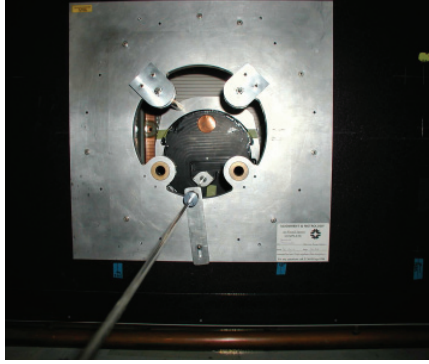


Figure 7: Target wheel (nuclear targets)

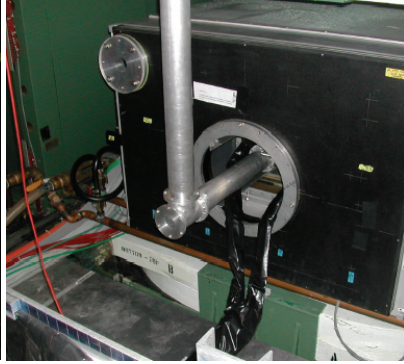


Figure 8: Cryogenic Target

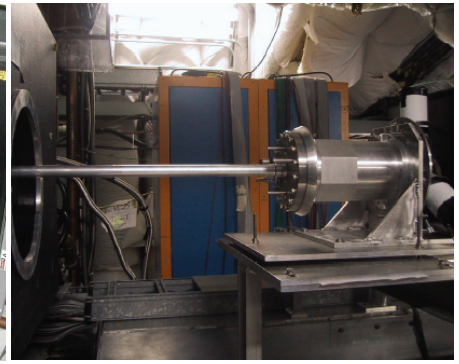
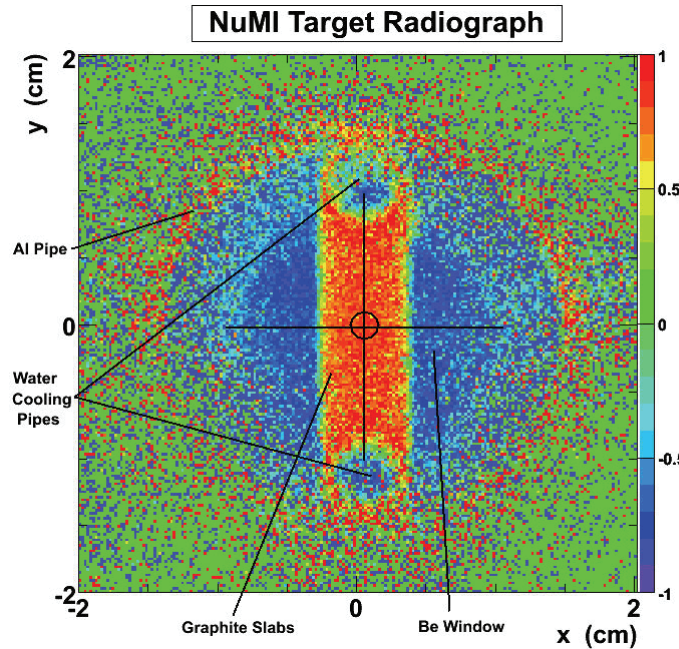


Figure 9: NuMI Target

The Alignment Group support during the experiment run period consisted of: precisely aligning the different targets, instrumentation, or experiment components (as needed) prior to each run, monitoring the network and experiment components during annual maintenance shutdown, performing analysis of the spatial geometry of all experiment components in relation to the beam, and providing the experimenters with detailed geometry information about each component, which then was incorporated into Geant/ROOT geometry description used by Monte Carlo and offline analysis software. Fig 10 shows the NuMI target alignment results during the June 2006 run; the cross hairs represent the center of the target and the circle represents the beam profile determined using reconstructed beam chamber tracks for "on-target" data.

Figure 10: NuMI Target alignment ($x = 0.020$ mm, $y = 0.510$ mm)

The current experiment status is that the data analysis is in full progress and going well, expecting for the first results to be published very soon. Also, there is a proposal for the MIPP experiment upgrade and an expanded run plan in 2007, which has been submitted and waiting for approval.

