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Correlation Studies
Final Report

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All opinions herein expressed are solely those of the authors.
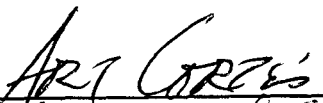
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Correlation   Studies

for

Loral ADST

Contract   SO-242894-T

Final   Report

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1.0   Introduction

This document summarizes the correlation studies conducted by the Institute for Simulation and Training for Loral Western Development Labs in support of the BDS-D Delivery Order "BDS-D Architecture Definition and DIS Standards Development."

1.1   Purpose

The purpose of this study is to develop methods of measuring discrepancies among heterogeneous networked simulators that interact in a common gaming area. By quantifying these discrepancies, the interoperability of the training exercise can be predicted. In addition, vendors can determine common sources of error and develop methodologies to enhance interoperability among networked synthetic environments.

1.2   Scope

The remainder of this document is organized as follows:

- Background and Review of Previous Work
- Description of Research
- Summary of Results
- Conclusions
- Recommendations
- Appendices (Project Plan, Test Plan, Interim Report, Use of the Metrics)

"Background and Review of Previous Work" provides a brief description of the correlation problem and previous studies.

"Description of Research" summarizes the approach taken to develop the metrics and describes the results of metric testing.

The "Summary of Results" provides a synopsis of all metrics developed and their ability to measure correlation between heterogeneous networked simulations.

The final sections of this document provide conclusions of this research and recommendations for further correlation studies.

Finally, the appendices include documents that have been previously delivered as part of this research as well as instructions on installation and use of the metrics.

2.0 Background and Review of Previous Work

With development of standards such as Distributed Interactive Simulation (DIS), connectivity increases among dissimilar simulators [IST93]. These networked simulators are designed to train multiple individuals or multiple teams in the same scenario and gaming area. Therefore, each individual player must observe the same environment. However, current simulation technology requires separate representations of the same gaming area on each of the simulators in the network.

The methods by which these multiple representations of the gaming area are produced can lead to dissimilarities in the players' perceived environment. Each simulator may use different algorithms for modeling the gaming area or provide different methods with which to display this common environment. These heterogeneous representations can produce significantly different perceptions among players in the same exercise.

Heterogeneous representations of the common gaming area impede the effectiveness of the training exercise in two ways. First, dissimilarities in the representations can provide unfair advantages to one player over another. For instance, one player may assume that he has hidden his tank behind a hill. From an opponent's perspective, that same tank may be in full view. Typically, the advantage goes to the lower fidelity player since he is not constrained by physical models (e.g., vehicle dynamics, terrain following) to the degree of the high fidelity player [Woodard92]. Second, unrealistic actions may occur due to the heterogeneous representations. Such actions could include an opponent's tank floating above the ground due to differences in terrain elevation data among simulators. Such effects were observed at the Interoperability Demonstration at the Interservice/Industry Training Systems and Education Conference held in November 1992.

To approach the goal of similar perceptions of the gaming environment among players of various fidelities, discrepancies between representations must be both qualified and quantified. Qualification includes identification of sources of the discrepancies. Quantification consists of measuring these sources of discrepancy to determine how they affect perception and the training effectiveness.

In reviewing recent research in correlation issues, several efforts have been made to qualify the discrepancies by stating what discrepancies

should be measured or what criteria should be applied.   However, a definition of correlation is yet to be provided that quantifies the degree of correlation that must be achieved for successful interoperability between heterogeneous networked simulators.

Steven McCarter of Loral Western Development Labs approaches correlation through study of the interoperable visual databases used by the networked simulators [McCarter92].   McCarter makes a valid point that the degree of correlation is dependent on the particular mission scenario.   For instance, a completely ground-based scenario would require a higher degree of correlation between terrain, culture, two-dimensional and three-dimensional model representations than an air-to-air combat scenario.   However, no definitions of low, medium, or high correlation among the databases or specific guidelines for correlation measurements are provided.

Woodard, et. al., view correlation from a system validation and performance measurement standpoint [Woodard92].   In their paper, the authors cite four areas that affect interoperability: fidelity of the individual simulators, differences in fidelity between simulators, the accuracy of the simulations with respect to the real world, and the perceived realism provided by individual simulators.   Furthermore, the paper makes reference to measuring specific qualities in these four areas in order to determine a specification for interoperability. However, the authors do not define the thresholds of fidelity differential that determine when training via heterogeneous networked simulators can be effectively transferred to the real world.   Yet, they do suggest that this fidelity threshold is a function of the particular exercise.

Zvolanek and Dillard provide a good survey of previous correlation efforts in both visual and multi-sensory networked simulations [Zvolanek92].   This paper proposes correlation testing at different points throughout the transformation of the data from the original source data to the final rendered image.   The authors point out that strictly man-in-the-loop correlation testing of the final rendered images in a simulator can become time consuming, costly, and highly subjective.   The authors support testing early on in this transformation process through automated testing.   Suggested correlation methods consist of automated database correlation combined with interactively observed display correlation.   As was discussed by McCarter and Woodard, et. al., the authors infer that correlation may be expressed in degrees and not in a strictly "correlated/not correlated" fashion.   This article is also unique in that it is one of the first to propose specific metrics for database

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correlation.   However, the proposed metrics will only detect a discrepancy and not necessarily indicate its source.

Previous work in correlation began at IST through the Multiple Image Generator Database Project (MIDB) in 1991 and 1992.   Some studies in an automated approach were conducted in measuring visual database correlation through an elevation difference histogram similar to the algorithm proposed by Zvolanek [Lisle92].   However, this technique only indicated when discrepancies occurred and not the source of the discrepancy.

An interactive, "man-in-the-loop" approach is currently being taken at IST through development of the Line Of Sight Intervisibility Metric (LOSIM) [Uliano92].   This metric takes random Line Of Sight (LOS) intervisibility samples using a computer image generator (CIG) and produces a correlation prediction based on inferential statistics.   No results have been published to date for this project.

3.0   Description of Research

3.1   Goals of Current Research

The goal of the this research was to develop techniques which could be used to quantitatively determine discrepancies in perceived gaming environments in heterogeneous networked simulators.   These quantitative techniques would be developed into metrics which would be used to determine degrees of correlation required for particular mission scenarios.   A secondary goal was to measure correlation at various stages in the production of the visual representations of the gaming environment.   Therefore, research focused on the visual databases and the final rendered image of the gaming environment.

3.2   Research Methods

This research consisted of four phases which includes project planning, algorithm development and implementation, data collection, and testing. Project Planning consisted of development of a Project Plan (Appendix A) and a Test Plan (Appendix E) which specifically describes the steps taken for these phases.

3.2.1   Algorithm Development

For algorithm development, the concept was to develop one set of metrics for measuring specific discrepancies between geometric visual

databases and a second metric set for rendered images of heterogeneous networked simulators. Through testing at different stages in the processing pipeline, significant errors could be discovered quickly and corrected with reduced costs. The metrics were designed with the following criteria in mind when used to compare two similar data sets (i.e., images or geometric visual databases):

(1) The metric must indicate when discrepancies are present;
(2) The metric must indicate the type of discrepancy; and,
(3) The metric must indicate the magnitude of the discrepancy.

The last two criteria allow a degree of correlation to be established when testing for different mission scenarios.

In determining the type of discrepancies to detect, one must consider the transformations that a visual database undergoes. This can be perceived as two distinct phases: the database production phase and the image generation phase. These phases are illustrated in Figure 3.2-1. The former consists of the transformations of the original source data into a three-dimensional, run-time visual database for a computer image generator (CIG). The second phase describes the manipulation of this database by the CIG to produce a two-dimensional rendered image. Measurement of correlation for these two phases will be referred to as geometric correlation and rendered image correlation, respectively.

3.2.1.1   Algorithm   Development   for   Visual   Database   Correlation

A typical database production phase is illustrated in Figure 3.2-2. Although these processes may vary from CIG to CIG, these steps are essentially the same for construction of visual databases for most commercially available CIGs [BBN90a, BBN90b, MGTO92, Lisle92].

Some of the data inputs can remain fairly consistent. Terrain and culture data inputs using the SIF/HDI data exchange format can be considered constant for different CIGs. The SIF interchange format, developed through the Tri-Service Project 2851, provides a method for converting a single repository Standard Simulator Data Base (SSDB) into different vendor formats. Thus regeneration of source and culture data is unnecessary [Lisle91].

Source Terrain &
Culture Data
(i.e. SIF or DMA)

Source Data is converted to
CIG-Specific, 3D, Run-Time
Visual Database. Typically, this is
done off-line on an Engineering
Workstation.

**Database
Production
Phase**

Run-Time
CIG-specific
Visual
Database

HOST   **CIG**

3D Run-Time Visual Database is
converted to 2D Rendered Image
based on user's perceived
postion in the synthetic
environment.

**Image
Generation
Phase**

Simulator

Rendered
Image on
Display
Hardware

Figure   3.2-1:   Database   Production   and   Image   Generations
Phases
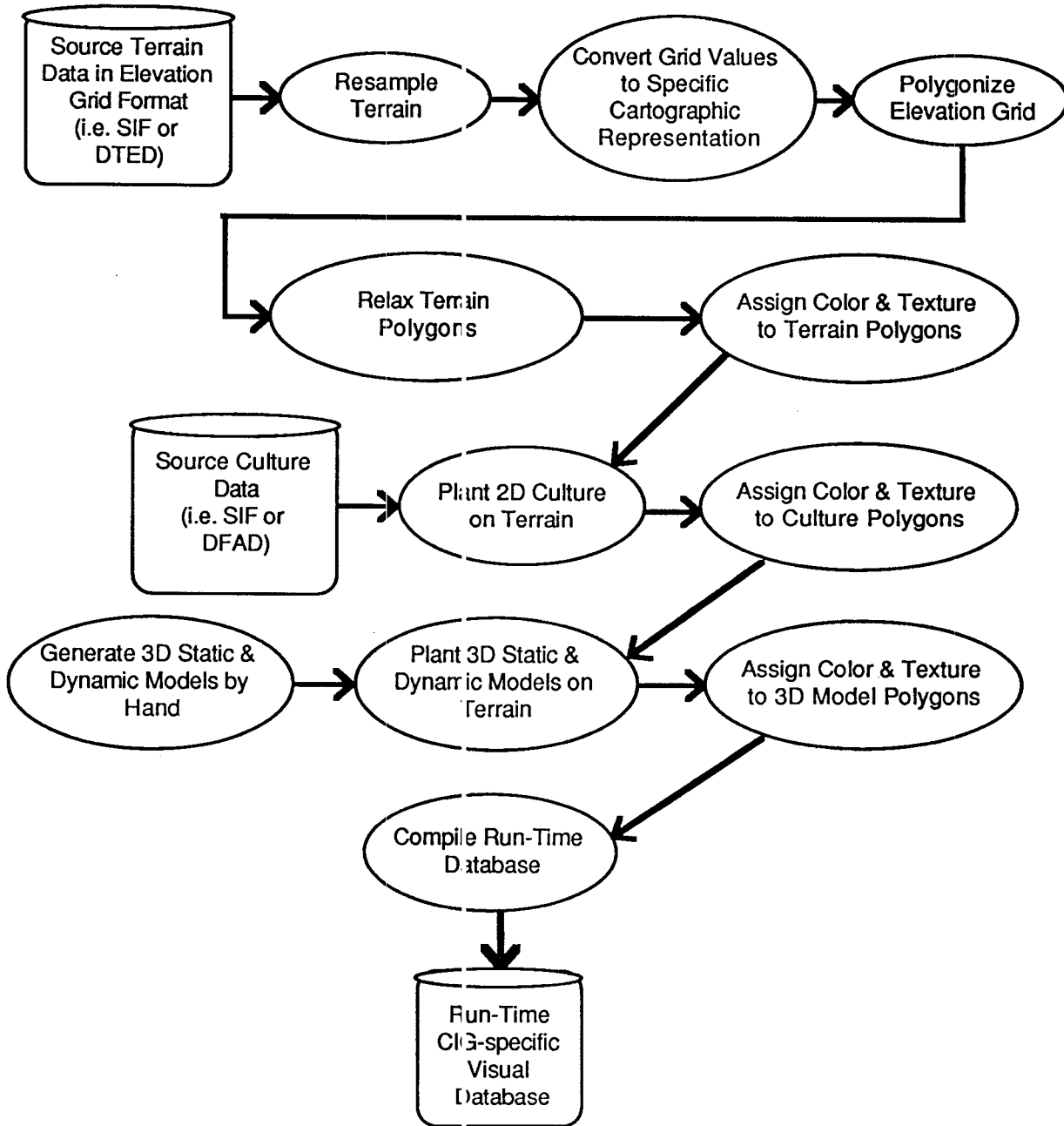
Figure   3.2-2:   Typical   Processes   for   Construction   of   a   Vendor-Specific   Run-Time   Visual   Database   for   Computer   Image   Generators

Each phase of the database production pipeline shown in Figure 3.2-2 can also introduce discrepancies in converting from the SIF input data to the run-time CIG visual database. Differences at each processing step arise from choice of algorithm, algorithm implementation, numeric resolution of the computer on which the database is constructed, and discretion of the database modeller [Farsai92, Lisle92]. For instance, the choice of polygonization algorithm used to construct a run-time database is not only CIG-specific, but also based on the decision of the modeller for the particular exercise [MGT092, BBN90a, BBN90b]. Cartographic projections represent another example. Numerous choices of projections exist [Chevrier70, MILH91, Robinson84]. However, selection of a more popular method, such as Universal Transverse Mercator, can still induce discrepancies through input of different parameters. The effects of modification by hand modeling of terrain, culture, and model polygons or numerical errors should also be taken into account. As stated at a recent discussion of database interchange formats and interoperability, "Interchange of data does not guarantee interoperability." [Farsai92]. Figure 3.2-3 summarizes the discrepancies that can occur during database production.

Resampling	Cartographic Projections	Polygonization
Terrain Polygon Relaxation	Hand Modeling or Modification	Numerical Accuracy Limitations

Figure 3.2-3: Possible Sources of Discrepancy that can Occur during Vendor-Specific Run-Time Visual Database Production

Due to the wide number of discrepancies that can occur during the database production phase and the limited amount of time for this research, metric development for geometric correlation was focused on a subset of the data that is transformed during database production and a subset of the discrepancies that can occur between databases on heterogeneous simulators. Specifically, attention was focused on terrain data since this serves as the foundation to which all other data is referenced. Other studies have indicated the importance of examining

terrain data in achieving the first steps in correlated interoperable simulations [McCarter92, Zvolanek92].

Some of the discrepancies that can produce correlation errors include shifts, skews, warping, and sampling. Shifts arise when one terrain representation is translated either horizontally or vertically with respect to a second representation of the same terrain. The former will produce a misalignment of latitude or longitude while the latter will produce a disagreement in elevation between databases. Shift discrepancies can arise due to hand modeling or differences in numerical accuracy of different algorithms or implementations. Skewing involves a rotation of the database along any vertical or horizontal axis. This will also produce disagreement in latitude, longitude, or elevation and can be produced through hand modeling or numerical accuracy differences. Warping arises when different cartographic projections are used for different representations of the same terrain. These different cartographic projections can produce disagreement in latitude, longitude, and elevation as well. Sampling errors occur when elevation data for one database is sampled at a lower frequency than another terrain database. Subsampling can eliminate critical terrain features or produce features that did not exist in the original terrain. For example, widely spaced elevation measurements of hilly terrain may polygonize to a plateau.

It was also determined that once metrics could be developed to measure these "global" discrepancies, the metrics could be further modified to detect discrepancies in portions of the terrain. Once these "local" measurements could be made, the metrics could be further modified to measure correlation for culture and three-dimensional models.

To develop metrics to detect these type of discrepancies, algorithms were discovered through literature searches and developed internally within IST. The literature search covered areas such as digital signal processing, image processing, statistics, artificial intelligence (e.g., pattern recognition), cartography, and visual databases. For a more detailed description of this development process and references from the literature, please refer to the Interim Report in Appendix C.

3.2.1.2 Algorithm Development for Rendered Image Correlation

Once the run-time database is produced, it is then installed in the CIG to pass through the image generation phase illustrated in Figure 3.2-4. Although the number and type of processes may vary between CIGs, this figure illustrates the transformation of a run-time database into a rendered image for most commercial CIGs [BBN87, Cyrus, EVANSU92,

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Lisle92, SGI92].   Each one of these processes represent a collection of algorithms implemented in hardware and software.   Some of the features that are implemented by these internal algorithms which can also affect the final rendered image are listed in Figure 3.2-5.   Each of the processes shown in Figure 3.2-4 and the features shown in Figure 3.2-5 which are implemented within those processes can all contribute to miscorrelations.   Furthermore, each vendor implements each of these processes differently in their particular CIG.

Due to the limited time available, the large number of processes employed within different vendors CIGs, and the lack of information on their proprietary algorithms, metric development did not focus on effects of CIG processes on the final rendered image.   Instead, metric development focused on a subset of the perceived discrepancies that can occur between the rendered images from different CIGs.   Some of these discrepancies include shifts (i.e., translation parallel to the image plane), skew (i.e., rotation about an axis perpendicular to the image plane), and dilation (i.e. scene magnification).   Additional discrepancies between rendered images may be possible.

Algorithms were specifically sought to measure shifts, skews, and dilation between images.   As with the geometric correlation studies for databases, literature searches and internal algorithm development were pursued.   For more detailed information on the rendered image correlation metric development, please refer to the Interim Report in Appendix C.

One caveat to consider in measuring correlation due to image generator effects is that one of two assumptions must be made.   The first assumption is that the databases of two networked heterogeneous simulators are 100 percent correlated.   The second assumption is that an acceptable level of correlation is achieved between the databases and effects of remaining miscorrelations on CIG processes are known.   From discussions of the previous section and results of other studies, it has been shown that 100 percent correlation is not feasible [McCarter92, Farsai92].

Furthermore, these studies only considered rendered images from an "out-the-window" visual display.   Correlation studies on other visual outputs (i.e., infrared, radar, etc.) were beyond the scope of these studies.

Host

Run-Time CIG-specific Visual Database

Select region of database to load on IG based on vehicle position via Vehicle Dynamics and User Inputs

Select subregion of database to display based on number of channels and Field of View (Database Traversal Culling)

Image Generator

Rotate/Translate objects with respect to Eyepoint

Clip polygons of objects that are on the boundary of the viewing frustrum (Visibilty Culling)

Perform perspective transformation to convert polygons from 3D to 2D

Rendered Image on Display Hardware

Send commands to display hardware to illuminate appropriate pixels

Assign color and texture to pixels

Determine pixels that represent polygon to display (Rasterization)

Figure 3.2-4:   Typical Processes within a Computer Image Generator for Rendering an Image from a Three-Dimensional Visual Run-Time Database

Environmental Effects	System/Load Management	Rendering
		Color
Time of Day	Level of Detail	Shading
Illumination Sources	Fade Control	Texture
Clouds	Frame Rate Control	Anti-Aliasing
Fog/Haze	Dynamic Priority	
Storms/Lightning	Static Priority	
Glare		

Figure 3.2-5:   Typical Computer Image Generator Features that can Affect the Final Rendered Image

3.2.1.3   Algorithm   Implementation

Once algorithms were devised, metrics for database and rendered image correlation were developed on engineering workstations. Primarily, the algorithms were coded in the C programming language. For the revised Fourier metric (described below), the Khoros software system was used [KHOROS91]. Khoros is an X Windows based signal processing environment with a visual programming language. Khoros is available via anonymous ftp over Internet and runs on a wide variety of computer workstations. The primary benefit to Khoros is the ability to rapidly prototype complex algorithms for different types of signals.

For additional information on algorithm implementation, please refer to the Project Plan (Appendix A), the Test Plan (Appendix B), and the Interim Report (Appendix C). Additional information on Khoros is available in Appendix D.

3.2.2   Data   Collection

Data collection was essentially divided into two sets. Set A data was considered as a control set that could be generated internally within IST. This control set allowed a single error to be induced in the data which could be used to test metrics. This data was generated for both databases and images as shown in Figure 3.2-6 and 3.2-7, respectively. For each Source Database, a single discrepancy was induced (i.e. shift, skew, warping, subsampling) to produce a miscorrelated database. Similarly, for each Source Image, an Error Image was produced by introduction of a single error (i.e., shift, skew, dilation).
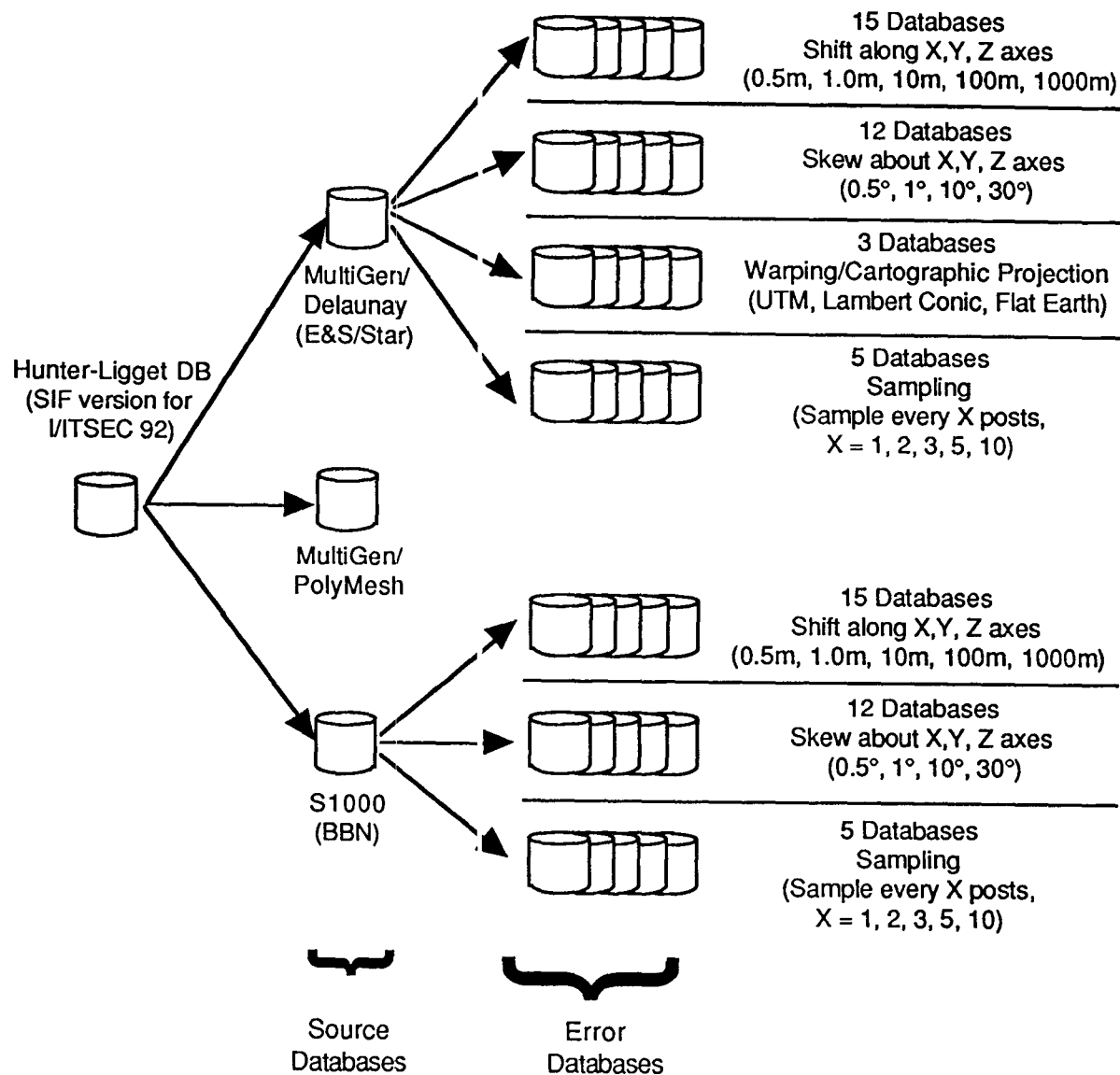
Figure 3.2-6:   Generation of Set A Test Databases

8 Images
Shift along X & Y axes
(as % of image size: 1%, 5%, 10%, 25%)

6 Images
Skew about axis perpendicular to image plane
(1°, 3°, 5°, 10°, 15°, 30°)

4 Images
Dilation (Magnification)
(% size of original image: 75%, 50%, 25%,
10%)

Source
Images

Error
Images

Note: Similar Error Image Sets generated
for each Source Image
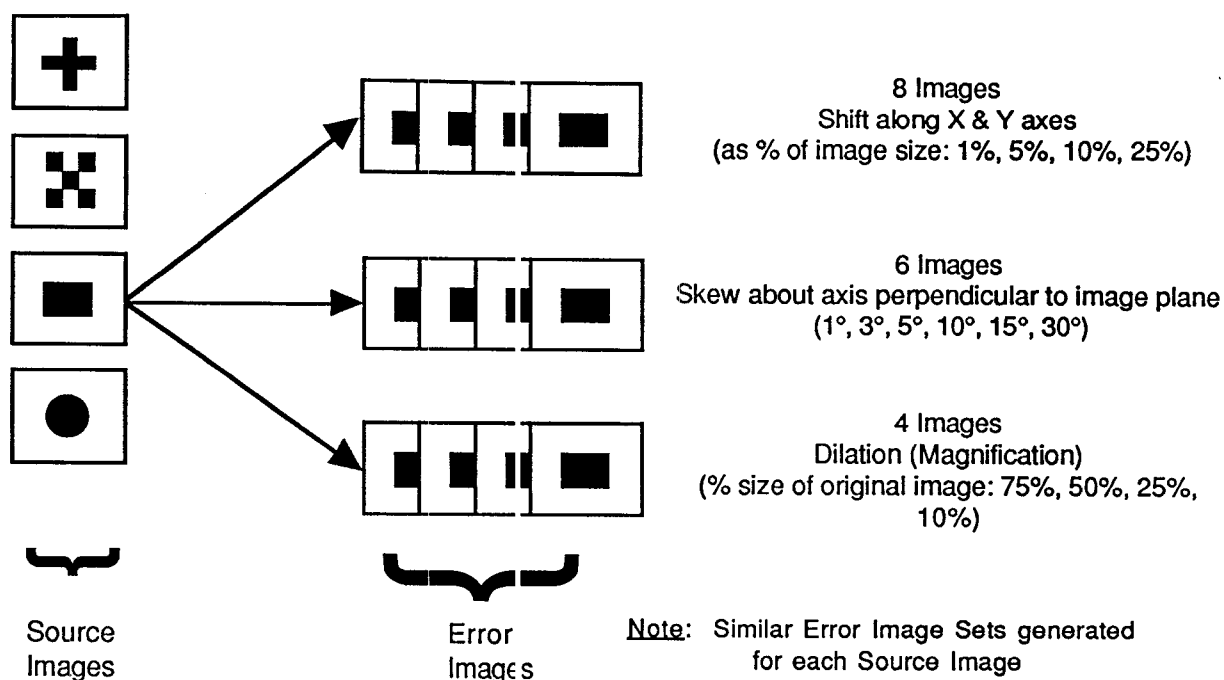
Figure 3.2-7: **Generation of Set A Test Images**

Set B data consisted of data obtained from the Interoperability Demo at
the 1992 Interservice/Industry Training Systems and Education
Conference (I/ITSEC). Photographs were taken of the displays of image
generators from a selection of participants at the demonstration. These
photographs are referred to as Set B images. Copies of the databases
used by the CIG vendors were also sought for the Set B Databases.

For more detailed information on the data generation and collection,
please refer to the Project Plan in Appendix A and the Test Plan in
Appendix B.

3.2.2   Metric   Testing

Testing consisted of three phases. The first phase involved testing of the
metrics using the Set A data. For Set A databases, the Source Database
was tested against each Error Database using all applicable metrics. The
original SIF version of the database was not used to eliminate the effects
of polygonization and terrain relaxation. In this manner, the metric
could be evaluated on its ability to detect a particular discrepancy in a
database without affects from other discrepancies. A similar approach
was taken for Set A Images by testing the Source Image against each
corresponding Error Image from which it was generated.

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The next phase of testing concentrated on the Set B data gathered from the I/ITSEC Interoperability Demonstration. The Set B photos taken of the I/ITSEC participants' rendered images were to be scanned and tested by the metrics. However, as shown in Figure 3.2-8, the photos showed different scenes even though the eye points for each vendor's CIG were placed at the same location and orientation in the database (refer to the Test Plan in Appendix B). This indicated that significant discrepancies existed between the vendors databases. It was then decided by Loral and IST that the metrics could not be effectively tested with the Set B images.

Similar problems occurred with collection and testing of the Set B databases. Both Evans & Sutherland and Star Technologies were unable to provide their versions of the I/ITSEC run-time database in the format requested by IST. General Electric and BBN did provide databases, but IST personnel have been unsuccessful to date in converting the databases into a format that can be read by the metrics. A standard interchange format for *run-time* databases might have alleviated this problem.

Another point to consider is that any correlation discrepancies discovered between the I/ITSEC vendor databases could not have been verified. Verification was not possible because no provisions were made at the I/ITSEC 92 Interoperability Demonstration to measure correlation among the vendor databases. Without some form of correlation data, verification of the metrics with the Set B databases would prove difficult.

The third phase of testing was planned for implementation of the metrics on CIGs at the Loral ADST office in Orlando. However, insufficient time and limited availability of the CIGs made this impractical.

A detailed description of the test phases and their procedures is provided in the Test Plan in Appendix B.
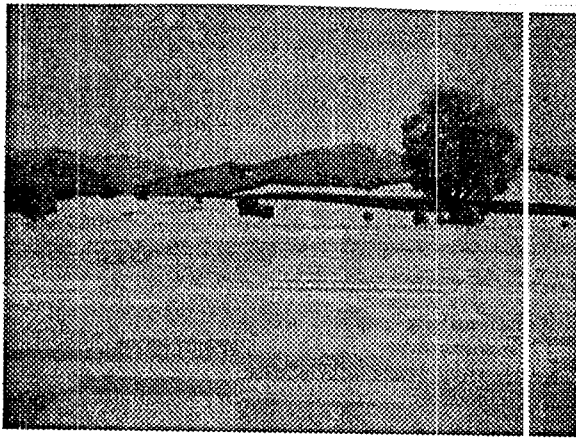
(a) BBN -
    No Texture,
    Time of Day: Noon

(b) IBM/Evans & Sutherland -
    Shading, Texture,
    Time of Day: Noon

(c) Loral/General Electric -
    No Haze, Texture,
    Time of Day: Noon

Figure 3.2-8 Views of the Ft. Hunter Liggett Database from
        Particpants at the 1992 I/ITSEC Interoperability
        Demonstration   (UTM FQ7080, High Detail Area,
            Heading: 125° Clockwise from North)

3.3 Description of Results

Results of all first phase testing are summarized in the Interim Report (Appendix C). This includes a description of all metrics developed and evaluated for this study (e.g. Feature Metric, Fourier Metric, Hausdorf Metric, MinMax Metric, and Volume Metric). First phase testing results since the Interim Report are summarized below. This includes improvements to the Fourier metric and the latest experimental results.

3.3.1 Results Since the Interim Report

Following the recommendations of the Interim Report, further development of the Fourier metric was pursued. The algorithm for this revised Fourier metric and the results to date are presented below.

3.3.1.1 Algorithm for Revised Fourier Metric

With assistance from Dr. Tom Clarke/IST and his graduate assistant, Larry Crochet, the Fourier metric was revised for use with databases and rendered images. In the case of databases, the algorithm is designed to detects rotations about the Z axis and translations along X (latitude) or Y (longitude) axes. For rendered images, the metric seeks translations in the image (XY) plane, rotations about an axis perpendicular to this plane (Z), and differences in dilation (i.e. magnification). To simplify the discussion, both rendered images and databases will be referred to as images. The algorithm is described below.

If $f_B(x,y)$ represents a translated (i.e., shifted), rotated (i.e., skewed), and dilated replica of the image $f_A(x,y)$, according to the Fourier Shift Theorem, the Fourier Rotation Theorem, and the Fourier Scaling Theorem, their transforms are related by

$$F_B(u,v) = e^{-j\,2\pi(ux_o + vy_o)}\,F_A(d_o(u\cos\theta_o + v\sin\theta_o), d_o(-u\sin\theta_o + v\cos\theta_o))$$

where F_A and F_B are the Fourier transforms of f_A and f_b, respectively [Gonzalez92]. The quantity d_o is the scale (dilation) factor and the quantities θ_o and (x_o, y_o) represent the amount of relative rotation (skew) and translation between the images. By taking the magnitude of the Fourier transform, the equation becomes

$$\left|F_B(u,v)\right| = \left|F_A(d_o(u\cos\theta_o + v\sin\theta_o), d_o(-u\sin\theta_o + v\cos\theta_o))\right|$$

and we eliminate the relative translation effects between the images by removing the phase component of the transform.

By mapping the two dimensional spectrum into polar coordinates, we can quickly determine the rotation and scaling factor [Mesner85, Schwartz77]. This mapping, referred to as a log-rho-theta warping, is accomplished by defining new coordinate axes for the image plane as

$$\theta = \tan\left(\frac{u}{v}\right)$$

$$L\rho = \ln\left(\sqrt{u^2 + v^2}\right)$$

where θ is mapped to the x axis and $L\rho$ is mapped to the y axis. We then can compute the normalized cross spectrum of the two spectrums as

$$C^W = \frac{F_A^W {}^* F_B^W}{\left| F_A^W {}^* F_B^W \right|}$$

where the absolute value in the denominator is the root mean square (RMS) of the cross spectrum and the asterisk (*) denotes complex conjugation. Computing the inverse Fourier Transform gives the cross correlation which appears as a 2D image with a spike. The location of the spike in the plane indicates the scale factor d_0 along the $L\rho$ axis and the rotation angle θ_0 along the θ axis.

By applying an inverse rotation transformation $R^{-1}(\theta_0)$ and inverse scaling transformation $S^{-1}(d_0)$ to f_B and again taking the Fourier transform of both f_A and f_B, we can use cross correlation to determine the relative translations. The cross spectrum can be expressed as

$$C^T = \frac{F_A^* F_B^{RS}}{\left| F_A^* F_B^{RS} \right|}$$

where $F_B{}^{RS}$ is the Fourier transform of the scale-rotation corrected image f_B. The inverse Fourier transform of C^T provides us with the relative translations (x_0, y_0) within the image plane in a manner similar to C^W. These values are obtained by determination of the location of the spike in the inverse transform (or cross correlation) plane. The x axis provides the x_0 value and the y axis provide y_0.

For this algorithm, the Fast Fourier Transform (FFT) is used to compute the Fourier Transform [Gonzale;92, Press88]. A figure summarizing the Fourier metric algorithm is provided in Figure 3.3-1.

The advantage of this algorithm over the Fourier metric algorithm presented in the Interim Report is that no iteration is necessary. Thus, the speed of the metric is increased.
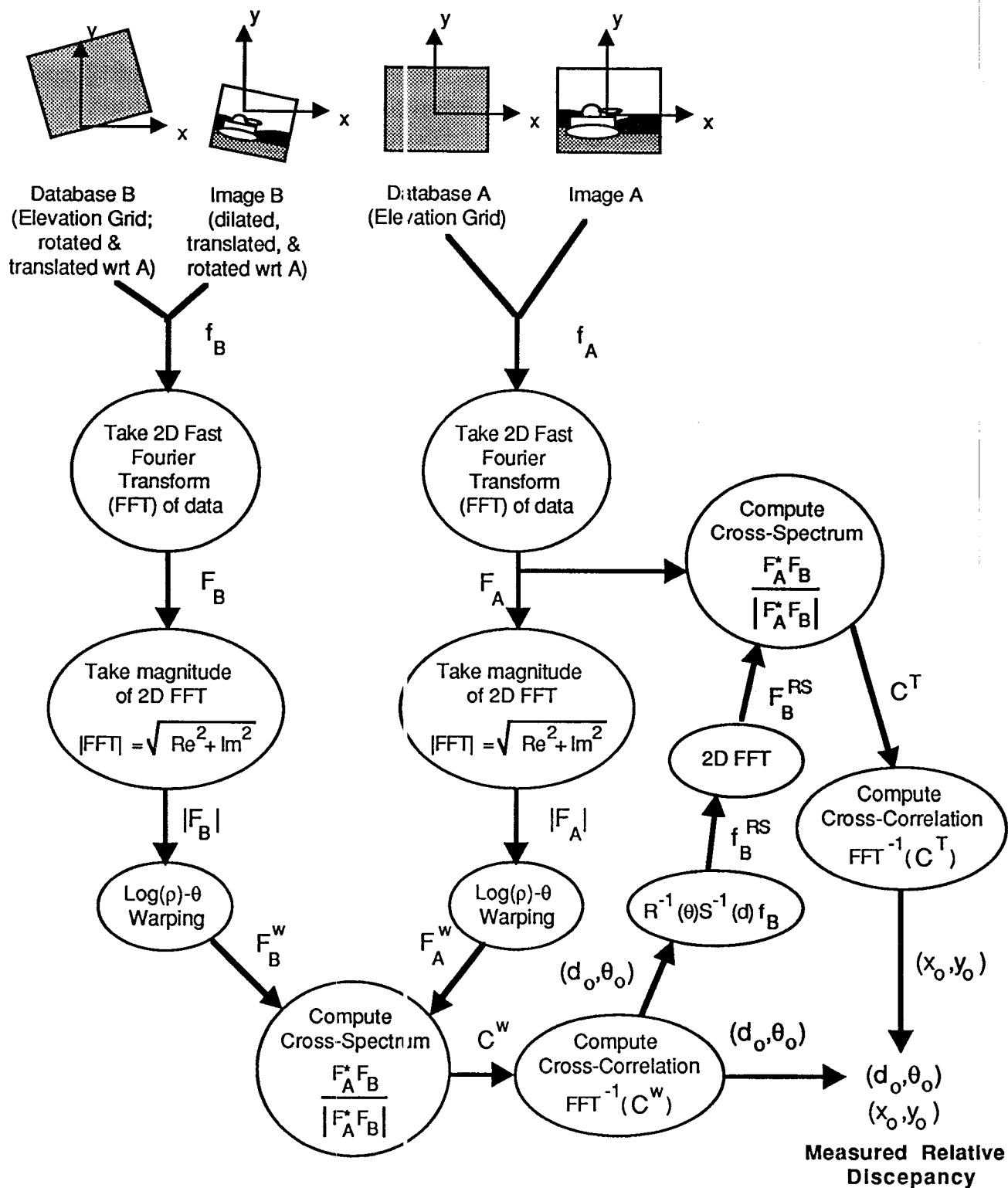
Figure 3.3-1: Algorithm for Revised Fourier Metric

3.3.1.2 Results for Revised Fourier Metric

Results for the tests on the Set A databases are shown in Tables 3.3-1 through 3.3-4.

Tables 3.3-1 and 3.3-2 present results of shift error testing on the metric. As shown by these tables, X and Y axis shifts of 10 meters or less are not detected. This is expected since the metric is unable to detect any shifts much smaller than its sampling interval (i.e., 125 meters). By increasing the sampling rate or by using interpolation techniques, errors of smaller magnitude could be detected. X and Y shift errors are detected as they approach the sampling interval. For instance, 100 meter shifts get mapped into 125 meter estimated shifts. This rounding up effect is due to the original grid resolution of 125 meters. For shifts greater than 125 meters, the errors are generally detected and rounded up to multiples of the sampling interval, 125 meters. In some instances, numerical accuracy and grid resolution may cause the error measurement to vary by one unit (1 unit = 125 meters). This is the case when the 1000 meter X axis shift error reads as 875 meters in the MultiGen databases.

Other anomalous readings include the 100 meter Y axis shift that reads as a 125 meter X axis shift in the MultiGen databases or the 1000 meter Y axis shift that is measured as a 500 meter shift in the S1000 databases. These discrepancies between induced and measure error may be due to the small size of the elevation grid (e.g., Multigen databases: 12 X 14; S1000 databases: 113 X 31). Such small data sets can produce artifacts that contribute noise. Further study is required to verify the sources for these erroneous measures.

For Z shifts, we would expect the Fourier metric to be unable to detect these discrepancies since it produces a translation perpendicular to the XY plane. Such shifts would be analogous to an increase in image intensity which would be eliminated in the normalization of the cross correlation. This appears to be so in the case of the S1000 databases. However, for the MultiGen databases, anomalous readings occur for 100 meter and 1000 meter Z-axis shifts. This again may be due to the small size of the sample grid of the MultiGen databases (e.g., 12 X 14) versus the size of the S1000 grid (113 X 31).

Skew (rotational) error results are shown in Tables 3.3-3 and 3.3-4. For the MultiGen databases, we find a close correspondence between induced and measured Z-axis rotations. Tests for S1000 data presented

equally good results for Z rotations. Indicated translations may be due to noise.

Although not part of the original design, the Fourier metric was also tested against X and Y rotations to determine their effects. As shown in the tables, small X and Y rotations do not produce any measured error for the Fourier metric. However for larger rotations about the X or Y axes ($\theta > 10°$) these single errors appear as both X/Y translations and Z rotations. These types of rotations could be perceived as translations in the image plane. For instance, a rotation about the X axis may appear as a translation along the Y axis when using this metric. Additional study is required to filter out these affects.

Initially, when these skews error tests were conducted, the Fourier metric was unsuccessful in detecting the induced skews. This was due to the fact that the rotations were moving the database out of the sampling window and, therefore, losing information. Figure 3.3-2 illustrates this point. In this figure, the sampling windows for database A and B remain aligned. Yet, information is lost for database B when it is rotated out of this window. This anomaly can be avoided by enlarging the sampling window and placing a boundary around the database that is large enough to avoid information loss upon rotations. This is referred to as "padding" or "zero-padding" the data in signal processing For the results shown in Tables 3.3-3 and 3.3-4, a 1000 meter wide boundary of zero meter elevation values was used.
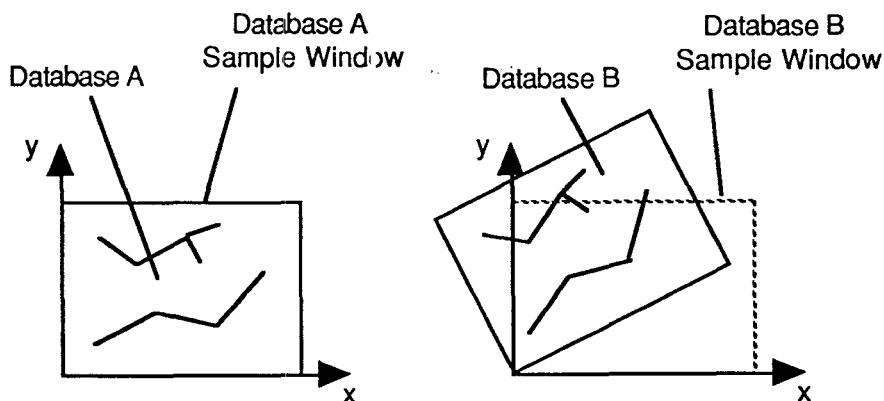
Figure 3.3-2: Example of Information Loss Due to Rotations

Errors in Set A Images could not be detected by the Fourier metric. Further study is required to determine the source of this problem.

However, in testing with more complex images, rotations and translations were successfully detected. Dilations were also detected in simple test images in a limited range of $1/2 < d < 2$. This range is probably limited due to noise.

Table 3.3-1:   Shift Errors Detected in Set A MultiGen Databases
by Revised Fourier Metric

Induced Error	Measured XY Translation	Measured Z Rotation
X Shift: 0.5 m	(0 m, 0 m)	0°
X Shift: 1.0 m	(0 m, 0 m)	0°
X Shift: 10.0 m	(0 m, 0 m)	0°
X Shift: 100.0 m	(0 m, 0 m)	0°
X Shift: 1000.0 m	(875 m, 0 m)	0°
Y Shift: 0.5 m	(0 m, 0 m)	0°
Y Shift: 1.0 m	(0 m, 0 m)	0°
Y Shift: 10.0 m	(0 m, 0 m)	0°
Y Shift: 100.0 m	(125 m, 0 m)	0°
Y Shift: 1000.0 m	(0 m, 1000 m)	0°
Z Shift: 0.5 m	(0 m, 0 m)	0°
Z Shift: 1.0 m	(0 m, 0 m)	0°
Z Shift: 10.0 m	(0 m, 0 m)	0°
Z Shift: 100.0 m	(125 m, 125 m)	0°
Z Shift: 1000.0 m	(1000 m, 1625 m)	250°

Table   3.3-2:   Shift   Errors   Detected   in   Set   A   S1000   Databases   by
Revised   Fourier   Metric

Induced Error	Measured XY Translation	Measured Z Rotation
X Shift: 0.5 m	(0 m, 0 m)	0°
X Shift: 1.0 m	(0 m, 0 m)	0°
X Shift: 10.0 m	(0 m, 0 m)	0°
X Shift: 100.0 m	(125 m, 0 m)	0°
X Shift: 1000.0 m	(1000 m, 0 m)	0°
Y Shift: 0.5 m	(0 m, 0 m)	0°
Y Shift: 1.0 m	(0 m, 0 m)	0°
Y Shift: 10.0 m	(0 m, 0 m)	0°
Y Shift: 100.0 m	(0 m, 125 m)	0°
Y Shift: 1000.0 m	(0 m, 500 m)	358.59°
Z Shift: 0.5 m	(0 m, 0 m)	0°
Z Shift: 1.0 m	(0 m, 0 m)	0°
Z Shift: 10.0 m	(0 m, 0 m)	0°
Z Shift: 100.0 m	(0 m, 0 m)	0°
Z Shift: 1000.0 m	(0 m, 0 m)	0°

Table 3.3-3:   Skew Errors Detected in Set A MultiGen Databases
by Revised Fourier Metric

Induced Error	Measured XY Translation	Measured Z Rotation
X Rotation: 0.5°	(0 m, 0 m)	0°
X Rotation: 1.0°	(0 m, 0 m)	0°
X Rotation: 10.0°	(125 m, 125 m)	0°
X Rotation: 30.0°	(125 m, 750 m)	0.71°
Y Rotation: 0.5°	(0 m, 0 m)	0°
Y Rotation: 1.0°	(0 m, 0 m)	0°
Y Rotation: 10.0°	(125 m, 0 m)	0°
Y Rotation: 30.0°	(125 m, 0 m)	3.52°
Z Rotation: 0.5°	(0 m, 0 m)	0°
Z Rotation: 1.0°	(0 m, 0 m)	0°
Z Rotation: 10.0°	(0 m, 0 m)	11.25°
Z Rotation: 30.0°	(0 m, 125 m)	29.53°

Table 3.3-4:   Skew Error; Detected in Set A S1000 Databases
by Revised Fourier Metric

Induced Error	Measured XY Translation	Measured Z Rotation
X Rotation: 0.5°	(0 m, 0 m)	0°
X Rotation: 1.0°	(0 m, 0 m)	0°
X Rotation: 10.0°	(125 m, 2625 m)	1.41°
X Rotation: 30.0°	(4000 m, 3750 m)	8.43°
Y Rotation: 0.5°	(0 m, 0 m)	0°
Y Rotation: 1.0°	(0 m, 0 m)	0°
Y Rotation: 10.0°	(0 m, 0 m)	0°
Y Rotation: 30.0°	(1750 m, 0)	0°
Z Rotation: 0.5°	(125 m, 0 m)	0.7 °
Z Rotation: 1.0°	(125 m, 0 m)	0.7 °
Z Rotation: 10.0°	(125 m, 0 m)	9.84°
Z Rotation: 30.0°	(125 m, 125 m)	30.23°

The following points summarize the results for the revised Fourier metric:

1) Errors cannot be detected that are smaller than the grid size. For example, a 50 meter relative x shift between databases will not be detected if both databases are sampled at 125 meters. However, as the sampling interval becomes smaller (< 125 meters), the precision of this metric should improve.

2) This metric will not detect an error if information from an image is partially lost. This loss can occur when data (e.g., an image or database) is rotated out of the sampling window. This condition occurs more frequently with rendered images and less frequently with terrain databases.

3) This metric may not work well on small sample grids. Images or elevation grids less than 256 X 256 may not have enough information to extract frequencies. However, the metric should perform well for images or terrain elevation grid databases which are larger than 256 X 256 (pixels or grid points).

4.0 Summary of Results

Table 4.1 and 4.2 summarizes the results of the rendered image and spatial correlation studies. The numbers shown in the table indicate the criteria satisfied by the metric. These criteria were first stated in Section 3.2.1 of this report.

For a description of algorithms other than Fourier or their test results, please refer to the Interim Report in Appendix C.

In examining these results, the Fourier and Hausdorf metrics perform the best in detecting discrepancies between visual databases and rendered images.

One must keep in mind that these metrics can only detect a small subset of possible discrepancies between heterogeneous networked simulators as discussed in section 3.2.1 of this report.

Table 4-1 Summary of Results for Spatial Correlation Metric Testing

Metric	MinMax	Feature	Hausdorf Distance	Volume	Fourier
Error					
Shift-X	1, 3	1	1, 2*, 3	I	1, 2, 3
Shift-Y	1, 3	1	1, 2*, 3	I	1, 2, 3
Shift-Z	1, 3	1	1, 2*, 3	I	
Skew-X	1		1, 3	I	1*
Skew-Y	1		1, 3	I	1*
Skew-Z	1		1	I	1, 2, 3
Warping			1	I	1, 2*
Sampling			1, 3	I	1, 2*, 3*

Key: 1 - Indicates when discrepancy is present.
2 - Indicates the type of discrepancy.
3 - Indicates the magnitude cf the discrepancy.
* - Requires further development of metric.
I - Inconclusive.

Note: The errors listed above are only a subset of possible discrepancies between visual terrain databases.

Table 4-2 Summary of Results for Image Correlation Metric Testing

Metric	MinMax	Hausdorf Distance	Fourier
Error			
Shift-X	1, 3	1	1, 2, 3*
Shift-Y	1, 3	1	1, 2, 3*
Skew-Z	1	1	1, 2, 3*
Dilation		1	1, 2, 3*

Key: 1 - Indicates when discrepancy is present.
2 - Indicates the type of discrepancy.
3 - Indicates the magnitude of the discrepancy.
* - Requires further development of metric.
I - Inconclusive.

Note: The errors listed above are only a subset of possible discrepancies between CIG-generated rendered images.

5.0   Conclusions

From this study, the following conclusions are made:

1) **One hundred percent correlation is not achievable in heterogeneous networked simulators.   Degrees of correlation must be determined based on the degree of interaction between entities and the environment.   Perceptions of the synthetic environment through different simulators may establish additional correlation thresholds.**

   Similar conclusions have been reached through other correlation efforts [McCarter92].

   The large number of processes involved in transforming a database into a final rendered image have a wide variety of hardware and software implementations.   Without a standardized approach, various implementations make it difficult to develop one-to-one mappings of discrepancies between the simulators' databases and image generators.

   A more obtainable goal is to determine degrees of correlation necessary to interoperate for specific types of exercises [McCarter92, Zvolanek92, Woodard92].   This correlation threshold is dependent on the degree of interaction between entities and the environment.   For example, a ground-based vehicle requires a high degree of correlation with the terrain and other vehicles.   In contrast, air-to-air applications require minimal interaction among entities and the terrain and therefore require a lower degree of correlation.

