ANALYSIS OF THE ORBIT ERRORS IN THE CERN ACCELERATORS USING MODEL SIMULATION*

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1. INTRODUCTION

Traditionally, the commissioning and start-up of accelerator facilities is laborious, expensive, and very time–consuming. With large machines like LEP and SLC coming on-line the expenses involved in trying find errors quickly become a significant amount of money (around $10,000/hour). This situation is compounded by the fact that no useful physics is being done during the usually lengthy start-up. We therefore believe that a change of attitude is needed to deal with these extremely complex problems. In the old days a physicist could just "knob" the machine to bring it up to desired performance. As machines became more complex, the machine physicist would take a set of data to his office and analyze it for weeks. Clearly, this method is inadequate for modern-day machines. To meet this need, a new program, PLUS (Prediction from Lattice Using Simulation),[1] has been developed that incorporates the power of models and simulation together with modern graphical interfaces into a powerful machine analysis system.

This paper will describe the use of the PLUS program to find various types of machine and beam errors such as, quadrupole strength, dipole strength, beam position monitors (BPMs) , energy profile, and beam launch. We refer to this procedure as the GOLD (Generic Orbit & Lattice Debugger) Method which is a general technique that can be applied to analysis of errors in storage rings and transport lines. One useful feature of the Method is that it analyzes segments of a machine at a time so that the application and efficiency is independent of the size of the overall machine. Because the techniques are the same for all the types of problems it solves, the user need learn only how to find one type of error in order to use the program.

We believe that because this program is so general over so many types of systems and errors that it is the first truly generic program for use at an accelerator facility. The program was written by machine physicists as a machine and beam diagnostic tool especially useful for commissioning and start-up. We have kept the program independent of any control system to avoid the interfacing problems that invariably occur when programs are added to existing complex control programs. The interface to the program from an existing control system database is simply "putting" and "getting" the neccessary values using the routines from the control system.

The procedure utilizes a graphical interface that allows any user to quickly learn its use. The information returned by PLUS is so clear to the user that the correct solution to a problem is obvious. In fact, the procedure is so simple and fun to use that the previously arduous and time-consuming task of finding errors has been reduced to playing a video game! The GOLD Method also reduces the time required to find errors from weeks or months to hours. This huge savings is particularly important for large machines where finding alignment errors is extremely difficult.

2. THE GOLD METHOD

The GOLD Method is divided into three parts. The first part involves finding error-free regions in the system. The second part pinpoints where the errors are located between the good regions. The third part finds "gold" corrections that compensate for the errors found in the second part. We will now describe the parts of the Method in turn.

1) An error-free, or good, region is defined by a section of the beam line within which the simulated natural betatron oscillation from the model matches the BPM values. PLUS can vary the phase and amplitude of the betatron oscillation in order to fit two or more BPM monitors. We consider a region to be good if the fit is satisfactory over at least three monitors. Thus the good region includes the first monitor that fits well through to the last monitor that fits well. The graphical interface displays a plot of the actual BPM data and the fitted BPM data. The interactive nature of the Method allows the user to search over different regions very efficiently. This procedure is repeated until all the good regions in the system have been found. In some cases there will be a gap between two adjacent good regions. In other cases, two adjacent good regions will overlap. In either case the bad region will be in the vicinity of the end of the first good region and the beginning of the next good region.

2) After doing 1), we know that the errors are in the vicinity of two adjacent good regions. To better localize which element is causing the problem, we try each of the elements in the bad region to see which one gives the best fit to the trajectories of the good regions surrounding the bad region. The grapical interface makes the comparison of the various fits extremely fast and easy.

3) "Gold" corrections may be simply calibration factors as in the case of quadrupole or dipole strength errors, or actual physical correctors in the case of a quadrupole misalignment, or an offset as in the case of a BPM misalignment. Corrections become gold when the model and data are in agreement.

In conventional error-correcting schemes, the correctors have tendency to "fight", or compensate each other, so that power supplies become saturated. Using only gold correctors means they will avoid fighting each other because the gold corrections are the closest to the *correct* solution.