2.3. ILC Test Ares

The International Linear Collider Test Areas (ILCTA) at Fermilab is an important part of Fermilab's R&D program to participate to the Global Design Effort (GDE) for the ILC, focusing on the design, manufacturing, and testing of the cavity and cryomodule. Fermilab's present R&D plan and priorities in these areas are [7]:

- To determine cavity processing parameters for a reproducible cavity gradient of 35 MV/m;
- Test one ILC RF unit at ILC beam parameters, high gradient, and full pulse rep rate;
- Design, produce and test the ILC-specific cryomodule.

Currently, Fermilab is developing the infrastructure for cavity processing and testing and fabrication of cryomodule by designing and constructing High Power Test Facilities in the Meson Detector Building (ILCTA-MDB), New Muon Lab (ILCTA-NML), and Industrial Building 1 (ILCTA-IB1), and also a Cryomodule Assembly Facility (CAF) in the MP9 Building.

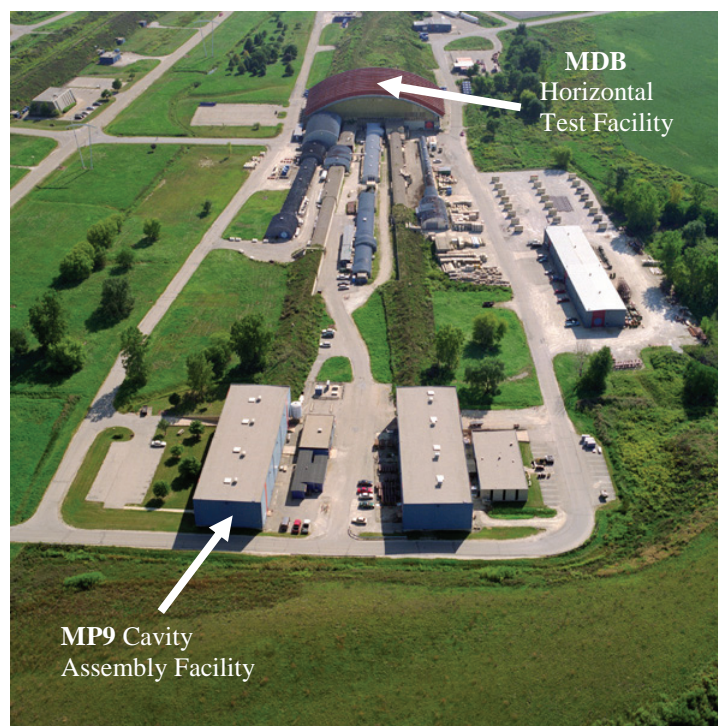


Figure 11: The Meson Detector Building and the MP9 Building site

ILCTA-MDB uses the Meson Detector Building as the 3.9 GHz/1.3 GHz Cavity Horizontal Test Facility. It is the only U.S. facility capable of performing this test. Cavities will be dressed in CAF for the horizontal test at ILCTA-MDB. The horizontally tested cavities will then be assembled into a string at CAF, where also the cryomodule fabrication will take place. Figure 11 shows the site view of the ILCTA-MDB and CAF buildings. The infrastructure for horizontal testing has been completed. Currently, the first TESLA 9-cell 1.3 GHz "ILC-like" cryostat (Capture Cavity II) is undergoing testing. Figure 12 shows the Capture Cavity II inside the cave for cryogenics testing at MDB

The Alignment Group activities to support the Horizontal Cavity Testing facility at Meson Detector Building consisted of: referencing the cavities after arrival from DESY, establishing a high-accuracy network throughout MDB (including ties to Fermilab Primary network), performing monitoring deformations surveys, establishing the beam line,

supporting the installation, and providing precise alignment of the cavity inside the testing cage. Figure 12 shows the Capture Cavity II inside the cave for cryogenics testing at MDB.

