Status Report on the Alignment Activities at SLAC*

Catherine Le Cocq, Brian Fuss, Robert Ruland
Stanford Linear Accelerator Center, Stanford, CA, USA

1. INTRODUCTION

The alignment activities at SLAC are the responsibilities of the Alignment Engineering Group. This group along with the Magnetic Measurement and Quality Insurance Groups form the Metrology Department which has three primary goals:

- Support SLAC physics experiments.
- Guide all surveying and mapping efforts at SLAC.
- Promote accelerator alignment technologies inside and outside the laboratory.

Supporting physics experiments is the ultimate goal for any group at SLAC in either a direct or indirect fashion. Metrology does both through hands-on measurements of existing or future accelerator components and supporting hardware. Specifically, the Alignment Engineering Group does this through surveying and mapping while Magnetic Measurements does it through actual electo-mechanical measurements of magnets, and Quality Insurance through probes, images and other quality control techniques. All these activities involve continuous monitoring and updating of various accelerator alignment technologies through study, practical experience, or various conferences offered throughout the world.

This report mainly focuses on the Alignment Engineering Group which deals with all aspects of activities involving surveying and alignment at SLAC. These activities are grouped into the following three areas:

- Field work
- Ongoing studies
- Mapping effort

These will each be covered in detail in the following sections. In general, field work holds the highest proportion of time and effort although we are happy to not have neglected the other two areas that also help us to improve through research and collaboration with individuals outside of SLAC.

2. FIELD WORK

The majority of field work at SLAC is initiated and directed by the various current physics experiments. Presently a major scientific experiment known as PEP-II was completed and has turned out to be a true success. (http://www.slac.stanford.edu/accel/pepii).

* Work supported by Department of Energy contract DE-AC03-76SF00515.

TOC

As PEP-II switched into operational mode, another major project was fully ramping up: SPEAR. The Stanford Synchrotron Radiation Laboratory (SSRL) had been preparing the upgrade of the SPEAR2 synchrotron ring to create a higher current machine called, logically enough, SPEAR3. (*http://www-ssrl.slac.stanford.edu*) The Alignment Engineering Group has been working closely with SSRL to ensure that the new synchrotron ring with be positioned very near the old one still in operation today. In this section various details on this project will be presented followed by some information on the following future projects:

- SPEAR3 *http://ssrl.slac.stanford.edu/spear3*
- LCLS *http://www-ssrl.slac.stanford.edu/lcls*
- GLAST *http://www-glast.stanford.edu*
- NLC *http://www-project.slac.stanford.edu/lc/nlc*

Figure 1 gives a generalized overview of the various project locations on the SLAC sight. The 3 km long linear accelerator dominates the left half of the figure showing where the positron and electron injectors are located. The right half shows existing structures such as End Stations A and B (ESA and ESB) and the Beam Switch Yard (BSY). The Linac Coherent Light Source (LCLS) will utilize the last third of the linac and continue out past the end of the existing Final Focus Test Beam (FFTB). The Next Linear Collider (NLC) will not be built on SLAC property but the Next Linear Collider Test Accelerator (NLCTA) is located next to the FFTB. The Gamma Ray Large Area Space Telescope (GLAST) is not shown since eventually it will be orbiting the earth.