   Perceptive discrepancies may also serve as criteria for developing additional correlation thresholds.   The lack of one-to-one mappings in CIG features and levels of fidelity may be overcome by measuring perceived differences in the final rendered image.   The task of matching color or texture patterns may be inconsequential if the simulation user *perceives no difference* between two displays of the same synthetic environment that are not 100% correlated.

2) **Any correlation metrics developed will be difficult to apply since no standard interchange format exists between heterogeneous simulators other than the original source data (i.e. SIF/HDI).   However, development of multiple interchange formats for correlation testing may be both difficult and costly.**
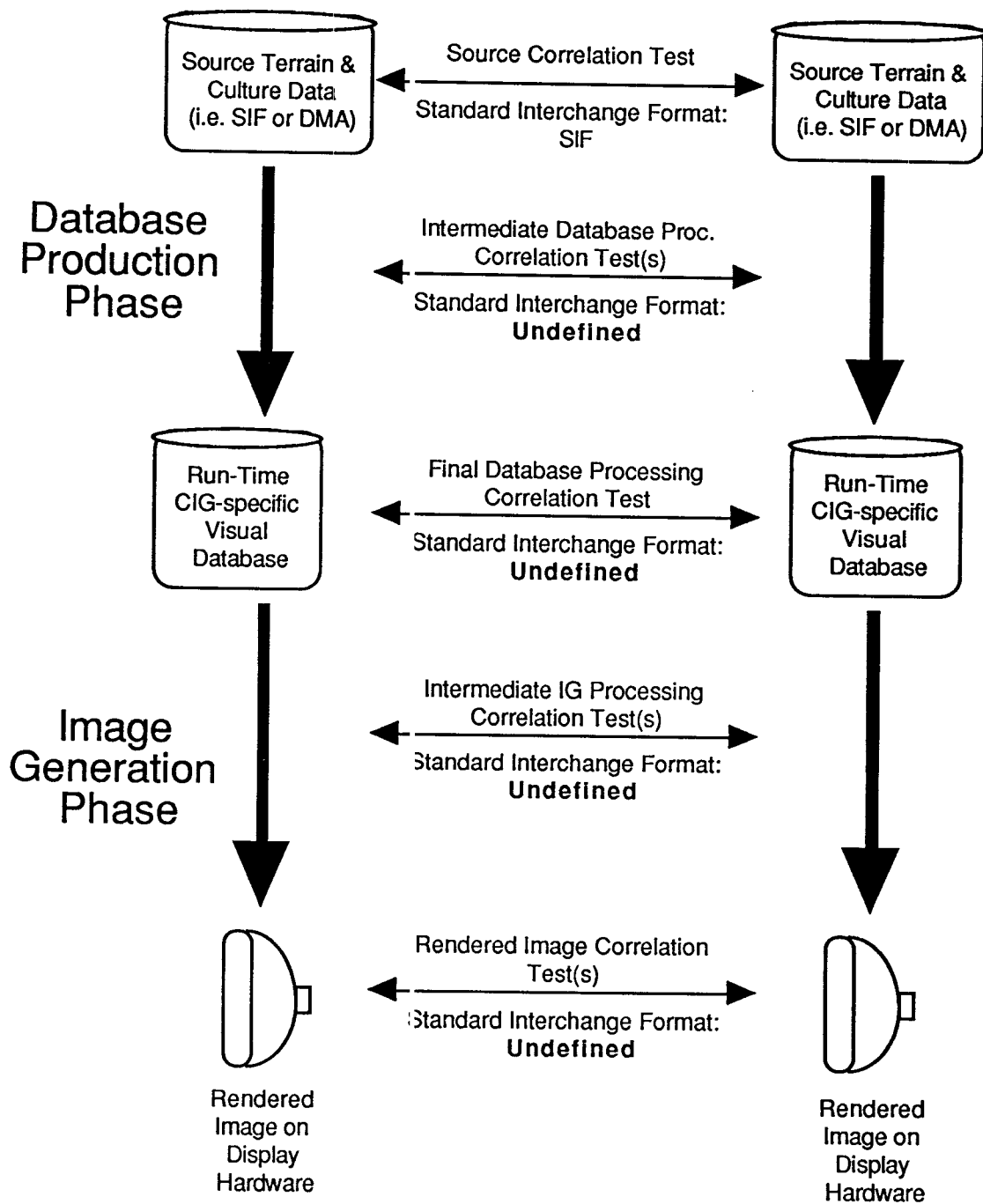
Standardizing source data through efforts such is Project 2851 is a necessary first step to achieve correlation. However, as pointed out previously, exchange of source data does not guarantee interoperability [Farsai92].

Without methods to interchange data at different points in the database construction and image processing pipeline, correlation measurement efforts will be severely impeded. Figure 5-1 provides examples. Assume that correlation tests for heterogeneous simulators are developed at intermediate points of the Database Production Phase, at the end of the Database Production Phase, at intermediate points of the image generation phase, and at final rendered image stage. Without standard data exchange formats at each of these points, such correlation tests will be difficult to conduct on a regular basis. A caveat to consider is that development of interchange formats at different points of the database production and image generator phase may be technically complex and costly for vendors.

3) **Correlation metrics may need extensive, in-depth research which requires several man-years of effort.**

As stated previously in section 3.2.1, each vendor applies different methods to every stage of the visual database and image generator processing pipelines. Although the processes are similar, enough variation exists between vendors' approaches to require a comparative study of each vendor's implementation of the different processes to develop effective correlation metrics. Efforts to develop correlation metrics will be further complicated as other features (i.e. Dynamic Terrain) are added to networked simulators.

Source Terrain & Culture Data (i.e. SIF or DMA)

Source Correlation Test

Standard Interchange Format: SIF

Source Terrain & Culture Data (i.e. SIF or DMA)

Database Production Phase

Intermediate Database Proc. Correlation Test(s)

Standard Interchange Format: **Undefined**

Run-Time CIG-specific Visual Database

Final Database Processing Correlation Test

Standard Interchange Format: **Undefined**

Run-Time CIG-specific Visual Database

Image Generation Phase

Intermediate IG Processing Correlation Test(s)

Standard Interchange Format: **Undefined**

Rendered Image Correlation Test(s)

Standard Interchange Format: **Undefined**

Rendered Image on Display Hardware

Rendered Image on Display Hardware

Figure 5-1: Example of Standard Data Interchange Formats for Correlation

6.0   Recommendations

1) **Run-time visual database correlation, especially terrain correlation, should be the next goal in achieving interoperable heterogeneous networked simulators.**

Culture, static models, and dynamic models are all referenced to the terrain. Without achieving an acceptable degree of terrain correlation between different simulators, other correlation tests will be difficult to apply.

Furthermore, a basic DIS concept assumes that all data is passed with respect to "ground truth". However, if different simulators maintain significantly different representations of terrain, a common ground truth is not possible.

Another consequence of requiring ground truth, is that culture and models, both static and dynamic, must be correlated to an acceptable degree. This includes the geometry of the culture or model and the location and orientation in the database.

There is another significant reason that correlation efforts should be focused on databases. Image generators are dependent on databases. Therefore, correlation tests conducted on image generators will prove extremely costly and will do little to alleviate correlation discrepancies unless the databases have been correlated to an acceptable degree.

2) **Standardization may accelerate correlation research and improve interoperability. A common abstract perception of the synthetic environment should be incorporated into DIS. This abstraction would serve to specify a vendor-independent representation of "ground truth" that interacting heterogeneous networked simulators must use to communicate in order to achieve interoperability.**

Enhanced interoperability through improved correlation may be achieved more rapidly by standardizing portions of the database production and image generation processes. Through Project 2851, this process has begun by providing a standard repository for source data. These efforts could be extended to the database production and image generation phases as well.

Standardization has been an approach taken by other industries in order to achieve interoperability. One particularly successful standard is the X-Windows user interface protocol used by UNIX workstation manufacturers. The need of the UNIX workstation industry for interoperability appears analogous to the current interoperability needs of the CIG industry.

In the mid-1980s, the Massachusetts Institute of Technology received donations of UNIX workstations from different vendors. In order to provide interoperability across heterogeneous networked engineering workstations, the X-Windows protocol was developed. By 1989, this protocol had been adopted by almost all UNIX computer manufacturers.

The main goal of establishing the X-Windows protocol was to have any application display the same user interface on any UNIX platform. In short, *the user interfaces on different platforms had to correlate to a degree sufficient for the user to have a common perception of the graphical application environment.*

The design of the X-Windows protocol supports high-performance, device-independent graphics and is based on an asynchronous network protocol. This basis has the following advantages [Nye89]:

1) Local and networked connections are independent from both the user and implementor's point of view;
2) The protocol can be implemented on a wide variety of languages and operating systems;
3) The protocol can be used on any reliable network; and,
4) Little performance penalty exists since the network is usually faster than a particular platform's graphics.

The key that provides interoperability for the X-Windows standard is that all entities communicating through the protocol must do so through a *common abstract perception of the environment.* Instead of each entity transmitting its own perception of the graphics environment (as is currently done in DIS), the entity maps its perception into the common abstract perception of the protocol.

This concept also arises in the analysis of the dynamics of multibody systems [Greenwood88, Shabana89]. To define the interaction between a system of bodies, a common frame of reference is defined. All information regarding forces, torques, accelerations, and velocities

can then be expressed in the common reference frame to determine the effects on individual bodies in the system.

Currently, DIS assumes all entities communicate via "ground truth," but it does not provide a definition of "ground truth." That is, no common reference frame is defined. A simulated entity interacting with other entities through the DIS protocol maintains its own perception of the environment (a key DIS concept) and therefore transmits its own perception of the environment to other entities. For example, assume Entity A transmits its position and orientation to Entities B, C, and D. Even though this information is transmitted via geocentric coordinates, it is Entity A's perception of the world in geocentric coordinates. If Entities B, C, and D do not know Entity A's perception of the synthetic environment (i.e., no common reference frame exists), then these entities have little hope of correctly interpreting information sent from Entity A.

To solve this problem through an X-Windows approach, a common abstraction of the environment should be defined for the DIS protocol that all entities can use to pass information. This could be considered as the DIS world view or common reference frame. Thus, Entity A could translate its position and orientation information into the DIS world view that could then be read by entities B, C, and D. From this point, Entities B, C, and D could translate from the DIS world view into their own perception of the synthetic environment.

So that all vendors can continue to use the DIS protocol, this world view should be specified so as to be vendor-independent in its implementation. This world view would serve as an unbiased, defined "ground truth."

In summary, extending the DIS protocol to include a common environment abstraction, or vendor-independent world view, for data base production and image generation process may aid in achieving improved interoperability.

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Appendix A

Project Plan

Loral Visual Terrain Data Base Correlation Project Plan

presented by

Institute for Simulation and Training
University of Central Florida

October 30, 1992

1.0 Introduction

This study will conduct correlation research oriented toward
computer image generation. This work is in support of the BDS-D
Delivery Order "BDS-D Architecture Definition and DIS Standards
Development". The subtask to be performed by the Institute for
Simulation and Training (IST) is called "Correlation Studies".

2.0 Purpose

With development of standards such as Distributed Interactive
Simulation (DIS), connectivity increases among training simulators.
These networked simulators are designed to train multiple
individuals or multiple teams in the same scenario and gaming area.
Therefore, each individual player must observe the same
environment. However, current simulation technology requires
separate copies of the same gaming area on each of the simulators in
the network.

The methods by which these multiple copies of the gaming area are
produced can lead to dissimilarities in the players' perceived gaming
area. Each simulator may use different algorithms for modelling the
terrain of the gaming area which can produce significantly different
terrain representations. This lack of common perception among
players can impede the effectiveness of the training exercise in two
ways. First, dissimilarities can provide unfair advantages to one
player over another. For instance, one player may assume that he
has hidden his tank behind a hill. From an opponent's perspective,
that same tank may be in full view. Second, unrealistic actions may
occur due to terrain database dissimilarities. Such actions could

include an opponent's tank floating above the ground due to differences in terrain elevation data among simulators.

The purpose of this study is to develop methods of measuring these discrepancies among terrain databases that are modelled after the same gaming area. By quantifying these discrepancies, the effectiveness of the training exercise can be predicted. In addition, vendors can determine common sources of error and develop methodologies to enhance commonality among various representations of the gaming area.

3.0 Objective

The objective of this study is to develop metrics for measuring the correlation among visual terrain databases. This correlation research shall investigate the existence of algorithms in statistical theory and image processing which may be suitable for use in computer image generation. These existing algorithms will be modified or new algorithms will be developed to measure correlation among terrain databases. It is the intent of this study to establish a sound statistical basis in the development of these metrics.

4.0 Project Description

During this study, IST will focus its research efforts on two areas of correlation. First, spatial correlation between the geometry of similar terrain databases will be explored. Second, correlation of the rendered images of these similar terrain databases will be examined. The project will consist of four phases which include project planning, correlation metric development, testing and data collection, and analysis and reporting.

4.1 Project Planning

This phase consists of a detailed design of procedures for metric development, evaluation, and testing. Metric development will be explained including algorithm selection processes, implementation strategies and software systems, and database and scenario requirements. These plans will be summarized in the Test Plan Document.

4.2 Correlation Metric Development

The main effort of this study is to develop methods to quantitatively measure the degree to which two or more terrain databases are correlated. This phase will begin with a literature search in the areas of statistical theory and image processing to discover existing algorithms which are applicable to visual database correlation. Consultation will also be sought with individuals knowledgeable in these fields. Suitable algorithms will be modified or new algorithms will then be developed. Implementation will follow on engineering workstations.

As stated previously, the purpose of these metrics is to measure the discrepancies produced in generating different representations of the same area of terrain. Initially, terrain is represented by an x-y grid of elevation posts. Each vendor converts this representation into a collection of polygons for display on their Computer Image Generator (CIG). Each CIG typically utilizes a different polygonization algorithm which produces a different representation of the terrain.

Considering spatial correlation, specific discrepancies can occur during the modelling process which will also produce different terrain representations. Geometric correlation errors that may arise are shifts, skews, warping, and subsampling. Shifts arise when one terrain representation is translated either vertically or horizontally with respect to the original terrain. The former will produce a misalignment of latitude or longitude while the latter will produce a disagreement in elevation between databases. Skewing involves a rotation of the database along any vertical or horizontal axis. This will also produce disagreement in latitude, longitude, or elevation. Warping arises when converting from a flat-earth representation to a geodetic or other round-earth coordinate system. This can produce disagreement in latitude and longitude as well. Subsampling errors occur when elevation data for one database is sampled at a lower frequency than another terrain database. Subsampling can eliminate critical terrain features or produce features that did not exist in the original terrain. For example, widely spaced elevation measurements of hilly terrain may polygonize to a plateau.

Implementation of the spatial correlation metrics will be based on the extent to which a specific metric can detect the discrepancies

3

described above. Once algorithms are developed, prototypes will be implemented on engineering workstations. These prototypes will be evaluated on the number and type of correlation errors detected. The most successful prototypes will be converted into two metric suites. A metric suite is considered to be a collection of software procedures to read a portion of the terrain database, convert the data into appropriate data structures, compute the metrics, and provide a summary. These two metric suites will be developed for use strictly on engineering workstations and then for use with engineering workstations interfacing with computer image generators if funds and schedule permits.

Additional metrics will be developed which quantify differences in rendered images. A literature search will be conducted to locate image correlation methods which may be appropriate to CIGs. Existing image correlation methods obtained from the literature search will be analyzed and modified, if necessary and practical, to be applicable to the CIGs. Additional correlation methods will be developed by IST if funds and schedule permit. IST will also analyze correlation methods provided to IST by Loral. Loral's methods will be converted into algorithms, suitable for implementation on a digital computer if funds and schedule permit.

The primary emphasis on rendered image correlation algorithms will be to identify differences in scene content (based on the aggregate scene) to any degree desired by the operator, to identify scene shifts (translational and rotational), scene magnification, and the effects of specific image generator processes (e.g., LOD, smooth surface shading, etc.).

The entire set of correlation algorithms for data bases and rendered images will be analyzed for their practicality in actual experimentation. IST anticipates that certain algorithms may have to be discarded because of the need for specialized measurement equipment, the lack of statistical significance, inability to measure because of CIG limitations, inability to integrate results into a cohesive metric, or lack of control parameters.
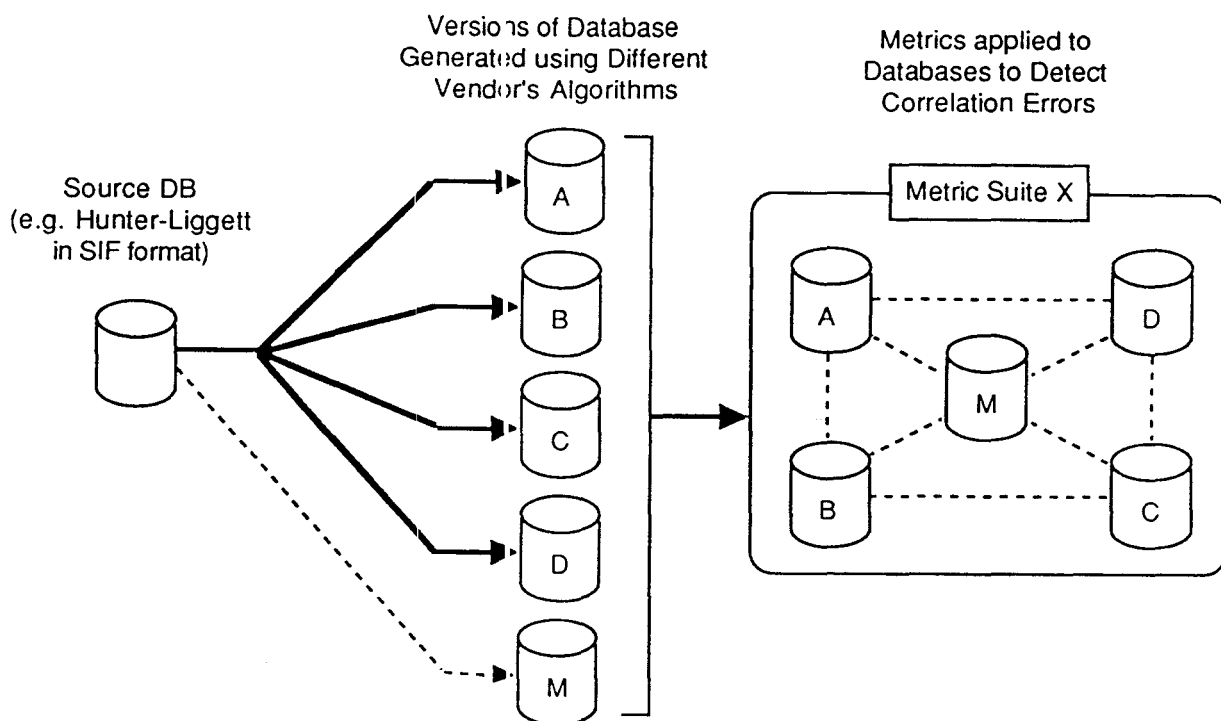
Figure 1: Data Collection and Testing Process

4.3 Testing and Data Collection

Terrain databases used for testing must be modelled after the same gaming area but produced for different Computer Image Generators (CIGs). Data collection for spatial correlation studies will proceed in several steps as shown in Figure 1. Initially, a database will be obtained to serve as the reference database to which all comparisons can be made. Next, this source database will be used to generate new databases using different polygonization algorithms. These algorithms will be similar to those used by various CIG vendors to prepare databases for display on their hardware.

Optimally, multiple sets of databases should be generated in this manner to test the soundness of the metrics. The first set of databases, referred to as Set A, will be prepared from the Hunter-Liggett SIF database produced for the 1992 I/ITSC. Set A will be generated under controlled conditions using MultiGen and S1000 database modelling tools which utilize multiple polygonization algorithms. For the second set of databases (Set B), IST will attempt to access individual vendor representations of the Hunter-Liggett database from the 1992 I/ITSC

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conference. If time and resources permit, additional sets will be produced. More details for database acquisition and processing will be provided in the Database Plan Document.

Testing will be conducted in several stages. First, prototypes will be evaluated using the first database set generated using MultiGen and the S1000 tools. The multiple polygonization algorithms used by these tools will assist in the evaluation of the metric prototypes in detecting spatial correlation errors. The vendor versions of Hunter-Liggett, if available, will then be used as a second battery of tests. Testing of the two metric suites will begin on engineering workstations at IST using the multiple database sets. Testing of the metrics will be continued by Loral on CIGs provided by Loral with support from IST if funds and schedule permit. The details of this test plan will be specified in a Test Plan Document.

IST will use the opportunity afforded by the 1992 I/ITSC to gather data for subsequent analysis. An interoperability demonstration of Distributed Interactive Simulation and Project 2851 is being conducted at the 1992 I/ITSC. This demonstration affords IST the opportunity to reduce efforts in building data bases specifically for this project. For I/ITSC 1992, a data base is being developed of a specific area of Fort Hunter-Liggett which is 100 km x 100 km. The data base has been divided into two sections; one 10 km x 30 km high detail area and the remaining 9700 square kilometers of lower detail. The high detail area is the only area where ordnance may be delivered to the ground and the only area where ground units may maneuver. SIMNET data is the source data base which is being converted to SIF. SIF data bases will contain gridded and polygonal representations of the terrain. Vendors have obtained the SIF data and are converting the data base into their own format. Vendors have been requested to match the SIF high detail polygonal representation to within one meter. The remainder of the data base can be based upon the gridded or polygonal SIF data.

IST will create specific experiments which take advantage of this data gathering opportunity. IST will attempt to gather data pertinent to the data base and rendered image portions of this task. The extent of data gathering will be dependent upon the willingness of vendors to comply with IST's request, pre-I/ITSC schedule coordination with vendors, and I/ITSC demonstration scheduling. Basically, IST will

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request data tapes of the data base in various stages of processing by an image generator. IST will supply the media for recording. With regards to the rendered images, IST will acquire a camera which will be used to capture images on vendors screens. IST will specify an area within the high detail area and an area outside the high detail area. A series of photographs will be taken in each area. Specific field of view and image generator setups will be requested which are consistent with image generator capabilities. All data will be subsequently analyzed by IST.

4.4 Analysis and Reporting

All phases of this study will be summarized in a final report. Data collected during the testing will be examined for detection of differences in terrain databases arising from polygonization algorithms used or modelling errors such as shift, skew, warping, or subsampling. The final report will include a discussion of the literature search, justification of the algorithms selected, results of the prototype implementation and selection, and analysis of the tests of the two metric suites with engineering workstations and Computer Image Generators.

An interim report will be provided to Loral after development of the metric suites. This report will describe the algorithms used by the metrics for detecting correlation errors.

5.0 Task Descriptions

A description of the individual tasks within this study are described below:

<u>Task 1.0</u> Project Plan Development

This task includes the project plan development summarized in this document.

> **Deliverable:** Project Plan Document

Task 2.0 Test Plan Development

Test plan development includes detailed specification of scenarios and a test matrix. This scenario and test matrix will be used in the selection of prototypes for implementation into the first and second metric suites and for evaluation of these metric suites when used with image generators. Dr. Mark Johnson (Department of Statistics/UCF) will be consulted. Details of the test plan will be summarized in a Test Plan Document.

Deliverable: Test Plan Document

Task 3.0 Database Conversion to Image Generator (IG)

Subtask 3.1 Study and Plan

Requirements for the databases to be used throughout this study will be developed at this point. These requirements will be applied to the small sample database used for evaluation of metric prototypes and for versions of the Hunter-Liggett database used for evaluation of the metric suites. The Database Plan Document will summarize these requirements.

Deliverable: Database Plan Document

Subtask 3.2 Create Databases for Prototype Testing

Subtask 3.2.1 Prepare Source Database (Set A & B)

The source database for Set A and Set B will be prepared from the Hunter-Liggett SIF database produced for I/ITSC 1992.

Subtask 3.2.2 Generate Test Databases (Set A)

The first database set, Set A, will be generated from the source database in Subtask 3.2.1 using the multiple polygonization algorithms available in MultiGen and the S1000 tool set.

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Subtask 3.3 Collect Database from ITSC Vendors (Set B)

Versions of the Hunter-Liggett database used at the 1992 I/ITSC will be obtained from different vendors. Data collected from this effort will serve as Set B of the databases used in testing the correlation metrics.

Task 4.0 Metric Development and Implementation

Subtask 4.1 Literature Survey

A literature survey in the areas of statistical theory and image processing will be conducted to explore correlation algorithms used in these fields.

Subtask 4.2 Algorithm Gathering and Survey

Subtask 4.2.1 Selection of Candidate Algorithms

Algorithms discovered through the literature search in addition to newly developed algorithms will be considered for prototyping at this time. Discussion of the candidate metrics will be conducted with Dr. Mark Johnson (Department of Statistics/UCF) and Dr. Weili Luo (Department of Physics/UCF) to ensure a sound statistical basis. Discussion of correlation algorithms will also be conducted with Drs. Moshell and Clarke of IST to ensure an independent evaluation of the technical soundness of algorithms selected for further evaluation.

Subtask 4.2.2 Prototype Implementation

Metrics selected for evaluation will be implemented as prototypes. An analysis tool such as Khoros from the University of New Mexico will be used to reduce the time spent in creating the prototypes.

Subtask 4.2.3 Prototype Evaluation

The prototypes will be evaluated based on their ability to detect differences in polygonization algorithms and modelling errors

such as shifts, skews, warping, and subsampling. These criteria will be elaborated upon within the Test Plan Document.

Subtask 4.3 Algorithm Selection

Based on criteria specified in the Test Plan Document, two groups of metric prototypes will be selected for implementation as the metric suites.

Subtask 4.4 Algorithm Implementation

Subtask 4.4.1 Algorithm Implementation for Workstations

The first metric suite will be coded in C for use on engineering workstations (Subtask 4 4.1.1). The coding of the second metric suite will follow (Subtask 4.4.1.2).

Subtask 4.4.2 Algorithm Implementation for Image Generators

With time permitting, IST will support Loral in modifying the first metric suite for use with Computer Image Generators (Subtask 4.4.2.1) followed by a similar modification for the second metric suite (Subtask 4.4.2.2).

Task 5.0 Metrics Applied to Databases

Subtask 5.1 Metrics Applied to Databases on Workstations

The first metric suite will be run on the versions of the Hunter-Liggett database using engineering workstations (Subtask 5.1.1). The second metric suite will then be run on the same databases (Subtask 5.1.2).

Subtask 5.2 Metrics Applied to Databases on Image Generators

With time permitting, IST will support Loral in application of the first metric suite using Computer Image Generators (Subtask 5.2.1) followed by application of the second metric suite (Subtask 5.2.2).

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<u>Subtask 5.3</u> Metrics Applied to Rendered Images

IST will implement the algorithms from Subtask 4.3 on workstations. IST will also digitize images obtained during the I/ITSC. The implemented algorithms will be applied on the digitized images.

<u>Task 6.0</u> Analysis and Reporting

<u>Task 6.1</u> Monthly Technical Reports

A technical summary of the work to date will be provided in the form of a written document at the end of each month.

Deliverable(s): Monthly Technical Reports

<u>Task 6.2</u> Interim Report

An interim report will be produced which describes the algorithms used in the metric suites for detecting correlation errors.

Deliverable: Interim Report

<u>Task 6.3</u> Test Results and Final Report

Results of running the metric suites will be analyzed for their ability to detect the correlation errors described previously. These results will be summarized with all previous tasks in the Final Report.

Deliverable: Final Report

6.0 Schedule

The attached document provides a schedule indicating completion of tasks and generation of deliverables.

Correlation Study for Loral ADST

	1992				1993							
	October	November	December	January	February	March	April	May	June	July
	7 14 21 28	4 11 18 25	2 9 16 23 30	6 13 20 27	3 10 17 24	3 10 17 24 31	7 14 21 28	5 12 19 26	2 9 16 23 30	7 14

- **1.0 Project Plan Development** — Project Plan Document delivered
- **2.0 Test Plan Development** — Test Plan Document delivered
- **3.0 Database Development & Acquisition**
  - **3.1 Study & Plan** — Database Plan Document delivered
  - **3.2 Create DBs for Prototype Testing**
    - 3.2.1 Prepare Source DB (Set A & B)
    - 3.2.2 Generate Test DBs (Set A)
  - **3.3 Collect DB from ITSC Vendors (Set B)**
- **4.0 Metric Development & Implementation**
  - **4.1 Literature Survey**
  - **4.2 Algorithm Gathering and Study**
    - 4.2.1 Selection of Candidate Algorithms
    - 4.2.2 Prototype Implementation
    - 4.2.3 Prototype Evaluation — 1st & 2nd Metric Suites Selected
  - **4.3 Algorithm Selection**
  - **4.4 Algorithm Implementation**
    - 4.4.1 For Workstations
      - 4.4.1.1 1st Metric Suite
      - 4.4.1.2 2nd Metric Suite
    - 4.4.2 For Image Generators
      - 4.4.2.1 1st Metric Suite
      - 4.4.2.2 2nd Metric Suite
- **5.0 Metrics Applied to Data Bases**
  - **5.1 Spatial Corr. Metrics On WorkStations**
    - 5.1.1 1st Metric Suite
    - 5.1.2 2nd Metric Suite
  - **5.2 Spatial Corr. Metrics On IGs**
    - 5.2.1 1st Metric Suite
    - 5.2.2 2nd Metric Suite
  - **5.3 Metric Applied to Rendered Images**
- **6.0 Analysis and Reporting**
  - **6.1 Monthly Technical Reports**
  - **6.2 Interim Report (Desc. of Metrics)** — Interim Report delivered
  - **6.3 Test Results/Final Report** — Final Report delivered

Shaded Areas Indicate Work Completed to Date

Institute for Simulation and Training

Thursday, October 29, 1992

Appendix   B

Test/Database   Plan

Loral Visual Data Base Correlation Project
Contract SO-242894-T

Test Plan

presented by

Mark C. Kilby
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January 1, 1993

1.0 Introduction

This document describes the test procedures for correlation metric development. These metrics are part of the image and geometric correlation research in support of the BDS-D Delivery Order "BDS-D Architecture Definition and DIS Standards Development". These studies, to be performed by the Institute for Simulation and Training (IST), are called "Correlation Studies". Please refer to the Correlation Project Plan for an overview of the proposed research.

1.1 Purpose

With increasing connectivity among simulators, perception of a common gaming area is critical for effective training exercises. As individual players or teams of players are networked for the same training exercise, the databases which represent the gaming environment must correlate to some degree with databases of other players in the exercise. These studies intend to measure this correlation among databases used for networked simulators to determine if a level playing field exists among the participants. Two approaches will be employed in this effort. One approach involves the measurement of correlation between the geometry represented by the databases. This is referred to as spatial correlation. The second approach, described as image correlation, consists of comparing displayed images of the same scene from multiple Computer Image Generators (CIGs).

1.2 Scope

This document describes the test procedures used in evaluating the correlation metrics developed in this study. This description also includes an explanation of data collection and generation techniques. Therefore, the Database Plan previously mentioned within the Project Plan is included within this document.

This test plan may be subject to modification if unanticipated results occur during testing that require further investigation, the utility of certain tests or metrics appear minimal, or the execution of tests or metrics appear infeasible due to an availability of resources

This document also provides a brief description of the metrics under study. These metrics are summarized in the appendix. A more detailed description of the metrics will be provided in the Interim Report.

1.3 Assumptions

As described previously, the correlation studies will be conducted in two areas. The first effort will study correlation of images taken from multiple CIGs. The second stage of the study will concentrate on comparisons of the geometric data used to construct the images. This second stage is referred to as spatial correlation. For both stages, the objective is to measure the discrepancies between two "similar" data sets. The term "similar" refers to the assumption that both data sets have been developed to represent the same data. For image correlation, the data sets are represented by images captured from the screen of an image generator. In the case of spatial correlation, the data set is represented as a geometric database which represents an area of terrain or some subregion.

All data used for these tests originates from the Project 2851 SIF data provided by the U.S. Air Force and PRC for the interoperability demonstration at the 1992 Interservice/Industry Training Systems and Education Conference (I/ITSEC). Databases generated or acquired for testing of spatial correlation metrics will be derived from this original SIF database. Images collected for image correlation studies were produced by photographing displayed scenes of the SIF database on CIGs at the 1992 I/ITSEC conference. For additional information on the databases and images obtained from this conference, please refer to the Project Plan.

1.4 Criteria

Criteria refers to the standards upon which the metrics will be evaluated. In, general, the following criteria will be employed to evaluate the effectiveness of the metrics used in measuring image and spatial correlation. When two similar data sets (i.e. images or geometric visual databases) are compared, the metric must be able to:

      (1) indicate when discrepancies are present;
      (2) indicate the type of discrepancy;
      (3) indicate the magnitude of the discrepancy; and,

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(4) locate where the discrepancy occurs (spatial correlation only).

1.5 Test Methods

All tests will be conducted on engineering workstations unless otherwise indicated. All data used in testing will be ported to the engineering workstation on which the metrics are being developed.

2.0 Image Correlation Tests

2.1 Overview

The purpose of the image correlation metrics is to provide a measure of the discrepancies between two similar rendered images. In particular, the image correlation tests will focus on the scene content of the rendered images. To measure such discrepancies, one must be aware of the types of errors that can be induced in the images In the context of scene content, the discrepancies that will be examined are scene shifts (both rotational and translational), scene magnification, and effects due to image generator processes (LOD, haze, etc.). The image correlation metrics under study are summarized in the appendix.

2.2 Data Generation and Collection

Data generation and collection will be pursued in two phases. The first phase will create a control set in which discrepancies can be induced in images in a controlled manner. This data set will allow evaluation of the effectiveness of the image correlation metrics in detecting different types and magnitudes of discrepancies. The second phase of the data acquisition process will involve collection of rendered images from CIGs. This set will be used to evaluate the effectiveness of the metrics in a CIG operational environment.

Set A Images

The first phase of the test procedure will begin with the generation of simple images for testing of the image correlation metrics. These will be referred to as Set A test images. These images will be used to induce CIG-independent discrepancies such as translations, rotations, and dilations. The simple images to be generated are:

1) A black square on a white background,
2) A black circle on a white background,
3) A black cross on a white background, and
4) A black and white checkerboard.

Each object in the simple images listed above will be centered on the image and no larger than fifty percent of the smallest display resolution value. This object size is selected to prevent losing part of the image when discrepancies such as rotations are introduced. The set of images listed above will be referred to as Set A Source Images.

Additional images will be generated from this simple set of images to induce specific discrepancies into the data sets. The type of discrepancies and magnitude are listed in Table 1.

Discrepancy	Magnitude
Translation - as a percentage of the smallest resolution value	1%, 5%, 10%, 25%
Rotation - counterclockwise about an axis through the center of the image - excludes circle image	1°, 3°, 5°, 10°, 15°, 30°
Dilation (Magnification)	75%, 50%, 25%, 10%

Table 1: Induced Discrepancies and Magnitudes in Set A Images

This set of images will be referred to as the Set A Error Images. All images will be stored as Encapsulated Postscript (EPS) files with a resolution of 320 by 240 pixels. This resolution is chosen to match the resolution of the images in the next phase of the data collection process.

Set B Images

Additional data was collected through the opportunity afforded by the 1992 I/ITSEC conference and represents the second phase of the data collection process. The images collected in this phase will be referred to as Set B images and are still photographs which were taken of images rendered by CIGs. A selection of vendors participating in the interoperability demonstration were requested to position the eyepoint of their CIG at the following locations and under the specified conditions:

    FQ7080 (UTM), 2 meters above the terrain. The bearing of a
    ray emanating from the eye point is 125 degrees clockwise from
    North (i.e. looking ESE). The orientation of the viewing plane
    should be perpendicular to the polygon at the Nadir to the eye

point. The field of view should be 20 degrees horizontal by 15 degrees vertical. The time of day is noon with no haze.

FQ6050 (UTM), 2 meters above the terrain. The bearing of a ray emanating from the eye point is 90 degrees clockwise from North (i.e. looking ESE). The orientation of the viewing plane should be perpendicular to the polygon at the Nadir to the eye point. The field of view should be 20 degrees horizontal by 15 degrees vertical. The time of day is noon with no haze.

Where possible, additional photographs were taken at the same locations with variations of CIG processes such as time of day, haze, texture, and fading.

2.3 Test Procedures

Testing of the image correlation metrics will proceed in two phases corresponding to the two sets of data described in the previous section.

2.3.1 Phase 1 - Set A Images/Controlled Testing

For each metric being evaluated, the test procedure for the Set A images is as follows:

1) Begin with translational discrepancies.
2) Apply the metric to the Set A Source Image and the Set A Error Image with the smallest known discrepancy value. Record the result of the metric.
3) Repeat step (2) for successively larger discrepancies.
4) Evaluate the range of results from the metric based on the range of the induced discrepancy and determine if a relationship exists.
5) Repeat steps (2), (3), and (4) for rotational and dilational discrepancies.
6) Evaluate the range of metric values for each error induced and determine if different types of errors can be differentiated based on their metric value.

2.3.2 Phase 2 - Set B Images/Rendered CIG Images

For each metric being evaluated, the test procedure for the Set B images is as follows:

1) Begin with images corresponding to location FQ7080 (UTM).
2) Apply the metric to two images from different vendors corresponding to the same location and same environmental conditions (i.e. noon, no haze, no fading). Record the result of the metric.
3) Repeat step (2) until all vendors' images have been compared.

4) Based on results of the Phase 1 Image Correlation Tests, determine the types
   of discrepancies that exists between images from different CIGs.
5) Apply the metric to two images from the same vendor at the same location.
   One image should represent a base condition (noon, no haze, no fading) and
   the other image should turn on one of the CIG features such as time of day,
   haze, fading, or texture. Record the result of the metric.
6) Evaluate the range of metric values based on the types of CIG processes
   employed.
7) Repeat steps (2) through (6) for images corresponding to location FQ5060
   (UTM).

2.4 Analysis and Reporting

Phase A tests will be used in determining metrics to be tested in Phase B.
These results of Phase A will be summarized in the Interim Report including a
description of the metrics that were selected. All remaining analysis and
conclusions will be summarized in the Final Report.

3.0 Spatial Correlation Test Procedures

3.1 Overview

Spatial correlation metrics are designed to measure the geometric discrepancies
that arise between visual databases. The terrain serves as the foundation for
the visual database since all other data is referenced to the terrain. Therefore,
correlation of culture and three-dimensional models is difficult to obtain unless
the terrain from two visual databases has been correlated to some acceptable
level and any discrepancy in terrain representations has been quantified. With
this in mind, tests on the spatial correlation metrics will focus primarily on
terrain.

Specific discrepancies that can occur during generation of terrain
representations include polygonization, shifts, skews, warping, and
subsampling. Based on the algorithm used to convert terrain data from an
elevation grid to a polygonal representation, significantly different terrain can
be produced. Shifts arise when one terrain representation is translated either
vertically or horizontally with respect to the original terrain. The former will
produce a misalignment of latitude or longitude while the latter will produce a
disagreement in elevation between databases. Skewing involves a rotation of
the database along any vertical or horizontal axis. This will also produce
disagreement in latitude, longitude, or elevation. Warping arises when
converting from a geodetic or other round-earth coordinate system to a flat-
earth representation such at Universal Transverse Mercator (UTM). This can
produce disagreement in latitude and longitude as well. Subsampling errors

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occur when elevation data for one database is sampled at a lower frequency than another terrain database. Subsampling can eliminate critical terrain features or produce features that did not exist in the original terrain. For example, widely spaced elevation measurements of hilly terrain may polygonize to a plateau.

Certain discrepancies, such as shifts and skews, can occur on either a global or local scale. In the case of shifts, a global shift would correspond to all points in the database being uniformly translated with respect to the corresponding points in the other database. A local shift would only include the translation of a small subset of features in one terrain database being translated with respect to the same features in another database. Analogously, a global skew refers to a uniform rotation of one database with respect to another while a local skew refers to features of one database being rotated with respect to features in another database. These local discrepancies could be detected by the same metrics used to measure global effects by successively subdividing the terrain databases into smaller regions and performing comparisons. Correlation metrics to measure discrepancies in culture and three dimensional models could be adapted from such local correlation measurements.

Testing of the spatial correlation metrics will proceed in three phases. The first two phases will be conducted on engineering workstations. This approach allows for a small iteration loop between metric development and testing. The third phase, if time and resources permit, will consist of running the metrics on CIGs and databases provided by Loral. This approach will demonstrate the applicability of the metrics on simulation hardware in the field where workstations and other support equipment for visual database construction may not be available. The metrics under study for spatial correlation are summarized in the appendix.

3.2 Data Generation and Collection

As with image correlation, data collection for spatial correlation tests will proceed in multiple phases. The first phase produces a collection of terrain databases, referred to as Set A Databases, with induced errors under controlled conditions. This allows the metrics to be evaluated on their effectiveness in detecting different types, magnitudes, and locations of correlation errors between the databases. The second phase will consist of collections of terrain databases used by participants in the interoperability demonstration at the 1992 I/ITSEC conference and will be labeled Set B databases. For this phase, the metrics can be evaluated on databases produced specifically for networked simulations. The third phase of the database generation and collection process involves production of "flyable" databases for use on CIGs at Loral ADST. This set will be referred to as Set C.

For rapid development of the metrics, all databases in Set A and Set B will be converted to IST's Anim and Elev formats. The Anim format is a polygonal format while the Elev format represents the database as an elevation grid. Both of these formats are used for metrics that test databases in either of these two representations. Furthermore, tools have previously been developed at IST to convert other database formats into these representations. When converting a database to Elev format, the same elevation grid post spacing will be used as in the master SIF database.

Set A Databases

All databases in this set originate from the SIF version of the Hunter-Liggett database provided by the U.S. Air Force and PRC for the 1992 I/ITSEC conference. This database serves as the master database. First, three databases are generated which each use a different polygonization algorithm: MultiGen-PolyMesh, MultiGen-Delaunay, and S1000/SIMNET. These databases will be referred to as the Set A Source Databases and represent "CIG-like" databases.

The procedure for generating the Set A Source Databases are as follows:

1) Run the MultiGen Flight application software.
2) Using the terrain option of MultiGen, read in the elevation grid data for the SIF version of the Hunter-Liggett database.
3) Convert the elevation grid to a polygonal representation using the following preferences
       - post spacing = 1
       - projection type = UTM
       - Polygonization Algorithm: Delaunay
       - Tolerance = 0
This produces the first of the Source Databases. A post spacing of one and zero tolerance ensure that all elevation grid posts are used to generate polygons and that effects from terrain relaxation are eliminated.
4) Repeat step (3) using the PolyMesh algorithm instead of Delaunay. This produces the second Source Database.
5) Quit MultiGen and run the S1000 Land tool.
6) Generate the SIMNET polygonal terrain using the following preferences
       - post spacing = 1
       - projection type = UTM
       - Terrain Relaxation: OFF
       - Epsilon = 0
This produces the third of the Source Databases.
7) Convert the three databases into both IST's Anim and Elev database file formats.

6) Generate a new Anim format database from the Anim Source Database by rotating 0.5° about the X axis.
7) Generate an Elev format database from the rotated Anim database in step (6).
8) Repeat steps (6) and (7) for 1°, 10°, and 30°.
9) Repeat steps (6), (7), and (8) for rotations about the Y and Z axes.

To generate Set A Error Databases with warping discrepancies, the following procedure will be followed:

1) Run the MultiGen Flight application software.
2) Using the terrain option of MultiGen, read in the elevation grid data for the SIF version of the Hunter-Liggett database.
3) Convert the elevation grid to a polygonal representation using the following preferences
  - post spacing = 1
  - projection type = Lambert
  - Polygonization Algorithm: Delaunay
  - Tolerance = 0
4) Convert the file into IST's Anim and Elev file formats.
5) Repeat step (3) and (4) for a Flat Earth Projection and a Flat Earth Skewed Projection.

To generate Set A Error Databases with sampling discrepancies, the following procedure will be followed:

1) Run the MultiGen Flight application software.
2) Using the terrain option of MultiGen, read in the elevation grid data for the SIF version of the Hunter-Liggett database.
3) Convert the elevation grid to a polygonal representation using the following preferences
  - post spacing = 2
  - projection type = UTM
  - Polygonization Algorithm: Delaunay
  - Tolerance = 0
4) Convert the file into IST's Anim and Elev file formats.
5) Repeat step (3) and (4) for a post spacing of 3, 5, and 10.

Set B Databases

The databases in this set will consist of the databases used by participants in the 1992 I/ITSEC interoperability demonstration. At a minimum, IST will request that vendors deliver a version of the high detail area of the Hunter-Liggett

Additional databases are generated which induce specific types of errors and discrepancies. These databases will be referred to as Set A Error Databases. The type of discrepancies induced and their magnitude (i.e. shifts, skews, sampling) or representation (i.e., warping) are listed in Table 2. Where references are made to X, Y, and Z axes, these can be considered as axes parallel to a line of latitude, longitude, or elevation, respectively.

Discrepancy	Magnitude/Version
Shift - in meters - separate databases generated for translation along X, Y, and Z axes	0.5m , 1.0m, 10.0m, 100m, 1000m
Skew - in degrees - separate databases generated for rotation along X, Y, and Z axes	0.5°, 1.0°, 10°, 30°
Warping	Lambert, UTM, Flat Earth
Sampling - posts per sample	1, 2, 3, 5, 10

Table 2: Induced Discrepancies and Magnitudes/Versions in Set A Databases

The projections used for inducing warping discrepancies are available in MultiGen. The Lambert and Universal Transverse Mercator Projections are standard projections whose algorithms are described in the military handbook MIL-HDBK-600008, "Transformation of Datums, Projections, Grids and Common Coordinate Systems", available from the U.S. Army Engineering Topographic Laboratories. The Flat Earth projection uses latitude at the origin to derive a single convergence factor for adjusting every x value and results in a rectangular database.

Set A Error Databases that contain shift and skew errors can be produced directly from the Set A Source Databases using the following procedure:

1) Select a Source Database in Anim file format.
2) Generate a new Anim format database from the Source Database by translating 0.5 meters along the X axis.
3) Generate an Elev format database from the translated Anim database in step (2).
4) Repeat steps (2) and (3) for 1.0m, 10m, 100m and 1000m.
5) Repeat steps (2), (3), and (4) for translations along the Y and Z axes.

terrain in a polygonal format. Once received, these files with be converted to IST's Anim and Elev file formats

Set C Databases

Databases in Set C consist of "flight-ready" databases for CIGs located at Loral ADST. Loral will receive databases from Set A and enhance them for operation on CIGs located at the Orlando office.

3.3 Test Procedures

The test procedures will be conducted in three phases. The first phase will test the metrics on engineering workstations using the control set of databases (Set A). The second phase of testing will also be conducted on engineering workstations to study application of the metrics to databases developed for an actual interoperability exercise (Set B). The third phase, with time permitting, will consist of tests conducted directly on CIGs to show application of the metrics in a field setting (Set C).

For all tests in which discrepancies are being measured between databases, it is assumed that the metrics will utilize all terrain data from both databases being compared. Should a particular metric require samples of the database, the required sampling rates and determination of sample coordinates will be discussed in the Interim Report.

3.3.1 Phase 1 - Set A Databases/Controlled Testing

As shown previously, databases in this test set have been developed such that a single discrepancy is introduced between two databases that will be compared. Discrepancies introduced include different polygonization algorithms, shifts, skews, different cartographic projections (warping), and different sampling rates. The tests outlined in this section follow the same methodology. Tests are developed for each type of discrepancy.   In some instances, metrics are designed to detect only a single type of discrepancy or a small subset. For this reason, each metric may not undergo all of the tests described below.

Metrics that prove useful in detecting the indicated discrepancies will be included in two metric suites. A metric suite consists of a collection of metrics used to detect different types of correlation errors. The two metric suites resulting from this phase of testing will be used in subsequent phases.

3.3.1.1 Shift Error Tests

These tests are used to determine if a metric can detect relative translations between two interoperable databases. This displacement can occur along a line of latitude, longitude, or elevation. Ideally, these tests will indicate if the metric can determine that a translation has occurred, its direction, and its magnitude relative to another database. The procedure for these tests are as follows:

1) Apply the metric to the Set A Source Database and the Set A Error Database derived from the Source Database which has been translated by the smallest value along the X axis. Use either the Anim or Elev database formats depending on the input requirements of the metric. Record the result of the metric.
2) Repeat step (1) for successively larger shifts/translations along the X axis.
3) Repeat step (1) and (2) for shifts/translations along the Y and Z axes.
4) Evaluate the range of results from the metric based on the range of the induced discrepancy. Determine if the direction and magnitude of the discrepancy can be derived from the output of the metric.

The Set A Error Database is compared against the corresponding Source Database instead of the SIF Master Database to eliminate effects due to polygonization or cartographic representations.

3.3.1.2 Skew Error Tests

Similar to the Shift Tests, these tests are used to determine if a metric can detect relative rotations between two interoperable databases. Rotations can occur about a line of latitude, longitude, or elevation. These tests will indicate if the metric can determine that a rotation has occurred, its axis of rotation, and its magnitude relative to another database. The procedure for these tests are:

1) Apply the metric to the Set A Source Database and the Set A Error Database derived from the Source Database which has been rotated by the smallest value about the X axis. Use either the Anim or Elev database formats depending on the input requirements of the metric. Record the result of the metric.
2) Repeat step (1) for successively larger skews/rotations about the X axis.
3) Repeat step (1) and (2) for skews/rotations about the Y and Z axes.
4) Evaluate the range of results from the metric based on the range of the induced discrepancy. Determine if the direction and magnitude of the discrepancy can be derived from the output of the metric.

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As in the shift tests, the Set A Error Database is compared against the corresponding Source Database instead of the SIF Master Database to eliminate effects due to polygonization or cartographic representations.

3.3.1.3 Warp Error Tests

These tests indicate if the the metrics can detect if two databases have used different cartographic projection algorithms to convert from a round earth to a flat earth representation. It is assumed that the round earth representation is geodetic since the data originates from the original SIF database. The procedure for testing the metrics is as follows:

1) Apply the metric to the Set A Source Database using a UTM projection with MultiGen-Delaunay triangulation and the Source Database using the Lambert projection. Use either the Anim or Elev database formats depending on the input requirements of the metric. Record the result of the metric.
2) Repeat step (1) and replace the Lambert projection database with the Flat Earth projection and the Flat Earth Skewed projection.
3) Evaluate the range of results from the metric to determine if a difference in projections can be detected and to determine the type of projection.

3.3.1.4 Subsampling Error Tests

The purpose of these tests is to determine if miscorrelation among databases are generated by different sampling rates of terrain elevation. These tests are conducted in the order listed below:

1) Apply the metric to the Set A Source Database using a post spacing of one with MultiGen-Delaunay triangulation and the Error Database using the post spacing of 2. Use either the Anim or Elev database formats depending on the input requirements of the metric. Record the result of the metric.
2) Repeat step (1) and replace the three post spacing database with databases using post spacings of 3, 5, and 10.
3) Evaluate the range of results from the metric to determine if differences in sampling rates can be detected.

3.3.2 Phase 2 - Set B Databases/Interoperable Databases

As stated previously, these tests will be conducted on engineering workstations using databases developed for the interoperability demonstration at the 1992 I/ITSEC. The purpose of these tests is to use the results of the Phase 1 spatial correlation tests to determine what types of discrepancies may exist between the vendor databases. The application of these tests is dependent on the

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Appendix

Summary   of   Metrics

Introduction

This appendix serves as a brief summary of the metrics currently under examination for the Loral correlation project. The summary is divided into two sections. First, a brief description is provided of the metrics under study. The second section describes some additional algorithms used for preprocessing of the databases or rendered images.