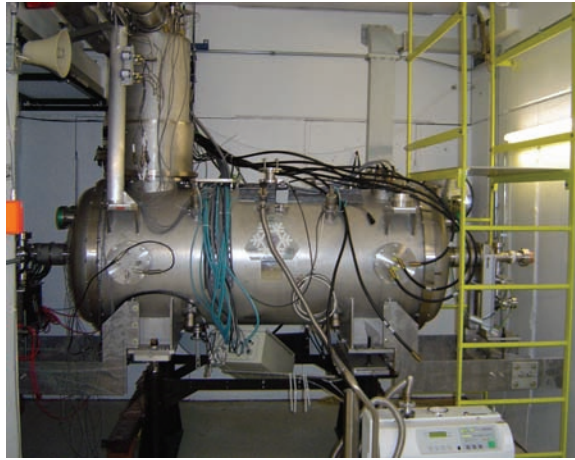


Figure 12: Capture Cavity II testing inside the cryo cave

ILCTA-NML is the dedicated ILC Cryomodule Beam Test Facility in the New Muon Lab. Figure 13 shows the site view of the ILCTA-NML. This facility will be the only U.S. facility capable of testing completed cryomodules at high accelerating gradients. The goal is to produce and test a single RF unit (two Type-III+ and one Type-IV cryomodules) by the end of 2009.



Figure 13: The New Muon Lab site

The ILCTA-NML facility will be also used in the following R&D areas [8]:

- Cavities: determine each cavity's maximum operating gradient, evaluate gradient spread and its operational implications, and measure dark currents, cryogenic loads, and radiation levels.

- Cryomodules: measure using conventional techniques the alignment of the quadrupole, cavities and BPM, measure vibration spectra of cryomodule components, and the system trip rates and recovery times.
- RF Systems: develop LLRF and control systems.
- Beam Based Measurements: beam energy, stability, and energy spread, the effects of cavity fundamental and HOM on transverse beam dynamics, Wakefield measurements, and perform studies of HOM based alignment.

The infrastructure for testing is currently under development. The NML building is cleaned out, Figure 14, including the removal of the CCM magnet. The installation of the cryogenic system has started and it is scheduled for completion in 2007.

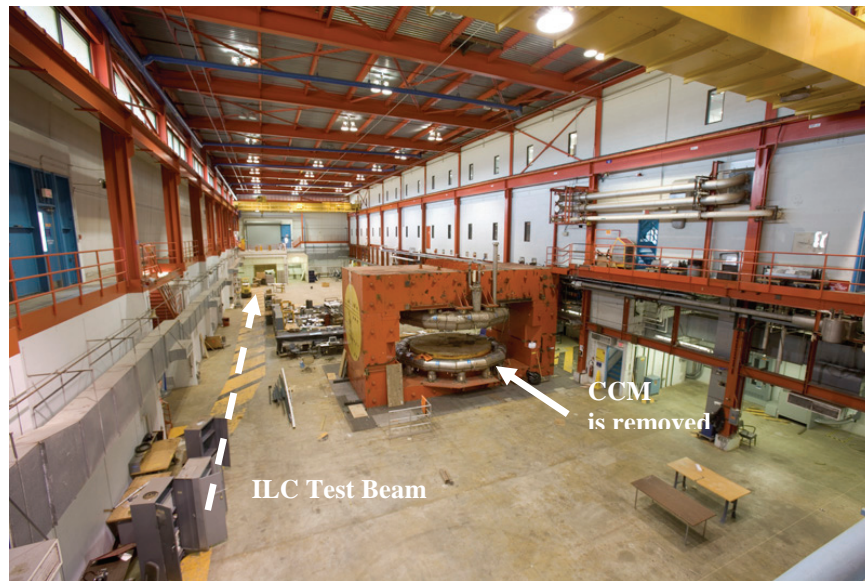


Figure 14: The New Muon Lab facility

Also in 2007, the FNPL Photo-injector, Figure 15, will be moved to NML and installed to provide electron beam. Then, in 2008, the upgraded FNPL will provide beam tests of ILC cryomodules.