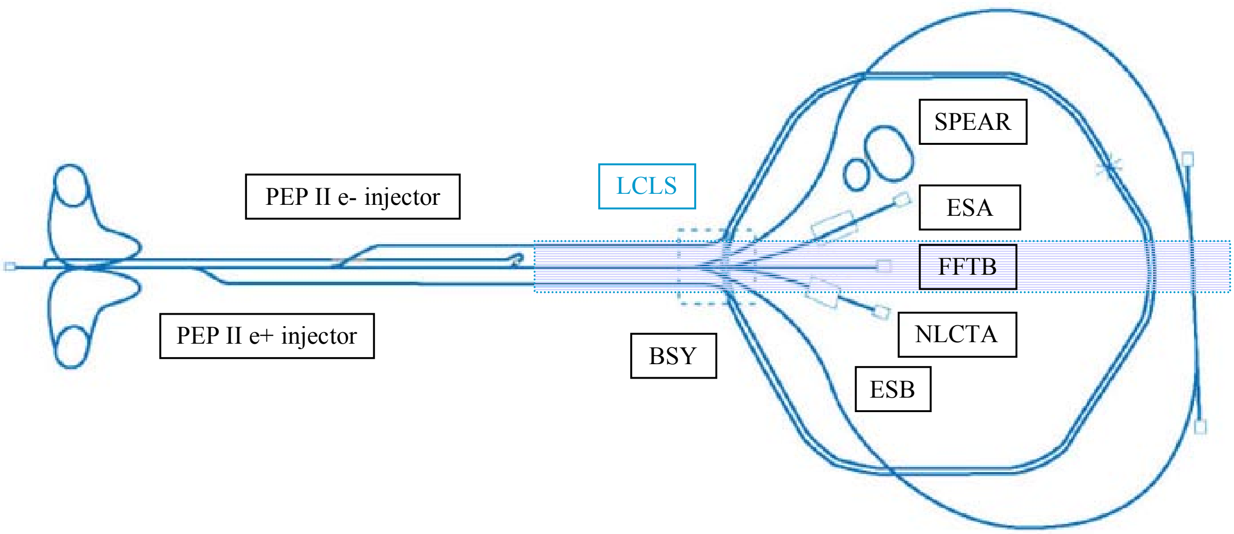

Fig. 1 Overview of SLAC Projects

2.1 PEP II

2.1.1 Review

PEP-II is built as two independent storage rings located atop each other in SLAC's PEP tunnel (Fig. 2 and Fig. 3). The high-energy ring stores a 9-GeV electron beam, while the low-energy ring, stores 3.1-GeV positrons. The construction of PEP-II was a collaboration of SLAC, LBL and LLNL. SLAC's contribution to the alignment of the magnets and components was substantial.

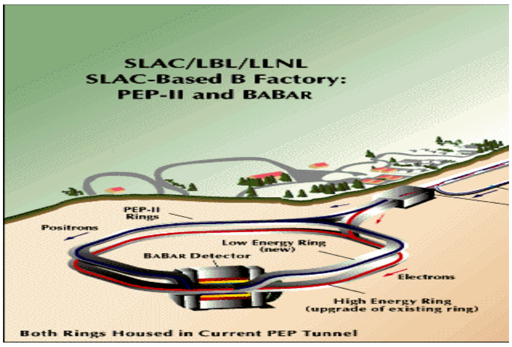

Fig. 2 PEP-II and other facilities at SLAC

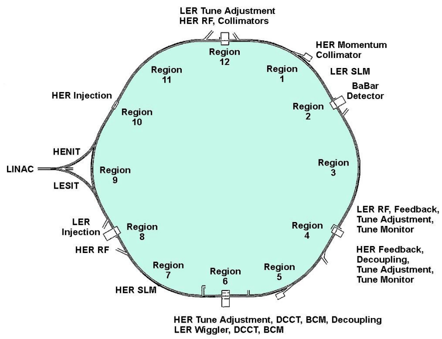

Fig. 3 PEP-II High Energy and Low Energy Ring Layout

PEP-II has been operating very successfully since being commissioned in July 1998.

2.1.2 Alignment Results

The PEP-II ring has had two complete surveys since our last report at IWAA 97. The first survey was a map of the overlapping high and low energy ring components. The mapping began in November 2000 and was completed in mid December. The network adjustment for this survey included all the observations on the monuments and magnets as well as all the local (regional) remaps done in order to obtain a smoothed curve for the beam path. Care had to be taken to ensure that the smoothed path would not cause components to wander too far off of the originally planned beam path. LEGO was used for the adjustment with the following settings:

- Free datum based on monuments (floor and wall)
- Individual distance offsets for each tracker position

The adjustment results were excellent and since then the ring has been operating very successfully producing a great deal of data for the physicists.

A scheduled "down-time" took place during the summer and fall of 2002. This was an opportunity to complete a new map of the ring components. Free-stationing techniques utilizing the SMX 4500 laser tracker was used in combination with Leica's Na3000 automatic level. The network consisted of 349 wall monuments and 109 floor targets. To give an idea of the scope of this survey, the high energy ring (HER) consisted of 290 quadrupoles and 12 sextupoles and skew quadrupoles. The low energy ring (LER) consisted of 315 quadrupoles, 2 bend magnets and 58 sextupoles and skew quadrupoles. Fixtures in form of a triangle had to be used for the LER quadrupoles. The HER quadrupoles had four tooling ball positions permanently welded on the top of the magnet and two on the side.

