# SIMS: The SLAC Industrial Measurement System

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## 1. Introduction

The development of electronic sensors and of small powerful computers, and their integration together have led to the development of what has come to be known as Industrial Measurement Technology (IMT). Industrial Measurement Systems feature one or more electronic sensors and a computer with powerful software. The software has three essential components: data collection, data reduction and data analysis. In the field of industrial surveying, the IMT system is the automated theodolite system, but other systems such as the laser tracker are on the horizon.

## 2. History of IMS at SLAC

Kern was the first survey company to market an Industrial Measurement System when it released ECDS (Electronic Coordinate Determination System) in the mid-1980s. Originally written for the PDP-11, a version was later released for the PC (ECDS-PC). SLAC purchased this system in 1986 and immediately began to use it for the alignment of the SLC (Stanford Linear Collider). Although ECDS enabled us to perform tasks with a speed never before achieved, we experienced limitations in the software. Since Kern proved unresponsive and we were unable to purchase the source code for any amount of money, we set about writing our own portions of code. We first wrote a system of menus tailored for our specific alignment tasks, and disabled much of the ECDS menu structure. Due to dissatisfaction with the ECDS bundle adjustment program, we wrote our own bundle adjustment in 1988. A further step toward having our own complete IMS was to develop a data capture program, a task which has been underway since the beginning of this year. We do not yet have data analysis features that are fully integrated, but we do have stand-alone packages that have been written at SLAC. When we first started tinkering with ECDS there was no intention of developing a complete system, but we now have all the elements of such a system - SIMS, the SLAC Industrial Measurement System.

This paper describes the features of our system and some of the uses we have made of it.

# 1. SIMS Described

## 1.1 Hardware

The sensor used in SIMS is the Kern E2 electronic theodolite, our workhorse of the past few years, but it is planned to expand SIMS to handle Wild T3000 theodolites. Our choice of computer is the Compaq III portable because of its convenient size, but any 286 machine can be used. A 287 co-processor is advisable, but not essential, for the heavy-duty number-crunching software modules. The hardware is housed in a wooden crate mounted on the back of a small electric cart for easy portability around the laboratory. This crate contains the computer, a printer, and the power supply for the theodolites. Space is provided for other devices, such as an inclinometer interface box which is usually housed in the bottom. A panel on the outside of the crate provides receptacles for the cables to the theodolites as well as to other instruments such as the inclinometers. The panel has four E2 ports but more theodolites can be connected by using little mutliplexer boxes built at SLAC.

## 1.2 Software

In order to avoid retraining operators and to maintain consistency with old ECDS data sets, the SIMS programs were originally designed in a style similar to ECDS. As time has gone on, though, and SIMS has evolved into an entity totally distinct from ECDS, the two IMS systems have diverged in their looks and functionality.

Whether the measurement tool be a theodolite, a laser tracker or a CMM, IMS software has three major components:

(*a*) *Data Capture:* The software to control the measurement heads and record data from them. Elementary error checking should be included.

(*b*) *Data Reduction:* The software to calculate coordinates from the raw data, preferably using rigorous least-squares methods.

(*c*) *Data Analysis:* Software to analyse and evaluate the computed coordinates. Capabilities should include coordinate transformations and geometrical fits (e.g., circles, planes).

The SIMS software is written in Microsoft C and Microsoft. Fortran to run under DOS.

### 1.2.1 Data Collection

The data capture program offers all the functionality of ECDS with the addition of several features that we have found necessary for our work at, SLAC. It was because ECDS did not offer these features that we developed our own data capture program. Some of these features have become available in later versions of ECDS, but they were not available when we had need of them.

1. *Direct and Reverse Measurements.* ECDS allowed observations on only one face. A measurement job in the summer of 1988 required vertical angles exceeding 50°. By taking measurements on both faces a substantial improvement was obtained in the strength of the bundle adjustment. Since then our standard measurement procedure has been to measure all points on both faces, no matter what the vertical angle. For steep sights the mean of direct and reverse measurements eliminates certain instrument and set-up errors. For all observations, the mean of direct and reverse measurements eliminates collimation errors. With electronic theodolites the collimation error can be corrected electronically, but we have had problems with these correction values drifting significantly over time. It is our recommendation that all measurements for industrial survey be two-faced, something that has been ingrained into us in school for good reason.

2. *Re-initialization of any theodolite at any time.* For a large object, or even for a small one in which one cannot see all points from one set-up, the theodolites are moved to new locations for further measurements. In ECDS this required exiting the program and starting all over again with the re-initialization of all instruments. Often it is not desirable that all instruments be moved. SIMS has therefore been written to allow any instrument to be moved and re-initialized at any stage in the program without disturbing the other instruments or the program.