Figure 15: FNPL Photo-injector

The Alignment Group effort to support the Cryomodule Beam Test Facility infrastructure development in the New Muon Lab consisted of: establishing a high accuracy network throughout NML (including ties to Fermilab Primary network), various surveys to support either the design of test facility beam line or the installation of various components, monitoring deformations surveys, and high-accuracy as found and referencing of all Photo-injector components at A0 in preparation for the new installation and alignment at NML.

2.4. Alignment Data Management System

The Alignment and Metrology Group database functions as a repository of coordinate positions of various control monuments, beam line components, fiducials, and other location points, as well as field observation data, for the Fermilab's accelerator complex and associated beam lines. The overall database integrity is in AMG responsibility.

In the recent years, some issues have arisen for users of the current database regarding the organization of data, non-uniformity of data collection, as well as access to data. Some of the organization issues derive from the fact that multiple projects are in progress simultaneously and, with various levels of involvement in different phases of the projects, multiple storage locations and data formats are generated. Non-uniform data collection has its roots mainly in the fact that, in today's era of electronic data collection and computers, much data is still handwritten in logbooks. With data coming from many types of equipment, this inconsistency in data collection formats creates difficulties not only for the quality control, but also for accessing the data. As a result, the efficiency in turnaround time before the client receives the data decreases and also the changes are more difficult to track.

Over time, the volume of data has increased and also the users have put forward newer requirements (for example the Accelerator Division wants to include alignment data in each device database). As we have gained better understanding of users requirements and activities, in order to satisfy additional requirements and to improve the response time, it was decided to redesign a new relational database and develop user-friendlier user interfaces. Figure 16 shows an outline of the new database.