In terms of network adjustments, a similar observation plan was used for this particular down-time survey as was done in 2000. The 2002 data analysis was also based on a free datum approach but no distance offsets were introduced. The final 2002 adjustment is currently in process and will subsequently be compared with the 2000 and even earlier results.

Table 1 PEP-II Network Description

	2000	2002
Stations	604	359
Points	3636	3507
Tracker Triplets	13699	10446
Height Differences	1109	1311
Unknowns	15140	12679

Table 2 PEP-II Network Standard Deviations

	2000	2002
D µm	30	50
h µm / D	40	50
v µm / D	100	50
h µm	50	50

2.2 SPEAR

2.2.1 Review

SPEAR3 is an extensive project at SLAC whose goal is to replace magnets and vacuum chambers in the existing SPEAR ring. The first ring (SPEAR1) operated at a maximum energy of 2.4 GeV and then in 1974 it was upgraded to SPEAR2 which operated up to 3.5 GeV, 100 mA. SPEAR3 will also be at 3 GeV but with a current of 200 mA.

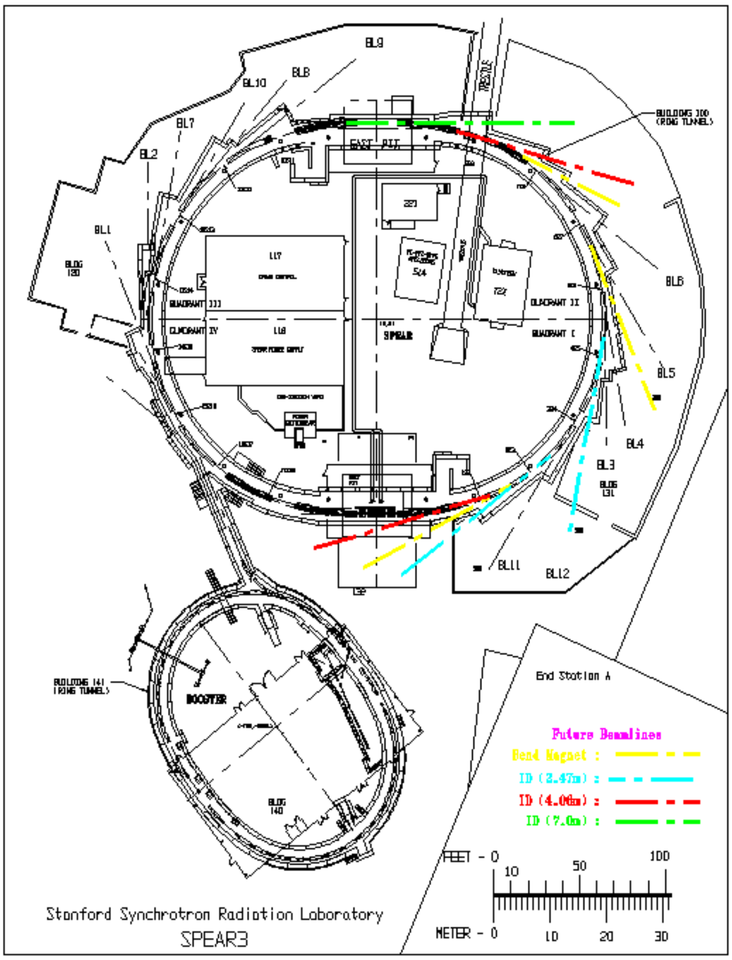

Fig. 4 SPEAR3 Layout

2.2.2 Alignment Results

Future alignment of SPEAR3 requires knowledge of SPEAR2 magnet positions. As part of the preparation for the removal of existing SPEAR2 components and extensive upgrades in infrastructure, the Alignment Engineering Group has been working on three primary areas:

- Mapping the ring
- Fiducialization
- Raft assembly

Mapping of the SPEAR2 ring was, without question, difficult due to many factors. Significantly the worst problems included the lack of proper prior surveys. Although a substatial effort to map the existing SPEAR2 ring within the past ten years has provided some useful reference data in terms of leveling, the lack of some more detailed earlier data has been troublesome. This coupled with the tightly arced geometry of the narrow tunnel and related lack of geometrically significant three-dimensional targets leaves little in terms of a solid surveying network. Many targets were also destroyed due to construction at various regions around the ring including the old east and west pits. This creates an even greater challenge in controlling the monumentation so that future components can be placed in a similar manner as the SPEAR2 components.