In general, when finding errors the first step is to check the validity of the model using difference trajectories and then to check for dipole errors using absolute trajectories. However, the data used in the analysis of the EPA and LEAR data were taken over a year ago so it was not possible to get the difference trajectory. Also, some of the rings did not have corrector magnets that make generating difference trajectories trivial.
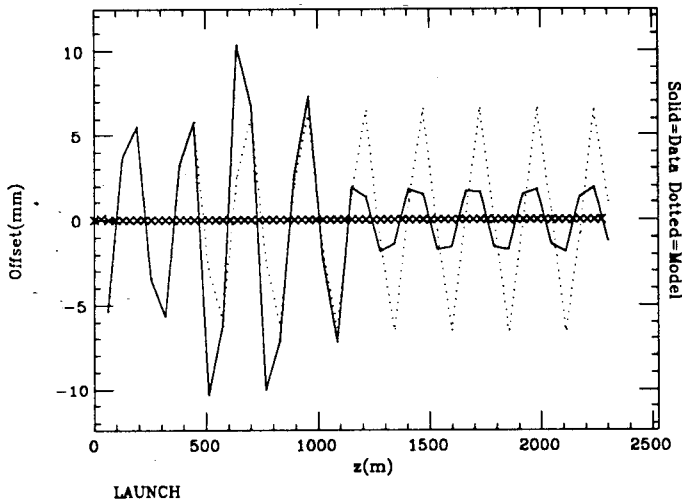
Figure 1. PLUS fit to first three monitors. Goodness of the fit extends to monitor 7.

In the following sections we will illustrate the GOLD Method through analysis of SPS (Super Proton Synchrotron), EPA (Electron–Positron Accumulator), and LEAR (Low Energy Antiproton Ring) BPM measurements.

3. APPLICATION TO THE SPS

The SPS is divided into six sextants each with 18 BPMs. Over a year ago it was decided to make a change in the closed orbit of the machine. As there are no correctors in the machine such a change requires moving of the magnets. To test the GOLD Method we took the difference between the old closed orbit data and the new closed orbit data after the magnets were moved to find the errors. This is similar to a situation where the elements may have moved due to settling.

Figure 1 shows the PLUS graphical display fitting to the first three monitors. As can be seen in the figure the fit is good out to the seventh monitor even though monitors four through seven were not explicitly fit. Thus the segment of the machine between monitors 1 and 7 defines the first good region.

Next, we try to find the next good region by fitting to the first three monitors after the previous good region, namely, monitors 8 through 10. Figure 2 shows the result of fitting to monitors 8–10. This time the fit is good to monitor 13 so the second good region is monitors 8–13 and the first bad region is between monitors 7 and 8.
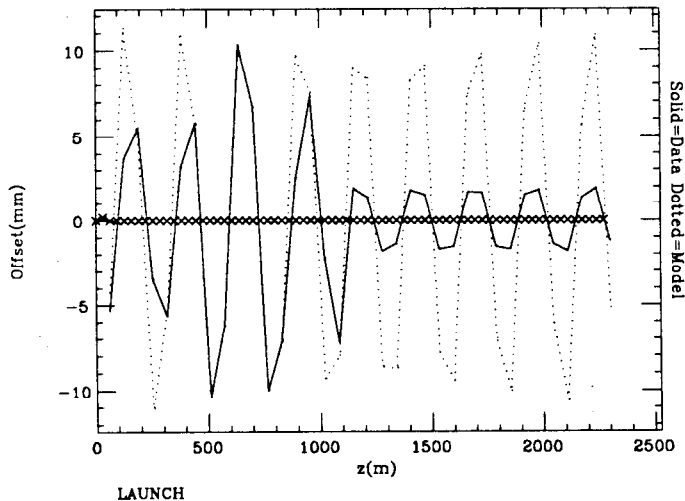

Figure 2. PLUS fit to monitors 8–10. Fit is good for monitors 7–13.

In figure 3 we fit to the third good region, monitors 14–16. The third good region is defined by monitors 14–19. In figure 4 we fit to monitors 20–22 and the fit is good to the end of the segment, 36 monitors.
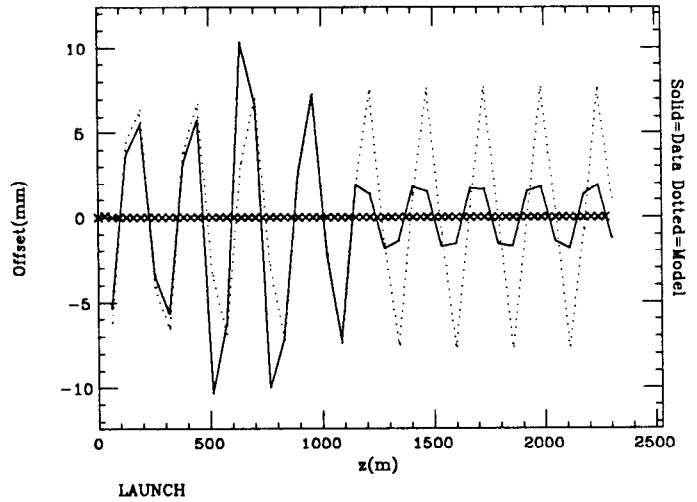