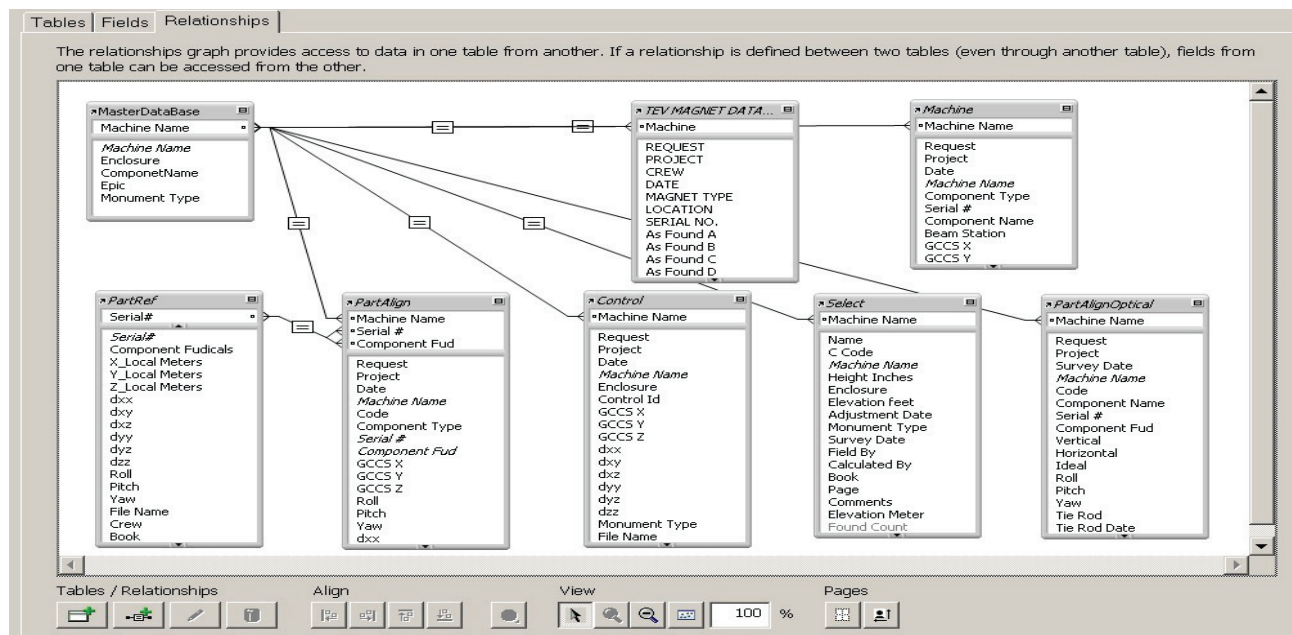


Figure 16: Database Outline

The database consists of five different tables. The first table is the Ideal Location of each component in a beam line. It consists of X,Y,Z coordinates and the rotations of the component, along with its associate covariance matrix and an unique series number. The second is Part Reference. This table is composed of the referenced X,Y,Z coordinates of the component in a local system and its associate covariance matrix, along with the unique series number that identifies it in the beam line. The third table is the Control network for each of the beam lines. It consists of the X,Y,Z coordinates and the covariance matrix and a unique series number. It should be noted that all coordinates, with the exception of Part Reference, are in a common site system. The forth table is the Vertical Network, in which we maintain, temporarily, vertical control points with “old” elevations only, from the previous database, until they are updated to the current datum. The fifth table is Part Align, which represents the “as found” or “as set” locations the components in each beam line. It also consists of X,Y,Z coordinates, the rotations, the covariance matrix and the unique series number. With this information implemented in the database, we have started to bar code all the control points and all the components with their unique series number. Therefore, any control point or beam line component can be easily tracked throughout its life. Figures 17 and 18 show a database example and, respectively a query example of the new database.

Figure 17: Database Example.

Figure 18: Query Example

Additionally, as a solution to parts of the database issues, and in order to have cohesion and consistency among different sections working within the group, it was decided to improve the data collection techniques.

For the organization of data, regardless of data collection technology used, we imposed as a standard for all alignment tasks that data should be collected, checked, analyzed, and transported to client electronically. Also, a single data storage location and data format has been implemented.

For consistency and uniformity in situation when instruments with no electronic data collection capabilities are used, we have developed software, along with using other computer data collection tools, like Excel. Regarding data collection using Excel, we have created templates with rigid outlines to follow. These files automate the checks, create summaries and have a direct interaction with the database to ensure that data used in the alignment task are up to date, making the quality control process much easier. Because some of the checks are automated and data is organized and stored in one central place, client turnaround time is much faster and more efficient. Figure 19 shows an example of Excel data collection program and automatic imports direct from database.

