UNIVERSITY OF ALBERTA

THE POSTERO-ANTERIOR CEPHALOMETRIC RADIOGRAPH

- Landmark Identification Errors
- The Effects of Head Rotations
- Reference Planes for Symmetry Analysis

BY

Donald Edison Johnston

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND

RESEARCH IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

CLINICAL SCIENCES

FACULTY OF DENTISTRY

EDMONTON, ALBERTA

SPRING 1991

UNIVERSITY OF ALBERTA

ISBN 0-315-66590-4

UNIVERSITY OF ALBERTA

RELEASE FORM

Donald Edison Johnston

THE POSTERO-ANTERIOR CEPHALOMETRIC RADIOGRAPH

- Landmark Identification Errors
- The Effect of Head Rotations
- Reference Planes for Symmetry Analysis

Master of Science in Clinical Sciences

1991

Donald Johnston

24 Tulip Place

Truro, Nova Scotia

B2N 5Y6

Date: April 21, 1991

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled

THE POSTERO-ANTERIOR CEPHALOMETRIC RADIOGRAPH

- Landmark Identification Error
- The Effect of Head Rotations
- Reference Planes for Symmetry Analysis

submitted by

DONALD EDISON JOHNSTON

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE.

Dr. P. Major ....

Dr. G. Faulkner ....

Dr. D.Scott ....

Dr. K. Glover ....

Dr. J.A.Hargreaves ....

Date: April 21,1991

To my wife Sheila and my Parents

ABSTRACT

An investigation was carried out to determine: the identification error associated with fifty-two individual landmarks visible on the PA cephalometric image; the effects of 5^{o} head rotations about the transverse and vertical axes on the identification error; the differences between intra-examiner and inter-examiner identification error; the landmarks which would be best suited to construct a horizontal reference line to be used in PA analysis; and the landmarks which would be best suited to construct a vertical reference line to be used in PA analysis.

Thirty-three skulls exhibiting no gross facial asymmetry were radiographed in a normal position and rotated each way about both the transverse and vertical axes. Each radiograph was digitized by one operator five times and twenty selected films digitized once by each of four operators.

The results indicate that: each landmark has its own characteristic envelope of error; there are relatively few differences in identification error caused by rotations of the head within the cephalostat; the differences between intra- and inter-examiner identification errors are significant for only those landmarks with the largest identification error; there are certain landmarks in the upper facial skeleton which are best suited to establishing a horizontal reference line for use in PA analysis; there are pairs of landmarks in the upper facial skeleton which are suited to establishing a vertical reference line through the skull; and rotations about the vertical axis have deleterious effects on the determination of a vertical reference line for use in PA analysis.

ACKNOWLEDGEMENTS

The author would like to express his grattitude to the many people whose help and encouragement were instrumental in the successful completion of this project:

My partner in crime, Dr. Brien Stackhouse, whose sense of humor and friendship made the past three years so enjoyable.

Dr. Paul Major, for his guidance and contribution throughout the course of completing this project.

Dr. Ken Glover, Dr. Mike Pawliuk, Dr. Rowland Haryett, Dr. Gerry Mills, Dr. Ron Mullen, Dr. Subash Alimchandani, and Dr. Bill Lobb for their excellent instruction in the clinical part of my graduate training.

Mrs. Maureen Dmytrash, Ms. Brigette Klemp, Mrs. Shelly Aman, and Ms. Carol Gervais for putting up with me in the clinic, lab and office.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

LIST OF FIGURES

FIGURE PAGE

I. INTRODUCTION

A. Uses

Cephalometric radiographs have been available to the orthodontic profession since the introduction of standardized cephalometric techniques[1].

Over the years these radiographs have become one of the major diagnostic tools in clinical orthodontics. Cephalograms can be utilized in many ways that include; the study of normal and abnormal growth of the skull, identification and diagnosis of pathologic conditions, prediction of growth direction and amount, to assist in diagnosing the etiologies of various malocclusions, to aid in orthodontic treatment planning, and to assess changes in dental and skeletal morphology during orthodontic treatment.[2-6]

To date, the lateral cephalogram has been utilized to a much greater extent than the PA cephalogram since clinicians do not routinely take PA cephalograms, but reserve their use for those cases exhibiting obvious facial asymmetries and/or transverse jaw disharmonies.

structures; to assess the width of the nasal cavities; and to determine the presence and location of vertical and/or transverse skeletal asymmetries.[2-7]

Despite the amount of information available from PA cephalograms, they have not achieved the wide clinical acceptance of the lateral cephalogram. The reason for this can be attributed, at least in part, to two distinct factors. The first of these is the fact that there are technical problems associated with cephalometric radiographs as a whole, and PA cephalograms in particular. The second factor is the difficulty in determining planes of reference which can be used to evaluate the relative vertical and horizontal relationships between the structures seen on the PA cephalogram which can be termed analytical problems.

B.Technical Problems

Technical problems arise during both the production of the cephalometric image and in the act of tracing and analyzing cephalograms. These problems produce errors which can be classified into two general categories, namely: projection errors and tracing errors.[8]

i. Projection errors

Projection errors are those types of errors which are inherent in the system utilized to produce the cephalogram. Included in this category are: 1. errors due to the geometry of the radiographic equipment; 2. errors related to film variables; and 3. errors related to patient positioning within the cephalostat.[8,9]

1. The geometry of the radiographic setup gives rise to two distinct sources of error. One type of error occurs due to the fact that the x-ray beam originates from a source which has a finite size. This leads a penumbra effect or optical blurring.[10,11] The second type of error is due to the fact that the x-ray beam does not consist of parallel rays. This leads to an overall magnification of the object being radiographed and radial displacement of all points not on the principal axis. This type of error has been well documented in the literature[9,12-15] and correction factors do exist, but are not considered practical for routine use.[12-13,15-18]

2. Film variables include such things as film speed, collimation, and intensifying screens. Errors introduced by these factors influence the quality of the image produced. Image quality depends on the contrast between areas on the film, the density of different areas of the film and the sharpness of the image produced. All of these factors will affect the diagnostic value of the film and must be strictly controlled to minimize patient exposure while maintaining image quality.[19-25]

3. The third type of projection error arises from patient positioning within the cephalostat. The main purpose of the cephalostat is to orient the patient's head,

with Frankfort horizontal parallel to the floor, during the imaging procedure. By ensuring the position of the patient is reproducible, one should be able to take additional radiographs of the patient that allow direct comparisons between the films.[26,27]

The greatest errors due to patient positioning occur when there are changes in the head position within the cephalostat due to rotation about either vertical, antero-posterior or transverse axis . Rotation about any of these axes may result in distortions in the radiographic image, with the degree of distortion dependent upon the orientation of that axis in relation to the central ray of the x-ray beam. If the axis of rotation is parallel to the central ray the image will rotate accordingly on the film but no distortion will result. If the axis of rotation is not parallel to the central ray a distorted image will be produced. Thus for a PA cephalogram, rotation about the AP axis will cause no distortion. For the lateral cephalogram, rotation about a transverse axis causes no distortion.

Most cephalostats are designed such that they have ear rods which fit into the external auditory meattus' to keep the head from rotating about the vertical and antero-posterior axes. A third reference marker which touches the bridge of the nose, in the region of nasion, prevents rotation about a transverse axis.[26,27] Since these devices contact soft tissues, which may change during growth the potential for error in patient positioning exists.

If the patient is positioned properly within the cephalostat the ear rods should fit snugly into the external auditory meattus' limiting the amount of rotation which could occur about the antero-posterior and vertical axes. These rotations are small, but combined with any variation in the positions of the external auditory meattus', either vertically or antero-posteriorly, may result in significant rotations of the head.

Rotation about the AP axis would not affect the image produced on a PA cephalogram as it is parallel to the central x-ray beam. Rotations about a vertical axis will cause distortions in the PA cephalometric image as it is not parallel to the central x-ray beam.

Rotation about the transverse axis can occur much more readily in a cephalostat due to the nature of the soft tissue reference on the bridge of the nose, and the fact that positioning Frankfort horizontal parallel to the floor is a subjective determination made by the operator. The relationships between landmarks in the vertical dimension would be the most subject to change with this type of rotation and may create limitations when trying to compare successive films for growth or treatment changes.

ii. Tracing errors

Tracing errors are those which arise during the act of tracing and analyzing the cephalogram. This category of error includes: 1. those that arise from instrumentation; and 2. those that arise from identification of cephalometric landmarks.

1. The errors from instrumentation are due to such factors as the perceptive limits of the human eye, the accuracy of the measuring instruments, and the thickness of the pencil line for tracings.[28]

2. Errors from identification of landmarks are due to the uncertainty involved in pinpointing a specific spot on a radiographic film. The precision with which any landmark can be identified depends on many factors.[8,9,29] The ones which have the greatest effect on landmark identification are:

- the radius of the curve the point lies on - the smaller the radius the easier the landmark can be identified;
- the contrast in the area of the landmark - points in high contrast areas easier to identify;
- the superimposition of other structures in the area of the landmark - points located in areas where there is superimposition of other structures being more difficult to locate;
- the definition of the landmark - more precision in the definition allows less room for interpretive errors;
- and the experience of the operator - increased knowledge of the anatomy and radiologic appearance of the skull makes for greater precision in landmark identification.

Tracing errors are, to a certain extent, dependent upon the projection errors. If the geometric, film or patient positioning variables are poorly controlled then one would expect a general increase in tracing errors. The goal therefore becomes: to control the sources of error from both projection and tracing sources and, recognizing the deficiencies in the system, ensure that any analysis used minimizes the inherent error.

C. Analytical Problems

Analytical problems arise from the fact that in order to derive meaningful information from a cephalogram, one must have a starting point or reference system from which to make measurements. The first of the major requirements which must be met by a reference system is that it must be stable over time. Secondly, it must be located in a region of the skull that is unaffected by treatment and thirdly the structures must be readily identifiable on the cephalometric image.[30]

With the lateral cephalometric image, structures in the cranial base region fulfil all of these requirements.[31-33] In the PA cephalometric image however, these requirements are harder to fulfil due to two factors. The first is that stable structures in the cranial base are generally midline structures, and therefore are localized in the centre of the PA image, thus limiting their usefulness. Secondly there is a great deal of superimposition of these structures both on one another and on other parts of the facial skeleton, making visualization more difficult.

The PA cephalogram has an additional requirement for its reference system which is that it must be in a region of the facial skeleton that is relatively unaffected by asymmetry.

D. STATEMENT OF PROBLEM

The effects of head rotations within the cephalostat have not been thoroughly investigated.[37] With PA cephalograms rotations about either the vertical or transverse axes will have an effect on the image produced. Rotations about a transverse axis are of particular interest since they may occur relatively easily.

The impact these rotations have on the ability to identify the landmarks and the relationships of the landmarks to one another has not been examined closely for PA cephalograms.

Each landmark utilized in an analysis of a cephalogram will have some error associated with its identification which may give rise to inaccuracies. In order to keep the analysis as accurate as possible, it is desirable to use those landmarks with the least amount of identification error. A relatively small amount of research has been directed toward landmark identification for the PA cephalogram[29] and the great majority of PA analyses utilize landmarks whose identification error has not been reported.

When considering the analytical problems associated with PA cephalograms the symmetry of the reference system is critical in determining the usefulness of the analysis. There have been comparatively few studies into the symmetry of the reference systems used in PA analyses and none which take into account both the symmetry and the reliability of the landmarks used in the reference system.

E. PURPOSE OF THE STUDY

The purpose of this study is to: examine the identification errors associated with landmarks on the PA cephalometric image; determine the effects of rotation of the skull by 5^o about the vertical and transverse axes on the magnitude of the error; and determine which landmarks in the skull are best suited to establishing reproducible horizontal and vertical reference planes for use in asymmetry analyses.

Since the potential for rotations of the skull within the cephalostat exist, this study is designed to identify differences in identification error between the normal skull position and 5^o rotations about both the vertical and transverse axes, between intra-examiner and inter-examiner error, and between bilateral landmarks.

Deviation analyses will be used to determine the magnitude of variance between the slope of lines through bilateral landmarks versus the best horizontal line through the skull. Two similar analyses will be employed to examine the best vertical line through the skull. The first will evaluate the fit of each midline landmark and bisector of bilateral landmarks to the best vertical line and the second will examine the variation of the slope of lines through selected pairs of landmarks in the upper facial skeleton with respect to the best midline.

The ultimate goal of the study is to propose landmarks which can be used to construct reference planes for use in PA symmetry analyses which are based upon landmark identification error and freedom from the effects of head rotation.

F. RESEARCH QUESTIONS

1. What is the magnitude of the identification error for postero-anterior cephalometric landmarks?
2. Does the identification error change significantly with rotations of the head?
3. Is there a significant difference between the magnitude of intra-examiner and inter-examiner identification error?
4. Is there a significant difference in the magnitude of the identification error for opposite sides of the skull?
5. Does the slope of the line between any two bilateral landmarks differ from the best horizontal line through the skull?
6. Which midline points and bisectors of bilateral points best fit the best vertical line through the skull?
7. Which combination of points on the upper part of the skull best approximates the best vertical line through the skull?
8. Which of the combinations of upper skull points is least affected by skull rotations?

G. HYPOTHESES

1. Ho - The landmark identification error is not significantly different for the various postero-anterior cephalometric landmarks.

   Ha - The landmark identification error is significantly different for the various postero-anterior cephalometric landmarks.

2. Ho - There is no significant difference in landmark identification error with a 5^{o} rotation of the skull about a vertical axis.

   Ha - There is a significant difference in landmark identification error with a 5^{o} rotation of the skull about a vertical axis.

3. Ho - There is no significant difference in landmark identification error with a 5^{o} rotation of the skull about a transverse axis.

   Ha - There is a significant difference in landmark identification error with a 5^{o} rotation of the skull about a transverse axis.

4. Ho - There is no significant intra-examiner difference in the identification error for bilateral landmarks.

   Ha - There is a significant intra-examiner difference in the identification error for bilateral landmarks.

5. Ho - There is no significant difference between inter- and intra-examiner identification error.

   Ha - There is a significant difference between inter- and intra-examiner identification error.

6. Ho - There is no significant inter-examiner difference in the identification error for bilateral landmarks.

   Ha - There is a significant inter-examiner difference in the identification error for bilateral landmarks.

7. Ho - There is no significant difference between the slope of the line through any of the bilateral landmarks and the best horizontal line through the skull.

   Ha - There is a significant difference between the slope of the line through the bilateral landmarks and the best horizontal line through the skull.

8. Ho - Rotations of the skull of 5^{o} about a vertical axis do not significantly affect the fit of the slope of the lines through bilateral landmarks with the best horizontal line through the skull.

   Ha - Rotations of the skull of 5^{o} about a vertical axis significantly affect the fit of the slope of the lines through bilateral landmarks with the best horizontal line through the skull.

9. Ho - Rotations of the skull of 5^{o} about a transverse axis do not significantly affect the fit of the slope of the lines through bilateral landmarks with the best horizontal line through the skull.

   Ha - Rotations of the skull of 5^{o} about a transverse axis significantly affect the fit of the slope of the lines through bilateral landmarks with the best horizontal line through the skull.

10. Ho - All midline points and bisectors of bilateral points fit the best vertical midline through the skull.

Ha - There are differences in the fit of the midline points and bisectors of bilateral points and the best vertical midline through the skull.

11. Ho - All of the combinations of points in the upper part of the skull give a constructed midline that fits the best midline equally well.

Ha - There are differences in the fit of constructed midlines with the best midline.

12. Ho - Rotations of the skull of 5^{o} about a vertical axis do not significantly affect the fit of the constructed midlines with the best midline.

Ha - Rotations of the skull of 5^{o} about a vertical axis significantly affect the fit of constructed midlines with the best midline.

13. Ho - Rotations of the skull of 5^{o} about a transverse axis do not significantly affect the fit of the constructed midlines with the best midline.

Ha - Rotations of the skull of 5^{o} about a transverse axis significantly affect the fit of constructed midlines with the best midline.

II. LITERATURE REVIEW

Cephalometric radiography plays an important role in the processes of diagnosis and treatment planning for orthodontic patients. Since its introduction in 1931,[1] cephalometry has been studied extensively from many different viewpoints. The great majority of this work has been directed toward the lateral cephalogram with the PA view receiving much less attention.

This relative lack of interest in the PA cephalogram stems from two different but related problems which affect cephalograms in general and the PA view in particular - technical problems and analytical problems.

Technical problems arise during the production of the cephalogram and during the procedures of tracing and analyzing the cephalometric image. Analytical problems are those which are associated with the determination of reference planes which act as the bases for cephalometric analyses.

A. Technical Problems

Technical problems give rise to errors which affect the accuracy of the cephalometric process. According to Van Aken [34], the total error associated with any cephalogram is the sum of the errors from all sources combined. If one error is very large in comparison to the others, it will be the main determinant of the magnitude of the total error. Thus, in order to reduce the error by the greatest amount, effort must be directed at reducing the largest source of error. Technical problems lead to errors which, depending on their source, can be separated into the categories of either projection or tracing.

Projection errors are those which arise during the process of generating cephalograms, and come from three distinct sources: 1. the geometry of the cephalometry equipment; 2. the film related variables; and 3. the patient positioning within the cephalostat.

Tracing errors are those that arise from the process of tracing and analyzing the cephalograms and come from two sources: 1. the instruments used in analyzing the cephalogram; and 2. the identification of landmarks used in the analysis.

i. Projection Errors

The existence of projection type errors has been known since the advent of cephalometric techniques. These errors, because of their nature, cannot be eliminated, but can be controlled to minimize their effects.

1. The geometry of the radiographic equipment gives rise to errors of two different types. The first is the penumbra effect or optical blurring. This was described by Thurrow[10] as originating from the fact that the source or focal spot, which produces the x-rays, has a finite size. Each part of the object being radiographed receives x-rays from all areas of the source which results in a blurring of the image on the film (figure 1).

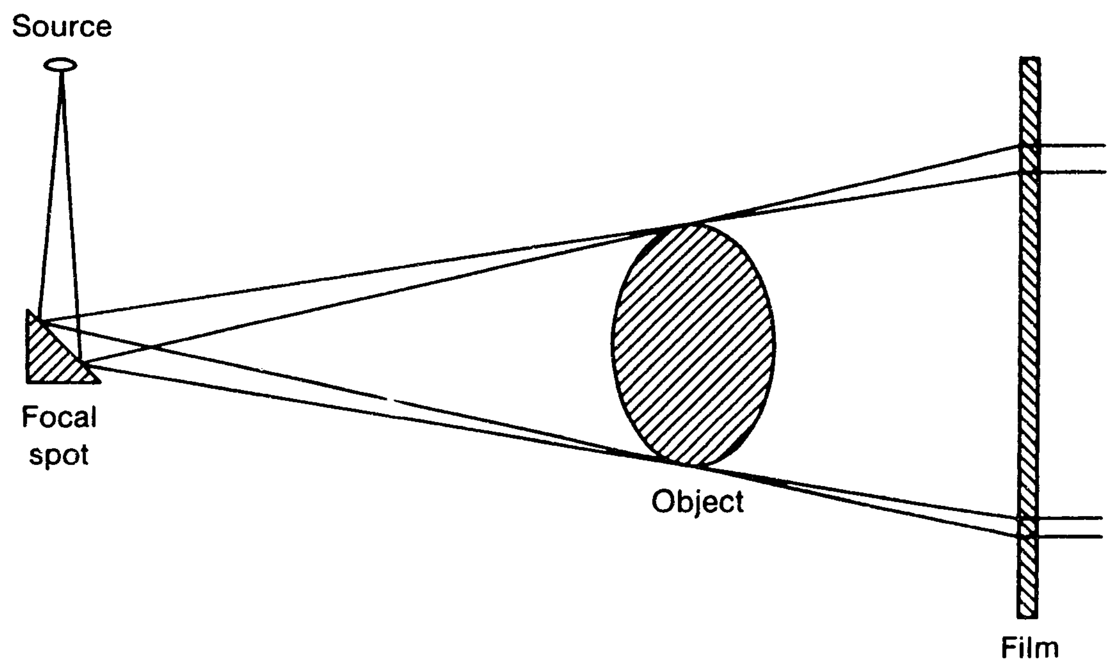


Figure 1. Penumbra Effect

The size of the penumbra is a function of: the size of the focal spot; the distance from the source to the object and the distance from the object to the film. Thus the amount of optical blurring can be calculated using the formula:

$$\text{penumbra size} = \frac{\text{focal spot size X object-film distance}}{\text{focal spot-film distance}}$$

Thus it can be seen that decreasing either the size of the focal spot or the object to film distance will decrease the size of the penumbra, and increasing the focal spot to film distance will also decrease the size of the penumbra.[10,11]

The magnitude of the error introduced by the penumbra effect is generally quite small due to the long focal spot to film distances (generally over 150 cm) , the small size of the focal spot (2-3 mm diameter), and the relatively short object to film distances (less than 20 cm). Van Aken [34] estimated the size of the penumbra to be less than 0.2 mm and Newman and Meredith [11] calculated it to be between 0.3 and 0.4 mm.

