Vertical Track Stiffness Measurement System (VTSM)

Project Review
and
Phase 1 Progress Report

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TABLE OF CONTENTS

Introduction 1
Background 1
Project Status 1
Report Objective 2
VTSM Development Overview 2
Review of Proposed Measurement Technique 2
Adaptation of System to GRMS Consist 5
Phase 1 Goals and Objective 6
Phase 1 Laboratory Testing Objectives 6
Phase 1 Laboratory Testing Equipment 7
Hardware 7
Software 8
Phase 1 Laboratory Testing Set-Up 8
Test Procedures and Results 9
Target Design and Data Correlation Quality 10
Objective 10
Procedure 10
Results 10
Scale Factor Determination and Sensitivity Analysis 11
Objective 11
Procedure 12
Results 13
Scale Factor 13
Sensitivity Analysis 13
System Resolution Testing 16
Objective 16
Procedure 16
Results 17
Image Quality Sensitivity Analysis 18
Objective 18
Procedure 18
Results 19
Conclusion 22
Laboratory Testing Results Summary 22
Preliminary Field Test Plan 24
Set-up 24
Procedure 24
Tentative Schedule 25
Appendix A – Target Designs 26
Appendix B – Target Correlation Matrices 29
Appendix C - Correlation Matrices for out of plane rotation 34
Appendix D – Correlation Matrices for distance sensitivity 37
Appendix E – Results for directly digitized data 40
Appendix F – Results for Recorded Data 44
Appendix G – Results for Data taken with mill at an angle 48

TABLE OF FIGURES

Figure 1: Walking Beam Concept........ 2
Figure 2: Truck-Based Reference........ 3
Figure 3: Prototype Measurement Technique........ 4
Figure 4: System Field Test Configuration........ 5
Figure 5: VTSM Lab Development Equipment........ 7
Figure 6: Block Diagram of Test Setup........ 9
Figure 7: Image Processing Procedure........ 9
Figure 8: Target Design Results........ 11
Figure 9: Scale Factor Target........ 12
Figure 10: Scale Factor Sensitivity Lab Set-Up........ 13
Figure 11 and 12: Target at 0 deg. Target at 5 deg........ 14
Figure 13 and 14: Target at 15 feet. Target at 14ft 10in........ 14
Figure 15: VSTM Coordinate Model........ 15
Figure 16: MathCad Model Results........ 15
Figure 17: Mill and Target Arrangement........ 16
Figure 18: Dial Indicator Instrumentation........ 17
Figure 19: Tilted Mill Table........ 17
Figure 20: X and Y Resolution Results........ 18
Figure 21: Overexposed Image........ 20
Figure 22: Under Exposed Image........ 21
Figure 23: Properly Exposed Image........ 22
Figure 24: Field Test Consist........ 24

Executive Summary

The following is an interim progress report covering the development work on a prototype Vertical Track Stiffness Measurement system (VTSM). The Federal Railroad Administration's Office of Research and Development has begun development of a prototype, dynamic track stiffness measurement system to quantify the relative strength of railroad track in the vertical plane. This effort is design to promote improved railroad safety through quantitative analysis of the strength of track structures. This report provides a review of the technical foundation for the proposed system, reports the results of Phase 1 laboratory testing, and outlines the remaining steps necessary to complete Phase 1 development and to obtain a working prototype.

To date, VTSM development efforts have progressed from an initial feasibility study through the selection of a design concept, and initial testing and development of a functioning prototype. To develop and refine data collection instrumentation and software, laboratory experimentation tasks have been completed. These tests have determined the ultimate system resolution and sensitivity to conditions that may be present in the field. These results, detailed in this report, indicate that the design concept should provide adequate resolution and accuracy for making dynamic displacement measurements, and the system is ready for field testing.

In addition, the report describes the proposed field testing procedure for the prototype VTSM. The field test will be made using purchased components as well as a significant amount of contractor-supplied equipment. Also, the MMID Railway will contribute motive power, rolling stock, and crew personnel and track time to support these field test activities. Field tests will determine if the prototype system can make accurate and repeatable dynamic vertical stiffness measurements.

Introduction

Background

The Federal Railroad Administration's Office of Research and Development has initiated a research project with the goal of developing a dynamic vertical track strength measurement system (VTSM) for railroad application. Achieving this goal will significantly increase the FRA's ability to measure railroad track parameters which have a direct impact on the safety of train operations. Presently, there exist a few systems which can measure vertical track deflection under load using wayside, static techniques. These systems are typically installed at a specific location along the track right-of-way, and some require that instrumentation be imbedded in the subgrade layer beneath the track. While generally regarded as accurate, these existing systems are cumbersome and time-consuming to install, and can only provide "spot" measurements of vertical track stiffness. The usefulness of these systems for wide-area data collection, i.e. for developing track strength databases, degradation models, and for insuring safe operating conditions, is limited. The FRA has determined that a dynamic measurement system, one that can make continuous stiffness measurements under load, is a useful and necessary tool to satisfy their objective of ensuring the safety of railroad operations.

Project Status

The first task under the Vertical Track Stiffness Measurement system (VTSM) project was to perform a feasibility study on the topic. The objective of the study was to determine if recent advances in measurement technologies, e.g. laser optics and digital signal processing systems, could be employed to facilitate the development of a dynamic vertical track strength measurement system. The procedure for completing this task involved researching previous attempts at making dynamic measurements, both in the railroad and highway industries, as well as investigating current, state of the art technology for its application to this measurement task. Furthermore, system configuration proposals were developed and analyzed. The results of the feasibility study were presented to the FRA in September 1998, in a report entitled "Feasibility Study: Vertical Track Stiffness Measurement System".

After presentation of the feasibility study report, research activities focused on developing a best-fit approach for the development of a prototype system. Many factors were considered during this effort, including system cost, measurement complexity, and time-to-deployment issues. These efforts culminated in a presentation to the FRA in January 1999, where a single-vehicle, dynamic vertical track stiffness measurement system proposal was presented. The proposed system utilizes advanced, yet affordable, optical and digital signal processing technology combined with standard railroad rolling stock to perform dynamic stiffness measurements under realistic loading conditions. This system is described in greater detail in the sections that follow. During the presentation, the FRA approved this prototype system proposal and authorized work to commence on Phase 1 development efforts. Phase 1 development involves two main activities, laboratory testing to develop and refine the measurement technology, and field testing to demonstrate the system's ability to make dynamic measurements.

Report Objective

The objective of this report is to provide a review of the technical foundation for the proposed VTSM prototype, to report the results of the Phase 1 laboratory testing, and to outline the remaining steps required to complete the Phase 1 system development effort.

VTSM Development Overview

Review of Proposed Measurement Technique

This section provides a brief review of the development process associated with the proposed measurement technique for the prototype VTSM. The results of the VTSM feasibility study concluded that an accurate measurement of vertical track stiffness could be made using a "walking beam" reference system, as illustrated in Figure 1.

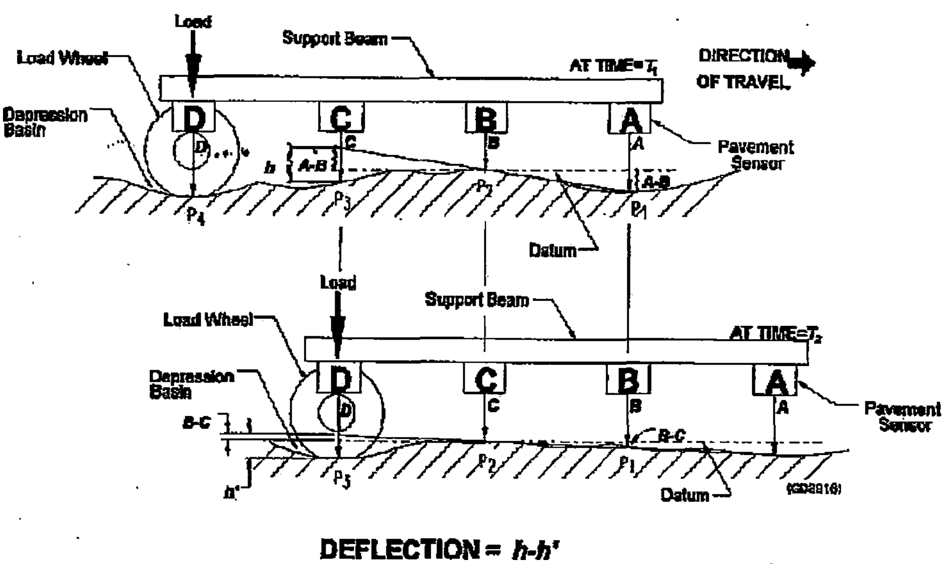


Figure 1: Walking Beam Concept

This measurement technique has been successfully employed in the highway industry for pavement deflection measurement tasks, and could be adapted to the railroad environment. The primary difficulty in transferring the walking beam system from the highway arena to the railroad environment is related to the system's ability to track the path of the rails. The walking beam method dictates that multiple sensors, in this case mounted to a vehicle, pass over the same location as the vehicle proceeds. In the case of highway pavement testing, it is a simple matter to travel between two locations in a straight line such that all sensors follow the same path. On the railroad, however, the sensors must follow the path of the rails. As a rail vehicle travels through curves and turn-outs, the rails move laterally with respect to the vehicle path, and the various walking beam sensors must follow the path of the rails. Further compounding this difficulty is the fact that the distance between each sensor of the walking beam system must remain fixed for valid measurements of deflection. A system designed to track the rails through curves and turn-outs could be designed using either contact or non-contact sensors and equipment, but the cost and complexity of such system would be prohibitive given the time and funding considerations of this project.

After additional research, a new design was developed which utilized the walking beam method of measurement, but in place of the car body reference platform, this new technique uses the standard 3-piece truck assembly as a reference platform from which to make measurements. Figure 2 translates the walking beam method from a car body reference system to a truck reference system. This new method replaces the two sensors, A and B, which describe a reference line from which measurements are made, with a beam connecting the truck wheels.

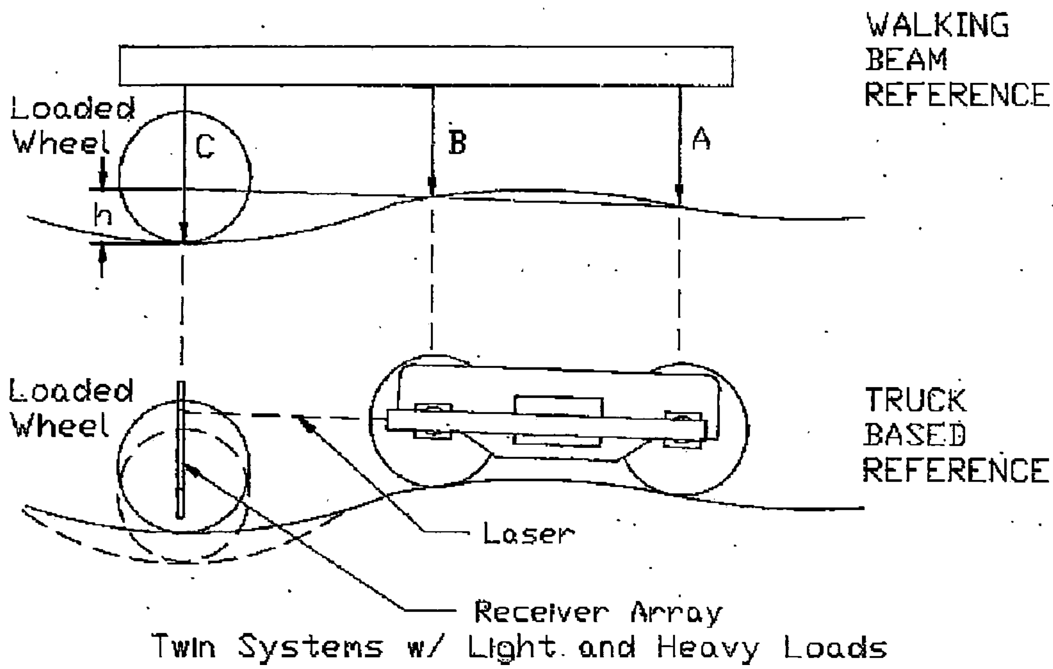


Figure 2: Truck-Based Reference

Combining two separate truck reference systems, one associated with a light load and the other a heavy load, a track deflection per unit load (stiffness) calculation can be made. The measurement technique and the associated stiffness calculations are illustrated in Figure 3.

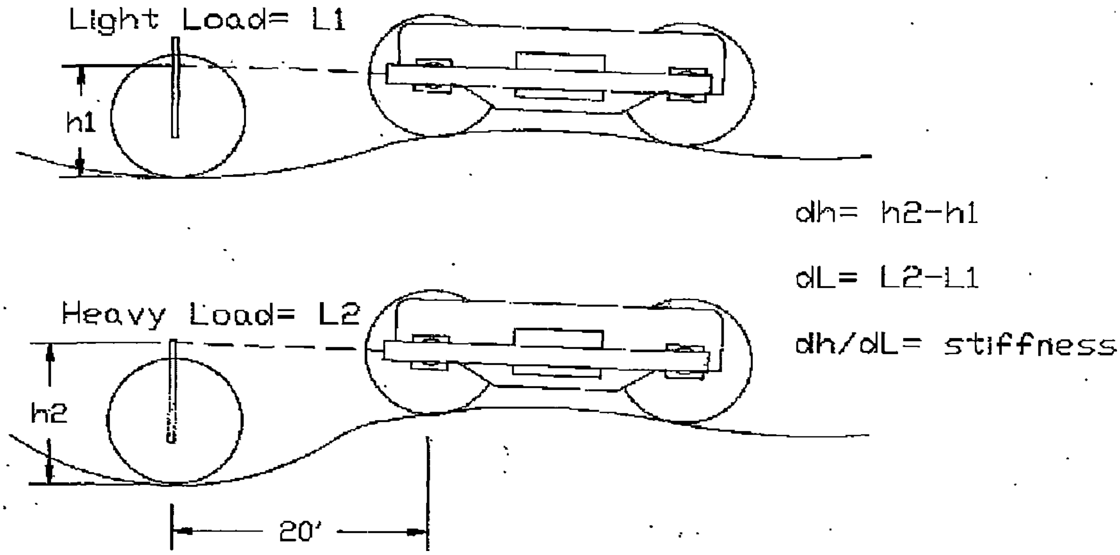


Figure 3: Prototype Measurement Technique

Figure 3 illustrates the simplicity of the proposed measurement technique. Vertical track stiffness is calculated using only four measurements: (1) Light Load (L1,lbs.), (2) Heavy Load (L2, lbs.), (3) Height of light load target relative to truck reference (h1, ins.), and (4) Height of heavy load target relative to truck reference (h2, ins.). Compared to the traditional walking beam technique, this new method significantly reduces the total number of measurements required, and greatly simplifies the system design.

Successful implementation of the truck-based measurement technique is dependent on two factors. First, each truck assembly (reference platform) must track the rails along an identical path. This particularly important in the vertical plane of reference. For each point of interest along the track, the truck assemblies (light and heavy) must provide an identical reference from which to make target position measurements. Any change in reference position between the two truck assemblies introduces an error in the stiffness calculation. It is felt that the truck tracking characteristics can be controlled through truck load and wheel profile configurations. Each truck will support an identical vertical load, and all truck wheels will have cylindrical profiles and identical diameters.

The second key factor is the target position measurement system. As shown in Figure 3, the wheels of the truck assembly provide a two-point rail head reference which describes a line connecting two references points (wheel/rail contact positions) to the target. The measurement system must project this reference line to the target and measure the position of the target relative to the reference line. Non-contact, optical sensors were found to provide the best resolution for this task. Laser sensors and cameras have been considered as potential measurement instruments.

Adaptation of System to GRMS Consist

Initial goals for VTSM development included using the existing FRA research consist as a development platform. Specifically, the installation was expected to occur on the existing GRMS platform: DOTX206, UP37183. After conducting a feasibility analysis it has become clear that installing the prototype VTSM system on the GRMS consist at this time will be difficult and may impede the development process. Initial testing of the prototype system is best conducted using other available equipment. After refinement of the measurement technique, it is anticipated that the VTSM will be a good fit for the existing GRMS consist.

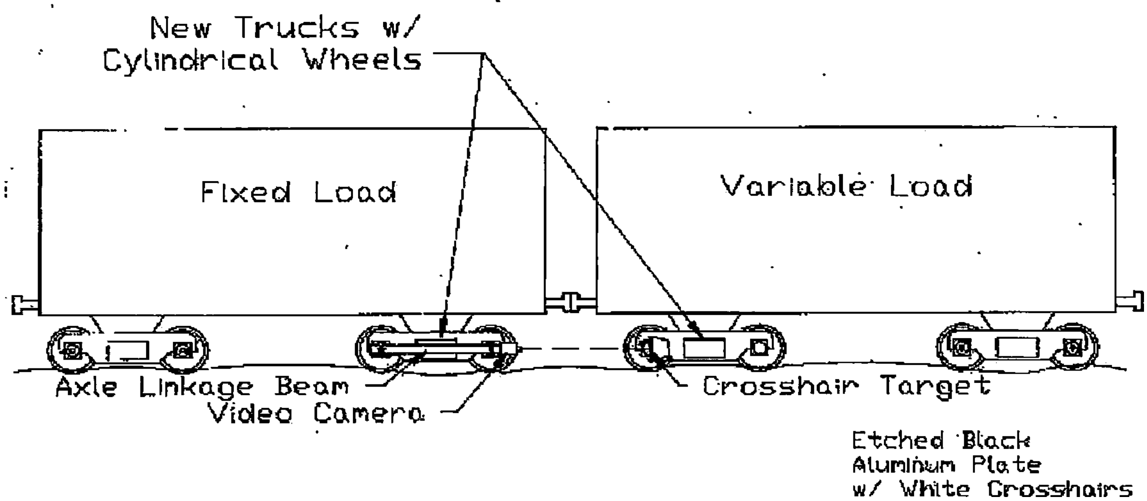


Figure 4: System Field Test Configuration

To reduce development costs and simplify field test procedures, initial system testing will be conducted using the two-car consist shown in Figure 4. These cars will be loaned to the program from Maryland Midland Railway for the purpose of executing field tests. The main difficulties in using the T-6/Hopper consist for this testing are related to the type of trucks used on T-6, and the internal configuration of the Hopper car. Since the proposed system relies on the precise tracking of freight trucks to establish a measurement reference, it is important that each truck be identically constructed. T-6 uses passenger car style trucks and the hopper has standard freight trucks. This mismatch in truck design may cause errors in tracking. Furthermore, the hopper car is currently configured for GRMS testing, and has hydraulic and paint equipment, as well as flooring mounted inside the car. This equipment would need to be removed for VTSM field trials to facilitate changing the vehicle weight (variable load car in drawing). For these reasons, the GRMS consist will not be used for the initial field tests of the VTSM, however, after development of the prototype system, the VTSM may be suitable for installation in the GRMS consist.

Phase 1 Goals and Objective

Phase 1 of the VTSM development effort is focused on translating the research conclusions into a working prototype VTSM. The objective of this phase of effort is to develop a working prototype VTSM system which can measure vertical track deflection under known loads to the required accuracy. Specific goals that must be reached as the effort progresses towards this objective include: (1) Demonstrate the repeatability and accuracy of the truck-based reference system. (2) Determine the overall system resolution. (3) Demonstrate the system's ability to measure track deflection.

The Phase 1 effort has been broken down into two primary activities. First, laboratory testing of various measurement system components will be conducted to determine the best hardware and software design and configuration for the system. Second, a field test will be run to test the system's ability to measure track deflection. With the successful conclusion of these activities, the most important technical questions regarding the feasibility of the proposed VTSM design will have been answered. If successful, these activities will provide the technical justification for the development of a single-vehicle VTSM designed for efficient, production-level data collection activities.

Phase 1 Laboratory Testing Objectives

The laboratory testing activities associated with VTSM Phase 1 development centered around choosing the right equipment with which to make the target position measurements and configuring this equipment in a suitable manner for the anticipated field testing activities. Primary investigations focused on camera/lens selection, target design, analysis software development, and system sensitivity and error analysis. Specific objectives for the laboratory activities were defined as follows:

1. Select and procure optical equipment required to perform target position measurements.
2. Develop hardware and software system to analyze/correlate captured data to yield target displacement results.
3. Determine appropriate target design and develop method which defines the quality of data correlation
4. Determine scale factor (inches/pixel) for camera data collection system and perform system scale factor sensitivity analysis on the following variables:
    - Change in distance between camera and target
    - Target tilt relative to camera
    - In and out of plane target rotation
    - Define system sensitivity to track curvature and resultant change in relative position of camera and target within system.
5. Perform testing to determine if an analog data collection system provides sufficient resolution for the measurements.
6. Perform analysis of image quality sensitivity to following variables:
    - Lighting effects: indoor v. outdoor, ambient v. high intensity lighting, etc.
    - Lens aperture settings (F-stop)
    - Shutter Speed

Successful completion of these objectives will yield important information regarding ultimate system performance, and will provide a technical foundation from which to design the hardware configuration and test plan for execution of the system field test. The maximum accuracy and resolution of the system will be defined, and the system's sensitivity to variables that will likely be encountered during the field test will be defined and understood. In addition, the processing software will be developed and the overall data collection system will be defined.

