# REVIEW OF ALIGNMENT ACTIVITIES AT JEFFERSON LAB*

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## 1. INTRODUCTION

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) comprises a 6 GeV continuous electron beam accelerator (CEBAF) delivering beam to three experimental halls, and a kilowatt range tunable free electron laser (FEL), currently being upgraded to a 10 kW machine. The progression into steady state experimental runs at the facility has allowed the alignment group the opportunity to incorporate new developments into the alignment system. Two of these are discussed, together with some of the more unusual (e.g. gyrotheodolite survey) and the more routine surveys performed at the lab over the last three years.

## 2. SURVEY WORK

### 2.1 Routine Surveys

Much of the routine work carried out by the alignment group is focused on the experimental areas. Of the three experimental halls, Hall B has the most stable configuration, consisting of the CEBAF large acceptance spectrometer (CLAS), a superconducting toroidal magnet surrounded by drift chambers. Hall C contains two general-purpose spectrometers as standard equipment [1], but was intended to allow for the installation of experiment specific equipment. As such, the configuration of the hall changes regularly, resulting in the need for frequent survey support. Hall A contains two identical high-resolution spectrometers, and is somewhere between the other halls as far as configuration changes are concerned. As well as supporting the new experimental configurations, the alignment group carries out pre-run and post-run surveys on targets, spectrometers, and position monitors. The standard equipment for the group consists of electronic theodolites (Leica T3000s and TC2002s) and Brunson optical tooling instruments.

### 2.2 Special Projects

Two of the more unusual surveys carried out over the past three years are the Hall C target X-ray survey, and the accelerator gyro-theodolite survey. The X-ray survey was more of a confidence building exercise rather than one which presented any technical challenges. Given that the target was inaccessible, it was thought expedient to verify its mechanical operation by actually measuring it in the inserted position. Two steel wire grids were established on beamline

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upstream and downstream of the target. These acted as reference frames for the x-rays, against which the image of the target could be viewed. The results did not yield any great precision (millimeter level), but the survey did provide a certain level of comfort, and gives an example of an unusual combination of survey techniques and X-ray imaging.

Since the lab started using a polarized injector as its sole source of electrons, it has become necessary to characterize the precession of the electron spin around the accelerator. A significant part of this was to determine the angle through which the beam passes and therefore the azimuth of the linacs and experimental lines with respect to the injector [2]. Although the original survey network was believed to be of sufficient accuracy, there was always a possibility of systematic errors, which would be difficult to define. In the summer of 2000, arrangements were made with the Stanford Linear Accelerator Center (SLAC), to borrow a Gyromat 2000 gyro-theodolite. This instrument has a +/- 3 second accuracy and offered a totally independent check on the main azimuths in our survey network and in the accelerator.

A total of fifteen measurements were made around the accelerator and in the halls [3]. Each full measurement consisted of two observations at one end of the line, then a further two at the other end. A baseline was established in the south linac, which was typically measured at the beginning and end of each day. Six full measurements were made of the baseline. These measurements were used to define the mean difference between our survey grid and the north reference from the gyro (Table 1 “Grid-Gyro”). This difference was then applied to the remaining lines in order to determine the effective difference (in degrees) between the gyro azimuth and our grid azimuth. The results are given in Table 1.

Table 1. Gyro Survey Results

| Line | Grid Azimuth | Gyro Azimuth | Grid – Gyro | Difference |
|---|---|---|---|---|
| S. Linac | 269.9927 | 243.6455 | -26.3472 | 0.0001 |
| | 269.9927 | 243.6450 | -26.3477 | -0.0004 |
| | 269.9927 | 243.6454 | -26.3473 | 0.0000 |
| | 269.9927 | 243.6458 | -26.3469 | 0.0004 |
| | 269.9927 | 243.6456 | -26.3471 | 0.0001 |
| | 269.9927 | 243.6452 | -26.3475 | -0.0002 |
| **Mean** | | | **-26.3473** | |
| Inj. 1 | 88.1774 | 61.8283 | -26.3491 | -0.0018 |
| Inj. 2 | 88.7343 | 62.3859 | -26.3484 | -0.0011 |
| N. Linac | 90.0024 | 63.6555 | -26.3469 | 0.0004 |
| BSY 1 | 270.0032 | 243.6580 | -26.3452 | 0.0021 |
| BSY 2 | 272.9016 | 246.5511 | -26.3505 | -0.0032 |
| Hall A 1 | 307.5470 | 281.1993 | -26.3477 | -0.0004 |
| Hall A 2 | 307.4930 | 281.1448 | -26.3482 | -0.0009 |
| Hall C 1 | 232.4882 | 206.1396 | -26.3486 | -0.0013 |
| Hall C 2 | 232.4084 | 206.0589 | -26.3495 | -0.0022 |