Metrics

The intent of these metrics is to provide the database designer with tools to assist in construction of interoperable databases across heterogeneous hardware platforms. Ideally, these tools should be applied as early as possible in the rendering pipeline to reduce development costs. Therefore, many of these metrics are being designed with the intent of applying them before formatting for particular Computer Image Generators (CIGs). However, if this proves infeasible, some metrics may be applicable on the CIGs.

The metrics under consideration are listed below.

The Hausdorf Distance
Applicability: Rendered Image and Spatial Correlation

This method compares two sets of points in a general metric space. First, we define the distance function between a point a in set A and all the points in set B as

$$d1(a, B) = \min\{d0(a,b), \text{ for all } b \text{ belonging to set } B\}.$$

The function d0 can be a measure such as Euclidean distance defined as

$$d0(a,b) = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2}.$$

Next, we define a distance function between the two sets as

$$d2(A,B) = \max\{d1(a,B) \text{ for all } a \text{ belonging to set } A\}.$$

The Hausdorf distance is then defined as

availability of the databases from the vendors. The tests will be conducted in the following manner:

1) Convert two of the vendor databases into Anim or Elev database formats depending on the input requirements of the metric.
2) Apply the metric to the two vendor databases. Record the result of the metric.
3) Evaluate the results from the metric and, if possible, determine the type and magnitude of the discrepancy.
4) Repeat until all available Set B databases have been compared with each other.

3.3.3 Phase 3 - Set C Databases/Image Generator Tests

With time permitting, databases and metrics will be converted to operate on CIGs available at Loral ADST. As stated previously, Loral is responsible for the preparation of the databases. IST will convert the metrics to run on the host computer of the CIG. This conversion will require replacing routines that read a database file with new routines that access the on-line database of the CIG. Testing will consist of comparing the on-line database with the original SIF version of Hunter-Liggett. Details of these tests are dependent on personnel and equipment available from Loral. However, the test procedure will follow the approach listed below:

1) Load the SIF version of the database into the CIG host computer memory.
2) On the host computer, compare the on-line database against the SIF database using the available metric suites.
3) Applying the results of the Phase 1 and Phase 2 testing, determine discrepancies between the two databases.

3.4 Analysis and Reporting

Phase 1 tests will determine which metrics to be included in the metric suites used in Phase 2 and Phase 3 testing. The results of the Phase 1 testing and the conclusions that lead to the selection of metrics for the metric suites will be summarized in the Interim Report. All remaining analysis and conclusions for Phase 2 and Phase 3 testing will be summarized in the Final Report.

This metric is equally applicable to the geometric databases or the final rendered images from different CIGs. For either set of data, this metric provides a quantitative measure of the differences between the data sets.

Fourier Transform
Applicability: Rendered Image and Spatial Correlation

Algorithms for the Fast Fourier Transform (FFT) are well known and can be extended to functions of two variables. This form of the Fourier transform is often referred to as the 2D Fourier transform. A single valued difference, referred to as a norm, can be calculated that provides a measure of the differences in the two data sets in the frequency domain. For comparing rendered images, this approach can be applied to either color or intensity values. For measuring correlation among geometric databases, elevation grids can be compared. One of the benefits of using Fourier is that rotational and translational differences may be eliminated. This property is especially useful in comparing geometric databases by detecting warping errors or differences in sampling rates of the terrain.

Method of Moments
Applicability: Rendered Image and Spatial Correlation

A common tool used in statistical analysis is the mean and standard deviation of a data set. These are also referred to as the first and second moments of the data set, respectively. For purposes of this study, the data set can exist as the difference between sampled elevations in a geometric terrain database or color/intensity values in rendered images. The mean provides an indication of the average difference between the databases (geometry or rendered image). The standard deviation indicates the range of differences about the average and can be used to indicate global or local effects.

Volume Difference
Applicability: Spatial Correlation

Consider a terrain database as a function of latitude and longitude which returns an elevation value. That function can be expressed as $f(x, y)$. A second terrain database can be described similarly as $g(x, y)$. An overall measure of the discrepancy between the databases can then be given as:

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<u>Line of Sight/Intervisibility</u>
Applicability: Databases

Typically, these tests involve placing the eyepoint of two or more CIGs at identical locations in the database and determining if prespecified targets can be detected at different ranges. Based upon the mission type (i.e., air-to-air, air-to-ground, ground-based, etc.), different elevations are selected for the eyepoint. Usually, the tests consider numerous factors such as level of detail, color, lighting, and environmental effects in addition to geometry.

Support Routines

In examining geometric databases and rendered images, various algorithms for preprocessing the data sets are also under consideration.

<u>Scarlatos Methods</u>

Dr. Lori Scarlatos has developed polygonization algorithms which retain critical features within terrain databases. These features are classified as critical points (peaks and pits) and critical lines (ridge lines and valley lines). In order to reduce the amount of data to be processed by the metrics, the databases will be reduced to critical points and lines for some of the metric testing. Serving as a data compression technique, this preprocessing will allow miscorrelations to be detected throughout the database as well as in critical areas.

<u>Discrete Cosine Transforms</u>

For rendered images, various data compression techniques can also be applied. The popular JPEG image compression technique utilizes cosine transforms to reduce the amount of data.

Appendix   C

Interim   Report

CORRELATION STUDIES

Interim Report

This document is the Interim Report under Contract SO-242894-T,
sponsored by Loral Systems Company.
All opinions herein expressed are solely those of the authors.

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Loral Visual Data Base Correlation Project
Contract SO-242894-T

Interim Report

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March 5, 1993

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1.0 Introduction

This document summarizes the progress to date for correlation metric development. These metrics are part of the image and geometric correlation research in support of the BDS-D Delivery Order "BDS-D Architecture Definition and DIS Standards Development." These studies, to be performed by the Institute for Simulation and Training (IST), are called "Correlation Studies."

1.1 Purpose

As described in the Project Plan and the Test Plan documents, the first stage of this study began with a search for existing algorithms and development of prototype algorithms to measure discrepancies between rendered images or geometric terrain databases. Evaluation of these algorithms followed. This document summarizes this development and evaluation period for rendered image and geometric correlation.

1.2 Scope

The remainder of this document is organized as follows:

- Criteria
- Test Methods
- Correlation Metrics Under Study
- Proposed Metrics Not Studied
- Summary of Results
- Conclusions
- Recommendations

The Criteria section outlines the standards by which metrics were evaluated and "Test Methods" gives a brief description of the procedures used in the evaluation.

The following section, "Correlation Metrics Under Study," reviews the metrics that were prototyped and evaluated. For each metric, the algorithm is described followed by results for image correlation tests, spatial correlation tests or both. All tests in this section use the Set A images and databases as described in the Test Plan.

The section, "Proposed Metrics Not Studied," describes other metrics proposed, but not studied. A brief description of each metric's algorithm is provided with a justification for rejection of the metric.

The remaining sections summarize the results, provide conclusions, and give recommendations for the remainder of this project.

Please refer to the Correlation Project Plan for an overview of the proposed research.   The Correlation Test Plan describes the test procedures and methods of generating and collecting test data.

1.3   Criteria

Criteria refer to the standards upon which the metrics were evaluated. In, general, the following criteria were employed to evaluate the effectiveness of the metrics used in measuring rendered image and spatial correlation.   When two similar data sets (i.e., images or geometric visual databases) are compared, the metric must be able to:

(1) indicate when discrepancies are present;
(2) indicate the type of discrepancy; and,
(3) indicate the magnitude of the discrepancy.

Some of the discrepancies that can occur between rendered images include shifts (i.e., translation parallel to the image plane), skew (i.e., rotation about an axis perpendicular to the image plane), scene magnification, and effects due to image generator processes (LOD, haze, time of day, etc.).   Metrics were specifically developed to measure shifts and skews between images.   Additional metrics were developed to detect the magnitude of the discrepancy between the images, but not for a particular type of error.   Therefore, these metrics could be applicable to numerous types of miscorrelation among images.

Some of the effects producing geometric correlation errors include shifts, skews, warping, and sampling.   Shifts arise when one terrain representation is translated either vertically or horizontally with respect to the original terrain.   The former will produce a misalignment of latitude or longitude while the latter will produce a disagreement in elevation between databases.   Skewing involves a rotation of the database along any vertical or horizontal axis.   This will also produce disagreement in latitude, longitude, or elevation.

Warping arises when converting from one cartographic representation of the terrain to another.   Typical cartographic projections include Universal Transverse Mercator (UTM) and Lambert conic projections [Robinson84, Chevrier1970, and MILH91].   Tools such as MultiGen by Software Systems provide modelers with additional representations

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[MGTO92].   These different cartographic projections can produce disagreement in latitude, longitude, and elevation as well.

Sampling errors occur when elevation data for one database is sampled at a lower frequency than another terrain database.   Subsampling can eliminate critical terrain features or produce features that did not exist in the original terrain.   For example, widely spaced elevation measurements of hilly terrain may polygonize to a plateau.

Other sources of discrepancies between geometric databases include polygonization and terrain relaxation.   Polygonization refers to the specific algorithm used in converting the database from an elevation grid to a polygonal format for use on an image generator.   Various algorithms exist to generate polygons from elevation posts [Scarlatos89, MGTO92].   The most popular approach, the Delaunay algorithm, exists in multiple variations [Scarlatos89, DeFloriani87].   In particular, polygonization algorithms vary between vendors.   Terrain relaxation consists of merging multiple polygons that are close to lying in the same plane into a single polygon.   This reduces the polygon count of the database to allow traversal in real-time.   As with polygonization, the terrain relaxation algorithms exist in multiple forms and vary from vendor to vendor.

Metrics for geometric correlation were developed to measure shifts, skews, warping, and sampling discrepancies.   Additional metrics were developed to detect the magnitude of the discrepancy between the databases, but not a particular type of discrepancy.   Therefore, these metrics could be used for other types of miscorrelation between databases.   Because of the wide variety of polygonization and terrain relaxation algorithms and their lack of availability, no metrics were developed to specifically measure differences arising from these sources of error.

1.4   Test   Methods

All tests were conducted on engineering workstations unless otherwise indicated.   Data were generated and tests were conducted according to the Test Plan.   An exception to data generation procedures stated in the test plan include generation of the MultiGen databases.   Due to the size of the original MultiGen version of the Hunter-Liggett high detail area, the database was split into six segments.   Tests were then conducted on a selection of the segments.

All tests on Set A data were developed to measure parameters that were considered controllable.   As stated in the previous section, the proprietary nature of the algorithms for polygonization and terrain relaxation eliminated the possibility of measuring these types of discrepancies with the given time constraints for this research. Therefore, the tests for geometric correlation were designed to eliminate effects of terrain relaxation and polygonization.

2.0   Correlation   Metrics   Under   Study

The following metrics were considered applicable in measuring rendered image or geometric correlation.   These metrics were developed either through advice of consultants or from papers discovered during the literature search.   The literature search covered areas such as digital signal processing, image processing, statistics, artificial intelligence (e.g., pattern recognition), cartography, and visual databases.

In this section, the metric and its results in measuring correlation will be presented.   First, the algorithm is described.   Next, results for image correlation, spatial correlation, or both are presented.

2.1   MinMax   Metric

Applicability: Rendered Image and Spatial Correlation

Errors to Detect: Shifts, Skews (terrain databases and images)

Input Data Type: - elevation grid (terrain databases)
                            - array of gray-scale or color values (images)

2.1.1   MinMax   Metric   -   Algorithm

The following algorithm was developed from references collected from the literature search.

As pointed out by Scarlatos, terrain databases consist of significant features that can be considered as critical points [Scarlatos92].   These critical points are the local minima and maxima that occur throughout the database.   The local minima and maxima can be considered as peaks of mountains and pits of lakes or valleys, respectively.   Since these peaks and pits characterize a database, this metric uses this information to measure the difference between two databases.   This becomes more efficient than comparing the entire elevation grid of one database against another.   Images consisting of arrays of gray-scale or color

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values are analogous to elevation grids. Therefore, a similar approach can be used for rendered images.

To generalize the discussion, rendered images and geometric terrain databases will both be referred to as data sets. A data set will consist of points with each point located in the set by an (x, y) pair. Each point will also have a value associated with it. For databases, this value is elevation. For rendered images, this value is a color or grey-scale quantity.

2.1.1.1 MinMax Metric - Algorithm (Detecting Shifts)

One implementation of the MinMax metric seeks to measure the relative translation (i.e., shift) between one data set and another. In the algorithm below, a neighbor point refers to one of the eight points in the same database that are immediately adjacent to the point under examination. The algorithm is as follows for measuring the discrepancy between data sets A and B:

MinMax Metric - Shift Error Measuring Algorithm

1. For each point 'a' in data set A,
        if point 'a' has a greater value than its neighbors,
                record 'a' as a peak.
        Else, if point 'a' has a lesser value than its neighbors,
                record 'a' as a pit.
2. Repeat step 1 for data set B.
3. For each peak in data set A,
        find the corresponding point in data set B by calculating the distances to all peaks in data set B. The shortest distance indicates the corresponding point.
4. Repeat step 3 for pits in data set A.
5. Average the x, y, and z distances from steps 3 and 4 to give the average global shift of one data set with respect to another.

Steps 3 and 4 above assume that the smallest distance from a point in data set A to a point in data set B indicates that these points represent the same location in both data sets.

2.1.1.2 MinMax Metric - Algorithm (Detecting Skews)

A second variation of the MinMax metric measures the relative rotation (i.e., skew) between one data set and another. This algorithm extracts the peaks and pits as in the algorithm above. To determine the angle of

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rotation between the data sets, a pair of corresponding peaks (or pits) are selected in both data sets to serve as vectors. The vector dot product is then used to calculate the angle. The algorithm is described as:

MinMax Metric - Skew Error Measuring Algorithm

1. For each point 'a' in data set A,
   if point 'a' has a greater value than its neighbors,
       record 'a' as a peak.
   Else, if point 'a' has a lesser value than its neighbors,
       record 'a' as a pit.
2. Repeat step 1 for data set B.
3. For each peak in data set A,
   find the corresponding point in data set B by calculating the distances to all peaks in data set B. The shortest distance indicates the corresponding point.
4. Repeat step 3 for pits in data set A.
5. Select a pair of peaks/pits in data set A and form a vector.
6. Repeat step 3 for a corresponding pair of peaks (i.e. nearest neighbors) in data set B.
7. Calculate the angle between the two vectors to determine the skew between the databases.

2.1.2   MinMax   Metric - Image   Correlation   Results

2.1.2.1   MinMax   Metric - Image   Correlation   Results
(Shift   Error   Tests)

In examining Figures 2.1.2.1-1 through 2.1.2.1-8, the metric appears to
perform sporadically in measuring translations between images.   For
most of the tests, a relative magnitude appears to be indicated.
However, for some cases, the wrong axis is indicated (e.g., Fig. 2.1.2.1-2
and Fig. 2.1.2.1-7) or the axis of shift is difficult to tell (e.g., Fig. 2.1.2.1-1
and Fig. 2.1.2.1-5).   In general, the performance of the metric is
unsatisfactory.

FIG 2.1.2.1-1: MinMax Metric - Measurement of Shift-X Errors in Set A Images (Cross)
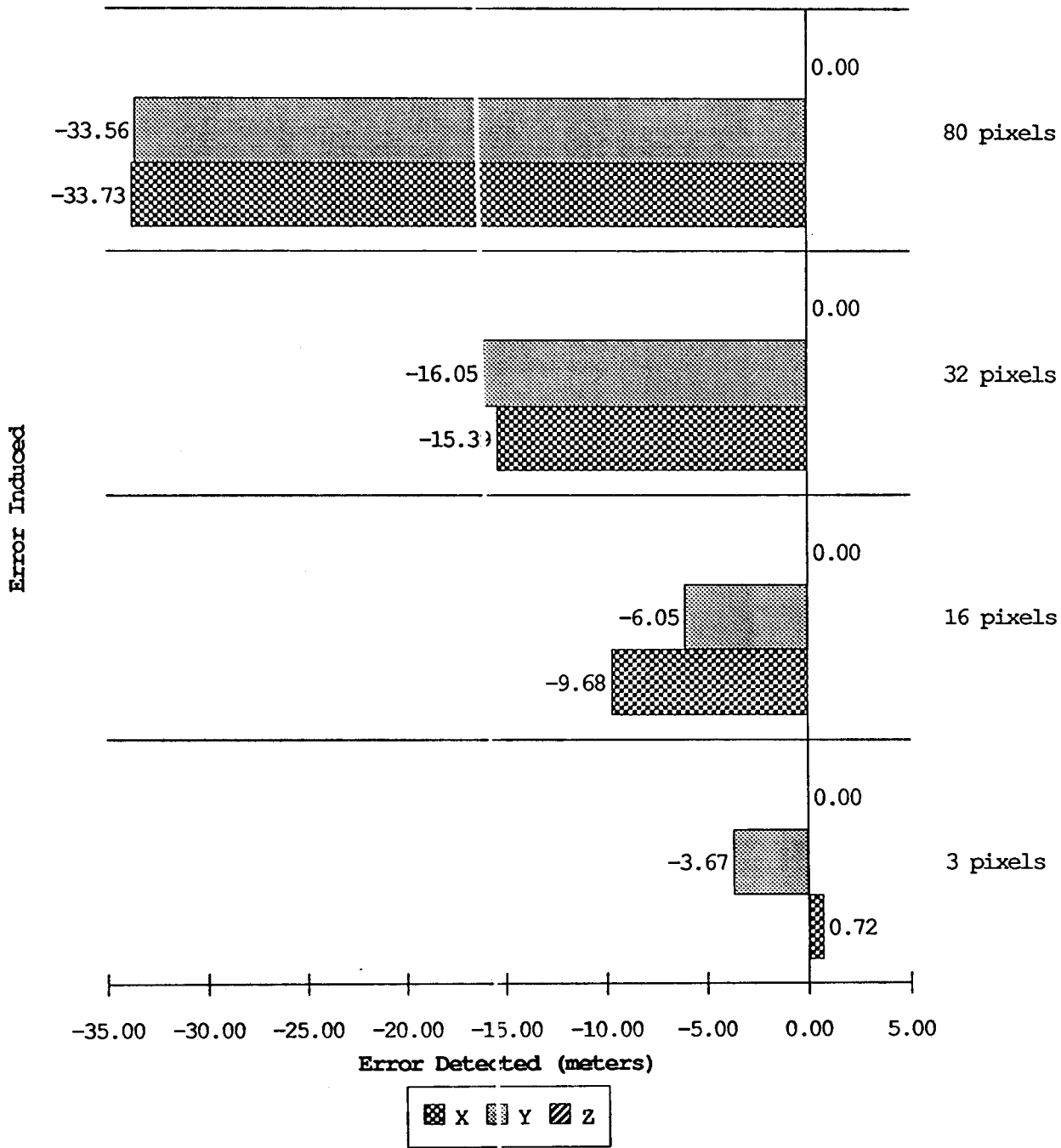
FIG 2.1.2.1-2: MinMax Metric - Measurement of Shift-X Errors in Set A Images (Checkerboard)

Error Induced

80 pixels
- 0.13
- −43.99
- −13.66

32 pixels
- 0.13
- −29.82
- −7.90

16 pixels
- 0.13
- −21.18
- −3.04

3 pixels
- 0.13
- −15.89
- 0.52

X-axis: −45.00 −40.00 −35.00 −30.00 −25.00 −20.00 −15.00 −10.00 −5.00 0.00 5.00

Error Detected (meters)

Legend: X Y Z

FIG 2.1.2.1-3: MinMax Metric – Measurement of Shift-X
Errors in Set A Images (Square)

Legend: X Y Z

X-axis: Error Detected (meters)
Y-axis: Error Induced

FIG 2.1.2.1-4: MinMax Metric – Measurement of Shift-X Errors in Set A Images (Circle)

Error Induced (vertical axis)

- **80 pixels**: 0.43, −14.57, −20.14
- **32 pixels**: 0.42, −18.58, −30.25
- **16 pixels**: 0.42, −7.58, −19.50
- **3 pixels**: 0.42, −10.75, −10.92

Horizontal axis: −35.00 −30.00 −25.00 −20.00 −15.00 −10.00 −5.00 0.00 5.00

Error Detected (meters)

Legend: X Y Z

FIG 2.1.2.1-5: MinMax Metric – Measurement of Shift-Y Errors in Set A Images (Cross)

FIG 2.1.2.1-6: MinMax Metric – Measurement of Shift-Y
Errors in Set A Images (Checkerboard)

Error Induced

0.14	
−78.77	80 pixels
−1.15	
0.13	
−34.49	32 pixels
−0.11	
0.13	
−23.30	16 pixels
0.27	
0.13	
−17.82	3 pixels
0.79	

−80.00 −70.00 −60.00 −50.00 −40.00 −30.00 −20.00 −10.00 0.00 10.00

Error Detected (meters)

X Y Z
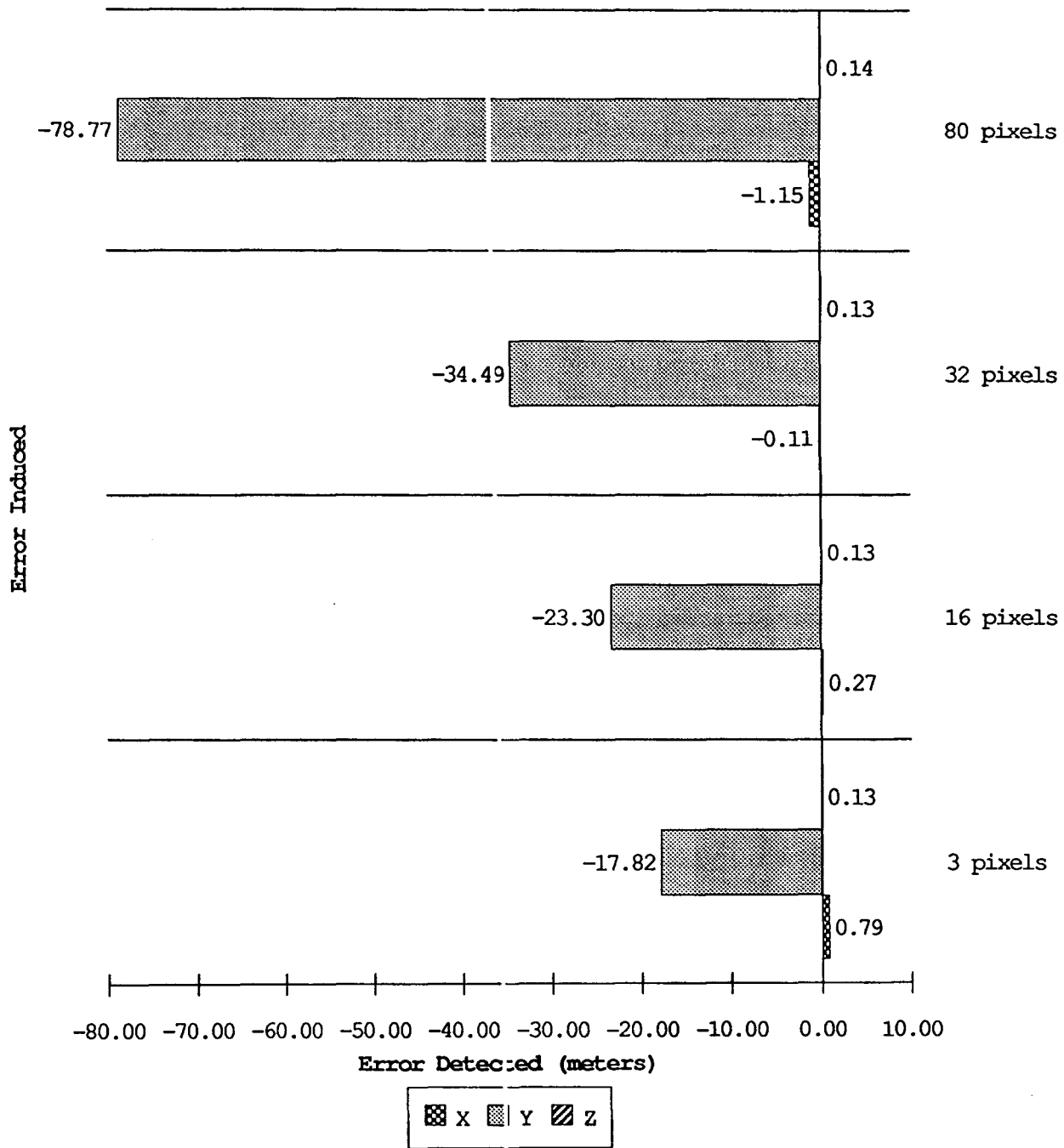
FIG 2.1.2.1-7: MinMax Metric - Measurement of Shift-Y Errors in Set A Images (Square)

Legend: X Y Z

Y-axis: Error Induced

X-axis: Error Detected (meters)

Data points:
- 80 pixels: 0.43, −76.43, 2.43
- 32 pixels: 0.43, −35.29, 2.43
- 16 pixels: 0.43, −21.57, 2.43
- 3 pixels: 0.43, −10.43, 2.43

X-axis scale: −80.00 −70.00 −60.00 −50.00 −40.00 −30.00 −20.00 −10.00 0.00 10.00

FIG 2.1.2.1-8: MinMax Metric - Measurement of Shift-Y Errors in Set A Images (Circle)

Horizontal bar chart. X-axis: Error Detected (meters), ranging from -80.00 to 0.00. Y-axis: Error Induced.

- 80 pixels: -71.11 (0.00, 0.00)
- 32 pixels: -29.33 (0.00, 0.00)
- 16 pixels: -14.67 (0.00, 0.00)
- 3 pixels: -2.75 (0.00, 0.00)

Legend: X Y Z

FIG 2.1.2.3-1: MinMax Metric – Measurement of Dilation Errors in Set A Images (Cross)

2.1.2.2 MinMax Metric -]mage Correlation Results
(Skew Error Tests)

As shown by Figures 2.1.2.2-1 through 2.1.2.2-4, no discernible pattern
can be detected by this metric for relative rotations between images.

This could be due to information being modified or lost in the sampling
area when a rotation occurs.   Figure 2.1.2.2-A provides an example.   In
this figure, Data Set A represents the original data. Data Set B, illustrated
by the rectangle with the solid line, represents the rotated data.   The
rectangular area with dashed lines represents the location of the Data
Set A information in Data Set B.   Maxima and minima are illustrated by
the dots.

As shown, only one of the extrema from Data Set A appear in Data Set B.
This makes it difficult for the algorithm to identify which point this
single extrema corresponds to in the original data set.   In addition, other
minima and maxima may be introduced into Data Set B that also
interferes with the algorithm.

Data Set A   Data Set B
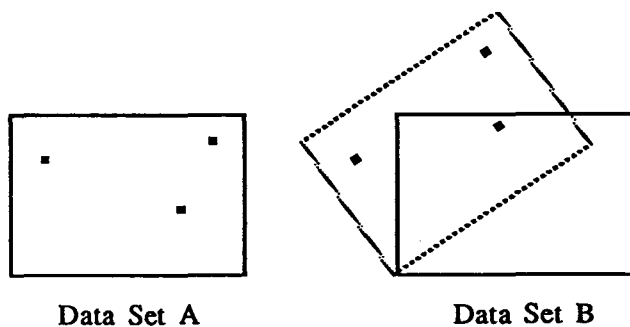
**Figure 2.1.2.2-A   Example of MinMax Information Loss Due to
Rotation**

FIG 2.1.2.2-1: MinMax Metric - Measurement of Skew Errors in Set 1 Images (Cross)
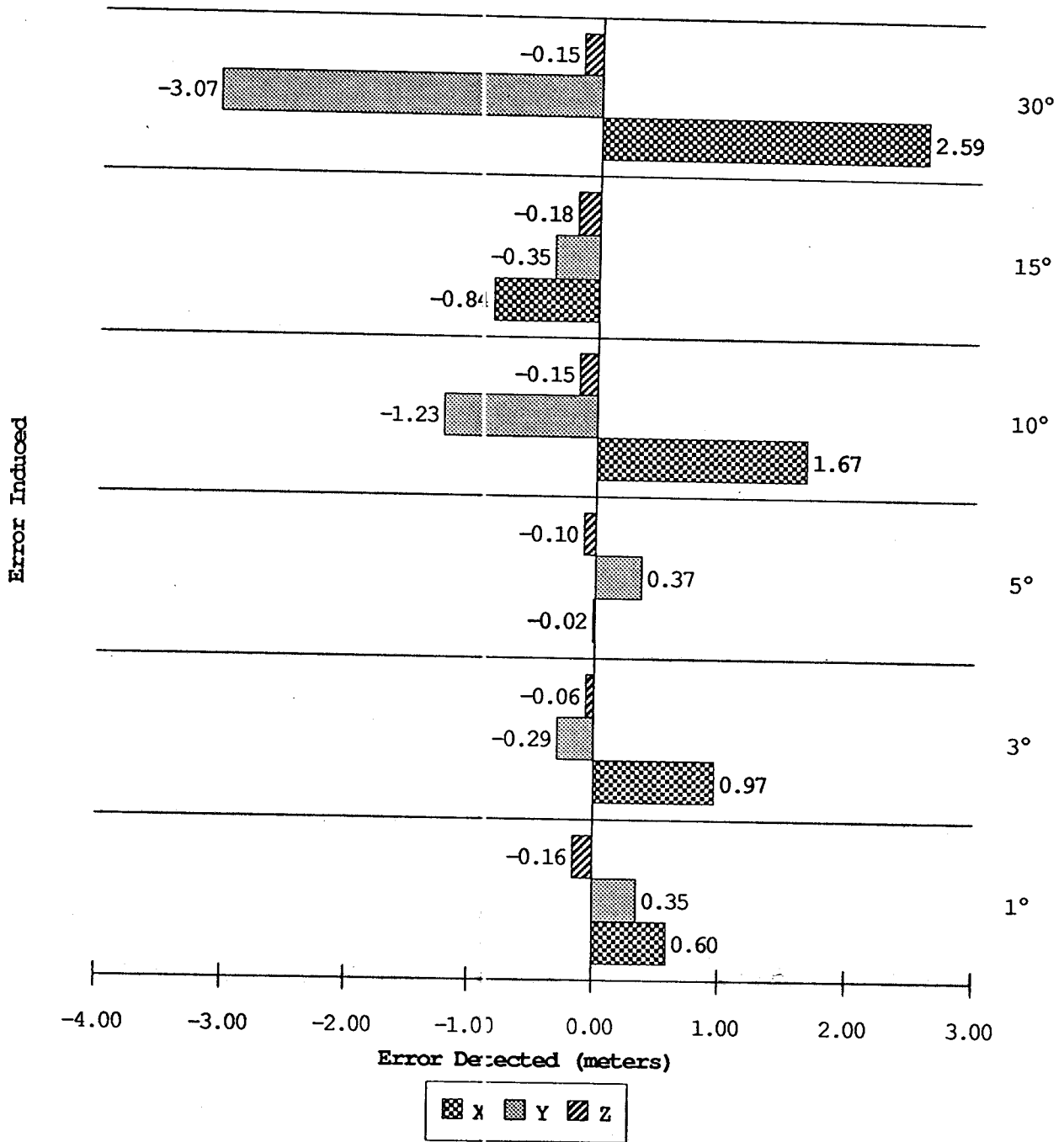
FIG 2.1.2.1-2: MinMax Metric - Measurement of Shift-X Errors in Set A Images (Checkerboard)
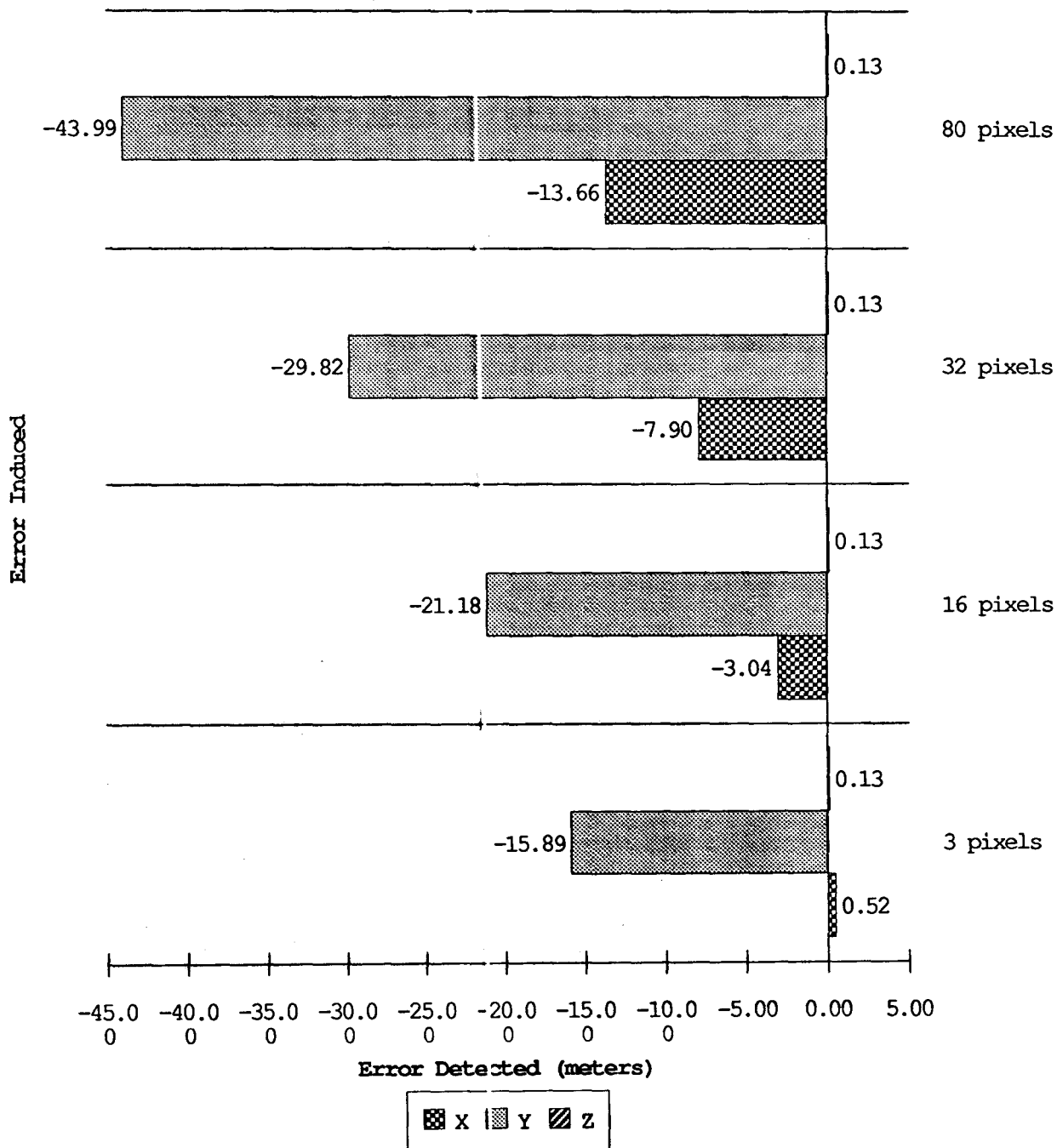
2.1.2.3 MinMax Metric - Image Correlation Results (Dilation/Magnification   Error   Tests)

One could consider dilation (i.e., change in magnification) as a non-uniform shift of the data. However, in observing the data from Figures 2.1.2.3-1 through 2.1.2.3-4, no pattern arose that can prove this metric useful in detecting different magnifications.

FIG 2.1.2.2-2: MinMax Metric - Measurement of Skew Errors in Set A Images (Checkerboard)

Horizontal axis: Error Detected (meters), ranging from -2.50 to 1.00

Vertical axis: Error Induced

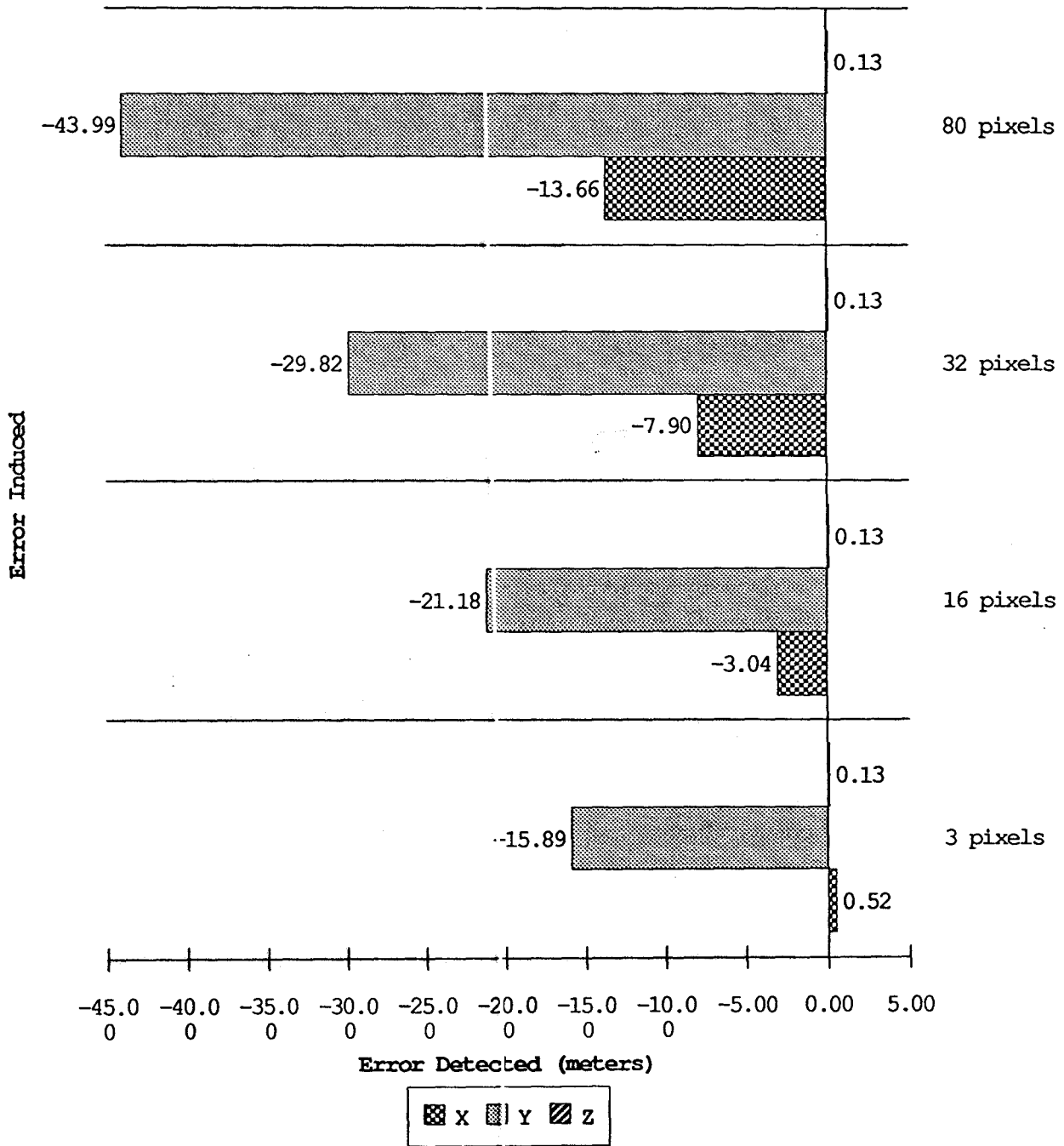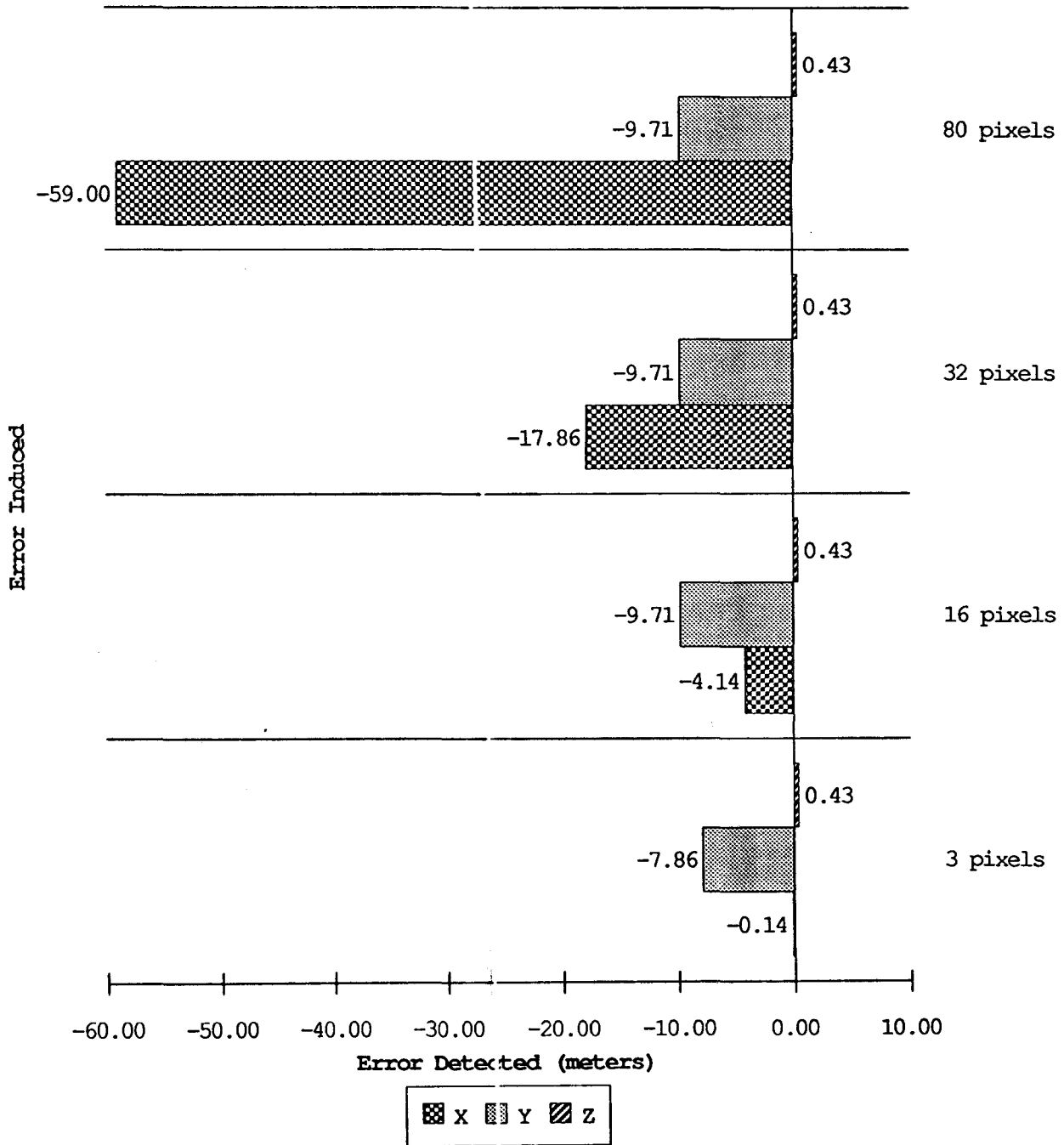| Error Induced	X	Y	Z
30°	0.33	-0.77	0.12
15°	0.02	-1.95	0.12
10°	-0.08	-2.50	0.13
5°	0.85	-1.93	0.13
3°	-0.41	-1.84	0.13
1°	-0.27	-1.51	0.12

Legend: ▨ X ▨ Y ▨ Z
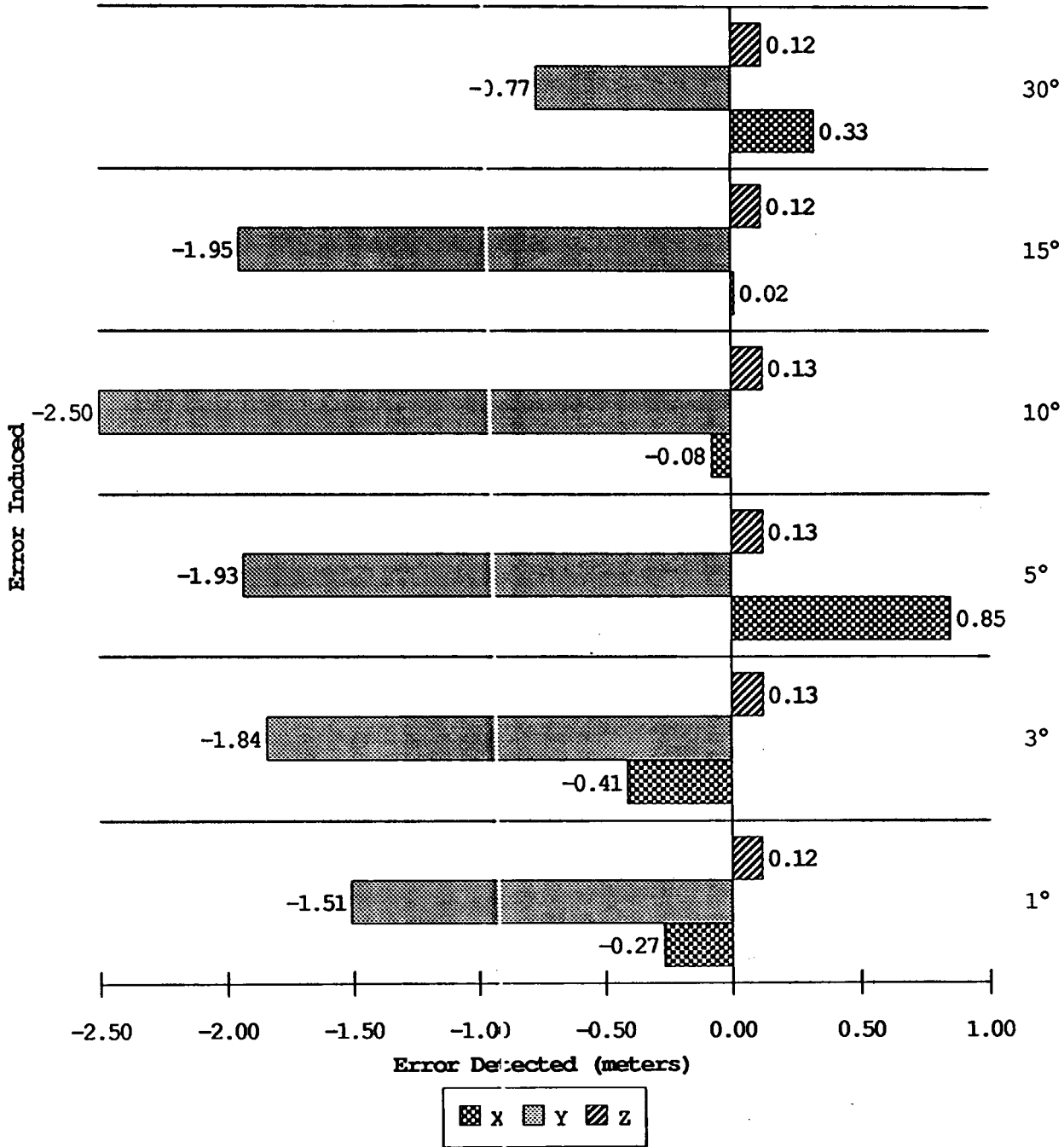
FIG 2.1.2.2-3: MinMax Metric - Measurement of Skew Errors in Set A Images (Square)
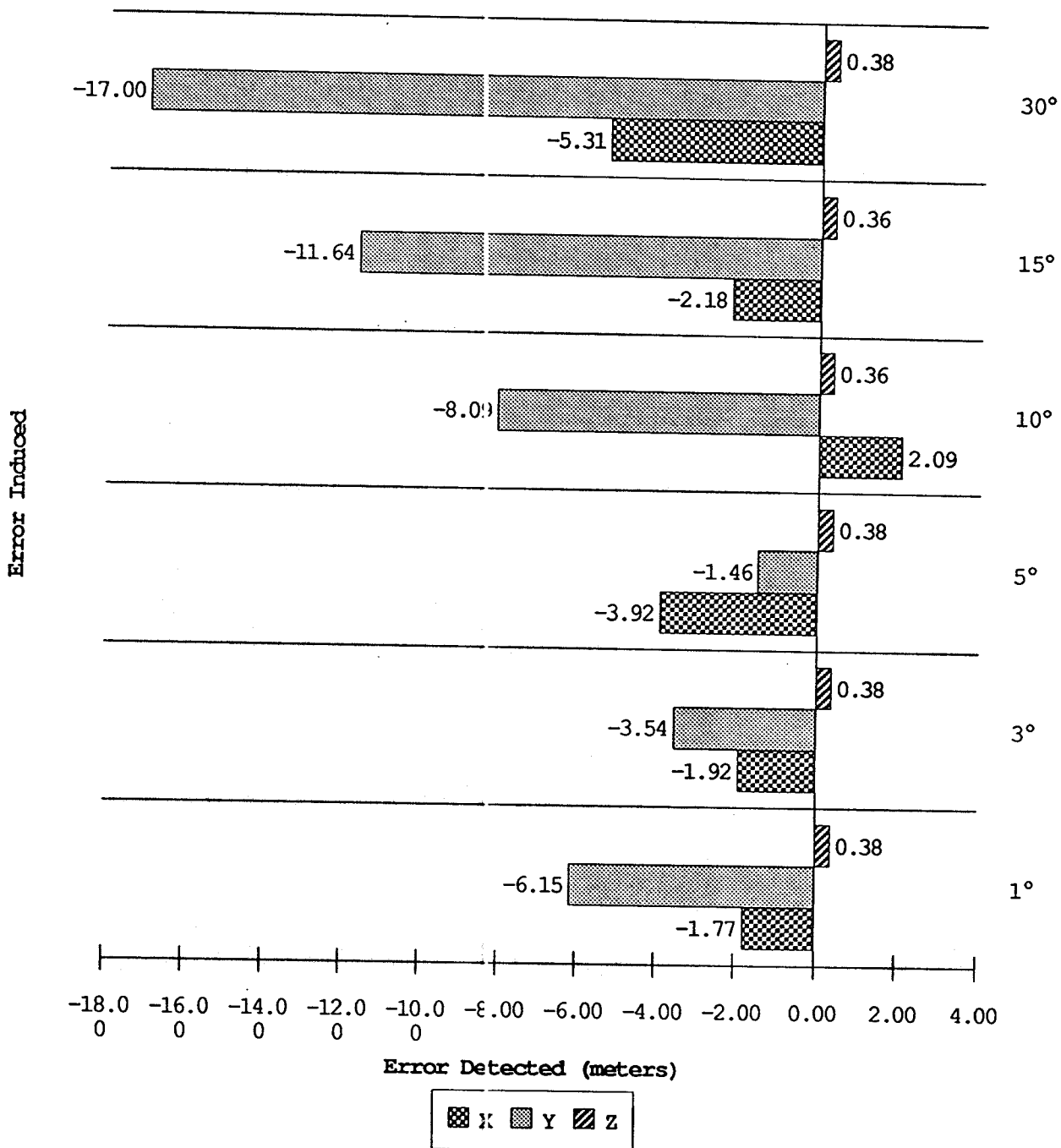
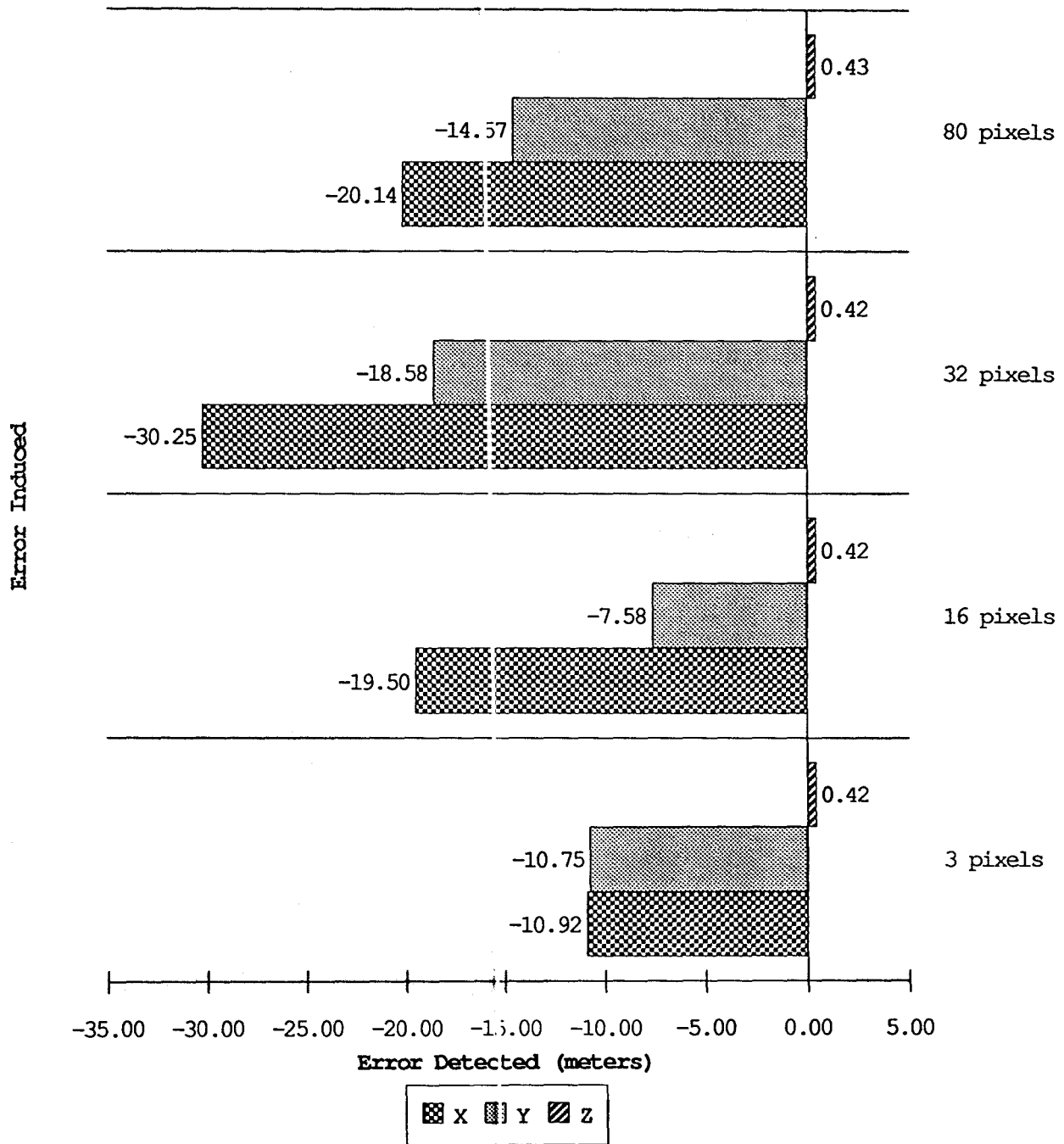**FIG 2.1.2.2-4:   MinMax Metric - Measurement of Skew Errors in Set A Images (Circle)**
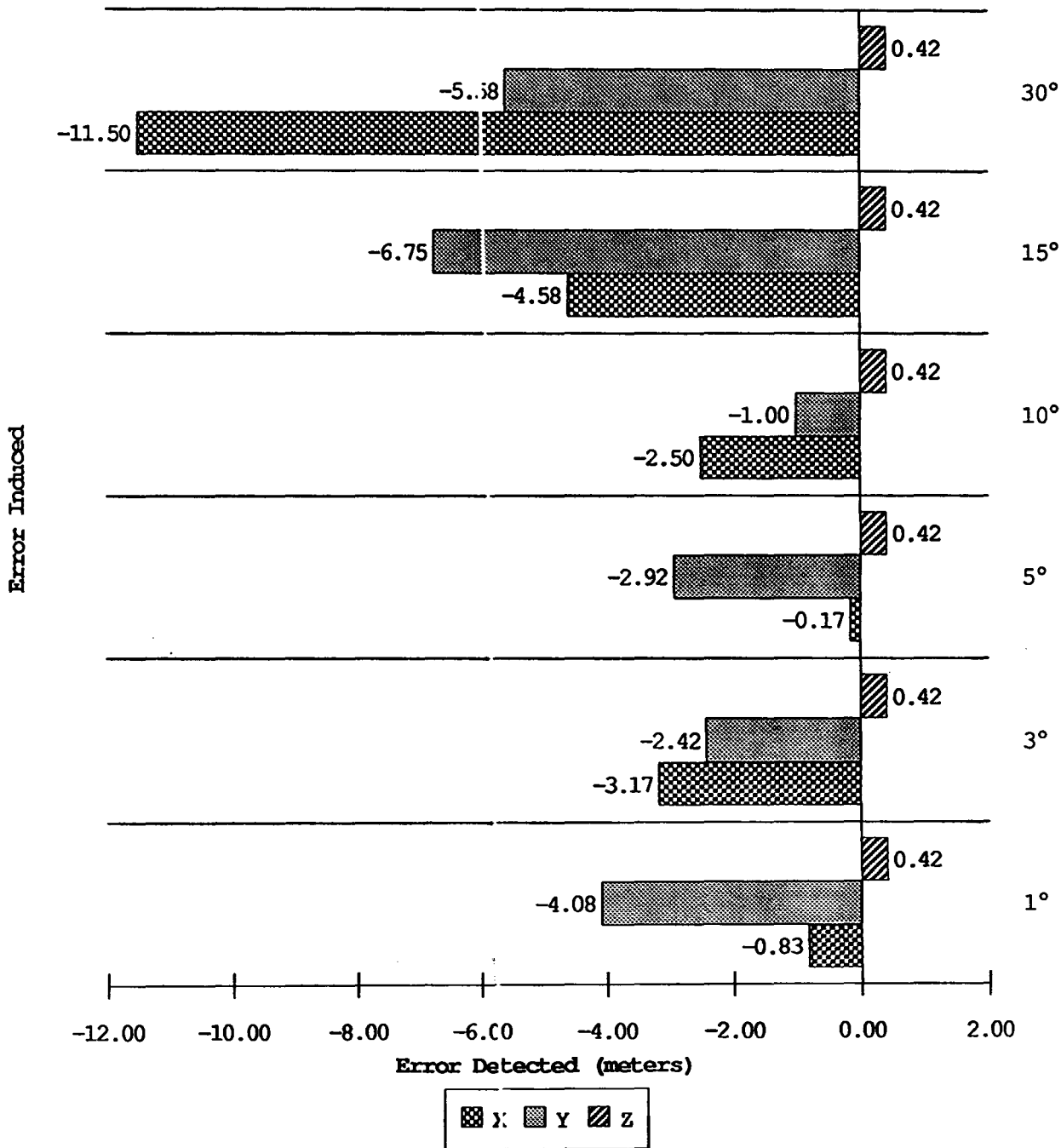
Bar chart. Vertical axis: Error Induced. Horizontal axis: Error Detected (meters), ranging from −12.00 to 2.00.

