

## Accelerator Simulation Using Computers\*

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### 1 Introduction

Every accelerator or storage ring system consists of a charged particle beam propagating through a beam line. Although a number of computer programs exist that simulate the propagation of a beam in a given beam line, only a few provide the capabilities for designing, commissioning and operating the beam line. This paper shows how a "multi-track" simulation and analysis code can be used for these applications.

In practice, trajectory errors are frequently measured under different conditions. For example, by changing the strength of dipole correctors in a systematic manner, a set of trajectory deviations can be produced for analysis. These deviations can be analyzed collectively by the method referred to as the multi-track analysis. Two examples of applying this method to resolve optics errors in the SLC beam lines at SLAC are presented.

### 2 Terminology

While the procedures required to operate an accelerator may differ between facilities, there will be several common features:

- |           |  |
|-----------|--|
| Look      | The operator looks at the beam parameters, $V$ , and decides which element parameters, $U$ , need adjustment.                                |
| Analyze   | The operator uses a simulation program to calculate the change of element parameters, $dU$ , which will alter the value of $V$ to $V + dV$ . |
| Interpret | The operator decides whether to implement the solution based on the predicted beam parameter changes.  |

*Invited talk presented at the International Conference CUM Workshop on Current Trends in Data Acquisition and Control of Accelerators, Calcutta, India, November 19-21, 1991*

\*Work supported by Department of Energy contract DE-AC03-76SF00513.

- |         |   |
|---------|---|
| Adjust  | The operator makes the adjustments, $dU$ , and checks the resulting value of $dV$ . |
| Iterate | Based on the value of the result, the operator may choose to repeat this procedure. |

### 3 Requirements

Multi-track analysis requires a flexible beam line modelling and simulation code with a state-of-the-art graphical user interface for :

1. Design-to simulate the effects of changes in the strengths or position of beam line elements on the particle beam trajectory
2. Commissioning-to find possible causes of particle trajectory errors. Possible causes include errors in element position, alignment, and strength as well as errors in monitors or energy gain
3. Operation-to find the strengths of orbit correctors that will compensate existing beam line element errors.

Such a code would simplify designing, commissioning and operation of existing and future machines.

#### 3.1 Design Study

Design studies usually involve investigation of error tolerances and evaluation of correction systems. Each task requires multi-track simulation since each requires determining the effects of beam line element errors over a variety of conditions. For error tolerance studies, the designer simulates the effects of various errors in fabrication, calibration, and/or installation of beam line elements on beam trajectories. For correction system studies, the designer finds the best locations and the strength of correctors to compensate trajectory errors. By examining an ensemble of likely errors, it is possible to derive : 1) constraints on the sensitivity of beam position monitors (BPMs); 2) optimal location of both monitors and correctors; 3) strengths of correction elements.

#### 3.2 Model Assisted Commissioning

One of the main goals in commissioning an accelerator is to verify if there are unknown errors in the beam line elements by applying the multi-track analysis with the on-line model of the beam line. (The on-line model is the model belonging to the control program.) An inaccurate model may indicate errors in the beam line elements leading to inefficient machine operation under model reference control since the on line model will not predict the correct beam parameter changes. Thus, success in commissioning and operating a machine depends on having an accurate model of the beam line.

Modelling errors in the beam line element parameter values can be located and corrected using multi-track analysis. In general, this involves 4 basic steps :

1. Assume a set of particular error candidates.
2. For each error candidate, compute the magnitude of the modelling error that minimizes the difference between predicted and measured trajectories.
3. Compare the results of all possible sets of error candidates.
4. Select the best set as the solution.