Phase 1 Laboratory Testing Equipment

Hardware

The following pieces of equipment were chosen and acquired for use in the VTSM laboratory testing exercise. Most of this equipment can be used for the field testing portion of Phase1.

Item	Qty	Description	Source
1	2	Pulnix TM-9701 2/3" B/W progressive scan cameras w/digital and analog output	Purchase
2	2	Nikkor 135mm, f/2.8 fixed focal length, manual focus lenses w/C-mount adapters	Purchase
3	2	Pelco EH3512 Camera enclosures w/120V AC heater	Purchase
4	2	SLIK U 6000 Camera Tripods	Purchase
5	1	National Instruments 1408 analog image capture board	Purchase
6	1	Pentium 200 based PC computer	ENSCO
7	2	Panasonic AG-6720 S-VHS/VHS high density VCR	ENSCO
8	1	Milling machine index table	ENSCO
9	2	Magnetic base Dial Indicators	ENSCO
10	1	Pentax digital spot meter	ENSCO
11	1	Intel Smart Video Recorder III frame grabber w/ image acquisition software	ENSCO
12	1	MathCad software	ENSCO
13	1	IMAQ Vision for LabView software	Purchase

Figure 5: VTSM Lab Development Equipment

In addition to the laboratory equipment, certain long lead items have been ordered for the Phase 1 field test activity. These components are:

- 2 ea. 100-ton truck assemblies, including springs, side bearings, and bearing adapters
- 4 ea. 61/2x12 36" multi-wear wheelset with cylindrical profile

Software

Software requirements for the Phase 1 development efforts are focused on developing a cross-correlation algorithm to quantify the change in target position relative to the truck reference. The procedure is to capture two pixelized images of the target, one under light load conditions and the other under the heavy load, and through digital processing techniques, quantify the target position change. Two digitized images are cross correlated using a standard algorithm and relative displacement is output as set of coordinates (x,y). Additional information related to the quality of the correlation is output as a matrix of normalized correlation values. This information is very useful for system design and quality control activities.

Initially, MathCad was used to develop an image cross correlation routine to determine the relative displacement of two otherwise identical images. Initial tests were conducted comparing a known image with an image that was shifted in software by a set number of pixels. Results were satisfactory, but the processing time requirements were excessive.

The image-processing algorithm was rewritten using C++, and processing time has been reduced dramatically. The image processing software takes two images as input, and outputs the relative displacement in pixels. Static tests with artificially induced, known offsets have been performed on a full 640x480 image, and results correspond to the actual displacements. In addition, the software also reports a normalized correlation coefficient, which is a measure of the correlation quality. In an idealized case with a perfect correlation, the correlation factor should have a value of 1.000. This has been verified in laboratory tests. The software also includes a sequential registration test, which keeps a running total of accumulated error values for each possible offset. If a threshold is exceeded, processing for that position is halted, and processing of the next position begins. This greatly reduces processing time for positions with poor correlation, and improves overall processing time. For field test data analysis, this existing software will be incorporated into LabView. All data from field tests will be analyzed in a post-test manner.

Phase 1 Laboratory Testing Set-Up

The current system uses a single camera/single target configuration, with the signal running from the camera and through the VCR to the Intel frame grabber (Fig 6). The camera is located at 15' from the target, with the target mounted to a milling machine index table. Two dial indicators mounted to the milling machine allow for precise measurement of both vertical and horizontal displacements of the target. Still images of the target are captured at a resolution of 640x480, and saved to disk in a bitmap format.

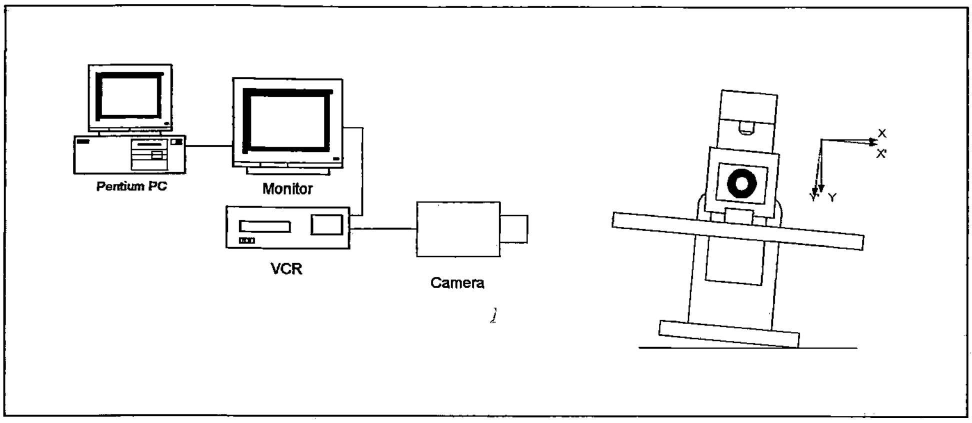


Figure 6: Block Diagram of Test Setup

The processing routine begins by capturing an image with the Intel frame grabber and its accompanying software. Images are saved to disk in a windows bitmap format. The bitmap files are then read into MathCad, which saves them to disk in an ASCII text format. A series of these ASCII files (1 per image) is then read by the image processing software, which outputs the correlation matrix for each image, as well as vertical and horizontal offsets. The maximum value of each correlation matrix is also displayed, as illustrated in Figure 7, below.

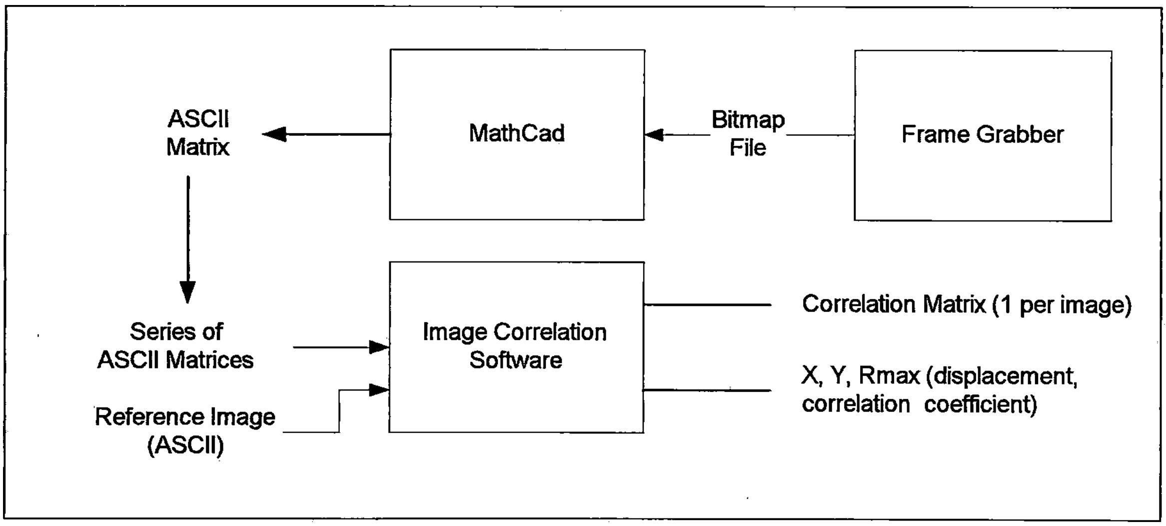


Figure 7: Image Processing Procedure

Test Procedures and Results

The following section will describe the testing procedures used to complete the laboratory portion of Phase 1 VTSM development. Results from each test are summarized in this section; additional data is provided in the Appendices of this report. The first two objectives for this phase of development have already been discussed.

Target Design and Data Correlation Quality

Objective

To determine an appropriate target design and to develop a method which defines the quality of data correlation

Procedure

To determine the offset of a target, the maximum value of the correlation factor within the image matrix is found. In order to determine how accurate this offset is, it is necessary to determine how well the correlation factors define the peak in the correlation matrix. It is preferable to have a clearly defined, sharp peak as opposed to a flatter curve in order to minimize any error due to signal noise. The objective of this test was to choose a target that has the most clearly defined peak. Each of five targets target was digitized, and using Paint Shop Pro, a 57 X 60 pixel area around the center of the target was chosen as a reference image. All targets were printed on an 8 ½" x 11" piece of paper. Target designs can be found in Appendix A. The image correlation routine was then run on each target and its corresponding reference image, and the correlation coefficients R(x,y) were written to a file. This matrix was then plotted using MathCad, and the individual peaks examined.

Results

The images below (Figure 8) show three of the targets tested, as well as their corresponding correlation matrices. The plots represent a 10 X 10 pixel area around the peak of the correlation function. It can clearly be seen that the last target yields the most clearly defined peak, and thus this target was chosen as the best design.

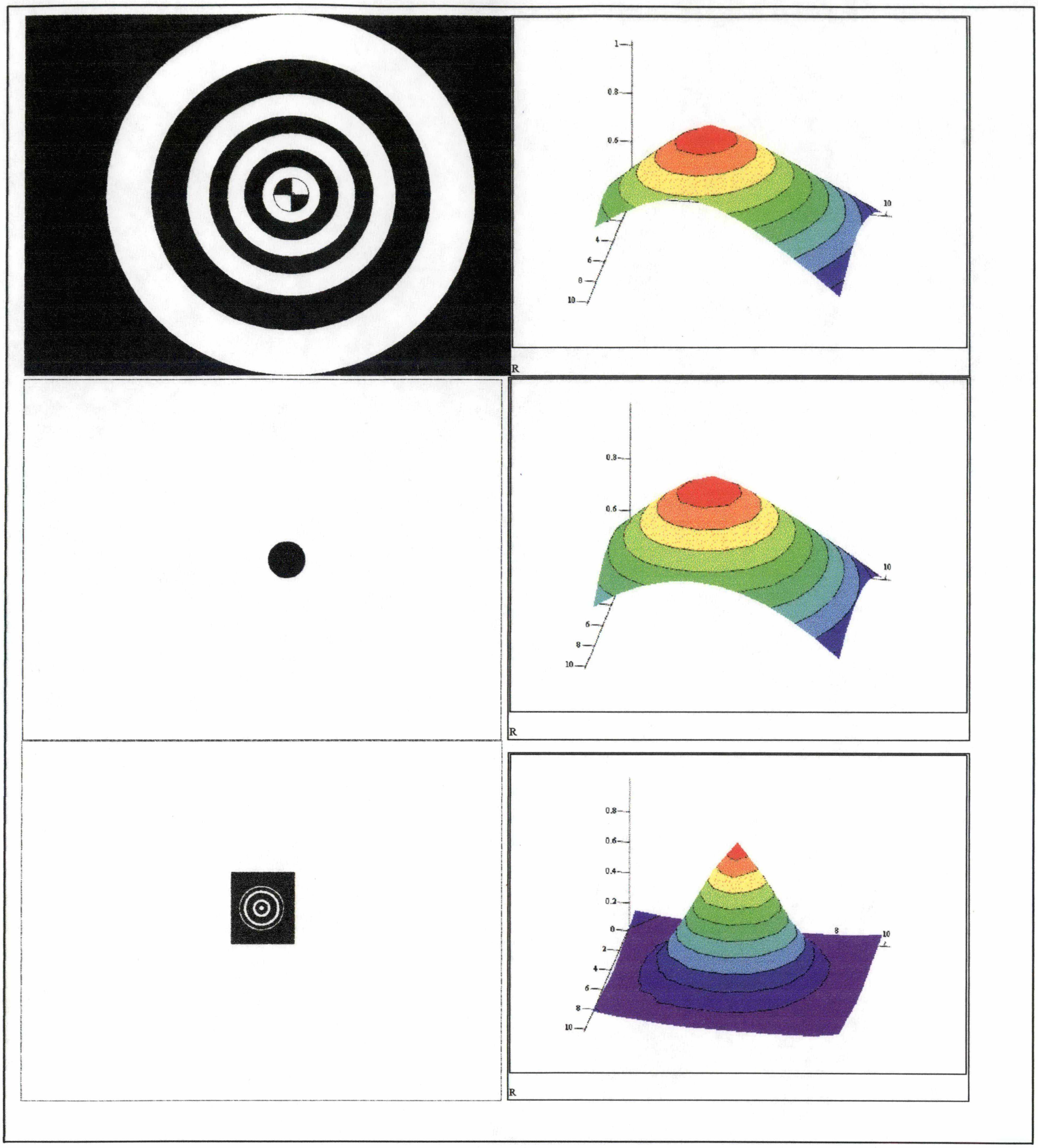


Figure 8: Target Design Results

Scale Factor Determination and Sensitivity Analysis

Objective

To determine scale factor (inches/pixel) for camera data collection system and perform system scale factor sensitivity analysis on the following variables:

- Change in distance between camera and target
- Target tilt relative to camera

- In and out of plane target rotation
- Define system sensitivity to track curvature and resultant change in relative position of camera and target within system.

Procedure

Scale factor was determined by recording an image with reference marks of known dimensions. The target has two sets of reference marks (i.e. rulers) at 90° to each other, as well as 2 circles of known diameter (Fig 9). Each rectangle is 1" x 1", and the circles have diameters of 6" and 8". The image was captured with the reference marks aligned so that they are perfectly horizontal and vertical in the field of view. The image was then examined using Paint Shop Pro, and independent scaling factors for horizontal and vertical displacements can be obtained by the following relationship:

Scale Factor = (actual distance between reference marks)/(pixels between reference marks)

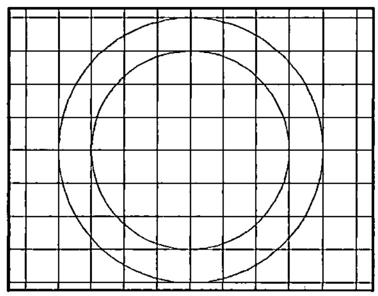


Figure 9: Scale Factor Target

Once the scale factor was obtained for laboratory testing, a sensitivity analysis of the scaling factor was performed in order to determine the change in distance between the target and camera due to track parameters such as curvature, as the scale factor is a function of distance. After calculating the expected angle and distance changes, these movements were simulated on the mill in order to see if a good correlation could still be obtained. In order to determine the effects of out of plane rotation, the target was digitized at an angles of 0°, ±2.5°, and ±5° (Fig 10). The correlation routine was run on each image, and the resulting correlation matrices were plotted.

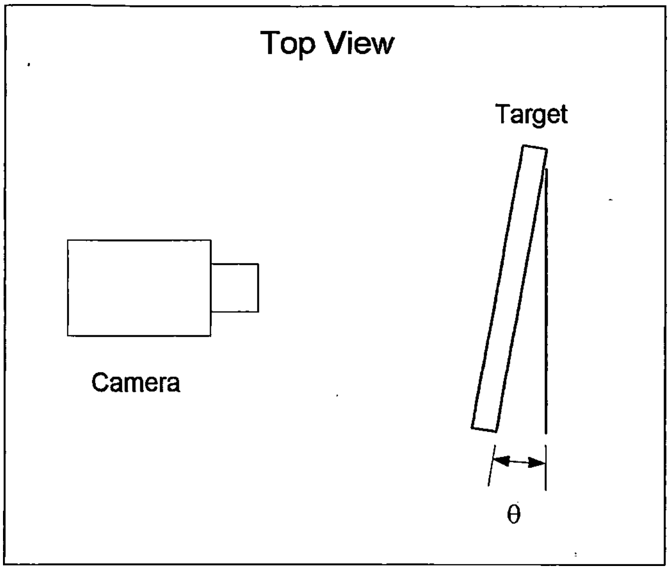


Figure 10: Scale Factor Sensitivity Lab Set-Up

Sensitivity to distance changes was determined in the same fashion by obtaining images of the target at 0”, ±1”, ±2” from its initial position. Once again, the resulting correlation matrices were plotted. In addition to the correlation matrix, x and y coordinates of the target were also measured.

Results

<u>Scale Factor</u>

The scale factor has been determined to be 60.375 pixels/inch (~.0166”/pixel) in the horizontal direction, and 59 pixels/inch (~.0169”/pixel) in the vertical direction.

<u>Sensitivity Analysis</u>

Results indicate that the target distance may increase or decrease by much as 2” while traversing a 20° curve. Since the scale factor varies linearly with distance, a 2” change in distance at a range of 10 feet would give an error of 1.7% or .017”/inch. Assuming the measured displacements are fairly small (<1/2”) this would yield a maximum error of .0085”.

Both distance and out of plane rotation test show a crisp, well defined peak in the correlation matrix, even at the maximum rotation and maximum distance of the target from the camera (Figs 11-14). Therefore, the system appears to be relatively insensitive to changes in direction or out of plane rotation for the estimated range of motion expected during field tests. The complete set of correlation matrices can be found in Appendix C and D.

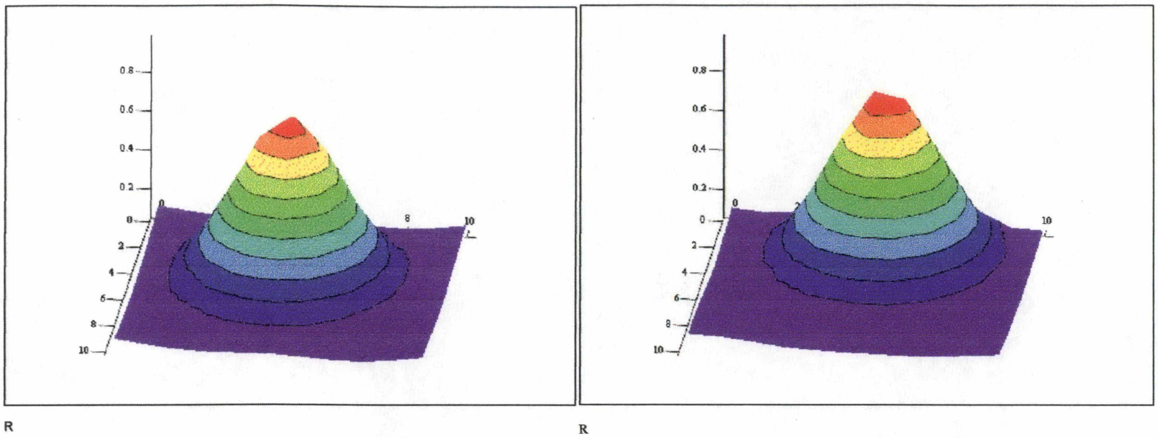


Figure 11 and 12: Target at 0 deg. Target at 5 deg.

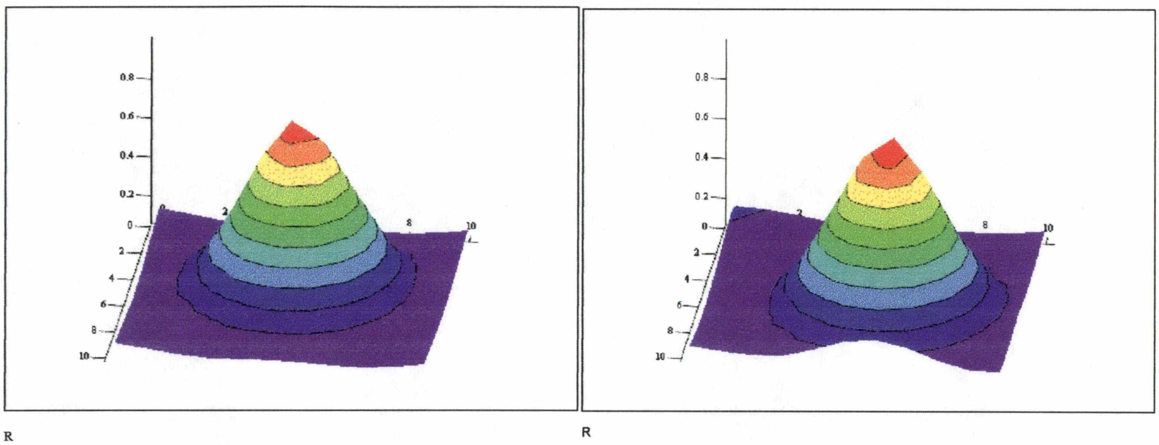


Figure 13 and 14: Target at 15 feet. Target at 14ft 10in.

To simulate the change in distance between the camera and target over a range of expected track characteristics (curvature), a VTSM coordinate model was developed in MathCad. The model was constructed to simulate the effect of curvature on the distance between the target and camera – and the resultant scale factor effects on the displacement measurements. Figure 15, below, illustrates the MathCad model.