Currently the effort has been to remap the entire SPEAR2 ring including existing magnets but also to map and tie in the connected booster ring (see Fig. 4). Laser trackers, total stations, and digital levels were used and substantial post processing was necessary to tie everything together. Table 3 summarizes these results:

Table 3 SSRL Network Description

Stations	168
Points	326
Triplets	1335
Height Differences	400
Unknowns	1810

Free-stationing was used everywhere except for two instances of forced-centering in the Booster-To-SPEAR (BTS) area. This region was very narrow with almost no choice in terms of geometrically sound target and instrument positions. Forced-centering actually provided a means to improve an almost impossibly poor network in this area. Overall a free network based on selected floor points in the SPEAR ring was used. Total station observations were grouped together depending on a combination of the specific instrument and specific prism used. One distance offset was also included in each group. Of note is that some observations were necessary that actually went in and out of various buildings. Standard deviations for this complete survey are as follows:

- Standard deviation of tracker distance 50 µm, total stations 200 µm
- Standard deviation of height differences 50 µm
- Standard deviation of horizontal angles 60 µm / distance
- Standard deviation of vertical angles 75 µm / distance
- Some individual standard deviations for shots going in and out buildings

Fiducialization has been a very time-consuming task. SPEAR3 components including specialized gradient dipole magnets and vacuum chambers presented new challenges in precision fiducialization. For example, the dipole magnets had to have the mechanical centerline positioned relative to the magnetic centerline. This involved extensive collaboration with Metrology's Magnetic Measurements Group [3]. Physicists at SSRL later decided that this offset was not directly needed. Another example is the vacuum chambers. Fiducialization involved many iterative steps that included using the laser tracker to act as a surface scanner as well as a 3-D point determiner. As for other magnets, quadrupoles and sextupoles were very efficiently measured by Alignment Engineering personal working in the Quality Inspection Group. A manual Coordinate Measuring Machine (CMM) was used to fiducialize a number of welded-on tooling ball positions. Verification of this process was accomplished by independent measurements of these same fiducials using the laser tracker.

Raft assembly involved placing all the fiducialized magnets and vacuum chambers onto a series of girders that link together to form portions of the SPEAR3 ring. Although somewhat questionable, the goal is to pre-align the components onto a raft and then very accurately place the raft in the SPEAR tunnel using a combination of alignment pin and hole or slit for positioning. The hope being that no component would have to be moved individually! To achieve this, components have to meet certain positioning tolerances as presented in Table 4.

Table 4 SPEAR3 Tolerances

Component	Rotation rms (mrad)	*Displacement rms error (mm)		
	Roll	X	Y	Z
Bend Mag	0.50	0.15	0.15	0.50
Quadrupole	0.50	0.20	0.20	0.75
Sextupole	0.50	0.20	0.20	0.75
RF cavity	0.50	0.20	0.20	0.75
Corr. Mag.	0.50	0.20	0.20	0.75
Vac Cham	-	0.20	0.20	0.50
Kicker	0.50	0.50	0.50	0.50
Ins Dev	0.50	0.25	0.25	0.50

2.3 Future Projects

2.3.1 LCLS

One future challenge for the Metrology Department involves a special new machine being developed that creates a single-pass X-ray Free Electron Laser (FEL). This is known as the Linac Coherent Light Source (LCLS). It is a multi-institutional project to develop and create such a device with an operational wavelength of 1-15 Å at energies up to 15 GeV using electron beams from SLAC's linac. (http://www-ssrl.slac.stanford.edu/lcls).