For many of these lines it had been several years since any of the survey network had been measured (specifically 8 years in the case of the injector). There was, therefore, a reasonable possibility that individual monuments had moved from their previously surveyed location. Having said this, the agreement with the main network was generally good; the maximum difference being 0.0032 degrees (11.5 seconds) on BSY line 2. A more recent survey of elements along this line agrees to within 3 seconds of the gyro value, illustrating that the disagreement shown was probably with the original network observations. The repeatability of the Gyromat on the south linac baseline was, at least in my view, quite impressive, with a deviation of +/- 0.0004 degrees or 1.4 seconds. Overall the survey was a success and gave a good indication of the accuracy of the relevant azimuths in the accelerator.

## 3. NEW DEVELOPMENTS

### 3.1 FaroArm portable CMM

Towards the end of 1999, after an assessment of available instruments, the Jefferson Lab alignment group took delivery of a Faro 08 gold series portable coordinate measuring arm. This arm has an 8-foot diameter working volume and a 2-sigma accuracy (per manufacturer) of +/- 0.051mm. Initially, the proposed uses for the instrument included fiducialization of moderately sized components, quality control work and as-built surveys, short distance measurements, and even component surveys if tie-in to the overall coordinate system could be achieved. The advantages foreseen were that it could replace time consuming optical tooling set-ups, add the capability of accurate distance measurements up to 2.4 meters (the Mekometer being limited to over 4 or 5 meters), and also add the capability of characterizing components using surfaces, planes, apertures etc. This last capability was particularly difficult using our theodolite system or optical tooling.

Verification of the measuring accuracy of the FaroArm has regularly been carried out using a calibration ball bar. During this calibration, a bar of standard length is measured in multiple locations pivoting on a reference socket on the FaroArm base. Typically between 30 and 100 measurements are made, and the difference between the maximum and minimum value is less than 100 microns. In addition to the ball bar calibration, other tests have been made on the accuracy of measurement. These tests included measuring two scale bars (1.0 m and 1.5 m in length), and magnet fixtures. Both the shorter scale bar and the magnet fixtures were previously measured on a Mitutoyo model B710 coordinate measuring machine (CMM) with a +/-0.010mm accuracy. A comparison of the results gave an agreement at the 50 micron level. The longer scale bar (1.5m) did not agree so well, but this was largely due to poor repeatability of tooling balls.

Two tests were also carried out using the “leap-frog” method of transferring positional information from one set up to the next [4]. In the first test, three tooling balls were measured from the first FaroArm position, and used to orientate the arm for the next position. This was repeated, going out approximately 2 meters, then coming back measuring the same tooling balls, giving a total of seven positions occupied. The second test was similar, but used six tooling balls as a tie between the arm positions. In each test the three similar positions were compared (positions 1 and 7, 2 and 6, and 3 and 5) showing the differences between six, four and two leaps. The results can be seen in Table 2. As expected, the more leaps there are, the larger the difference between initial and final coordinates. Nevertheless, they provide a useful guideline in assessing the accuracy of the leapfrog method.

Table 2. Results from Leap Frog Tests

| Transfer Points | Leaps | Average Difference |
|---|---|---|
| 3 POINT | 6 LEAPS | 0.89mm |
| | 4 LEAPS | 0.70mm |
| | 2 LEAPS | 0.09mm |
| 6 POINT | 6 LEAPS | 0.65mm |
| | 4 LEAPS | 0.48mm |
| | 2 LEAPS | 0.14mm |

As far as field applications are concerned, the FaroArm has proved to be a versatile and productive addition to the lab's survey tools. The three examples discussed below illustrate how the arm has been used for fiducialization, alignment, and quality control work.