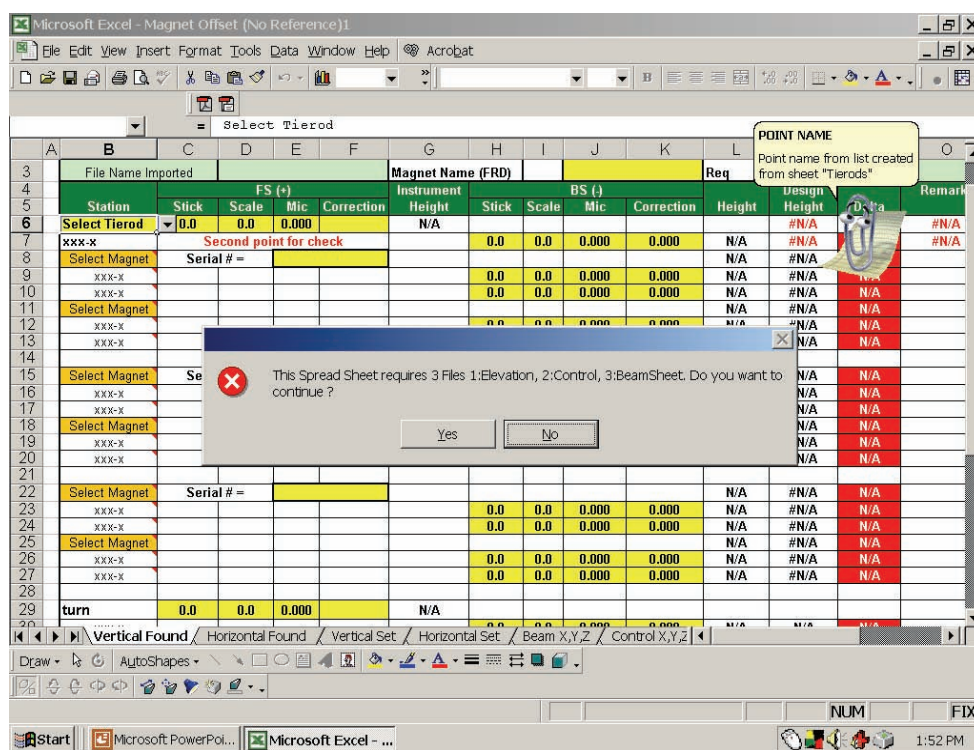


Figure 19: Example of Excel data collection program

Moreover, data and other information from the database can now be accessed through the Web, making its portability and accessibility by the clients, as well as field crews, much faster and more efficient. The bar codes makes the process automated and can help crews find data in the field where they need it. The retrieved data is then used with other programs, like Excel, to create a circular pattern of input-output with little or no interference by the crew. The speedy access to database has made it much easier for the crew, or other clients, to track changes and look at historic views.

The current status of the database is that, although there is still much data from the old database to make the transition, the data pertinent to all ongoing projects and experiments has been commissioned and implemented and released to users.

3. CONCLUSION

In the past two years, the Alignment and Metrology Group had an extremely busy schedule, putting the main focus and a considerable amount of effort and expertise into successfully completing the new experiments at Fermilab, NuMI/MINOS, the Electron Cooling, and MIPP, which are currently taking data for physics.

Other major group activities have been the completion of the TeVnet and the upgrade of the horizontal and vertical survey networks for the Tevatron accelerator complex and associated beam lines, in an effort to ensure the correct positioning of beam line components and compliment the beam based analysis data. The contributions made to the Tevatron beam line by all participating departments during the annual shutdown maintenance period culminated with a series of records in peak luminosity and integrated luminosity. In addition, our group has participated actively to the ILC Test Area project as a part of Fermilab's R&D program for the ILC, and also completed the development and implementation of the Alignment Data Management System. Despite the loaded schedule, our group has taken steps to continuously improve the methods and technology of measurement techniques, analysis and computations.

In the next years, a major part of our group's activities will focus on the R&D program and participation to the Global Design Effort for the ILC in the area of geodesy, alignment and instrumentation.

Acknowledgment

The authors thank all their colleagues from the Fermilab's Alignment and Metrology Group for their efforts and their contribution to the success of the projects. They also thank their colleagues on loan from the Argonne, SLAC and Brookhaven National Laboratories for their competent and enthusiastic help during the loaded periods of the shutdowns.

References

- [1] V. Bocean: "Status Report on the Geodetic and Alignment Results for the NuMI/MINOS Project at Fermilab", IWAA06, SLAC, Stanford, USA, September 2006.
- [2] B. Oshinowo, "Survey and Alignment of the Fermilab Electron Cooling System", IWAA06, SLAC, Stanford, USA, September 2006.
- [3] J. Greenwood, G. Wojcik, "Massive Metrology: Development and Implementation of a 3D Reference Frame for the Realignment of Fermilab's Tevatron", IWAA06, SLAC, Stanford, USA, September 2006.
- [4] Chen Yong-qi, "Analysis of deformation surveys – A generalized method." Department of Geodesy and Geomatics Engineering Technical Report No. 94, University of New Brunswick, Fredericton, New Brunswick, Canada , 1983.
- [5] DEFNAN Version 2.05 DEFormationN Analysis Software. Canadian Centre for Geodetic Engineering Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, New Brunswick, Canada, 2006.
- [6] P907, "Proposal to Measure Particle Production in the Meson Area Using Primary and Secondary Main Injector Beams", Fermilab, USA, May 2000.

- [7] R. Kephart, S. Mishra and S. Nagaitsev, “Cavity and Cryomodule R&D Priorities and Plans at Fermilab“, Fermilab, USA, June 2006.
- [8] R. Kephart, “Fermilab Plans for ILC R&D“, ILC Industrial Forum Meeting, Fermilab, USA, September 2005.