The second type of geometric error stems from magnification of the radiographic image. Magnification occurs during all radiographic techniques and is due to the fact that the source of the x-rays is very small and the x-ray beams radiate in all directions outward from the source (figure 2).[12,13] Andrew and Warren [14] examined the magnification produced in radiographs taken at various target to film distances by placing brass rods of known length at various distances from the film and then altering the target to film distance. They produced charts

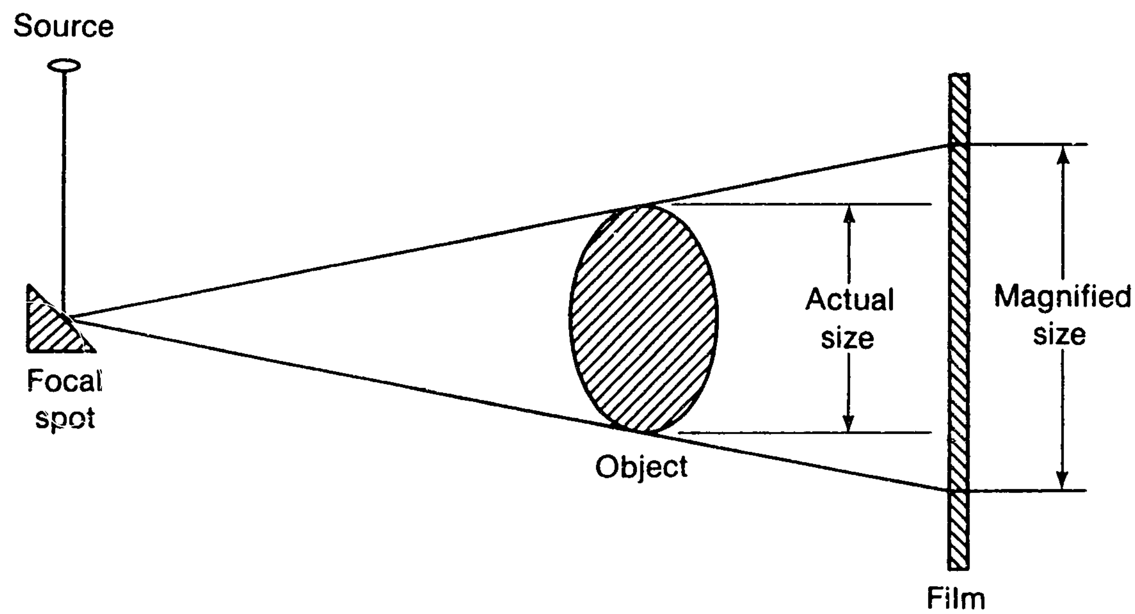


Figure 2. Magnification

that enable one to calculate the percentage of magnification for any given target to film and object to film distances.

The size of the projected image is related to the distance between the source of the x-rays and the film, and the distance between the object and the film by the following formula:[15]

$$\text{Image size} = \frac{\text{object size x object-film distance}}{\text{source-film distance}}$$

Thus the farther the object is from the film and/or the closer the film to the source the greater the enlargement of the radiographic image. Since the object to film distance is limited by the size of the skull,it would seem reasonable to increase the source to film distance as much as possible to decrease the amount of magnification. The amount of reduction possible with this method however, is limited. Bergerson [13] points out the fact that the concentration of penetrating x-rays varies inversely with the square of the distance from the source. Thus for distances above five feet there are considerable increases in exposure with relatively small decreases in enlargement, making very large source-film distances impractical.

Because the amount of magnification varies with the distance of the object to the film, structures within the same skull will have varying amounts of enlargement relative to their distance from the film. While all structures in the mid-sagittal plane will have the same amount of enlargement, any structures closer to the film will have less and those further away more. This differential enlargement is especially important when making measurements on the cephalograms between structures not the same distance from the film.[10,35]

With lateral cephalograms these differences can be minimized by using the midpoint between the images of the two sides. This averaging of the bilateral structures does not eliminate the problem of differential enlargement but does reduce it greatly.[10,35].

The magnification due to divergence of the x-rays causes a differential distortion of the cephalometric image with peripheral structures being enlarged more than central structures.[12] This type of distortion can be termed radial displacement and occurs with all structures not on the central ray.

Adams[12] attempted to overcome the problems associated with magnification through the production of scales which could be used to correct measurements of structures depending on their distance from the mid-sagittal plane. These scales corrected for both radial displacement and differential magnification. He used them to compare the measurements on radiographs with direct anthropometric measurements on skulls. The results showed that the corrected measures compared well with the direct measurements but there were no statistical comparisons performed on the data. He did however note that these corrective scales were not applicable to the PA cephalometric image.

Wylie and Elasser[16] in 1948 designed a "compensator" which enabled the distances between structures on the PA and lateral image to be corrected for magnification. The "compensator" consisted of a specialized drawing board and t-square which used radii of a sphere instead of parallel lines. The distances between structures could be corrected for magnification and in the process an undistorted vertical projection of the skull could be constructed.

Newman and Meredith[11] utilized corrective scales to measure bigonial diameter from PA radiographs in children from five to eleven years of age. By using lateral headfilms produced with the same head holding device as the PA films, they were able to measure the distance of the bigonial plane from the film for each PA radiograph. Since the source to film distance was known, a simple algebraic equation enabled the actual bigonial dimension to be calculated from the measured distance on the radiograph. This method fails to allow for correction of the radial displacement of structures.

Hallet in 1959[15] used a pantographic approach to correct for enlargement in lateral headplates. This method utilized various pantographs to trace structures located at different distances from the mid-sagittal plane. This method required that the distances of each structure that was to be traced be known for each patient and also made no compensation for radial displacement.

Vogel in 1967[17] made an adaptation of Wylie's technique in order to be able to account for incorrect patient positioning. Through modification of the "compensator" to allow the lateral film to be projected as well as the PA and by tracing both sides of the bilateral structures as seen on the lateral cephalogram he was able to more accurately reproduce anthropometric measurements on skulls. This was not however backed up with any statistical tests.

Bergerson[13] in 1980 attempted to simplify the process of compensating for magnification by producing tables for the lateral and PA views as well as an adaptation table for the most commonly used cephalometers. The tables give differential compensation factors for various structure to film distances. As with Adams' method, correction for enlargement on the PA view is dependent on measurements made from the lateral cephalogram.

As yet a simple method for correction of magnification has not been developed which is practical for routine usage by the clinical orthodontist. Magnification cannot be eliminated and for the purposes of analyzing individual patients does not require any compensatory measures. Magnification comes into play only when attempting to make comparisons between different films of the same individual or between individuals. As yet the only practical way to overcome the problem of magnification is through standardization of technique which will result in the same amount of magnification on each film.[10,26,27]

2. The second group of factors which create projection errors are the variables related to the production of the radiographic image on the film. These film variables include such things as collimation, intensifying screens and film speed, all of which can have an effect on the radiographic image quality.

Image quality however is not a simple entity to quantify and depends not only on the amount of detail which can be seen on a film but also on the information that one needs to extract from it.[36] There are no specific criteria which can be applied to determine if a film is of sufficient quality to be of diagnostic value and in general efforts have been aimed at minimizing patient exposure while maintaining high image quality.

Collimation is one method which achieves both objectives at the same time. Through collimation of the x-ray beam by means of extended tube heads or prepatient blocking there is a reduction in the patient exposure and a concomitant increase in image quality through a reduction in the amount of scatter and secondary radiations produced.[18]

Since the introduction of rare earth intensifying screens and faster films, many studies have been performed to try to assess the effect of these exposure reducing devices on radiographic image quality.

Halse and Hedin[19] in 1978 performed both subjective and objective comparisons of five fast screen/film combinations with a conventional high definition system. By subjective evaluation all of the fast screen/film combinations were deemed inferior in image quality to the conventional system. By objective comparison, which consisted of two angular and two linear measurements on each film, the differences in image quality only slightly affected the cephalometric recordings. There were, however, no statistical comparisons made on the data.

McWilliam and Welander in 1978[20] evaluated several rare earth intensifying screen/fast film combinations to determine whether they could be utilized for cephalometry. In the experiment five experienced orthodontists quantitatively evaluated fifteen different screen/film combinations by marking selected landmarks on radiographs of phantom skulls. They found that there were significant differences in the ability of the operators to identify landmarks with only the most sensitive screen/film combinations. This finding was however true for only those landmarks showing the lowest standard deviations. The authors therefore questioned its clinical significance and recommended the use of high intensifying screens for cephalometry.

Hurlburt in 1981[21] subjectively compared four fast screen/film combinations utilizing radiographs of phantom skulls. Seven orthodontists evaluated each film and rated the adequacy of the radiographic image of eight landmarks on each of the four screen/film combinations. All of the films were deemed adequate for diagnostic purposes and while some films were ranked above others there was no statistical difference found.

Kaugers and Fatouros [22] performed a blind clinical trial comparing conventional and rare earth screen/film combinations. Their study, conducted by questionnaire, found the fast screen/ film combinations to be comparable to the conventional systems.

McNichol and Stirrips [23] in 1985 did another subjective type comparison between fast screen/film combinations. The results of their study showed a lack of inter-observer correlation. For this reason they concluded that subjective evaluations of radiographic quality were inadequate for the purpose of comparison.

Stirrips in 1986[24] utilized an objective clinical method to comp the accuracy of locating six landmarks between two screen/film combinations. No significant difference was found between the two methods although the mean location error was greater for all the landmarks on the faster film. He concluded that rare earth screen/film combinations should be utilized to reduce patient exposure.

Stathopoulos and Poulton[25] also performed an objective study comparing rare earth screen/film combinations with the conventional methods. This investigation utilized one hundred independent measurements of each of the eighteen landmarks studied and the amount of error associated with each landmark for both systems calculated. The results showed that only six of the landmarks showed significant differences in the amount of error, with three favouring the rare earth screens and three the conventional method. Based on this evidence, the use of the faster rare earth screen/film combinations was recommended.

While the image quality of a cephalogram may be affected by exposure reduction techniques it appears that the diagnostic value of the radiograph itself is not significantly affected by film related variables.

3. The third factor which can cause projection errors is the position of the patient within the cephalostat. Errors in patient position, whether due to poor technique or anatomical problems, can result in distortions of the image which could potentially lead to diagnostic inaccuracies. This is especially true for the PA cephalometric image as it is much more susceptible to positioning problems than the lateral cephalogram.

This susceptibility is due to the fact that PA cephalograms are affected by rotations of the head within the cephalostat to a much greater extent than lateral cephalograms. The lateral cephalogram is affected by rotations about the antero-posterior and vertical axes, while the PA is susceptible to rotations about the vertical and transverse axes. Because of cephalostat design, rotations about the transverse axis occur relatively easily in comparison to those about the vertical and antero-posterior axes. Since the PA view is susceptible to these rotations, errors in patient positioning can result in distorted images on the radiographs. Rotations about the antero-posterior and vertical axes are limited to small amounts by the ear rods of the cephalostat but may still significantly affect the PA image while the lateral view remains relatively unaffected. This is due to the fact that with the lateral cephalogram any distortions introduced by rotations can be minimized through averaging the images of bilateral structures on the radiograph.[10,47,48]

Van Aken[34] performed calculations to determine the effects that head rotation, and deviation away from the median plane (mid-sagittal plane for lateral cephalograms and interporionic axis for PA cephalograms) would have on the length of radiographic images compared to actual lengths of the object. In his study he set a limit of 0.5 mm as an acceptable amount of error between the actual length of the object and the length projected on the film. From the results it can be seen that objects located closer to the film than the median plane will have less error due to magnification but the closer to the film they are, the greater will be the effects of head rotations. Although his paper dealt with only the lateral cephalogram the same principles can be applied to the PA view. From his study he concluded that in order to keep the error down to 0.5 mm or less head rotations should be kept very small.

Ishiguro et al[37] in a PA cephalometric study of cleft palate patients from birth to six years of age stated that rotation of the head of ten degrees or less either up-down or left-right was a negligible factor in breadth measurements but did however affect height measurements to a greater extent. Based on this information they eliminated all cephalograms which were rotated over ten degrees either vertically or laterally. It is unclear how they determined the degree of rotation of the head by examination of the radiographs and the data from which they made their cutoff point of ten degrees is not presented.

Eliasson et al[49] in 1982 presented the basic mathematics which could be utilized to calculate the two dimensional image that arises from the cephalometric projection. In a second paper the effects of misalignment between the source, the cephalostat, and the film as well as malpositioning of the object were considered.[50] From this work it can be seen that for the PA cephalogram, rotation of the head about the vertical axis will have small effects on vertical measurements but much greater effects on horizontal measurements. Rotations about the transverse axis were not discussed specifically but the effects would be just the opposite, with vertical measurements affected to a much greater extent than horizontal measurements.

Ahlqvist et al[47] in 1986 used mathematical calculations to study the effects of various head rotations on linear cephalometric measurements. The results of their investigation revealed that the error introduced by head rotations of five degrees or less results in an insignificant amount of error (less than 1 percent) in the distance measurements. The error increases when rotation in more than one plane is considered. The inclination of the line being measured with respect to the axis of rotation will affect the amount of distortion which occurs. A line parallel to the axis will be least affected and a line that is perpendicular the most affected. They stated that head rotations of greater than five degrees should not occur with careful patient positioning. This information however was calculated for measurements in the median plane of the lateral cephalogram and thus may not be applicable to the PA image where the landmarks are located away from the median plane.

In another study done in 1988, Ahlqvist et al [48] examined the theoretical changes in angular measurements due to rotations of the head within the cephalostat. They found that, for head rotations of ten degrees or less in any one plane, the distortion of the angular measurement did not exceed 0.6 degrees. When rotations were in more than one plane the amount of distortion was increased. This study was however done for the lateral cephalometric image using angles in the mid-sagittal plane and may not be applicable to the PA view where the points are not in the median plane.

It is apparent that patient positioning can introduce errors in cephalometric radiography and that the magnitude of the error depends on not only the amount of malpositioning but also on the type of measurement and the relative positions of the structures being measured.

ii. Tracing Errors

The second type of technical problem that is inherent in the cephalometric technique are the errors associated with tracing. These errors, like projection errors, may be reduced but not eliminated.

1. The first type of tracing error is that which arises from the instruments used to trace and analyze the cephalogram. These errors are dependent on factors such as the thickness of the pencil lead (if a tracing is used), the accuracy of the measuring devices and the perceptive limits of the human eye.[28] The analysis can only be as precise as the devices used to perform the measurements. Thus if the pencil line is one half of a millimetre thick and the ruler is accurate to a tenth of a millimetre, any measurement can only be made to the nearest half millimetre and theoretically could be as much as six tenths of a millimetre off, based solely on instrumentation error.

With the introduction of computerized digitization techniques the amount of error introduced by these factors can be reduced, both through the removal of the tracing error, and the elimination of the necessity to measure angles and linear dimensions with separate devices.

Bergin et al[39] performed a study which compared the error of a computerized method of measuring directly on radiographs with a strictly manual method. They found that the errors introduced by transference of the points to the computer and the rounding errors in the computer were small in comparison to other sources of error.

Richardson[51] made a comparison of the reproducibility of direct digitization of landmarks, with that of using hand instruments. The digitization technique showed lower standard deviations for the majority of landmarks, and it was felt that it had the greatest advantage when locating the most reliable cephalometric points. The author felt that when using landmarks which were difficult to identify the digitizer afforded no gain in accuracy because of the large identification error.

Cohen[40] in 1984 utilized a digitizer to make a comparison of measurements made: on tracings of radiographs; on modified dot tracings; and directly on the radiographs. The results of the study show that direct digitization was a more reproducible method than either of the tracing methods. The author felt that this was due to the fact that with tracings two estimates are required - first, in the tracing of the landmark itself; and second, in recording the exact position of the pencil line. He recommended the use of direct digitization as there is less room for error.

Sandler [41] performed another study on the effect of making tracings on the reproducibility of cephalometric measurements. In this study he compared the reproducibility of linear and angular measures between: hand tracing and measurement; direct digitization of the radiograph; and tracing prior to digitization. The results showed that there was appreciable error associated with all three methods, and direct digitization was the most reproducible for angular measurements.Direct digitization was not however as reliable for linear measures involving bilateral structures. Despite this the author recommended the use of direct digitization due to the quickness of the technique and the fact that it removes the possibility of incorrect reading of measuring devices as a factor.

2. The second type of tracing error arises from the uncertainty of identifying specific landmarks on a radiograph. This is termed landmark identification error and is dependent upon many factors including: the sharpness of the curve a point lies on; the contrast in the area of the landmark; the superimposition of other structures in the area of the landmark; the precision of the definition of the landmark; and the experience of the operator.[9,42,52,53]

Savara et al in 1966[38] analyzed the errors involved in making cephalometric measurements on tracings. From their work, which separated the sources of variance, it was shown that landmark identification error was five times as large as the error arising from tracing sources.

Richardson[52] investigated the reproducibility of some points used in lateral cephalometric analyses. He found that the reproducibility varied between points, and that the magnitude of the vertical and horizontal errors differed for each point with some being quite reproducible vertically and not horizontally and vice versa for others.

Mattila and Haataja[43] studied the accuracy of determining certain reference points in cephalometry. Radiographs of twenty skulls were taken, and then traced independently by two operators. A further radiograph was then taken with metal indicators glued to the skulls at the location of the anatomic point and a third tracing made. The three tracings were superimposed and the points transferred to millimetre paper. The resultant scattergraphs show the size and shape of the variation around each point. From this they found that the amount of error associated with landmark identification was quite high and differed between operators.

Baumrind and Frantz[9] through the use of a digitizer and computer programs calculated the magnitude of the identification error for sixteen commonly used landmarks. In their study twenty lateral radiographs of patients were chosen and each one traced and then digitized by each of five operators. From this data the identification error for each of the points was calculated both vertically and horizontally. They concluded that there is an appreciable amount of error in landmark identification and that each landmark had its own characteristic and non-circular envelope of error.

Midtgard et al[44] studied the reproducibility of identifying fifteen landmarks on consecutive radiographs taken during the same examination. They looked at the mean differences in landmark locations between the two radiographs and for duplicate determinations on the same radiograph. The results showed that there were significant differences between the landmark locations on the consecutively taken radiographs as well as for duplicate readings of one radiograph. The magnitude of the error depended on the location of the landmark. There were no significant differences found between the amount of identification error between the two methods. They concluded that the differences in measurements depend, for the most part, on the uncertainty associated with identifying the landmarks and that the error introduced by the consecutive radiographs is relatively minor.

Broch et al [45] utilized thirty lateral cephalograms of children between 9 and 10 years of age to determine the identification error of fifteen commonly used landmarks. Duplicate digitizations were carried out, and the error of each landmark calculated for both the vertical and horizontal dimensions. The results show that each landmark had its own characteristic distribution of error, and that while the errors in landmark identification may be of minor significance in group studies, for single individuals such errors are of considerable concern.