One of the more frequent uses of the FaroArm at Jefferson Lab is for the fiducialization of components. It is clear that for conventional magnets of up to 2 meters in size, the FaroArm provides a rapid and accurate way in which to reference the fiducials to the pole tips. Several magnets for the upgraded FEL machine have been fiducialized in this way, saving manpower and time over a conventional optical tooling approach. The arm really succeeds, however, where the geometric references are of a complex nature. Such a project was the fiducialization of the Helium 3 target for experimental Hall A. This target consists of glass tubes containing helium3 centered on four large electro-magnetic coils (see fig.1). The fiducialization was carried out by characterizing the circular coils, and then creating a coordinate system based on their central axes. The fiducials on the base plate of the target were then measured, providing values for alignment on the beamline. Once again the use of the FaroArm saved time and manpower compared to either a complex optical tooling or theodolite set-up, and also provided more data on which to base the fiducialization.

The FaroArm is also used in certain circumstances for the alignment of components into their ideal position on the beamline. Most notably this applies to the alignment of cryogenic targets. These generally consist of six target cells ("beer-cans") arranged in blocks and attached to a lifting mechanism (see fig. 2). Control points located on the scattering chamber are surveyed using theodolites and tied into the overall geodetic coordinate system. These are then translated and rotated into a target-centered beam following system, which the FaroArm uses as control points. Alignment is then carried out using the edges and faces of the cell blocks to define pitch and roll, and the cell block flanges to project and define the center of the cells. Previously, the entire survey was carried out with theodolites shooting fiducials on the cell blocks. This was time consuming given the fact that each cell needed to be moved into the beamline in order to be visible from the theodolites. Using the faces and edges of the cell blocks also eliminates fiducialization errors. Another advantage of using the FaroArm on target surveys is the ability to use it in spatially restricted situations. In Hall C, the use of lead shielding walls has severely restricted lines of sight. By orienting from control that is clearly visible, it has been possible to conduct surveys with the FaroArm without the need to unstack and re-stack shielding walls.

Fig.1 FaroArm Fiducialization of Hall A polarized target.

Fig. 2 Alignment of Cryo target using FaroArm

The third example of FaroArm application involves quality control work carried out on the new cryomodules for the SNS project. Two types of cryomodule are being produced by Jefferson lab as part of the SNS project. These are the medium beta and high beta modules which are 4.2m and 6.3 m long respectively. The alignment group had been asked to verify that certain key features such as support rings, rails, flanges and ports had been manufactured within tolerance. Once again, a theodolite or optical tooling survey could have been used, raising the problem of adequate targeting of features. The FaroArm on its own does not have the working volume to span these components, and the build up of errors using the standard leap-frog method would exceed the desired measurement accuracy of +/- 0.25mm. A scheme was developed whereby theodolites were used to establish a reference frame in which the FaroArm could measure the features of the components, and then change location and re-orient itself based on the theodolite control. In this manner the build up of errors associated with the leap-frog method were eliminated, whilst the critical features of the components were directly measured with the Faro probe.

Many other uses have been found for the FaroArm, including measuring detector planes relative to the beamline, locating semi-hidden flanges, and some direct distance measurements. In general it has proved advantageous for accurate measurements of small scale objects, for the ability to characterize geometric features, and for the ability to access relatively confined spaces. It is certainly not a 100% solution, however. One drawback is that it provides a unique solution, without redundancy. As such, care must be taken to carry out reasonable verifications during the work. The stability of the set-up is crucial. We have experienced problems with the base of the FaroArm coming loose, and also with small deflections of the support. The relatively small working volume is also a disadvantage at times. However, used in conjunction with theodolites, and taking adequate care, we have found the FaroArm to be a valuable addition to the survey tools at Jefferson lab.

### 3.2 ACAMS software

Over the past three to four years the alignment group has also taken steps to modernize the basic survey system used at the lab. After a visit to Brookhaven at the end of 1998, it was clear that making use of all the features available on the Leica theodolites could make our system more efficient. Up to that point we had been using a system adapted from SLAC when the group started in 1990. This used DOS based programs, and either E2s or Leica theodolites, but required an operator at the computer to record observations. It was evident that a more up to date windows based software system could both increase the group's capabilities as well as reduce the average crew size by a third. After trying commercially available packages it was felt that that they were too restrictive (particularly as far as file handling was concerned) to provide a comprehensive package for the group. We therefore started a major initiative to develop our own software package, which would improve the overall scope and versatility of the group's activities.