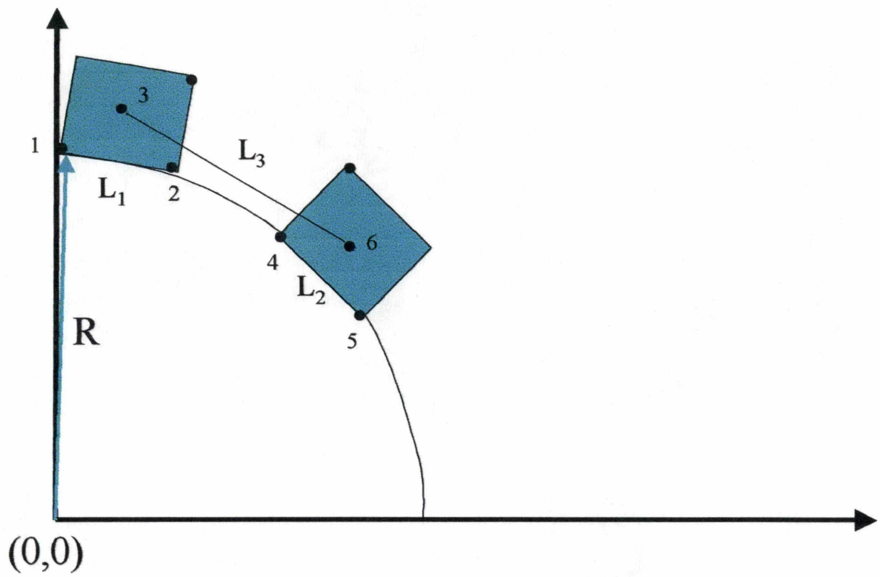


Figure 15: VSTM Coordinate Model

The MathCad model was run through a series of curves varying from 0 to 25 degrees. The corresponding change in displacement between the target and camera is illustrated in Figure 16. The results indicate that the change in distance between the camera and target will not exceed 2 inches for curves of less than 20 degrees. Therefore, the error in the scale factor of the system should be of the same magnitude as measured from the mill trials.

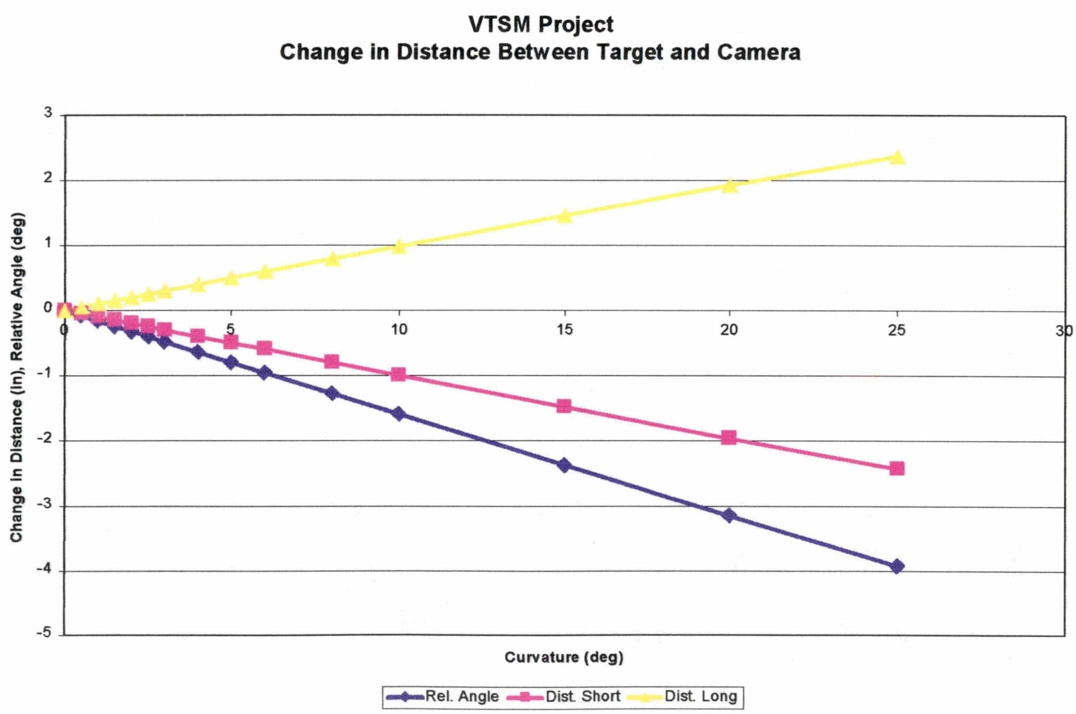


Figure 16: MathCad Model Results

In summary, it is clear that the scale factor for the camera/target system is a function of the distance between the two components and, for a given camera to target distance, errors in the scale factor due to anticipated track characteristics are well below the system resolution level.

System Resolution Testing

Objective

The objective of this series of tests was to determine the resolution of the system, and to determine whether an analog based video system satisfied the resolution requirement of .050".

Procedure

System resolution was determined by mounting the target on a milling machine index table (Fig. 17). The target was then moved in the horizontal direction in ten increments of .010", followed by ten increments of .050 inches. The target was then moved in the vertical direction using these same increments. In order to minimize gear backlash effects from the measurements, actual offsets were measured using dial indicators mounted to the mill (Fig 18). At each increment, the image was recorded to S-VHS videotape for a duration of 30 seconds using the alarm input on the VCR to trigger recording. As each image was recorded, it was simultaneously digitized as a bitmap file, and the data set was analyzed using the image processing software.

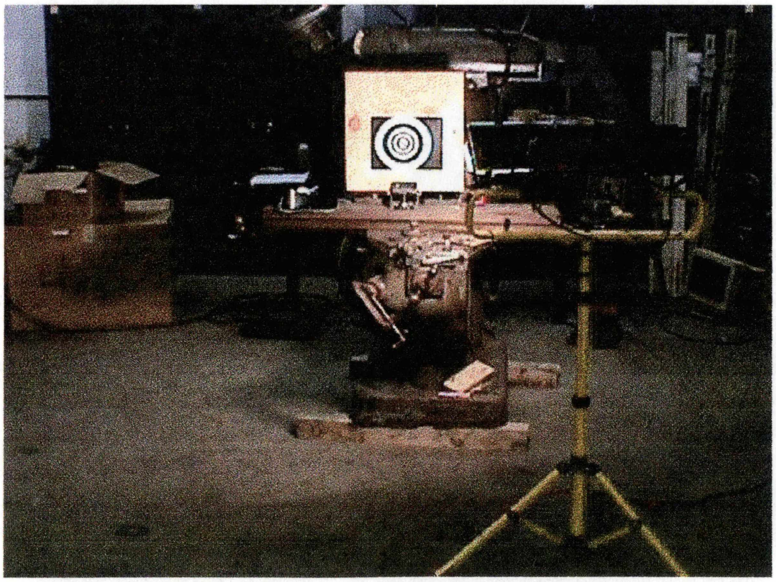


Figure 17: Mill and Target Arrangement

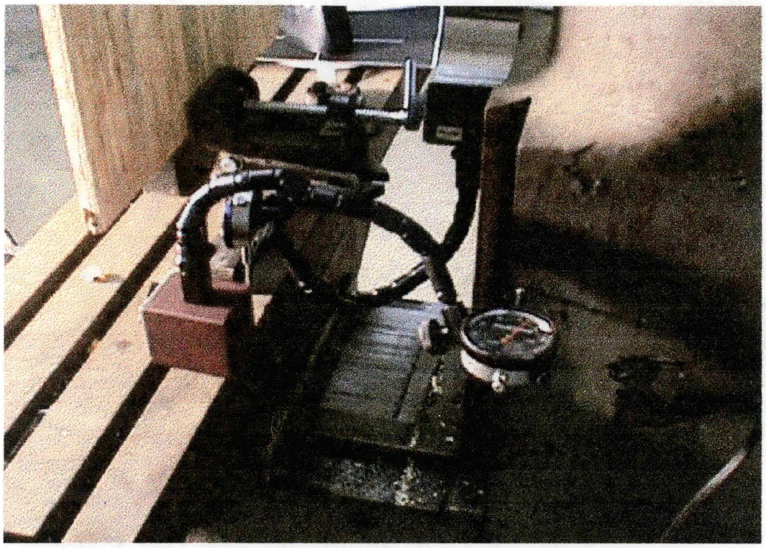


Figure 18: Dial Indicator Instrumentation

The recorded images were then digitized from videotape while the VCR was in playback mode, and this data set was once again processed using the image correlation software. It should be noted that when the VCR is paused however, the image does exhibit some jitter, therefore digitizing an image while the VCR is paused is not recommended.

In order to determine the effects of simultaneous movement in both the horizontal and vertical directions as would be experienced in the field, the mill was placed at a known angle to the camera, and another data set was digitized using the same increments as before. The mill was tilted relative to the camera by raising one end by 1.556" with a hydraulic jack. (Fig. 19). Images were not recorded to tape.

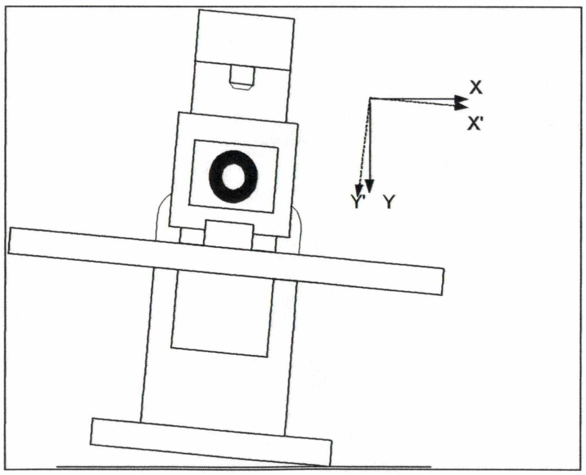
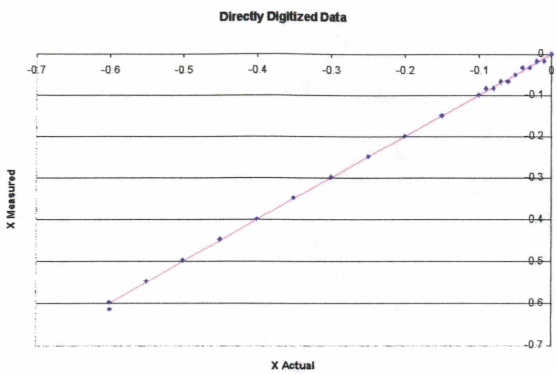


Figure 19: Tilted Mill Table

Results

After processing the image sets, and plotting the measured displacement vs. actual displacement, it can be shown that system resolution is within .020". Figure 20 shows these graphs for both the x and y directions. Detailed test results can be found in Appendix E.



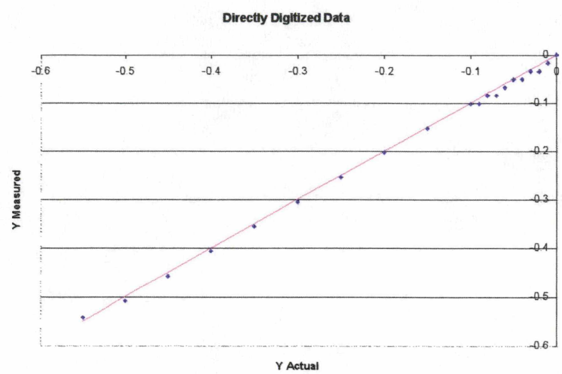


Figure 20: X and Y Resolution Results

The results of the recorded data set are nearly identical to the directly digitized data set, showing almost no loss of resolution due to the recording process. These results indicate that field tests can be conducted using S-VHS tape to record data without degradation in the data quality. This greatly reduces the cost and complexity associated with the field tests. Results for this data set can be found in Appendix F.

In the case of the mill at an angle, it was necessary to transform movements in the coordinate system of the mill (X',Y') to the coordinates of the camera (X,Y). The following equations were used to convert from one coordinate system to the other:

$$X = X' \cos(\theta) - Y' \sin(\theta)$$
$$Y = X' \sin(\theta) + Y' \cos(\theta)$$

As in the previous cases, system resolution is within .020", indicating that an analog based system has sufficient resolution, and that a fully digital system is not necessary at this point in system development. Results can be found in Appendix G.

Image Quality Sensitivity Analysis

Objective

Perform analysis of image quality sensitivity to following variables:

- Lighting effects: indoor v. outdoor, ambient v. high intensity lighting, etc.
- Lens aperture settings (F-stop)
- Shutter Speed

Procedure

All previous test were performed indoors with high intensity lighting on the target. Shutter speed was set to 1/500 of a second to insure a crisp, clear image in the field, while still allowing a reasonable amount of light to enter the camera. It should be noted that shutter speed and lens aperture are not independent of each other. For set of lighting conditions, any change in shutter speed requires a corresponding change in aperture (i.e. if the shutter speed is increased by a factor of 2, the aperture must be decreased by 1 f-stop). It is preferable to keep the f-stop as high as possible in order to maximize depth of field, i.e. the distance behind an in front of the focal point where the target remains in focus.

In order to determine the effects of different lighting conditions, the target was taken outdoors, and images of the target were recorded under different lighting conditions. Lighting conditions that were examined were:

- Target in direct sunlight with the sun behind the camera
- Target in shadow i.e. a shroud blocking the sunlight
- Target w/shroud and high intensity lighting on the target

In addition, a reading was taken with the light meter for each set of lighting conditions.

Results

Initially a light reading was taken indoors with high intensity lighting on the target. This gave a reading of 13 2/3 (Scale is from 1 to 20, with each number corresponding to a change of 1 f-stop). Camera settings were as follows:

Shutter Speed: 1/500 s
Aperture: f/8
Light meter reading 13 2/3

Next, the target was placed in direct sunlight, and the shutter speed an aperture settings were left identical to those used indoors. This caused the image to be completely overexposed and washed out (Fig. 21). In order to obtain a well exposed image it was necessary to change the f-stop by 3 levels, which was confirmed by the light meter. Camera settings for obtaining a clear image under these conditions are as follows:

Shutter Speed: 1/500 s
Aperture: f/22
Light meter reading: 16 2/3

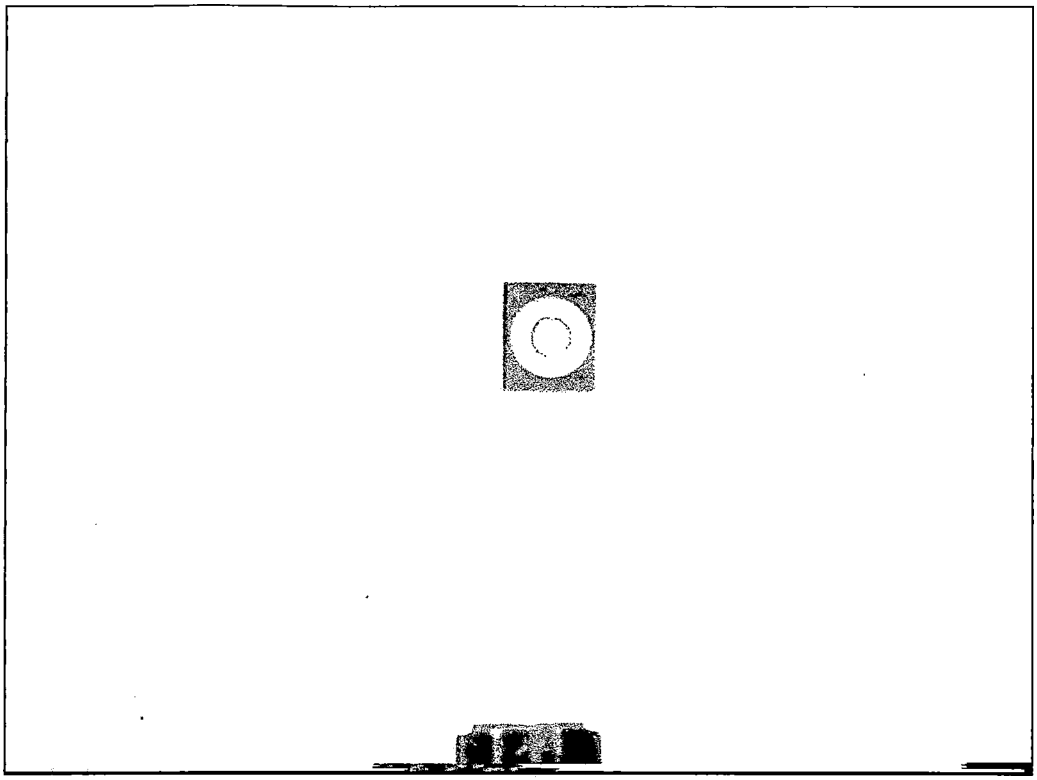


Figure 21: Overexposed Image

The target was then shrouded, and a light meter reading of 12 was obtained. Keeping the settings identical to those with the target in direct sunlight now yielded a completely underexposed image (Fig 22). In order to obtain a clear image the f-stop needed to be changed to f/5.6. The shutter speed was kept at 1/500 of a sec. This indicates that in the field, the system would not be able to handle varying light conditions such as going from sunlight to shadow. In order to correct this problem it is therefore necessary to either use a camera with an automatic gain, or to control the lighting conditions by using a shroud and high intensity lighting.

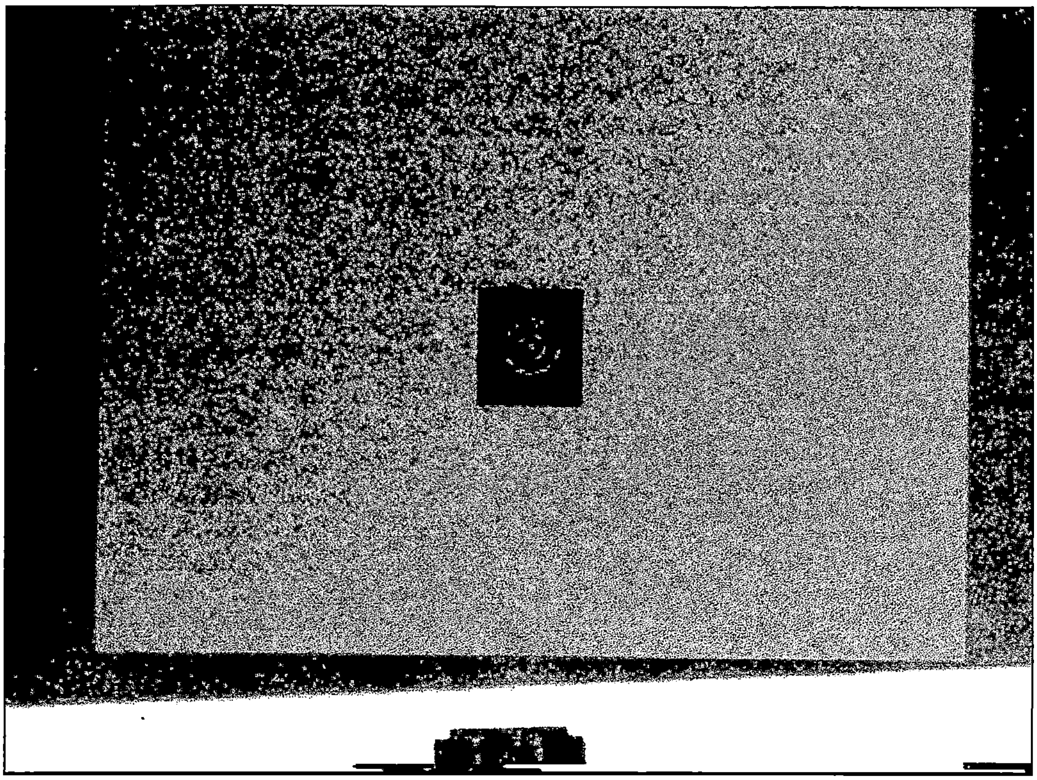


Figure 22: Under Exposed Image

By putting a shroud on the target and illuminating it with high intensity lighting (outdoors with sunshine) a clear image of the target was obtained by using the same camera settings as indoors(Fig. 23). Light meter reading were also very close to those obtained in the laboratory. Camera settings were as follows, and will be used as the initial settings for the field tests.