Stabrun and Danielsen [46] examined the differences between intra- and inter-examiner identification error for fourteen cephalometric landmarks. Two operators each made double determinations on a sample of 100 lateral cephalograms. The results showed that the intra-examiner error was less than the inter-examiner error and that this difference may be significant if the same radiograph was registered by more than one observer.

El Mangoury et al[29] in 1987 studied the landmark identification error for thirteen landmarks on the PA cephalometric image. Forty radiographs of adult subjects were each digitized twice by one operator. The identification errors for each landmark were calculated for the horizontal, vertical, and radial dimensions. The results showed that the dental landmarks were in general less reliable than the skeletal points and that the envelopes of error for each landmark were peculiar to that point.

Vincent and West [8] performed an investigation into the magnitude of identification error for twenty-two landmarks on the lateral cephalometric image. Twenty cephalograms were each traced five times and then digitized to establish the identification error. The magnitude of the identification error was slightly larger in this study than in others of this type. The authors explained this as being possibly due to the use of five, instead of two, determinations for each film. A more likely explanation would be the fact that tracings were utilized instead of direct digitization.

Landmark identification error accounts for a significant proportion of the total error in analyzing both PA and lateral cephalometric images. Care must be taken both in selection of landmarks and the manner in which the landmarks are used, in order to minimize the effects of identification error.

B. Analytical Problems

Analytical problems arise during the process of analyzing cephalometric images and are related to the reference planes which serve as the bases for analyses. Since one of the major uses of PA cephalometric images is to assess both the degree and location of asymmetries, an examination of asymmetry in the "normal" population must be conducted first.

The question of symmetry has been widely studied and the fact that even a "normal" skull exhibits asymmetry to some degree is well known. Woo[54] investigated asymmetry in 800 Egyptian skulls from the 26th to 30th dynasties by anthropometric methods. From his series of 63 measurements on each skull, he found that the human skull is markedly asymmetrical and that there is a predominance of larger dimensions of individual bones on the right side. His results showed that the most highly correlated measurements between right and left sides were the anterior homologous lengths of the face and forehead.

Letzer and Kronman [55] investigated facial symmetry in individuals with both excellent occlusion and those with malocclusions. No significant differences were found between the excellent occlusion and malocclusion groups with respect to symmetry, and the anterior cranial base region exhibited a high degree of symmetry for both groups.

Shah and Joshi [56] examined forty-three subjects with no apparent facial asymmetry, to determine the range and distribution of asymmetry in the "normal" face. By defining triangles located in different parts of the face and comparing the area of these triangles between sides they found that asymmetry exists even in those people with excellent occlusions and no apparent facial disharmonies. Their results showed that the right side was significantly larger than the left and that the maxillary regions showed a greater degree of asymmetry than other components of the face.

Jain and Jain [57] in an anthropometric study of 118 normal adult skulls found that there were no significant differences between the measurements made on opposite sides of the skull except for two instances. They concluded that the two halves of the skull are symmetrical with respect to transforaminal distances and that the widths of the anterior, middle and posterior cranial fossae on the two sides were the same.

Hewett[58] and Vig and Hewett [59] studied facial asymmetry on randomly selected children by means of PA cephalograms. The results of these investigations showed that there was an overall facial asymmetry in the sample and that the left side of the face was larger.

Farkas and Cheung [60] in a study of facial asymmetry in 154 healthy north American Caucasians found that asymmetry was very common with the right side usually the largest. This study, however, was performed using anthropometric measurements of living patients and therefore may have been influenced by soft tissue deformation.

Greene [61] looked at asymmetry in infants and states that asymmetry of the occipital region is common in infancy and can be accompanied by an associated asymmetry of the face.

Mulick [62] performed a study of craniofacial asymmetry using a serial twin method with: six sets of same-sex triplets; six identical twin sets; and twelve fraternal twin sets. This enabled him to assess whether the asymmetry seen in normal individuals was due to hereditary or environmental factors. His results showed that there were no significant differences between the identical and fraternal twin groups and thus it was concluded that heredity is not the controlling factor in the production of craniofacial asymmetry.

The amount and location of asymmetry found in the "normal" individual varies from person to person. There are however some conditions in which the degree of asymmetry is greatly exaggerated. Thompson [63] studied twenty-five cases of abnormal asymmetry and classified the causes of asymmetry according to their origins. Asymmetry can be due to congenital or acquired defects, damage to growth centres or direct injuries to the face. He states that malocclusion is not a cause of asymmetry but rather one of the symptoms of asymmetry.

Cheney [64] classified facial asymmetry into four categories which included: unilateral antero-posterior displacements; vertical displacements; lateral displacements; and rotary displacements. All of these types of asymmetry can be seen on PA cephalograms except for the unilateral antero-posterior displacements, which cannot be evaluated because of projection geometry.

Cleft lip and palate has been shown to be a significant factor in the development of facial asymmetry. Harvold [65] states that the asymmetry seen in cleft patients in the areas of the nasal septum and premaxilla occur early in fetal life and thus establish an inconsistent pattern of growth and development. Later alterations in environment such as surgical repair of the cleft can alter this pattern.

Molsted and Dahl [66] in a study of asymmetry in thirty one unilateral cleft-lip and palate children found that the pattern of symmetry aberrations in the group was quite complex. The asymmetry was due to a flattening of the alveolus and reduced vertical maxillary development on the cleft side, combined with deviation of the nasal septum toward the cleft side and deviation of the anterior nasal spine toward the non-cleft side. They found no differences in interorbital dimensions.

Other factors from both natural and unnatural sources have been shown to cause facial asymmetry. Hemi-hypertrophy, [67] hemifacial microsomia [68] and early closure of the coronal sutures [69] have all been shown to cause facial asymmetries of varying severity.

Bjork and Bjork [70] examined the effects of artificial deformation of the skull upon facial symmetry through the study of 149 ancient Peruvian skulls. Their investigation showed that in those cases where the cranium was asymmetrically deformed, there was a corresponding asymmetry of the cranial base and to a lesser extent in the facial skeleton. This lessening of the severity of the asymmetry in the facial region was thought to be due to compensatory growth of these parts.

One of the greatest problems facing the use of PA cephalograms to assess facial symmetry is the choice of reference planes to be used in the analysis. The problem arises from the fact that any linear or angular measurement, which is used to characterize or describe a particular part of the cranial morphology, must have a starting point or area of reference to give it meaning.

The region of the skull on the PA cephalogram which has been utilized to the greatest extent as a reference system has been the upper part of the facial skeleton, including the anterior cranial base and the region around the orbits. This is due to the fact that it fulfils the criteria for a reference system better than any other part of the skull visible on the PA image.

An ideal reference system for the PA view should have certain characteristics including: 1. separation from the lower facial skeleton; 2. stability over time; 3. freedom from asymmetry; and 4. easy identification.

1. Separation from the lower facial skeleton is important in that the reference planes should be free from the effects of treatment. If the treatment modality affects the reference system, then it will be of little use in the assessment of any changes which have occurred. For this reason the reference plane or planes should be located in the upper part of the face away from the maxilla and mandible.

2. Stability over time is important when comparisons are to be made between successive films of the same patient or when studying growth patterns in populations. If the structures which act as references are changing a great deal with

growth, the determination of changes within the other parts of the skeleton due to growth or treatment effects is made much more difficult. The structures in the anterior cranial base region of the skull have been shown to be relatively stable after the age of six to seven years in both the vertical and sagittal planes [32,33] and the region around the orbits has been shown to be stable after eight years of age.[71,72]

3. A reference plane which exhibits freedom from asymmetry is important for the PA cephalogram since in order to assess symmetry in different parts of the facial skeleton the reference plane must be in itself symmetric. The work of several authors [54-57,66] has shown that the region of the skull about the forehead and anterior cranial base show a high degree of symmetry.

4. The reference system must also be easily identifiable with a minimum of identification error associated with it. If the reference system is difficult to establish or has a large amount of uncertainty associated with it then the accuracy of any analysis becomes questionable. El Mangoury et al [29] examined two landmarks in this region and found that there was a significant amount of error associated with the identification of these points.

Numerous investigations utilizing similar methodologies have examined various aspects of facial asymmetry on PA cephalograms.

Harvold [65] in 1958 established the x-line method for determining facial symmetry in cleft patients. This method consisted of a horizontal line connecting the lateral parts of the zygomatico-frontal sutures and a vertical line representing the median plane of the face, drawn at right angles to the horizontal line through the root of crista galli. According to the author this method of locating the midline of the face, in normal cases, showed very little deviation of the anterior nasal spine from this line. In ninety percent of cases the anterior nasal spine was less than 1.5 mm from the x-line. He also stated that when the distances were measured from the temporal border of the zygomatic bone and from the zygomatico-maxillary sutures on the malar processes to the x-line the index of symmetry closely corresponded to anthropologic findings. There were however, no references to the specific anthropologic findings to which the comparisons were made, and no statistics presented to illustrate these findings. This analysis did not include an evaluation of vertical disharmonies which can also be seen on the PA cephalogram.

In 1959, Harvold et al[73] looked at the x-line method on 113 normal individuals between the ages of seven and fifty years. They found that in ninety percent of cases the median plane divided the distance between the left and right zygomatic bones into amounts which differed by less than 3 mm and, at subnasale, the median plane was very close to the intermaxillary suture, the distance rarely exceeding 3 mm. They also found that a median plane based on the intermaxillary suture at subnasale and passing through the root of crista galli would be unreliable in the region of the zygomatic bones. Again there were no statistics presented to back up these findings.

Letzer and Kronman [55] proposed a method of analyzing the PA cephalogram for symmetry of the anterior cranial base and the mandible. In this investigation the establishment of a median plane of the skull was accomplished separately for both the cranial base region and the mandible. These median planes were constructed as the bisectors of the angles formed between specific lateral structures and the midline structure crista galli. The lateral structures in the anterior cranial base region were the points of intersection of the upper border of the lesser wings of the sphenoid bone with the superolateral border of the orbits. The points used on the mandible were the most outward inferior point on the angle of the mandible. This investigation is well suited for comparing the symmetry within and between these regions but does not consider symmetry of the maxilla or dental structures.

Hewitt[58] along with Vig and Hewitt[59] examined asymmetry of the facial skeleton by means of an analysis which made comparisons between the unit areas of certain regions on one side of the face to corresponding unit areas on the other side. Initially two midline axes were derived in the middle third of the face (maxilla) and the lower third of the face (mandible), based on the best fit line through selected midline points and the bisectors of bilateral points. The angle of divergence between these two axes gave the relative degree of asymmetry between the middle and lower thirds of the face. Determination of the magnitude of asymmetry in seven regions of the face was made by the construction of triangles between bilateral and midline points. In this analysis there was no specific information gained with respect to vertical and horizontal relationships in the individual regions of interest.

Svanholt and Solow[74] examined midline discrepancies on PA cephalograms by comparing both the skeletal and dental relationships in the maxilla and mandible, to the facial midline. The facial midline was constructed by dropping a vertical line through the base of crista galli perpendicular to the horizontal line between the left and right intersection of the lateral orbital contours and the innominate line. The deviations of the dental and skeletal components of each jaw was then measured with respect to the facial midline. There was however no evaluation of vertical asymmetries included in this analysis.

Chebib and Chamma[75] performed a study in which they described a method of producing indices of craniofacial asymmetry based on the PA cephalometric image. In this study eight mid-sagittal points and twelve bilateral points were utilized to construct two midlines of the skull from which the indices were determined. The two midline axes were: the M-axis, which was the best fit line through the mid-sagittal points; and the L-axis, which was the best fit line through the bisectors of the bilateral points.

The axes were then examined for deviation from each other both laterally and angularly to give indices of lateral expansion and oblique distortion. Each of the pairs of bilateral points were examined for their deviation from the L-axis in both the vertical and horizontal dimensions to give indices of vertical and horizontal distortion. The midline points were also evaluated for their deviation from the M-axis to give an index of horizontal distortion for each of these points.

Butow and Van der Walt[76,77] introduced the "Stellenbosch"- triangle analysis for PA and basilar cephalograms. In the PA analysis two horizontal axes were defined: the first was the C-axis, which is the line through the points where the lesser wing of the sphenoid crosses the medial orbital margin bilaterally; and the second was the D-axis, which was the line between the most inferior points on the mastoid processes. A geometric axis was then constructed by joining the midpoints of each of these horizontal axes. Individual structures could then be evaluated for deviation from the geometric axis. Triangles were also constructed to relate the basal bone of the maxilla and mandible to the geometric axis and the C-axis. The lengths of the sides of the triangles gave information regarding the relative vertical and horizontal differences between sides of the skull. The information from the PA view can be combined with similar information from the basilar view and a conventional analysis of the lateral view to give a three dimensional picture of the facial skeleton.

Ricketts [7] proposed a frontal analysis in which symmetry was assessed through measurement of bilateral structures relative to a mid-sagittal plane. This plane consisted of a vertical line dropped through the top of the nasal septum or crista galli, perpendicular to the line through the centres of the zygomatic arches. This is similar to Harvold's x-line method [67] except for the position of the points which determine the horizontal axis. This analysis also made no reference to vertical asymmetry.

Stabrun[78] examined symmetry in the mandible on patients with juvenile rheumatiod arthritis. In this study the superior borders of the orbits were utilized to establish a horizontal reference line from which a perpendicular vertical line was dropped through nasion as the median plane. Vertical and horizontal measurements were then taken relative to the reference lines to determine the amount of asymmetry exhibited in the mandible.

Grummons and Van de Coppello[3] presented a frontal asymmetry analysis in 1987. This analysis made use of vertical, horizontal, and angular measures to determine the presence and location of asymmetries. Vertical relationships were determined through measurements made with respect to several horizontal reference lines which were located in different regions of the face. Horizontal relationships were made with respect to a mid-sagittal reference line which was constructed between crista galli and the anterior nasal spine. An advantage of this analysis is that vertical relationships can be evaluated both within and between regions of the face.

Molsted and Dahl[66] studied asymmetry in children with complete unilateral cleft lip and palate. The horizontal reference was drawn between the bilateral points where the greater wings of the sphenoid bone cross the lateral orbital contours. From the midpoint of this line a perpendicular was dropped to represent the midline of the face. Vertical and horizontal measurements were made with regard to these reference planes.

The choice of which reference planes to use for symmetry analysis of the PA cephalogram is not a simple matter. A variety of reference planes have been utilized in the literature for both the vertical and horizontal dimensions. There is, as yet, no one analysis which has proven superior to the others and the reference planes which best enable the symmetry of the skull to be delineated are still in question.

III. MATERIALS AND METHODS

A. Sample

A sample of 33 skulls was chosen from those available at the Faculty of Dentistry at the University of Alberta. These were selected on the following basis:

- all skulls had full permanent dentitions, up to the stage of second molar eruption;
- the first molars and cuspids were all present;
- all the cranial structures were intact;
- there were no gross asymmetries based on visual assessment;
- the mandible could be placed into centric occlusion with the maxilla.

All the skulls fitting the above criteria were selected to obtain the sample. The skulls were prepared for the radiographs first by removal of all the screws and springs attaching the mandible to the skull. Secondly the mandibles were fitted to the skulls in centric occlusion, determined by a manual best fit of the upper and lower dentitions, and fastened in four places with masking tape.

No information was available regarding the age, race or gender of the skulls. The Angle classifications were recorded based on the antero-posterior relationships of the first molars. Of the 33 skulls, 24 were class I (73%), 8 were class II (24%), and 1 was class III (3%). Two of the class II skulls exhibited subdivisions.

B. Radiographic technique

All the radiographs were taken utilizing a standardized cephalometric technique in the Division of Radiology. The source to film distance was a constant 160 cm and the distance from the middle of the ear rods to the film 17.5 cm. The film type was Kodak Ortho G film and the exposures were taken at 90 Kv and 50 milliamps with the Bucky screen on. The exposure times varied between 1/30th and 1/50th of a second depending on the size and density of the skull.

Each skull was stabilized in the cephalostat by placing the ear rods into the external auditory meattus and then using masking tape to secure it and prevent rotation. The skulls were oriented with Frankfort horizontal parallel to the ground by means of a skull orientation device which was fixed to the cephalostat (figures 3 and 4). The removable pointer was referenced to an indelible mark placed on each skull at or near the level of the infraorbital rim.

Five radiographs were taken of each skull. The initial radiograph was taken with the skull not rotated (normal view). Next, two radiographs were taken with the skull rotated 5^{o} to either side about a vertical axis (left and right views). And a final two films were taken with rotation of the skull by 5^{o} up and down about a transverse axis (up and down views) (figure 5).

The rotation about the vertical axis was accomplished by rotation of the cephalostat itself about a vertical axis centred between the two ear rods This could be done very precisely by means of reference marks on the cephalostat.

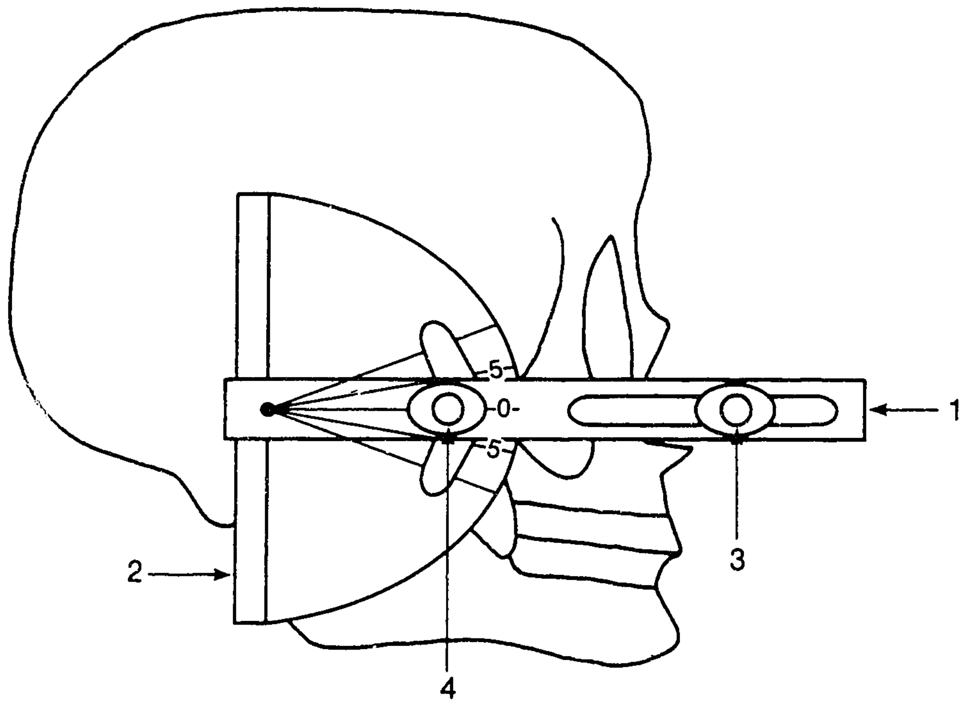


Figure 3. Orientation Device — Side view
1 - Vertical adjustment arm
2 - Protractor
3 - Pointer adjustment screw
4 - Vertical adjustment screw