3. *On-line checking of observations against nominal coordinates.* For much of the work for which SIMS is used, nominal coordinates are available for the points being measured. This is so when the task is to align elements into their design locations, or to undertake an as-built survey to check conformity with design coordinates. It is possible in SIMS to measure the control points on an object, exit the program to run the bundle adjustment and any necessary coordinate transformations, and return to the data capture program in the same place but now with known coordinates for the theodolites in the object coordinate system. This permits on-line checking for the consistency of observations with the nominal coordinates of the points. For each measurement point a check is made of the control file. Points in the control file can be identified as fixed or approximate, and separate tolerances can be applied to these two types of points. This feature is useful in trapping blunders such as misnamed points or sighting on the wrong point something

that can frequently happen if there are a lot of closely-spaced points.

4. *Non-sequential instrument addresses.* The address switch on the Kern E2 theodolites can be set from 0-9, but ECDS required the instruments to be numbered sequentially from 1. Since our theodolites are identified by the address switch the number being assigned in the order of their acquisition, this forced us to change the numbers, making it difficult to keep track of which physical instruments were used for a particular survey. SIMS has been written to handle any addresses from 0-9 and they can be non-sequential. The only requirement is that two instruments not have the same address. This enables us to know exactly which physical instruments have been used.

### 1.2.2. Data Reduction

The data reduction part of SIMS consists of 3 programs:

(a) MEAN: calculates the mean of the direct and reverse measurements and prints this to the output file, together with the horizontal and vertical differences between the observations. Differences greater than 5 mgon are flagged.

(b) INTER2: computes approximate coordinates for the theodolites and for the object points, using data in the control file.

(c) 3DCD: the bundle adjustment which is a rigorous, iterative least-squares adjustment (Gaunt, 1988). The 3DCD print-out contains not only the final coordinates, but also the residuals in the observations, standard errors for the object points and theodolite stations. Relative errors between any two points can be optionally requested in the input file. The residuals are in angular units, unlike the ECDS bundle adjustment which gave residuals as the perpendicular distance offset from the observed point; this is of little value since it is as dependent on the distance between the instrument and the point as it is on the angular accuracy of the observation.

There are two versions of 3DCD, one on the PC the other on the mainframe computer. The programs are identical except for the number of observations and points they can handle:

| | Theodolite Stations | Object Points | Observation Pairs |
|---|---|---|---|
| PC version | 10 | 70 | 700 |
| Mainframe | 25 | 350 | 8750* |

### 1.2.3. Data Analysis

The data analysis part of SIMS exists as a set of stand-alone programs, mostly on the mainframe, that have not yet been integrated with the suite of

SIMS programs on the PC. There is not a pressing need for this integration since it is usually more convenient to do the data analysis back in the office while the field crew continues to record data. The programs used most often are the 7-parameter coordinate transformation package and the plane and circle fit routines.

## 2. Use of SIMS at SLAC

### 2.1 SLC Manget Junctions

The two arcs of the SLC are each about 1400m in length and contain about 460 magnets, divided into sets of 20, each set being known as an achromat. Although the tolerances on the absolute position of each magnet are tight, it is the relative alignment of each magnet relative to its neighbors that is especially critical. Due to topographical restrictions of the site, the SLC arcs undulate up and down as well as being curved in the horizontal plane. As a result, each magnet is pitched and rolled out of the horizontal by up to 10º in pitch and 15º in roll. The change in pitch and roll from magnet to magnet is small, except at the achromat junctions where there can be an abrupt change in attitude. Because of these large discontinuities in magnet orientation across achromat junctions, it proved impossible to develop a mechanical jig for the alignment of the adjacent magnet ends. It was for the alignment of these junctions that we first used ECDS, and it quickly proved its worth. The method was to survey the fixed end of one magnet and then, having performed the necessary coordinate transformations, measure the adjacent adjustable end of the next magnet in the coordinate system of the fixed end. Although ECDS proved itself useful for data collection and for the bundle adjustment, its shell was cumbersome for SLAC's needs. Consequently we wrote our own shell program, tailored specifically to the project, and incorporated only such parts of ECDS as were needed (Oren, 1987). In addition our shell contained interfaces to databases of magnet calibration values and of ideal coordinates as well as interfaces to other electronic equipment such as inclinometers and electronic digital indicators.

Thus was started our history of dabbling in ECDS, a process which eventually led to the development of a completely independent system, though this was not envisaged at the time.

### 2.2. Fiducialization of Beamline Components

The standard feature that is used as a reference or fiducial on beamline components is the quarter-inch tooling socket. Prior to installation, coordinates must be determined for these sockets in a coordinate system based upon the magnetic or geometric centerline of the part,. Small parts are taken offsite to a contract measurement service with a Coordinate Measuring Machine (CMM). Parts too large for this CMM have been measured at SLAC using SIMS. In this case, SIMS is operating like a large but portable CMM.

### 2.3. Alignment of Detector Components

SIMS has proven useful as an alignment tool in the construction phase of SLD components. The Cerenkov Ring Imaging Detector (CRID) is built inside a cylinder 3.5m in diameter and 7m long. The various subassemblies of CRID lie on planes and circles at various distances from the centerpoint. It was easy then to fit circles and planes through measured points, using the residuals from these best-fits to bring the parts into their ideal locations. Several iterations were made to bring the points within tolerance.

Due to its size, the assembly of CRID did not lend itself easily to optical tooling, but SIMS proved its worth as an alignment tool.