- 30°: Z = 0.42, Y = −5.58, X = −11.50
- 15°: Z = 0.42, Y = −6.75, X = −4.58
- 10°: Z = 0.42, Y = −1.00, X = −2.50
- 5°: Z = 0.42, Y = −2.92, X = −0.17
- 3°: Z = 0.42, Y = −2.42, X = −3.17
- 1°: Z = 0.42, Y = −4.08, X = −0.83

Legend: X   Y   Z

2.1.2.3   MinMax   Metric   -   Image   Correlation   Results
(Dilation/Magnification   Error   Tests)

One could consider dilation (i.e., change in magnification) as a non-uniform shift of the data.   However, in observing the data from Figures 2.1.2.3-1 through 2.1.2.3-4, no pattern arose that can prove this metric useful in detecting different magnifications.

FIG 2.1.2.3-1: MinMax Metric - Measurement of Dilation Errors in Set A Images (Cross)

- -0.44 (75%)
- 0.23
- 0.08
- -0.27 (50%)
- -2.60
- -2.84
- -0.15 (25%)
- -0.44
- 0.37
- -0.11 (10%)
- -0.47
- 0.29

Error Induced

-3.00   -2.50   -2.00   -1.5)   -1.00   -0.50   0.00   0.50
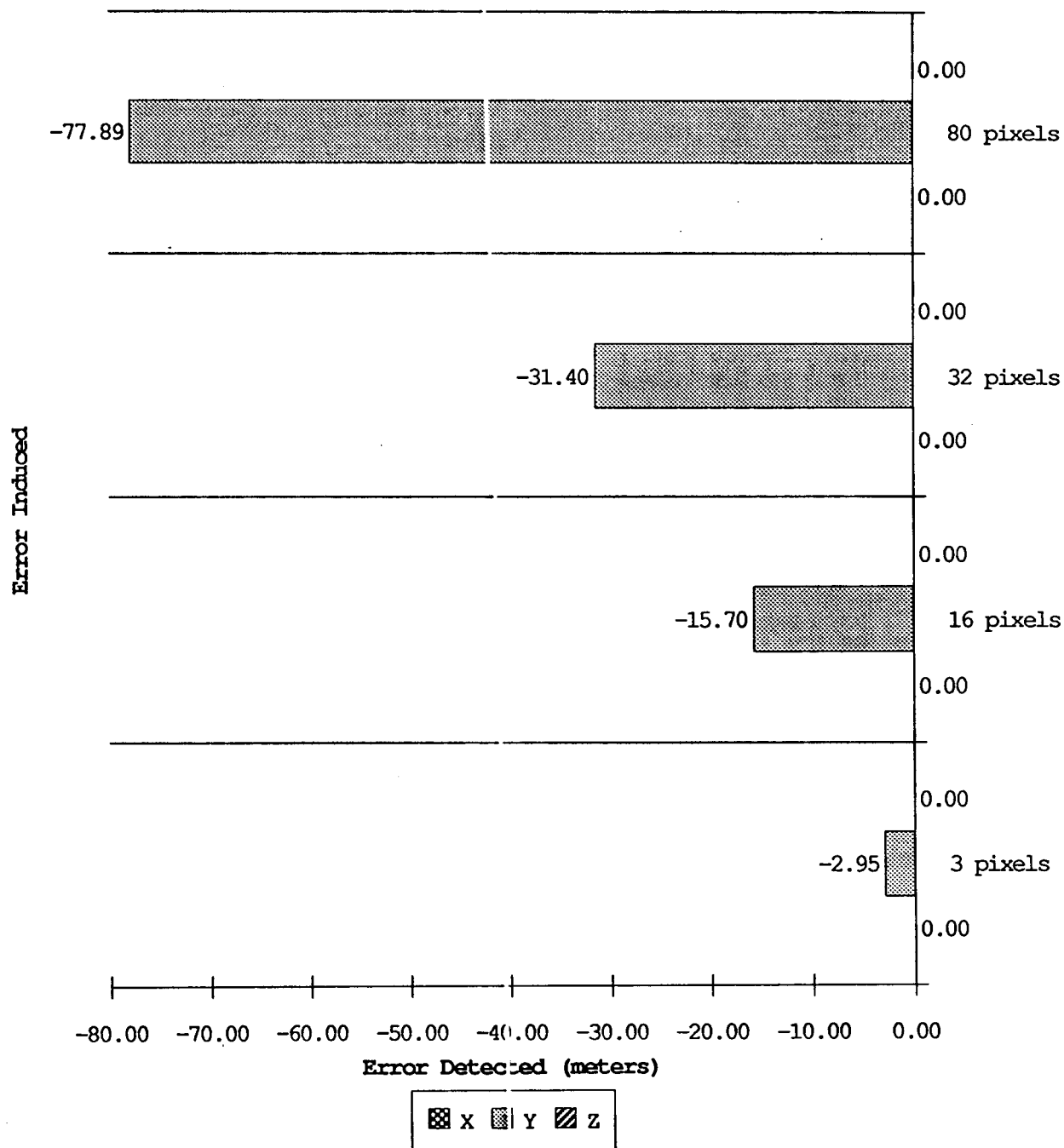
Error Detected (meters)

X   Y   Z
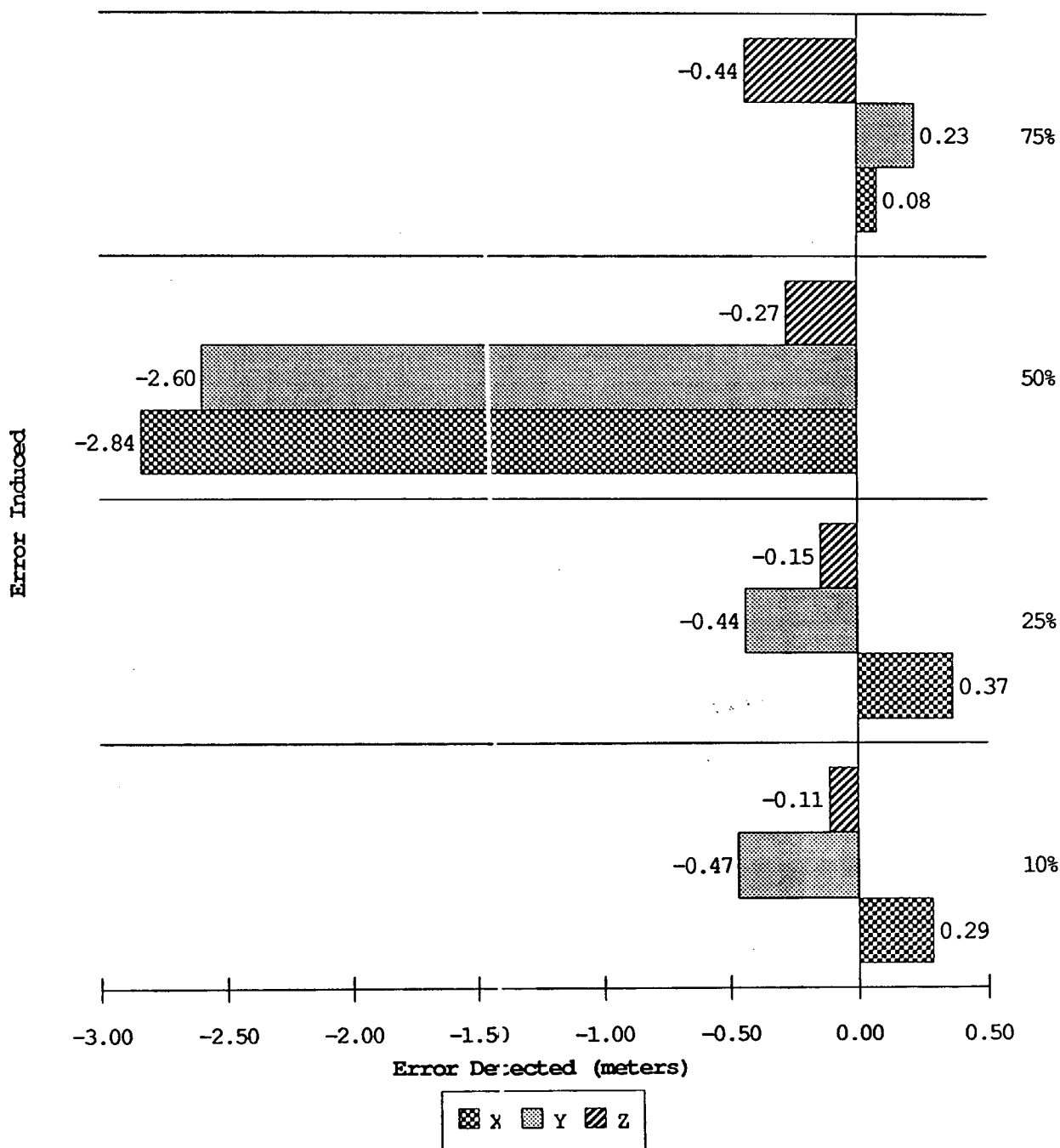
FIG 2.1.2.3-2: MinMax Metric – Measurement of Dilation Errors in Set A Images (Checkerboard)
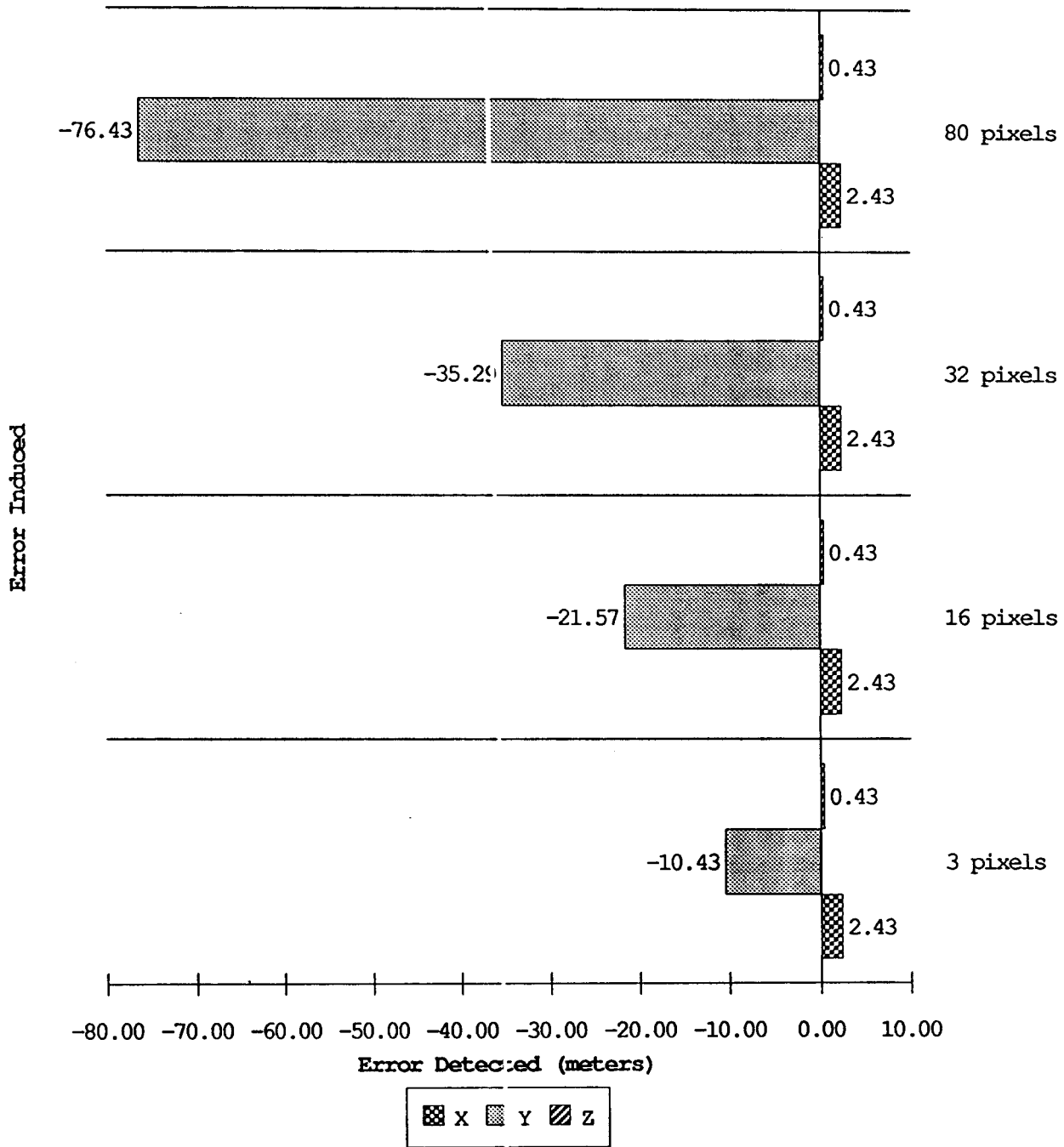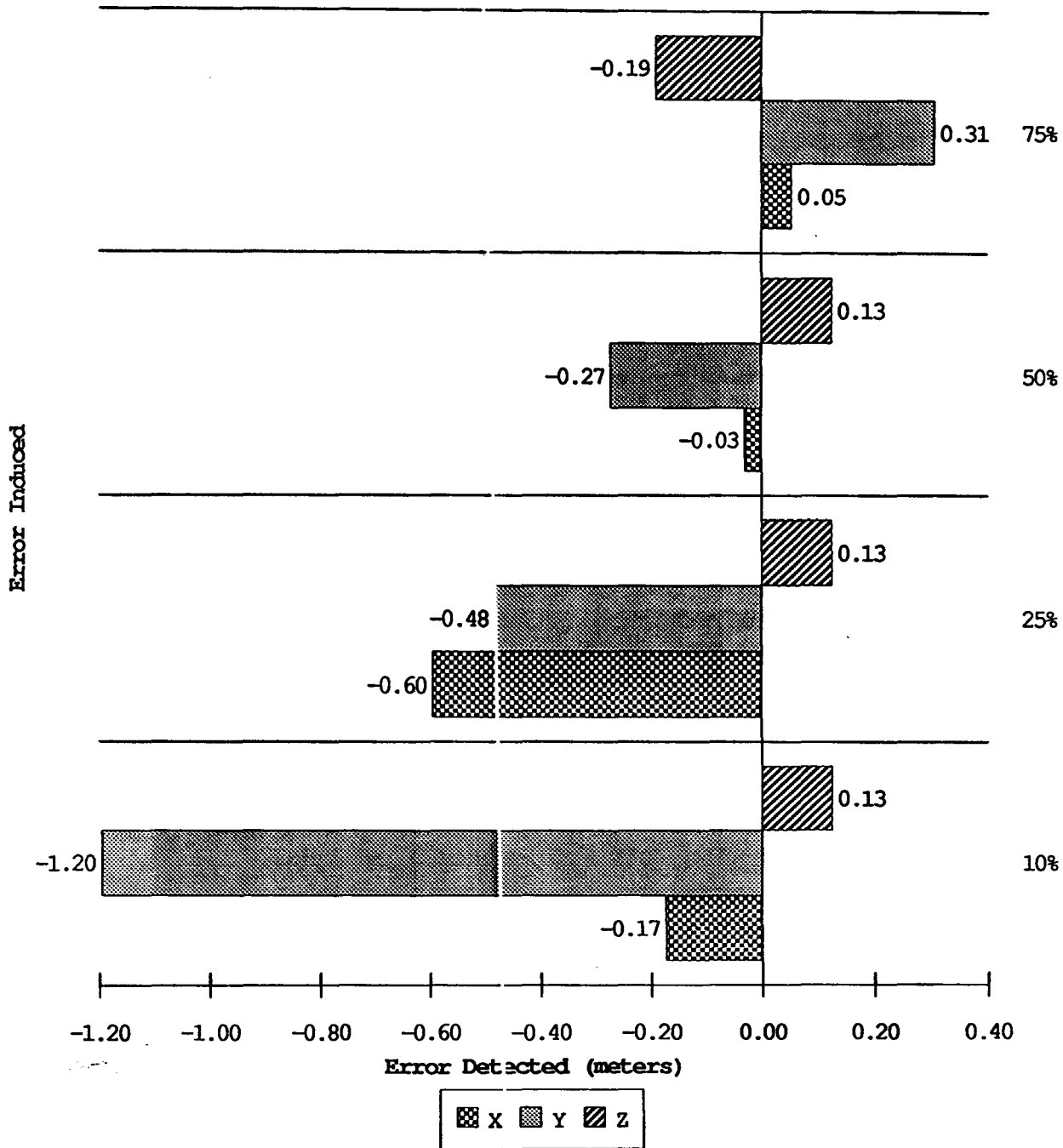
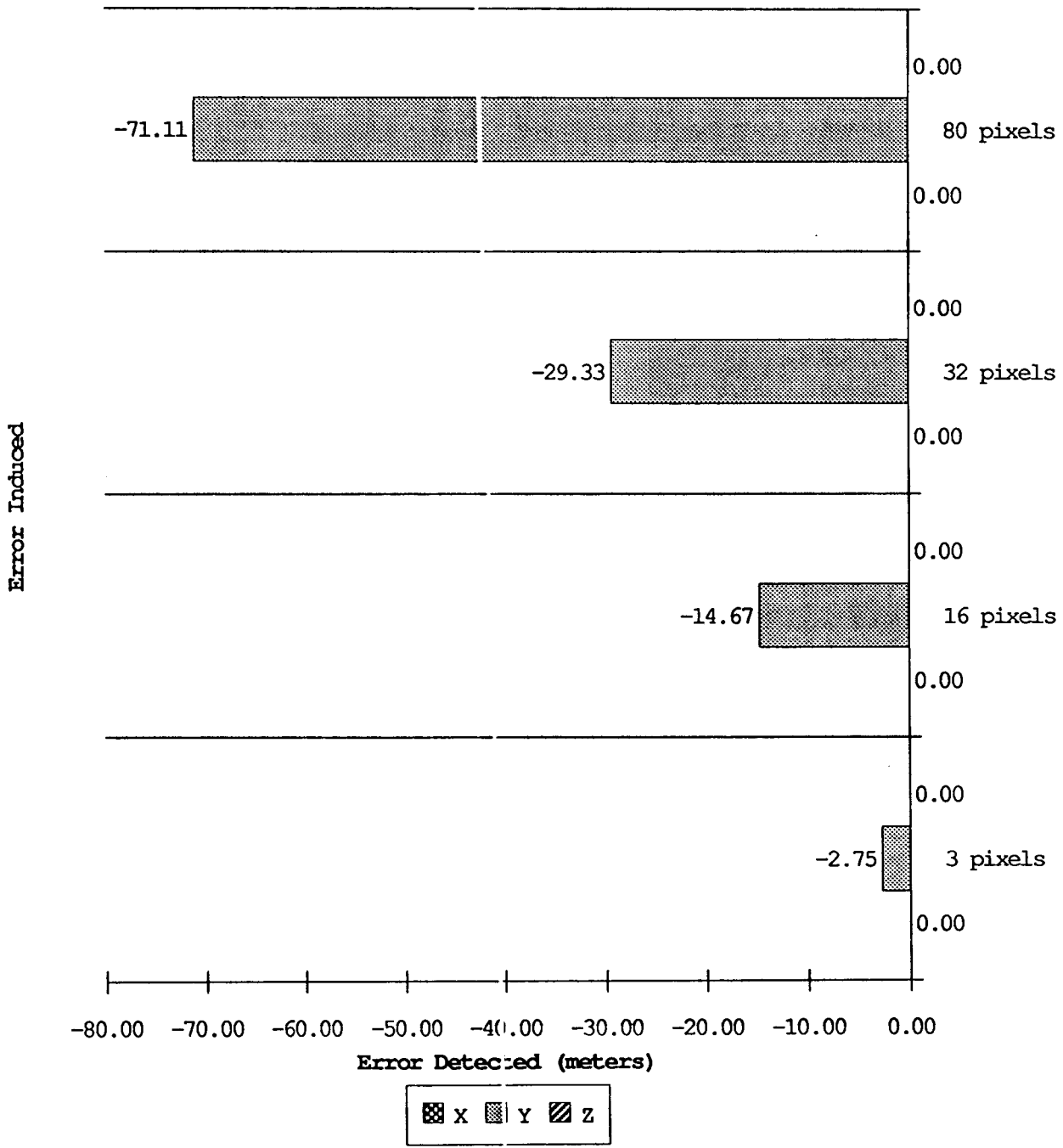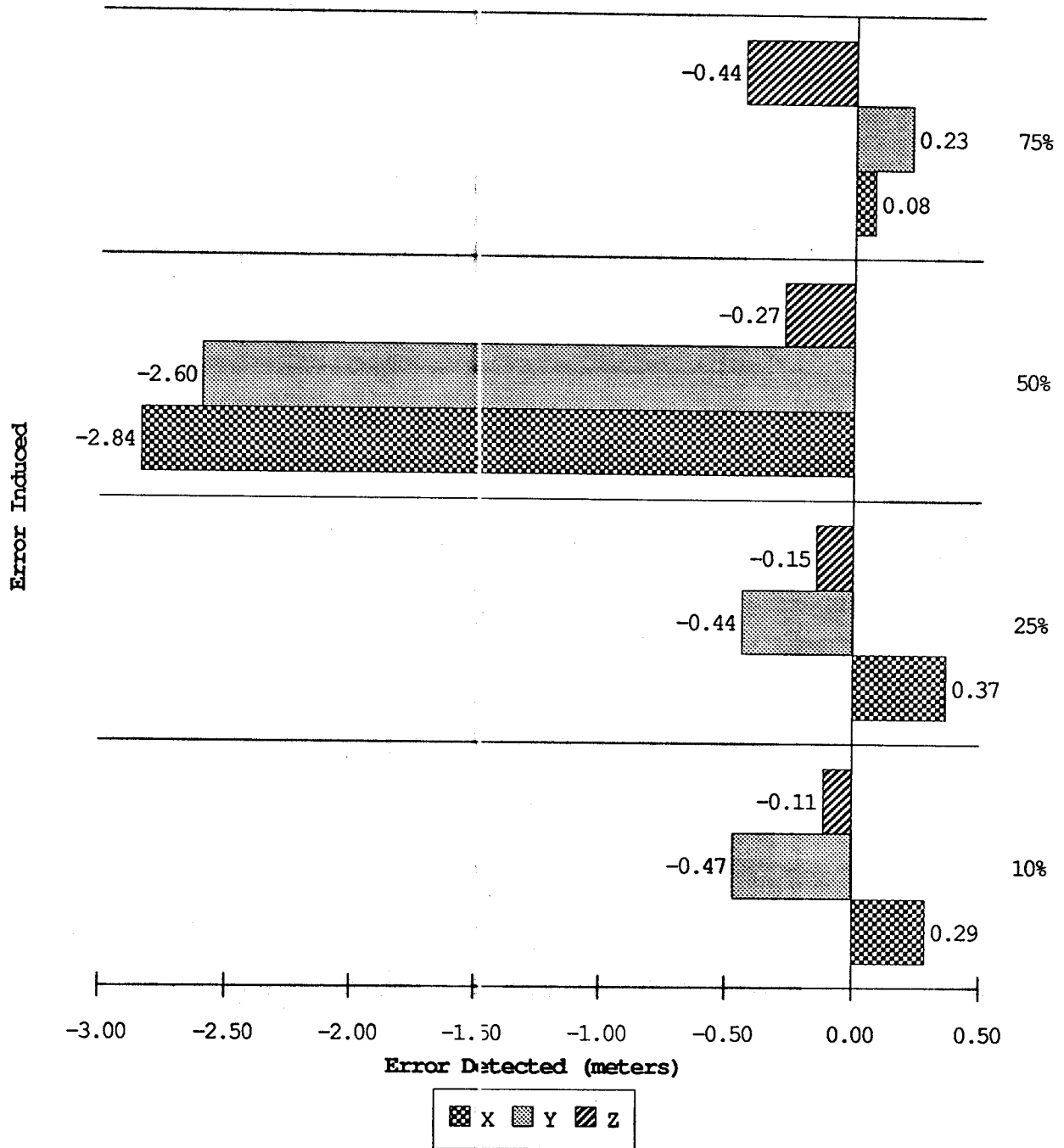FIG 2.1.2.3-3: MinMax Metric - Measurement of Dilation Errors in Set A Images (Square)
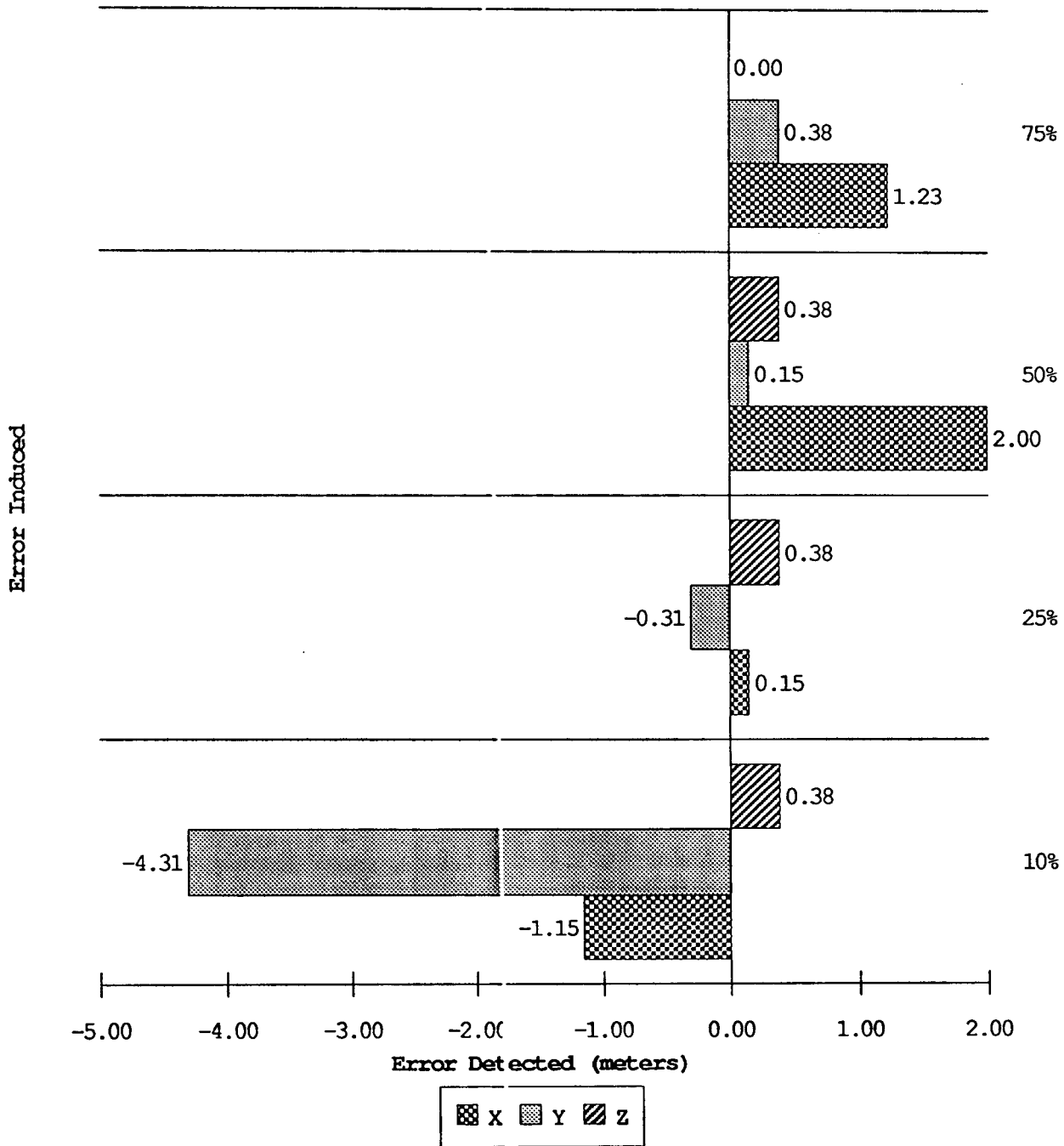
FIG 2.1.2.3-4: MinMax Metric - Measurement of Dilation
Errors in Set A Images (Circle)
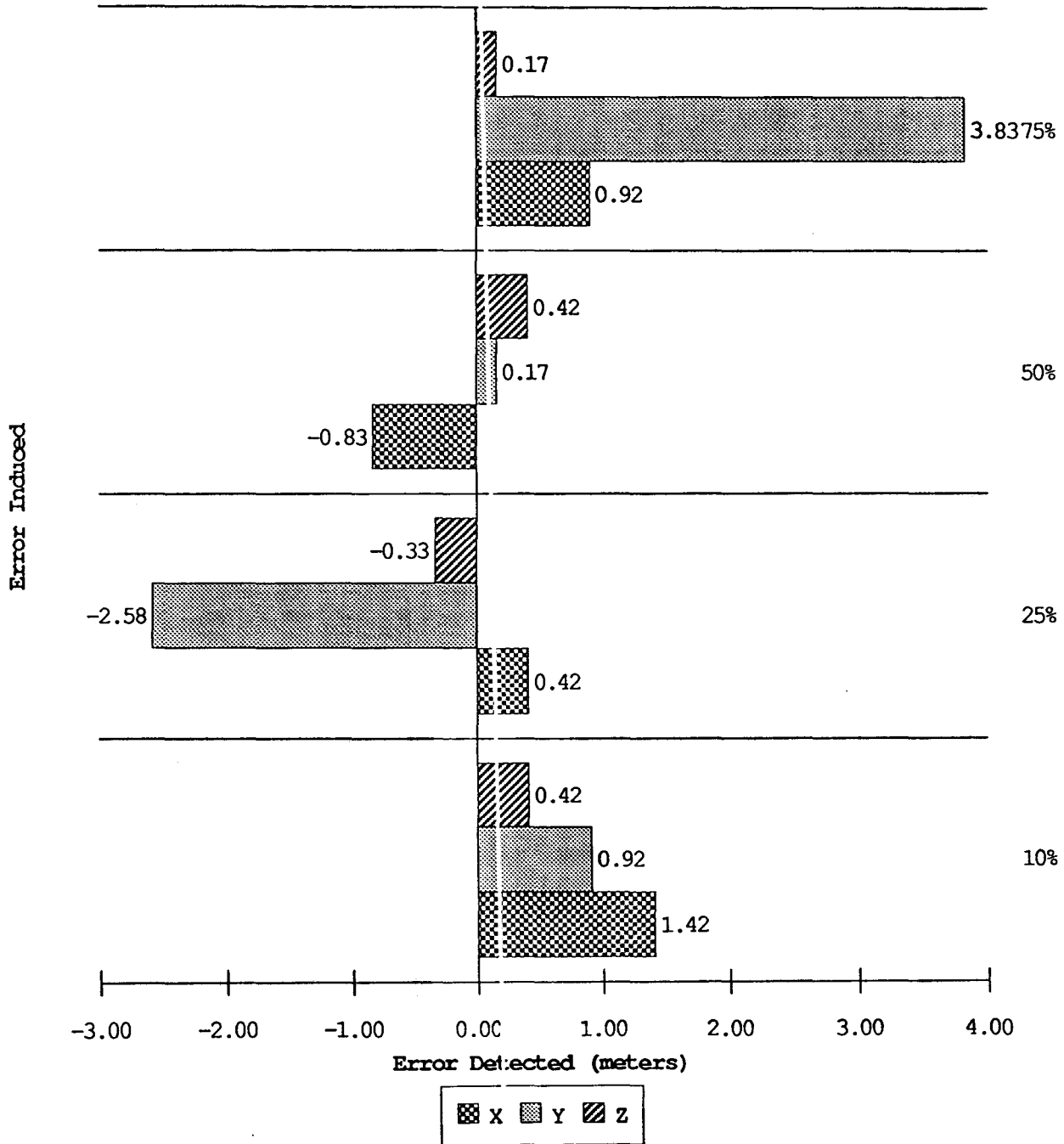
2.1.2.4   MinMax   Metric   -   Image   Correlation   Results
(Synopsis)

- Can detect a discrepancy, but not the particular type of discrepancy.
- Can measure relative magnitude of shifts in X and Y.

NOTE: These results are based on a single error induced on the database.

2.1.3 MinMax Metric - Spatial Correlation Results

2.1.3.1 MinMax Metric - Spatial Correlation Results (Shift Error Tests)

Figures 2.1.3.1-1 through 2.1.3.1-6 show the performance of the MinMax metric when shifts occur.

The first three figures illustrate the MinMax metric on the MultiGen databases. For shifts in X and Y that are much smaller than the sampling rate, the MinMax metric appears unsuccessful in detecting the discrepancy. Recall that the sampling rate (i.e., post spacing) is 125 meters. As the discrepancy becomes larger, the metric indicates the axis and relative magnitude of the shift. This may be an affect of the particular polygonization algorithm. Further study would be required to verify this hypothesis. For shifts in Z, the MinMax metric provides a relative magnitude. The difference of the measured error versus the induced could also be an effect of the polygonization algorithm.

In examing Figures 2.1.3.1-4 and 2.1.3.1-6, the metric was more successful in detecting the induced shifts in the S1000 databases. In both these figures, measured error is closer to the induced error. Also, for induced X shifts, the discrepancy is detected for all shifts. This further supports the position that the metric may be sensitive to different polygonization schemes. The results of Figure 2.1.3.1-5 may be erroneous. This possibility is indicated by most of the cases where the measured shift is much larger than the induced shift.

Certain effects were noted for both the MultiGen and S1000 test cases.

In certain instances, shifts along X will be indicated in both the X and Y axes. Analogous behavior is observed in the X and Y axes for Y shifts. This effect may be due to the conversion software that changes a polygonal terrain database into an elevation grid.

For all cases where shifts in X and Y occur, Z values change as well. This effect is illustrated by Figure 2.1.3.1-A. In this figure we see a two dimensional profile of the terrain. As the samples (indicated by dashed lines) are shifted, elevations change.
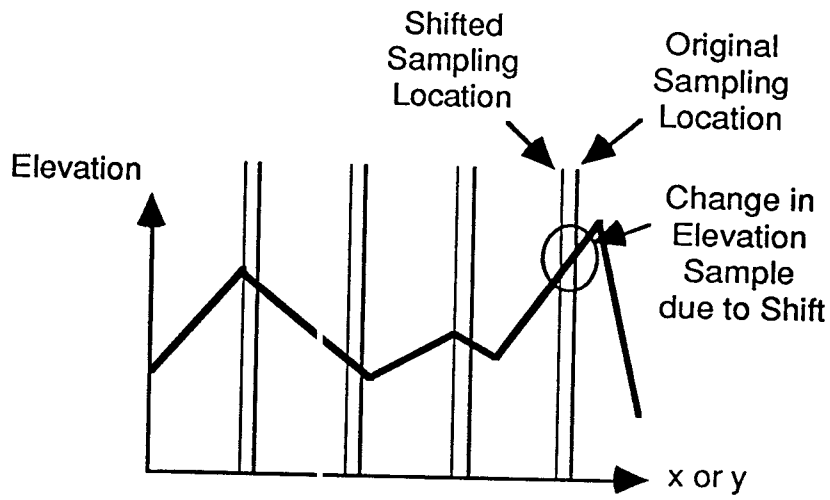
Figure 2.1.3.1-A   Example of Change in Elevation Due to Shift
:n X or Y

FIG 2.1.3.1-1: MinMax Metric - Measurement of Shift-X Errors in Set: A Databases (MultiGen)
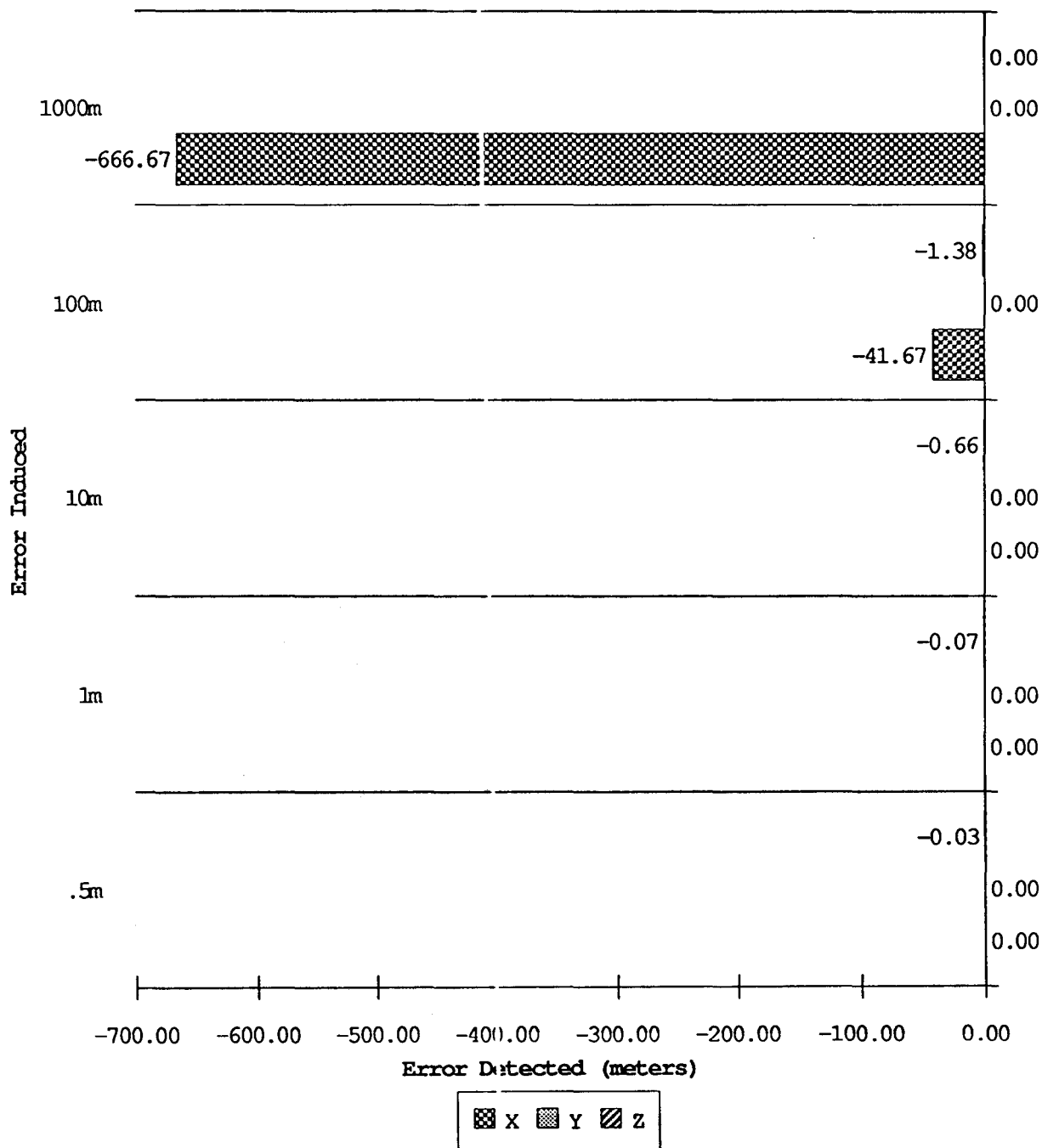
FIG 2.1.3.1-2: MinMax Metric - Measurement of Shift-Y Errors in Set A Databases (MultiGen)

A horizontal bar chart plotting Error Induced (vertical axis) against Error Detected (meters) on the horizontal axis.