### 3.3 Model Reference Operation

It is natural to operate a machine with the same codes that were used in designing it. In general, these procedures can be classified as Modeling and Inverse Modeling. Modeling involves making a change in the values of a beam line element position or strength,  $U$ , and noting the effects on the beam parameters,  $V$ , at the observation points. Inverse Modeling, on the other hand, involves finding the value of corrections,  $dU$ , that will minimize beam parameter errors,  $V$ . For example, a Modeling procedure is used in error tolerance studies and an Inverse Modeling procedure is used in error correction studies. For simplicity, these two procedures will be represented symbolically as :

$$\text{Modeling} \quad V = MdU$$

$$\text{Inverse Modeling} \quad dU = M^{-1}V$$

Both processes require visual aid. Visual aid in modeling is useful since it permits accelerator operators to see both the predicted and actual effects while making manual adjustments to beam line element parameters. It is especially useful in Inverse Modeling where the operator must change the beam parameters,  $V$ , by making small incremental changes to the machine element parameters,  $U$ . At each step, the desired change in the beam parameter values,  $dV$ , determine the changes to the machine element parameters through  $dU = M^{-1}dV$ . For example, in beam steering applications,  $dV$  is the measured residual trajectory error, and  $dU$  is the predicted strength of correction elements.

Most beam simulation codes today can analyze only one trajectory or track at a time forcing the scientist to use a laborious trial-and-error search procedure where, repeatedly a solution for one track is found, tested against the other tracks, and modified until an optimal solution is found. Multi-track simulation codes, on the other hand, analyze a set of trajectory deviations collectively and thereby save considerable time and effort.

## 4 Multi-Track Simulation and Analysis Software

There are a few simulation codes available that analyze multiple tracks. Some analyze the multi-track data to find the errors in the beam line elements directly while others find errors in the beam transport matrix between observation points. Codes that find transport matrix errors allow the operator to compensate such errors using correctors without knowing the underlying causes. If the correction method fails, the source of the beam line errors must be found. Using RESOLVE beam line errors can be found directly.

## 4.1 RESOLVE

RESOLVE is a charged particle beam simulation code developed to meet the requirements needed for design, commission and operation of beam lines. The program runs on a number hardware platforms and operating systems and provides an X-window system graphical interface that utilizes mouse, windows, and pop-up menus. For ease of integration, a special layer of C or "FORTRAN-callable" routines separates the numerical functionality of the code from its graphical user interface. This enables the user to link the program with the database of any I/O or control system as well as embed it into other software modules. Special operations such as beam injection control and beam steering can thus be automated by embedding RESOLVE into an expert system or adaptive control system. (It has been used to develop rules for an expert system to automatically analyze single track data and to train a neural network in an adaptive feedback system to control beam launch conditions.) Additionally, the object oriented coding style allows easy addition of new features and new types of elements.

Internally, RESOLVE uses a matrix formalism to compute the effects of beam line elements on the particle coordinates. Specifically, for first order effects the formalism is a conventional  $6 \times 6$  beam transport matrix, and for second order effects it is a  $6 \times 6 \times 6$  matrix, making it applicable to beam lines containing sextupoles, solenoids, and coupling elements.

Using the terminology defined in section 2, it is possible to specify five different levels of automation :

- Level 1     Automated Adjust.
- Level 2     Automated Adjust and Look.
- Level 3     Automated Adjust, Look, and Analyze.
- Level 4     Automated Adjust, Look, Analyze, and Interpret.
- Level 5     Automated Iteration of the given Adjust-Look-Analyze-Interpret Procedure.

RESOLVE was designed to function within a control system that has any or all of these five levels of automation. It also provides an interactive environment for error tolerance studies and correction systems design as well as for user tracing. Since the code is highly user-friendly, accelerator operators can easily perform the iterative look-adjust procedure required for manual operation. During manual operation, the operator analyzes and interprets beam trajectories at each iteration to decide whether to continue or terminate the procedure.

## 5 Examples of a Multi-Track Analysis

Two applications of multi-track analysis at the SLC (Stanford Linear Collider) project at SLAC are presented.

### 5.1 Example 1

The first application occurred during the Summer of 1987. After many months of manual effort, the commissioning team was unable to deconvolve a matched beam from the North Damping Ring to the LINAC. It was suspected at that time that there were optic errors in the NRTL (the beam

transport system from the North Ring to the Linac). For this analysis, the operators measured four sets of beam position monitor readings by changing the strengths of two horizontal correctors (X250 and X264), and two vertical correctors (Y214 and Y248).