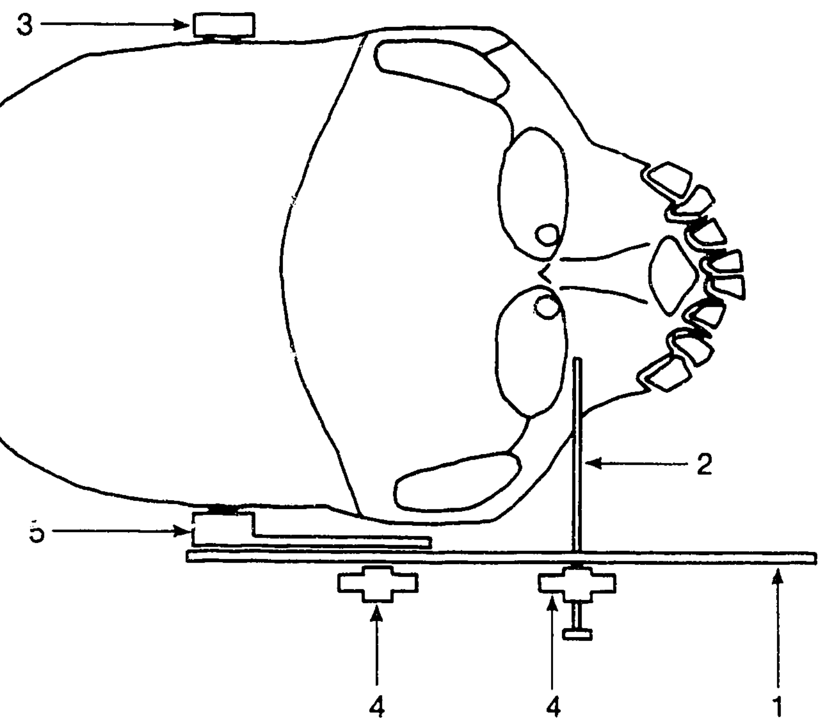
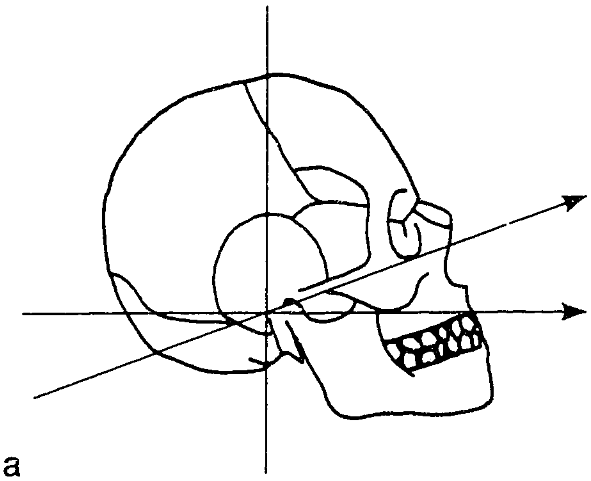
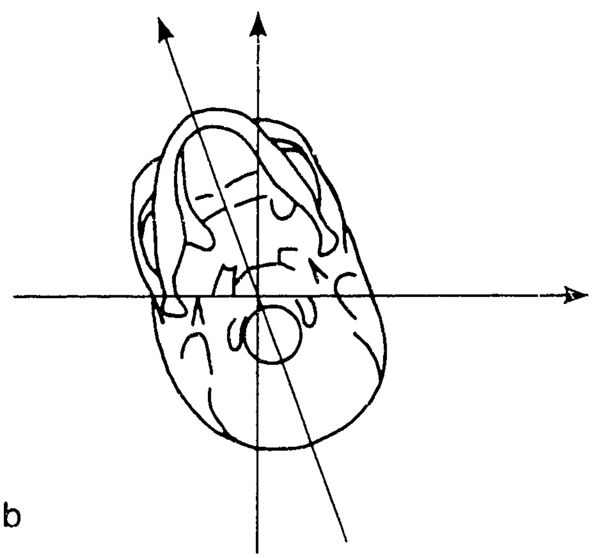


Figure 4. Orientation Device — Top view
1 - Vertical adjustment arm
2 - Pointer
3 - Ear rods
4 - Adjustment screws
5 - Protractor



a



b

Figure 5. Axes of Rotation. a. rotation about the transverse axis.
b. rotation about the vertical axis.

The rotation about the transverse axis was accomplished by changing the angulation of the pointer on the orientation device by 5^0 both up and down, removing the masking tape and then rotating the skull in the cephalostat about the ear rods to realign the pointer and the mark on the skull, and then resecuring the skull with masking tape.

In order to minimize any movement of the skull in the cephalostat, the normal view was always taken first, followed by the left and right rotated views, and the up and down rotated views last . Lead markers were utilized to signify the rotation of the skull directly on the radiograph and the skull number was marked on each film prior to processing. A metal marker within each ear rod was also projected onto each film and a pinhole placed at the superior edge of each marker to serve as reference points during the digitization procedures.

C. Landmarks

Fifty two commonly used landmarks were used, of which 36 were bilateral skeletal, 8 were midline skeletal, and 8 were dental (figure 6). The definitions of the landmarks are as follows:

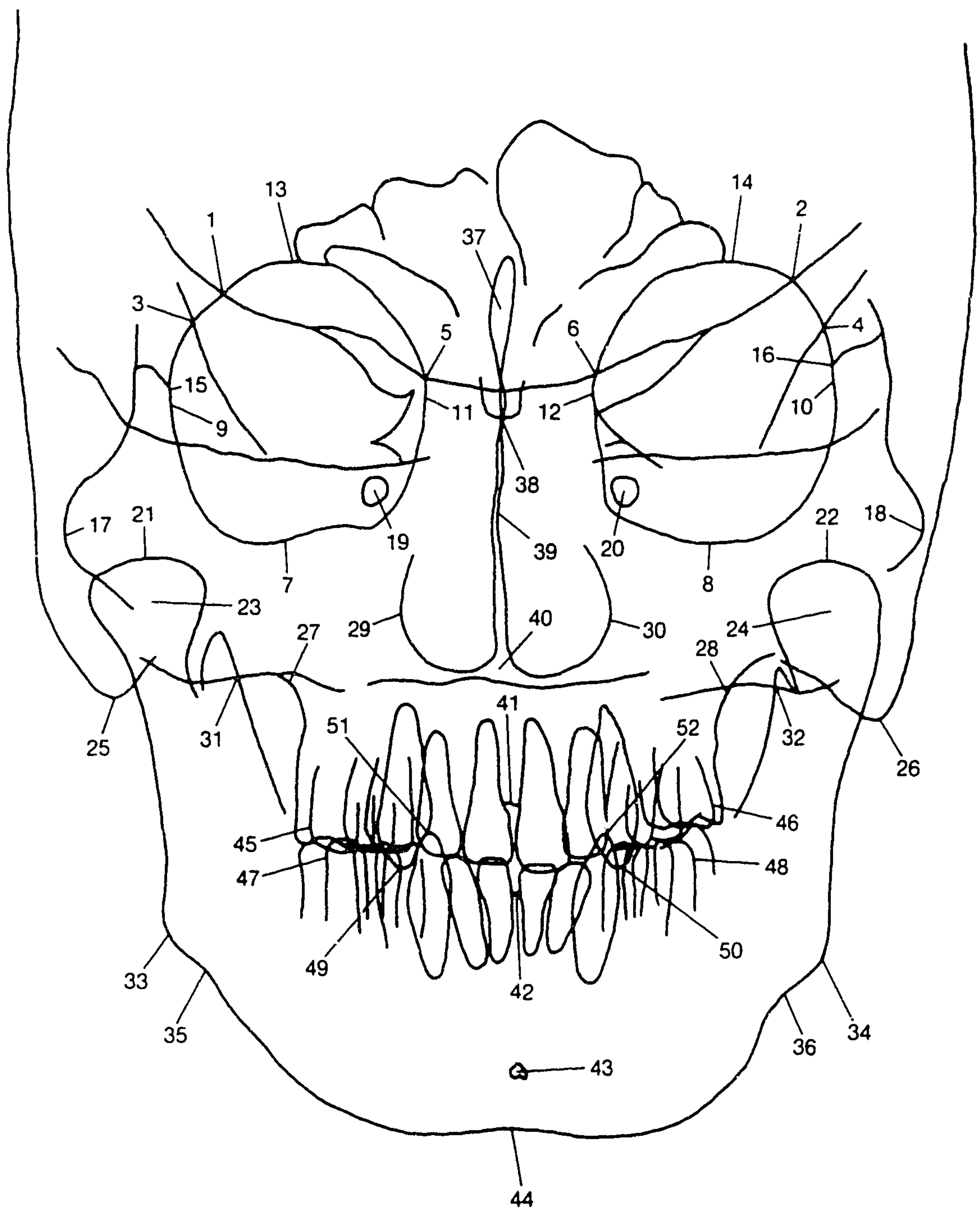


Figure 6. Schematic Diagram of PA Cephalogram.

i. Bilateral skeletal

1/2 GWSOL/R - Greater Wing Superior/Orbit - the intersection of the superior border of the greater wing of the sphenoid bone and the lateral orbital margin left and right.

3/4 GWIOL/R - Greater Wing Inferior/Orbit - the intersection of the inferior border of the greater wing of the sphenoid bone and the lateral orbital margin left and right.

5/6 LWOL/R - Lesser Wing/Orbit - the intersection of the superior border of the lesser wing of the sphenoid bone and the medial orbital margin left and right.

7/8 OL/R - Orbitale - the midpoint of the inferior orbital margin left and right.

9/10 LOL/R - Lateral Orbit - the midpoint of the lateral orbital margin left and right.

11/12 MOL/R - Medial Orbit - the midpoint of the medial orbital margin left and right.

13/14 SOL/R - Superior Orbit - the midpoint of the superior orbital margin left and right.

15/16 ZFL/R - Zygomatic Frontal - the intersection of the zygomatic-frontal suture and the lateral orbital margin left and right.

17-18 ZL/R - Zygomatic - the most lateral aspect of the zygomatic arch left and right.

19/20 FRL/R - Foramen Rotundum - the centre of the foramen rotundum left and right.

21/22 CSL/R - Condyle Superior - the most superior aspect of the condyle left and right.

23/24 CCL/R - Centre Condyle - the centre of the head of the condyle left and right.

25/26 MPL/R - Mastoid Process - the most inferior point on the mastoid process left and right.

27/28 ML/R - Malar - the deepest point on the curvature of the malar process of the maxilla left and right.

29/30 NCL/R - Nasal Cavity - the most lateral point on the nasal cavity left and right.

31/32 MBOL/R - Mandible/Occiput - the intersection of the mandibular ramus and the base of the occiput left and right.

33/34 GL/R - Gonion - the midpoint on the curvature at the angle of the mandible (gonion) left and right.

35/36 AGL/R - Antegonial - the deepest point on the curvature of the antegonial notch left and right.

ii. Midline skeletal

37 CG - Crista Galli - the centre of crista galli.

38 ST - Sella Turcica - the most inferior point on the floor of Sella Turcica.

39 NSM - Nasal Septum - the midpoint of the nasal septum between crista galli and the anterior nasal spine.

40 ANS - Anterior Nasal Spine - the centre of the intersection of the nasal septum and the palate.

41 IPU - Incisor Point - the crest of the alveolus between the upper incisors.

42 IPL - Incisor Point - the crest of the alveolus between the lower incisors.

43 GT - Genial Tubercles - the centre of the genial tubercles of the mandible.

44 ME - Menton - The midpoint on the inferior border of the mental protuberance.

iii. Dental

45/46 MX6L/R - the midpoint on the buccal surface of the maxillary first molar left and right.

47/48 MD6L/R - the midpoint on the buccal surface of the mandibular first molar left and right.

49/50 MX3L/R - the tip of the maxillary cuspid left and right.

51/52 MD3L/R - the tip of the mandibular cuspid left and right.

D. Digitization

Digitization procedures were carried out using a GP6 Sonic Digitizer* in conjunction with an IBM compatible computer and a program developed utilizing Basic. The published accuracy of the digitizer was ± 0.1 mm. Prior to digitization each radiograph was identified by number, orientation (normal, up, down, left or right), and operator code. This information was recorded as the file name. Conditions for the digitization were standardized in a darkened room with all extraneous light from the light box blocked out.

An individual coordinate system was established for each radiograph by including two fiducial points in the digitization procedure. The fiducial points consisted of two pinholes placed at the top of the ear rod markers on each radiograph. These points were digitized first which enabled the digitization program to calculate the slope of the line between the two pinholes, which was used as the x axis of a cartesian coordinate system. The y axis was calculated as the line perpendicular to the x-axis originating at the midpoint of the line between the two

----

* - Science Accessories Corporation, 200 Watson Blvd., Stratford Conn. 06497

pinholes. This process eliminated the orientation of the radiograph on the light box as a variable. The landmarks on each radiograph were then digitized and stored as cartesian coordinates in ASCII files.

In order to simplify the experimental process the study was broken down into five separate parts.

E. Reliability

The first portion of the study which used both the normal and rotated cephalograms was designed to determine the reliability of the method of digitizing skulls as well as the relative contributions of different factors to the total variance in the sample.

Each of the five skull orientations (normal, up, down, left, and right) for each of the 33 skulls was digitized five times by the principal investigator, with the exception of skull number fourteen, in which the down view was discarded due to part of the mandible not being visible on the film. The digitization procedure was spread out over a one month period and no one radiograph was digitized twice on the same day.

The five digitizations for each landmark on each radiograph were averaged and the standard deviation calculated horizontally and vertically. This information was screened for any landmark exhibiting a standard deviation greater than three millimetres. The raw data for any landmarks exhibiting this large standard deviation was then examined for any single digitization which differed from the average of the other four by greater than ten millimetres. If one digitization was responsible for the large standard deviation, the digitization of that radiograph was repeated. This procedure effectively eliminated any instances where the wrong point was digitized by mistake.

The reliability of the method was determined utilizing generalizability theory with an analysis of variance for both the raw data of horizontal and vertical landmark positions.[79] Five variables were recognized as possible contributors to the variability within the sample. These were;

- skull - the differences between overall scatter of landmark position between individual skulls,
- position - the differences between the scatter around individual landmark positions,
- side - right versus left sided variation,
- orientation - the differences due to the various rotations of the skull and,
- digitization - the differences between successive digitizations.

The reliability estimation made it possible to calculate the relative contributions of these factors to the total amount of variance seen in the sample. Two estimates of reliability were performed on the data. The first utilized the twenty-two bilateral landmarks and thereby enabled the variance due to side of the skull to be evaluated. The second estimation utilized all the landmarks and removed the variable of side as a factor.

F. Method Error

The second portion of the study was designed to determine the error of the method. This was established by repeated digitizations of a precisely defined point consisting of a pinhole in a radiograph. The means and standard deviations were calculated for both the horizontal and vertical dimensions. These figures represent the theoretical least amount of error for landmark identification and would include the error of the instrumentation. The portion of the error due to instrumentation was determined by rigidly fixing the digitizing cursor in one spot and repeatedly digitizing this spot. The means and standard deviations were calculated to give the error associated with the digitizer itself.

G. Intra-examiner Error

The objectives of the third portion of the study were to;

- determine the identification error for each landmark with respect to orientation,
- determine if a significant difference exists in identification error for each landmark due to orientation of the skulls,

- and determine if a significant difference exists in identification error between the same landmark on opposite sides of the skull.

The identification error for each landmark in the horizontal and vertical dimensions was calculated for each orientation by conventional methods and consisted of means, variances and standard deviations. A Levene's analysis was used to test the variance of the scatter around each point and comparisons made to test for differences in the variation around each point with respect to orientation. In this analysis the variable of side was eliminated and all fifty-two points included. Due to the large number of comparisons a Bonferoni analysis was used with a pair wise alpha level of 0.0001 in order to maintain the experiment wise alpha level of 0.05.[79,80]

A Levene's analysis was carried out utilizing the bilateral landmarks to test for significant differences in the identification error for the same landmarks on opposite sides of the skull.

H. <u>Inter-examiner Error</u>

The fourth portion of the study was designed to;

- determine the identification error for each landmark among five different operators,

- determine if there was any significant difference between the identification error for one versus multiple operators, and

- determine if there was any significant difference between the same landmarks on different sides of the skull.

In this part, twenty of the thirty-three non-rotated cephalograms were selected for their absence of asymmetry and excellence of image quality, as determined by visual inspection. These radiographs were then digitized once by each of four different operators.

The four operators consisted of one second year and two first year orthodontic graduate students, as well as one instructor of cephalometrics at the University of Alberta graduate orthodontic program. The two first year students had just completed their course in cephalometry and the second year student had completed the same course one year previously. All operators were given a visual demonstration on identification of the landmarks which included instruction on the use of the digitizer and digitizing program. Each operator was provided with both written descriptions and a schematic diagram of the landmark locations for reference during the digitizing procedures.

The digitizations for each skull were utilized to calculate averages and standard deviations for each landmark in the horizontally and vertically. These values were then examined for errant values in the same manner as previously described and radiographs digitized again as necessary.

Four factors were identified as sources of error in this portion (skull, position, side, and case) with orientation of the skull not applicable. A Levene's analysis was utilized to test the variance of the scatter around each landmark and multiple comparisons performed to test for statistical differences in identification error between one and four operators. The numbers were normalized between the one and four operator groups by randomly excluding one of the five digitizations in the one operator data. A Levene's analysis was also done using only the bilateral landmarks to test for significant differences in identification error between the same landmark on opposite sides of the skull.

I. Reference Planes

The fifth portion of the study utilized the data from the first and fourth parts and was designed to;

- determine a horizontal reference line through the skull on the PA view,
- determine a vertical reference line through the skull,
- to examine the relationship between the best fit horizontal and vertical lines through the skull,
- and select pairs of landmarks in the upper facial skeleton which would give the best estimate for the vertical reference line.

A best fit horizontal reference line through the skull was established by a least squares method utilizing the twenty-two bilateral landmarks. A deviation analysis was carried out to determine if there was a significant difference between the slope of the line through each set of bilateral landmarks and the best fit line.

The deviation analysis was conducted three times; firstly using all the skulls, one operator, and all orientations; secondly using the twenty selected skulls, one operator, and all orientations; and thirdly using the selected skulls, four operators, and the normal orientation only. These three analyses enabled evaluations to be made of the effects of; operator differences, differences between all the skulls and the selec[illegible]s and differences due to orientations. Comparisons were conducte[illegible] the differences due to orientation.

The determination of the vertical reference line was accomplished by constructing a best fit vertical line through the midline landmarks and the bisectors of all the bilateral landmarks. A deviation analysis was performed to determine the variance in deviation for each of the landmarks from the best vertical line. Comparisons were performed to examine the differences due to orientation.

The angular relationship between the best horizontal and vertical lines through the skull was examined and evaluated to see if these two lines were perpendicular to one another utilizing the intra-examiner data.

In order to determine a simple method of establishing a midline through the skull, pairs of landmarks in the upper facial skeleton were chosen (bisectors of bilateral landmarks and/or midline landmarks) and the line through each pair examined by means of a deviation analysis to determine the magnitude of variance between the slope of the line and the best midline.

Several landmarks were not used in this portion of the study to eliminate redundant measurements. The selection of which landmarks were eliminated was made on the basis of; deviation from the best midline (if a landmark exhibited significantly more deviation from the best midline than several other landmarks, it was deleted), position (when two landmarks were very close to one another on a similar structure, the one with the largest horizontal standard deviation was deleted), and magnitude of horizontal identification error (if the standard deviation was greater than one millimetre the landmark was deleted).

The choice of which pairs were to be examined was made on the basis that each landmark in a pair was separated from the other vertically. In order to ensure that the chosen landmarks were separated vertically, the upper facial skeleton was broken down into three regions: the supra-orbital region, which contained the landmarks GWSO (1/2), GWIO (3/4), SO (13,14), and CG (37); the mid-orbital region, which contained the landmarks LWO (5/6), LO (9/10), MO (11/12), ZF (15/16), and ST (38); and the infra-orbital region, which contained landmarks O (7/8), Z (17/18), FR (19/20), MP (25/26), and NSM (39).

With the exception of those landmarks eliminated due to position or deviation from the best vertical line, each landmark in a given region was combined with each landmark in the other two regions and the line through the two landmarks tested for deviation from the best vertical line. Each pair of landmarks was examined for differences due to orientation of the skull by means of multiple comparison tests.

IV. RESULTS

A. Reliability

Since reliability is a measure of how reproducible the method is in repeated trials, any variance due to differences between successive digitizations was considered undesirable. Therefore, subtracting the variation which could be attributed to case (including case in combination with any other factor or factors) from the total variance and dividing this by the total variance gives a measure of reliability. Reliability can be calculated by the formula:

$$R = \frac{Vt - Vd}{Vt}$$

where:

R = reliability of method

Vt = total variance within the sample

Vd = variance due to digitization

With this calculation the closer the value R is to 1.00, the greater the reliability of the method. The reliability was calculated using both the absolute values from each skull and Z-scores for both the horizontal and vertical dimensions. The utilization of Z-scores removes the variability due to size differences between skulls. In order for the side of the skull to be included as a variable the first estimation of reliability utilized only the bilateral landmarks. The results show (table 1) that the method is very reliable using both the absolute values and the Z-scores (R_x = .9997, R_y = .9988, R_{Zx} = .9999, R_{Zy} =.9999). A second estimation of reliability was carried out for the absolute values utilizing all the landmarks but removing side as a variable (table 2). This also showed a high reliability in both the horizontal and vertical dimensions (R_x = .9995, R_y .9992).