Shutter Speed: 1/500 s
Aperture: f/8
Light meter reading: 13 1/3

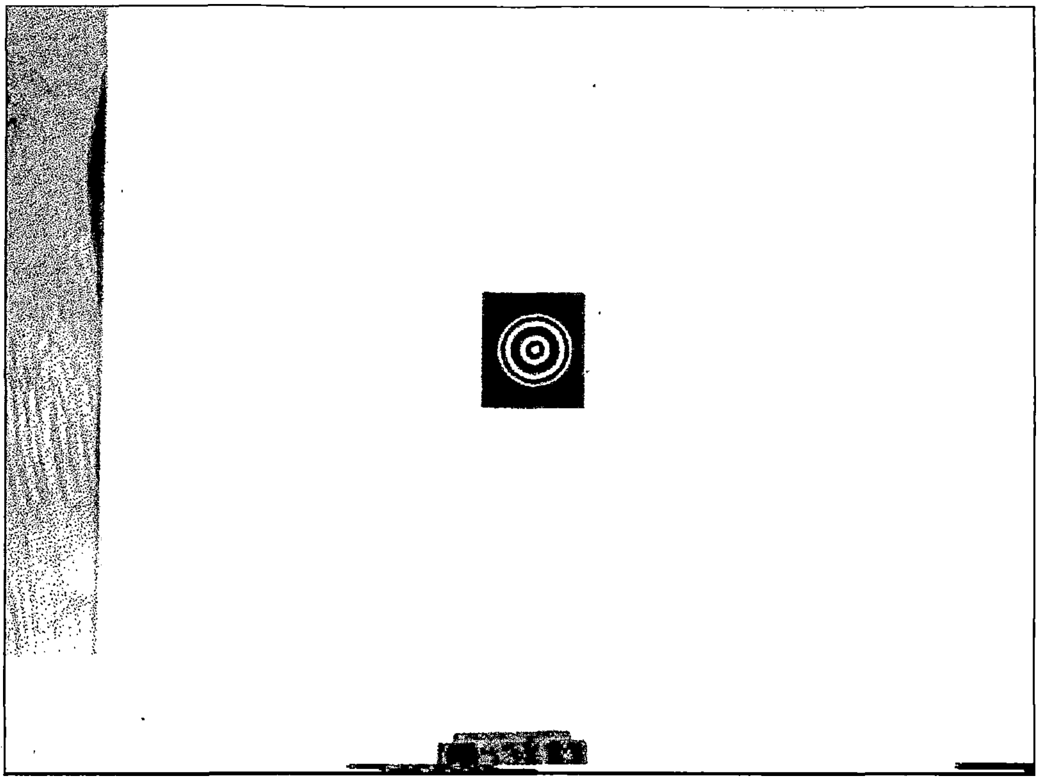


Figure 23: Properly Exposed Image

Conclusion

Laboratory Testing Results Summary

With the submission of this report, the laboratory testing activities of VTSM Phase 1 development are complete. The objectives for this effort have been met, and the results indicate that the proposed system should perform well for the field test activities. A summary of the laboratory activities follows.

The laboratory testing phase of this project was undertaken with some specific objectives. These objectives were met with the following results.

Select and procure needed equipment

Most of the required components for the VTSM data collection system have been acquired, either through purchase or ENSCO contribution. Additional equipment will be required to execute the field test but, at this time, the data collection system has been established and is working.

Develop a hardware and software data collection system

A hardware and software data collection system has been designed and developed. This system will capture and correlate target images to yield position change information in a post-test processed manner. Real-time data is acquired using a high resolution CCD camera and the images are stored on S-VHS tape. Data is digitized using a special PC card and computer and analysis is conducted using ENSCO-designed software. System outputs can be adjusted to suit changing data requirements as the system is developed.

Develop and test a target system and design a method of measuring the quality of target image correlation

Various target design concepts have been analyzed, and an appropriate target design has been selected for VTSM development. This target yields the most precise correlation results. Correlation data is output as x and y displacements of the target center. The quality of correlation is quantified using a normalized correlation coefficient. This coefficient can vary between -1 and 1, with a value of 1 being the highest correlation quality possible. In addition to the normalized coefficient, a coefficient matrix is displayed. This matrix includes a 10 x 10 array of correlation coefficients. When graphed in three dimension, the shape of this matrix gives a measure of the degree of uncertainty associated with the correlation between the two images. A sharp peak in this shape indicates that the correlation coefficients for the surrounding pixel trials were much lower than for the selected pixel location. In this case, there is a high degree of certainty that correlation routine has aligned the images well. If the shape is more rounded, there is less certainty in the correlation. This correlation coefficient/matrix shape analysis technique was used extensively during the laboratory testing efforts to quantify the results of various tests.

Define a scale factor for the system and perform a sensitivity analysis

A scale factor for the camera/target system was determined using a calibration target. The value of the scale factor is directly related to the distance between the target and camera. To the sensitivity of the scale factor, various tests were conducted to measure the change in scale factor due to target displacement. Also, a model was developed to simulate target-camera displacements that would occur as the system traveled along the track. In all cases, the errors due to camera/target alignment issues were much lower than the resolution of the system (less than 0.020").

Measure the resolution of the analog data collection system.

Tests were conducted to determine the maximum system resolution given the operating conditions planned for the field test. The maximum system resolution is currently 0.020", which exceeds the goal of 0.050" that was established during the feasibility study phase of this project. Sub-pixel resolution may be possible using an additional processing routine, but no testing of this routine has been conducted at this time. System resolution was tested by displacing the target a known distance and correlating the before and after images. The system outputs repeatable and linear results. At this time it is felt that the analog data collection system will provide sufficient resolution for system field testing.

Perform system sensitivity analysis to image quality changes

The system was tested under a variety of different lighting and hardware configurations. It has been demonstrated that a degraded image will adversely affect the system's ability to resolve the target image. Image quality can be controlled through the use of target and camera shielding and through the use of direct target lighting. Initial camera and lens settings were determined for field testing.

In conclusion, the laboratory portion of VTSM Phase 1 development has been concluded. All results indicate that the proposed camera/target system, and its associated data collection and analysis system, should perform the functions necessary to complete the field test activities.

Preliminary Field Test Plan

Set-up

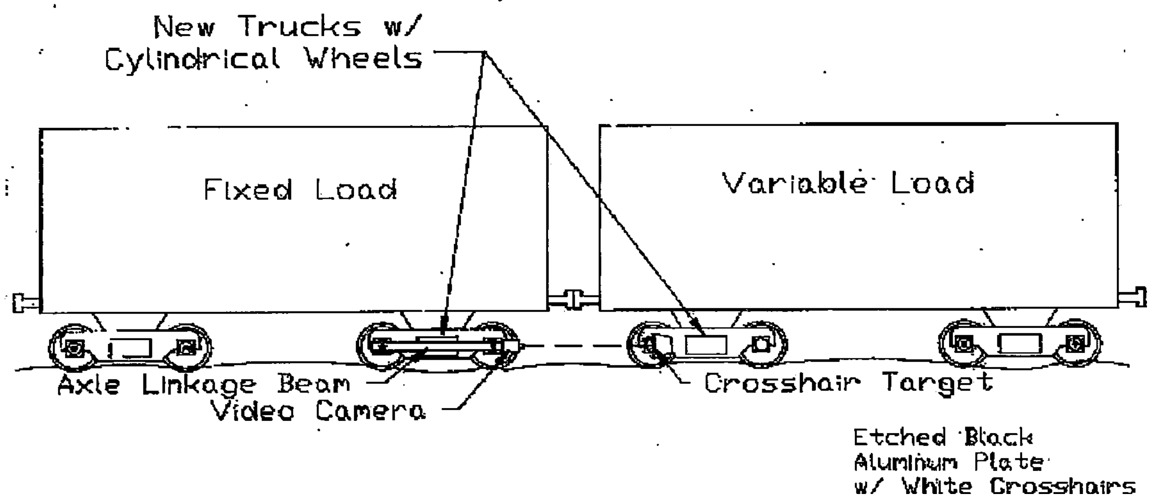


Figure 24: Field Test Consist

Figure 24 illustrates the proposed test configuration for the field test portion of Phase1. In addition to the two test vehicles shown, the consist will include a MMID-furnished locomotive and a borrowed caboose which will serve as the data collection platform. Data will be collected from two (right and left) camera/target systems and stored on VHS tape in real time. Additional information such as speed and track position will also be collected. All data will be time based to facilitate post-test data analysis.

Procedure

Field verification of the camera/target measurement system will be conducted at the Maryland Midland Railway in the May 1999 time frame. The objective for the field test exercise is to verify the performance of the prototype VTSM hardware and software configuration. The goals for the field test are defined as follows:

- Verify the repeatability of the two truck assemblies. Confirm that each truck follows the same path along the track at various speeds.
- Verify the performance of the data collection system.
- Measure track deflection under known loads.

The general approach to this effort will be to instrument and configure 3 rail cars, 2 test vehicles and 1 support car, for single-pass VTSM testing. All cars will be borrowed from the Maryland Midland Railway. A test zone of interest will be selected near the Union Bridge, MD yard that contains track features of interest such as curves, road crossings, bridges, etc. Data will be collected on this track section at various speeds (5, 10, 15, 20 mph) for analysis. Two sets of test runs will be conducted, one at a light loading level, the other at a high vertical loading level. Track deflection data, and system repeatability information will be available following post-test data reduction.

Tentative Schedule

The field test activities will be conducted in late May 1999. Post-test data reduction and report writing efforts should be complete by mid-July 1999.

Appendix A – Target Designs

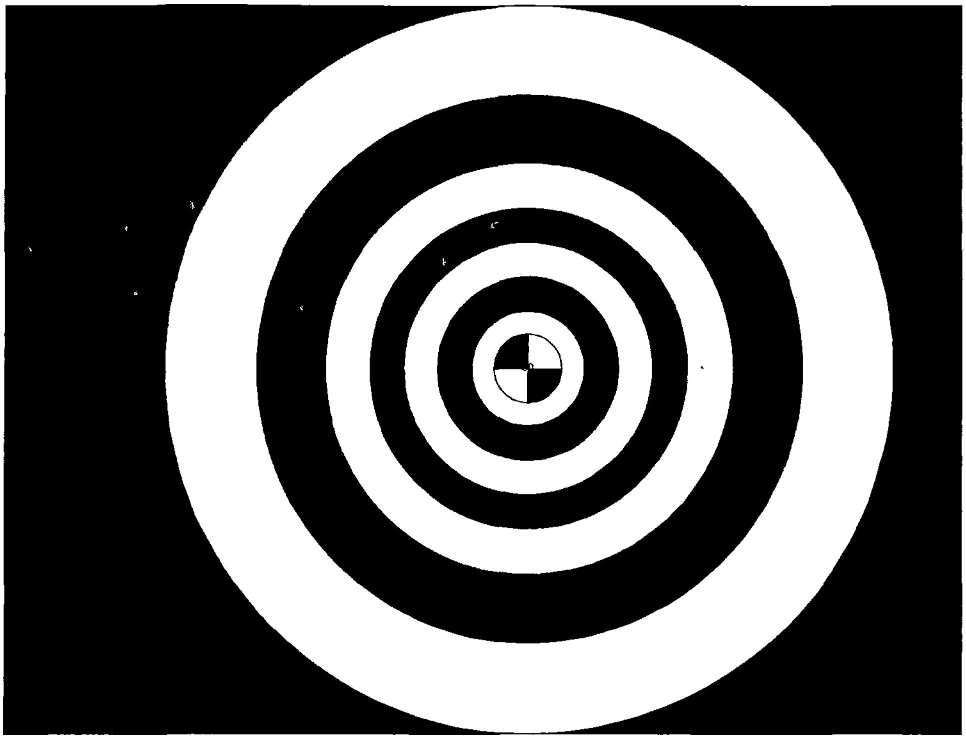


Figure 1: Target A

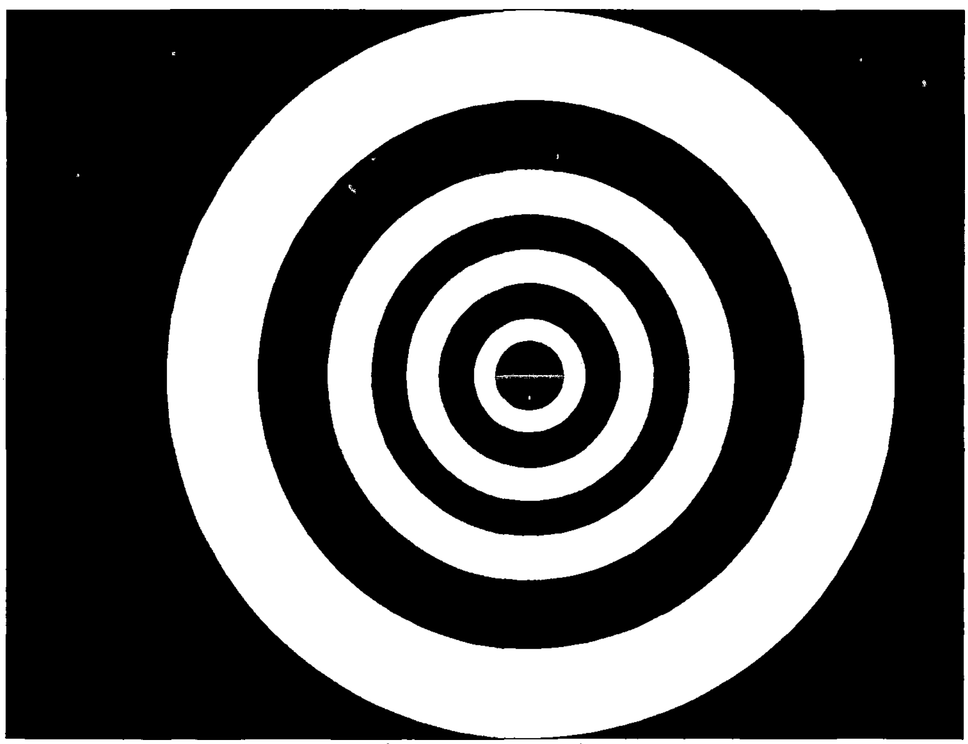


Figure 2: Target B

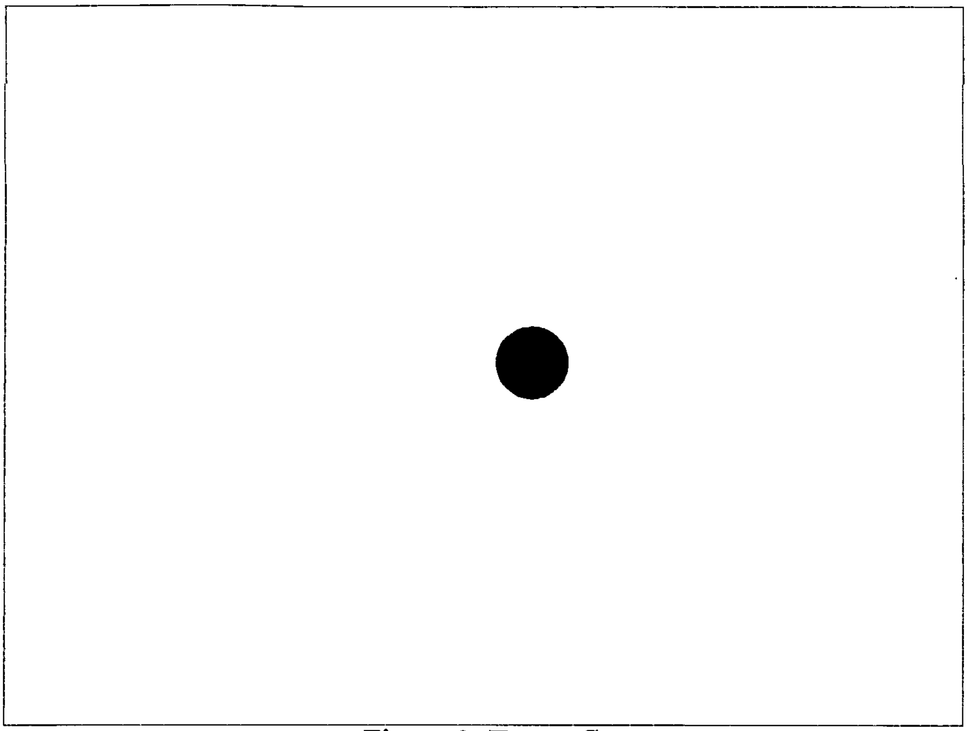


Figure 3: Target C

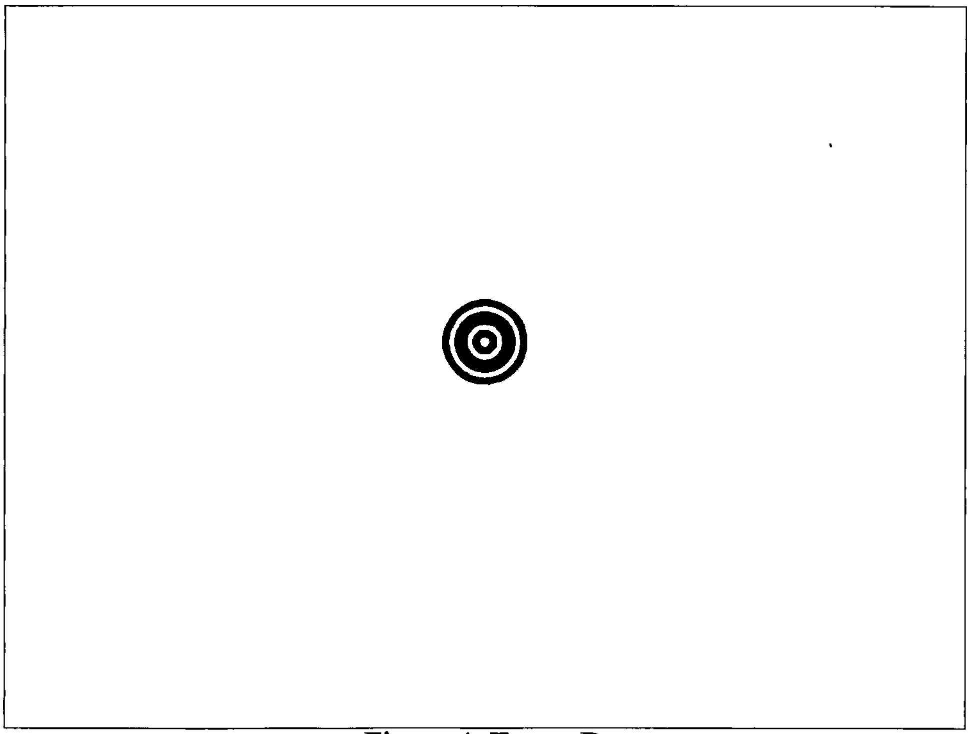


Figure 4: Target D

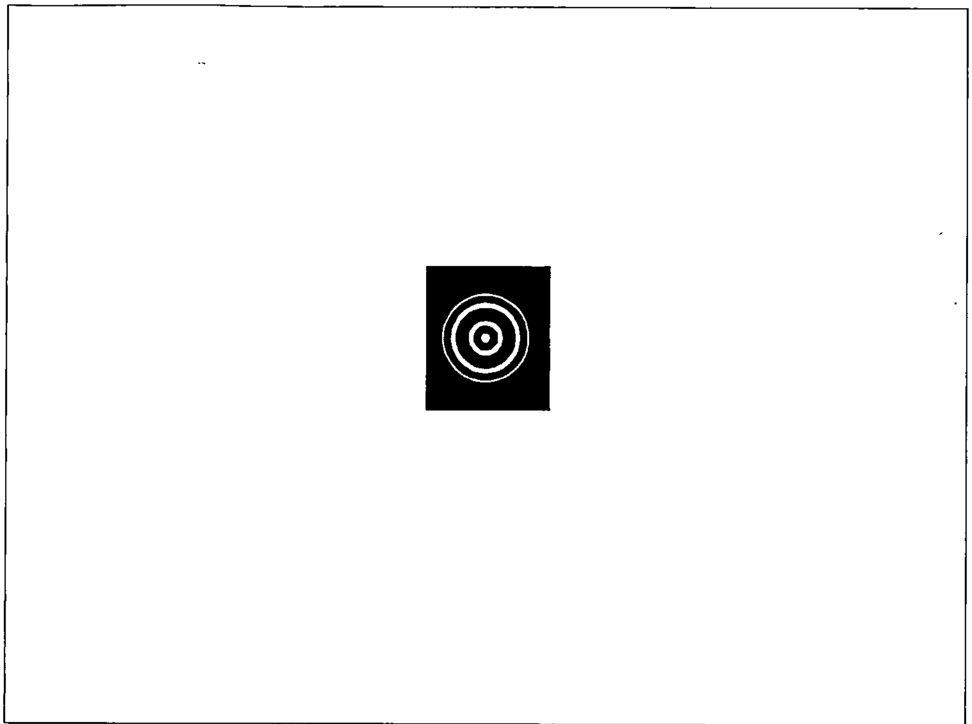
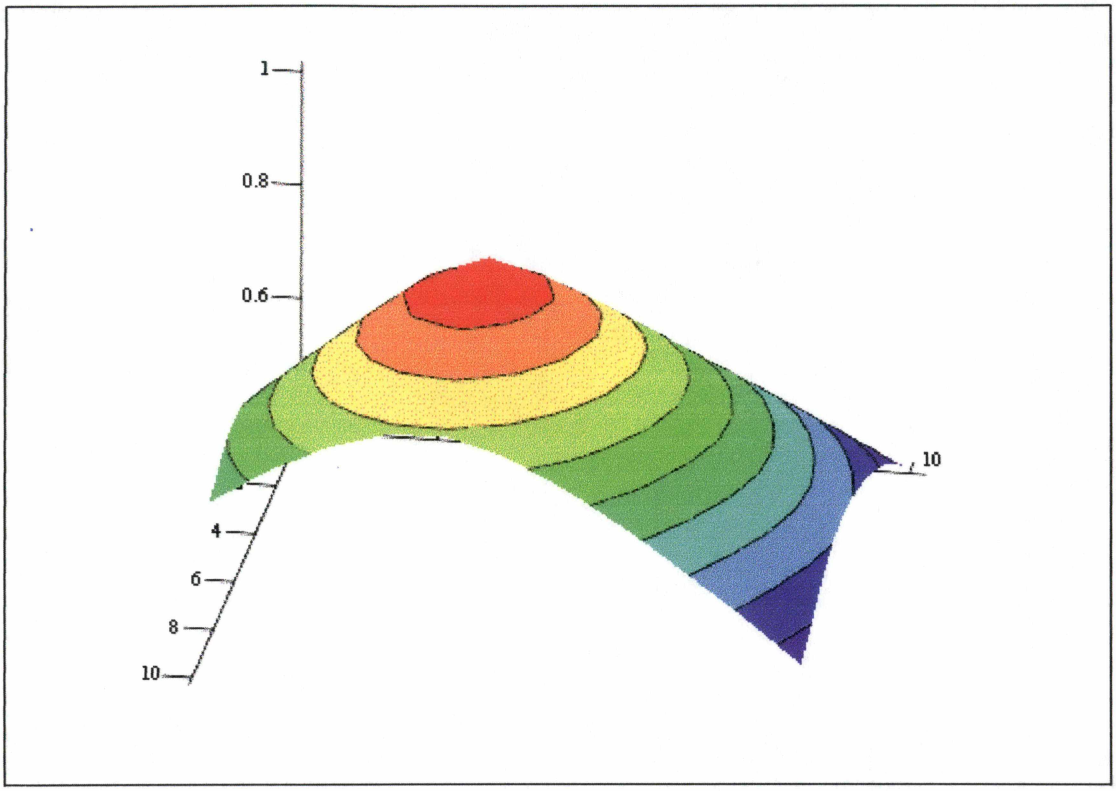