Vertical axis label: Error Induced

Error Induced categories (top to bottom): 1000m, 100m, 10m, 1m, .5m

Data values:

- 1000m: 0.00, −666.67, 0.00
- 100m: −0.72, −83.33, 41.67
- 10m: −0.52, −41.67, 0.00
- 1m: −0.06, 0.00, 0.00
- .5m: −0.03, 0.00, 0.00

Horizontal axis: Error Detected (meters) with ticks at −700.00, −600.00, −500.00, −400.00, −300.00, −200.00, −100.00, 0.00, 100.00

Legend: X Y Z
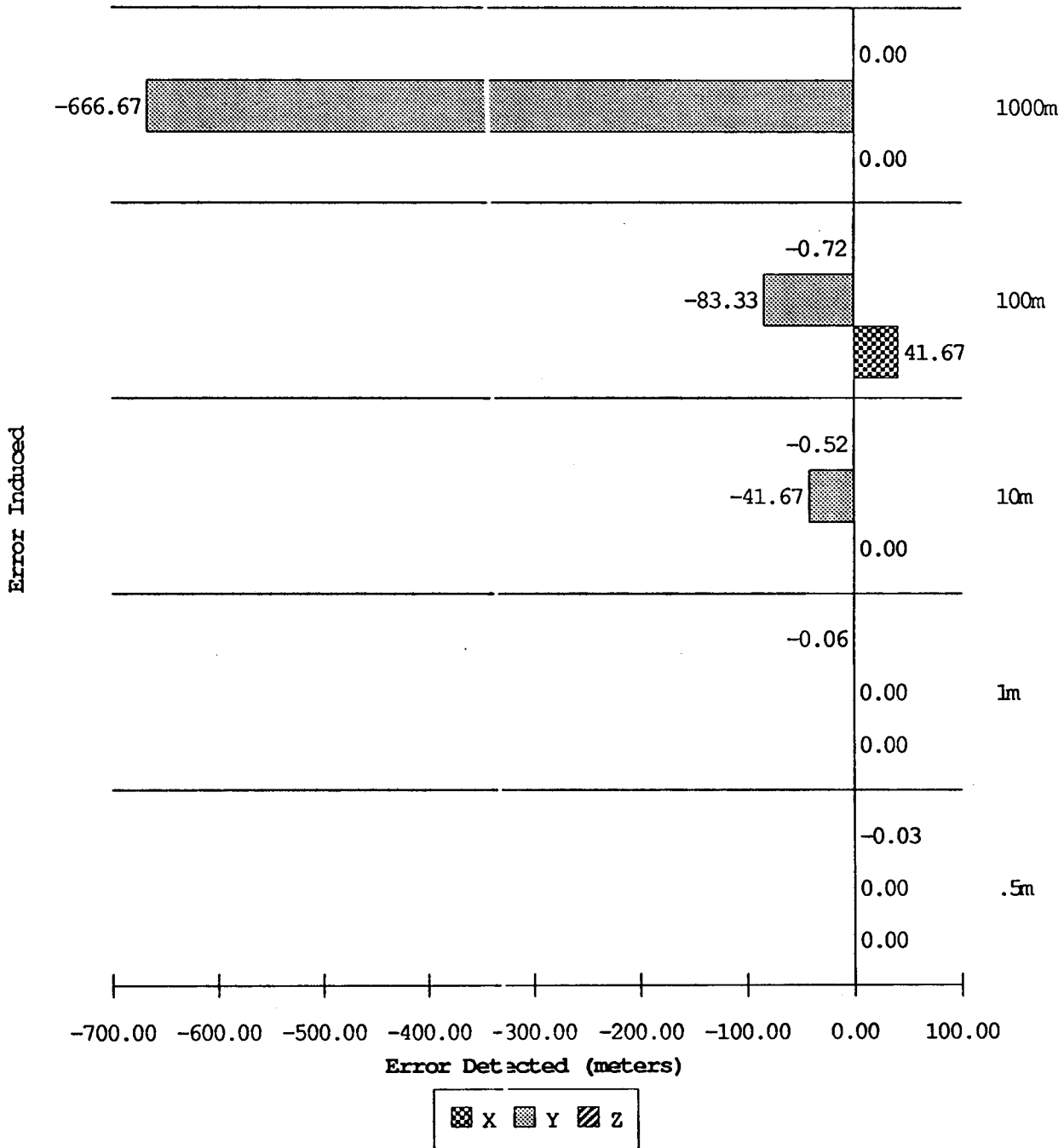
FIG 2.1.3.1-3: MinMax Metric - Measurement of Shift-Z Errors in Set A Databases (MultiGen)

Error Induced (y-axis)

Error Induced	left value	right values
1000m	−666.67	0.00 / 0.00
100m	−66.67	0.00 / 0.00
10m	−6.67	0.00 / 0.00
1m		−0.67 / 0.00 / 0.00
.5m		−0.33 / 0.00 / 0.00

X-axis: −700.00, −600.00, −500.00, −400.00, −300.00, −200.00, −100.00, 0.00

Error Detected (meters)

Legend: ⊠ X   ▦ Y   ▨ Z
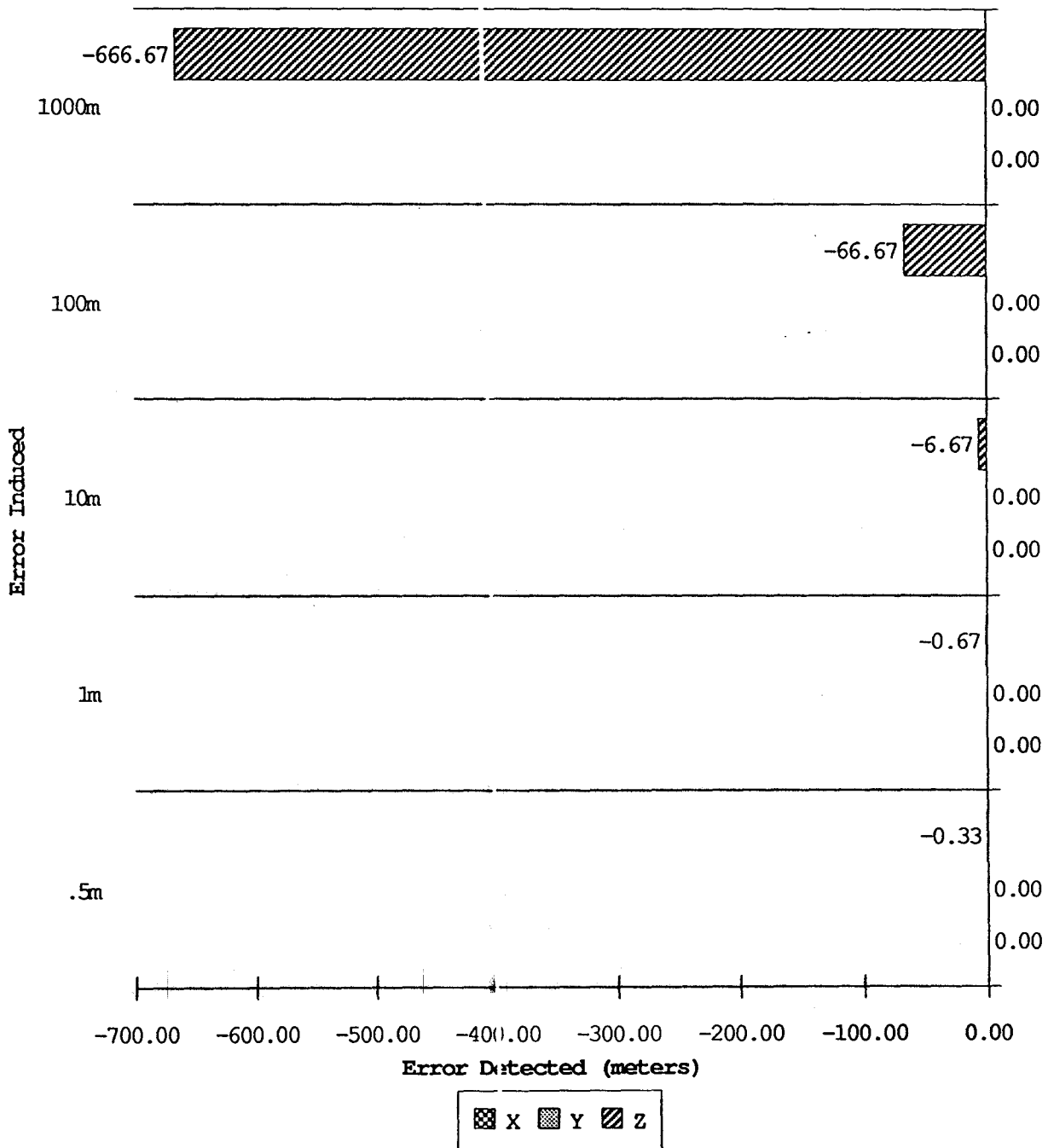
FIG 2.1.3.1-4: MinMax Metric – Measurement of Shift-X
Errors in Set A Databases (S1000)
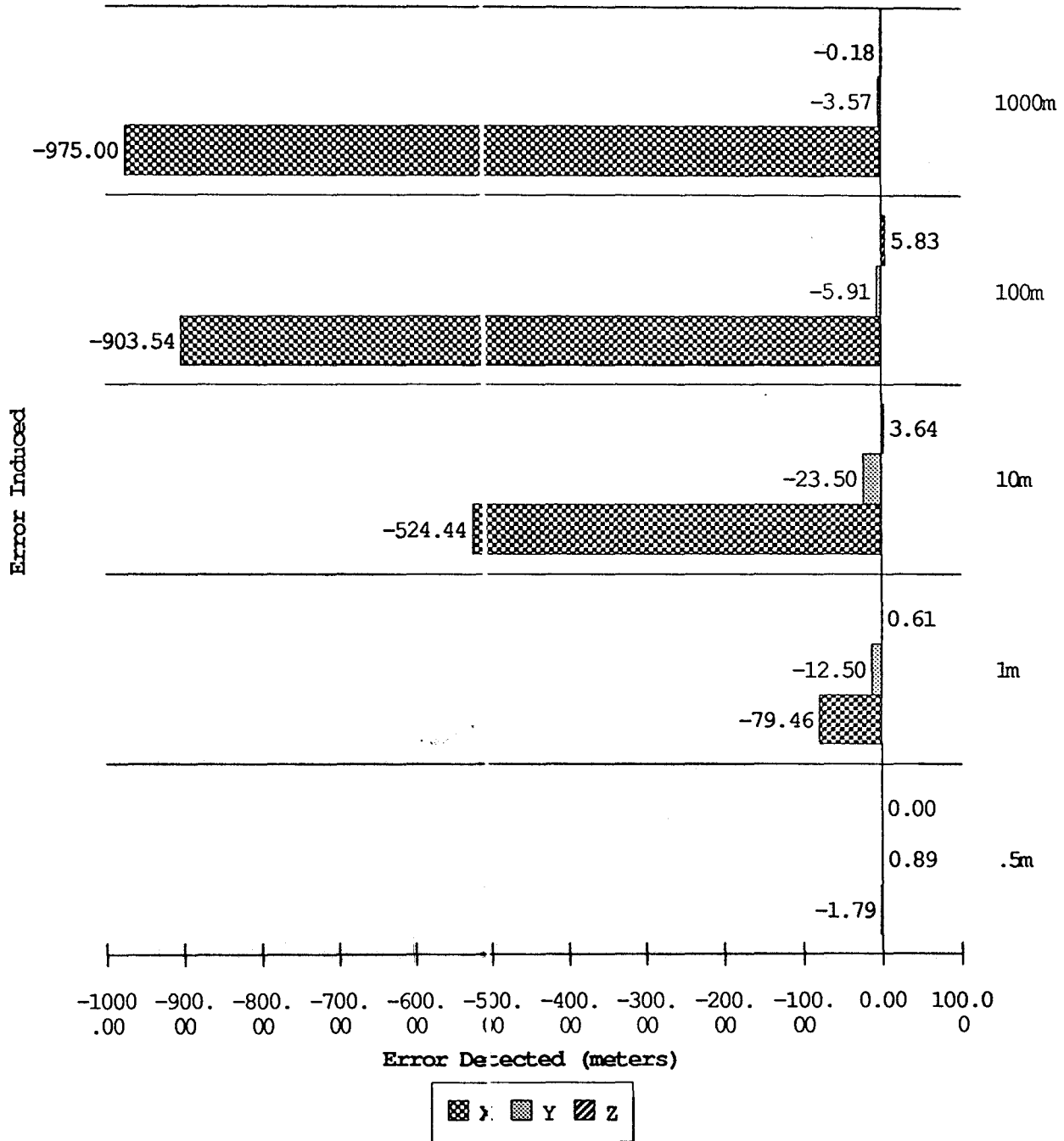
FIG 2.1.3.1-5: MinMax Metric - Measurement of Shift-Y Errors in Set: A Databases (S1000)

Error Induced

Error Detected (meters)

1000m
-0.70
-952.68
-100.00

100m
9.47
-82.63
-1310.38

10m
5.01
21.78
-632 58

1m
0.07
-0.89
-15.18

.5m
0.35
-2.70
-50.36

-1400.0 0   -1200.0 0   -1000.0 0   -800.00   -600.00   -400.00   -200.00   0.00   200.00

X   Y   Z
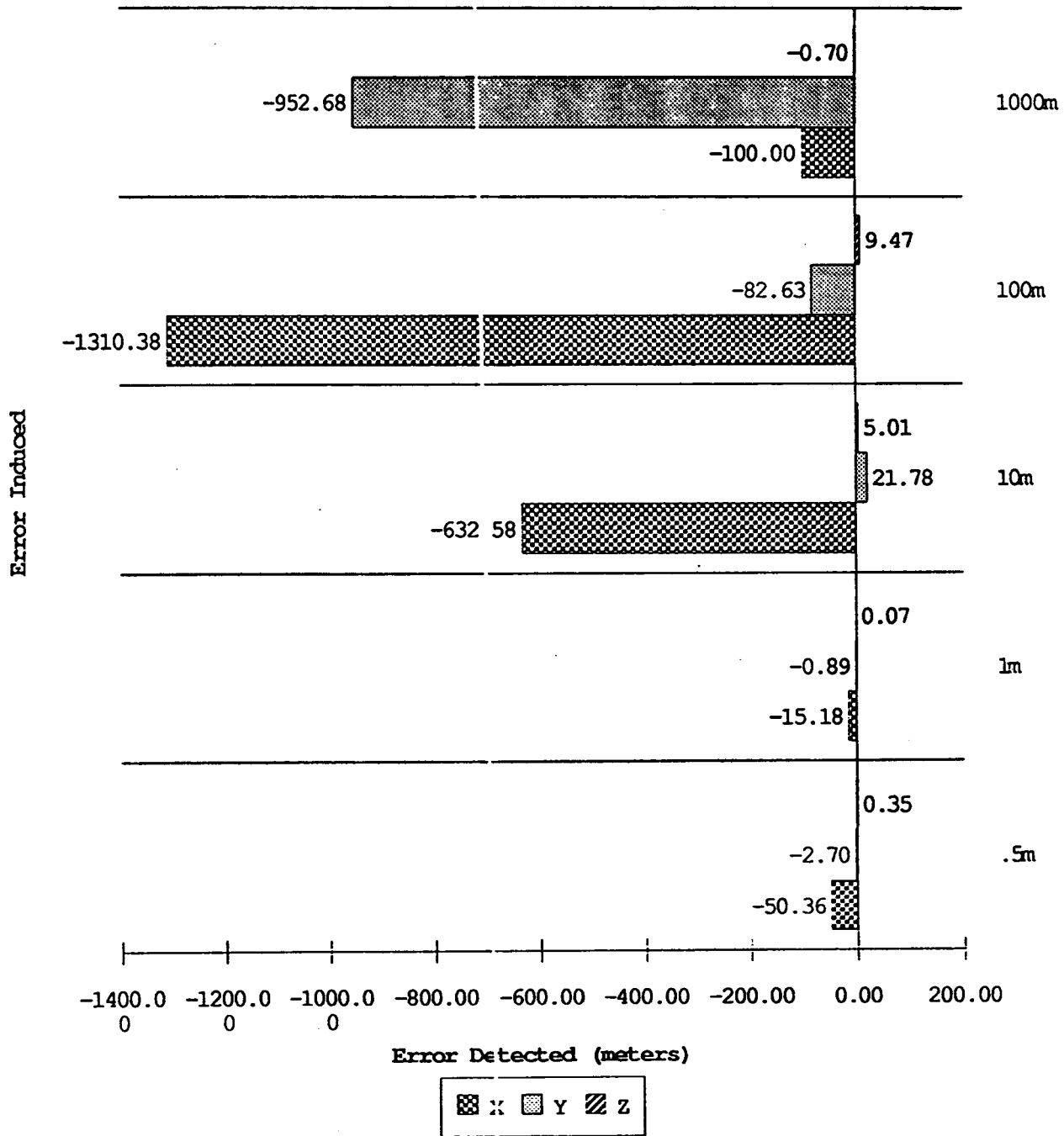
FIG 2.1.3.1-6: MinMax Metric - Measurement of Shift-Z Errors in Set A Databases (S1000)

Bar chart plotting Error Induced (vertical axis, logarithmic: 1000m, 100m, 10m, 1m, .5m) against Error Detected (meters) (horizontal axis, from -1000.00 to 0.00).

Values shown on chart:

- -992.86 (at 1000m), 0.00, 0.00
- -99.29 (at 100m), 0.00, 0.00
- -9.93 (at 10m), 0.00, 0.00
- -0.99 (at 1m), 0.00, 0.00
- -0.50 (at .5m), 0.00, 0.00

Horizontal axis labels: -1000.00 -900.00 -800.00 -700.00 -600.00 -500.00 -400.00 -300.00 -200.00 -100.00 0.00

X-axis title: Error Detected (meters)

Y-axis title: Error Induced

Legend: X Y Z

2.1.3.2 MinMax Metric - Spatial Correlation Results (Skew   Error   Tests)

Preliminary testing on databases indicated results similar to those found for rotated images. In the interest of time, no further tests were conducted for these cases.

2.1.3.3 MinMax Metric - Spatial Correlation Results
(Synopsis)

• Can detect a discrepancy, but not the particular type of discrepancy.
• Can measure relative magnitude of shifts in X, Y, and Z.   --
• May detect axis of shift (X, Y, Z).

NOTE: These results are based on a single error induced on the
database.

2.2 Feature   Metric

Applicability: Spatial Correlation

Errors to Detect: Shifts, Skews (terrain databases)   --

Input Data Type: - elevation grid (terrain databases)

2.2.1 Feature Metric - Algorithm

The following algorithm was developed from references collected from
the literature search.

Scarlatos also states that critical lines can characterize a terrain database
[Scarlatos92].   One set of critical lines consist of ridge lines that lie along
maxima which connect peaks to saddle points.   Saddle points are maxima
in one direction and minima in another direction.   Another type of
critical line, the channel or valley line, connects a pit to a saddle point
via minima.   These critical lines can also be used to detect global shifts
and skews between two terrain databases.

First, ridge and valley lines must be located within the database.   This is
accomplished by examining all points in an elevation grid for groupings
of maxima (ridge lines) or minima (valley lines).   We assume that a ridge
line starts with a peak.   The neighbors of the peak are then examined to
find the next highest point.   This becomes the next point in the ridge
line.   After examining the neighbors of this new point, excluding points
already on the ridge line, the next highest point is selected.   This process
continues until the next highest point is a neighbor of the current and
previous point on the ridge line.   This condition assumes that at the end
of the ridge line, the next highest neighbor of the terminating point will
lie on a slope on either side of the ridge line.   An analogous approach is
used in detecting valley lines.   The algorithm is shown below:

Feature Metric - Ridge and Valley Line Detection Algorithm

For each point 'a' in database A,
        if point 'a' has a greater value than its neighbors (i.e. a peak),
            start a ridge line with 'a' as the first point
            p_x <- highest point adjacent to point 'a'
            p_{x-1} <- point 'a'
            p_n <- highest point adjacent to point p_x
            loop until p_n (highest neighbor of p_x) is neighbor of p_{x-1}
                add p_x to ridge line

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$$px_{-1} <- px$$
$$px <- p_n$$

       p_n <- highest point adjacent to point px (previous p_n)
    end loop
else, if point 'a' has a smaller value than its neighbors (i.e. a pit),
    start a valley line with 'a' as the first point
    px <- lowest point adjacent to point 'a'
    px_{-1} <- point 'a'
    p_n <- lowest point adjacent to point px
    loop until p_n (lowest neighbor of px) is neighbor of px_{-1}
        add px to valley line
        px_{-1} <- px
        px <- p_n
        p_n <- lowest point adjacent to point px (previous p_n)
    end loop

2.2.1.1   Feature   Metric   -   Algorithm   (Detecting   Shifts)

To detect shifts between terrain databases using these critical lines, we determine the centroid of the ridge and valley lines. The centroid is the average of the (x, y, z) values of the points on the line. The displacement of a centroid of one ridge/valley line in database A with respect to a centroid of a corresponding line in database B determines the relative translation between the databases.

Ridge and valley lines are matched between the two databases by computing a length function. A ridge/valley line in database B corresponds to a ridge line in database A if the same length value is computed. The length equals the number of points in the ridge or valley line added to the number of times the line changes direction. This length function excludes the Cartesian length of the line since this can be affected by shifts and other correlation errors. The algorithm is as follows:

Feature Metric - Shift Error Measuring Algorithm

1. For each ridge line in database A,
    compute the length of the line,
        length = number of points on the line + number of times the
            line changes direction
2. Repeat step 1 for valley lines in database A.
3. For each ridge line in database A,
    compute the centroid of the line
        $x_{centroid}$ = average of x values of points on the line

$y_{centroid}$ = average of y values of points on the line
$z_{centroid}$ = average of z values of points on the line

4. Repeat step 3 for valley lines in database A.
5. Repeat steps 1-4 for database B.
6. For each ridge line in database A,

    find the corresponding line in database B: --

        for each ridge line in database B

            if length(line in A) = length(line in B)

                line in B corresponds to line in A

    Compute the distance between the centroid of the line in database
      A to the centroid of the corresponding line in database B.

7. Repeat step 6 for valley lines in database A.
8. Average the x, y, and z distances in steps 6 and 7.

2.2.1.1   Feature   Metric   -   Algorithm   (Detecting   Skew)

For skews, the angle between corresponding ridge/valley lines is
calculated. For each ridge or valley line to be compared, a vector is
formed from the endpoints of the ridge or valley line. The vector dot
product is then used to compute the angle of skew. The corresponding
line in the second database is determined through the same length
function. The algorithm is as follows:

Feature Metric - Skew Error Measuring Algorithm

1. For each ridge line in database A,

    compute the length of the line,

        length = number of points on the line + number of times the
            line changes direction

2. Repeat step 1 for valley lines in database A.
3. For each ridge line in database A,

    find the corresponding line in database B:

        for each ridge line in database B

            if length(line in A) = length(line in B)

                line in B corresponds to line in A

    Compute the angle θ between the line in database A to the line in
      database B:

        V_A <- vector formed from endpoints of line in database A
        V_B <- vector formed from endpoints of line in database B

$$\theta = \cos\left(\frac{V_A \bullet V_B}{\left| V_A \right| \left| V_B \right|} \right)$$

4. Repeat step 3 for valley lines in database A.

5. Average the angles in steps 3 and 4.

2.2.2   Feature   Metric   -   Spatial   Correlation   Results

2.2.2.1   Feature   Metric   -   Spatial   Correlation   Results
(Shift   Error   Tests)

Figures 2.2.2.1-1 through 2.2.2.1-6 indicate that this metric succeeds in detecting shifts in elevation only. No pattern seems apparent in the cases where X and Y shifts are induced. This result is due to the fact that the critical lines (i.e. ridge and valley lines) become altered with shifts in X and Y. Figure 2.2.2.1-A illustrates this phenomena. Database A contains a single critical line which is indicated by the thick line. After the database has been shifted to become database B, a portion of the line is lost.

Database A   Database B
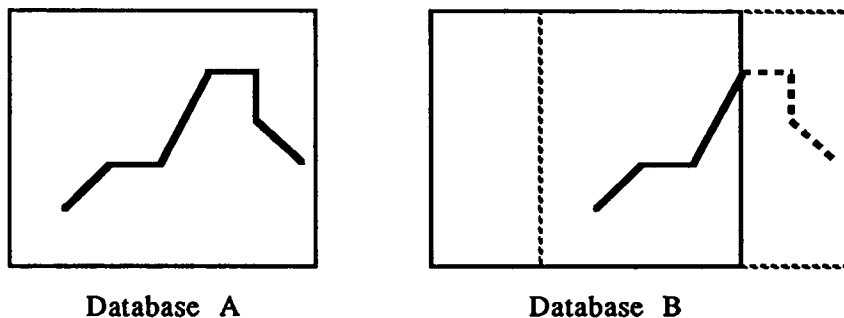
Figure   2.2.2.1-A   Example   of   Changes   in   Critical   Lines   with
Induced   Shifts   in   X   and   Y

For shifts in Z, a difference is exhibited again between the amount of error measured for MultiGen and S1000 databases. This may indicate that this metric is also affected by different polygonization algorithms.

FIG 2.2.2.1-1: Feature Metric - Measurement of Shift-X Errors in Set A Databases (MultiGen)

Error Induced

-104.17

0.00
0.00   1000m

-1.25
20.83   100m
-104.17

0.09
20.83   10m
0.00

0.03
0.00   1m
0.00

0.01
0.00   .5m
0.00

-120.00 -100.00 -80.00 -60.00 -40.00 -20.00 0.00 20.00 40.00

Error Detected (meters)

X   Y   Z

FIG 2.2.2.1-2: Feature Metric – Measurement of Shift-Y Errors in Set A Databases (MultiGen)
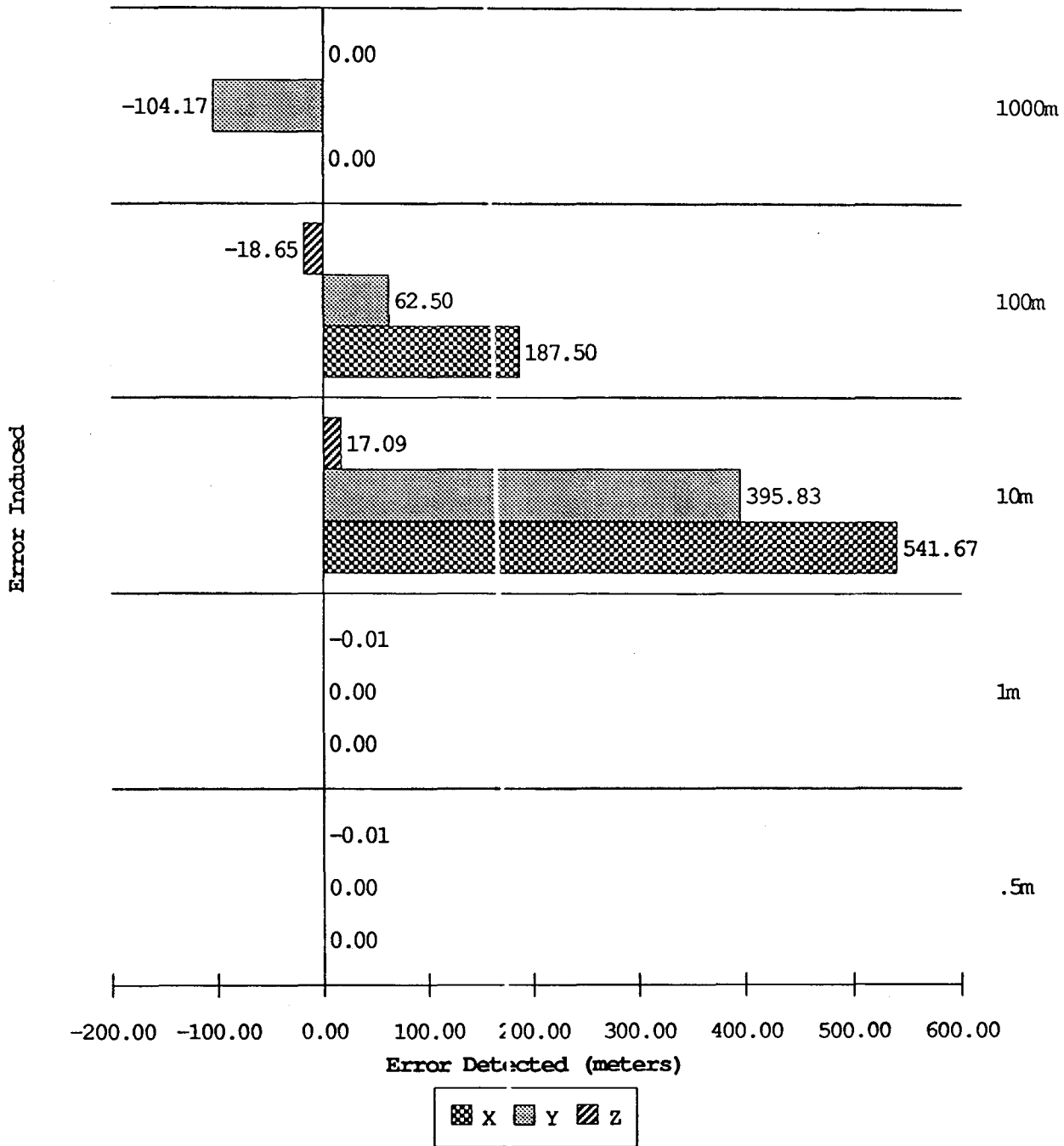
FIG 2.2.2.1-3: Feature Metric - Measurement of Shift-Z
Errors in Set A Databases (MultiGen)
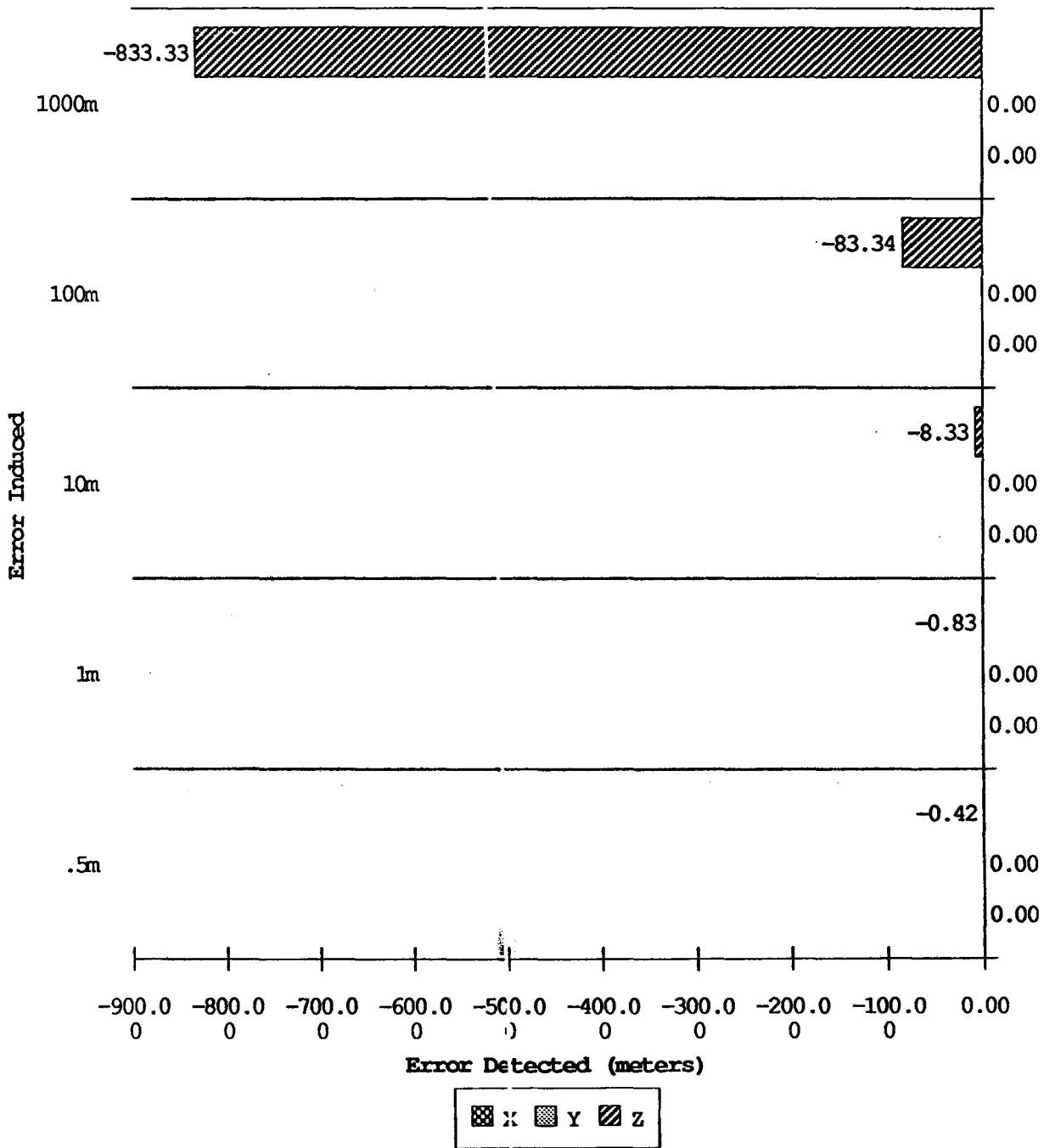
FIG 2.2.2.1-4: Feature Metric – Measurement of Shift-X Errors in Set A Databases (S1000)

Error Induced (vertical axis): 1000m, 100m, 10m, 1m, .5m

-115.38

0.00
0.00
-0.06
0.00
0.00
-0.02
0.00
0.00

Error Detected (meters): -120.00 -100.00 -80.00 -60.00 -40.00 -20.00 0.00

Legend: X Y Z
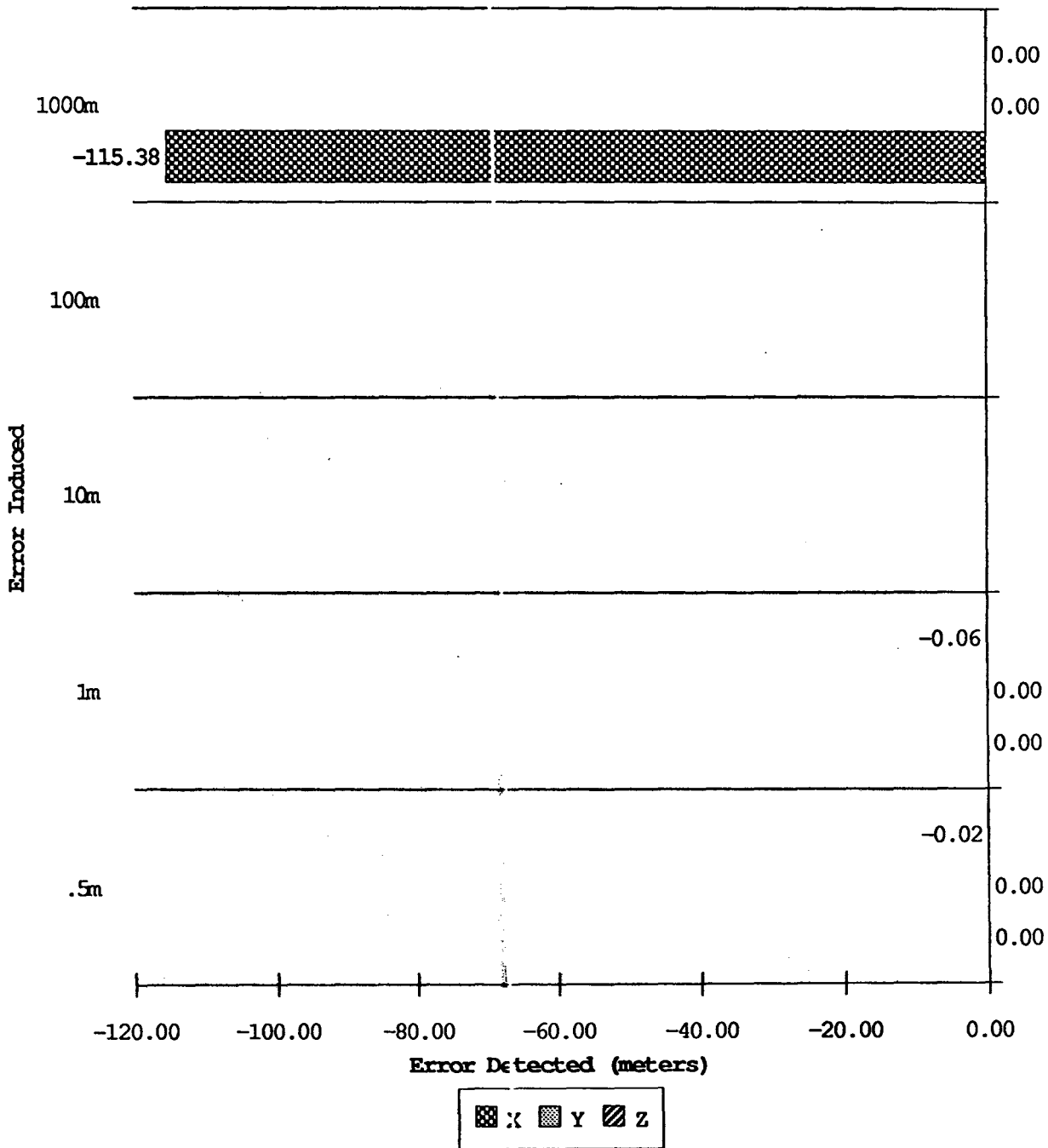
FIG 2.2.2.1-5: Feature Metric - Measurement of Shift-Y
Errors in Set A Databases (S1000)

Error Induced (vertical axis)

0.00
−115.38   1000m
0.00

100m

34.96
211.54 10m
−3769.23

−0.04
0.00   1m
0.00

−0.01
0.00   .5m
0.00

−4000.00 −3500.00 −3000.00 −2500.00 −2000.00 −1500.00 −1000.00 −500.00 0.00 500.00

Error Detected (meters)

X Y Z
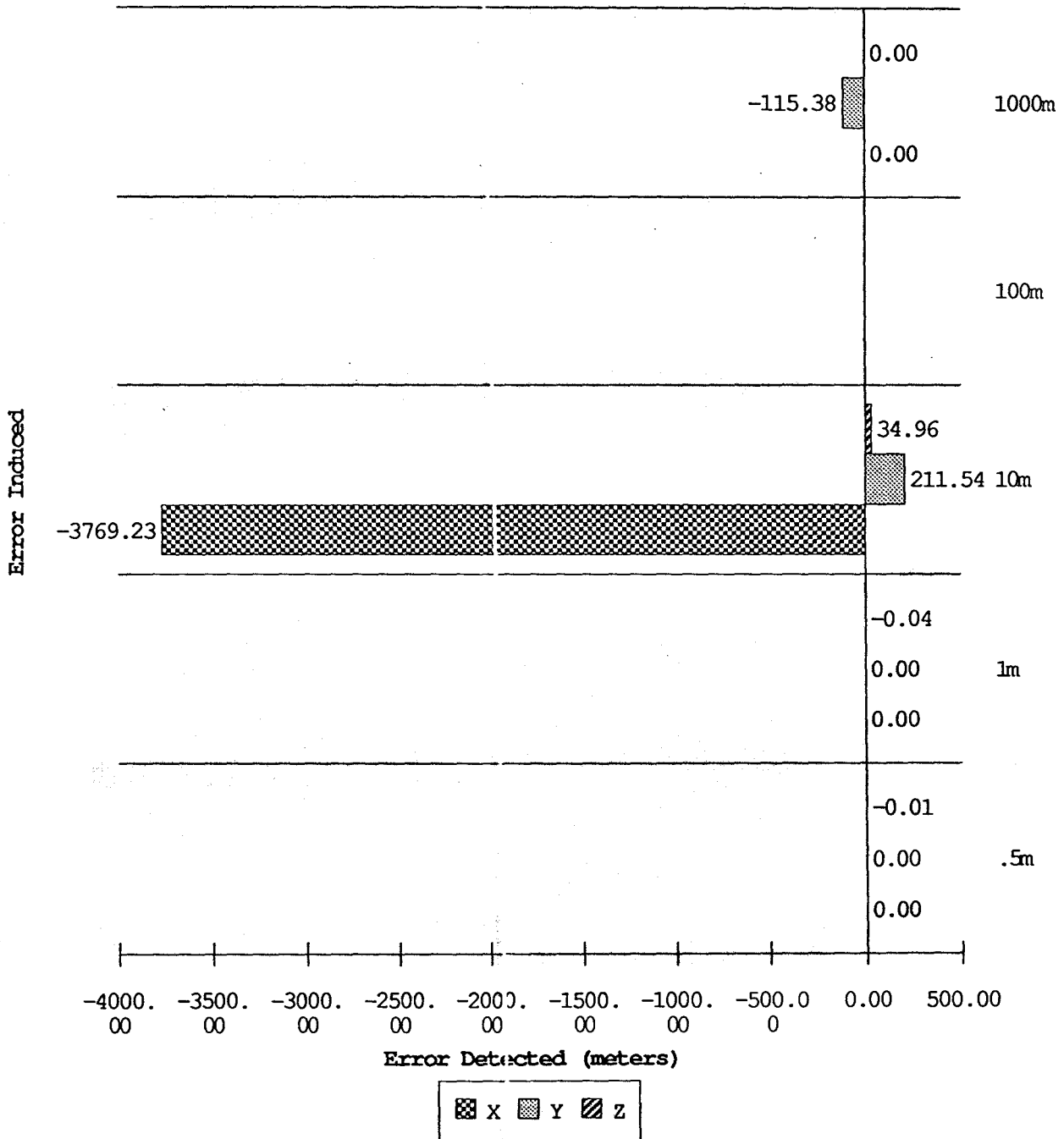
FIG 2.2.2.1-6: Feature Metric – Measurement of Shift-Z Errors in Set A Databases (S1000)

Error Induced

-923.08 (1000m) 0.00 0.00

-92.31 (100m) 0.00 0.00

-9.23 (10m) 0.00 0.00

-0.92 (1m) 0.00 0.00

-0.46 (.5m) 0.00 0.00

-1000.00 -900.00 -800.00 -700.00 -600.00 -500.00 -400.00 -300.00 -200.00 -100.00 0.00

Error Detected (meters)

X Y Z
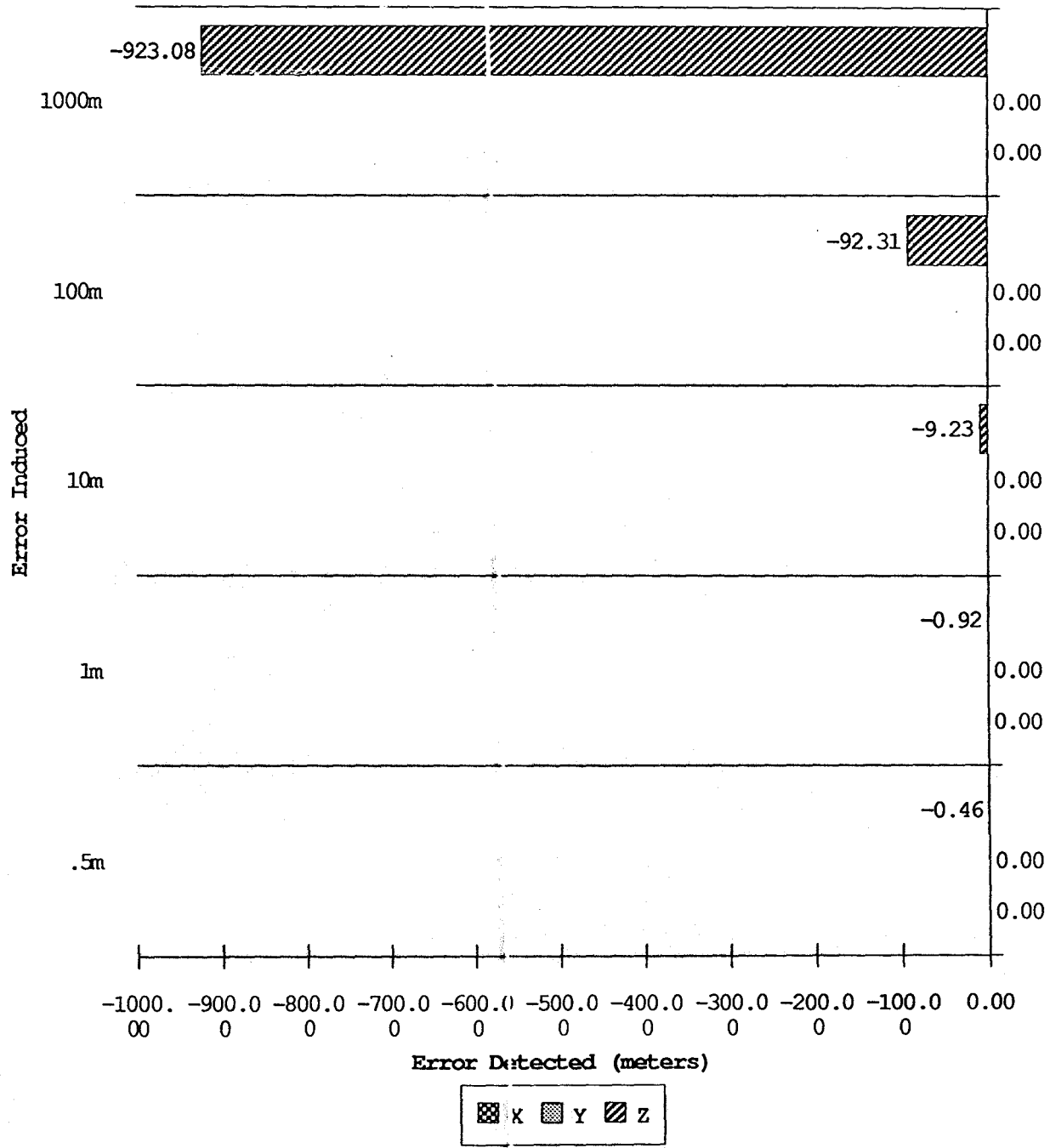
2.2.2.2 Feature Metric - Spatial Correlation Results
(Skew Error Tests)

From Figures 2.2.2.2-1 through 2.2.2.2-3, no patterns arise to indicate the success of the metric. In some of the test cases, the algorithm failed to output results. This effect arises due to the loss of information when rotations occur. Figure 2.2.2.2-A provides an example. A critical line is represented by the thick line within database A. Rotation of A produces database B whose boundaries clip the critical line to form two new lines. In such a case, the feature metric would be unsuccessful in matching the feature in A to one of the features in B.

Database A   Database B
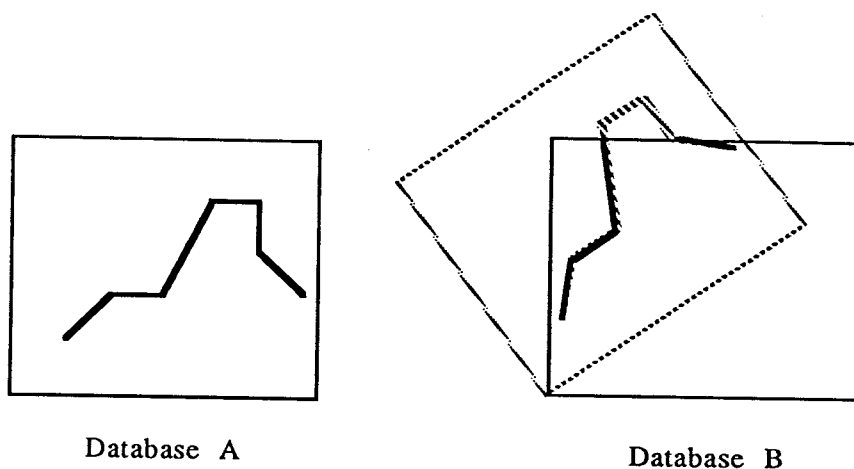
**Figure 2.2.2.2-A   Example of Loss of Information in Critical
Lines with Induced Skews**

FIG 2.2.2.2-1: Feature Metric - Measurement of Skew-X Errors in Set λ Databases (MultiGen)

Y-axis: Error Induced

X-axis: Error Detected (meters)

Legend: X Y Z

Values shown:
- 30°
- 10°: −3.44, 425.00, 575.00
- 1°: −5.70, 20.83, 0.00
- 0.5°: −1.93, 20.83, 0.00

X-axis scale: -100.00, 0.00, 100.00, 200.00, 300.00, 400.00, 500.00, 600.00
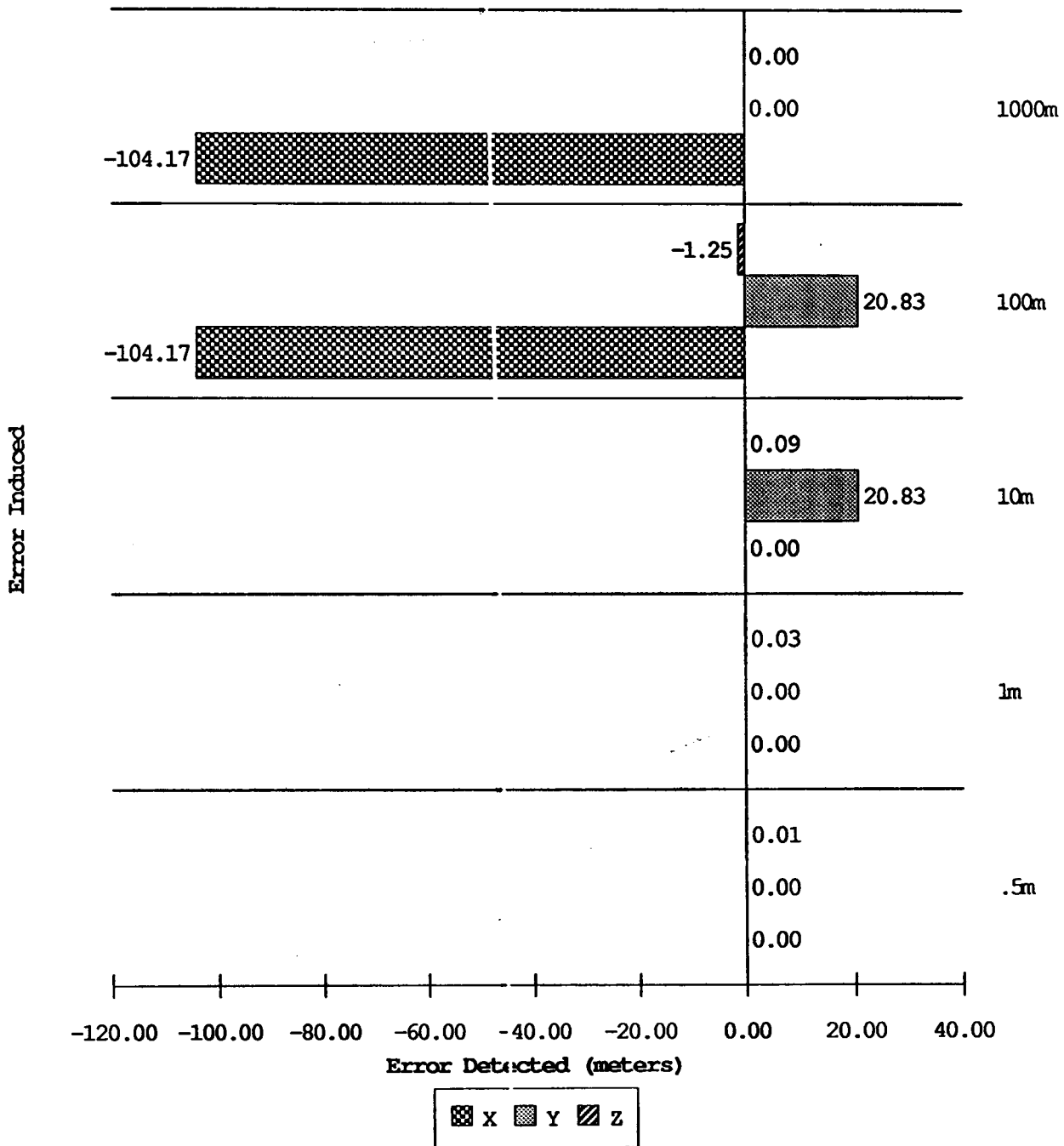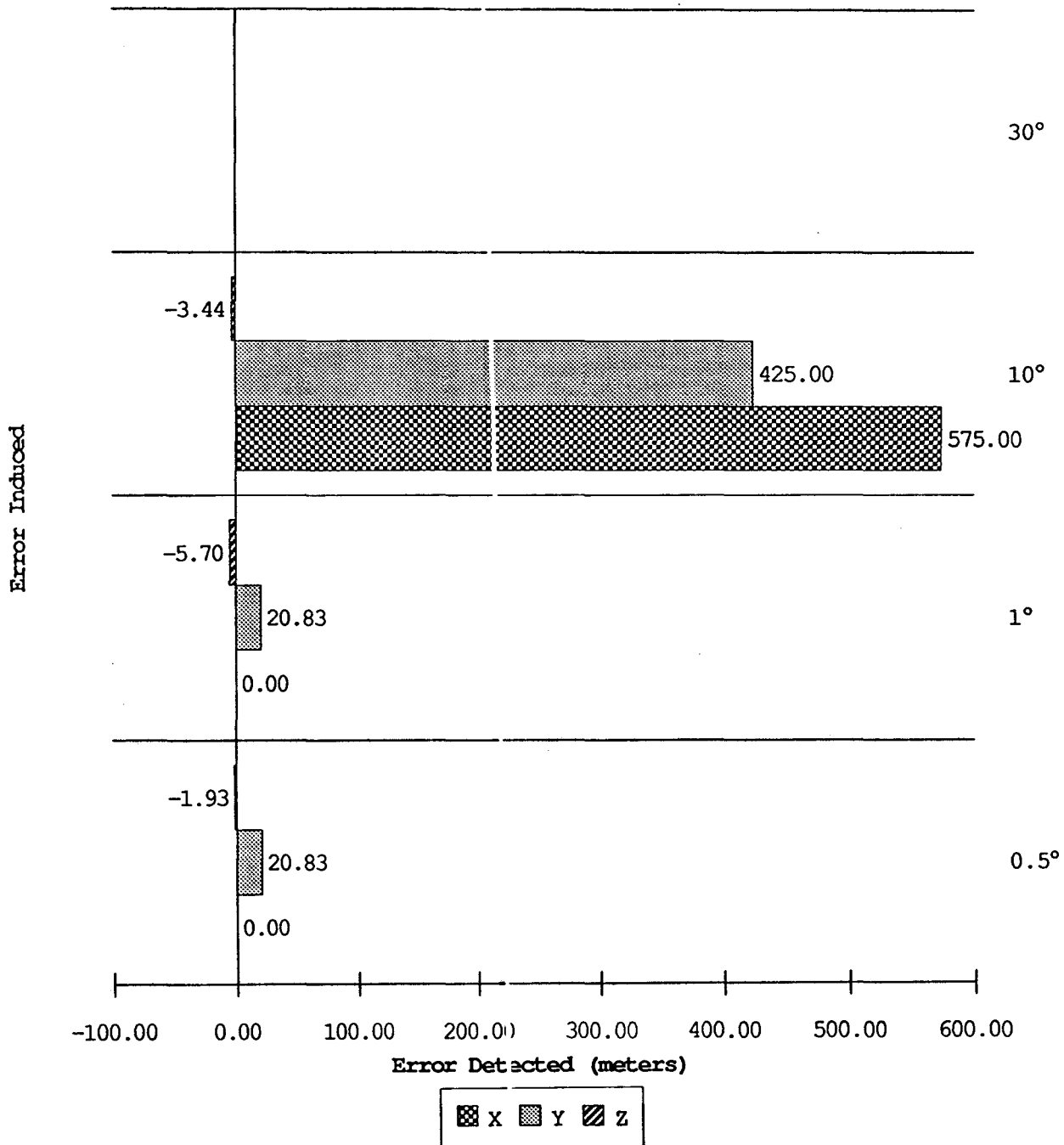
FIG 2.2.2.2-2: Feature Metric - Measurement of Skew-Y
Errors in Set λ Databases (MultiGen)