The measurements resulted in the four difference orbit tracks shown as dotted points in Fig. 1. The first step of the analysis required calibrating the strength of corrector kicks applied to generate each track. In the absence of errors, the simulated trajectories (lines) should perfectly match the measured data (dots). The simulated curves and the measured data agree very well in the  $y$  plane. They disagree, however, in the  $x$  plane. This indicates an error in the on-line model that affects the  $x$  trajectory but not the  $y$  trajectory. Since the difference trajectories are affected by focussing errors only, the trajectories indicate an error in the horizontal focussing elements.

Note that there are two malfunctioning monitors in Fig. 1 as indicated by points with '0' values. Although these monitors do not significantly affect the results in Fig. 1, they were deleted for the next step of the analysis.

In the next step, the search procedure described in Section 3.2 was applied. The analysis indicated a relatively large error in a horizontally focussing magnet family and a small error in a vertically focussing magnet family. Each family consists of four quadrupole magnets on a common power supply. The results show excellent agreement between simulation and BPM measurements on both of the horizontal tracks (see figure 2).

An estimated power supply error corresponding to a 3 percent error in the strength of the horizontally focussing quadrupole magnet family was found. When this error was corrected, the mismatch problem from the NRTL to the LINAC disappeared. Shortly thereafter, high quality electron beams were travelling to the end of the two mile LINAC for the first time. A month or so later, the SLC detected its first Z.

Originally the NRTL optics error was found using a single-track analysis method. Since the process was very tedious, it took many days to find this result. The same analysis could now be performed in less than a few hours using RESOLVE. This example demonstrates that a great deal of effort and valuable beam time could have been saved had the errors been discovered sooner.

## 5.2 Example 2

The second example is one of the most recent applications of multi-track analysis applied to the SLC. During the Spring 1991 run, an optical mismatch problem almost prevented the commissioning team again from reaching its goal: to deliver the same positron intensity from the SDR as the electron intensity from the NDR. (The SDR performs the same "damping" function on the positron beam as the NDR on the electron beam.) The goal was reached only after months of trial and error effort by manually adjusting the strength of quadrupole elements in the transport system from the Linac to the Ring (SLTR).

To analyze the SLTR optics, several sets of beam oscillation data were obtained by kicking the positron beam with orbit correctors. Multi-track analysis of these data sets showed a 5 percent error in the strength of a vertically focusing quadrupole magnet (QD1355) as the most-likely cause of the mismatch problem. After this result was obtained, the actual source of the focussing error was discovered: the pole faces were installed backward on the sector-type bending magnet, B1281. Since B1281 is located 180 degrees (betatron phase shift) upstream of QD1355, the edge focussing error in B1281 produces the same effect on the beam oscillations as the error at