The main components of the LCLS are:

- a photo-cathode rf-gun
- the last 1 km of the SLAC linac
- two bunch compressors
- a 120 m long undulator in the FFTB hall
- X-ray optics
- Experimental stations.

Presently the LCLS is at the early design stage. The 120 meter undulator presents an alignment challenge with a tolerance of only 25 µm over 150 meters or more specifically 20 µm for the length of the undulator. Based on a highly developed experiment, the Visible To Infrared Sase Amplifier (VISA) experiment has proven that the concept can work [1]. Being only 4 meters long, the use of laser interferometers has shown that a few microns can be repeatedly measured horizontally or vertically (see section 3.1). In terms of alignment, the LCLS will be a modified version of VISA where horizontal X-positions will be based on an absolute wire finder while the vertical Y-position will be based on an absolute ultrasound HSL (Hydrostatic Level) having micron resolution.

2.3.2 GLAST

GLAST (Gamma-ray Large Area Telescope) is what is known as a next generation high-energy gamma-ray observatory designed to make celestial gamma-ray source observations in the energy range from 10 MeV to over 100 GeV (*http://www-glast.stanford.edu*). Two experiments are planned:

- LAT (Large Area Telescope) from 30 MeV to 30 GeV
- GBM (Gamma-ray Burst Monitor) from 5 KeV to 30 MeV

Alignment Engineering will be involved in aligning the sensor towers that make up the detection unit. Presently the plan is to use the laser trackers to position each cell as the unit is assembled in a specially created clean-room located at SLAC. Particular monumentation has already been established in this room with targets located on support structures and on the floor.

2.3.3 NLC

The Next Linear Collider (NLC) is another international collaborative project where the goal is to design and build a high-energy, very large positron-electron collider (*http://www-project.slac.stanford.edu/lc/nlc*). In terms of alignment studies, SLAC is working in collaboration with Germany's DESY to design and test a Rapid Tunnel Reference Survey System (RTRSS). This collaborative effort's early results have already been presented at the Snowmass 2001 conference in Colorado by both groups. Results are reported in the *Detailed Summary of the Working Group on Environmental Control T6* that can be found at

http://www.slac.stanford.edu/econf/C010630/papers/T6001.PDF

For the magnetic measurement studies, SLAC is building a test stand using rotating coils to measure the magnetic axis of both the traditional and permanent quadrupoles with a resolution of about a micron.

3. ONGOING STUDIES

3.1 Instrumentation

In parallel with the projects discussed above, several instrumentation studies are in progress. Various conventional or classical instruments have been used at SLAC including:

- Laser Trackers and Total Stations
- Leveling Instrumentation
- Gyrotheodolites

An extensive study was published at SLAC (SLAC–TN–2000–1) detailing the operational accuracy of the SMX Laser Tracker alone or in combination with the Wild TC2002. The study concentrated on an apparent scale problem that analysis proved to be primarily due to a prism offset problem [2].

Fig. 5 FARO Keystone Laser Tracker

A new generation of laser tracker has been designed by SMX and produced now by FARO. SLAC's Alignment Engineering Group has tested one of the first Keystone trackers both in the controlled environment of the lab and in real operation as shown in Fig. 5. Results show some problems that have lead to shipping this tracker back to the manufacturer.

http://www.smxcorp.com/Products/Laser_Tracker.asp

Overall though, these laser trackers are compact and much lighter than the older models making them more truly portable. With the *SuperADM* ability these trackers are more versatile allowing for faster and more convenient absolute distance measurements without the worry of breaking the tracker beam. With all this in mind, these laser trackers should prove to be invaluable instruments in the confined regions of the new SPEAR3 ring at SLAC (see section 2.2).

Currently the Alignment Engineering Group has 3 types of precise levels:

- Leica Na3000 (automatic)
- Zeiss DiNi 12 (automatic)
- Wild N3 (manual)

The automatic levels presently have the favor of the Alignment Engineering survey crews due to speed but they do require good lighting for reading the bar code. Until recently the Leica Na3000 was the instrument of choice but now the Zeiss DiNi 12 is expected to be used for SPEAR3. The Metrology Department is planning on upgrading the "Sector 10" laboratory to include a vertical test bench for further leveling studies.