FIG 2.2.2.2-3: Feature Metric – Measurement of Skew-Z Errors in Set A Databases (MultiGen)

Error Induced

30°

10°

15.68

425.00   1°

575.00

18.51

395.83   0.5°

541.67

0.00   100.00   200.00   300.00   400.00   500.00   600.00

Error Detected (meters)

X Y Z
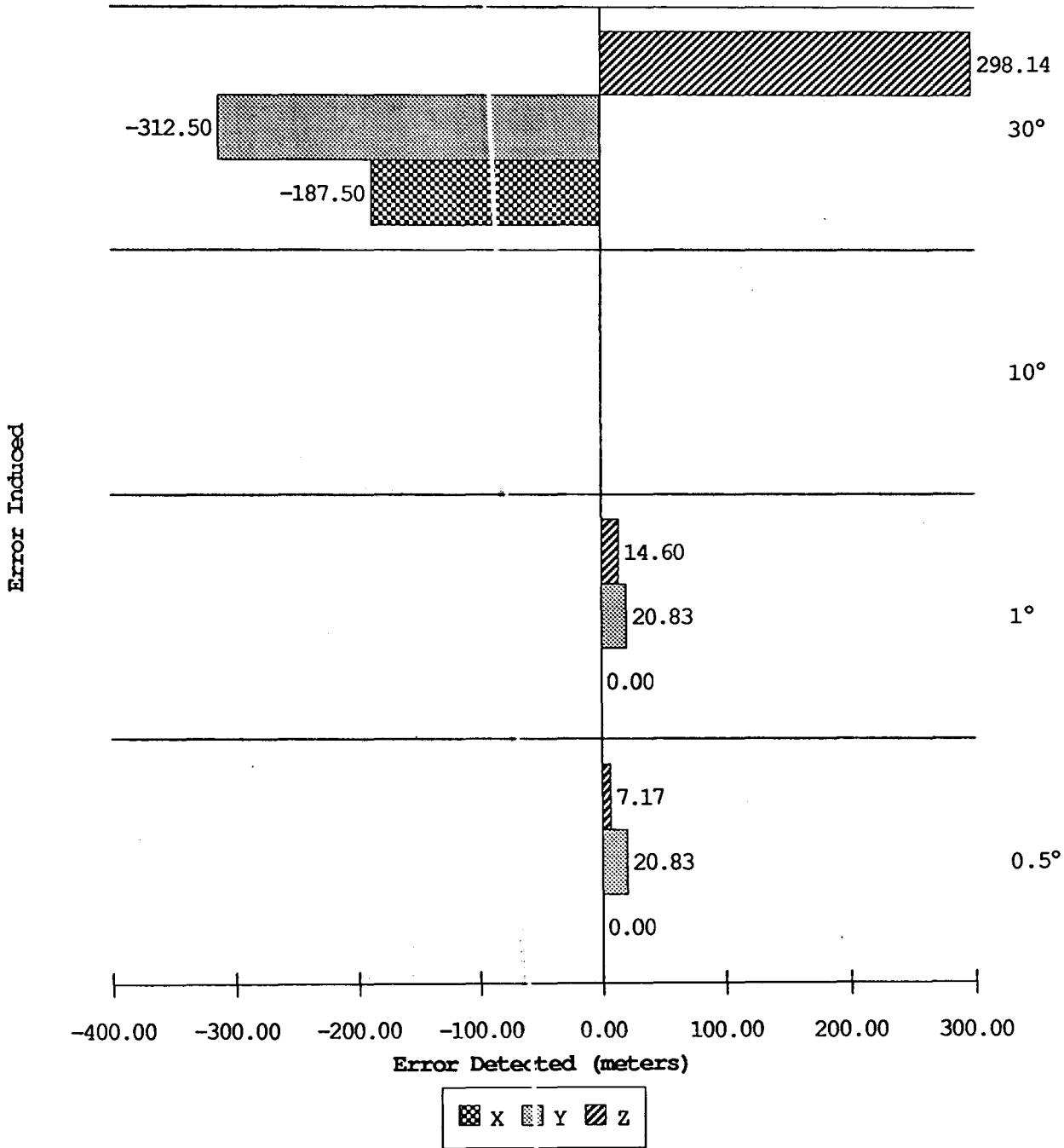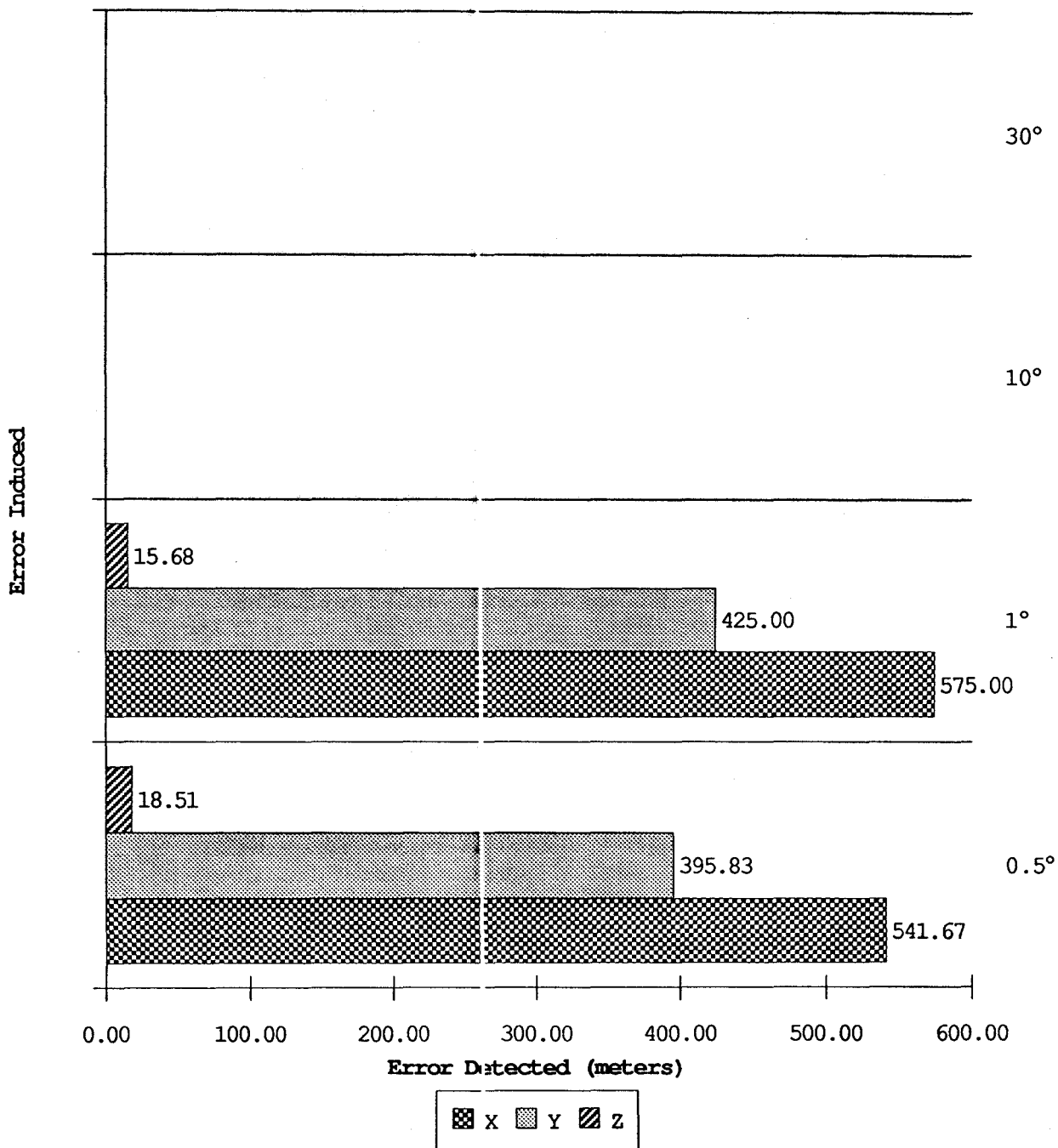
2.2.2.3 Feature Metric - Spatial Correlation Results (Synopsis)

- Can detect a discrepancy, but not the particular type of discrepancy.
- Cannot detect some skews.

NOTE: These results are based on a single error induced on the database.

2.3 Hausdorf Metric

Applicability: Rendered Image and Spatial Correlation

Errors to Detect: Shifts, Skews (terrain databases and images)
                                  Warping, Sampling (terrain databases)
                                  Dilation (images)

Input Data Type: - elevation grid (terrain databases)
                                  - array of gray-scale or color values (images)

2.3.1 Hausdorf Metric - Algorithm

The following algorithm was developed from references collected from
the literature search.

The Hausdorff distance provides a measure of the differences between
two data sets.   To understand the Hausdorff distance, the concept of a
metric space must first be established.

Definition: Let X be any set.   Let d be a function which maps two
members of the set into the real numbers.   Now if d satisfies the
properties

$$(1)\quad d(x,y) = d(y,x) \forall x,y \in X$$

$$(2)\quad d(x,y) \geq 0 \forall x,y \in X$$

$$(3)\quad d(x,y) = 0 \Leftrightarrow x = y \quad \forall x,y \in X$$

$$(4)\quad d(x,z) \leq d(x,y) + d(y,z) \forall x,y \in X \quad \text{(Triangle Inequality)}$$

then d is called a metric.   (X,d) is then called the metric space
[Rosenlicht68].   Intuitively, the metric can be thought of as a "distance"
between two members of a set.

For example, let X be the real plane (i.e. $X=\Re$).   Now for

$x=(x_1, x_2)$, $y = (y_1, y_2) \in \Re^2$, define d by

$$d(x,y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2}$$

Then d is a metric on the real plane.   Observe that this metric gives the
actual distance between two points on the real plane.

The Hausdorff distance is used to define a distance between sets of points in a general metric space. Suppose that a general metric space (X,d) is given. Then the Hausdorff distance will yield a numerical difference corresponding to the distance between subsets of X. The Hausdorff distance is constructed from the original metric of the metric space in the following way:

First, a distance from a point in X to a subset of X is needed. Consider a general subset, $S \subseteq X$, and any point, $x \in X$. Then define the distance, d_1 of point x to subset S as

$$d_1(x,S) = \min\{d(x,s): \forall s \in S\}$$

The constructed distance from a point to a set is then utilized to construct a distance between two subsets of X. Now consider any two subsets S_1, $S_2 \subseteq X$. Define the distance, d_2, from subset S_1 to subset S_2 as

$$d_2(S_1,S_2) = \max\{d_1(s_1,S_2): \forall s_1 \in S_1\}.$$

Thus a distance from one set to the other has been constructed. However, d_2 does not satisfy the symmetry property of a metric. To resolve this, define h as

$$h(A,B) = \max\{d_2(A,B), d_2(B,A)\}.$$

Then h is called the Hausdorf distance induced on the metric space (X,d) [Barnsley88].

The Hausdorf distance is equally applicable to geometric and rendered image correlation. For geometric correlation, the two subsets are represented by two elevation grids from terrain databases to be compared. The (x, y, z) triplet corresponds to latitude, longitude, and elevation, respectively. For rendered image correlation, the subsets are represented as arrays of gray-scale or color values. The x and y values of the (x, y, z) triplet for images represents the row and column location of the pixel. The z value is the gray-scale or color value. For both types of data, the algorithm is as follows:

Hausdorff Distance Metric Algorithm

1. For each point in data set A,
        compute the distance to each point in data set B
        select and store the minimum distance
2. Calculate the maximum value from step 1.

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3. For each point in data set B,
   compute the distance to each point in data set A
   select and store the minimum distance
4. Calculate the maximum value from step 3.
5. Output the maximum distance between steps 6 and 7.
6. Average and output the x, y, and z distances in steps 1 and 3.

Because the Hausdorff distance indicates only the magnitude of the discrepancy and not the type (e.g. shift, skew, warping, sampling, or dilation), step 6 attempts to detect shifts along individual axes. This approach is similar to the MinMax metric.

2.3.2 Hausdorf Metric - Image Correlation Results

During the writing of this report, an error was discovered in the implementation of the image correlation Hausdorf metric. Those results that could be regenerated in the time remaining are shown in the following sections.

2.3.2.1 Hausdorf Metric - Image Correlation Results (Shift Error Tests)

As shown in Figures 2.3.2.1-1 through 2.3.2.1-4, can detect the magnitude of the shift to some degree. However, this appears to be dependent on the image type. Thus the metric could only be used to detect the discrepancy, but not the magnitude.

FIG 2.3.2.1-1: Hausdorff Metric – Measurement of Shift-X
Errors in Set A Images (Checkerboard)

FIG 2.3.2.1-2: Hausdorff Metric - Measurement of Shift-X Errors in Set A Images (Circle)

FIG 2.3.2.1-3: Hausdorff Metric – Measurement of Shift-Y Errors in Set A Images (Checkerboard)

Error Induced

- 80 pixels: −22.00, 5.00, −21.00
- 32 pixels: −22.00, 5.00, −21.00
- 16 pixels: 1.00, 5.00, −16.00
- 3 pixels: 1.00, −3.00, −3.00

Error Detected (meters)

Legend: ▦ X ▥ Y ▨ Z
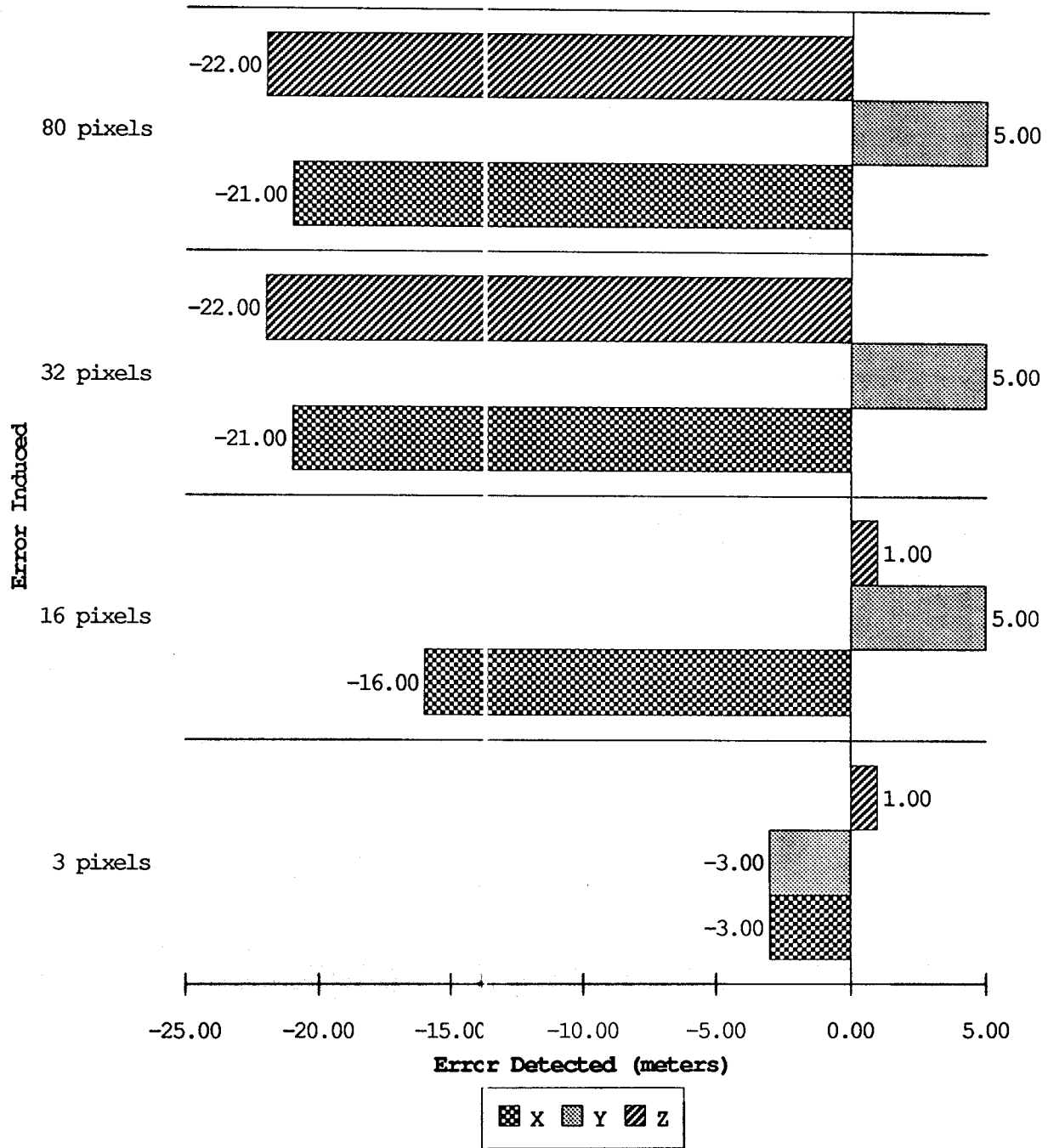
FIG 2.3.2.1-4: Hausdorff Metric - Measurement of Shift-Y
Errors in Set A Images (Circle)
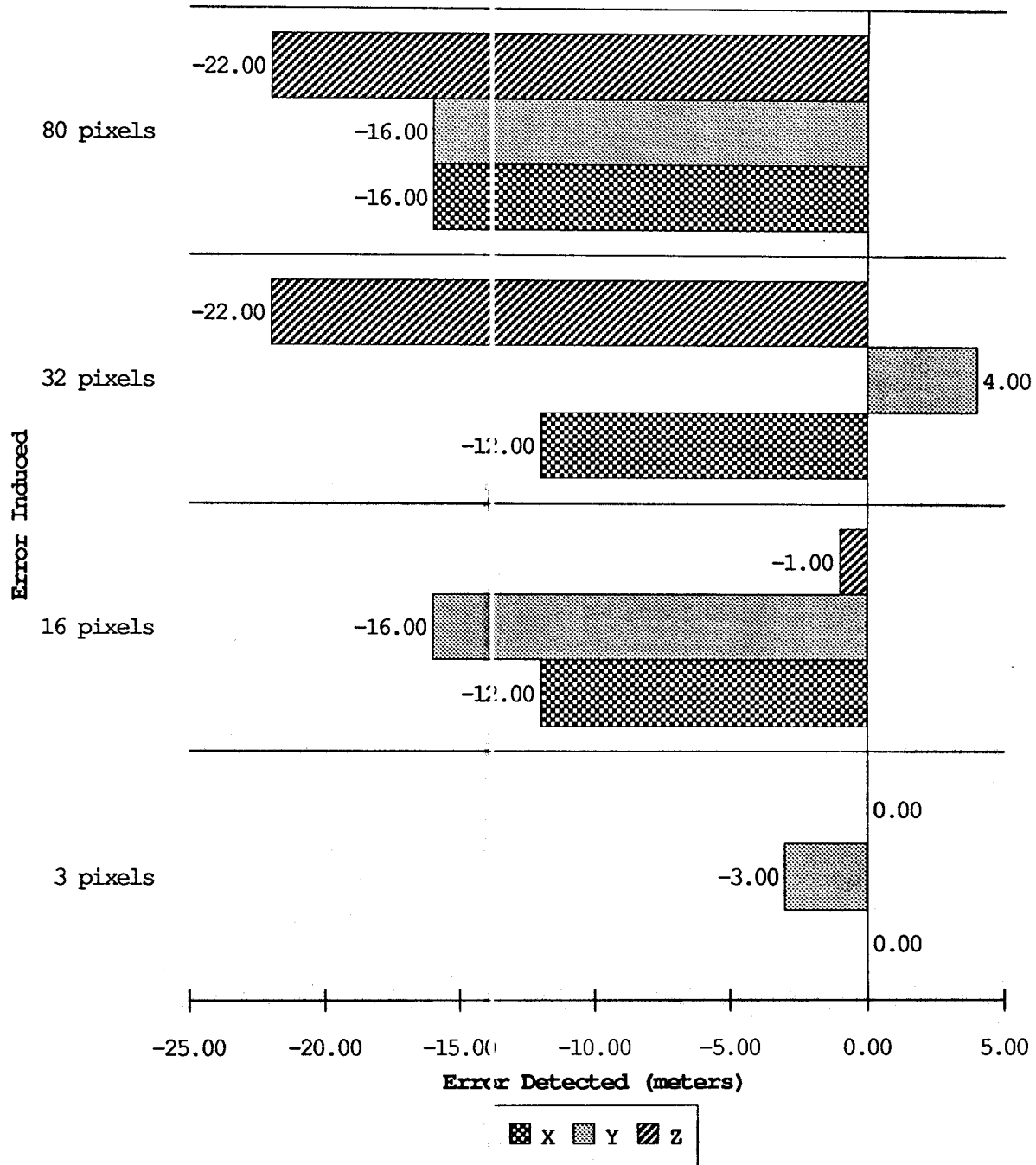
**2.3.2.2 Hausdorf Metric - Image Correlation Results
(Skew   Error   Tests)**

As with shifts, measurement of the amount of skew is dependent upon
the type of image.   This is illustrated in Figures 2.3.2.2-1 and 2.3.2.2-2.
Thus, this metric may not be capable of measuring the magnitude of
skew.

FIG 2.3.2.2-1: Hausdorff Metric – Measurement of Skew-Z Errors in Set A Images (Checkerboard)

Error Induced

-22.00
21.00
21.00   30°

-22.00
-21.00   15°
21.00

-22.00
18.00   10°
22.00

1.00
10.00   5°
-14.00

-1.00
7.00   3°
9.00

-1.00
7.00   1°
4.00

-25.00 -20.00 -15.00 -10.00 -5.00 0.00 5.00 10.00 15.00 20.00 25.00

Error Detected (meters)

X Y Z
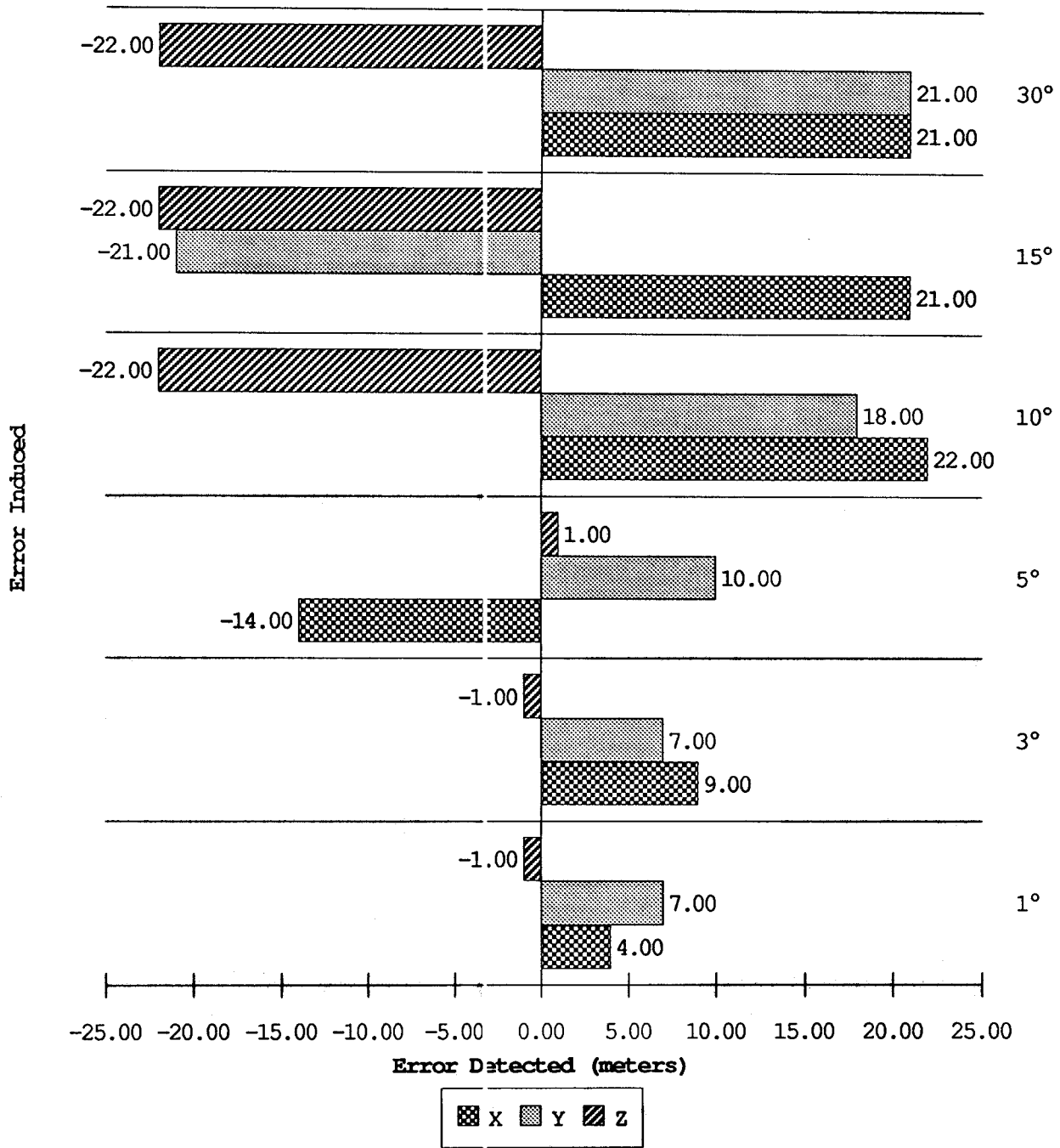
FIG 2.3.2.2-2: Hausdorff Metric - Measurement of Skew-Z Errors in Set A Images (Circle)
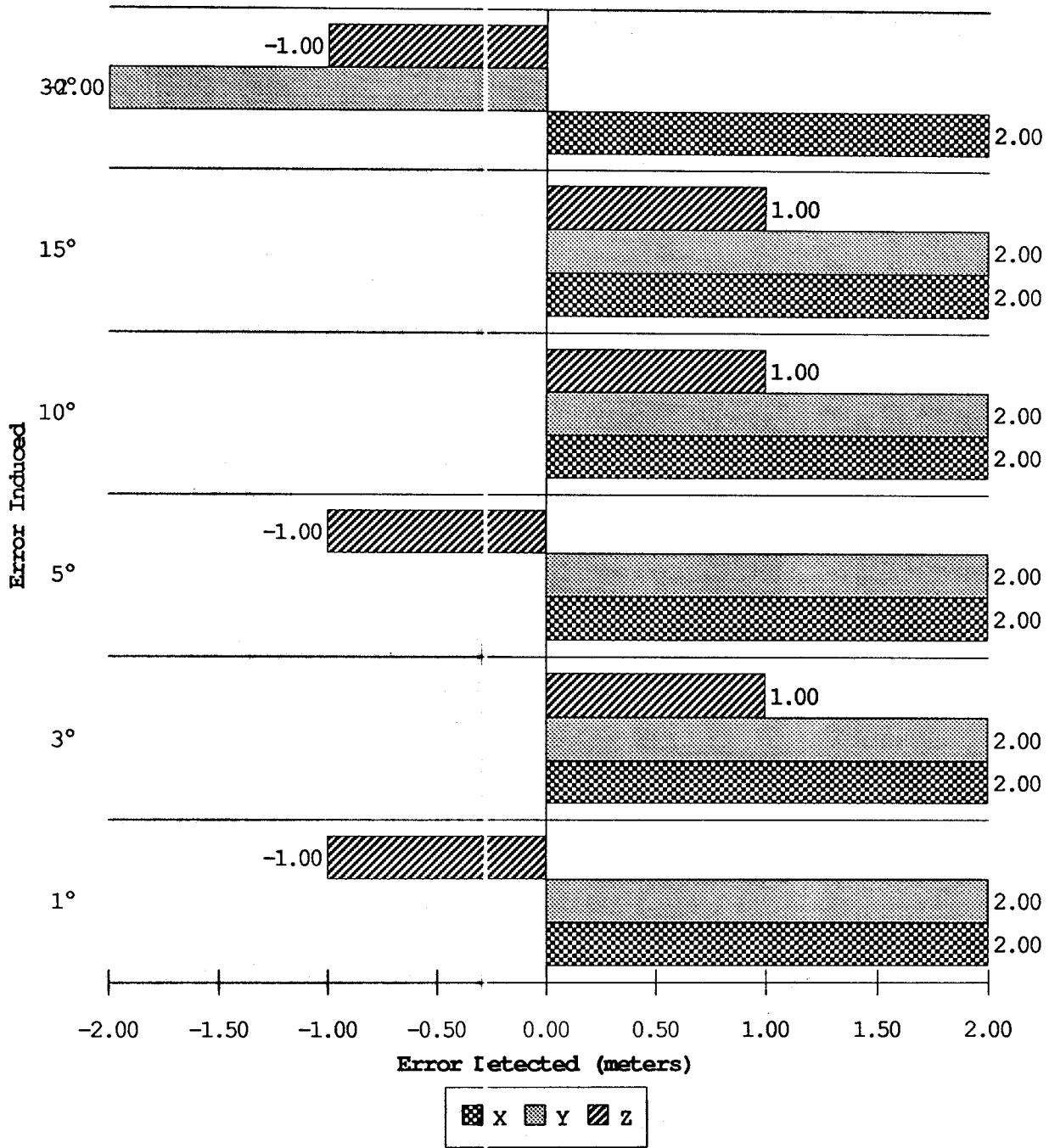
2.3.2.3   Hausdorf   Metric   -   Image   Correlation   Results
(Dilation/Magnification   Error   Tests)

Measurement of the degree of dilation also appears unfeasible with the Hausdorf Metric.   Figures 2.3.2.3-1 and 2.3.2.3-2 show no discernible pattern between measured error and amount of induced error.

FIG 2.3.2.3-1: Hausdorff Metric – Measurement of Dilation
Errors in Set A Images (Checkerboard)
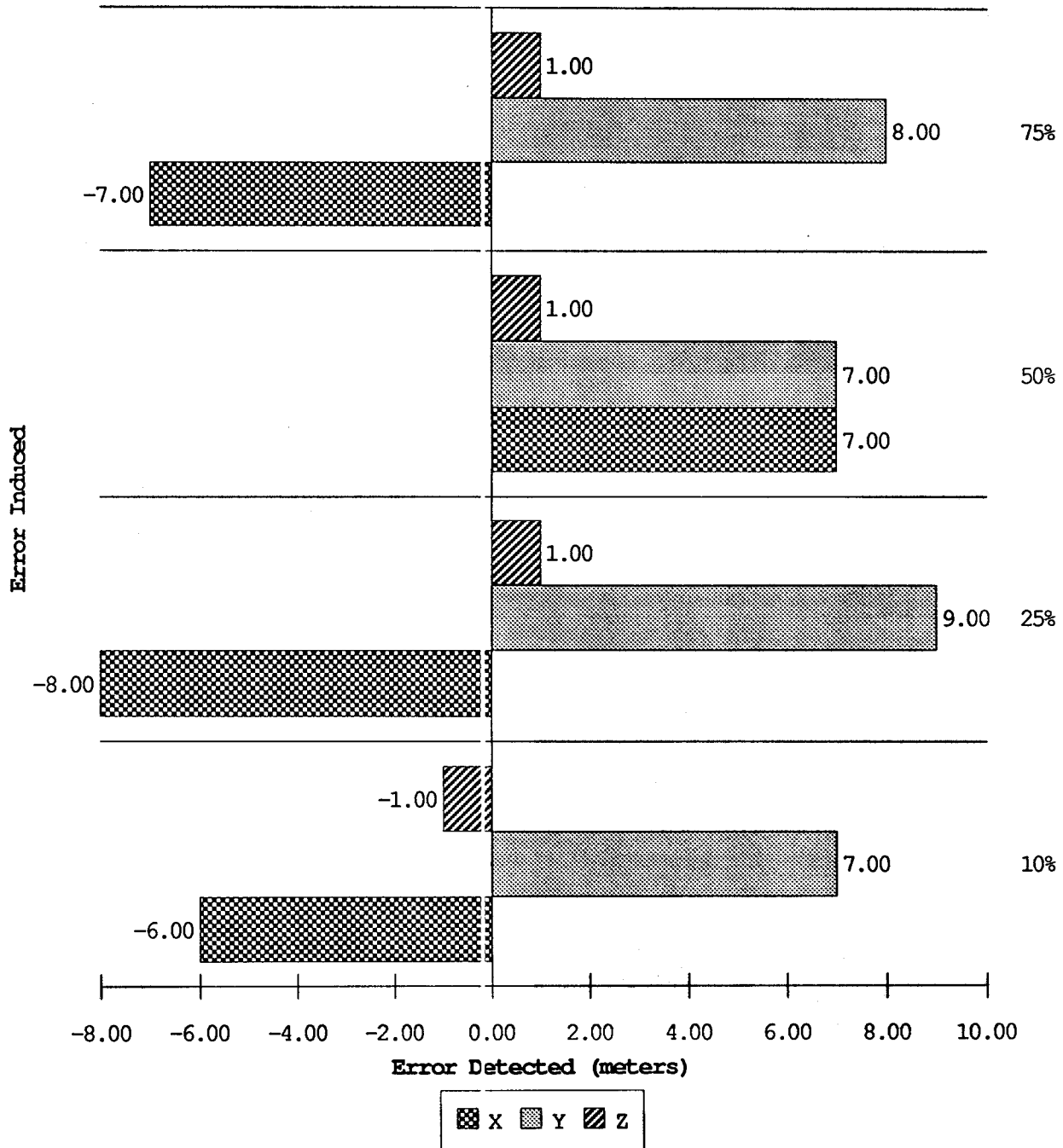
FIG 2.3.2.3-2: Hausdorff Metric – Measurement of Dilation Errors in Set A Images (Circle)

Y-axis label: Error Induced

X-axis label: Error Detected (meters)

X-axis values: -2.00, 0.00, 2.00, 4.00, 6.00, 8.00, 10.00, 12.00, 14.00, 16.00

Right-side labels: 75%, 50%, 25%, 10%

Bar values:
- 1.00
- -2.00
- 2.00
- 1.00
- 15.00
- 15.00
- 1.00
- 6.00
- 6.00

Legend: X Y Z
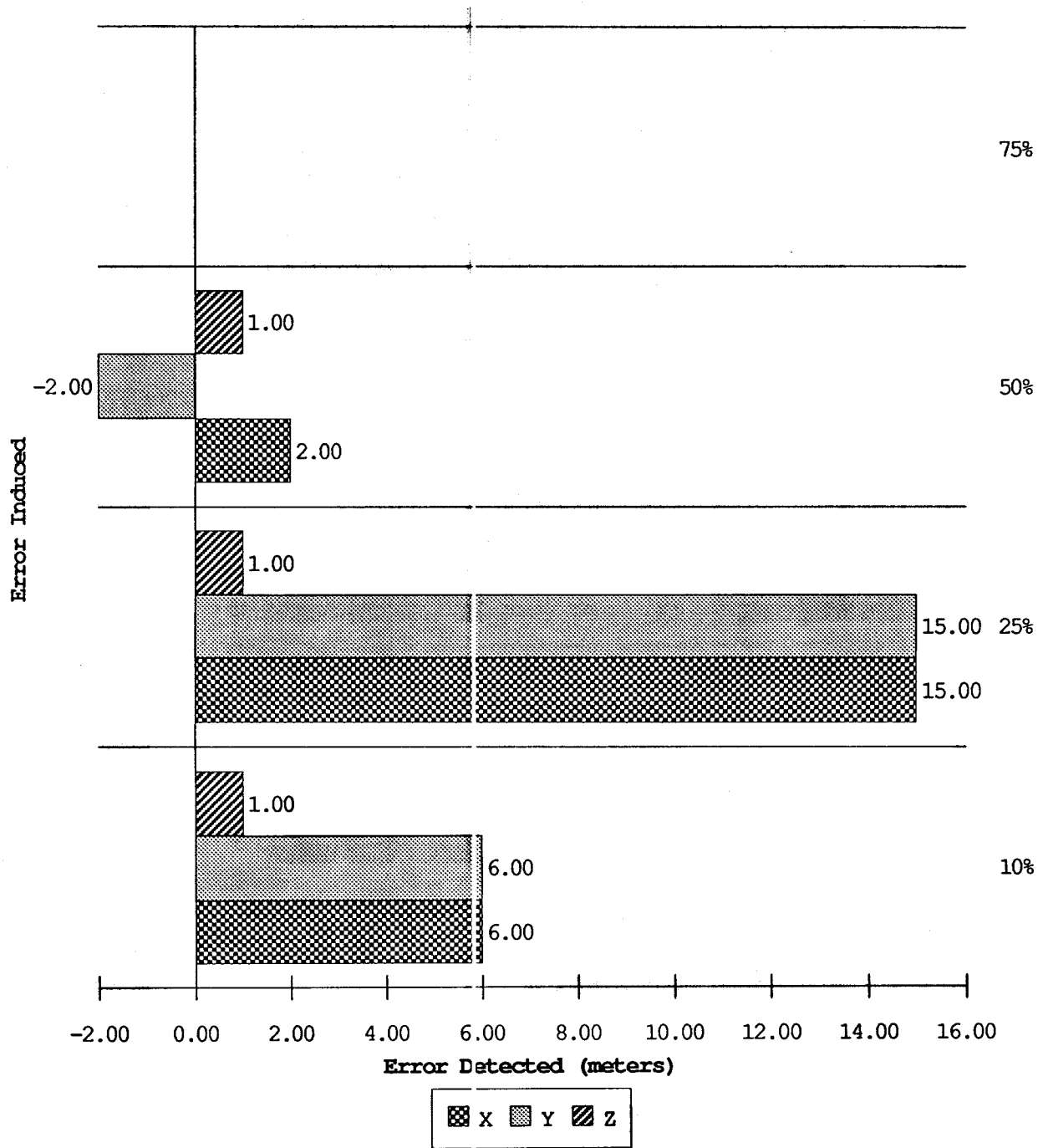
2.3.3.5   Hausdorf Metric - Image Correlation Results
(Synopsis)

- Can determine if shift, skew, or dilation present, but cannot identify type.
- Cannot determine magnitude of error.

NOTE: These results are based on a single error induced on the database.

2.3.3 Hausdorf Metric - Spatial Correlation Results

During the writing of this report, an error was detected in the code for the spatial Hausdorf distance prototype metric. Instead of calculation of the Hausdorff distance, the H value in the following charts represents the following quantity:

$$H = \sqrt{X^2 + Y^2 + Z^2}$$

where X, Y, and Z are the values shown in the following charts. Recall that X, Y, and Z represent the averages of the x, y, and z distances between nearest neighbor points in the two databases.

2.3.3.1 Hausdorf Metric - Spatial Correlation Results (Shift Error Tests)

Figures 2.3.3.1-1 through 2.3.3.1-6 indicate Hausdorff can detect the relative magnitude of induced shifts along any axis. In closer examination of cases with induced X and Y shifts, it may be possible that this metric can also detect the axis and magnitude of shifts as large as, or larger than, the elevation grid resolution. Changes in Z occur for these cases because the sampling locations have changed, as explained previously in Section 2.1.3.1 and Figure 2.1.3.1-A. For Z shifts, this metric can produce a good estimate of the discrepancy for small differences in elevation (Figures 2.3.3.1-3 and 2.3.3.1-6).
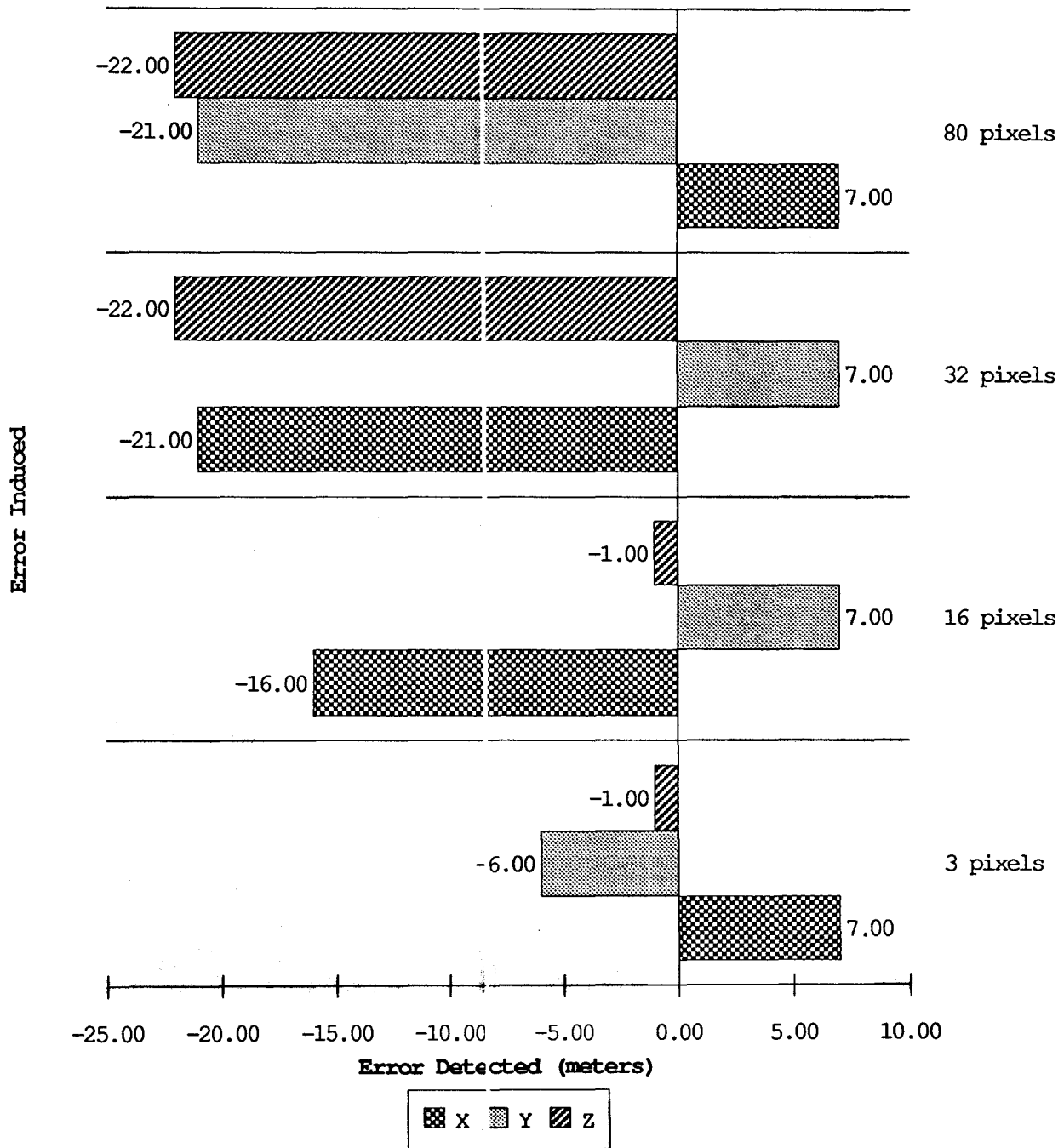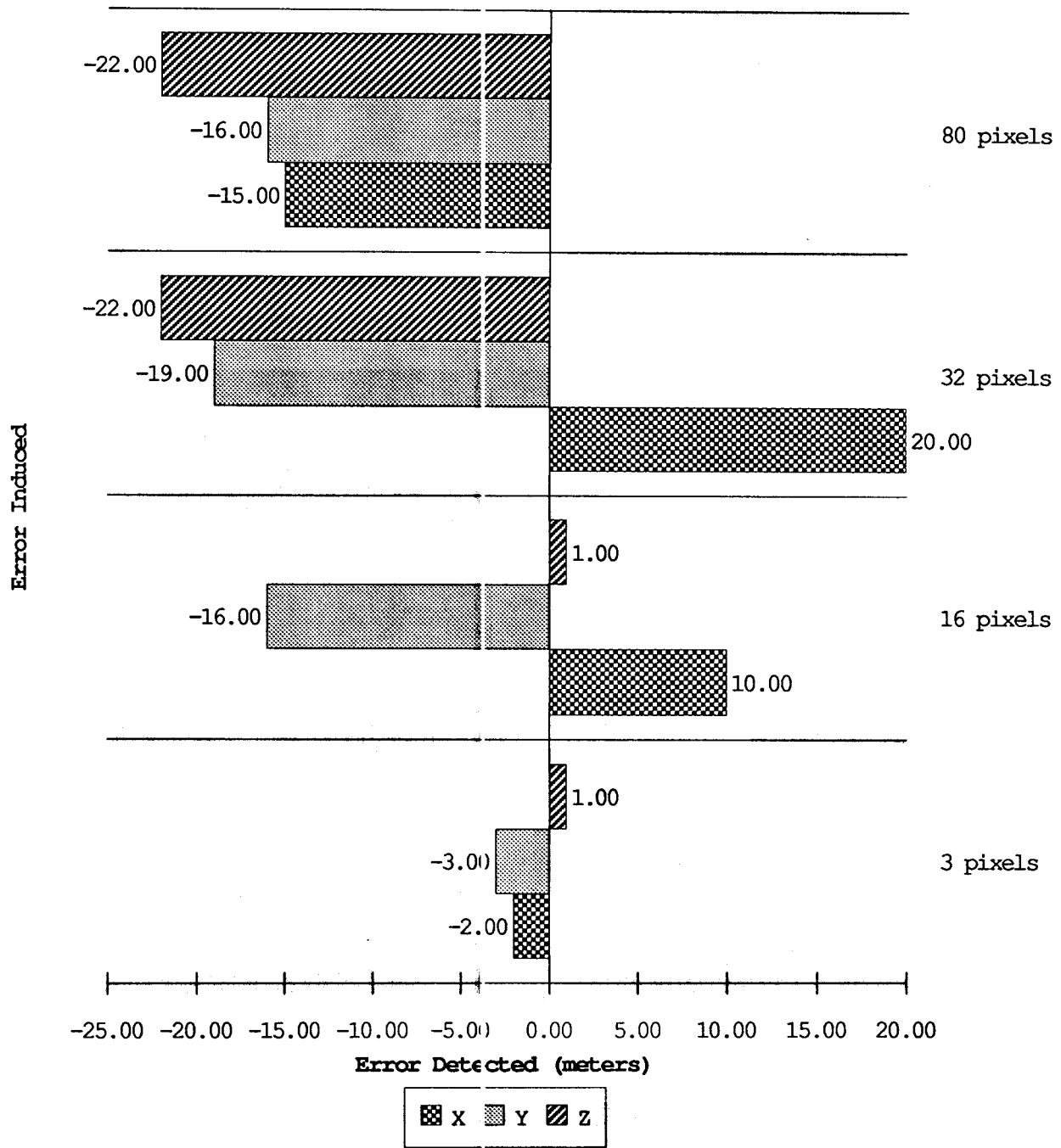
FIG 2.3.3.1-1: Hausdorff Metric - Measurement of Shift-X
Errors in Set A Databases (MultiGen)
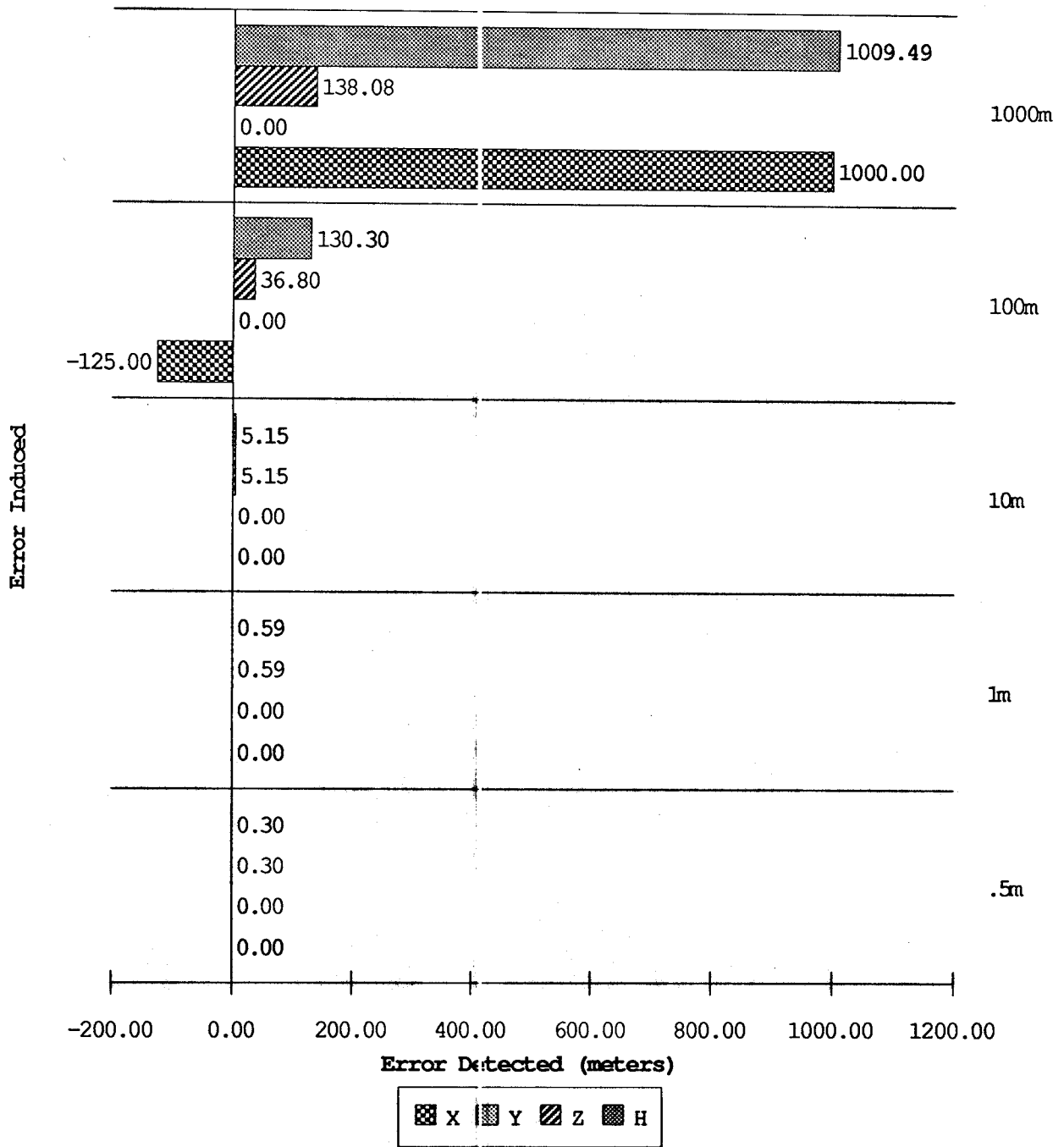
FIG 2.3.3.1-2: Hausdorff Metric – Measurement of Shift-Y Errors in Set 1. Databases (MultiGen)

Error Induced

1018.80		1000m
194.79		
1000.00		
0.00		
130.77		100m
38.43		
-125.00		
0.00		
4.51		10m
4.51		
0.00		
0.00		
0.45		1m
0.45		
0.00		
0.00		
0.23		.5m
0.23		
0.00		
0.00		

-200.00   0.00   200.00   400.00   600.00   800.00   1000.00   1200.00

Error Detected (meters)