Fig 1 First Step of NRTL Analysis — Amarth

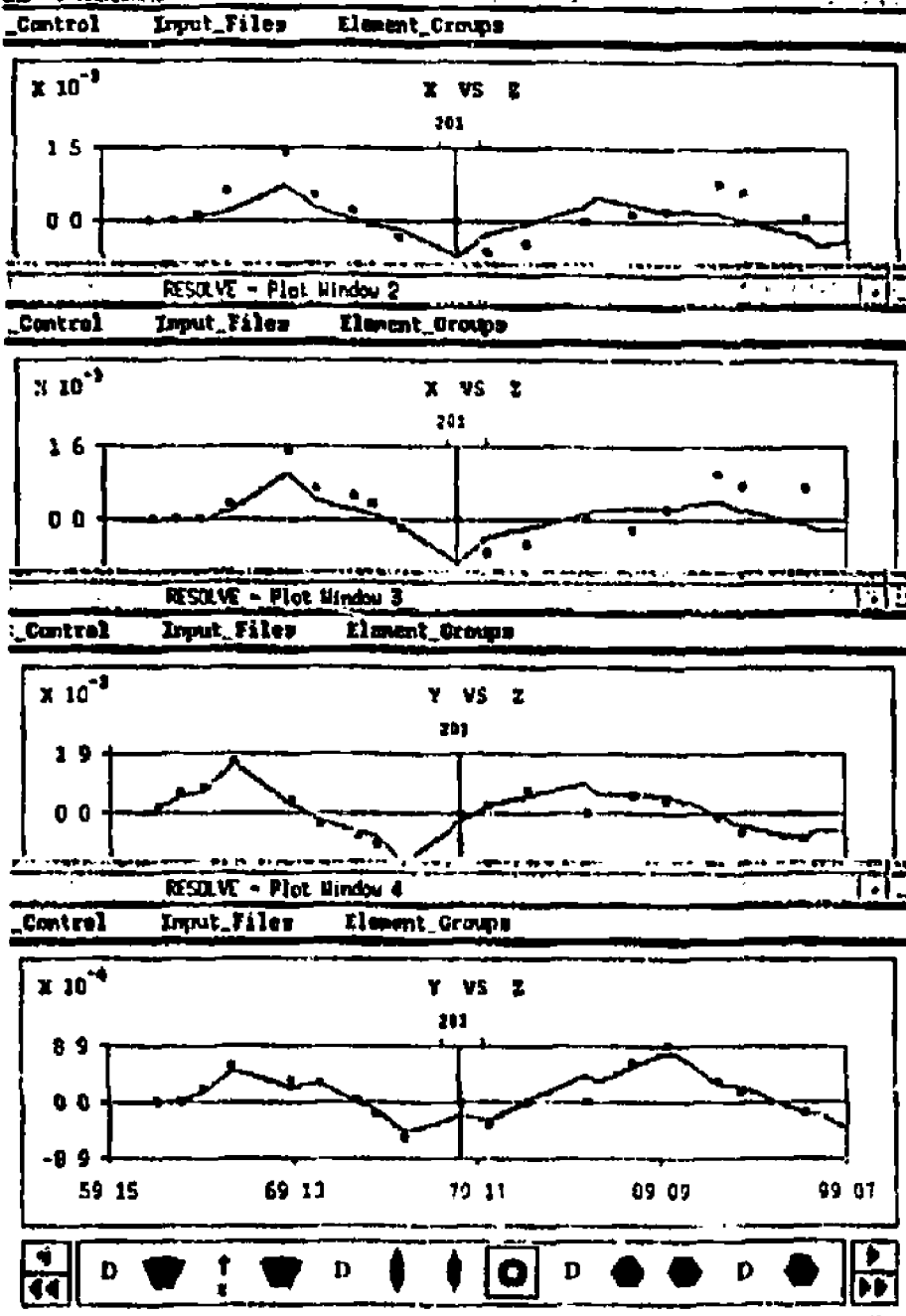


Figure 1: First Step of the NRTL Analysis

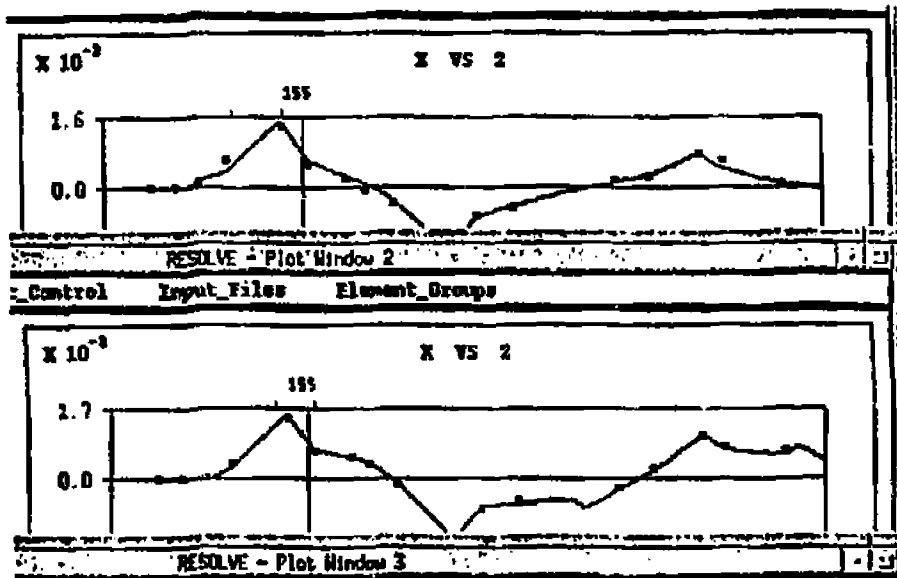


Figure 2: Final Results of the NRTL Analysis

**QD1355.** These pole face errors resulted in a modelling error in the "on-line" beam line optics program. And the modelling error caused a mismatch of the positron beam to the SDR.

To check these results, the following experiment was performed. First, the strengths of all SLTR magnets were restored to their "design" values according to the on-line model. Then the strength of QD1355 was varied and the effect on the positron intensity delivered from the SDR was observed. The peak in the delivered positron intensity was found at the predicted value (4 percent strength error on QD1355) as shown in Fig. 3. This experiment confirmed the error predicted by RESOLVE and proved that the fringe field error at the B1281 was the source of the optic mismatch problem.