The relative contributions of the five variables can be seen in tables 1 and 2. For both the absolute values and Z-scores, when side is considered, the largest contributors to the variance in the horizontal dimension are: the side of the skull (x = 83.5%, Zx = 83.6%); and the position/side combination (x = 15.7%, Zx = 15.8%). For the vertical dimension the position of the landmark is the greatest contributor to the total variance (y = 97.8%, Zy = 99.2%).

When the variable of side is taken out (table 2), and all the landmarks are utilized, the position of the landmark becomes the greatest contributor to the total variance in both the horizontal (97.9%) and vertical (97.8%) dimensions.

B. Method Error

The results (table 3) show that the amount of error associated with the method (SDx = 0.13 mm, SDy = 0.10 mm) is of the same magnitude as that associated with the digitizer (SDx = 0.10 mm, SDy = 0.11 mm). These values are very close to the $\pm$ 0.1 mm accuracy of the digitizer claimed by the manufacturer.

Table 1 - Variance and Reliability

Contributions of sample characteristics to total variance and estimates of reliability. Bilateral landmarks only.

	Absolute values		Z-scores	
Variable	x	y	Zx	Zy
I	.016	.028	.0000269	.000
P	.000	10.726	.000	.898
S	25.434	.0000097	1.934	.0000034
O	.095	.088	.000	.000
D	.000013	.000012	.000	.000
IP	.000	.06	.000	.002
IS	.037	.003	.000	.000245
IO	.008	.002	.000	.000
ID	.000	.0000239	.000	.000
PS	4.7850	.000769	.365	.0000662
PO	.021	.033	.002	.003
PD	.000	.000623	.000	.0000475
SO	.000013	.000	.000	.000
SD	.000	.000005	.000	.000
OD	.000004	.000005	.000	.000
IPS	.045	.007	.003	.000573
IPO	.001	.002	.000082	.000134
IPD	.000019	.000324	.000	.000023
ISO	.000086	.001	.000	.000103
ISD	.000032	.000075	.000	.000
IOD	.000402	.000272	.000002	.000
PSO	.003	.002	.000253	.000152
PSD	.000283	.000075	.000021	.000006
POD	.000	.000292	.000	.000
SOD	.00013	.000011	.000	.000001
IPSO	.003	.002	.000231	.000133
IPSD	.000214	.000111	.000017	.000009
IPOD	.000	.004	.000	.000288
ISOD	.000	.004	.000	.000014
PSOD	.000182	.000045	.000014	.000004
IPSOD	.007	.003	.000563	.000288
Total	30.456261	10.9675626	2.3142099	.9050901
Reliability	.9997	.9988	.9999	.9999

x and Zx - horizontal, y and Zy - vertical
I - variance due to skull, P - variance due to position, S - variance due to side
O - variance due to orientation, D - variance due to digitization

Table 2 - Variance and Reliability

Contributions of sample characteristics to total variance and estimates of reliability. All landmarks, absolute values.

Variable	x	y
I	.036	.034
P	13.058	11.860
O	.109	.103
D	.0000033	.0000322
IP	.046	.075
IO	.003	.003
ID	.000012	.0000311
PO	.023	.033
PD	.000131	.000652
OD	.0000095	.0000114
IPO	.004	.004
IPD	.000206	.000472
IOD	.000421	.000390
POD	.000143	.000557
IPOD	.006	.008
Total	13.3415168	12.1221457
Reliability	.9995	.9992

x - horizontal
y - vertical
I - variance due to skull
P - variance due to position
O - variance due to orientation
D - variance due to digitization

Table 3 - Method Error

Standard deviations and variances for error of method and digitizer error.

	SDx	SDy	Vx	Vy
method	0.13	0.10	0.018	0.010
digitizer	0.10	0.11	0.010	0.011

SD in millimeters

C. Intra-examiner

The error associated with the identification of each landmark was calculated for each of the five skull orientations (normal, up, down, left , and right) in both the horizontal and vertical dimensions and reported as standard deviations (tables 4-7). The results show that there is a wide range in the amount of identification error both between landmarks and between the vertical and horizontal error for each particular landmark. Multiple comparisons, utilizing the Student Newman-Keules test for significance, were performed to see if significant differences existed between the normal orientation and the rotated positions for each of the landmarks. The results indicate that rotation of the skull caused very few significant differences in identification error for both the horizontal and vertical dimensions.

Significant horizontal differences from the normal orientation showed up in three instances: landmark Foramen

Table 4 - Horizontal Standard Deviations

Standard deviation in the horizontal dimension for the bilateral skeletal landmarks. One operator, all skulls, all orientations.

SDx for Orientations

Landmark	N	U	D	L	R
1 GWSOL	0.45	0.39	0.76	0.47	0.46
2 GWSOR	0.52	0.37	0.90	0.45	0.45
3 GWIOL	0.37	0.36	0.49	0.36	0.43
4 GWIOR	0.33	0.39	0.47	0.40	0.43
5 LWOL	0.75	0.73	0.81	1.00	0.76
6 LWOR	0.93	0.84	1.18	0.75	1.05
7 OL	0.93	1.27	1.11	0.98	1.32
8 OR	1.23	1.20	1.04	1.31	1.18
9 LOL	0.59	0.63	0.66	0.67	0.65
10 LOR	0.54	0.66	0.67	0.61	0.72
11 MOL	0.99	0.87	0.79	0.80	0.88
12 MOR	1.02	0.86	0.76	0.98	0.76
13 SOL	0.56	0.80	0.96	0.79	0.70
14 SOR	0.90	0.96	0.90	0.92	0.82
15 ZFL	0.67	0.50	0.63	0.62	0.60
16 ZFR	0.69	0.62	0.62	0.59	0.57
17 ZL	0.24	0.43	0.45	0.33	0.30
18 ZR	0.32	0.39	0.49	0.34	0.29
19 FRL	0.85	0.55	1.22	0.85	0.76
20 FRR	0.62	0.70	1.16*	0.93	0.80
21 CSL	1.01	0.83	0.89	0.83	0.84
22 CSR	0.93	0.91	0.96	0.75	1.05
23 CCL	0.86	0.91	1.02	0.85	0.90
24 CCR	1.01	0.89	0.88	0.88	0.99
25 MPL	0.43	0.44	0.55	0.54	0.42
26 MPR	0.47	0.87	0.55	0.45	0.51
27 ML	0.38	0.45	0.53	0.39	0.52
28 MR	0.45	0.48	0.56	0.40	0.47
29 NCL	0.89	0.87	1.10	0.97	1.88
30 NCR	0.99	0.92	1.03	1.68*	1.34
31 MBOL	0.38	0.41	0.65	0.64	0.52
32 MBOR	0.57	0.47	0.97	0.63	0.42
33 GL	0.39	0.42	0.53	0.41	0.46
34 GR	0.36	0.43	0.44	0.39	0.36
35 AGL	0.54	0.49	0.63	0.47	0.50
36 AGR	0.61	0.49	0.66	0.72	0.54

* - significantly differe t from the normal orientation, $p < 0.05$
** - significant difference between same landmarks on opposite sides of skull.
all values in millimeters

Table 5 - Horizontal Standard Deviations

Standard deviation in the horizontal dimension for the midline skeletal and dental landmarks. One operator, all skulls, all orientations.

SDx for Orientations

Landmark	N	U	D	L	R
37 CG	0.39	0.37	0.53	0.37	0.40
38 ST	0.41	0.44	0.50	0.57	0.55
39 NSM	0.49	0.47	0.50	0.82	0.81
40 ANS	0.32	0.32	0.40	0.43	0.38
41 IPU	0.31	0.31	0.38	0.26	0.59
42 IPL	0.31	0.34	0.44	0.52	0.33
43 GT	0.32	0.34	0.38	0.33	0.35
44 ME	0.50	0.44	0.59	0.48	0.51
45 MX3L	0.56	0.75	0.85	0.97	0.79
46 MX3R	0.82	0.88	0.95	1.22	0.87
47 MD3L	0.71	0.74	0.61	0.73	0.76
48 MD3R	0.66	0.74	0.68	0.95	0.64
49 MX6L	0.70	0.74	0.89	0.67	1.00
50 MX6R	0.84	0.67	0.56	0.76	0.54
51 MD6L	0.96	0.96	1.26	0.82	1.28*
52 MD6R	0.85	0.76	0.84	0.91	0.65

* - significantly different from the normal orientation
** - significant difference between same landmarks on opposite sides of skull.
$p < 0.05$, all values in millimeters

Table 6 - Vertical Standard Deviations

Standard deviation in the vertical dimension for the bilateral skeletal landmarks. One operator, all skulls, all orientations.

SDy for Orientations

Landmark	N	U	D	L	R
1 GWSOL	0.26	0.32	0.42	0.36	0.32
2 GWSOR	0.33	0.37	0.53	0.35	0.32
3 GWIOL	0.36	0.46	0.57	0.40	0.51
4 GWIOR	0.35	0.43	0.48	0.48	0.44
5 LWOL	0.39	0.39	0.61	0.49	0.40
6 LWOR	0.42	0.52	0.84	0.42	0.54
7 OL	0.80	0.85	1.24	0.97	0.85
8 OR	0.68	0.95*	1.38	0.87	0.82
9 LOL	1.04	1.07	1.25	1.01	0.98
10 LOR	0.94	1.11	1.16	1.02	1.07
11 MOL	0.91	1.03	1.25	0.98	0.98
12 MOR	1.01	1.11	1.32	1.04	1.08
13 SOL	0.24	0.31	0.39	0.34	0.29
14 SOR	0.26	0.30	0.44	0.27	0.30
15 ZFL	2.12	1.63*	1.17*	1.64*	1.68*
16 ZFR	2.37	1.95*	1.41*	1.89*	1.85*
17 ZL	0.36	0.46	0.49	0.44	0.53
18 ZR	0.36	0.44	0.42	0.48	0.39
19 FRL	0.53	0.70	0.56	0.48	0.48
20 FRR	0.50	0.78	0.71	0.50	0.53
21 CSL	1.42	1.47	1.26	1.14	1.15
22 CSR	1.09	1.41	1.37	1.12	1.08
23 CCL	1.25	1.30	1.56	1.25	1.23
24 CCR	1.02	1.19	1.31	1.16	1.14
25 MPL	0.26	0.28	0.34	0.26	0.29
26 MPR	0.27	0.32	0.47	0.30	0.32
27 ML	0.61	0.67	0.81	0.98	0.71
28 MR	0.63	0.73	0.72	0.71	0.83
29 NCL	1.11	1.61	1.11	1.09	1.29
30 NCR	1.04	1.54	0.88	0.96	1.07
31 MBOL	0.42	0.31	0.74	1.03*	0.35
32 MBOR	0.51	0.37	0.99	0.65	1.22
33 GL	0.72	0.76	1.00	0.76	0.83
34 GR	0.89	0.80	0.87	0.70	0.63
35 AGL	0.58	0.40	0.70	0.56	0.42
36 AGR	0.56	0.40	0.62	0.66	0.48

* - significantly different from the normal orientation
** - significant difference between same landmarks on opposite sides of skull.
$p < 0.05$, all values in millimeters

Table 7 - Vertical Standard Deviations

Standard deviation in the vertical dimension for the midline skeletal and dental landmarks. One operator, all skulls, all orientations.

SDy for Orientations

Landmark	N	U	D	L	R
37 CG	0.78	1.05	0.67	0.76	0.65
38 ST	1.75	1.56	1.20*	0.73*	0.89*
39 NSM	2.83	2.36*	1.75*	1.44*	1.95*
40 ANS	0.36	1.58	0.41	0.35	0.40
41 IPU	0.34	0.45	0.56	0.36	0.39
42 IPL	0.45	0.93	0.45	0.43	0.38
43 GT	0.72	0.77	0.94	0.77	0.89
44 ME	0.23	0.28	0.41	0.26	0.32
45 MX3L	0.37	0.43	0.52	0.48	0.40
46 MX3R	0.41	0.42	0.49	0.50	0.43
47 MD3L	0.31	0.44	0.46	0.35	0.36
48 MD3R	0.38	0.36	0.51	0.49	0.45
49 MX6L	0.91	0.63	0.87	0.74	0.69
50 MX6R	0.84	0.59	0.91	0.79	0.68
51 MD6L	0.61	0.96	0.97*	0.70	0.79
52 MD6R	0.85	0.76	0.84	0.91	0.65

* - significantly different from the normal orientation, $p < 0.05$
** - significant difference between same landmarks on opposite sides of skull.
all values in millimeters

Rotundum Right (FRR) in the down orientation; landmark Nasal Cavity Right (NCR) in the left orientation; and landmark Mandibular Molar Left (MD6L) in the right orientation. In each instance the error for the rotated view was significantly larger than that of the normal view.

Significant vertical differences from the normal orientation occurred in seven instances: landmark Orbitale Right (OR) in the down orientation; landmark Zygomatic Frontal Left (ZFL) in all orientations; landmark Zygomatic Frontal Right (ZFR) in all orientations; landmark Mandibular Body Base of Occiput Left (MBOL) in the left orientation; landmark Sella Turcica (ST) in the down, left, and right orientations; landmark Nasal Septum Midpoint (NSM) in all orientations; and landmark Mandibular Molar Left (MD6L) in the down orientation. The error was larger than for the normal view for the landmarks Orbitale Right (OR), Mandibular Body Base of Occiput Left (MBOL) and Mandibular Molar Left (MD6L). The error was less than in the normal view for the landmarks Zygomatic Frontal Left (ZFL), Zygomatic Frontal Right (ZFR), Sella Turcica (ST), and Nasal Septum Midpoint (NSM).

The identification errors for each landmark are ranked according to the amount of error in the horizontal (table 8) and vertical (table 9) dimensions (bilateral landmarks are shown as an average of the standard deviation between the two sides).

Multiple comparisons were carried out to test for significant differences due to side of the skull in both the horizontal and vertical dimensions. The results show

Table 8 - Horizontal Standard Deviations

Rank ordering of standard deviation in the horizontal dimension for the all landmarks. Bilateral landmarks are shown as the average of the standard deviation of both sides.

Landmark			SDx
43	GT		0.34
17/18	Z	+	0.36
41	IPU		0.37
40	ANS		0.37
42	IPL		0.39
3/4	GWIO	+	0.40
37	CG	+	0.41
33/34	G		0.42
27/28	M		0.46
38	ST	+	0.49
44	ME		0.50
25/26	MP	+	0.52
1/2	GWSO	+	0.54
31/32	MBO		0.57
35/36	AG		0.57
15/16	ZF	+	0.61
39	NSM	+	0.62
9/10	LO	+	0.64
47/48	MD3		0.72
49/50	MX6		0.74
13/14	SO	+	0.83
19/20	FR	+	0.84
11/12	MO	+	0.86
5/6	LWO	+	0.88
45/46	MX3		0.88
21/22	CS		0.90
23/24	CC		0.92
51/52	MD6		0.93
7/8	O	+	1.16
29/30	NC		1.17

all values in millimeters

+ - landmarks located in upper facial skeleton

Table 9 - Vertical Standard Deviations

Rank ordering of standard deviation in the vertical dimension for the all landmarks. Bilateral landmarks are shown as the average of the standard deviation of both sides.

Landmark			SDy
44	ME		0.30
13/14	SO	+	0.31
25/26	MP	+	0.31
1/2	GWSO	+	0.36
47/48	MD3		0.41
41	IPU		0.42
17/18	Z	+	0.44
45/46	MX3		0.44
3/4	GWIO	+	0.45
5/6	LWO	+	0.50
42	IPL		0.52
35/36	AG		0.54
19/20	FR	+	0.58
40	ANS		0.62
31/32	MBO		0.66
51/52	MD6		0.71
27/28	M		0.74
37	CG	+	0.78
33/34	G		0.79
43	GT		0.82
49/50	MX6		0.86
7/8	O	+	0.94
9/10	LO	+	1.06
11/12	MO	+	1.07
29/30	NC		1.16
38	ST	+	1.23
21/22	CS		1.25
23/24	CC		1.25
15/16	ZF	+	1.76
39	NSM	+	2.06

all values in millimeters
\+ - landmarks located in upper facial skeleton

(tables 4-7) no significant differences in the identification error for the same landmarks on opposite sides of the skull.

D. Inter-examiner

The landmark identification error for four different operators was calculated for the twenty selected skulls in the normal orientation and reported as standard deviations (tables 10-11). The results show that there is a wide range of identification error in both the horizontal and vertical dimensions which is peculiar to each individual landmark. The range of identification errors is 0.31 mm to 2.10 mm in the horizontal dimension and 0.28 mm to 3.36 mm in the vertical dimension.

A comparison of the identification errors for the same landmarks on opposite sides of the skull revealed no significant differences with four operators.

A comparison was made between one operator and four operators utilizing the selected skulls and the normal orientation only (tables 12-15). In the horizontal dimension there were no significant differences in identification error between one and four operators. Significant differences were manifested in the vertical dimension for three landmarks namely; Condyle Superior Right (CSR), Condyle Superior Left (CSL), and Centre Condyle Right (CCR).

The determination of which landmarks should be used in any PA cephalometric analysis should be based upon the manner in which it will be used

Table 10 - Horizontal Standard Deviations

Rank ordering of standard deviation in the horizontal dimension for the all landmarks. Bilateral landmarks are shown as the average of the standard deviation of both sides. Four operators.

Landmark			SDx
42	IPL		0.31
41	IPU		0.34
40	ANS		0.36
39	NSM	+	0.43
33	GT		0.45
19/20	FR	+	0.47
38	ST	+	0.47
37	CG	+	0.48
33/34	G		0.64
25/26	MP	+	0.66
44	ME		0.66
35/36	AG		0.66
3/4	GWIO	+	0.67
9/10	LO	+	0.70
1/2	GWSO	+	0.80
5/6	LWO	+	0.90
45/46	MX3		0.92
27/28	M		1.01
49/50	MX6		1.07
47/48	MD3		1.12
13/14	SO	+	1.13
51/52	MD6		1.14
7/8	O	+	1.25
29/30	NC		1.25
11/12	MO	+	1.36
23/24	CC		1.63
17/18	Z	+	1.67
15/16	ZF	+	1.79
21/22	CS		1.82
31/32	MBO		2.10

all values in millimeters

+ - landmarks located in upper facial skeleton

Table 11 - Vertical Standard Deviations

Rank ordering of standard deviation in the vertical dimension for the all landmarks. Bilateral landmarks are shown as the average of the standard deviation of both sides. Four operators.

Landmark			SDy
23/24	CC		0.28
44	ME		0.37
19/20	FR	+	0.40
13/14	SO	+	0.44
25/26	MP	+	0.44
47/48	MD3		0.48
41	IPU		0.56
1/2	GWSO	+	0.57
45/46	MX3		0.67
40	ANS		0.69
35/36	AG		0.71
42	IPL		0.77
51/52	MD6		0.78
29/30	NC		1.03
49/50	MX6		1.04
5/6	LWO	+	1.07
33	GT		1.08
3/4	GWIO	+	1.10
33/34	G		1.27
37	CG	+	1.35
9/10	LO	+	1.51
31/32	MBO		1.51
11/12	MO	+	1.97
27/28	M		2.09
39	NSM	+	2.10
7/8	O	+	2.13
17/18	Z	+	2.89
38	ST	+	3.01
21/22	CS		3.32
15/16	ZF	+	3.36

all values in millimeters
\+ - landmarks located in upper part of facial skeleton

Table 12 - Horizontal Mean Variances

Mean variances in the horizontal dimension for the bilateral skeletal landmarks. Best skulls, normal orientation, one and four operators.