Figure 5: Target E

Appendix B – Target Correlation Matrices

M := READPRN("Ra.dat")

R := submatrix(M, 290, 300, 210, 220)



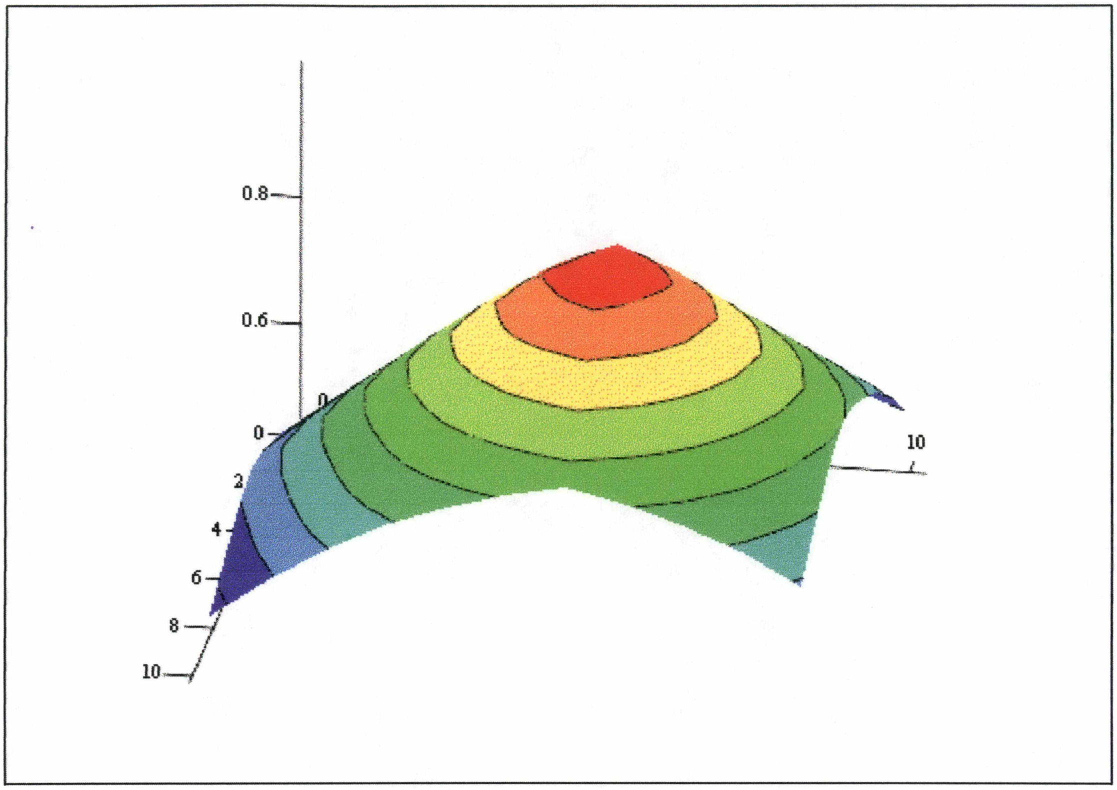
R

R =

	0	1	2	3	4	5	6	7	8	9	10
0	0.386	0.425	0.459	0.49	0.511	0.516	0.508	0.492	0.47	0.437	0.391
1	0.449	0.495	0.533	0.567	0.591	0.595	0.584	0.564	0.535	0.494	0.439
2	0.51	0.563	0.607	0.645	0.67	0.673	0.659	0.633	0.595	0.544	0.48
3	0.565	0.627	0.679	0.722	0.749	0.75	0.73	0.695	0.646	0.584	0.512
4	0.614	0.685	0.748	0.798	0.826	0.823	0.795	0.747	0.686	0.615	0.536
5	0.658	0.737	0.81	0.871	0.901	0.89	0.848	0.787	0.715	0.637	0.553
6	0.696	0.78	0.861	0.933	0.969	0.943	0.883	0.809	0.73	0.648	0.561
7	0.722	0.807	0.888	0.963	1	0.963	0.889	0.809	0.726	0.642	0.554
8	0.726	0.807	0.882	0.943	0.969	0.933	0.862	0.782	0.701	0.617	0.531
9	0.71	0.784	0.846	0.889	0.9	0.87	0.81	0.739	0.662	0.582	0.499
10	0.68	0.744	0.792	0.821	0.824	0.796	0.747	0.686	0.618	0.544	0.465

M := READPRN("Rb.dat")

R := submatrix(M, 338, 348, 202, 212)



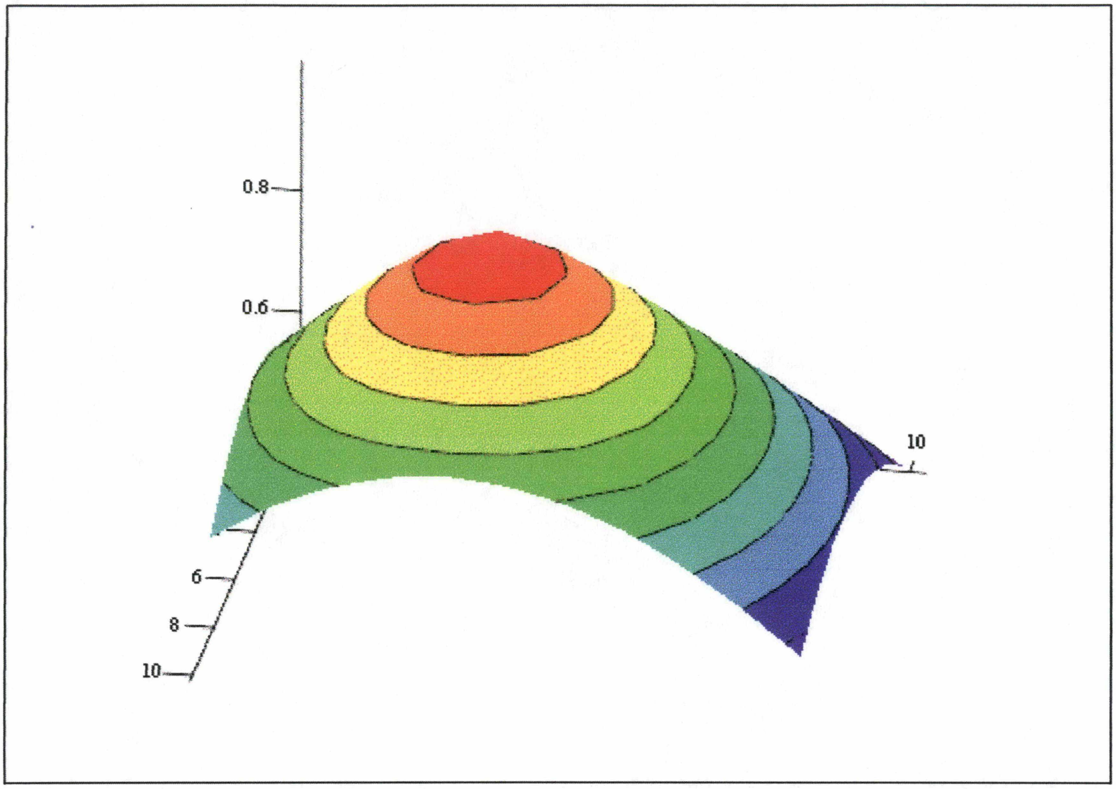
R

R =

	0	1	2	3	4	5	6	7	8	9	10
0	0.452	0.504	0.545	0.577	0.6	0.621	0.638	0.621	0.6	0.576	0.542
1	0.495	0.554	0.602	0.639	0.666	0.689	0.708	0.69	0.667	0.638	0.598
2	0.53	0.594	0.65	0.695	0.728	0.755	0.775	0.755	0.729	0.694	0.646
3	0.557	0.625	0.688	0.742	0.785	0.818	0.84	0.819	0.786	0.741	0.684
4	0.581	0.651	0.718	0.78	0.835	0.878	0.904	0.879	0.835	0.779	0.714
5	0.602	0.675	0.745	0.812	0.875	0.932	0.967	0.932	0.874	0.81	0.74
6	0.614	0.687	0.758	0.827	0.894	0.957	1	0.957	0.892	0.825	0.753
7	0.603	0.676	0.745	0.813	0.875	0.932	0.967	0.932	0.874	0.809	0.739
8	0.582	0.653	0.719	0.781	0.836	0.879	0.904	0.878	0.834	0.778	0.713
9	0.56	0.628	0.69	0.744	0.786	0.819	0.84	0.818	0.784	0.74	0.682
10	0.533	0.597	0.652	0.697	0.729	0.756	0.775	0.755	0.728	0.693	0.644

M := READPRN("Rc.dat")

R := submatrix(M, 338, 348, 202, 212)



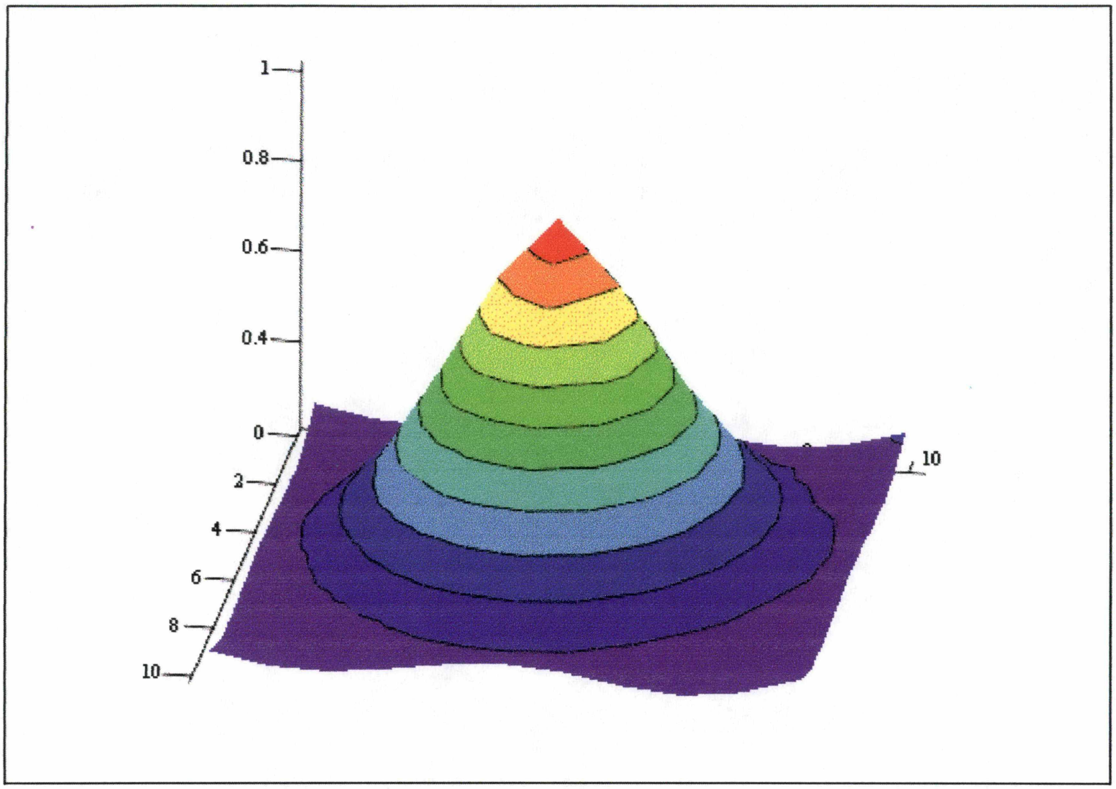
R

R =

	0	1	2	3	4	5	6	7	8	9	10
0	0.52	0.561	0.588	0.604	0.61	0.604	0.588	0.565	0.531	0.485	0.425
1	0.582	0.63	0.662	0.681	0.687	0.68	0.662	0.634	0.593	0.538	0.472
2	0.637	0.694	0.734	0.757	0.765	0.757	0.734	0.698	0.647	0.583	0.51
3	0.681	0.748	0.798	0.83	0.841	0.83	0.8	0.752	0.689	0.618	0.539
4	0.712	0.788	0.852	0.896	0.912	0.896	0.854	0.792	0.721	0.643	0.561
5	0.732	0.814	0.888	0.947	0.973	0.948	0.889	0.818	0.74	0.659	0.574
6	0.739	0.823	0.901	0.967	1	0.967	0.902	0.826	0.747	0.665	0.58
7	0.732	0.814	0.889	0.948	0.973	0.947	0.889	0.817	0.74	0.659	0.575
8	0.713	0.789	0.853	0.897	0.912	0.896	0.853	0.791	0.72	0.643	0.562
9	0.682	0.749	0.8	0.83	0.841	0.83	0.799	0.751	0.689	0.618	0.54
10	0.639	0.696	0.735	0.758	0.766	0.758	0.734	0.697	0.646	0.583	0.511

M := READPRN("Rd.dat")

R := submatrix(M, 312, 322, 183, 193)



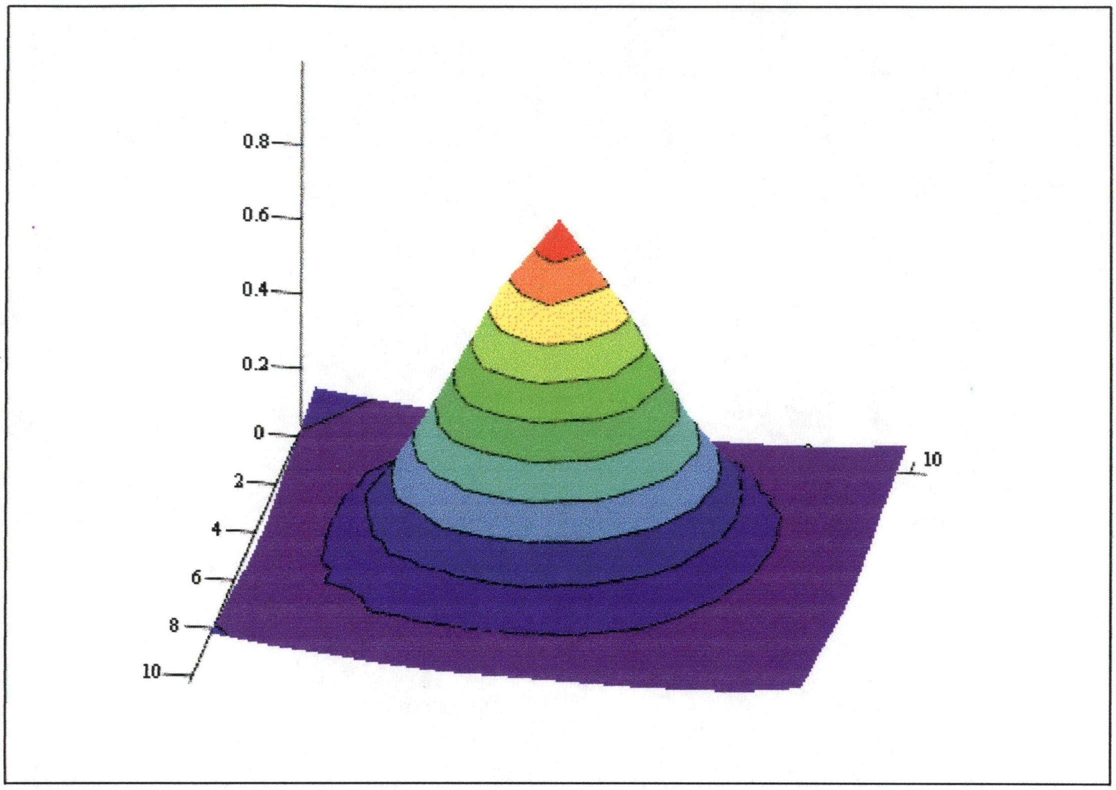
R

R =

	0	1	2	3	4	5	6	7	8	9	10
0	0.283	0.258	0.253	0.268	0.289	0.299	0.29	0.27	0.26	0.275	0.311
1	0.246	0.242	0.27	0.324	0.368	0.386	0.37	0.327	0.279	0.261	0.276
2	0.232	0.253	0.321	0.405	0.472	0.5	0.475	0.409	0.33	0.272	0.263
3	0.236	0.283	0.381	0.502	0.618	0.669	0.621	0.506	0.39	0.302	0.267
4	0.244	0.311	0.431	0.601	0.785	0.876	0.786	0.603	0.439	0.329	0.275
5	0.249	0.323	0.452	0.647	0.866	1	0.866	0.647	0.457	0.339	0.278
6	0.246	0.314	0.434	0.603	0.786	0.876	0.785	0.601	0.436	0.327	0.272
7	0.239	0.286	0.385	0.506	0.621	0.669	0.618	0.502	0.386	0.299	0.264
8	0.232	0.254	0.322	0.407	0.473	0.498	0.47	0.403	0.324	0.266	0.257
9	0.236	0.234	0.262	0.316	0.359	0.375	0.357	0.313	0.264	0.247	0.263
10	0.267	0.243	0.24	0.254	0.274	0.284	0.274	0.253	0.242	0.258	0.296

M := READPRN("Re.dat")

R := submatrix(M, 311, 321, 207, 217)