Figures 4 and 5 show the RESOLVE displays before and after simulating the edge error at B1281, respectively. There is clear agreement between the simulated (solid line) and measured (dots) trajectories showing that the corrected model is accurate. Although the error in B1281 could be corrected by remounting the pole pieces, this can not be done during the present run. The SLTR must continue to operate with this error. However, since an accurate beam line model has been found, it is possible to systematically match the positron beam to the SDR and to investigate other errors such as BPM offsets and quadrupole mis-alignments using the corrected model.

The same multi-track analysis method is presently being applied to other beam lines in the SLC and to the SPEAR light source where RESOLVE has been integrated into the on-line control system.

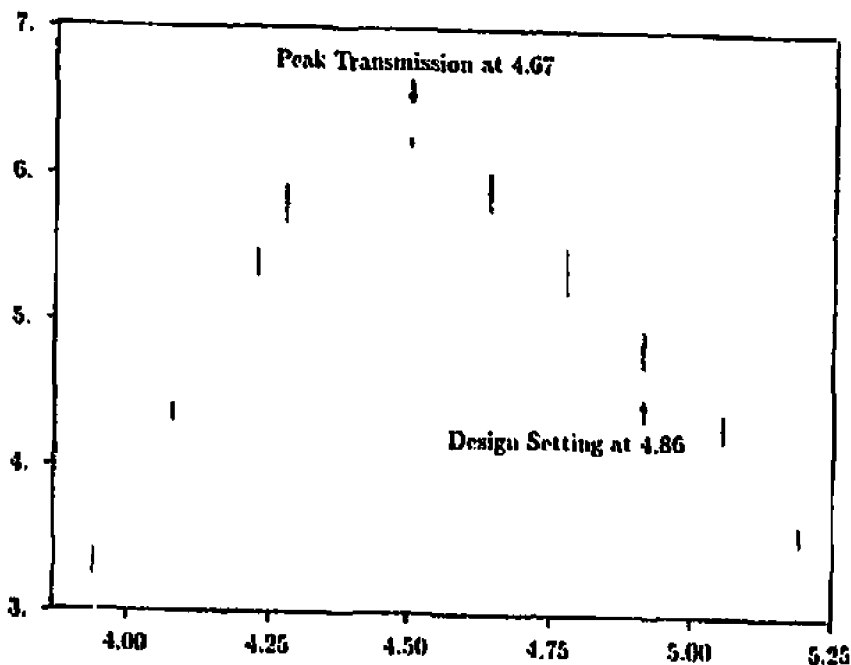


Figure 3: Positron Intensity vs. Strength of QD1355 for SRTL. Example

## 6 Acknowledgements

The authors would like to acknowledge Stephen Kleban for his assistance in the data analysis presented in the first example. The work of Martin Lee and William Corbett was supported by the Department of Energy, contract DE-AC03-76SF00515, DE-AC03-76SF00098, and DE-AA03-76SF00010.