	Mean variance x Operators	
Landmark	1	4
1 GWSOL	33.2	53.0
2 GWSOR	43.3	64.6
3 GWIOL	35.1	54.1
4 GWIOR	25.8	46.1
5 LWOL	47.1	61.9
6 LWOR	50.5	64.1
7 OL	99.8	114.3
8 OR	154.3	158.6
9 LOL	70.8	77.8
10 LOR	54.3	58.2
11 MOL	42.4	81.0
12 MOR	47.7	86.1
13 SOL	57.8	109.0
14 SOR	80.6	89.4
15 ZFL	75.0	129.5
16 ZFR	74.8	118.6
17 ZL	55.5	118.5
18 ZR	43.3	117.0
19 FRL	21.9	33.3
20 FRR	27.3	34.0
21 CSL	104.2	134.5
22 CSR	93.8	149.8
23 CCL	89.0	127.2
24 CCR	93.3	133.8
25 MPL	35.2	37.6
26 MPR	41.7	57.8
27 ML	39.7	73.8
28 MR	37.4	95.3
29 NCL	60.2	91.0
30 NCR	66.9	90.1
31 MBOL	93.6	170.5
32 MBOR	98.0	160.8
33 GL	39.8	54.7
34 GR	32.5	49.3
35 AGL	37.8	47.1
36 AGR	39.3	63.8

* - significant difference between one and four operators $p < 0.05$
+ - significant difference between same landmarks on opposite sides of skull.

Table 13 - Horizontal Mean Variances

Mean varainces in the horizontal dimension for the midline skeletal and dental landmarks. Selected skulls, normal orientation, one and four operators.

	Mean variance x Operators	
Landmark	1	4
37 CG	26.2	41.3
38 ST	32.1	41.1
39 NSM	27.5	36.8
40 ANS	24.9	31.7
41 IPU	22.9	28.1
42 IPL	26.1	27.6
43 GT	25.2	37.4
44 ME	36.9	49.9
45 MX3L	58.0	79.9
46 MX3R	64.0	75.5
47 MD3L	53.0	91.7
48 MD3R	45.4	63.7
49 MX6L	50.9	74.5
50 MX6R	60.2	88.8
51 MD6L	64.8	95.8
52 MD6R	79.0	93.5

* - significant difference between one and four operators, $p < 0.05$
+ - significant difference between same landmarks on opposite sides of skull.

Table 14 - Vertical Mean Variances

Mean variance in the vertical dimension for the bilateral skeletal landmarks. Best skulls, normal orientation, one and four operators.

Landmark	Mean variance y Operators 1	4
1 GWSOL	21.8	37.3
2 GWSOR	29.8	43.5
3 GWIOL	40.0	95.5
4 GWIOR	35.7	80.3
5 LWOL	41.3	77.5
6 LWOR	43.8	80.6
7 OL	115.6	161.5
8 OR	108.2	182.8
9 LOL	73.4	134.4
10 LOR	96.6	146.6
11 MOL	73.0	161.6
12 MOR	83.4	173.4
13 SOL	20.7	30.3
14 SOR	19.1	41.6
15 ZFL	208.2	306.4
16 ZFR	205.3	282.0
17 ZL	95.2	211.5
18 ZR	64.3	218.7
19 FRL	18.5	27.4
20 FRR	18.2	26.9
21 CSL	129.9	286.5*
22 CSR	120.8	296.2*
23 CCL	126.7	281.6
24 CCR	107.6	318.4*
25 MPL	21.1	27.1
26 MPR	24.1	39.1
27 ML	68.4	166.8
28 MR	62.0	185.3
29 NCL	87.5	85.2
30 NCR	74.7	82.8
31 MBOL	53.9	133.5
32 MBOR	42.5	120.3
33 GL	61.9	117.3
34 GR	87.0	95.4
35 AGL	39.5	53.5
36 AGR	37.4	64.0

* - significant difference between one and four operators $p < 0.05$
+ - significant difference between same landmarks on opposite sides of skull.

Table 15 - Vertical Mea.. Variances

Mean variances in the vertical dimension for the midline skeletal and dental landmarks. Selected skulls, normal orientation, one and four operators.

	Mean variance y Operators	
Landmark	1	4
37 CG	61.5	112.1
38 ST	269.0	353.6
39 NSM	207.4	186.8
40 ANS	40.0	60.7
41 IPU	28.1	39.9
42 IPL	34.0	43.4
43 GT	62.8	91.6
44 ME	19.1	30.2
45 MX3L	35.6	49.0
46 MX3R	38.6	54.8
47 MD3L	25.4	39.5
48 MD3R	28.8	34.2
49 MX6L	76.6	74.3
50 MX6R	64.3	98.9
51 MD6L	51.4	61.6
52 MD6R	51.5	63.0

* - significant difference between one and four operators $p < 0.05$
+ - significant difference between same landmarks on opposite sides of skull.

and the shape of its envelope of error. For example, landmark superior orbital margin (SO) has an envelope of error which is larger horizontally than vertically and therefore would be useful for linear measurements vertically but not horizontally. Landmarks such as the centre of the condyle (CC) and superior aspect of the condyle (CS) should be used with caution, if at all, due to their large errors both horizontally and vertically.

C. Reference Planes

i. Horizontal Reference - The results of the horizontal deviation analyses show that, with one operator, all the skulls and all orientations included (table 16), there are significant differences in the variance from the horizontal reference between different landmarks. Seven of the eleven landmarks exhibiting the least variation from the horizontal reference line were located in the upper part of the facial skeleton (Lateral Orbit (LO), Superior Orbit (SO), Medial Orbit (MO), Zygomatic Frontal (ZF), Orbitale (O), Foramen Rotundum (FR), and Greater Wing Superior Orbit (GWSO)). Significant differences in the magnitude of variation from the best horizontal line were shown by eleven landmarks. Four of these were in the upper facial skeleton including landmarks: Mastoid Point (MP), which was significantly greater than Lateral Orbital (LO); Lesser Wing Orbit (LWO) and Greater Wing Inferior Orbit (GWIO), which were significantly greater than Lateral Orbit (LO) and Superior Orbit (SO); and Zygomatic Arch (Z), which was

Table 16 - Deviation Analysis Horizontal

Rank ordering of mean variance of error for deviation of slope of lines through bilateral landmarks and best horizontal line through skull. All skulls, one operator, all orientations.

Landmark			Mean var.	
9/10	LO	+	1344	
13/14	SO	+	1523	
11/12	MO	+	1579	
21/22	CS		1729	
15/16	ZF	+	1741	
27/28	M		1744	
7/8	O	+	1809	
29/30	NC		1931	
47/48	MD3		1996	
19/20	FR	+	2103	
1/2	GWSO	+	2131	
45/46	MX3		2184	*1
31/32	MBO		2230	*1
25/26	MP	+	2313	*1
5/6	LWO	+	2371	*2
35/36	AG		2426	*2
3/4	GWIO	+	2584	*2
17/18	Z	+	2399	*3
51/52	MD6		2579	*4
23/24	CC		2699	*7
49/50	MX6		2764	*7
33/34	G		3004	*12

+ - landmarks located in upper facial skeleton.
The numbers following the * indicate the number of landmarks with significantly less variance starting with the first value in the table. ($p < 0.05$)
For example MP has significantly more variance than landmark LO and landmark Z has significantly more variance than landmarks LO, SO and MO.
significantly greater than Lateral Orbit (LO), Superior Orbit (SO), and Medial Orbit (MO).

With one operator, utilizing the twenty skulls selected for the inter-examiner portion, and all orientations, significant differences occurred with seven landmarks (table 17). Three of these were located in the upper facial skeleton including: Zygomatic Arch (Z), which was significantly greater than :Lateral Orbit (LO); Mastoid Point (MP), which was significantly greater than Lateral Orbit (LO) and Medial Orbit (MO); and Greater Wing Inferior Orbit (GWIO) which was significantly greater than Lateral Orbit (LO), Medial Orbit (MO), Superior Orbit (SO), and Condyle Superior (CS).

With four operators, the selected skulls, and the normal orientation (table 18), there were no significant differences in the amount of variation between the lines through the bilateral landmarks.

The results of the comparison between the different orientations of the skull (tables 19 - 20) showed no significant differences associated with orientation, both for all of the skulls and the selected skulls.

ii. Vertical reference - A best fit vertical midline through the skull was determined by a least squares difference method utilizing the midline landmarks and the bisectors of the bilateral landmarks. A deviation analysis was then performed to determine the magnitude of horizontal variance for each midline landmark and bisector of bilateral landmarks with respect to the best midline. The results (table 21) show that significant differences in the variance occurred with twenty five of the thirty landmarks. Thirteen landmarks exhibited significantly greater variation than landmark M, including eleven in the upper facial skeleton ile 17 - Deviation Analysis Horizontal

Mean variance of error for deviation of slope of lines through bilateral landmarks and best horizontal line through skull. Selected skulls, one operator, all orientations.

Landmark			Mean var.	
9/10	LO	+	1322	
11/12	MO	+	1473	
13/14	SO	+	1528	
21/22	CS		1591	
27/28	M		1693	
29/30	NC		1759	
7/8	O	+	1791	
15/16	ZF	+	1804	
47/48	MD3		1882	
1/2	GWSO	+	1926	
45/46	MX3		2021	
31/32	MBO		2100	
35/36	AG		2144	
19/20	FR	+	2151	
5/6	LWO	+	2249	
51/52	MD6		2463	*1
17/18	Z	+	2467	*1
25/26	MP	+	2555	*2
23/24	CC		2600	*3
3/4	GWIO	+	2712	*4
49/50	MX6		2716	*4
33/34	G		2796	*5

+ - landmarks located in upper facial skeleton.
The numbers following the * indicate the number of landmarks with significantly less variance starting with the first value in the table. ($p < 0.05$)

Table 18 - Deviation Analysis Horizontal

Mean variance of error for deviation of slope of lines through bilateral landmarks and best horizontal line through skull. Selected skulls, four operators, normal orientation.

Landmark			Mean var.
21/22	CS		1897
27/28	M		1937
23/24	CC		1974
31/32	MBO		1982
13/14	SO	+	2070
35/36	AG		2100
33/34	G		2155
9/10	LO	+	2216
51/52	MD6		2241
29/30	NC		2290
7/8	O	+	2374
1/2	GWSO	+	2399
47/48	MD3		2416
45/46	MX3		2430
49/50	MX6		2459
17/18	Z	+	2486
19/20	FR	+	2550
11/12	MO	+	2695
3/4	GWIO	+	2736
5/6	LWO	+	2785
25/26	MP	+	2881
15/16	ZF	+	3086

\+ - landmarks located in upper facial skeleton.
The numbers following the * indicate the number of landmarks with significantly less variance starting with the first value in the table. ($p < 0.05$)

Table 19 - Deviation Analysis Horizontal

Analysis of variance comparing overall variance of lines through bilateral landmarks with respect to orientation. One operator, all skulls.

Orientation		L	R	N	U	D
	Mean var	2202	2182	2142	2104	2091
D	2091	NS	NS	NS	NS	
U	2104	NS	NS	NS		
N	2142	NS	NS			
R	2182	NS				
L	2202					

NS - No significant difference
* - Significant Difference $p < 0.05$
N - Non-rotated orientation
U - Rotated up orientation
D - Rotated down orientation
L - Rotated left orientation
R - Rotated right orientation

Table 20 - Deviation Analysis Horizontal

Analysis of variance comparing overall variance of lines through bilateral landmarks with respect to orientation. One operator, selected skulls.

Orientation		L	N	R	U	D
	Mean var	2135	2100	2096	2035	2031
D	2031	NS	NS	NS	NS	
U	2035	NS	NS	NS		
R	2096	NS	NS			
N	2100	NS				
L	2135					

NS - No significant difference
* - Significant Difference $p < 0.05$
N - Non-rotated orientation
U - Rotated up orientation
D - Rotated down orientation
L - Rotated left orientation
R - Rotated right orientation

Table 21 - Deviation Analysis Vertical

Mean variance of error for deviation of bisectors of bilateral landmarks and midline landmarks from best midline. All skulls, one operator, all orientations. Deviation analysis for midline points from vertical reference.

Landmark			Mean var.	
27/28	M		0.51	
40	ANS		0.73	
49/50	MX6		0.79	
3/4	GWIO	+	0.82	
51/52	MD6		0.85	
1/2	GWSO	+	0.92	* 1
15/16	ZF	+	0.93	* 1
31/32	MBO		0.93	* 1
39	NSM	+	0.93	* 1
9/10	LO	+	0.98	* 1
38	ST	+	1.00	* 1
11/12	MO	+	1.03	* 1
13/14	SO	+	1.05	* 1
5/6	LWO	+	1.08	* 1
7/8	O	+	1.09	* 1
37	CG	+	1.10	* 1
19/20	FR	+	1.11	* 1
29/30	NC		1.11	* 1
17/18	Z	+	1.20	* 3
35/36	AG		1.38	*10
45/46	MX3		1.66	*19
43	GT		1.68	*19
47/48	MD3		1.68	*19
44	ME		1.69	*19
42	IPL		1.78	*20
33/34	G		1.80	*20
23/24	CC		1.88	*20
41	IPU		1.89	*20
21/22	CS		2.01	*20
25/26	MP	+	3.23	*29

+ - landmarks located in upper facial skeleton.
The numbers following the * indicate the number of landmarks with significantly less variance starting with the first value in the table. ($p < 0.05$)

(Greater Wing Superior Orbit (GWSO), Zygomatic Frontal (ZF), Nasal Septum Midpoint (NSM), Lateral Orbit (LO), Sella Turcica (ST), Medial Orbit (MO), Superior Orbit (SO), Lesser Wing Orbit (LWO), Orbitale (O), Crista Galli (CG), and Foramen Rotundum (FR)). Two landmarks in the upper facial skeleton exhibited significant differences from more than one other landmark (Zygomatic Arch (Z) and Mastoid Point (MP)). Only one landmark in the upper facial skeleton (Greater Wing Inferior Orbit (GWIO)) did not show significantly more variance than any other landmark.

The results of the comparison of variance associated with orientation of the skull (table 22) showed that there were no significant differences between the normal orientation and the up and down orientations. There were however, significant differences between these three orientations and the left and right orientations.

The results of the evaluations of the relationship between the best fit horizontal and vertical lines through the skull (table 23) show that they are significantly different from 90 degrees for all orientations of the skull and that the left and right orientations exhibited significantly greater variance than the normal, up and down orientations.

The next portion of the study involved the selection of pairs of landmarks in the upper facial skeleton to estimate the best fit midline of the skull. On the basis of vertical deviation (table 21) two landmarks were deleted: Zygomatic Arch

Table 22 - Deviation Analysis Vertical

Analysis of variance comparing overall variance of bisectors of bilateral landmarks and midline landmarks with respect to orientation. One operator, all skulls, all orientations.

Orientation		R	L	D	U	N
	Mean var	.190	.181	.097	.091	.088
N	.088	*	*	NS	NS	
U	.091	*	*	NS		
D	.097	*	*			
L	.181	NS				
R	.190					

NS - No significant difference
* - Significant Difference $p < 0.05$
N - Non-rotated orientation
U - Rotated up orientation
D - Rotated down orientation
L - Rotated left orientation
R - Rotated right orientation

Table 23 - Horizontal Versus Vertical

Analysis of angular relationship between vertical and horizontal best fit lines for one operator, all skulls, all orientations.

Orientation		L	D	N	U	R
	Mean var	91.55	90.33	90.13	90.08	89.08
R	89.08+	*	*	*	*	
U	90.08+	*	NS	NS		
N	90.13+	*	NS			
D	90.33+	*				
L	91.55+					

NS - No significant difference
* - Significant Difference $p < 0.05$
+ - significantly different from 90° $P < 0.01$
N - Non-rotated orientation
U - Rotated up orientation
D - Rotated down orientation
L - Rotated left orientation
R - Rotated right orientation

(Z), which showed significantly more deviation from the best midline than three landmarks; and Mastoid Point (MP), which exhibited significantly more deviation than all of the other landmarks.

On the basis of position and horizontal identification error two landmarks were omitted: landmark Lateral Orbit (LO) due to its close position to and larger horizontal error than landmark Zygomatic Frontal (ZF); and landmark Lesser Wing Orbit (LWO) due to its close position to and greater horizontal error than landmark Medial Orbit (MO).

Landmark Orbitale (O) was deleted for a horizontal standard deviation of greater than one millimetre (1.16 mm).

Deviation analyses were performed to determine the magnitude of variance between the line through the selected landmarks and the best midline. Multiple comparisons were conducted to determine if statistical differences existed in the magnitude of variance from the best midline within each pair of landmarks due to orientation.

The comparisons between orientations for each pair of landmarks (table 24) showed that there were no significant differences in estimation of the best midline when the skull was rotated about the transverse axis (up and down orientations). There were significant differences when the skull was rotated about the vertical axis (left and right orientations) for twenty of the twenty-six pairs tested. Four of these twenty pairs showed significant differences due to rotation about the vertical axis in one direction only, (SO/ZF); Superior Orbit/Sella Turcica (SO/ST); Greater

Table 24 - Deviation Analysis Vertical

Mean variances of deviation of vertical line between selected pairs of landmarks and best midline. One operator, all skulls, all ortientations.

Orientation Variances

Landmarks	Mean var	N	U	D	L	R
GWSO x NSM	173	126	124	142	237 *	236 *
SO x NSM	175	122	127	146	232 *	216 *
GWIO x NSM	181	134	128	151	244 *	250 *
CG x NSM	199	148	138	164	287 *	256 *
SO x MO	213	173	204	196	261 *	233
ST x NSM	215	152	147	181	308 *	287 *
ZF x NSM	219	163	150	187	310 *	288 *
GWSO x MO	220	156	172	175	278 *	321 *
MO x NSM	234	180	148	183	344 *	314 *
GWIO x MO	241	174	186	163	315 *	368 *
GWSO x FR	251	150	148	174	408 *	377 *
SO x FR	253	145	149	164	383 *	425 *
SO x ZF	262	232	217	286	297	280
SO x ST	267	217	223	284	322	287
GWIO x FR	271	162	159	196	436 *	400 *
GWSO x ST	277	184	222	292	337	351 *
GWSO x ZF	284	210	245	269	342	352
MO x CG	284	239	238	264	321	356
GWIO x ZF	303	242	206	274	372	423 *
FR x CG	313	177	164	209	552 *	462 *
CG x ST	324	269	236	333	369	413
GWIO x ST	333	230	255	285	458 *	436
ZF x FR	413	242	218	267	708 *	630 *
FR x ST	417	263	213	272	692 *	645 *
MO x FR	555	324	254	368	911 *	919 *
ZF x CG	676	741	426	856	762	595

* - significantly different from the normal orientation.
$p < 0.05$
N - Non-rotated orientation
U - Rotated up orientation
D - Rotated down orientation
L - Rotated left orientation
R - Rotated right orientation

Wing Superior Orbit/Zygomatic Frontal (GWSO/ZF); Medial Orbit/Sella Turcica (MO/ST); Sella Turcica/Nasal Septum Midpoint (ST/NSM) ; and Zygomatic Frontal/Crista Galli (ZF/CG).

V. DISCUSSION

A. Experimental Procedures

Ideally an experiment into landmark identification errors and the effects of head rotation would be performed using multiple radiographs of live patients. This is not possible due to the fact that radiation guidelines will not allow multiple radiographs on patients for experimental purposes. Therefore any experimentation which involves radiation must by necessity be performed on either cadaver material or dried skulls. The use of cadaver material would be the next best thing to live patients but the difficulty in obtaining cadaver material prevents such a study. This leaves the use of dried skulls which are relatively plentiful and do not suffer from the effects of excess radiation exposure.

Dried skulls also have an advantage over both live patients and cadaver material. This is the fact that there is no soft tissue on a dried skull, which eliminates soft tissue deformation as a factor, and enables the position of the skull to be very precisely controlled within the cephalostat.