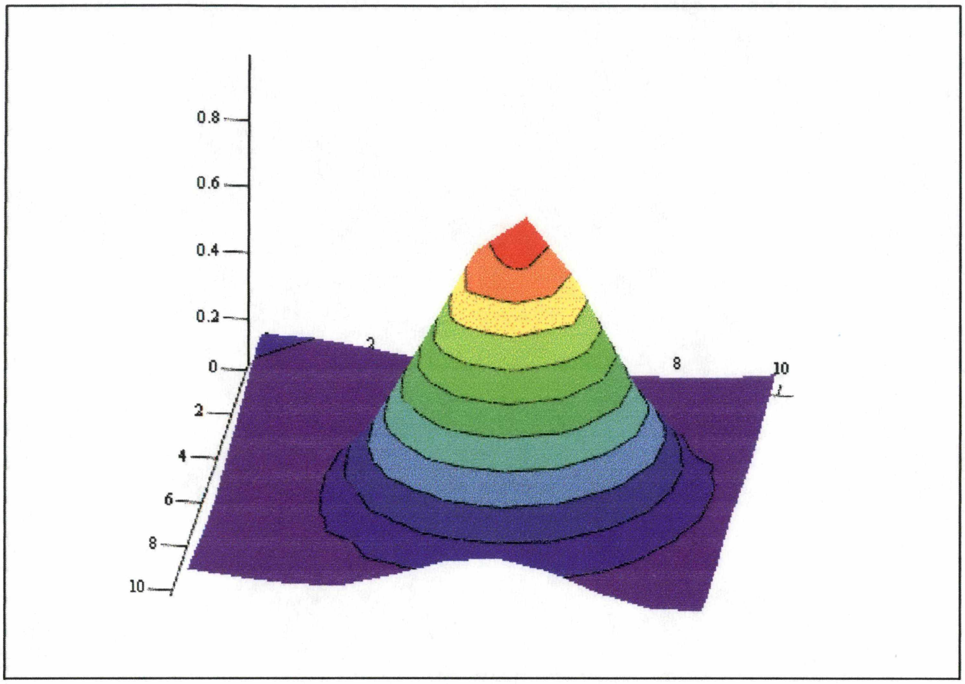


R

R =

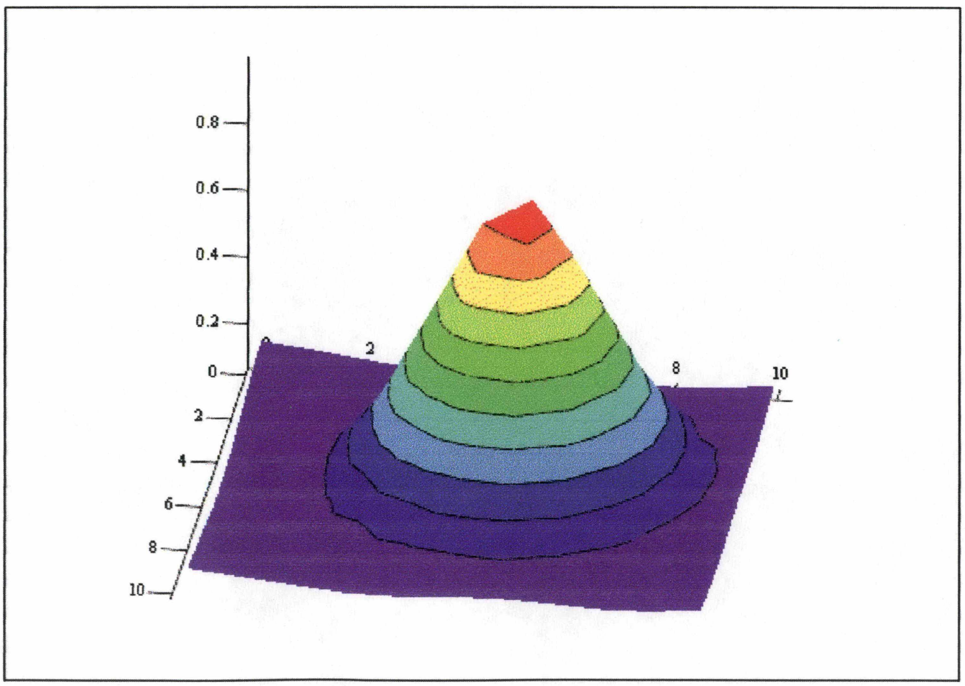
	0	1	2	3	4	5	6	7	8	9	10
0	0.171	0.15	0.135	0.119	0.11	0.109	0.105	0.105	0.106	0.112	0.133
1	0.156	0.141	0.128	0.139	0.159	0.166	0.154	0.125	0.1	0.104	0.117
2	0.145	0.127	0.151	0.212	0.272	0.302	0.268	0.196	0.123	0.09	0.106
3	0.127	0.123	0.196	0.325	0.475	0.544	0.472	0.31	0.169	0.087	0.089
4	0.111	0.128	0.246	0.458	0.699	0.826	0.696	0.444	0.219	0.092	0.073
5	0.103	0.13	0.269	0.515	0.802	1	0.799	0.501	0.241	0.093	0.066
6	0.105	0.123	0.242	0.453	0.695	0.822	0.692	0.44	0.213	0.086	0.068
7	0.117	0.114	0.188	0.315	0.466	0.536	0.463	0.303	0.16	0.077	0.081
8	0.133	0.116	0.14	0.199	0.26	0.291	0.258	0.187	0.113	0.08	0.098
9	0.142	0.128	0.115	0.126	0.145	0.153	0.143	0.113	0.088	0.093	0.107
10	0.157	0.136	0.122	0.106	0.096	0.096	0.094	0.092	0.095	0.101	0.122

Appendix C - Correlation Matrices for out of plane rotation



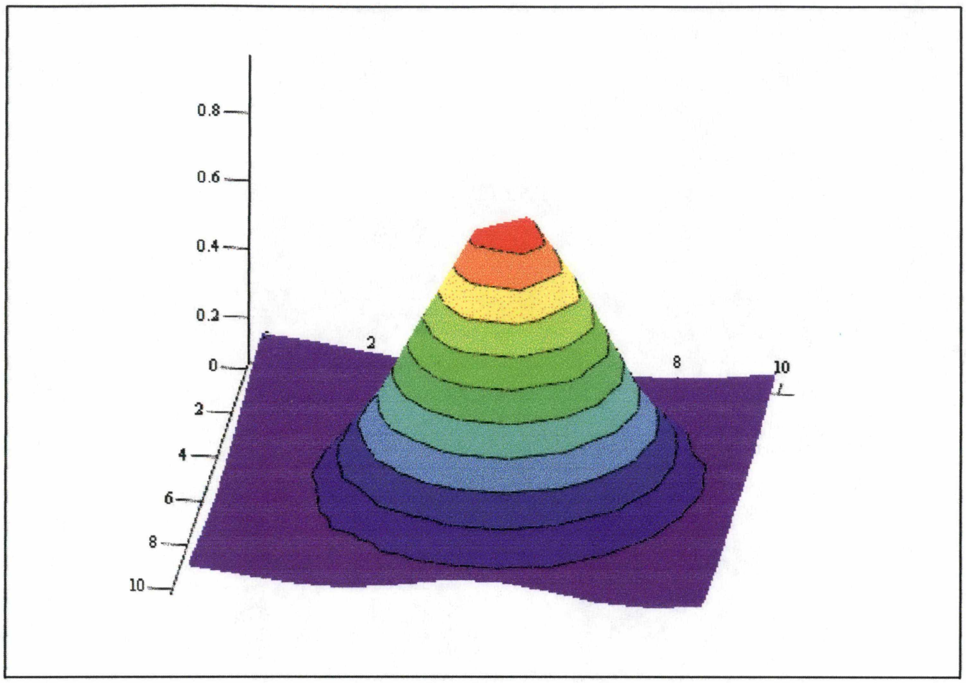
R

Target at 0°



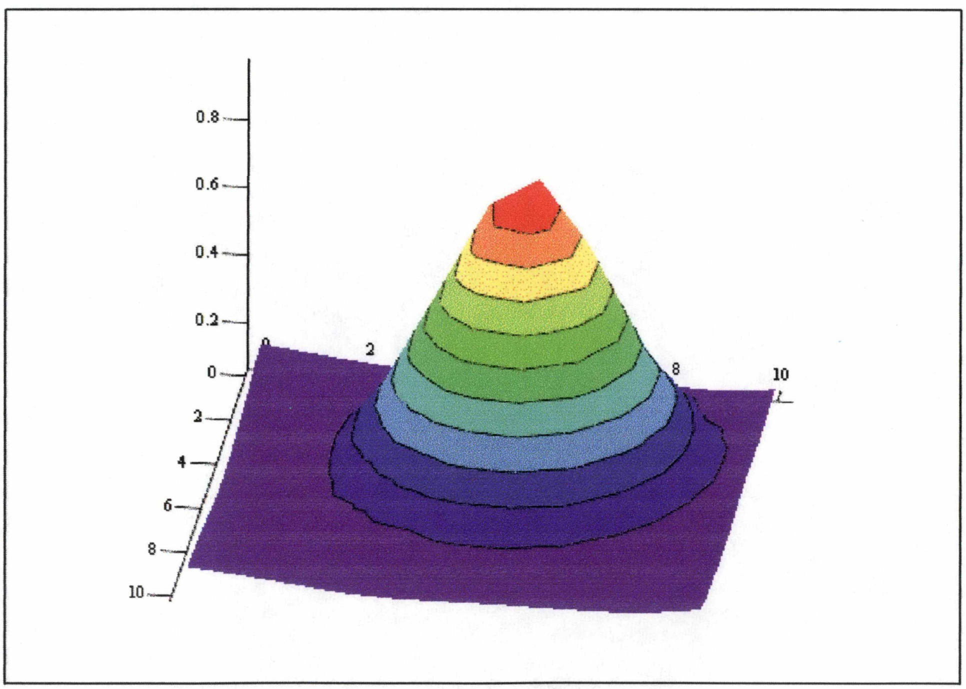
R

Target at 2.5°



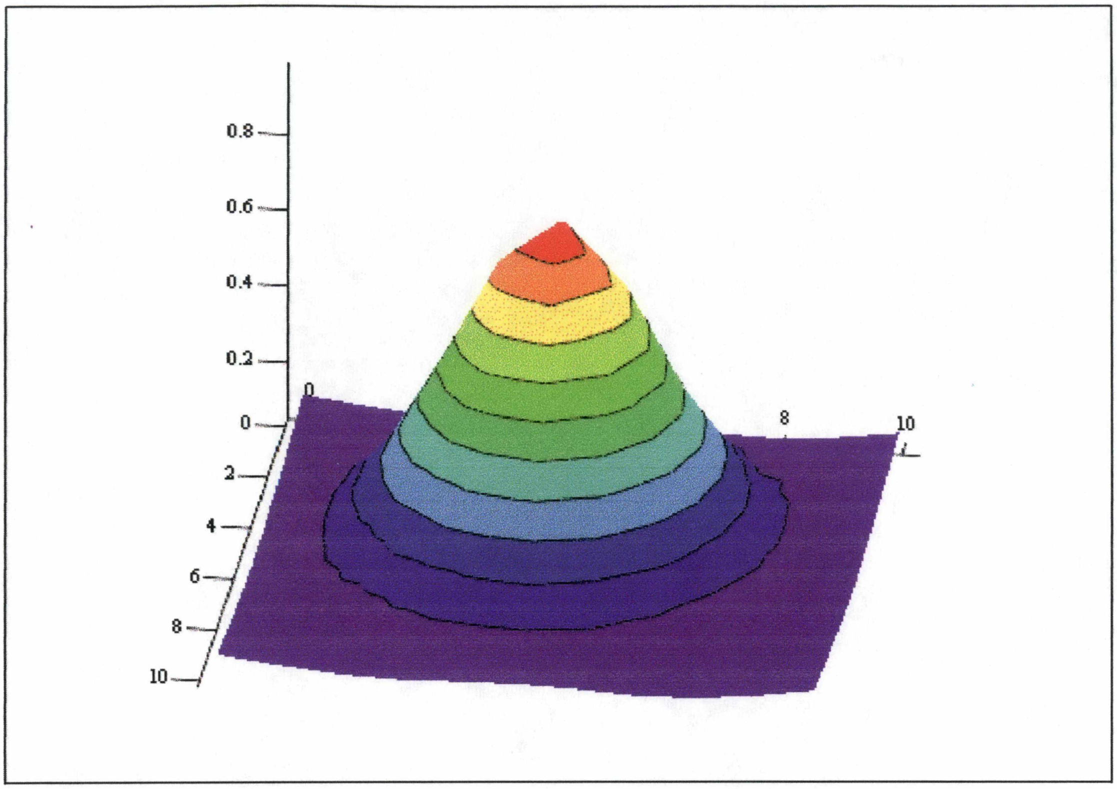
R

Target at 5°



R

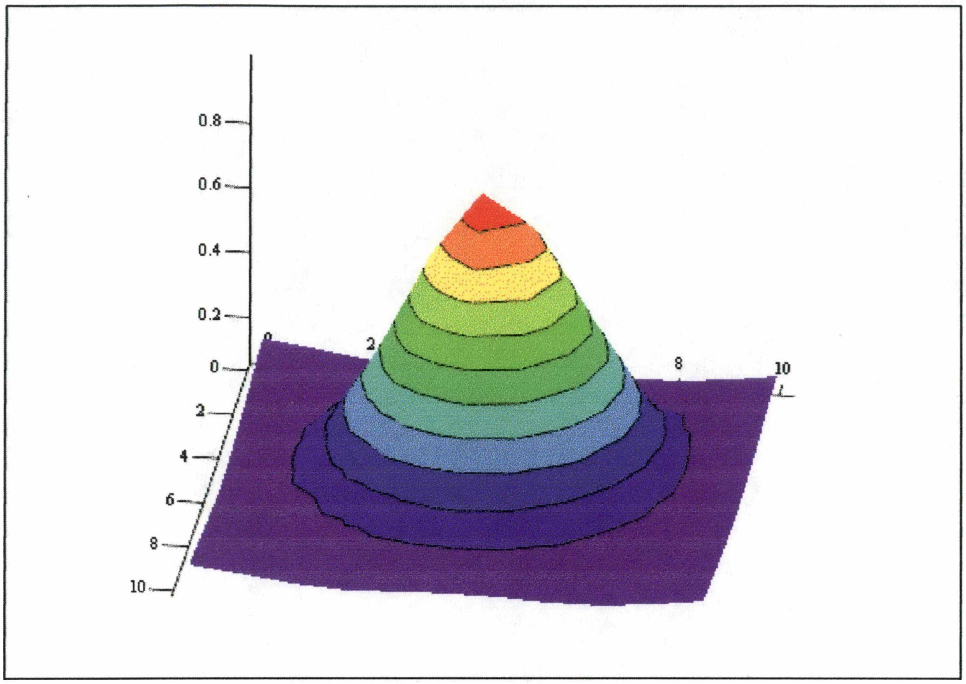
Target at –2.5°



R

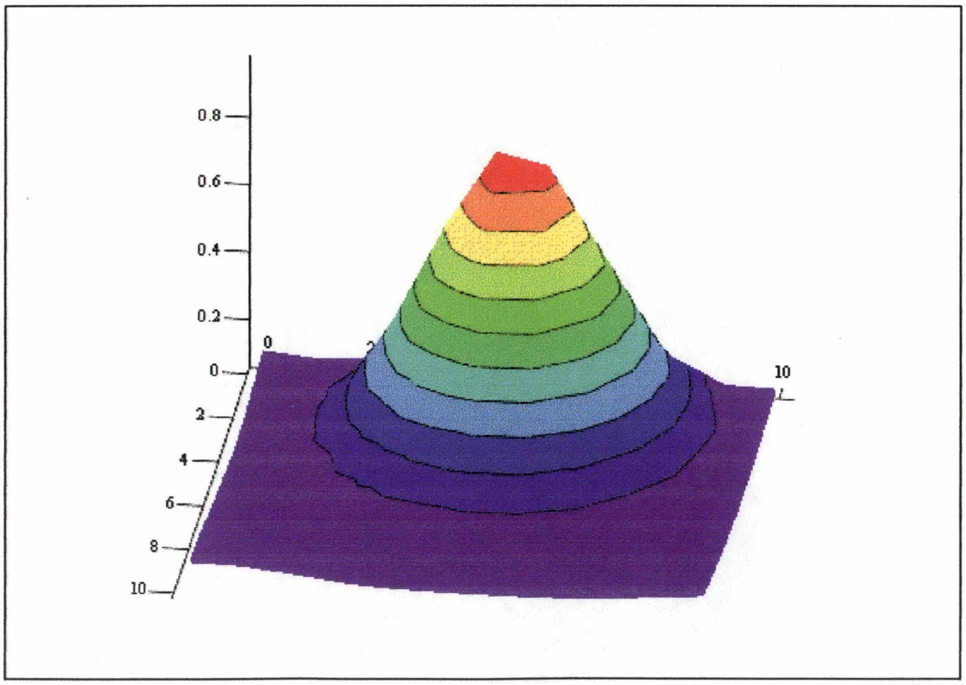
Target at –5°

Appendix D – Correlation Matrices for distance sensitivity



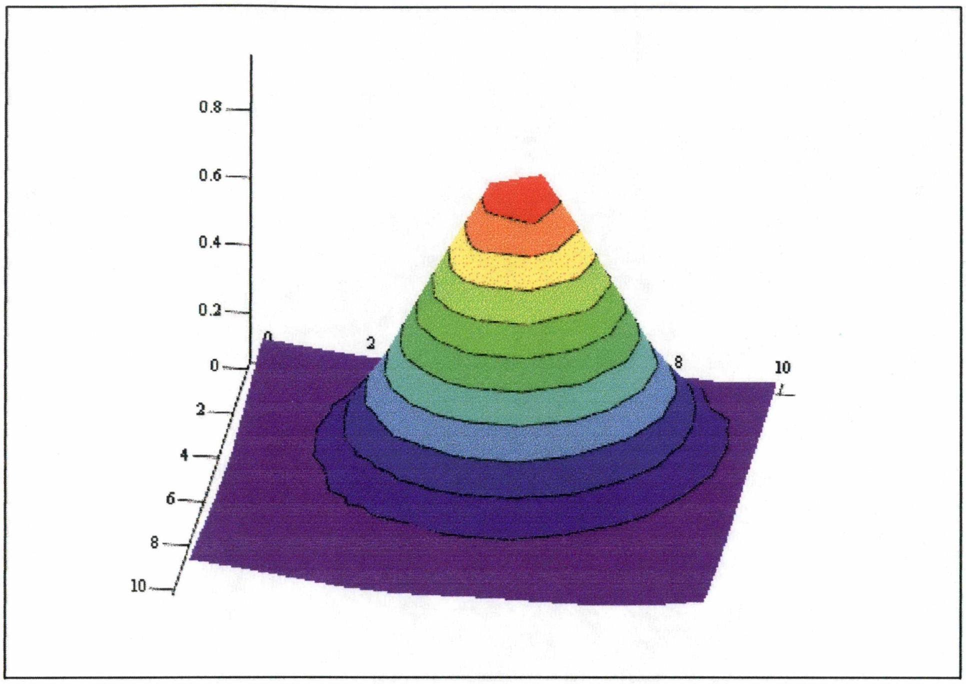
R

Target at 15'



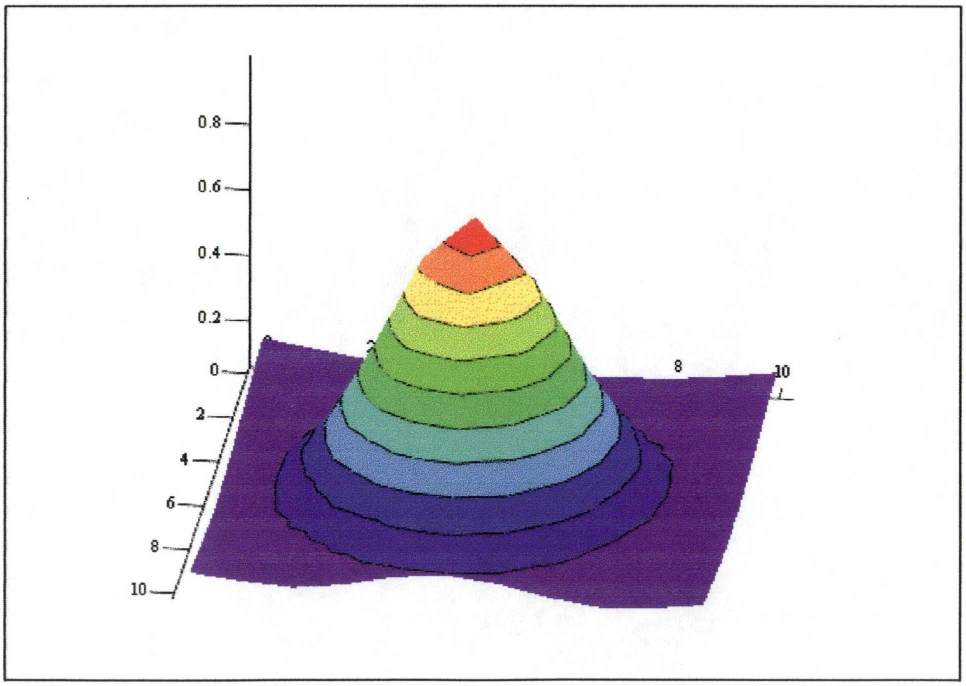
R

Target at 14'11"