Figure 3. PLUS fit to monitors 14–16. Fit is good for monitors 14–19.
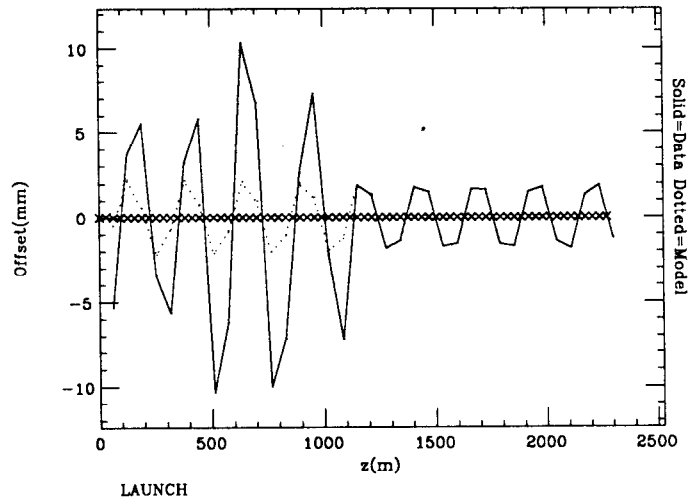

Figure 4. PLUS fit to monitors 20–22. Fit is good for monitors 18–36.

In the first bad region several magnets were tried as the possible source of the error. This means that an error was inserted into the model at this element and allowed to vary as a fit was done to the regions surrounding it, in this case the regions were monitors 1–7 and 8–13. The results of two of these optimizations is shown in figure 5. Clearly, the dotted curve corresponding to element 16 (figure 5b) is a much truer representation of the data than element 15 (figure 5a).

Each error region was analyzed in this way and the overall results are shown in figure 6.

This result demonstrates the power of the procedure by allowing all the errors to vary simultaneously to obtain the best overall fit. The location of the error and the correction strength are also graphically displayed for the user. Indeed, the results agreed remarkably well not only in terms of finding the correct elements, but in their strength values as well. The fit values and the actual values of the changes implemented in the SPS are tabulated in table 1.
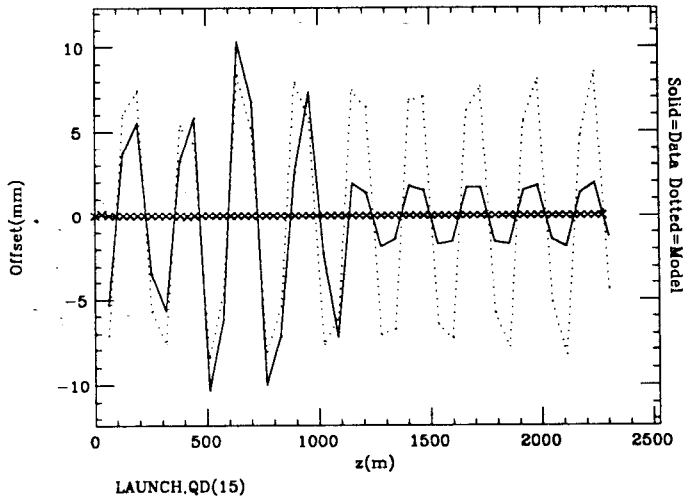
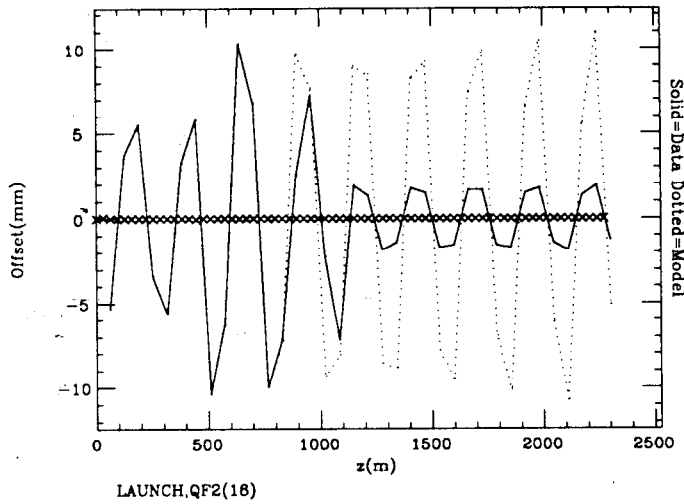Figure 5a.   PLUS fit using a correction at element 15.