In January 2001 we started development of the Accelerator Combined Alignment and Measurement System (ACAMS). The concept was that this should be a single package capable of including most of the instruments and techniques regularly used by the group. Our DOS based system included the SLAC bundling package used for fiducialization (SIMS), a program for stand alignment (Recebash), an in-house package for magnet alignment or step2 (S2AA), and a program for spectrometer pointings (Aalign). ACAMS was to combine all of these into one package, as well as provide additional features and flexibility for processing data.

At the core of the ACAMS package [5] is the 3DCD bundling adjustment software developed at SLAC. All elements of the ACAMS package feed into this adjustment engine via a processing program known as "Approx". This generates approximate coordinates and input data from the raw observations. ACAMS provides easy access to editing screens where elements of the input file can be adjusted. This allows weights to be changed on single observations, all observations from one theodolite, or even on control point coordinates. This last feature is particularly beneficial when working in experimental halls where spectrometers and other heavy objects are regularly moved around, temporarily distorting the vertical survey network

For stand alignment ACAMS has a Real Time Positioning (RTP) element. This allows real time coordinates to be generated from single face observations. Differences from the ideal position are clearly displayed on the screen, allowing the component to be aligned to the final tolerance. Before exiting the RTP mode a final as-found survey is made using two face observations, and recorded to disc.

In the step 2 portion of ACAMS, double-faced observations are always used. The observations are adjusted in 3DCD, and a table of differences from ideal location is generated. Observations can be re-observed and replaced for iterative alignment. In both the step 2 and spectrometer alignment portions, the default processing mode is a gravity based system. This constrains the rotations about the Z and X axes of the theodolites such that the Y-axis remains parallel to the direction of gravity. This system is useful when working near temporary deformations of the control network, as mentioned above, ensuring that the survey model does not tilt when fitting to the control.

Spectrometer surveys start out in a similar way to step 2 surveys, but then a six parameter transformation is performed in order to define the central axis of the spectrometer with respect to the beamline. Beam positioning devices (superharps) can be defined at the same time.

With the incorporation of the ACAMS software into everyday usage, the group has gained a single custom-built measurement package with the flexibility to be used across the Lab for a variety of purposes. The ACAMS software is now in use for fiducialization, step 2 alignment, pointing surveys, and stand alignment. We have also started to tie the FaroArm more closely into the overall system, especially on target surveys. It has become the standard tool for the group, and should prove to have the flexibility to enable the expansion of its capabilities, and for its further development in the future.

## 4. CONCLUSION

With the completion of the main accelerator and the move to steady state operations the alignment group at Jefferson Lab has been able to start upgrading their survey system. The addition of the FaroArm for small scale fiducialization, local alignments and quality control work has been a valuable supplement to the group's hardware. The group's software capabilities have been consolidated and expanded through the development of ACAMS, allowing multiple techniques to be performed in a single package. The near-term future of the lab involves participation in the Spallation Neutron Source (SNS) project, and an upgrade to the FEL facility to 10kW. Further in the future an upgrade to 12 GeV is planned for the main CEBAF accelerator. It is hoped that the developments in the alignment group should position us to meet the demands necessary over the next few years.

## 5. REFERENCES


[1] http://www.jlab.org/Hall-C/general/hallc-status_goals.html, October 2002.

[2] J. Grames, *Unique Electron Polarimeter Comparison and Spin-Based Energy Measurement.* Jefferson Lab Tech Note JLAB-TN-01-029, June 2001.

[3] C. J. Curtis, Jefferson Lab Alignment Group Data Transmittal #L625.

[4] R. Schwartz, C. Gould, *Faro Leap Frog Tests,* Unpublished Jefferson Lab Alignment Group results, June 2000.

[5] K. Baggett, K. Tremblay, *ACAMS User Manual version 1.0,* Jefferson Alignment Group unpublished documentation, July 2001.