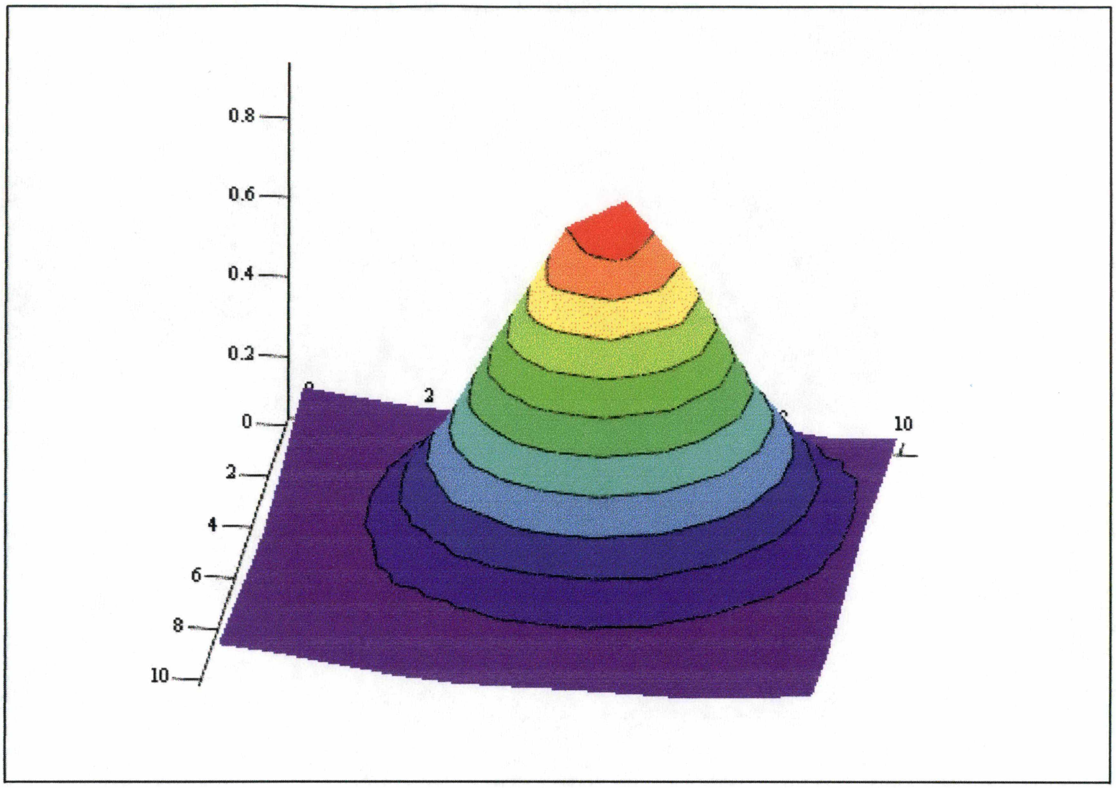
R

Target at 14’10”



R

Target at 15’1”

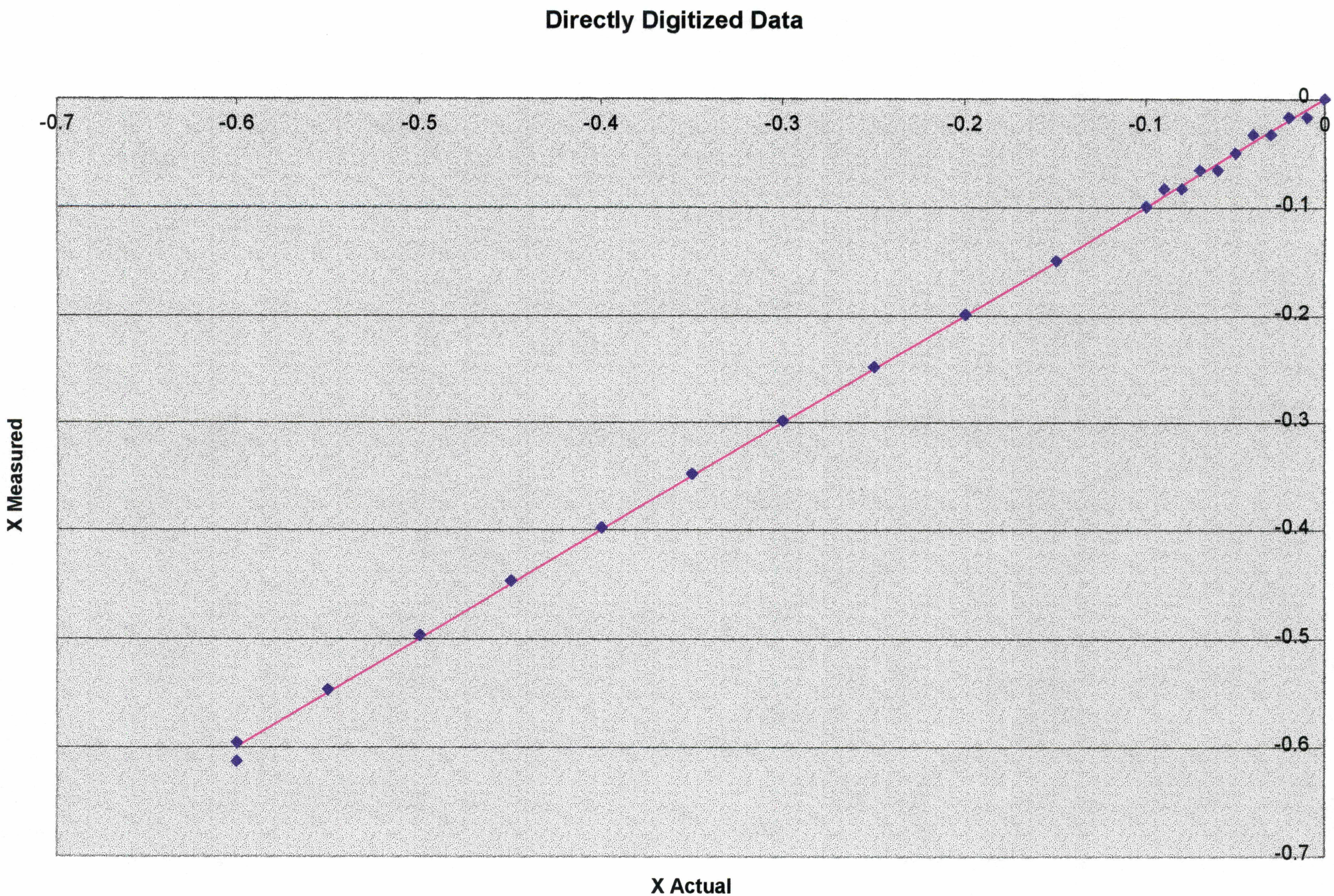


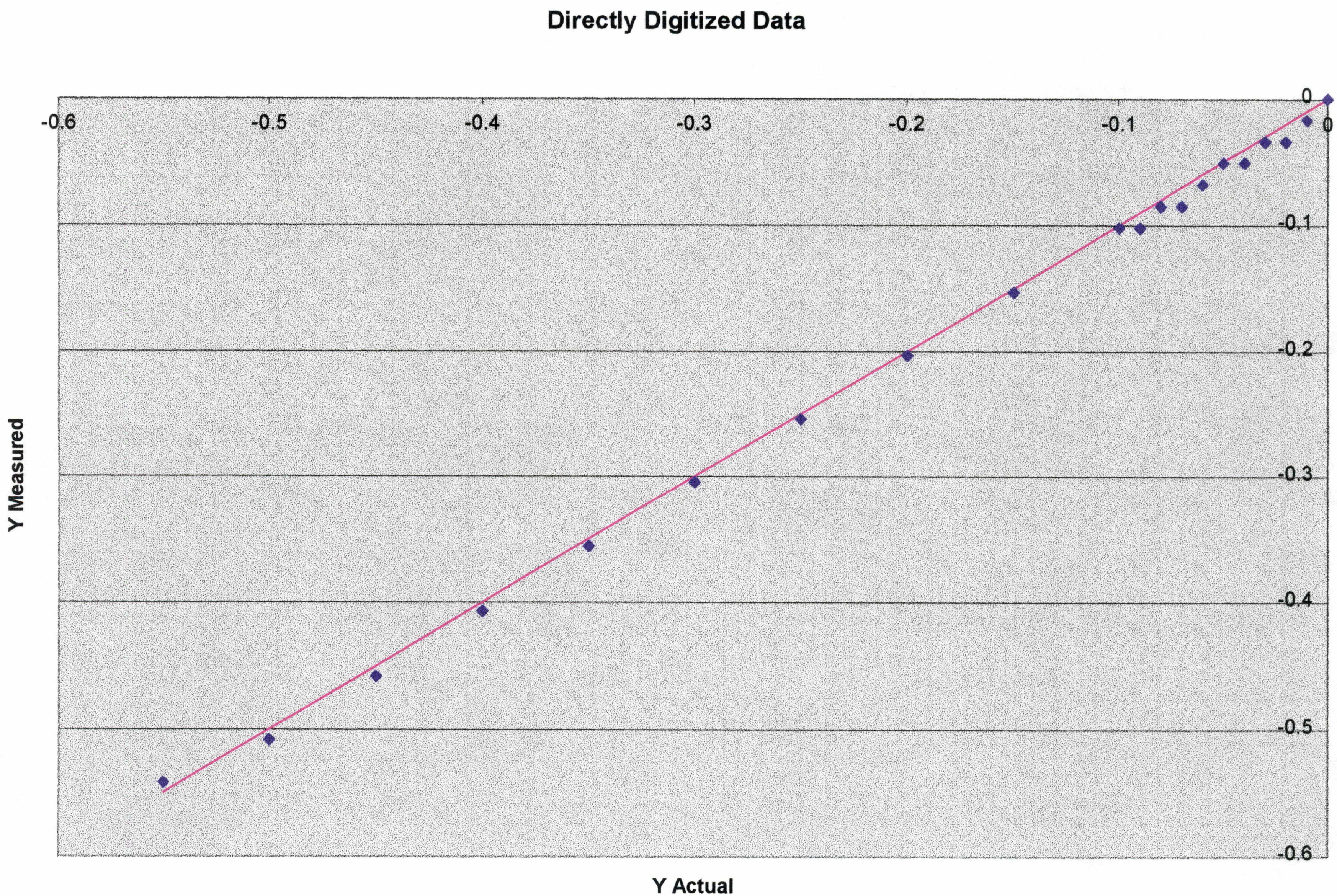
R

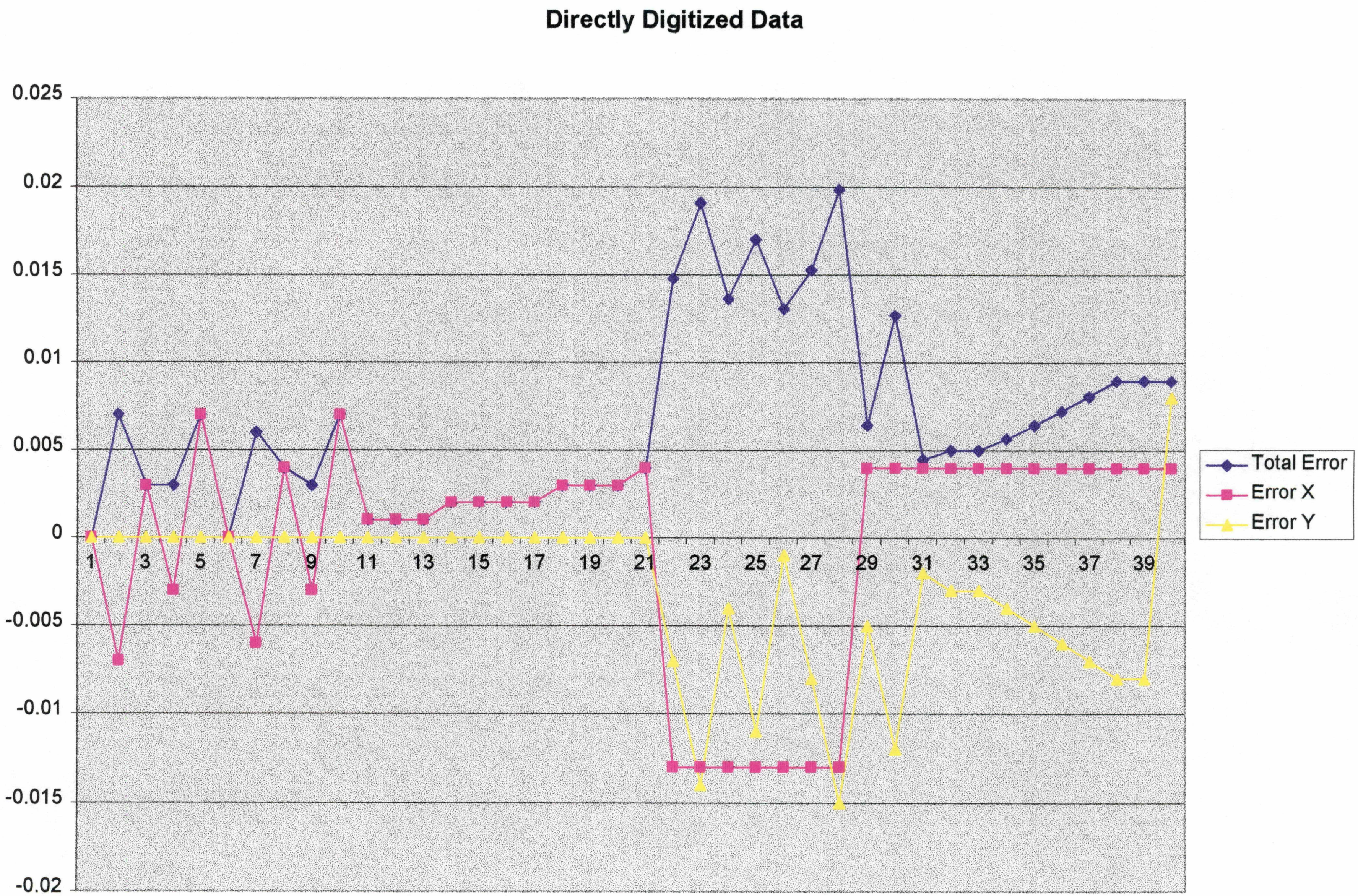
Target at 15’2”

Appendix E – Results for directly digitized data

f0.dat	x: +0.000	y: +0.000	R: +1.000
f1.dat	x: -0.017	y: +0.000	R: +0.964
f2.dat	x: -0.017	y: +0.000	R: +0.979
f3.dat	x: -0.033	y: +0.000	R: +0.986
f4.dat	x: -0.033	y: +0.000	R: +0.967
f5.dat	x: -0.050	y: +0.000	R: +0.987
f6.dat	x: -0.066	y: +0.000	R: +0.956
f7.dat	x: -0.066	y: +0.000	R: +0.975
f8.dat	x: -0.083	y: +0.000	R: +0.978
f9.dat	x: -0.083	y: +0.000	R: +0.970
f10.dat	x: -0.099	y: +0.000	R: +0.985
f11.dat	x: -0.149	y: +0.000	R: +0.976
f12.dat	x: -0.199	y: +0.000	R: +0.978
f13.dat	x: -0.248	y: +0.000	R: +0.983
f14.dat	x: -0.298	y: +0.000	R: +0.985
f15.dat	x: -0.348	y: +0.000	R: +0.979
f16.dat	x: -0.398	y: +0.000	R: +0.972
f17.dat	x: -0.447	y: +0.000	R: +0.964
f18.dat	x: -0.497	y: +0.000	R: +0.959
f19.dat	x: -0.547	y: +0.000	R: +0.948
f20.dat	x: -0.596	y: +0.000	R: +0.940
f21.dat	x: -0.613	y: -0.017	R: +0.968
f22.dat	x: -0.613	y: -0.034	R: +0.944
f23.dat	x: -0.613	y: -0.034	R: +0.955
f24.dat	x: -0.613	y: -0.051	R: +0.957
f25.dat	x: -0.613	y: -0.051	R: +0.937
f26.dat	x: -0.613	y: -0.068	R: +0.962
f27.dat	x: -0.613	y: -0.085	R: +0.932
f28.dat	x: -0.596	y: -0.085	R: +0.956
f29.dat	x: -0.596	y: -0.102	R: +0.962
f30.dat	x: -0.596	y: -0.102	R: +0.937
f31.dat	x: -0.596	y: -0.153	R: +0.941
f32.dat	x: -0.596	y: -0.203	R: +0.952
f33.dat	x: -0.596	y: -0.254	R: +0.968
f34.dat	x: -0.596	y: -0.305	R: +0.973
f35.dat	x: -0.596	y: -0.356	R: +0.981
f36.dat	x: -0.596	y: -0.407	R: +0.980
f37.dat	x: -0.596	y: -0.458	R: +0.968
f38.dat	x: -0.596	y: -0.508	R: +0.934
f39.dat	x: -0.596	y: -0.542	R: +0.956


Directly Digitized Data
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
X Measured
X Actual

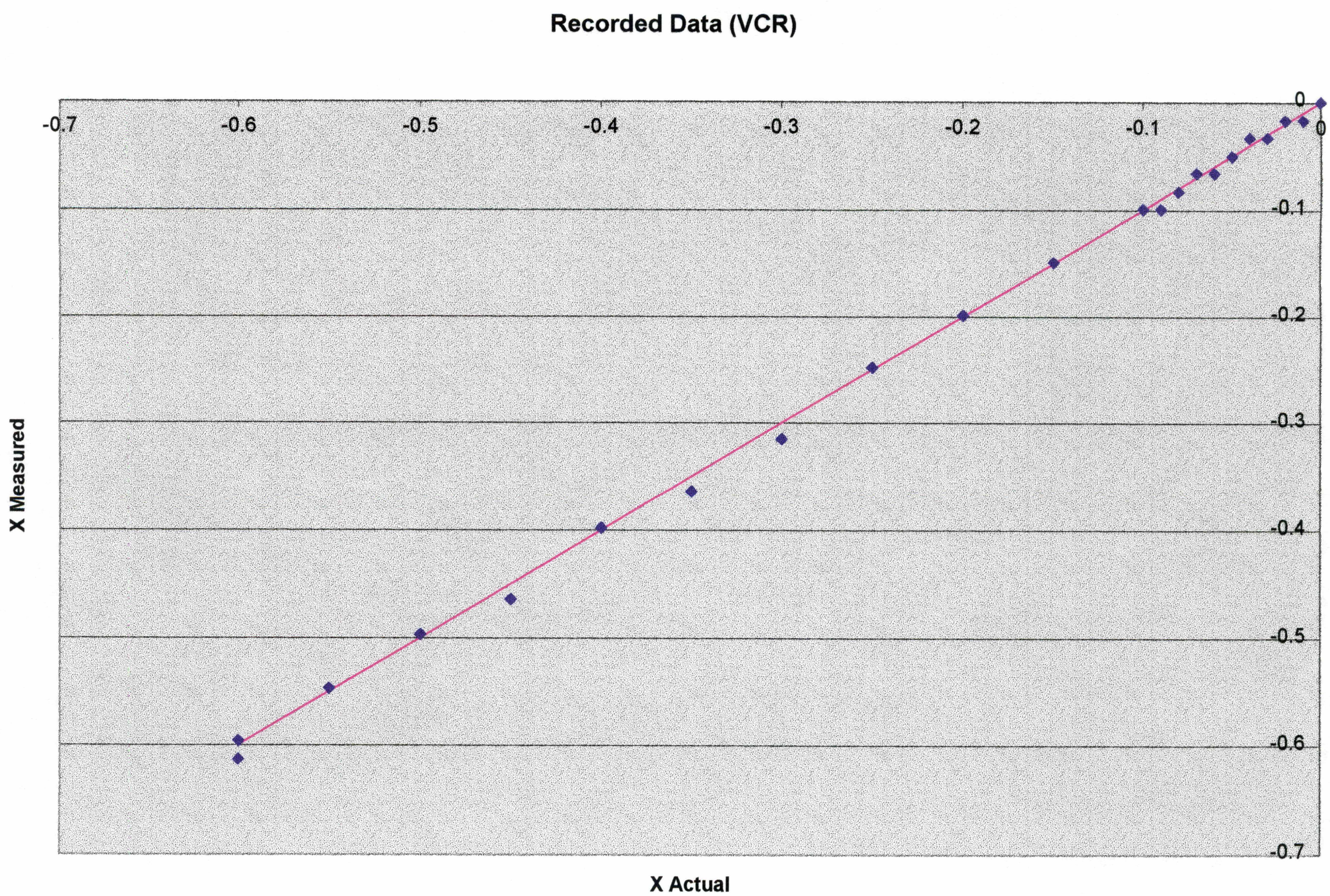

Directly Digitized Data
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Y Measured
Y Actual