SLAC was fortunate to obtain two Gyromat 2000's from the abandoned SSC project in Texas. They have been used in a few test cases but no conclusive findings in terms of accuracy have been independently obtained. Further study is warranted.

Other devices have also been part of our ongoing study process. The Elcomat 2000 from Möller-Wedel is one such device that accurately measures offsets. It has been used as a collimating device for the verification of the consistency of a linear rail used for fiducializing dipole magnets. Various inclinometers have been incorporated into similar efforts such as monitoring the position of an arm used to sense the magnetic fields of dipole magnets. Lastly, the Hamar Laser System was studied. A pair of mutually orthogonal rotating lasers provides two planes that can be used as references for measuring offsets. The use of auditory feedback for measuring the straightness of a stack of accelerator cups using the Hamar Laser was tested and the results are presented in the poster included in these proceedings [4].

Straightness measurements using HP lasers and interferometers have yielded some very precise results. The VISA project has the goal of creating high quality x-rays by using undulating magnets. Strict alignment tolerances were necessary to line up for of these magnets and this was best solved using one straightness interferometer for horizontal offsets and one for vertical offsets. Results suggested that offsets even under one micron were possible and repeatable (see also section 2.3.1).

3.2 Model and Software Development

The core network analysis package used and developed at SLAC is LEGO. Further enhancements have been included in the software since previous reports such as the following:

- Approximate coordinate determination
- New type of observations added

- Expanded error checking

The original computation for approximate parameters was based on a" 2D+1D" approach which works perfectly for theodolites and total stations because they are instruments leveled to gravity. In this method, the observations are reduced to the horizontal plane and a solution is first derived for this plane and then followed by a computation off the plane. This technique is still valid for most laser tracker applications as the laser tracker is generally setup on a vertical stand and is then oriented close enough to vertical for the approximate determination. The advantages of this technique are simplicity and speed. The limitations are in the size of the network and, of course, in the assumption that all instruments are "semi-leveled".

The new method is completely 3D and uses a resection algorithm based on the quaternion formalism for rotation representations. It is made for laser tracker surveys of any size and solves the problem of an instrument placed in any orientation (even upside-down). In the case of a complete absence of a-priori information, the process starts by setting the origin at the first instrument in the list and spreads by a series of intersection and resection steps. If the network is a combination of leveled and non-leveled observations, the algorithm disregards the leveled observations at first and adds an extra step of reorientation of the approximate network leading to fewer iterations in the resolution part for most cases. In the last PEP-II surveys the number of iterations went down from 7 to 3. The strength and limitation of this new routine is the assumption that triplet observations (2 angles and a distance) are available to any point in the network. When faced with theodolite observations only, the original routine has to be used. The architecture of LEGO is made such that you can start with the new routine and use the original one to complete or overwrite the previous calculation. The combination of the two methods has been proven to be very efficient.

To keep up with the instrumentation studies, azimuth observations have been integrated into LEGO. This has been tested against simulated data and is awaiting future studies of the Gyromat 2000 (see section 3.1). In order to limit pre-analysis, the height differences can be entered directly without worry if the end points are actually observed in the other dimension. This makes the studies of the rivets a lot more convenient and insures the right weighting of the original observations.

Along with LEGO, the visualization tool SIMS has been improved and enhanced. More flexibility in importing data (including autocad drawings) is now available and refinements are ongoing in many other areas including user interfacing. WinGEONET has also had some changes and upgrades as outlined in the posters included in these proceedings [5][7].

A study has been completed here at SLAC on the existing WinGEONET model for correcting distances using Owen's formula as well as the newest accepted model (IAG Special Commission SC3 – Fundamental Constants) developed by Philip E. Ciddor. Three points of interest have surfaced as a result of this study:

- In the case of the TC2002, WinGEONET's existing atmospheric model was not completely updating the wavelength of the instrument (5.3 ppm _= 850 nm at standard atmosphere),

- The difference between the corrected Owen's formula and the new Ciddor model is about 0.13 ppm at standard conditions and can possibly get as high as 0.40 ppm at extreme SLAC conditions,
- An error of 7 to 9 ppm was found in using the existing WinGEONET group model (i.e., Owen's formula) instead of the more appropriate phase model developed by Ciddor. This is for single frequency instruments such as laser interferometers.