⊠ X   ▦ Y   ▨ Z   ▨ H
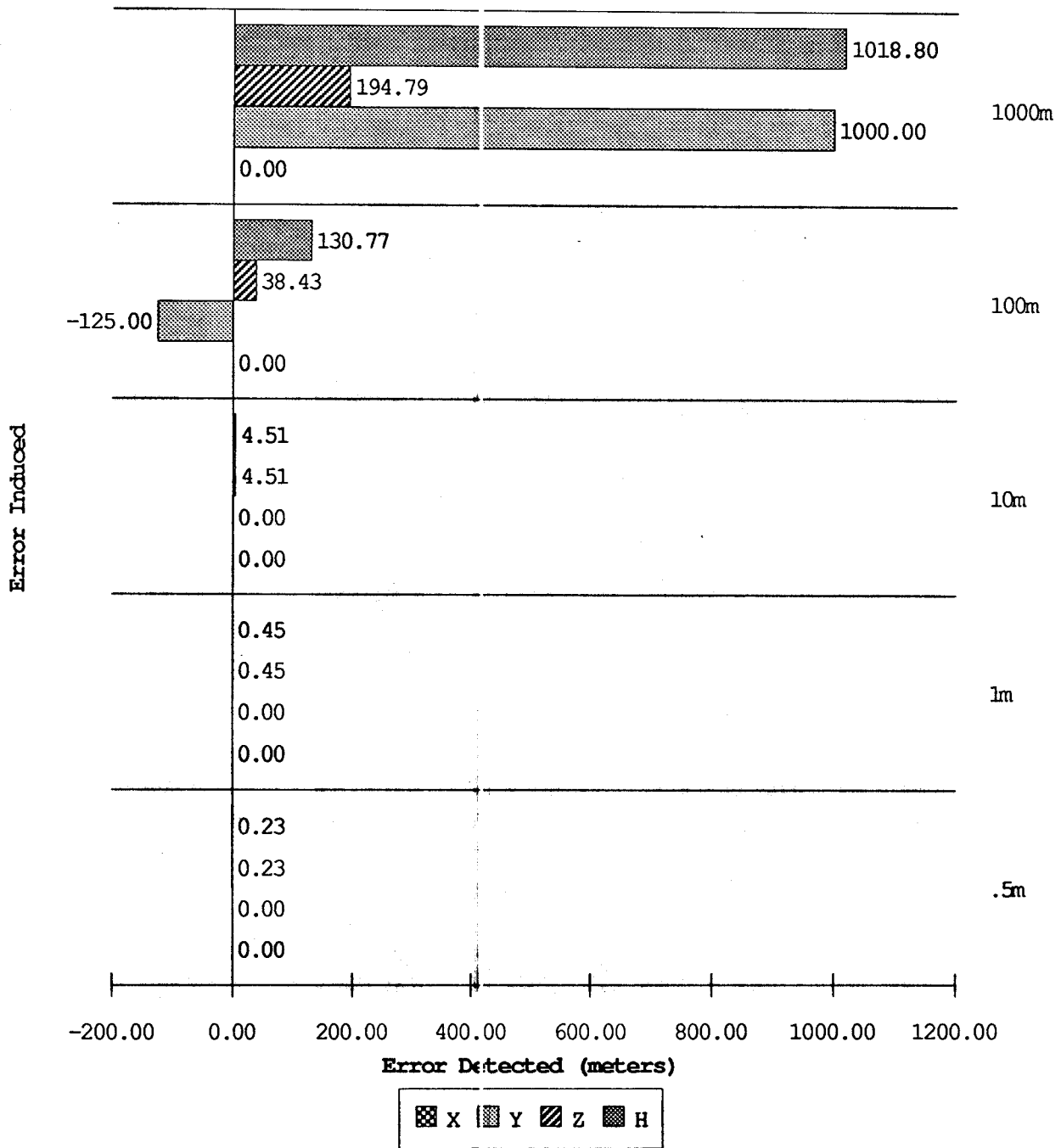
FIG 2.3.3.1-3: Hausdorff Metric – Measurement of Shift-Z Errors in Set A Databases (MultiGen)

Error Induced

1096.87
1000.00
−375.00
250.00
1000m

100.00
−100.00
0.00
0.00
100m

10.00
−10.00
0.00
0.00
10m

1.00
−1.00
0.00
0.00
1m

0.50
−0.50
0.00
0.00
.5m

−400.00 −200.00 0.00 200.00 400.00 600.00 800.00 1000.00 1200.00

Error Detected (meters)

X   Y   Z   H
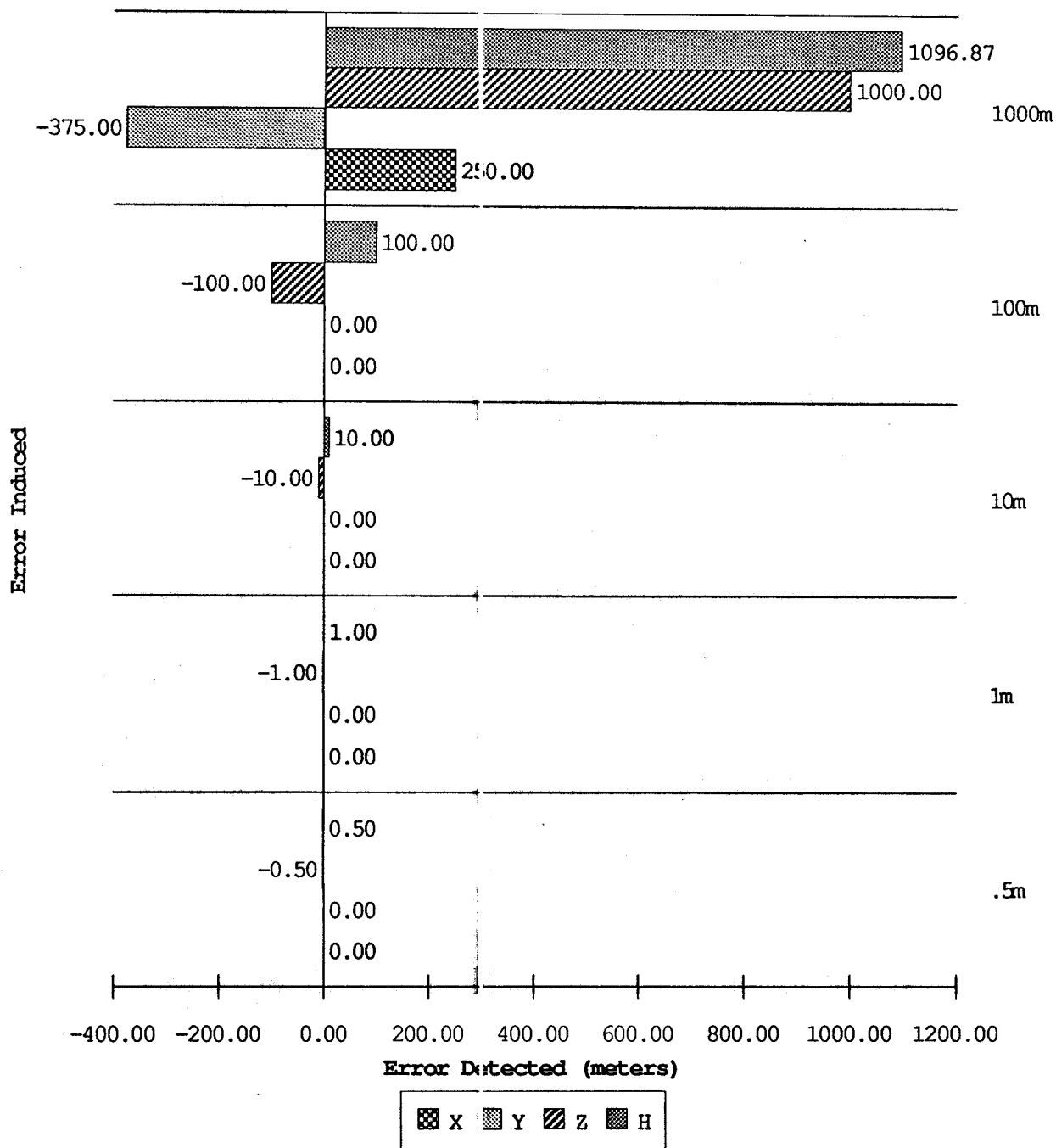
FIG 2.3.3.1-4: Hausdorff Metric - Measurement of Shift-X Errors in Set A Databases (S1000)
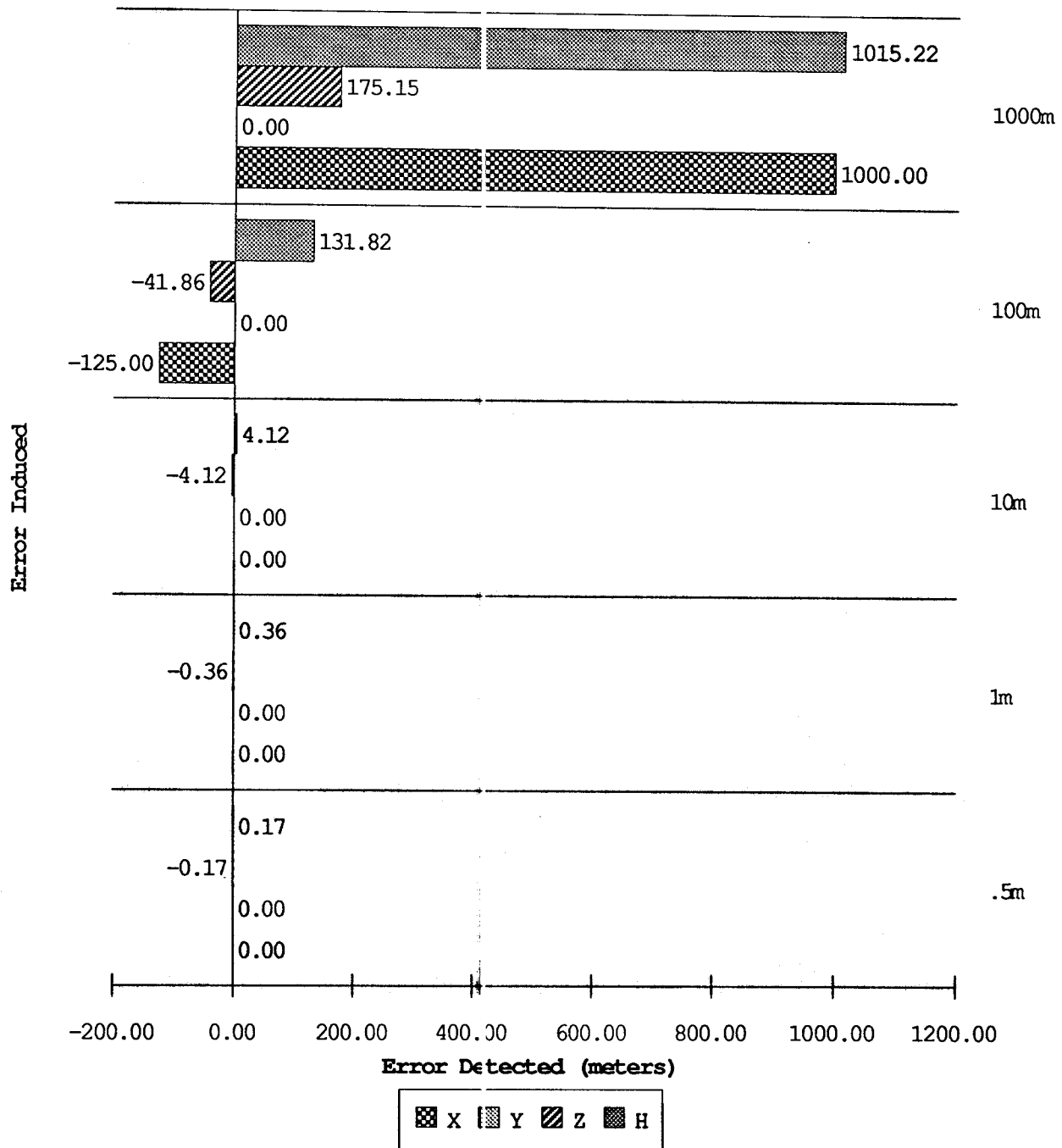
1015.22

175.15

0.00

1000m

1000.00

131.82

−41.86

0.00

100m

−125.00

4.12

−4.12

0.00

10m

0.00

0.36

−0.36

0.00

1m

0.00

0.17

−0.17

0.00

.5m

0.00

Error Induced

−200.00   0.00   200.00   400.00   600.00   800.00   1000.00   1200.00

Error Detected (meters)

X   Y   Z   H

FIG 2.3.3.1-5: Hausdorf: Metric – Measurement of Shift-Y Errors in Set A Databases (S1000)

Error Induced (vertical axis)

1000m
- 1013.74
- −166.32
- 1000.00
- 0.00

100m
- 136.69
- −55.31
- −125.00
- 0.00

10m
- 5.51
- −5.51
- 0.00
- 0.00

1m
- 0.53
- −0.53
- 0.00
- 0.00

.5m
- 0.25
- −0.25
- 0.00
- 0.00

Horizontal axis: −200.00, 0.00, 200.00, 400.00, 600.00, 800.00, 1000.00, 1200.00

Error Detected (meters)

Legend: X Y Z H
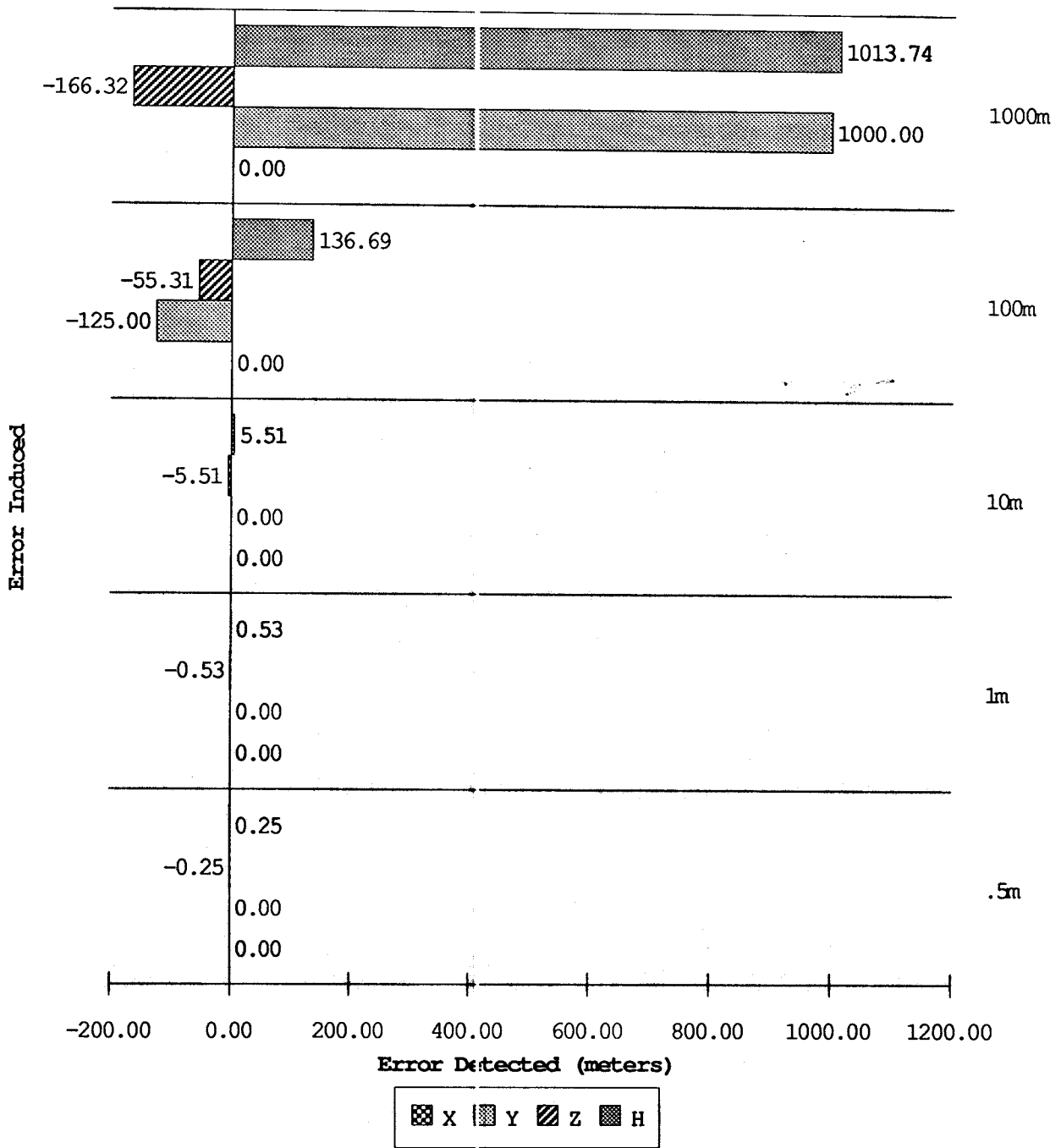
FIG 2.3.3.1-6: Hausdorff Metric - Measurement of Shift-Z
Errors in Set A Databases (S1000)
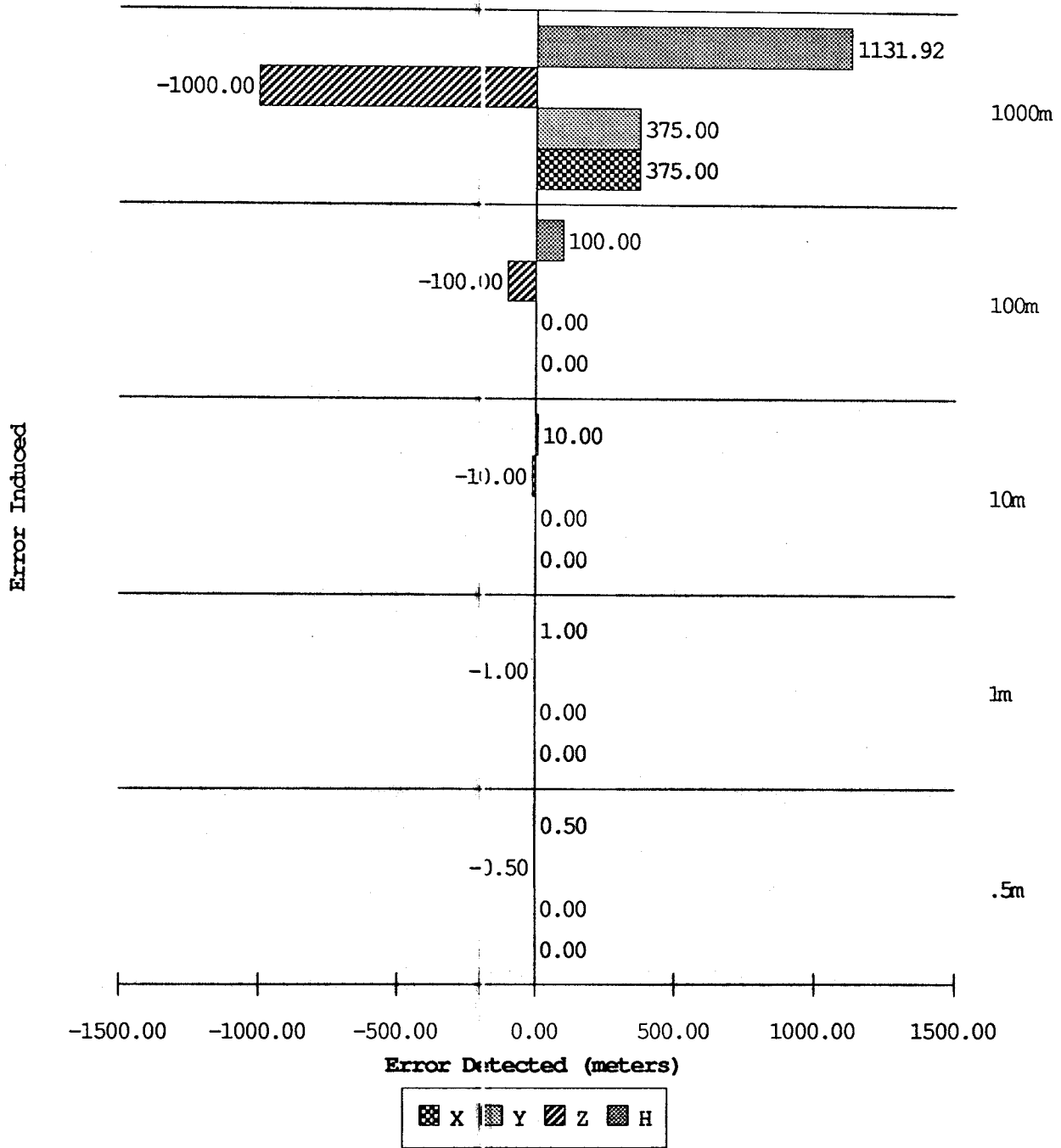
2.3.3.2 Hausdorf Metric - Spatial Correlation Results (Skew Error Tests)

For skews along the X and Y axes, this metric can detect the relative magnitude of the rotation, as shown by Figures 2.3.3.2-1 and 2.3.3.2-2. However, the metric is unsuccessful in detecting magnitudes of Z rotations (Figure 2.3.3.2-3). In all cases, the axis of rotation cannot be indicated for any type of rotation.

FIG 2.3.3.2-1: Hausdorff Metric - Measurement of Skew-X Errors in Set A Databases (MultiGen)

X-axis: Error Detected (meters)
Y-axis: Error Induced

Legend: X Y Z H

30°
- 1148.91
- 1019.18
- 375.00
- −375.00

10°
- 352.07
- 304.47
- 125.00
- −125.00

1°
- 29.16
- −29.16
- 0.00
- 0.00

0.5°
- 14.55
- −14.55
- 0.00
- 0.00

X-axis labels: −400.00 −200.00 0.00 200.00 400.00 600.00 800.00 1000.00 1200.00
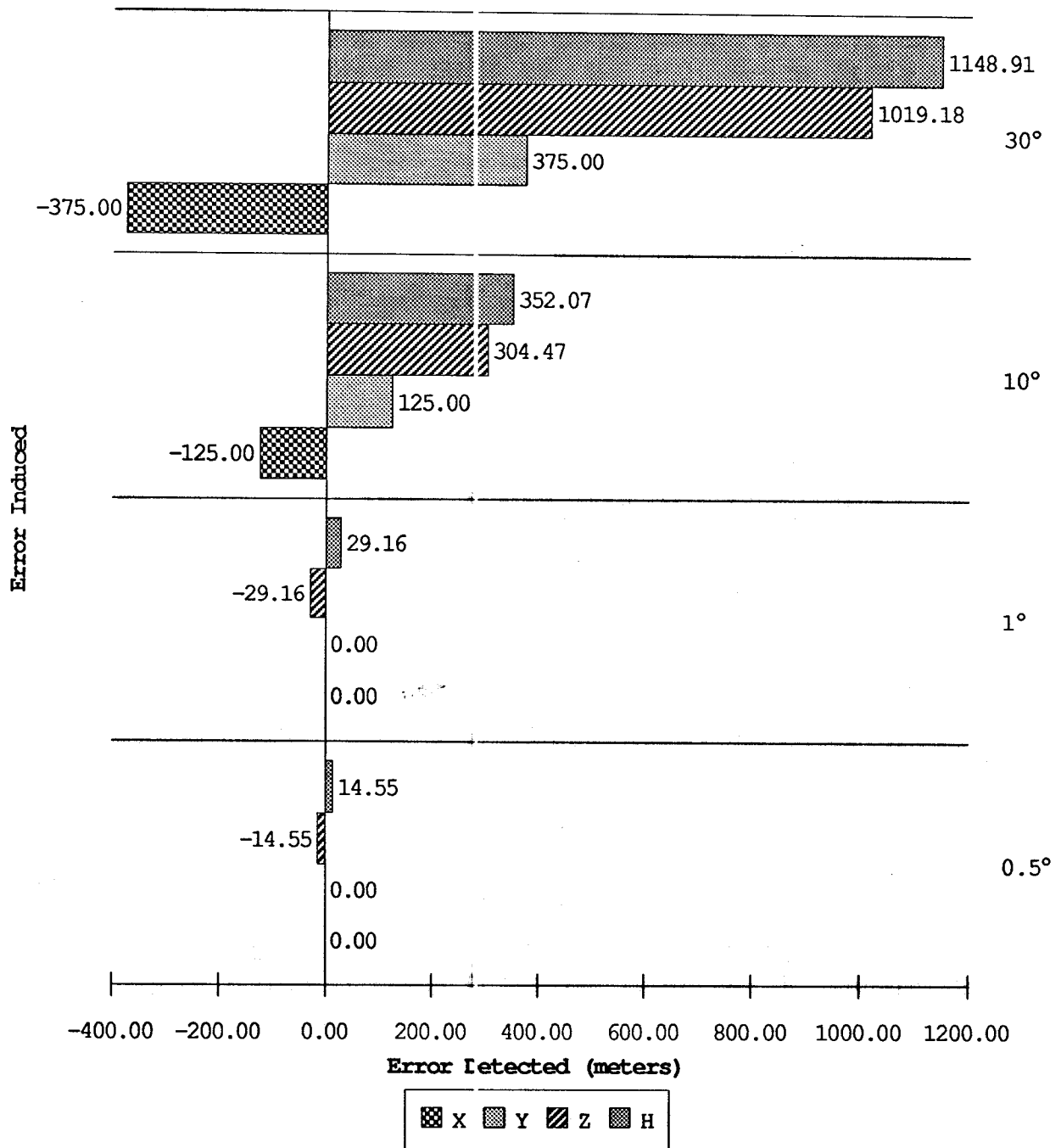
FIG 2.3.3.2-2: Hausdorff Metric – Measurement of Skew-Y Errors in Set A Databases (MultiGen)

Error Induced

809.93
−728.69
−250.00
250.00

30°

306.50
−250.39
125.00
125.00

10°

24.28
24.28
0.00
0.00

1°

12.13
12.13
0.00
0.00

0.5°

−800.00 −600.00 −400.00 −200.00   0.00   200.00   400.00   600.00   800.00 1000.00

Error Detected (meters)

X   Y   Z   H
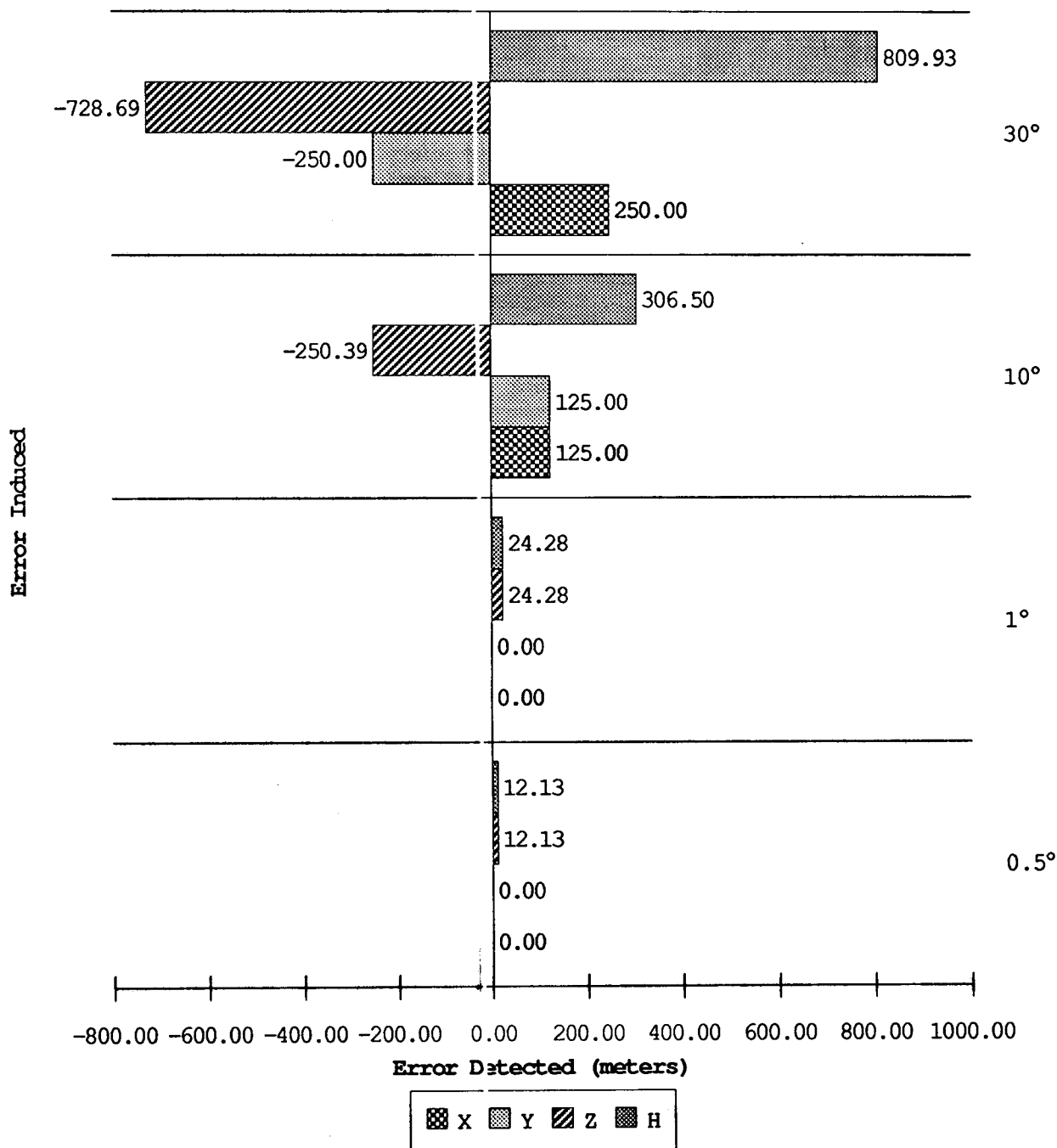
FIG 2.3.3.2-3: Hausdorff Metric – Measurement of Skew-Z
Errors in Set A Databases (MultiGen)
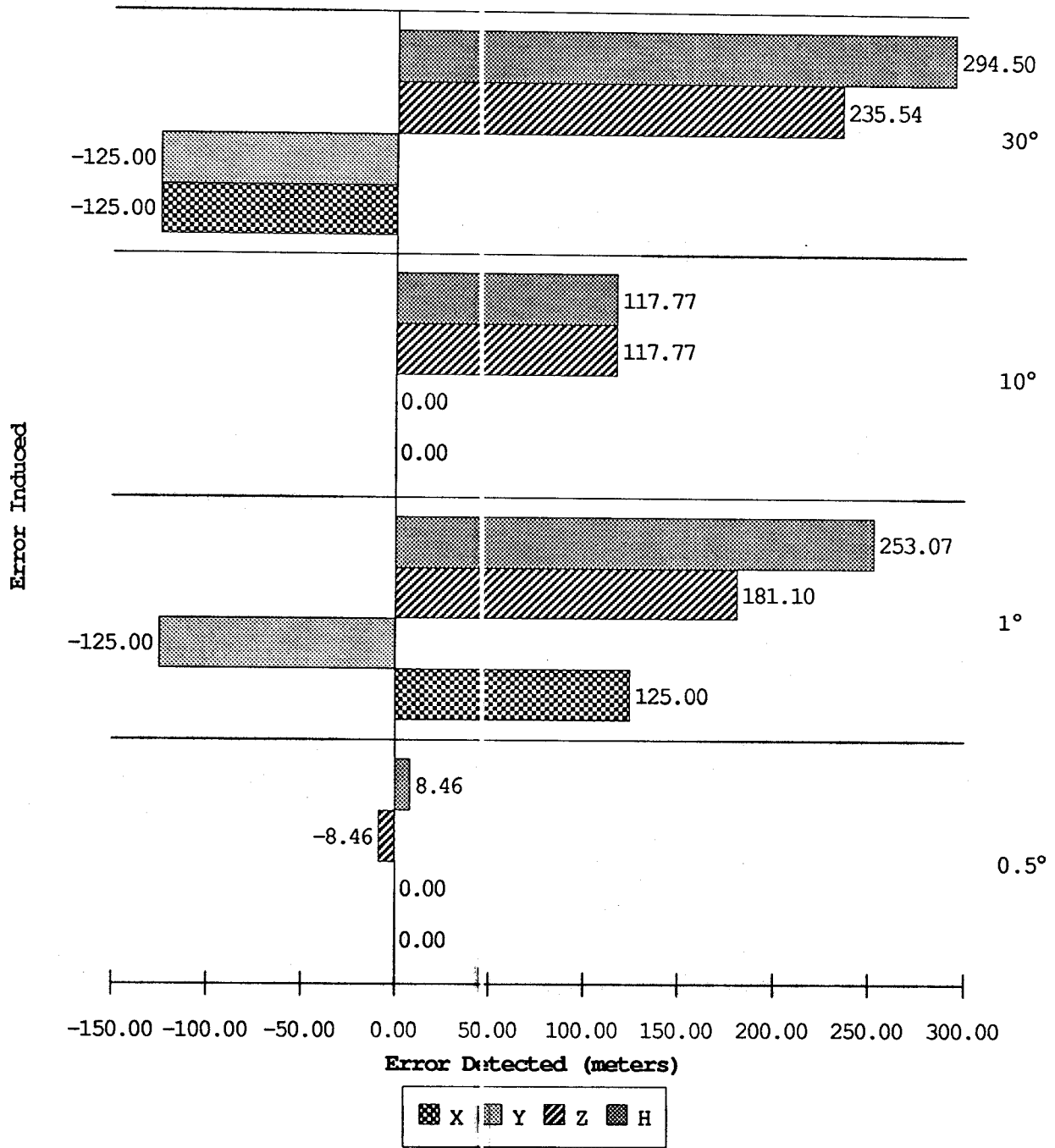
2.3.3.3 Hausdorf Metric - Spatial Correlation Results (Warping Error Tests)

As shown by Figure 2.3.3.3-1, this metric can also detect when different cartographic projections have been used to generate the databases.

FIG 2.3.3.3-1: Hausdorff Metric – Measurement of Warping Errors in Set A Databases (MultiGen)
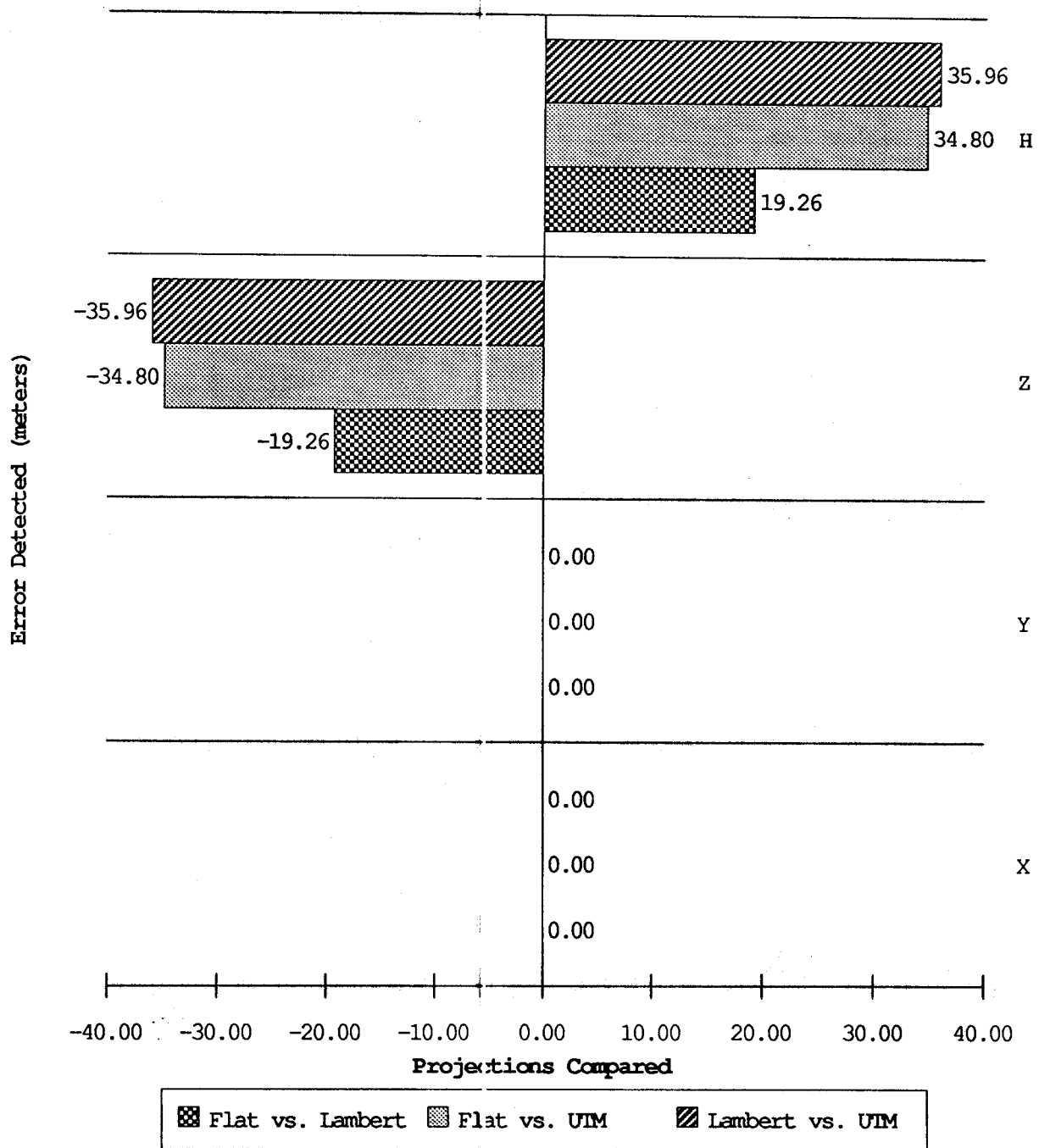
2.3.3.4 Hausdorf Metric - Spatial Correlation Results (Sampling Error Tests)

Figures 2.3.3.4-1 through 2.3.3.4-3 illustrate that this metric can also detect relative differences in sampling rates for the original elevation grids.

FIG 2.3.3.4-1: Hausdorff Metric – Measurement of Sampling
Errors in Set A Databases (MultiGen-Flat Earth)
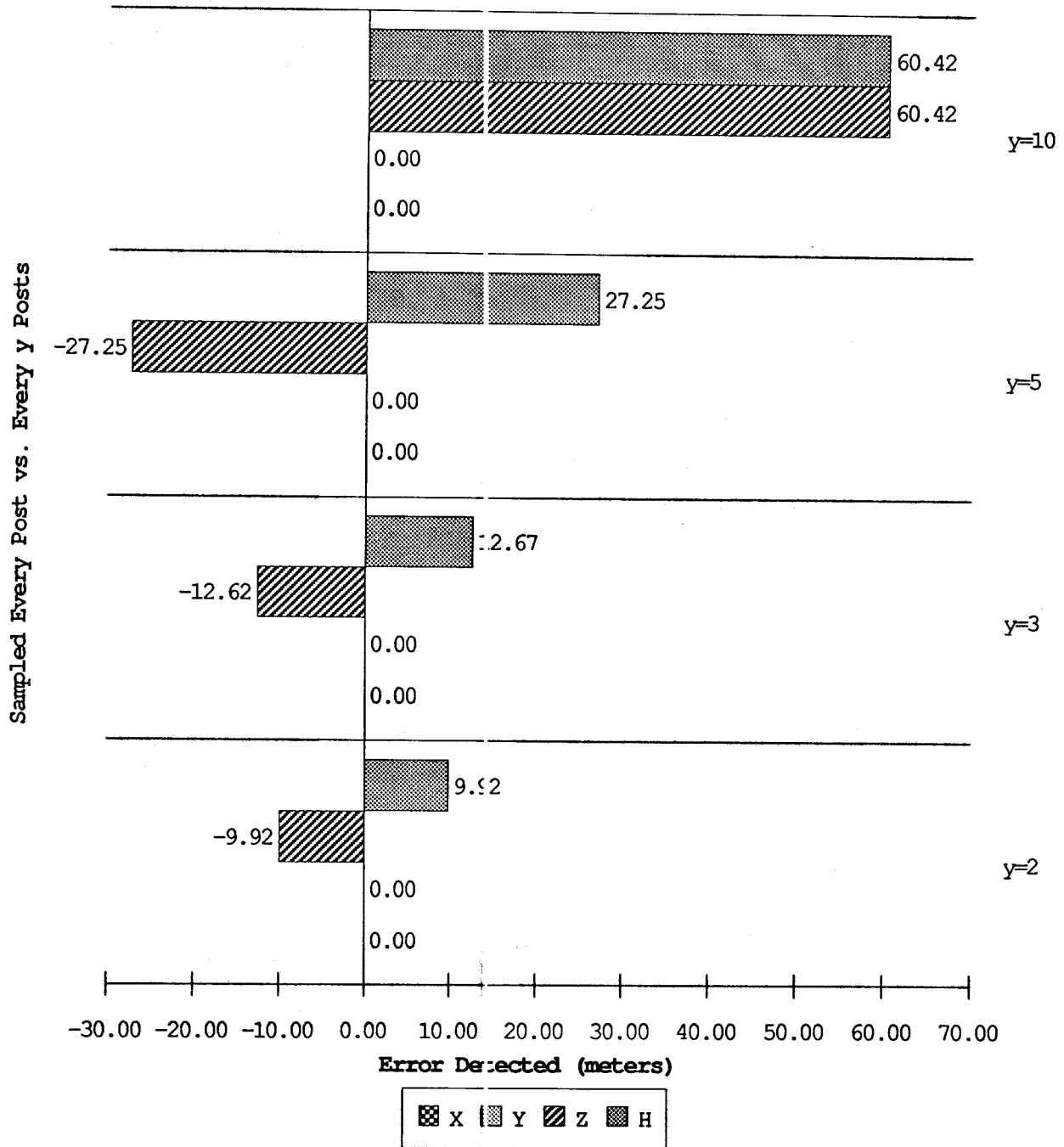
FIG 2.3.3.4-2: Hausdorff Metric – Measurement of Sampling Errors in Set A Databases (MultiGen-Lambert)
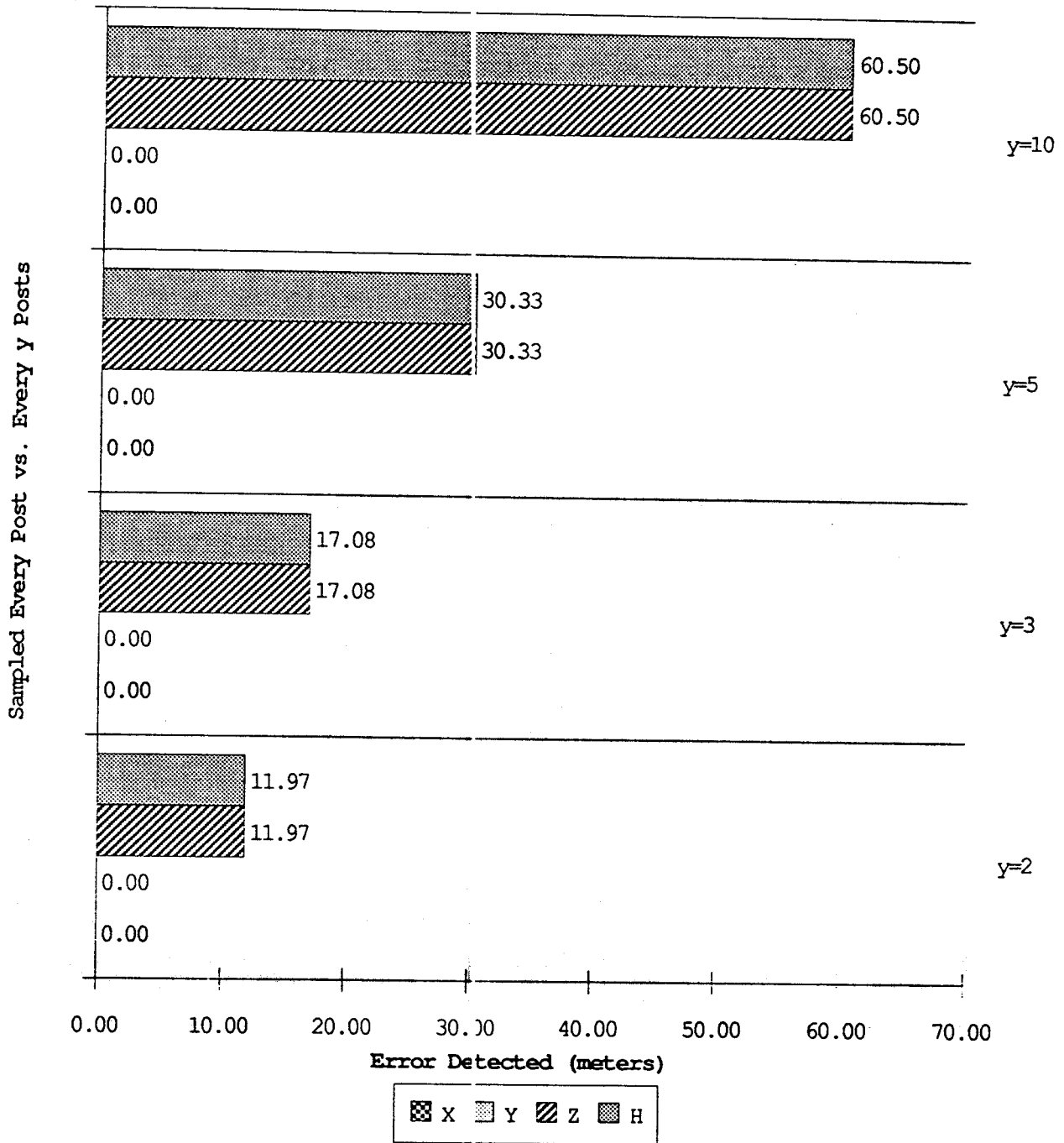
FIG 2.3.3.4-3: Hausdorff Metric - Measurement of Sampling Errors in Set A Databases (MultiGen-UIM)

Sampled Every Post vs. Every y Posts

58.29 — 58.29 — 0.00 — 0.00 — y=10

25.24 — 25.24 — 0.00 — 0.00 — y=5

12.23 — 12.23 — 0.00 — 0.00 — y=3

7.55 — 7.55 — 0.00 — 0.00 — y=2

0.00   10.00   20.00   30.00   40.00   50.00   60.00

Error Detected (meters)

X Y Z H
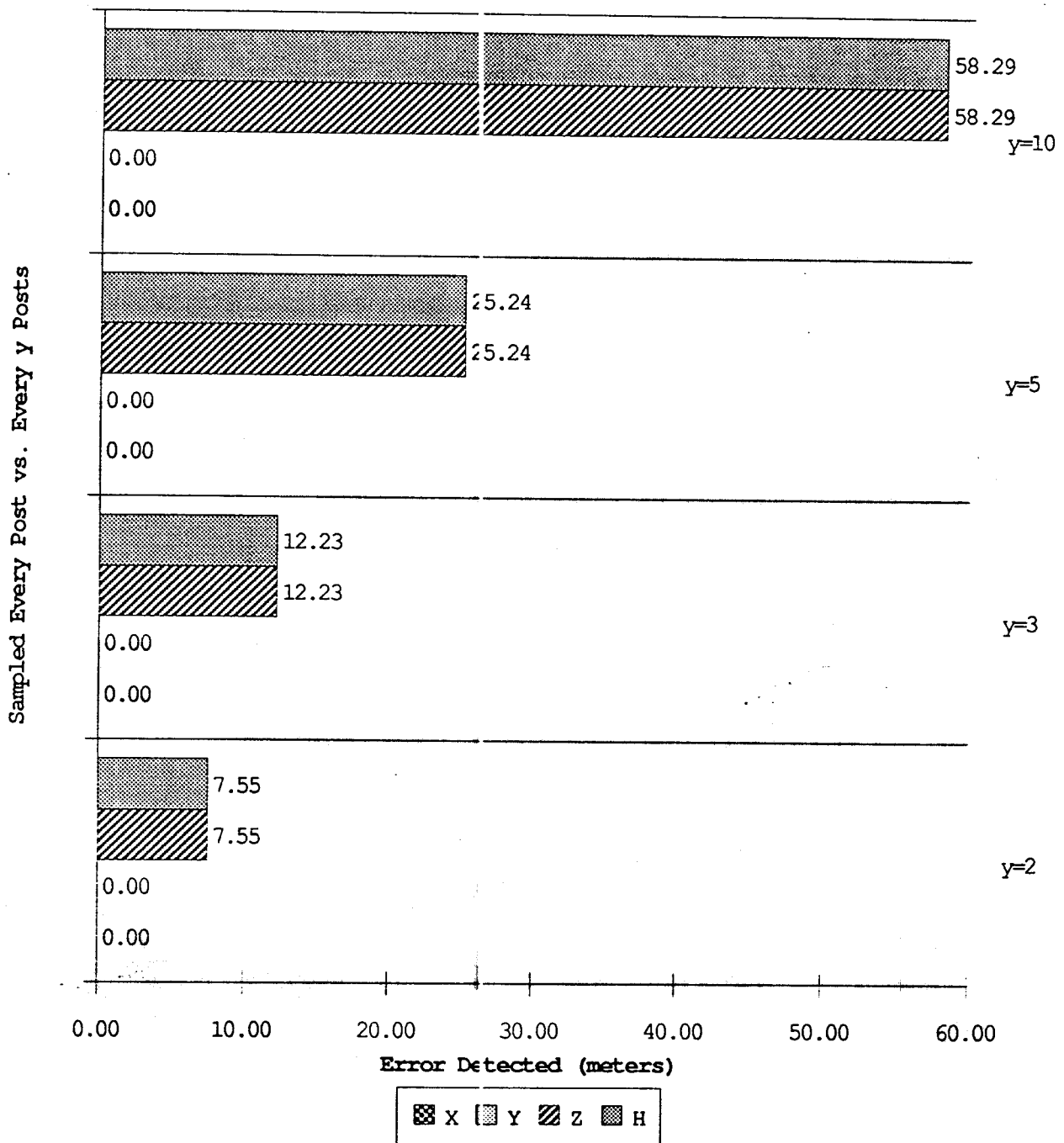
2.3.3.5 Hausdorf Metric - Spatial Correlation Results (Synopsis)

- Can determine qualitative measure of magnitude of shift, skew, and sampling discrepancies.
- Can determine if a different cartographic projection is used.
- For large shifts, may be able to determine axis and magnitude of shift.
- Cannot distinguish between sampling, warping, and small shifts and skews.
- Cannot detect axis of skew.

NOTE: These results are based on a single error induced on the database.

2.4 Volume Metric

Applicability:	Spatial Correlation

Errors to Detect: Shifts, Skews (terrain databases and images)
Warping, Sampling (terrain databases)
Dilation (images)

Input Data Type: - elevation grid (terrain databases)
- array of gray-scale or color values (images)

2.4.1 Volume Metric - Algorithm

The following metric was developed by Dr. Mark Johnson (Department Chair, Department of Statistics, University of Central Florida).

Given two terrain databases, A and B, we assume that determining the agreement between A and B can be accomplished through comparison of elevations over a common area of interest. Furthermore, it is assumed that the databases are based on their own sets of distinct polygonal regions. The region of interest R is represented as:

$$R = \bigcup_{i=1}^{n_A} T_i \text{ for database A}, \quad F = \bigcup_{i=1}^{n_B} S_i \text{ for database B},$$

where T_i and S_i represent polygons within the database. For any given polygon, the elevations at points interior to the polygon are determined by elevations of the vertices. In other words, we can define the functions

$$f_i(x,y) = a_{0i} + a_{1i}x + a_{2i}y \text{ and } g_i(x,y) = b_{0i} + b_{1i}x + b_{2i}y$$

that return the elevation at the point (x,y) in the databases A and B, respectively. The discrepancy between the two databases can be measured through the differences in the functions f and g. An overall measure of the discrepancy between f and g can be described as:

$$d = \int_R |f(x,y) - g(x,y)| \, dx \, dy$$

In a physical sense, this measurement represents the volume between the two polygonal representations described by f and g.