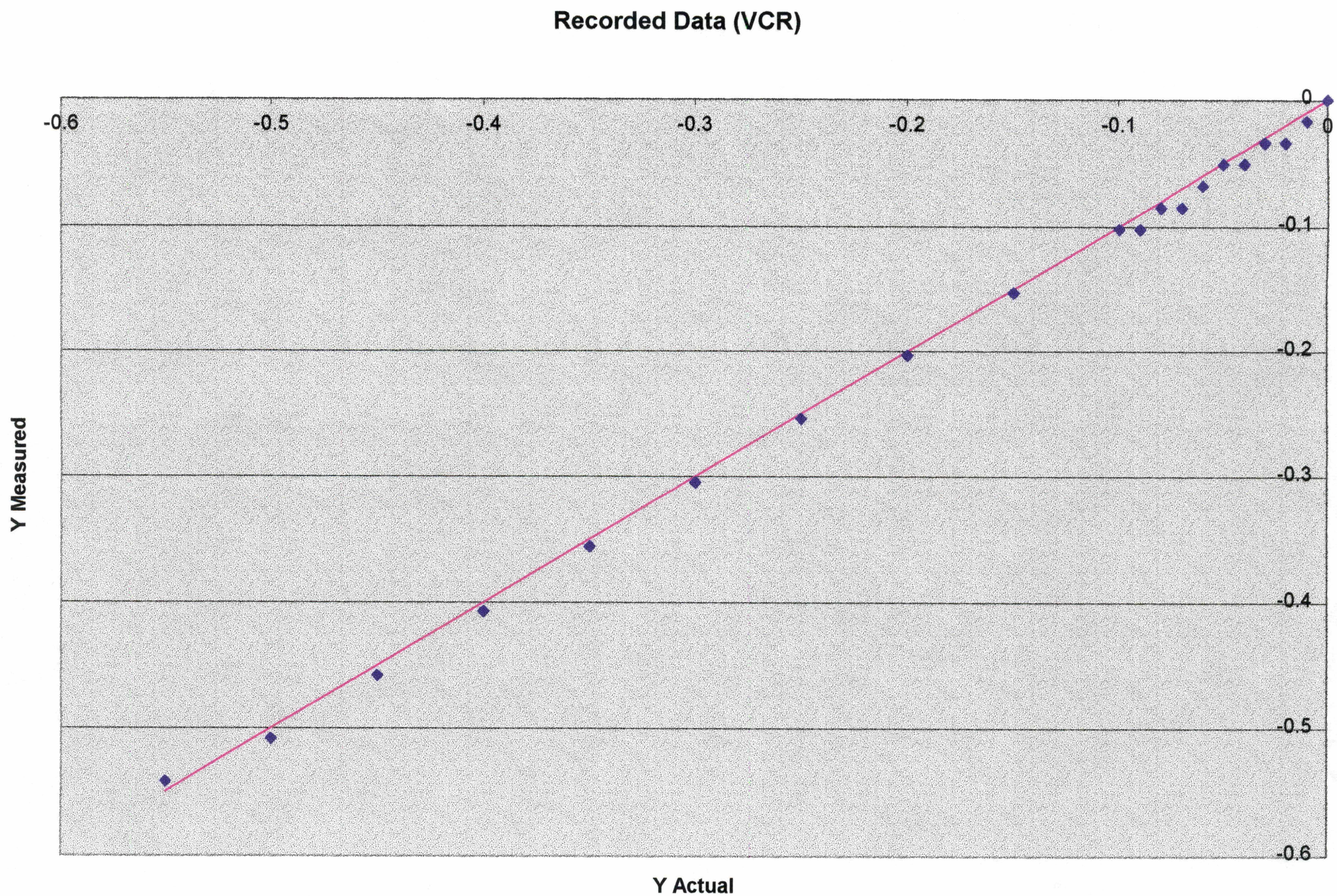
Directly Digitized Data
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Total Error
Error X
Error Y

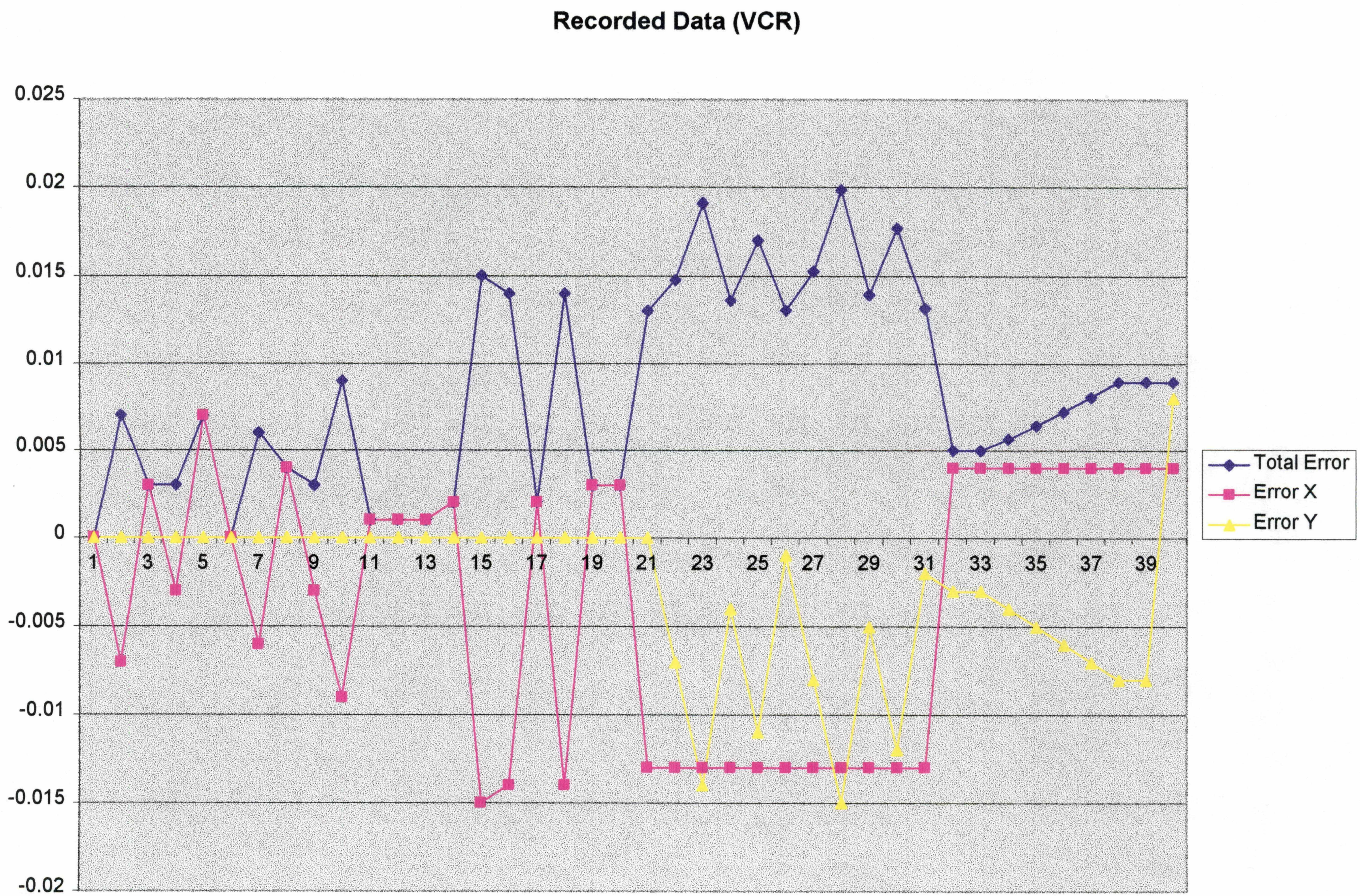
Appendix F – Results for Recorded Data

fr0.dat	x: +0.000	y: +0.000	R: +0.978
fr1.dat	x: -0.017	y: +0.000	R: +0.953
fr2.dat	x: -0.017	y: +0.000	R: +0.970
fr3.dat	x: -0.033	y: +0.000	R: +0.972
fr4.dat	x: -0.033	y: +0.000	R: +0.940
fr5.dat	x: -0.050	y: +0.000	R: +0.968
fr6.dat	x: -0.066	y: +0.000	R: +0.940
fr7.dat	x: -0.066	y: +0.000	R: +0.949
fr8.dat	x: -0.083	y: +0.000	R: +0.968
fr9.dat	x: -0.099	y: +0.000	R: +0.939
fr10.dat	x: -0.099	y: +0.000	R: +0.970
fr11.dat	x: -0.149	y: +0.000	R: +0.956
fr12.dat	x: -0.199	y: +0.000	R: +0.965
fr13.dat	x: -0.248	y: +0.000	R: +0.955
fr14.dat	x: -0.315	y: +0.000	R: +0.943
fr15.dat	x: -0.364	y: +0.000	R: +0.943
fr16.dat	x: -0.398	y: +0.000	R: +0.946
fr17.dat	x: -0.464	y: +0.000	R: +0.950
fr18.dat	x: -0.497	y: +0.000	R: +0.945
fr19.dat	x: -0.547	y: +0.000	R: +0.931
fr20.dat	x: -0.613	y: +0.000	R: +0.918
fr21.dat	x: -0.613	y: -0.017	R: +0.966
fr22.dat	x: -0.613	y: -0.034	R: +0.945
fr23.dat	x: -0.613	y: -0.034	R: +0.952
fr24.dat	x: -0.613	y: -0.051	R: +0.951
fr25.dat	x: -0.613	y: -0.051	R: +0.918
fr26.dat	x: -0.613	y: -0.068	R: +0.940
fr27.dat	x: -0.613	y: -0.085	R: +0.922
fr28.dat	x: -0.613	y: -0.085	R: +0.940
fr29.dat	x: -0.613	y: -0.102	R: +0.940
fr30.dat	x: -0.613	y: -0.102	R: +0.908
fr31.dat	x: -0.596	y: -0.153	R: +0.927
fr32.dat	x: -0.596	y: -0.203	R: +0.944
fr33.dat	x: -0.596	y: -0.254	R: +0.953
fr34.dat	x: -0.596	y: -0.305	R: +0.957
fr35.dat	x: -0.596	y: -0.356	R: +0.955
fr36.dat	x: -0.596	y: -0.407	R: +0.949
fr37.dat	x: -0.596	y: -0.458	R: +0.935
fr38.dat	x: -0.596	y: -0.508	R: +0.919
fr39.dat	x: -0.596	y: -0.542	R: +0.937



Recorded Data (VCR)
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
X Measured
X Actual

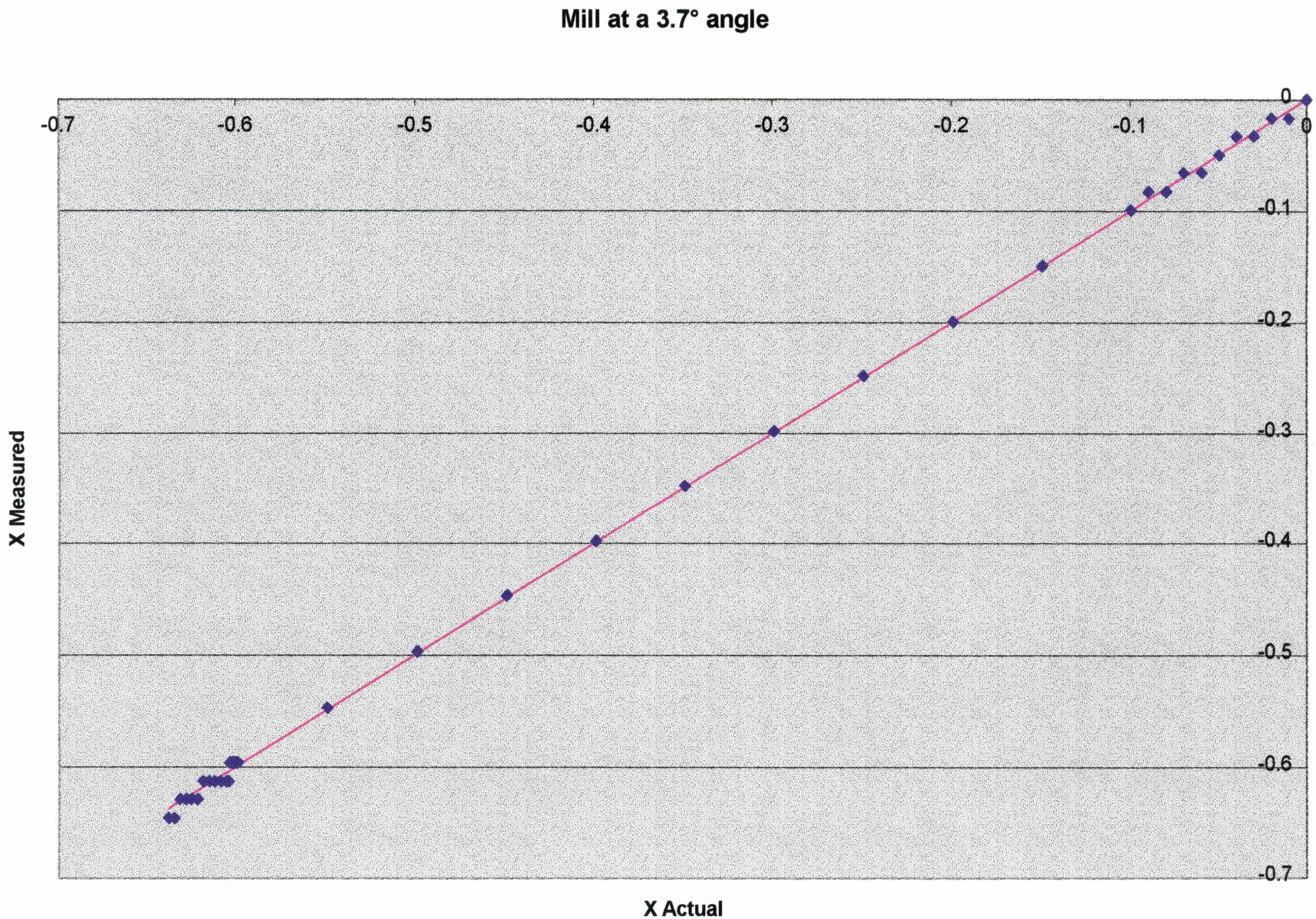

Recorded Data (VCR)
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Y Measured
Y Actual

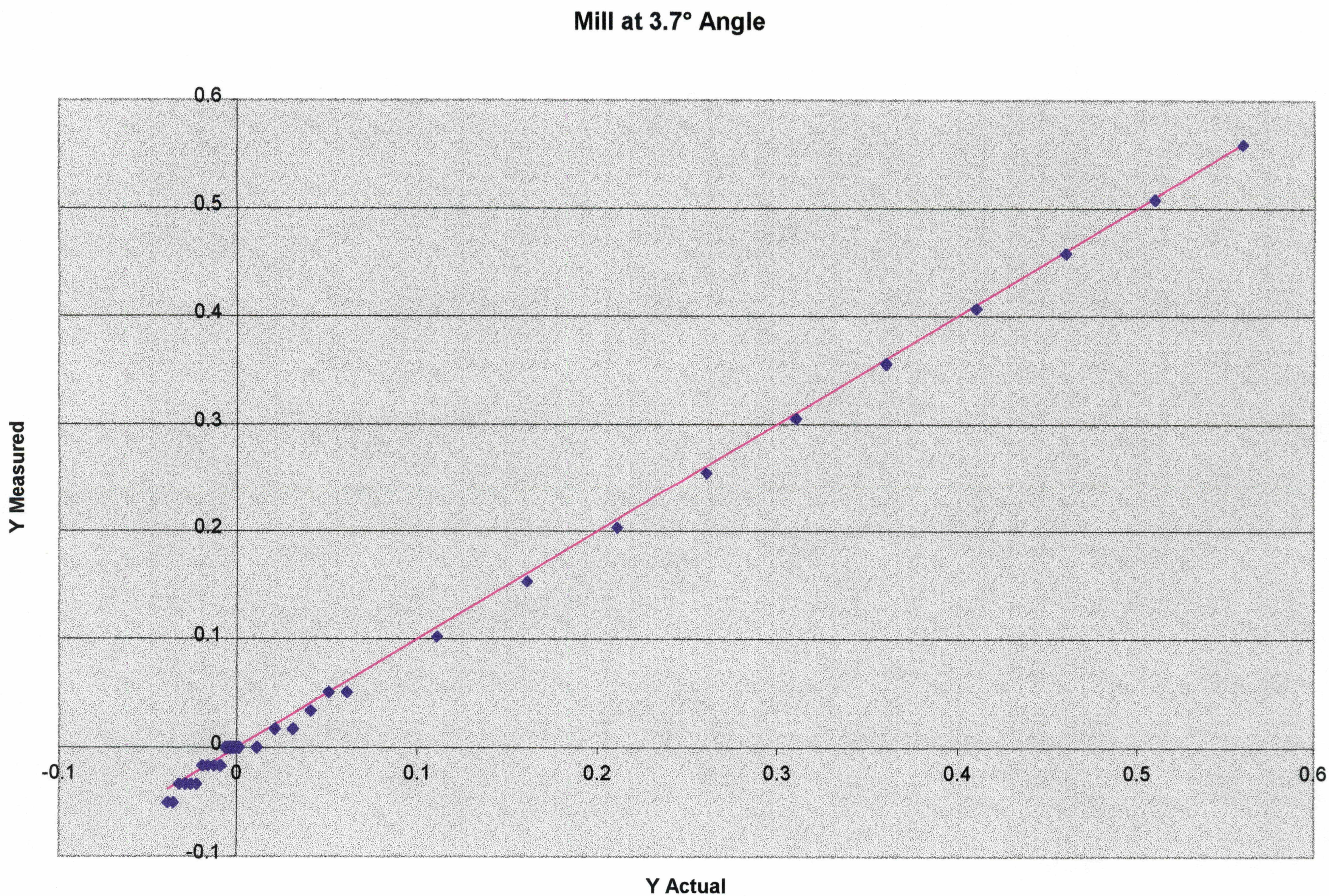


Recorded Data (VCR)
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Total Error
Error X
Error Y

Appendix G – Results for Data taken with mill at an angle

```
g0.dat     x: +0.000   y: +0.000   R: +0.955
g1.dat     x: -0.017   y: +0.000   R: +0.937
g2.dat     x: -0.017   y: +0.000   R: +0.939
g3.dat     x: -0.033   y: +0.000   R: +0.950
g4.dat     x: -0.033   y: +0.000   R: +0.921
g5.dat     x: -0.050   y: +0.000   R: +0.941
g6.dat     x: -0.066   y: +0.000   R: +0.924
g7.dat     x: -0.066   y: +0.000   R: +0.936
g8.dat     x: -0.083   y: +0.000   R: +0.921
g9.dat     x: -0.083   y: +0.000   R: +0.912
g10.dat    x: -0.099   y: +0.000   R: +0.921
g11.dat    x: -0.149   y: -0.017   R: +0.939
g12.dat    x: -0.199   y: -0.017   R: +0.957
g13.dat    x: -0.248   y: -0.017   R: +0.948
g14.dat    x: -0.298   y: -0.017   R: +0.944
g15.dat    x: -0.348   y: -0.034   R: +0.921
g16.dat    x: -0.398   y: -0.034   R: +0.953
g17.dat    x: -0.447   y: -0.034   R: +0.955
g18.dat    x: -0.497   y: -0.034   R: +0.948
g19.dat    x: -0.547   y: -0.051   R: +0.917
g20.dat    x: -0.596   y: -0.051   R: +0.954
g21.dat    x: -0.596   y: -0.034   R: +0.963
g22.dat    x: -0.596   y: -0.017   R: +0.928
g23.dat    x: -0.596   y: -0.017   R: +0.956
g24.dat    x: -0.596   y: +0.000   R: +0.941
g25.dat    x: -0.596   y: +0.000   R: +0.920
g26.dat    x: -0.596   y: +0.017   R: +0.948
g27.dat    x: -0.596   y: +0.017   R: +0.906
g28.dat    x: -0.613   y: +0.034   R: +0.934
g29.dat    x: -0.613   y: +0.051   R: +0.920
g30.dat    x: -0.613   y: +0.051   R: +0.928
g31.dat    x: -0.613   y: +0.102   R: +0.958
g32.dat    x: -0.613   y: +0.153   R: +0.969
g33.dat    x: -0.613   y: +0.203   R: +0.963
g34.dat    x: -0.613   y: +0.254   R: +0.951
g35.dat    x: -0.629   y: +0.305   R: +0.948
g36.dat    x: -0.629   y: +0.356   R: +0.966
g37.dat    x: -0.629   y: +0.407   R: +0.955
g38.dat    x: -0.629   y: +0.458   R: +0.919
g39.dat    x: -0.646   y: +0.508   R: +0.928
g40.dat    x: -0.646   y: +0.559   R: +0.938
```


Mill at a 3.7° angle
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
X Measured
X Actual


Mill at 3.7° Angle
Y Measured
Y Actual
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6

Mill Tilted 3.7°