### 2.4. As-built Surveys of Detector Components

In the past year a couple of projects have been undertaken which have proven very stretching both for our survey crews and for the SIMS software. At the same time, they have been excellent an proving ground for SIMS, and the current state of the software owes much to needs and ideas that arose during these projects.

Both projects required the measurement of a large number of points in as-built surveys of components for the SLD detector. No alignment was required, only XYZ coordinates in the coordinate system of the relevant chamber.

#### 2.4.1. The End-Cap Drift Chambers

The SLD detector has four end-cap drift chambers, two large chambers 3.5 m in diameter and two smaller chambers of 2m diameter. All four chambers are approximately 30cm thick and contain three layers of wires, rotated 60° with respect to one another. The task was to measure the location of each wire terminator block. Visibility was relatively poor because the blocks were recessed inside the layers and because the direction of the blocks on one layer was 60° or 120° different from the other layers. As a result it required many instrument set-ups to measure each chamber, even with four instruments in use. The most instrument stations used was 43 for one of the large chambers. The resultant data set was too large even for the mainframe version of 3DCD and was broken into two sets, of 27 and 16 stations. It was for this project that it was helpful to have software that facilitated the movement and re-initialization of any theodolite at any time. An interesting feature of this project is that it was easier to rotate the chambers than to move the instruments to see a new set of blocks. The X-axis of each chamber was marked on the top so that the theodolites could be pointed in the right direction during initialization.

### 2.4.2. The Central Drift Chamber

The SLD Central Drift Chamber (CDC) is a cylinder 2 m long and 2m in diameter with 40,000 wires stretched end to end. The wires are held in 640 terminator blocks in each end cap. We were requested to measure not only the location but also the attitude of each of the 1280 blocks. To determine the plane of each block required the measurement of at least three points on the target. fixture. Including the fiducial points and blocks that were re-measured after being replaced, over 4000 points were measured, each with direct and reverse observations from three theodolites. The geometry and measuring conditions were excellent, but the task of making 25,000 separate measurements imposed a strain on both the operators and the software. Through the course of this project a number of suggestions were made and implemented to streamline the SIMS software. Since there was no need for the simultaneous least-squares adjustment of all the points, the data was reduced in sets of up to 200 points as the work progressed.

The CDC was also rotated as the measurements progressed while the instruments stayed in place, but unlike the end-cap chambers which were rotated in the horizontal plane, it was rotated in a vertical plane about its horizontal axis. Consequently, there- were times when the theodolites were “upside-down” in the object coordinate system. In order for the bundle adjustment to run successfully it was necessary to enter the approximate orientation of the theodolites in the input file.

Neither of these projects would have been feasible just a couple of years ago. It is the development of IMS that has rendered such large surveys possible. Nor would the projects have been feasible with ECDS because the clumsiness of the software would have rendered the project prohibitively expensive in manpower requirements. Having proven our capability in handling such projects we expect requests for further as-built surveys. SIMS will be used unless the project lend itself to photogrammetry and funding is available for such.

## 3. Conclusion

SIMS has been developed from ECDS to suit the measurement tasks specific to SLAC. There is no pretence that it is the most suitable package for all industrial measurement needs. ECDS or the Wild MANCAT package may indeed be more suitable for more conventional tasks, but SIMS is adapted to the specialized requirements of accelerator alignment. It has been beneficial to develop our own in-house system. A particular advantage of this is that we have our own source code onsite so that new features can be incorporated as the need arose. SIMS has been evolving for the past three years and will surely continue to evolve to meet the ever-growing challenges of survey and alignment at SLAC.

## 4. References


1. Gaunt, J.M., Bundle Adjustments and Tri-dimensional Coordinate Determination, 198S, SLAC-PUB-4717.
2. Oren W., R. Pushor & R. Ruland, Incorporation of the Kern ECDS-PC: software into a project orientated software environment. *Proc. of the 47th. ACSAI-ASPRS Convention,* SLAC-PUB-4141.


## 5. Addendum

Since this paper was presented in August 1989, SIMS has been further enhanced and developed. Wild T3000 theodolites have been fully integrated, so that it is now possible to use Kern instruments alone, Wild instruments alone, or both simultaneously. Due to the different protocols of the two types of instruments, they are addressed over separate serial ports. SLAC does not use electronic theodolites from other manufacturers, but there is no reason why it would not be possible to expand SIMS to include such instruments.

A Compaq III 386 portable computer with 387 processor is now used. The increased speed is especially noticeable in the data reduction programs, but, has little effect. on the data capture program which is limited by operator input and by the fixed speed of the theodolite electronics. The PC version of the 3DCD least-squares adjustment program has been compiled under the NDP Fortran compiler which breaks the 640kB limit on the size of a. Fortran program under DOS. This has allowed the PC version to he enlarged so that it. is now identical with the mainframe version.

A small portable AC power supply has been built which provides power for the theodolites and interfacing and multiplexing capabilities. The unit has ports for four Wild theodolites and four Kern theodolites. Two serial ports are provided for direct connection to the computer.