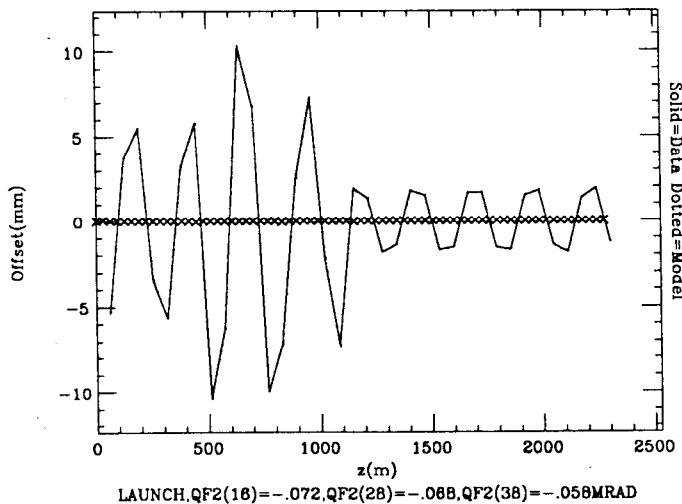Figure 5b.   PLUS fit using a correction at element 16.

Figure 6.   Overall fit to the data including corrections.

Table 1.   Measured and calculated errors from the SPS.

Element	Measurement (mrad)	GOLD Method (mrad)
16	.075	.072
28	.070	.068
38	.060	.058

The results shown above show that we have found the gold corrections. Also, the BPM measurements now agree so well with the model predictions that we now can say that the model is good, the BPMs are good, and the change in the magnet positions are also good.

The above example illustrates exactly how the GOLD Method is used to find alignment errors.

4. APPLICATION TO EPA

Although EPA is a much smaller machine than the SPS, we use the same GOLD Method to find the errors. EPA has two-fold periodicity and a total of 19 working BPMs. Two sets of data were used. After analyzing the first set we found several BPMs with large offsets. These values were experimentally verified and new data was taken which was analyzed for element errors.

Figure 7 shows the final results for the EPA analysis. The good regions are monitors 3–7, 7–10, and 10–19. Again, there are no correctors in the machine so that the corrections must be made by moving magnets. The location and value of the candidate corrections are shown by the off-axis X's on the plot. In addition, monitors 8, 11, and 12 still have small offset errors which can easily be included as offsets in the database of the control program. However, this is only a candidate solution. Unfortunately, this data is not sufficient to determine whether cause is due to a quadrupole or a dipole error. If this solution is implemented on the actual machine and the predicition is correct then we have found the gold corrections. If this solution does not work then the error may be due to quadrupole strength errors which can be understood from the tune measurement or using difference trajectories as was done with the SPS.
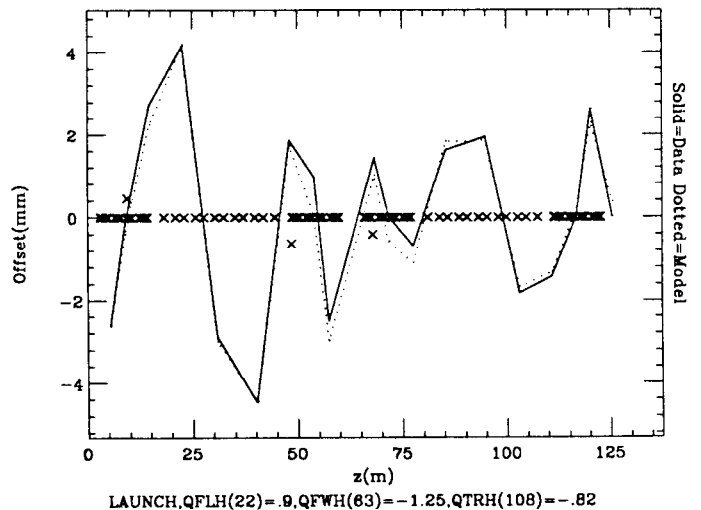

Figure 7.   Final results for the EPA analysis.