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When computing this integral, four possible cases can exist between a polygon **a** in database A and polygon **b** in database B:

1) Polygon **a** is directly above polygon **b**.
2) Polygon **a** is directly below polygon **b**.
3) Polygon **a** intersects polygon **b**.
4) Polygon **a** and **b** do not share a common area when
   projected into the X-Y plane.

In cases (1) and (2), the polygons share a common area when projected onto the X-Y plane. Case (3) consists of calculating the intersection points and the two partial volumes. In case (4), the two polygons do not share a common volume.

The algorithm compares each polygon in database A to every polygon in database B. The algorithm is as follows:

<u>Volume Metric Algorithm</u>

1. For each polygon **a** in database A,
        project polygon **a** into the X-Y plane.
        For each polygon **b** in database B,
                project polygon **b** into the X-Y plane.
                Clip polygon **a** by polygon **b**.
                If **a** and **b** have a common area,
                        triangulate the common area.
                        For each new triangle,
                                if one polygon (**a,b**) is above the other,
                                        compute the volume and add to the total
                                                volume (case 1 or 2)
                                else if polygon **a** and **b** intersect (case 3),
                                        calculate the intersecting points.
                                        Calculate the volume of each wedge formed
                                        by the intersection and add to the total
                                        volume.
                else,
                        reject this polygon pair (case 4).
2. Output the total volume.

The Sutherland-Hodgman algorithm is used for clipping the polygons in step 1 [Foley90]. Like the Hausdorf distance metric, this metric does not measure a specific discrepancy. Instead, an overall measure of the differences in the databases is computed.

2.4.2 Volume Metric - Spatial Correlation Results

In initial tests with small databases (e.g. 16 polygons), the volume metric ran successfully. However run time errors were encountered when using the Set A databases. Because an overall measure of database discrepancies was already implemented and running successfully (i.e. the Hausdorf distance metric) and resources were limited, no further development of this metric was pursued.

2.5 Fourier Metric

Applicability: Rendered Image and Spatial Correlation

Errors to Detect: Shifts, Skews (terrain databases and images)
                            Warping, Sampling (terrain databases)

Input Data Type: - elevation grid (terrain databases)
                            - array of gray-scale or color values (images)

2.5.1 Fourier Metric - Algorithm

The following algorithms were developed from consultations with Dr.
Tom Clarke of IST and through references collected from the literature
search.

As stated previously, rendered images and terrain databases can both be
represented as two dimensional arrays. For rendered images, the values
in each element of the array can represent either gray-scale or color
values. For a terrain database, the elements represents elevations. The
Fourier transform converts these spatial representations into a
frequency domain.

If the original data set, either rendered image or terrain, is represented
by a MxN array, this array represents a sampling of a continuous
function f(x,y). The discrete two-dimensional Fourier transform for this
function is defined as

$$F(u,v) = \frac{1}{MN} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) e^{-j\,2\pi(ux/M + vy/N)}$$

where u and v are frequency variables (u = 0, 1, 2, ..., M-1 and v = 0, 1,
2, ..., N-1), and

$$j = \sqrt{-1}$$

The inverse transform is defined as:

$$f(x,y) = \frac{1}{MN} \sum_{u=0}^{M-1} \sum_{v=0}^{N-1} F(u,v) e^{-j\,2\pi(ux/M + vy/N)}$$

for x = 0, 1, 2, ..., M-1 and y = 0, 1, 2, ..., N-1. F(u,v) represents a new
MxN matrix with complex components specified as:

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$$F(u,v) = R(u,v) + I(u,v)$$

where $R(u,v)$ is the real component and $I(u,v)$ is the imaginary component.   The spectrum, or magnitude, is defined as

$$\left| F(u,v) \right| = \left[R^2(u,v) + I^2(u,v) \right]^{1/2}$$

and

$$\phi(u,v) = \tan^{-1}\left[\frac{I(u,v)}{R(u,v)} \right]$$

represents the phase [Gonzalez92].   From these quantities produced by the Fourier transform, separate approaches were developed for detecting shifts and skews between two images or two databases and warping/sampling discrepancies between two databases.

2.5.1.1 Fourier Metric - Algorithm (Detecting Shifts and Skews)

If $s_t(x,y)$ represents a translated and rotated replica of the data set $s_o(x,y)$, according to the Fourier Shift Theorem and the Fourier Rotation Theorem their transforms are related by

$$S_t(u,v) = e^{-j\,2\pi(ux_o + vy_o)}\; S_o(u\,\cos\theta_o + v\,\sin\theta_o,\; -u\,\sin\theta_o + v\,\cos\theta_o)$$

where S_t and S_o are the Fourier transforms of s_t and s_o, respectively. The quantities θ_o and (x_o, y_o) represent the amount of relative rotation and translation between the data sets.

Next we define the ratio

$$G(u,v,\theta) = \frac{S_t(u,v)}{S_o(u\,\cos\theta + v\,\sin\theta,\; -u\,\sin\theta + v\,\cos\theta)}.$$

When $\theta = \theta_o$, this ratio becomes

$$G(u,v,\theta_o) = e^{-j\,2\pi(ux_o + vy_o)}$$

which represents a unity pulse translated by (x_o, y_o).   For comparing two data sets A and B, the algorithm is as follows:

<u>Fourier Metric 1 - Shift/Skew Error Measurement Algorithm</u>

1. Compute the Fourier transform of the data sets A and B.
2. Set $\theta = 0°$.
3. Compute the ratio $G(u,v,\theta)$.
4. Compute the inverse Fourier transform of $G(u,v,\theta)$, $g(x,y,\theta)$.
5. If the maximum of $g(x,y,\theta)$ is a unity pulse,
       output the location of the pulse in the X-Y plane (x_0, y_0) and θ_0.
       Stop.
    else if $\theta \geq 360°$,
       Stop.
6. else
       Increment θ.

Step 1 uses the two-dimensional Fast Fourier Transform (FFT) while step 4 uses the inverse FFT [Press88].

2.5.1.2 Fourier Metric - Algorithm (Detecting Warping and Sampling Discrepancies)

Although a specific algorithm for detecting warping and sampling was not discovered through the literature search, it is possible that examination of the Fourier spectrum of two databases may reveal characteristics of these effects. The algorithm used is as follows:

<u>Fourier Metric 2 - Warping/Sampling Error Measurement Algorithm</u>

1. Compute the Fourier transform of the data sets A and B. These will be referred to as F_A and F_B, respectively.
2. Compute $|F_A|$ and $|F_B|$.
3. Compute the difference in the spectra:
       $|F_{A-B}| = |F_A| - |F_B|$
4. Compute and output the minimum, maximum, average, and standard deviation of $|F_{A-B}|$.

Step 1 uses the two-dimensional Fast Fourier Transform (FFT) [Press88].

2.5.2 Fourier Metric - Image Correlation Results

Initially, Fourier Metric 1 was developed for spatial correlation tests with the intent to modify the code for image correlation tests. However,

the spatial correlation prototype did not perform as expected which left insufficient time for conversion to image formats.

Originally, the algorithm for this metric was developed to detect shifts and skews in images [DeCastro87] and may achieve improved results with further development.

2.5.3 Fourier Metric - Spatial Correlation Results

2.5.3.1 Fourier Metric - Spatial Correlation Results (Shift Error Tests)

Figure 2.5.3.1-1 and Figure 2.5.3.1-2 show this metric as being unsuccessful in indicating the relative magnitude or type of discrepancy (i.e. shift). However, the original algorithm for images was used in detecting the magnitude of shifts in X and Y [DeCastro87]. Therefore, additional development of this metric may yield more promising results.

FIG 2.5.3.1-1: Fourier Metric – Measurement of Shift-X
Errors in Set A Databases (MultiGen)

Error Induced

1000m
- 82.00 (Theta degrees)
- 25.00 (Y meters)
- 16.00 (X meters)

100m
- 81.00 (Theta degrees)
- 63.00 (Y meters)
- 18.00 (X meters)

10m
- 139.00 (Theta degrees)
- 14.00 (Y meters)
- 53.00 (X meters)

1m
- 80.00 (Theta degrees)
- 36.00 (Y meters)
- 45.00 (X meters)

.5m
- 152.00 (Theta degrees)
- 5.00 (Y meters)
- 17.00 (X meters)

Error Detected

0.00 20.00 40.00 60.00 80.00 100.00 120.00 140.00 160.00

Legend:
- ▨ X meters
- ▨ Y meters
- ▨ Theta degrees
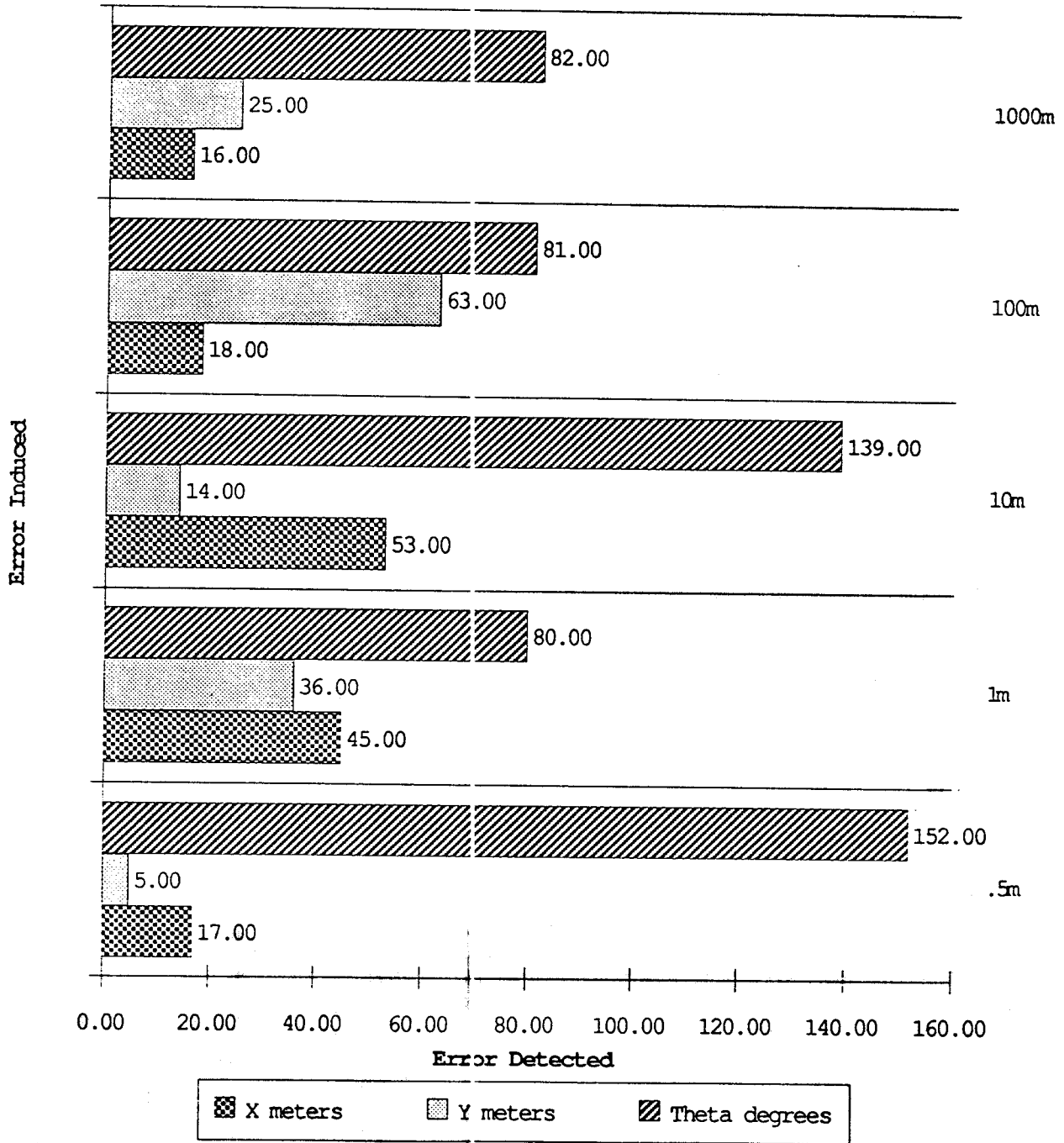
FIG 2.5.3.1-2: Fourier Metric - Measurement of Shift-Y Errors in Set A Databases (MultiGen)

Bar chart. X-axis: "Error Detected" ranging from 0.00 to 350.00. Y-axis: "Error Induced".

- 1000m: Theta degrees = 330.00, Y meters = 1.00, X meters = 27.00
- 100m: Theta degrees = 233.00, Y meters = 24.00, X meters = 59.00
- 10m: Theta degrees = 346.00, Y meters = 8.00, X meters = 8.00
- 1m: Theta degrees = 299.00, Y meters = 35.00, X meters = 7.00
- .5m: Theta degrees = 44.00, Y meters = 43.00, X meters = 9.00

Legend: X meters, Y meters, Theta degrees
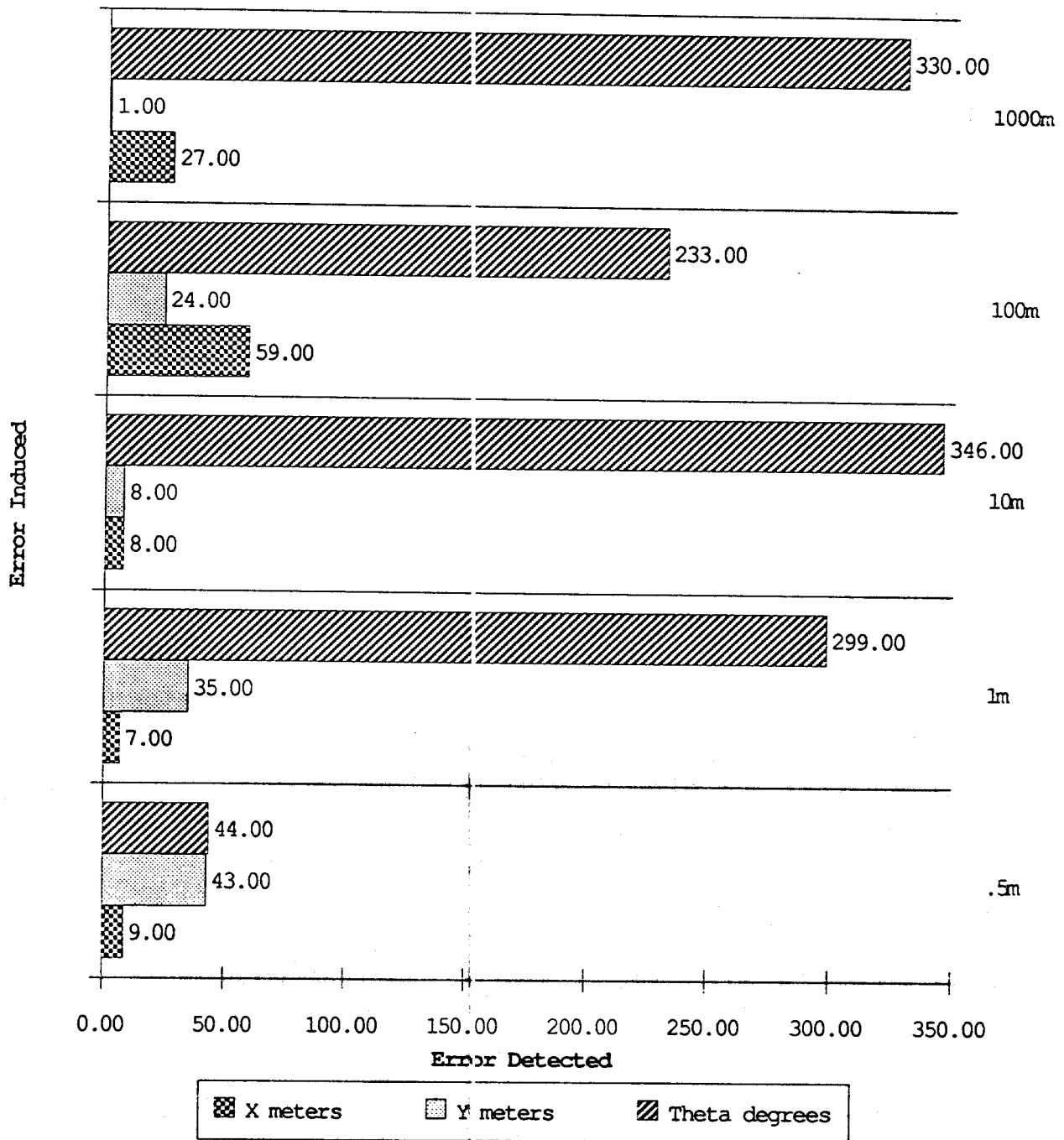
2.5.3.2 Fourier Metric - Spatial Correlation Results (Skew Error Tests)

The results of Figure 2.5.3.2-1 indicates that this metric cannot detect skews.   However, the original algorithm was also developed for detecting the magnitude of Z rotations [DeCastro87].   More development of this metric may produce improved results.

FIG 2.5.3.2-1: Fourier Metric – Measurement of Skew-Z Errors in Set A Databases (MultiGen)
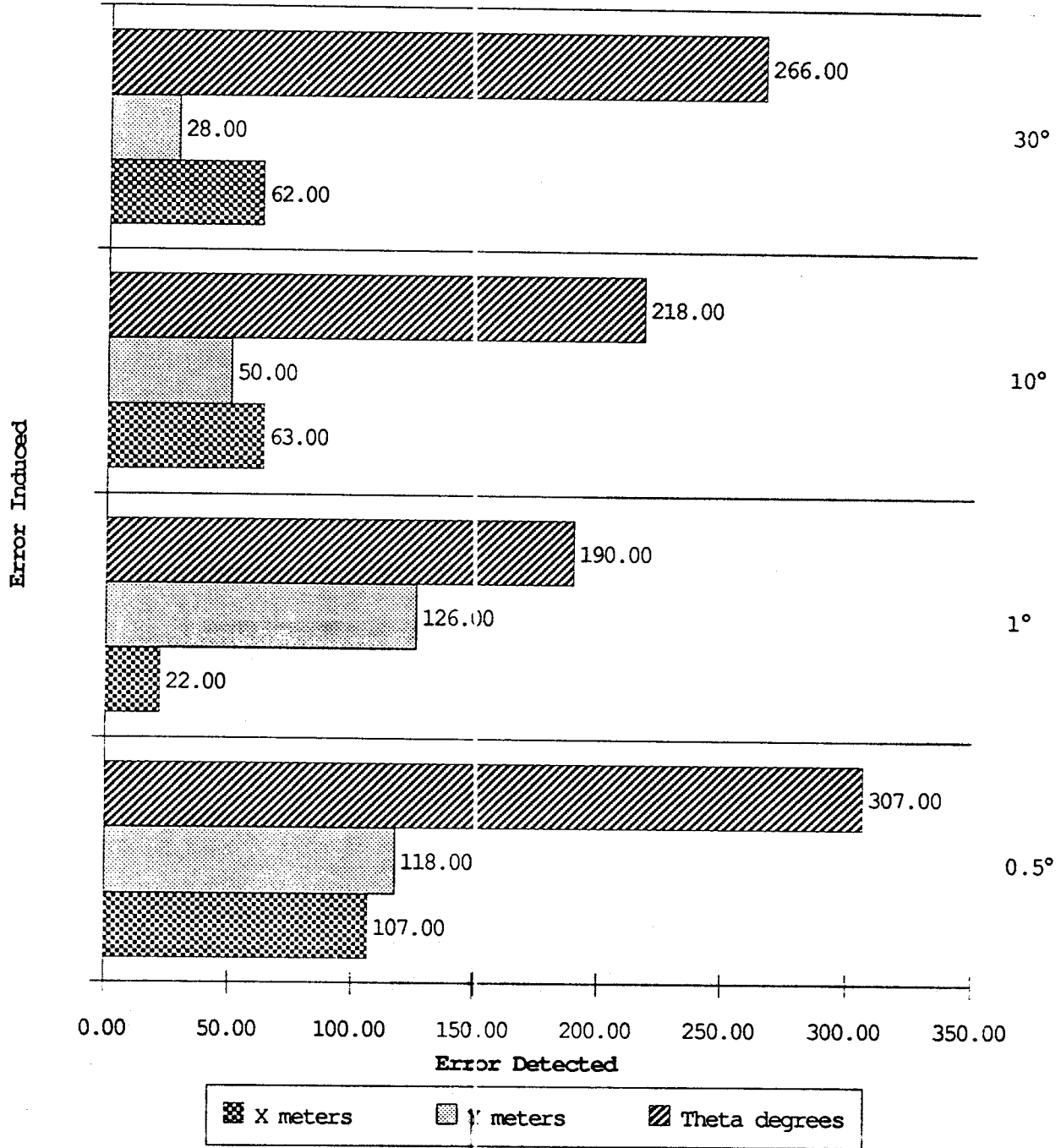
2.5.3.3 Fourier Metric - Spatial Correlation Results
(Warping Error Tests)

Figure 2.5.3.3-1   illustrates that the metric can successfully determine when different cartographic projections are used.   However, the type of projection used is inconclusive

FIG 2.5.3.3-1: Fourier Metric - Measurement of Warping
Errors in Set A Databases (MultiGen)

Bar chart with y-axis labeled "Error Detected" and x-axis labeled "Projections Compared".

Std. Dev.
- 1756.17
- 1634.86
- 1612.46

Avg.
- 1014.46
- 795.35
- 839.98

Max
- 15828.50
- 16232.57
- 9286.79

Min
- −9608.45
- −7552.49
- −10701.60

x-axis values: −15000.00, −10000.00, −5000.00, 0.00, 5000.00, 10000.00, 15000.00, 20000.00

Legend:
- Flat Earth vs. UTM
- Flat Earth vs. Lambert
- Lambert vs. UTM
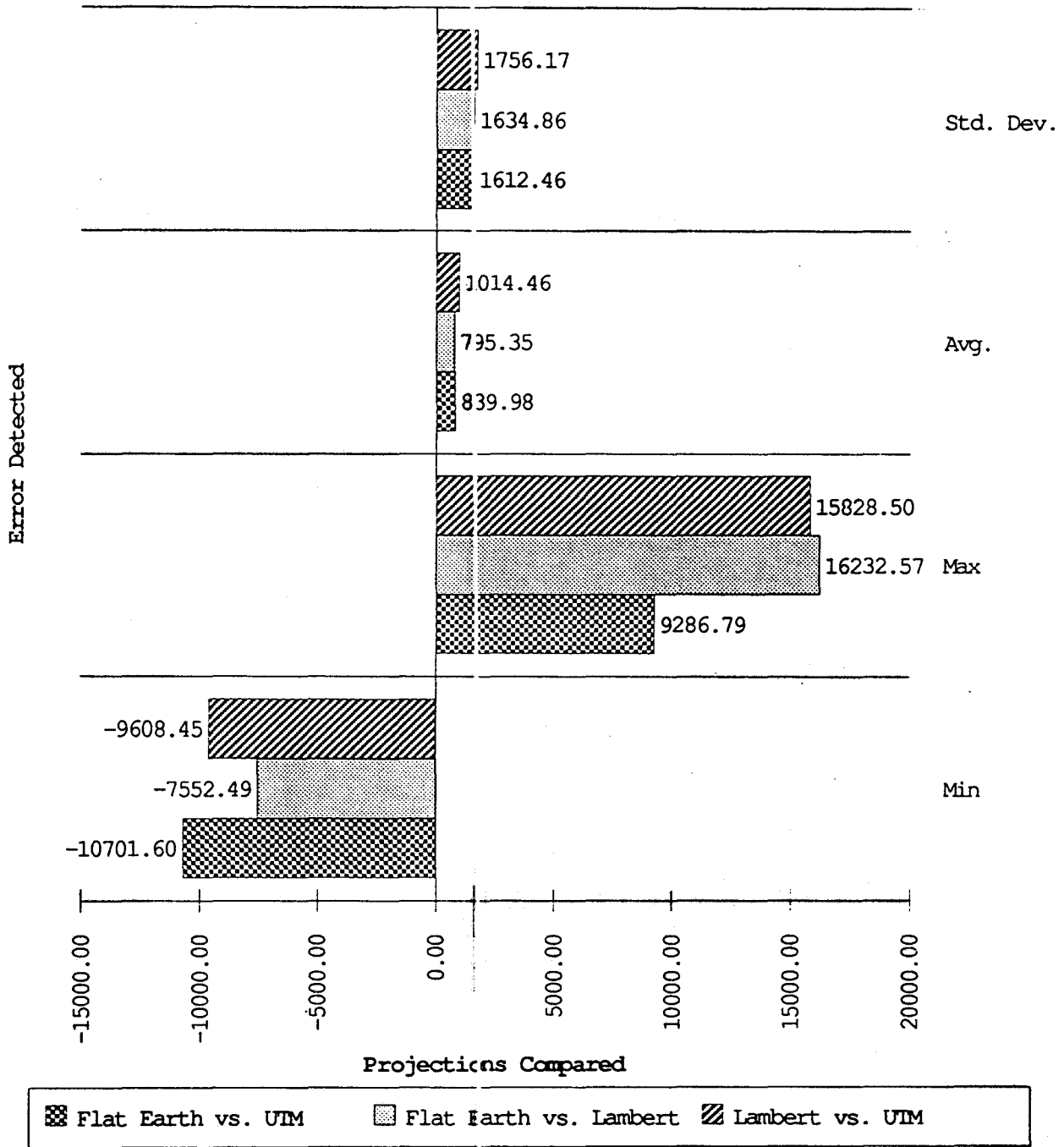
2.5.3.4 Fourier Metric - Spatial Correlation Results (Sampling Error Tests)

Different sampling rates can also be detected through the Fourier metric as illustrated in Figures 2.5.3.4 1 through 2.5.3.4-3. These figures also show that a qualitative measure of the magnitude of this discrepancy can also be produced.

FIG 2.5.3.4-1: Fourier Metric - Measurement of Sampling
Errors in Set A Databases (MultiGen-Flat Earth)
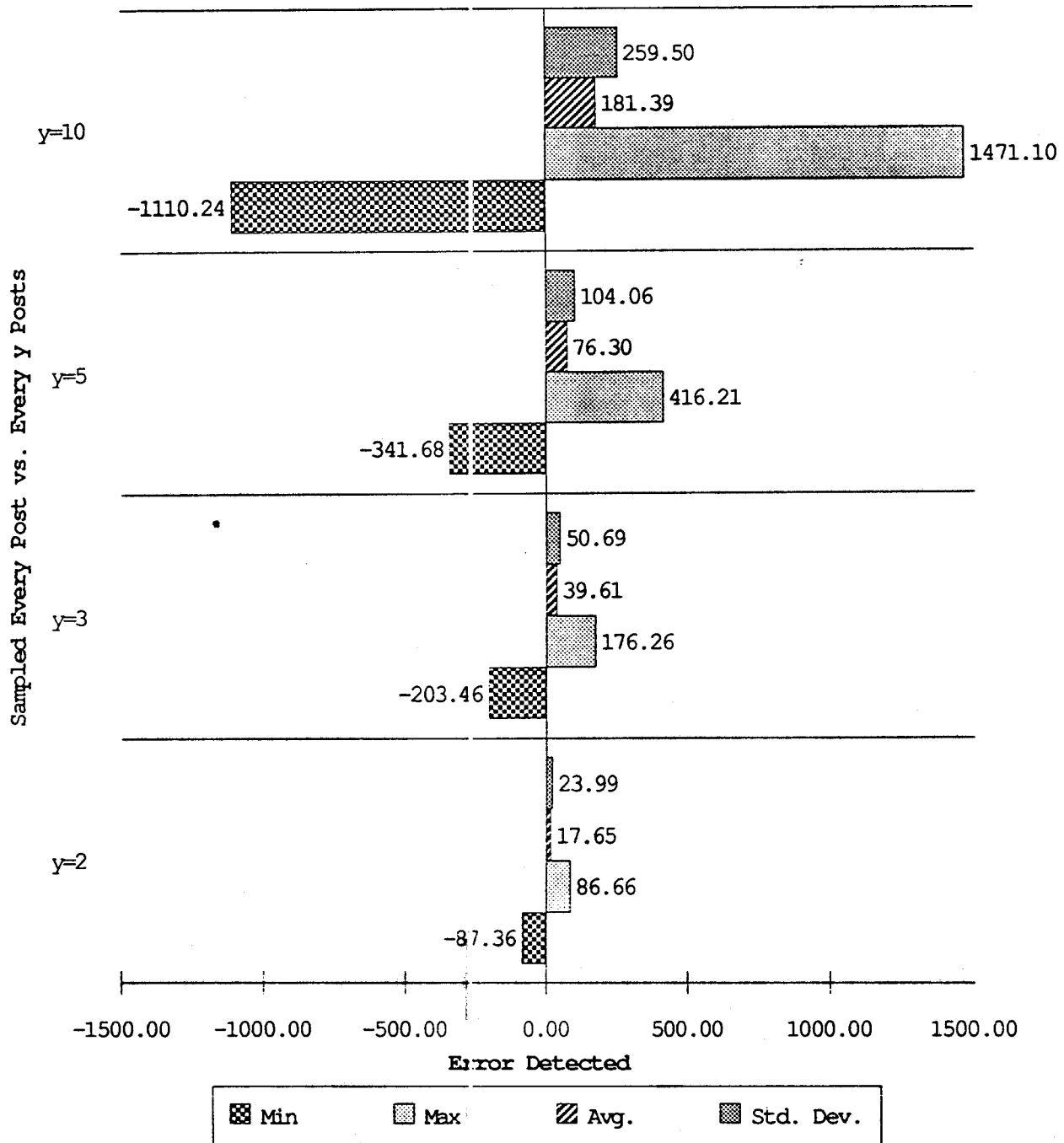
FIG 2.5.3.4-2: Fourier Metric – Measurement of Sampling Errors in Set A Databases (MultiGen-Lambert)
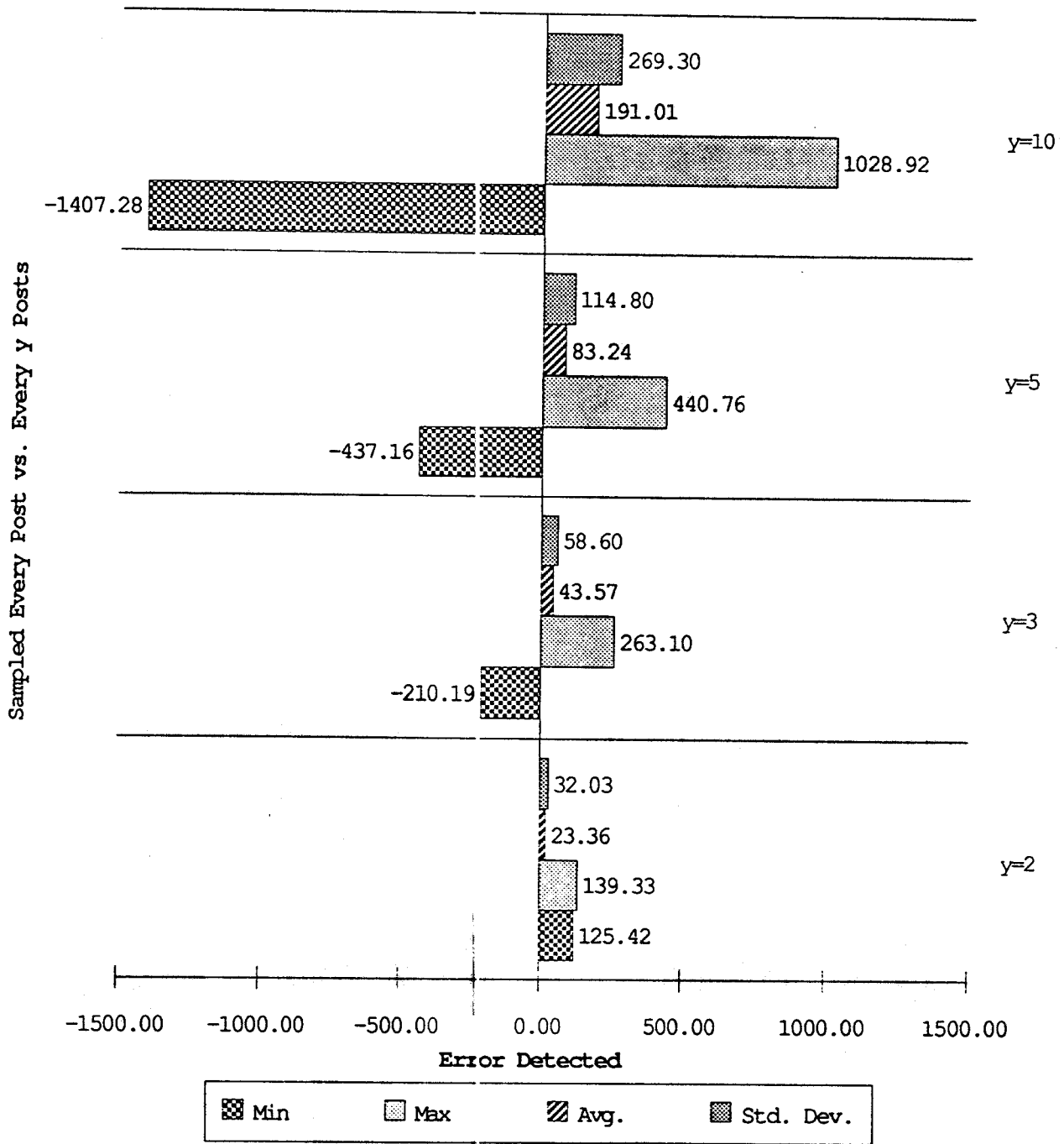
FIG 2.5.3.4-3: Fourier Metric - Measurement of Sampling Errors in Set A Databases (MultiGen-UTM)

286.31	y=10
205.69	
1079.89	
−956.08	
137.31	y=5
102.06	
578.75	
−468.34	
61.07	y=3
45.84	
246.99	
−185.84	
27.83	y=2
20.58	
91.34	
−100.23	

Error Detected

-1000.00   -500.00   0.00   500.00   1000.00   1500.00

Sampled Every Post vs. Every y Posts

Min   Max   Avg.   Std. Dev.
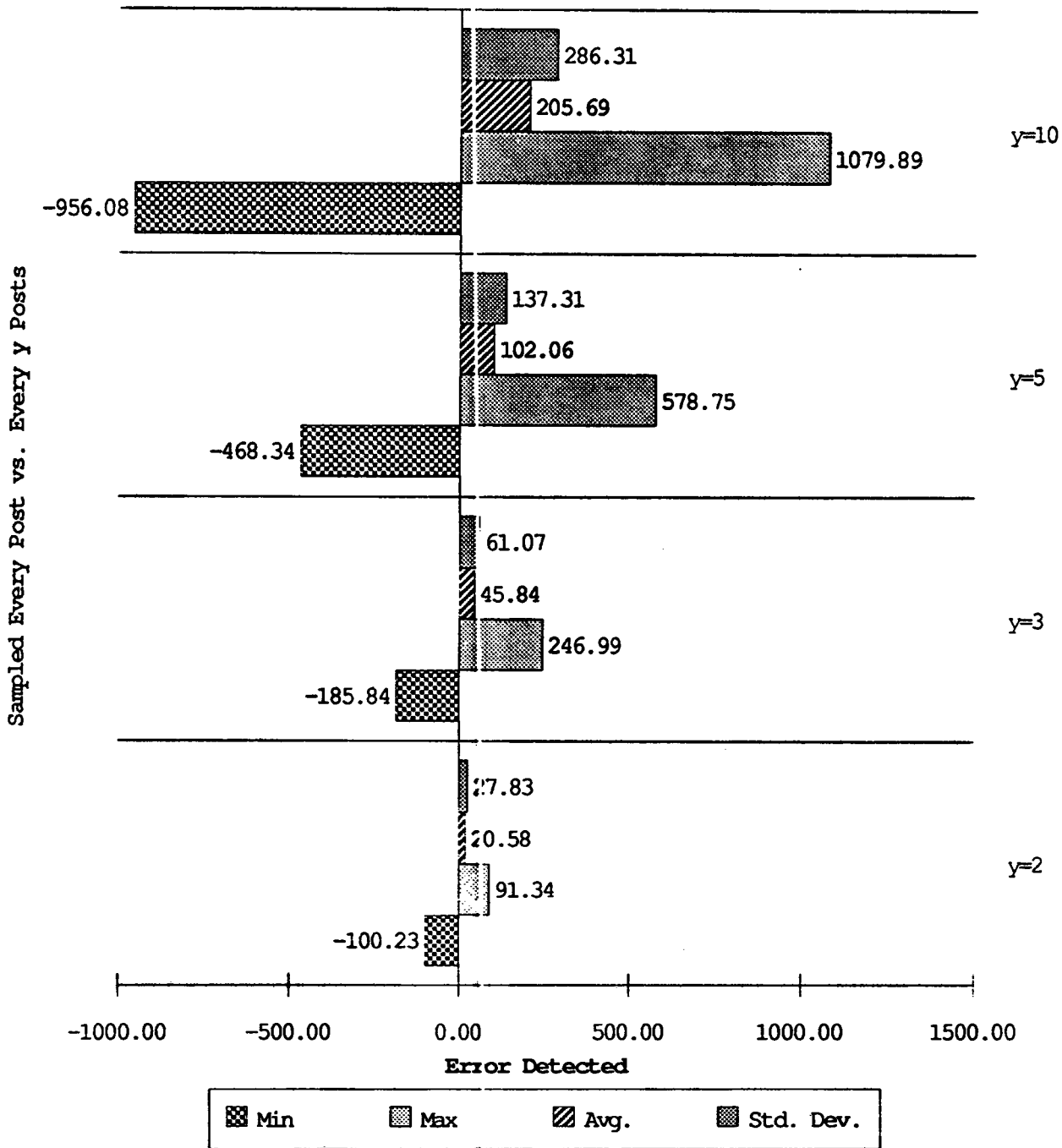
2.5.3.5 Fourier Metric - Spatial Correlation Results (Synopsis)

- Can determine qualitative measure of magnitude of sampling discrepancies. Exact differences in sampling may be possible through further development of metric.
- Can determine if a different cartographic projection is used but cannot determine type.
- Cannot determine shift or skew errors with current implementation. Shifts in X and Y and skews about Z may be detected with further development of this metric.
- Sampling discrepancy can be distinguished from warping discrepancy (magnitude of measured error much larger for warping errors).
- Methods for detecting warping and sampling should be invariant to shifts in X and Y according to Fourier theory. May be able to make the metric invariant with respect to Z rotations through further development of algorithm.

NOTE: These results are based on a single error induced on the database.

3.0 Proposed Metrics Not Studied

The following section describes proposed metrics that were not prototyped for study. For each metric, a brief description of the algorithm is provided as well as a justification for not continuing further study.

3.1 Method of Moments

A common tool used in statistical analysis is the mean and standard deviation of a data set. These are also referred to as the first and second moments of the data set, respectively. For purposes of this study, the data set can exist as the difference between sampled elevations in a geometric terrain database or color/intensity values in rendered images. The mean provides an indication of the average difference between the databases (geometry or rendered image). The standard deviation indicates the range of differences about the average and can be used to indicate global or local effects.

After consultation with Dr. Mark Johnson (Department of Statistics, UCF), it was discovered that two data sets can match through the nth moment and still have discrepancies between them. Dr. Johnson had previously conducted research in this area [Johnson80]. For this reason, this metric was not developed further.

3.2 Statistical Sampling

In this approach, a statistically significant number of points are selected within a terrain database. Readings of elevation values are collected and compared against the same set of points in a master database. Based on the number and magnitude of elevation differences, a measure is produced predicting the degree of correlation among the databases. This approach can be applied in two ways. First, an automated version of this test can be applied to databases before formatting for Computer Image Generators (CIGs). If this proves unfeasible, most CIGs have the capability of providing this information on a "flight-ready" database. This CIG-oriented approach can be applied when reformatted databases are unavailable.

From further consultation with Dr. Mark Johnson, this metric was not pursued either. The difficulty exist in selecting the "statistically significant" points in the database. Typically, such a selection is based on known characteristics of the database. Developing this

characterization of the data would require more time than was available for the current project.

3.3   Line   of   Sight/Intervisibility

Typically, these tests involve placing the eye point of two or more CIGs at identical locations in the database and determining if pre-specified targets can be detected at different ranges.   Based upon the mission type (i.e., air-to-air, air-to-ground, ground-based, etc.), different elevations are selected for the eye point.   Usually, the tests consider numerous factors such as level of detail, color, lighting, and environmental effects in addition to geometry.

A line of sight metric, referred to as the Line-Of-Sight Intervisibility Metric (LOSIM), has been developed at IST through a different project. This project is funded by the U.S. Army Simulation, Training, and Instrumentation Command (STRICOM) under contract number N61339-91C-0091.   LOSIM is currently undergoing testing.   Because this line of sight metric was already under development and testing, it was decided to pursue additional techniques for measuring geometric correlation.

3.4   Histogram

In comparing geometric databases, another common statistical tool, the histogram, can be applied.   The histogram is constructed from elevation differences in two terrain databases and illustrates the frequency with which various magnitudes of differences occur.   The distribution of these frequencies illustrate global and local miscorrelations among the databases.

This metric provides an overall measure similar to the Hausdorf metric and the Volume metric.   Furthermore, the literature search did not reveal techniques for interpreting histogram data to detect specific types of discrepancies.   Due to these factors, this metric was not developed further.

3.5   Contrast   Ratio/Color   Sampling

This algorithm compares two rendered images based on various thresholds.   Adjacent pixels in a image are evaluated to determine if a color or intensity threshold is exceeded.   As the entire image is examined, an array of binary values are constructed.   The same procedure is applied to another image and the two binary arrays are compared using edge detection/comparison algorithms.   The advantage

of this technique is that effects due to texture or certain color ranges can be filtered out.

Due to insufficient resources in personnel, this metric was not developed further.

4.0 Summary of Results

Table 4.1 and 4.2 summarizes the results of the rendered image and spatial correlation research. The numbers shown in the table indicate the criteria satisfied by the metric. These criteria were first stated in Section 1.3 of this report.

Table 4.1   Summary of Results for Spatial Correlation Metric Testing

Metric	MinMax	Feature	Hausdorf Distance	Volume	Fourier
Error					
Shift-X	1, 3	1	1, 2*, 3	I	1, 2*, 3*
Shift-Y	1, 3	1	1, 2*, 3	I	1, 2*, 3*
Shift-Z	1, 3	1	1, 2*, 3	I	
Skew-X	1		1, 3	I	
Skew-Y	1		1, 3	I	
Skew-Z	1		1	I	1, 2*, 3*
Warping			1	I	1
Sampling			1, 3	I	1, 3

Key:

1 - Indicates when discrepancy is present.
2 - Indicates the type of discrepancy.
3 - Indicates the magnitude of the discrepancy.
* - Requires further development of metric.
I - Inconclusive.

Table 4.2   Summary of Results for Image Correlation Metric
Testing

Metric	MinMax	Hausdorf Distance	Fourier
Error			
Shift-X	1, 3	1	I
Shift-Y	1, 3	1	I
Skew-Z	1	1	I
Dilation		1	I

Key:

1 - Indicates when d.screpancy is present.
2 - Indicates the type of discrepancy.
3 - Indicates the magnitude of the discrepancy.
* - Requires further development of metric.
I - Inconclusive.

5.0   Conclusions

(1) Of the metrics studied for spatial correlation, the Hausdorf and Fourier metrics perform the best in detecting different types and magnitudes of discrepancies between terrain databases.   However, neither metric can consistently classify the type nor the magnitude. With further study, these results may be improved.

(2) For image correlation, none of the metrics stand out in successfully detecting errors.   With additional development, the Fourier metric may be able to classify shift and skew discrepancies as well as provide magnitudes of these discrepancies.

(3) As was stated previously, the testing of the metrics was accomplished by inducing one error at a time into the data sets.   The effect of multiple discrepancies between two rendered images or two databases is unknown at this time.   Multiple errors may affect the performance of these metrics.

(4) The particular errors for which tests were conducted (i.e. shifts, skews, warping, dilation, and sampling) represent a subset of possible discrepancies that can occur between images and databases.   These errors were chosen for study because they were considered controllable parameters for prototype testing.   Other factors can affect the terrain database or final rendered image.   For instance, different polygonization and terrain relaxation schemes also induce discrepancies in terrain databases.   However, individual vendor algorithms make development of effective metrics to measure these discrepancies difficult.   Therefore, the metrics developed for this study are not intended to detect all possible discrepancies.

6.0   Recommendations

For the remainder of this study, the following is suggested:

(1) It is recommended that the Fourier metric be developed further for both image and geometric correlation.   This is the only metric with a the theoretical basis to handle multiple types of errors and can detect specific errors and magnitudes.

2) Improvements to the Hausdorf metric for spatial correlation should also be pursued.   This metric can be used to support the Fourier metric in verifying results and for measuring discrepancies not detected by Fourier.

(3) Effects of multiple errors on these metrics should be examined. It is unlikely that actual databases will have only a single discrepancy. Therefore, performance of the final metrics needs to be evaluated for multiple errors.

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Appendix D

Use of the Metrics

Appendix D

Use of the Metrics

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D1.0 Introduction

This appendix describes how to obtain, install, and use the metrics described in this report.

D2.0 Obtaining and Installing the Metrics

The metrics are provided with this report on a SGI tar format tape. The source code and all data files used for this research are included on this tape. To install the software, data files, and associated directories, insert the tape into the tape drive of your SGI workstation and type "tar -xv."

The main directory on this tape is subdivided into geometric and image correlation subdirectories. Each of these directories, in turn, are divided into subdirectories containing test data and source code for the metrics.

D3.0 Using the Metrics

Instructions for using the Feature Metric, the Hausdorff Metric, the Minmax Metric, and the Volume Metric are provided as text files (labeled README) in the subdirectories containing the source code for the particular metric. Where applicable, additional README text files are provided to describe the format of the files used by the metric.

The Fourier metric requires the Khoros software package. Instructions on the installation and use of Khoros are provided below.

D4.0 Using the Fourier Metric

D4.1 What is Khoros?

"Khoros is an X Windows and UNIX based software system that provides an integrated software development environment for information processing and data visualization' [Young92]. The main advantage of

Khoros is that it includes an extensive set of built-in routines and a visual programming language that allows rapid prototyping of algorithms. This set of built-in routines fall into five categories: image processing, image analysis, signal processing, arithmetic, and remote GIS. The built-in routines, visual programming language, and ability to extend Khoros through user-defined routines allowed us to develop the Fourier Transform Metric in the span of 2-3 weeks instead of the several months it could have taken developing a stand-alone program.

D4.2   Where and How to get Khoros

Khoros is currently available from the University of New Mexico (UNM) as an Open Software Package (i e., freeware). Khoros can be obtained by either tape or anonymous ftp. The management of this software is currently being transferred from UNM to Khoral Research, Inc. However, UNM will retain the copyright and will continue to distribute the software until further notice.

Khoros is available by anonymous ftp on pprg.eece.unm.edu in /pub/khoros. The process remains the same if Khoros is obtained via tape or ftp by obtaining installation documents. These documents can be obtained via ftp through the following commands:

    1) **ftp   pprg.eece.unm.edu**

    2) Name: **anonymous**

    3) Password: *your_e_mail_address*

    4) **cd   /pub/khoros/release**

    5) **binary**

    6) **get   announce.ftp**

    7) **get   chapter10.ftp**

    8) **bye**

Postscript versions of these files are available in the directory indicated above and are named announce.ps and chapter10.ps. Distribution and installation instruction via tape or ftp are provided by these documents. These files also include information on obtaining manuals.

D4.3 Setting Up Khoros to Run the Fourier Transform Metric

Environment variables must be established to run Khoros by typing the following commands:

1) setenv **KHOROS_HOME** *where_you_installed_khoros*

2) setenv **TMPDIR** **/tmp**

3) setenv **KHOROS_TOOLBOX** **$KHOROS_HOME/Toolboxes**

Once the environment variables have been defined, follow these steps:

1) **cd $KHOROS_HOME**

2) untar the tape provided using **tar -xv**

3) **cd geometric_correlation/metrics/fourier/Khoros**

4) **cp Toolboxes $KHOROS_HOME**

5) **cp cantata.form $KHOROS_HOME/repos/cantata**

6) **cp -r ist.toolboxes $KHOROS_HOME**

7) **cd $KHOROS_HOME/ist.toolboxes/conversions/src/rhotht**

8) Type **make** to compile

9) **mkdir ../../bin**

9) Move the file to the special toolbox bin directory by typing:
   mv rhotht ../../bin

10) Add *$KHOROS_HOME/bin* and
    $KHOROS_HOME/ist.toolboxes/conversions/bin to your path

D4.4 Loading the Fourier Transform Metric in Khoros

The Fourier Transform Metric workspace was written in the $KHOROS_HOME directory off the tape. You will probably want to move it elsewhere. To load the Fourier Transform Metric, follow these steps:

1) Load the visual programming language by typing **cantata**

2) Load the Fourier Transform Metric workspace by selecting *File Utilities* under the *Workspace* menu and filling in the filename in the *Input Filename* line

D4.5 Running the Fourier Transform Metric in Khoros

Each built-in or user-defined function within the cantata environment is referred to as a "glyph." Data flow is from left to right as indicated by the highlighted glyphs as it is running. Testing two databases using the Fourier Transform Metric is described below. These instructions assume you have completed the steps of all previous sections and are now running cantata. Reading through these instructions once before running the metric is recommended.

1) Looking at the Khoros environment and the Fourier Metric workspace, you can notice two *asc2viff* glyphs on the left-hand side. These convert a file of elevation grid values into the Khoros format VIFF. Open each *asc2viff* glyph by clicking on the top-middle box located o the glyph. This will bring up the values that can be defined for each glyph. Change the *Input Filename* field of each glyph to the databases that you wish to test and click on the *Glyph* button.

2) Click on the *run* button. IMPORTANT: Make sure to stop the *vrotate* glyph by clicking on the on-off switch located in the top-right of the glyph. This *vrotate* glyph should not be activated until the metric has first determined the relative rotation between the databases.

3) Once the rotation code has completed, find the "Max Peak" coordinates listed on the statistics window on the screen. The Rotation-within-Cantata is the x-coordinate of the Max peak location. To compute the True-Clockwise-Rotation, apply the following formula:

True-Clockwise-Rotation = (Rotation-within-Cantata / 512.0) * 360.0

This value is the relative Z-axis rotation between the databases.

4) Now open the *vrotate* glyph that was stopped earlier and change the rotation value to the negative True-Clockwise-Rotation just computed. This eliminates the rotation between the databases so relative translations between the databases can now be determined.

D-4

5) Click the *run* button again which will then run the translation code. This was not executed when the *vrotate* glyph was stopped in step 2. Allowing the *vrotate* glyph and the remaining translation code glyphs to run, another statistics window will appear with the Translation-within-Cantata equal to the location of the "Max Peak." To compute the True-Translation, apply the following formula:

True-Translation = TRANSPOSE(Translation-within-Cantata) mod 512

where TRANSPOSE(x, y) = (y, x). This quantity gives us the relative (x, y) translation between the databases.

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