The sample of skulls chosen was one of convenience, with all of the available skulls fitting the criteria included. The criteria for selection were based on the need for all the relevant skeletal and dental landmarks to be present with no obvious asymmetries.

A certain degree of asymmetry exists in a "normal" population[54-62] and the selection of skulls was made such that any cases of abnormal asymmetry were not included.

The normal orientation of the skulls in the cephalostat was with the ear rods in the external auditory meattus' and Frankfort horizontal parallel to the ground. The amount of rotation of the skull utilized was five degrees from the normal orientation in either direction about both the transverse and vertical axes. This amount of rotation was decided upon because a rotation of five degrees will create a deviation of 8.7 mm at a distance of ten centimetres which may not be evident at the time of patient positioning. Ahlqvist et al[47] felt that any rotation of the skull above five degrees should not be possible with careful patient positioning. Any greater rotation of the skull would cause more deviation from the normal position, with a deviation of 17.2 mm at ten degrees rotation.

The choice of the skeletal and dental landmarks utilized in the study was based on an examination of the landmarks which can be recognized on the PA cephalogram [81-83] and the ones which are most commonly utilized in PA analyses.[3,7,55,73-78] Since the definition of landmarks has been cited as a contributing factor in determining the magnitude of identification error[8,9,29,52,53] an attempt was made to ensure the definitions were precise.

The use of multiple digitizations of each radiograph was an attempt to reduce the possibility of gross errors in the identification of individual landmarks. With multiple digitizations of the same landmark, if any one digitization was greatly different from the average it was evident that a mistake had been made in the landmark localization and the entire radiograph was re-digitized and these values substituted to ensure that the calculated error was due solely to the difficulty of landmark identification.

Multiple digitizations have been utilized in several other studies into landmark identification error as a way of reducing the chance of one erroneous registration of a landmark creating a very large identification error for a particular landmark.[8,9] This is a drawback of the study by El Mangoury et al[29] into landmark identification error on PA cephalograms. This investigation only used two repeat digitizations of each radiograph, thus if one of the registrations was erroneous, there would be a very large identification error for the landmark in question. With multiple digitizations even if one registration is erroneous and not corrected the effects are reduced due to averaging. According to Baumrind and Miller[84] the use of four registrations of each point will halve the error introduced by random elements such as erroneous digitization.

The calibration of the different operators utilized in this study included a preliminary session in which the landmark locations and definitions were explained and discussed. Written definitions and a schematic diagram of landmark locations were made available during the digitizing procedure. This was an attempt to reduce the contribution of differences in opinion about landmark location to the identification error which is an important factor in determining the magnitude of the error.[85,86]

The use of fiducial points, which are digitized before the digitization of the landmarks, has been documented previously in the literature.[9,46,52] This method is an accurate means of establishing a standardized individual cartesian coordinate system for each radiograph.[37] The error involved in digitizing the fiducial points would be of the same magnitude as the error of the method since both involved digitizing pinholes in radiographs.

In an effort reduce the amount of error introduced by factors other than those which were under investigation, efforts were directed towards controlling the technical problems associated with the cephalometric system.

Projection errors introduced by optical blurring and magnification were controlled by fixing both the object to film, and the source to film distances. This method does not eliminate the errors introduced by these factors but ensures that the magnitude is constant for all the radiographs.

The film related variables were likewise controlled through standardization of technique and the use of collimation of the x-ray beam.

The errors introduced by patient positioning were one of the factors under investigation in the study. This means that while head rotations about the vertical and transverse axes were present, they were strictly controlled by the cephalostat and the head positioning device so that their effects could be studied.

Tracing type errors due to the instrumentation were controlled through the use of direct digitization of the radiographs. This has been shown to be more accurate than tracing followed by digitizing, as it removes tracing as a factor.[40,51]

The errors associated with landmark identification and the differences between operators were both factors under investigation and therefore nothing was done to control their magnitude aside from standardization of conditions.

B. Reliability

Reliability is a measure of the reproducibility or closeness of successive measurements of the same object to one another.[86] The reliability of the method used in this study has been shown to be very high in both the horizontal and vertical dimensions. Five factors were recognized as contributing to the total variability of the sample. These were: skull; position; side; orientation; and case.

When examining the relative contributions of these factors, it was seen that the side of the skull was the greatest contributor to the total variance in the horizontal dimension for both the absolute values and the Z-scores. This is due to the fact that the differences in the horizontal positions between the same landmarks on opposite sides of the skull are quite large. In the vertical dimension however side is a relatively minor contributor to the total variance. This is because the difference in vertical position between the same landmarks on opposite sides of the skull is quite small.

When side is removed as a factor the position of the landmarks becomes the largest contributor to the total variance in both the vertical and horizontal dimensions. The fact that the differences between skulls is such a small contributor to the total variance is somewhat surprising given that there were considerable differences in the size and shape of the various skulls utilized in the study. One explanation for this may be that the differences in size and shape of the skulls was due to differences between the calvaria of the skulls rather than the facial skeleton.

C. Method Error

The magnitude of the error due to instrumentation in both the horizontal and vertical dimensions was calculated by fixing the digitizing cursor in one spot and then digitizing it repeatedly. The error found was very close to the manufacturer's published accuracy of $\pm$ 0.1 mm. This is considerably less than the error of the method reported by El Mangoury et al[29] of 0.39 mm in the horizontal dimension and 0.27 mm in the vertical dimension. This difference is most likely due to the fact that, in the study by El Mangoury et al, the coordinate system was marked on each radiograph with a sharp pencil rather than through digitization of points directly on the radiograph. Even a very fine pencil line has appreciable thickness and the uncertainty introduced by this may have produced a method error of the magnitude seen in their study.

D. Intra-examiner Error

There is a great deal of variability in the magnitude of the horizontal and vertical landmark identification errors. This variability exists both within each landmark and between different landmarks. This is in agreement with the findings of other studies into landmark identification errors.[8,9,29,44-46] The range values for the errors (0.30-2.06) was of similar magnitude as that found by Vincent and West[40] (0.31-2.09) who also utilized five digitizations performed by the same operator. The previous study into PA cephalometric landmark identification error by El Mangoury et al[29] exhibited a range of error of 0.42 to 1.74. When the same landmarks were examined in this study, the range exhibited was of similar magnitude (0.30-1.76). The study by El Mangoury et al utilized patient radiographs which shows that the use of dried skulls creates no great improvement in the amount of error which might be expected due to the lack of soft tissues.

Scattergraphs for selected landmarks illustrate the fact that each landmark has its own characteristic envelope of error (figure 7). Each scattergram was made up of one hundred and sixty separate points which consisted of all the digitizations of each specific point.

It is evident that the envelopes of error for the same landmarks on opposite sides of the skull are like mirror images of each other (figures 8-10). This is to be expected because of the bilateral symmetry exhibited by the skull. The previous work by El Mangoury et al[29] into landmark identification for PA cephalograms

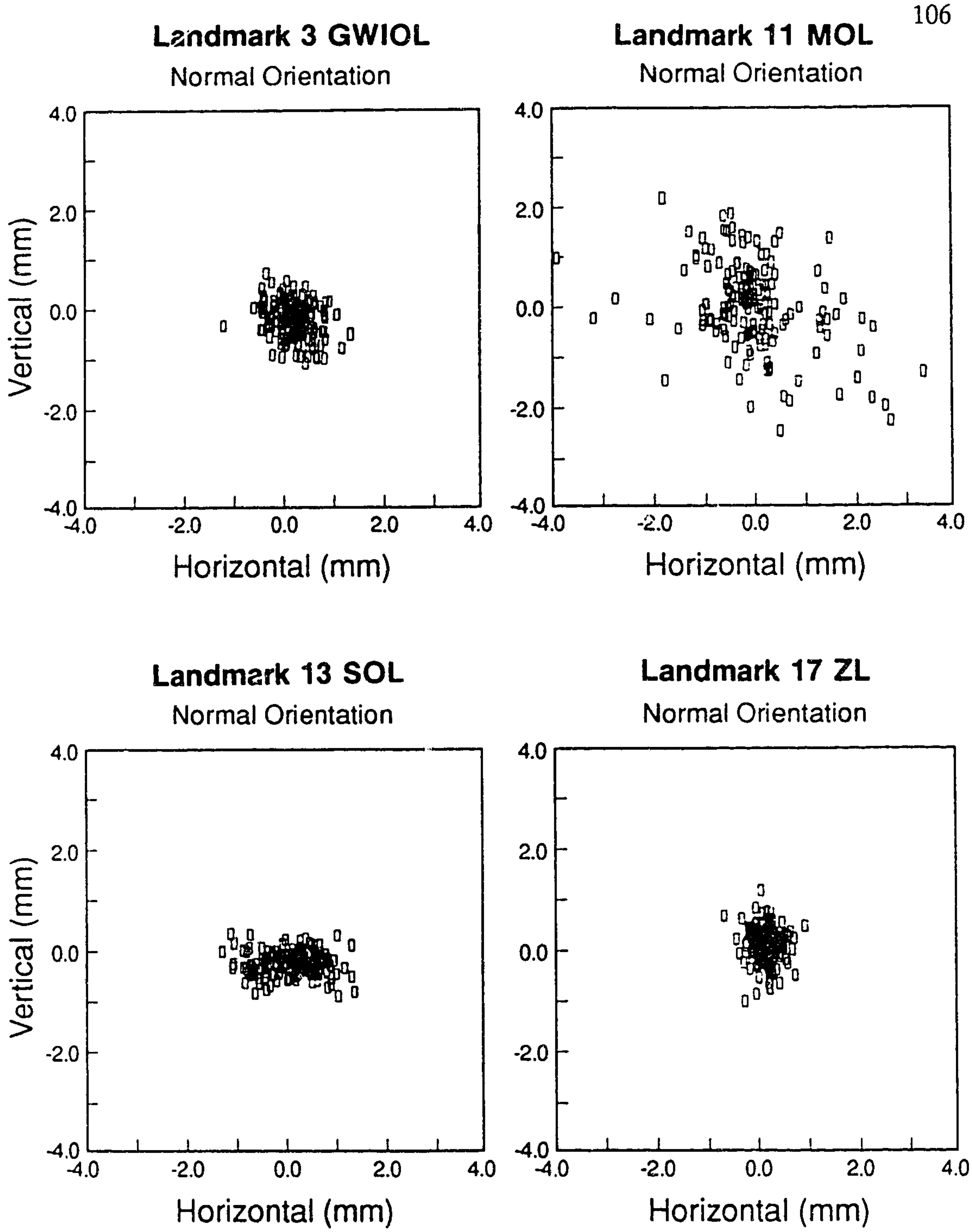


Figure 7. Scattergraphs of Landmarks

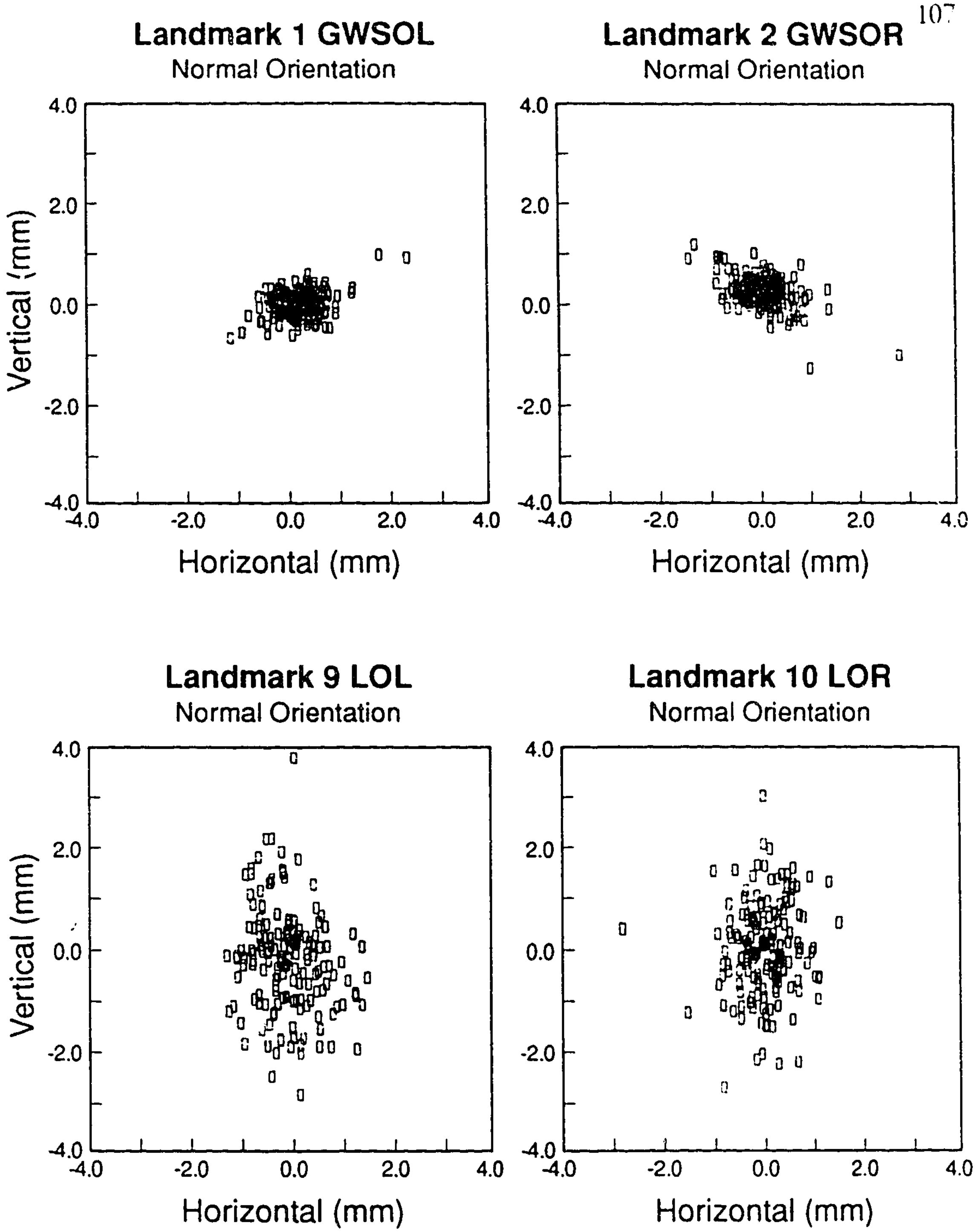


Figure 8. Scattergrapl of Selected Bilateral Landmarks

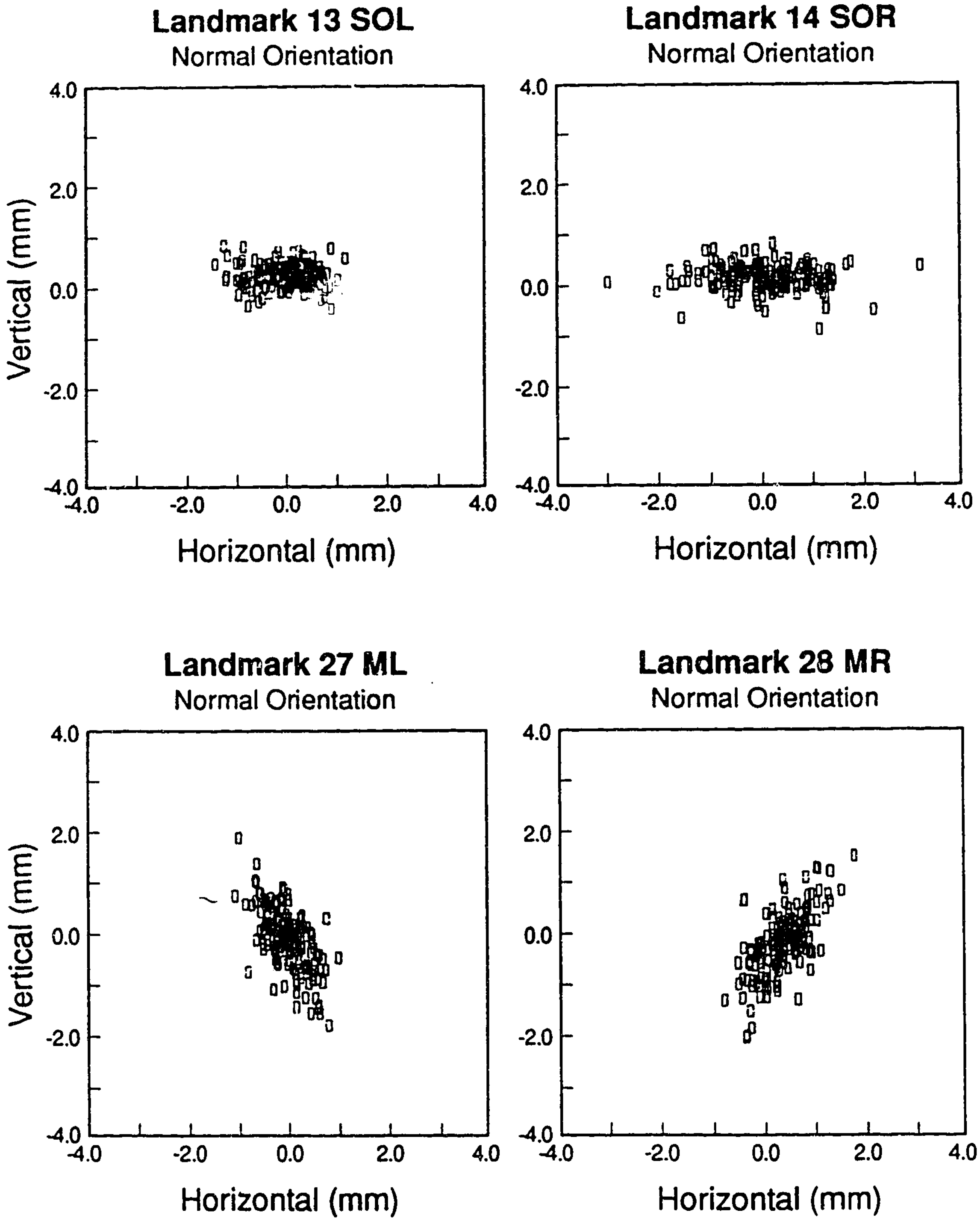


Figure 9. Scattergraphs of Selected Bilateral Landmarks

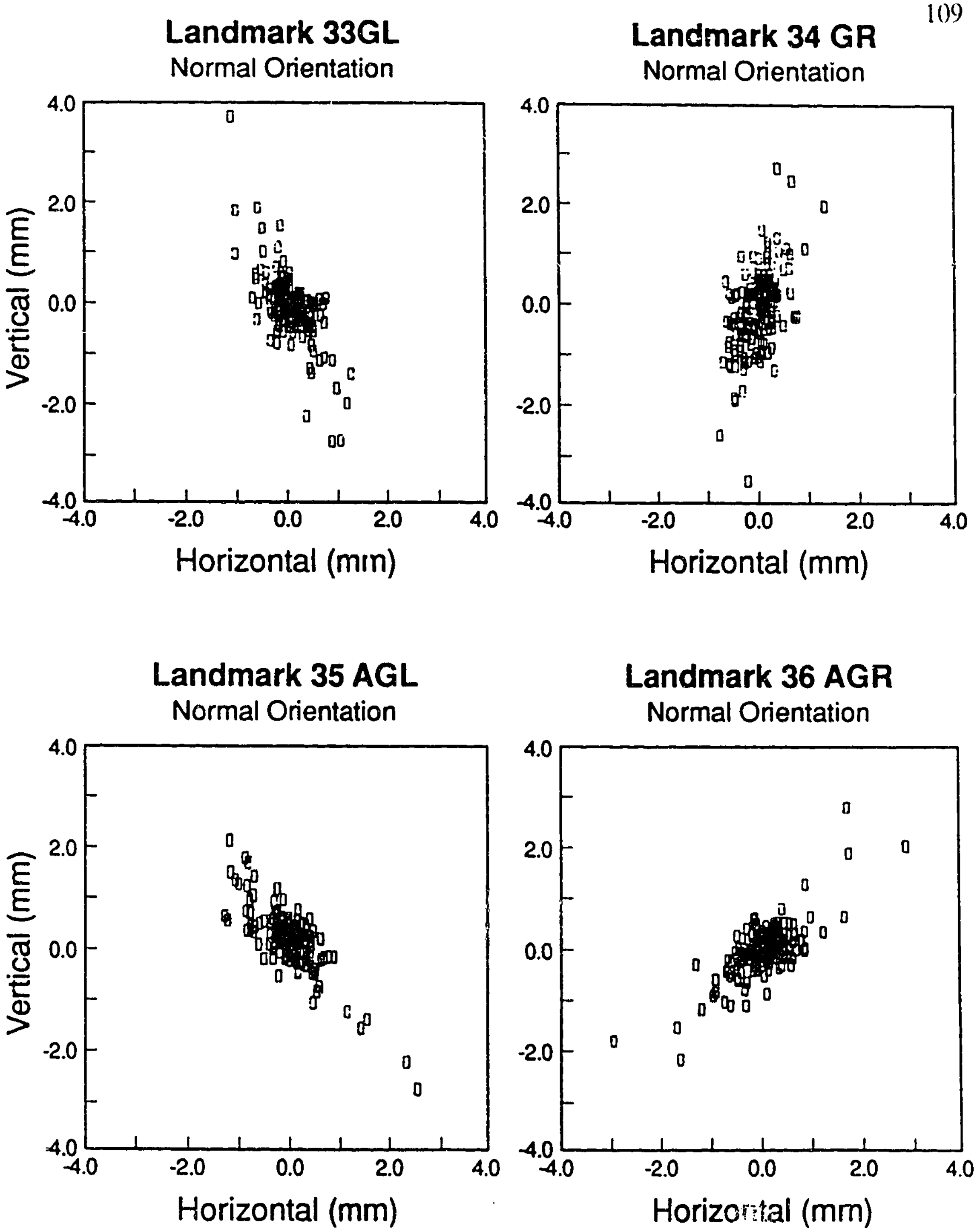


Figure 10. Scattergraphs of Selected Bilateral Landmarks

reported only the combined errors for bilateral landmarks and did not examine the shape of the scattergram for the individual landmarks.