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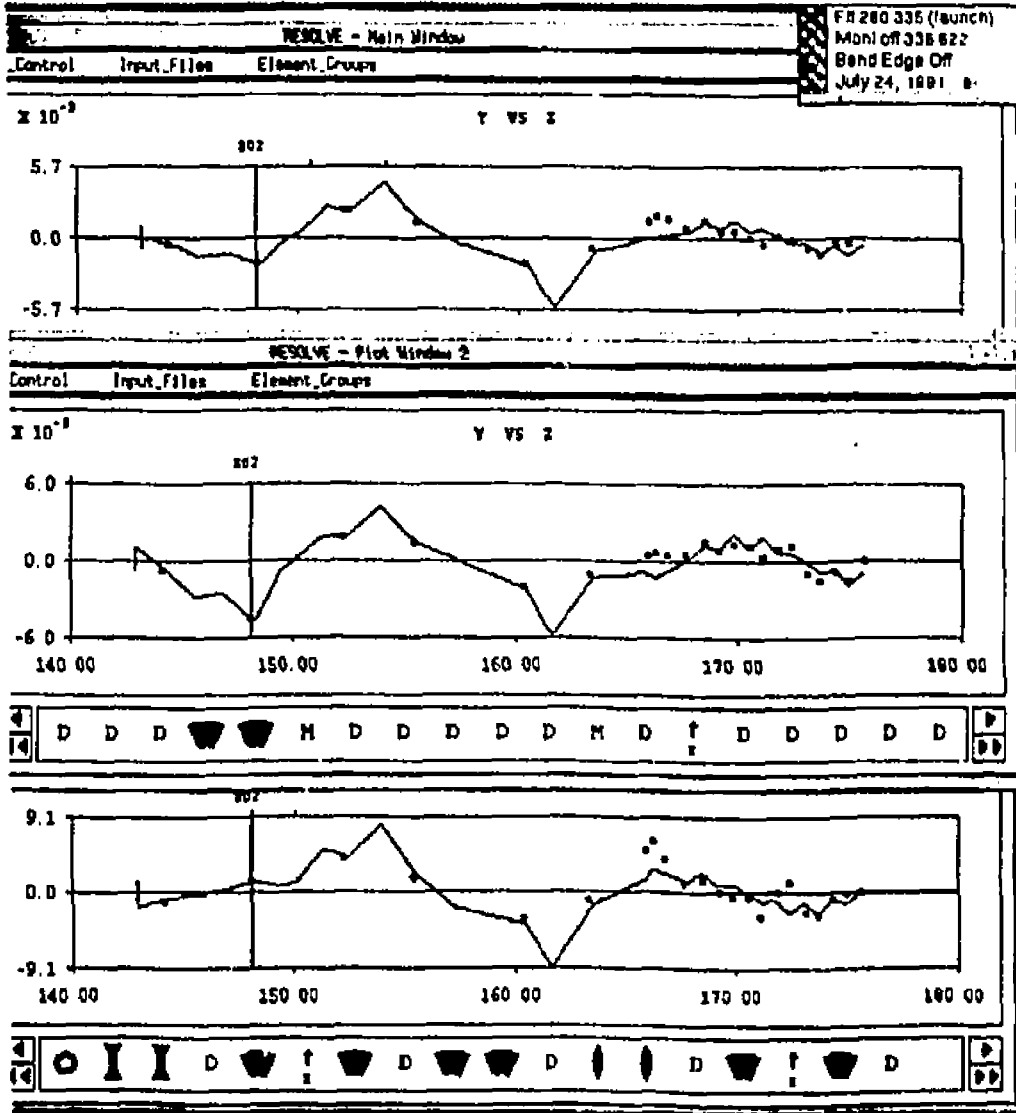