Lastly, the treatment of geodetic observations for accelerator alignment requires a constant effort in reevaluating what can be neglected or what should be corrected. In this aspect, a study of the tidal strain tensor applied to angle measurements was presented at the 22nd Advanced ICFA Beam Dynamics Workshop held at SLAC November 6-9 2000.

4. MAPPING EFFORT

To keep up with the new installation, SLAC is undergoing an update of its current site map. In this spirit, the Metrology Department acquired 3 GPS Leica SR-530 receivers in October 2001. The first action of the Alignment Engineering group was to update the tie of the SLAC network to an existing datum. Table 5 shows the current coordinates of our base station. Further details can be found in the Alignment Engineering web page and in the poster included in these proceedings [6].

Table 5 M40 Coordinates

	X_global Z_SLAC	**Y_global X_SLAC**	**Z_global**
ITRF2000	**-2703115.873**	**-4291767.294**	**3854247.829**
NAD83	**-2703115.209**	**-4291768.558**	**3854247.785**
SLAC	**60.54993**	**-2.41754**	

A large and complex project has been initiated that could lead to the use of Graphical Information Systems (GIS) at SLAC. Studies and on-site demonstrations lead the authors to conclude that using MicroStation V8 with GeoGraphics would be the best choice. With a site license already in place and the resolution being extremely fine, the decision was even easier to make. In combination with GPS (see above) a new and more refined survey of SLAC's buildings, roads and other landmarks has begun. The goal is to accurately measure these objects within a well determined coordinate system and to eventually link attribute data together so that a relational database can be used to construct countless queries. Highly accurate survey data will be readily available along with less spatially refined information in what should hopefully become a seamless graphical tool.

5. CONCLUSION

Various challenging new projects have been realized and some ongoing studies have shown that one can not always rely on accepted information. The Alignment Engineering Group along with the others are supporting many projects such as PEP-II, SPEAR3, LCLS, GLAST, NLC and has been exploring areas such as GPS and GIS along with new instrumentation used for everyday surveying such as a new generation of laser tracker. Many details on these projects can be found at the links presented in this paper or information specific to the Alignment Engineering Group can be found at *http://www.slac.stanford.edu/grp/met* .

Overall this is a very interesting and dynamic time at SLAC which has celebrated its 40th anniversary on October 2nd 2002 http://www-conf.slac.stanford.edu/40years.

40th Anniversary of Stanford Linear Accelerator Center

SLAC 1962-2002

6. REFERENCES

[1] R. Ruland, B. Dix, B. Fuss, C. LeCocq, Z.R. Wolf (SLAC), J. Aspenleiter, G. Rakowsky, J. Skaritka (Brookhaven), *Alignment of the VISA Undulate*, SLAC-PUB-8336, Feb 2000. 8pp, Presented at the 13th International Course on Engineering Surveying, Munich, Germany, 13-17 Mar 2000,

[2] C. LeCocq, B. Fuss, *Analysis of Laser Tracker and total Station Surveys*, SLAC-TN-00-001, July 2000 21pp.

[3] J. Tanabe, R. Boyce, D. Dell'Orco, N. Li (SSRL), Z. Wolf, C. LeCocq (SLAC), H. Ou, R. Hou (IHEP), *SPEAR3 Magnet Design, Measurement and Alignment,* Submitted to the conference on Synchrotron Light Source, Shanghai, China, October 2001.

[4] B. Fuss, *3D Arcing for Offset Measurements with a Hamar Laser,* Presented at the 7th International Workshop on Accelerator Alignment, Spring-8, Japan, 11-14 November 2002.

[5] L. Langer, *Bringing COM Technology to Alignment Software,* Presented at the 7th International Workshop on Accelerator Alignment, Spring-8, Japan, 11-14 November 2002.

[6] D. Behrend, C. Banuelos, C. LeCocq, *GPS Activities at SLAC,* Presented at the 7th International Workshop on Accelerator Alignment, Spring-8, Japan, 11-14 November 2002.

[7] M. Gaydosh, L. Langer, C. LeCocq, *WinGEONET: What's new?* Presented at the 7th International Workshop on Accelerator Alignment, Spring-8, Japan, 11-14 November 2002.