4. APPLICATION TO THE LEAR

LEAR is a small machine similar in size to EPA. Again we use the same GOLD Method to find the errors that affect the vertical orbit. In this analysis we were unable to find any good regions with more than three monitors. There are two possible explanations of this result. One, all the BPM readings are unreliable. Second, there are a large number of errors or a nearly

continuous source of error. Multiple errors can occur when elements are coupled together so that the same error repeats every time that element appears in the lattice. PLUS allows the user to couple the errors in the fitting to take this effect into account. Since the GOLD Method is not applicable for this case, we resorted to a trial and error method of guessing which elements were coupled. The results of this analysis are shown in figure 8. This result confirms another analysis which found tilt errors in the bending magnets of the ring. The results will be tested experimentally in the near future.
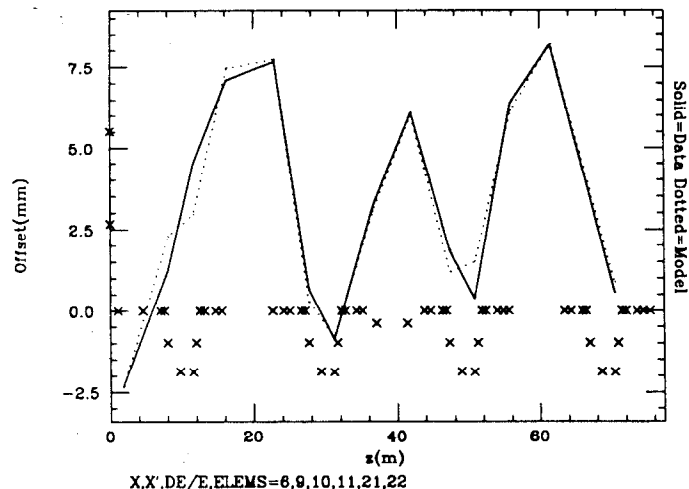

X,X',DE/E,ELEMS=6,9,10,11,21,22

Figure 8. Final results for the LEAR analysis.

5. CONCLUSIONS

Prior to the advent of the GOLD Method no accelerator facility had a general-purpose technique for finding errors. Although this paper only discussed analysis of dipole field errors, it is *obvious* that the same method can be applied to the domain of quadrupole strength errors by using the *difference* between BPM measurements instead of absolute BPM measurements[2] The examples show that closed orbit data can be analyzed as trajectory data. Also, the same method of the analysis can be applied to different size machines. Even the dispersion analysis can be done using this technique.

The power of the GOLD Method is in its simplicity. It took great effort to arrive at such a simple and concise technique. The use of the beam line simulator, PLUS in this case, expedited the analysis and eventually led to GOLD Method as the obvious solution. The GOLD Method is extremely valuable for laboratories that do not have much in-house expertise, such as SRRC and many industrial laboratories.

The PLUS program has been implemented at CERN, SLAC, LANL, LBL, SRRC, and SPRL (Stanford Photon Research Lab). Since the implementation of PLUS there has been a great deal of savings in time, money, and effort. This savings applies for all machines because the same number of tools are needed to analyze data independent of machine size. PLUS with interactive graphics presently runs on microVAX workstations, SUN workstations, and Apollo workstations.

A prototype expert system, ABLE,[3] has been developed that automates some of the lattice debugging features mentioned above. The GOLD Method has recently been incorporated into the ABLE expert system. We now have all the tools required for an integrated system called GOLD,[4] for debugging and correcting orbit errors in accelerator lattices. GOLD is now being used to do online analysis for the control of the SLC.

REFERENCES

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2. *Ibid.*

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4. Martin Lee, Scott Clearwater, "GOLD: Integration of Model-Based Control Systems with Artificial Intelligence and Workstations", Proceedings of the Workshop on Model-Based Accelerator Controls, Brookhaven National Laboratory, Upton, New York, August 17–18, 1987.