Figure 4 First Step of the SLTR Analysis

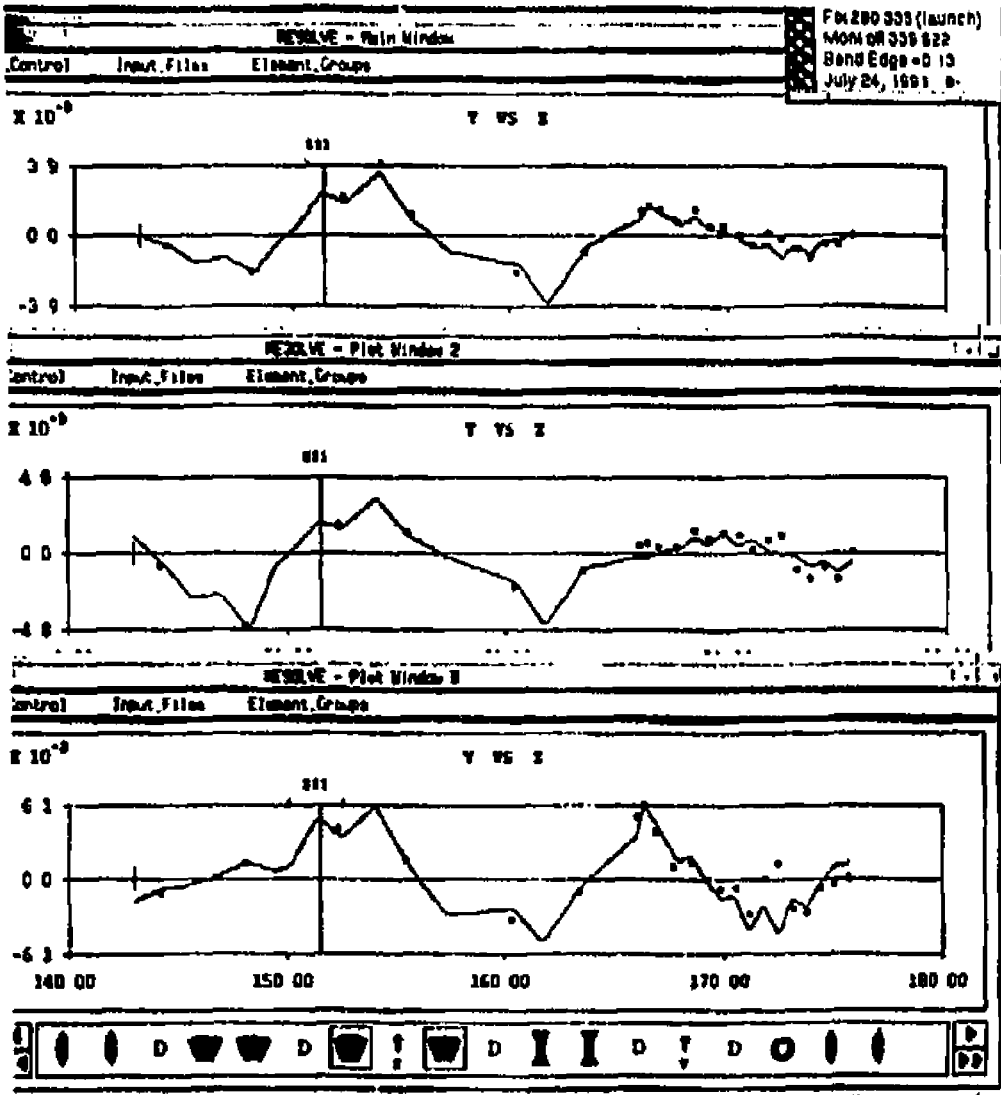


Figure 5: Final Results of the SLTR Analysis