The comparison of the error between the same landmarks on opposite sides of the skull revealed no significant differences in either the horizontal or vertical dimensions.

The orientation of the skull caused relatively few significant differences in landmark identification error in both the horizontal and vertical dimensions. There were three instances where the horizontal error was significantly different and seven instances where the vertical identification error was significantly different.

In each case where the horizontal error differed (Foramen Rotundum Right (FRR), Nasal Cavity Right (NCR), and Mandibular Molar Left (MD6L)), the rotated orientation had a larger standard deviation than the normal orientation. In these instances rotation of the head deleteriously affected the identification error (figures 11-12).

In the seven instances where vertical identification error was significantly different, three showed larger error (Orbitale Right (OR), Mandibular Body Base of Occiput Left (MBOL), and Mandibular Molar Left (MD6L)) and four showed significantly less error (Zygomatic Frontal Left (ZFL), Zygomatic Frontal Right (ZFR), Sella Turcica (ST), and Nasal Septum Midpoint (NSM)) than the normal orientation. Of the four exhibiting significantly less identification error, three were significantly less in all orientations, namely Zygomatic Frontal Right (ZFR), Zygomatic Frontal Left (ZFL), and Nasal Septum Midpoint (NSM) (figures 13-18).

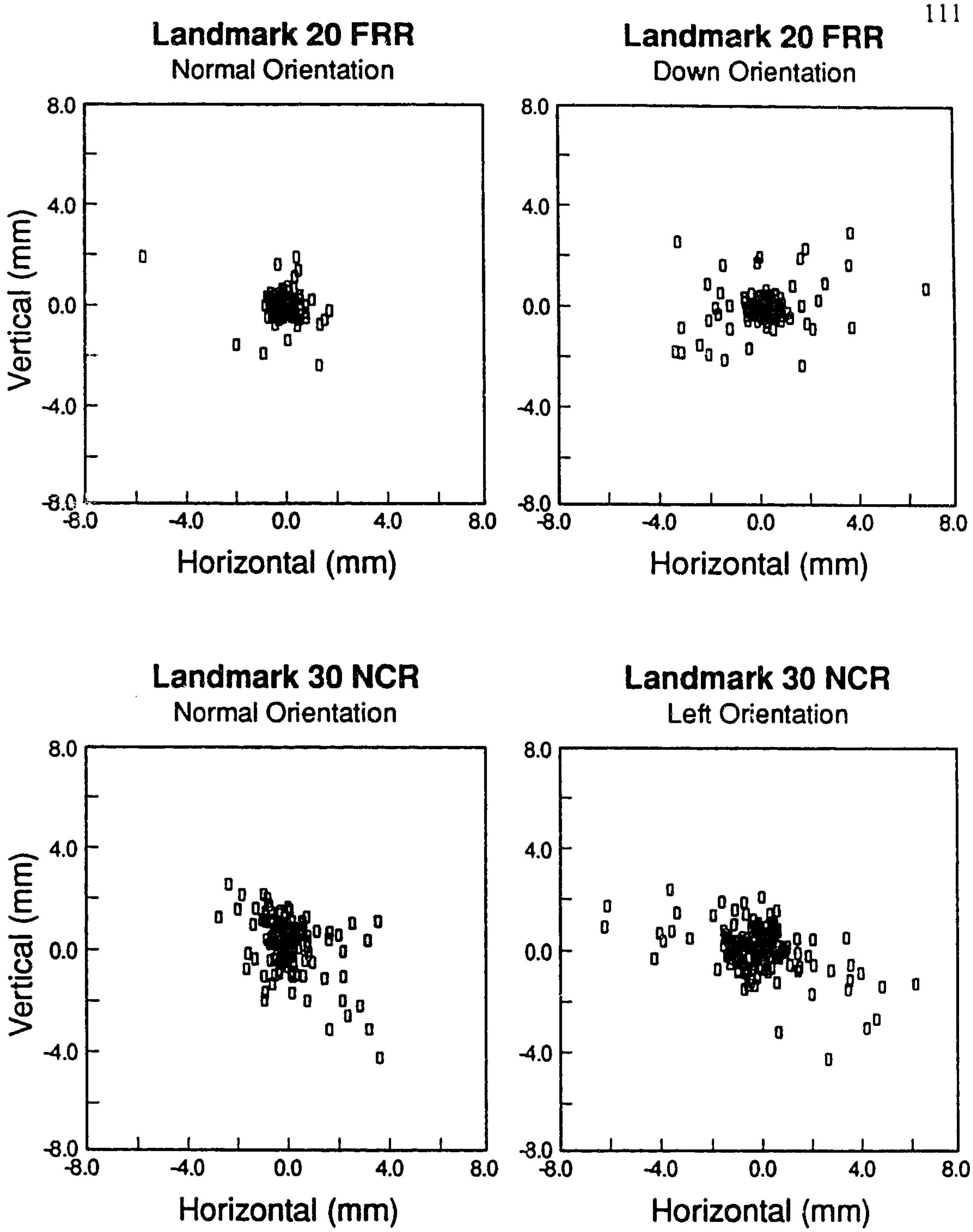


Figure 11. Significant Horizontal Differences

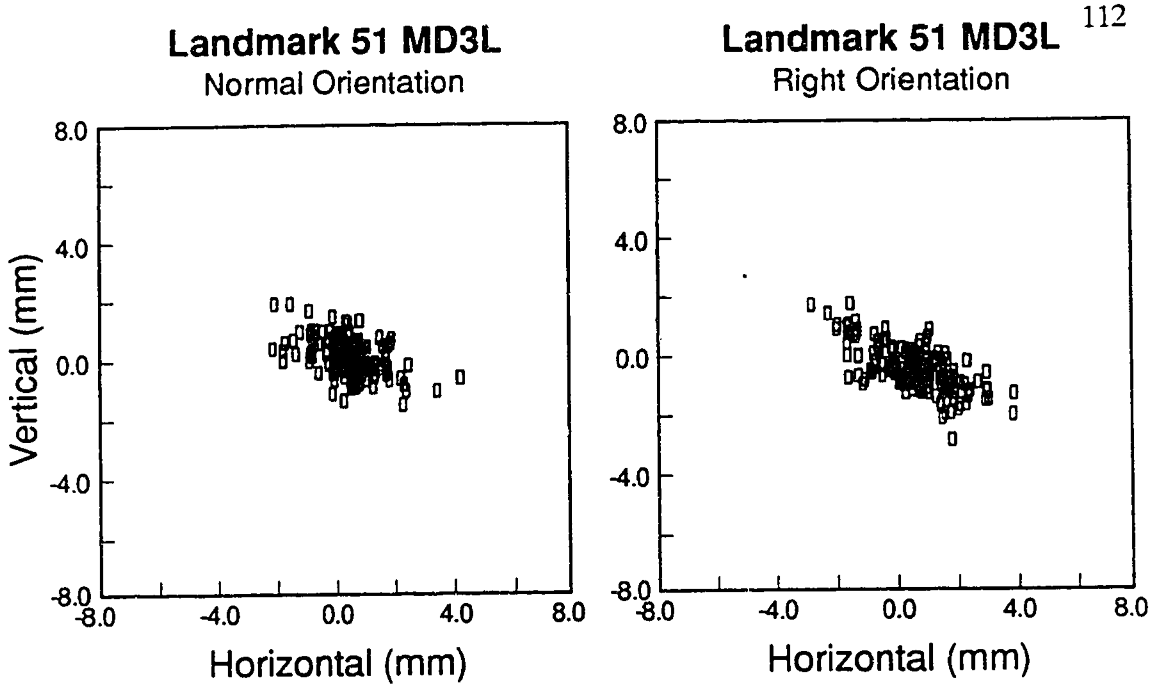


Figure 12. Significant Horizontal Differences

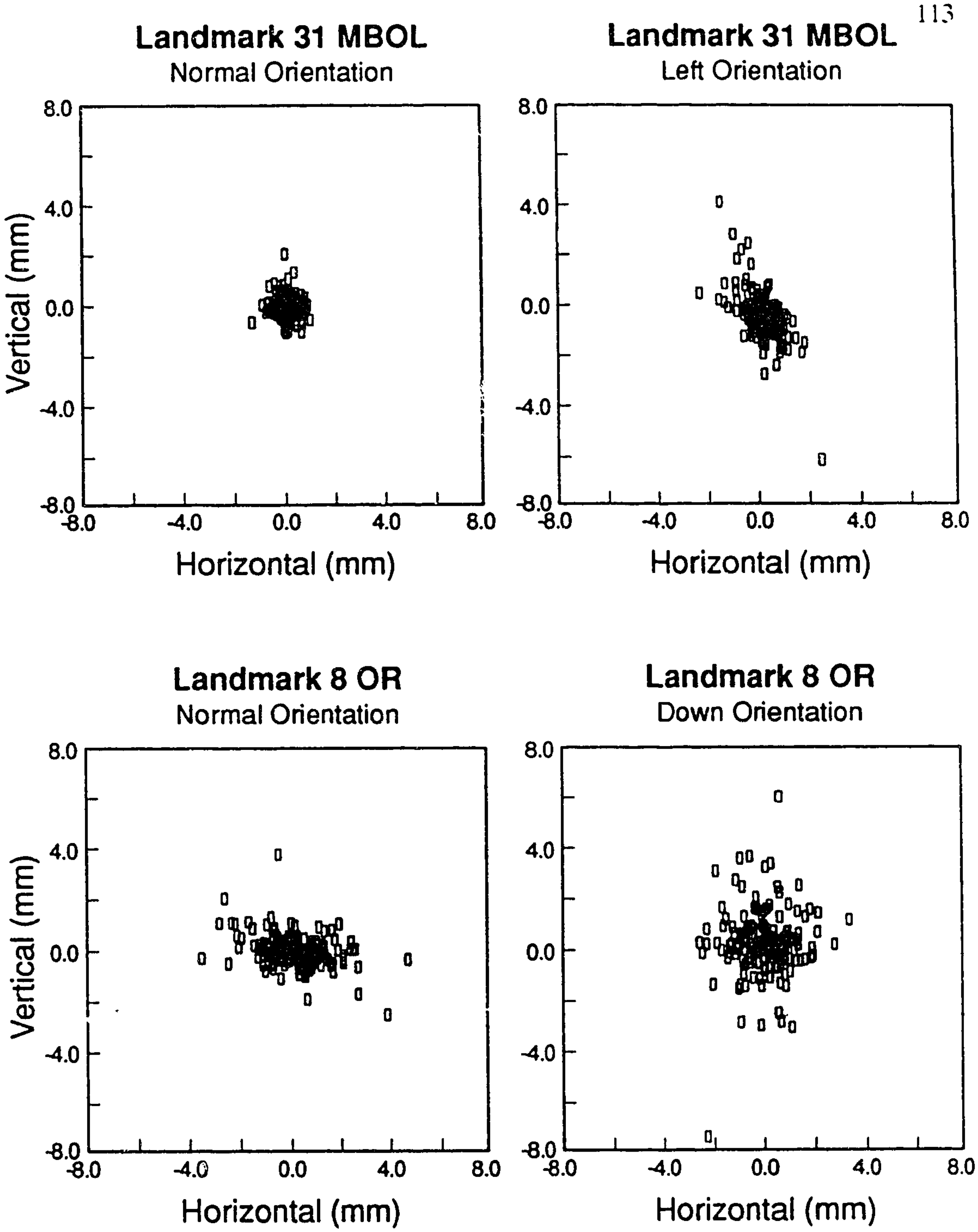


Figure 13. Significant Vertical Differences

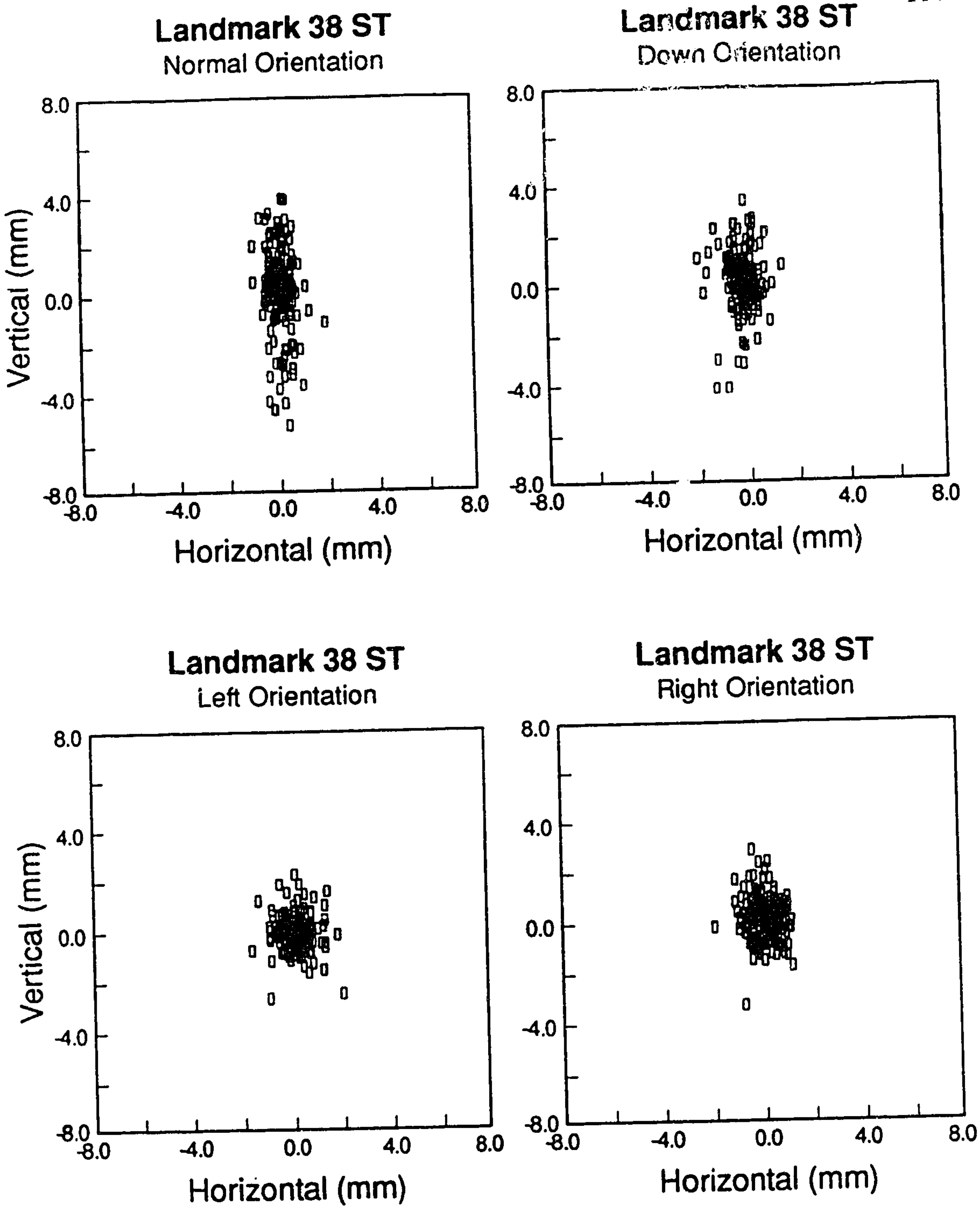


Figure 14. Significant Vertical Differences

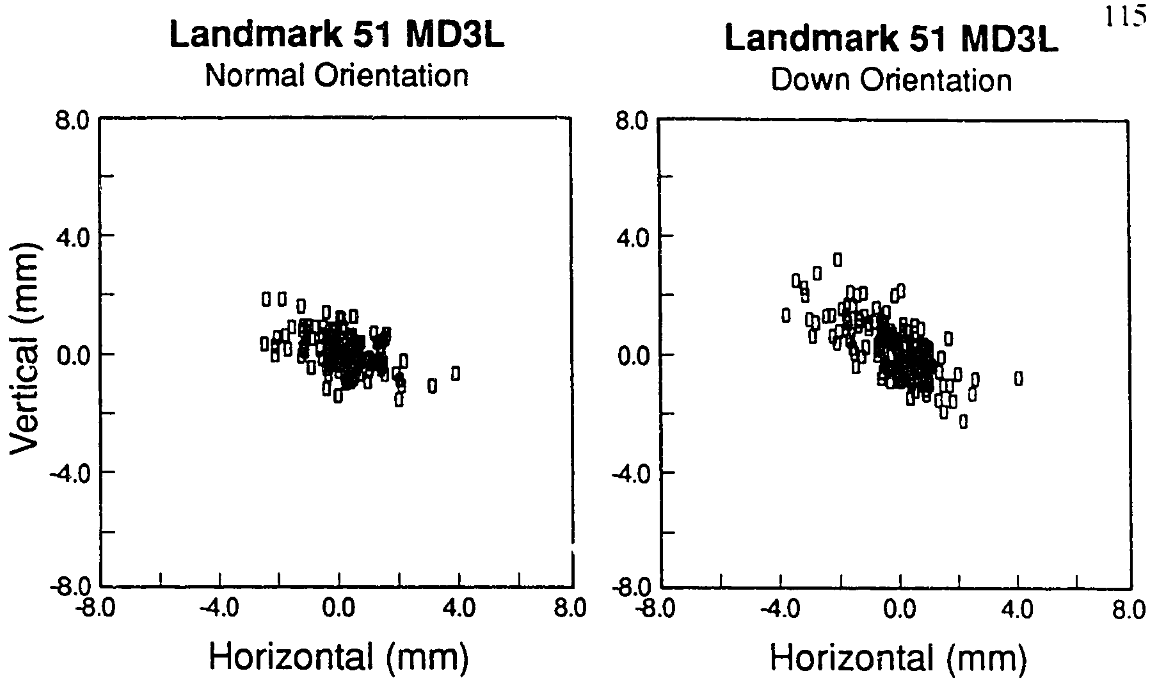


Figure 15. Significant Vertical Differences

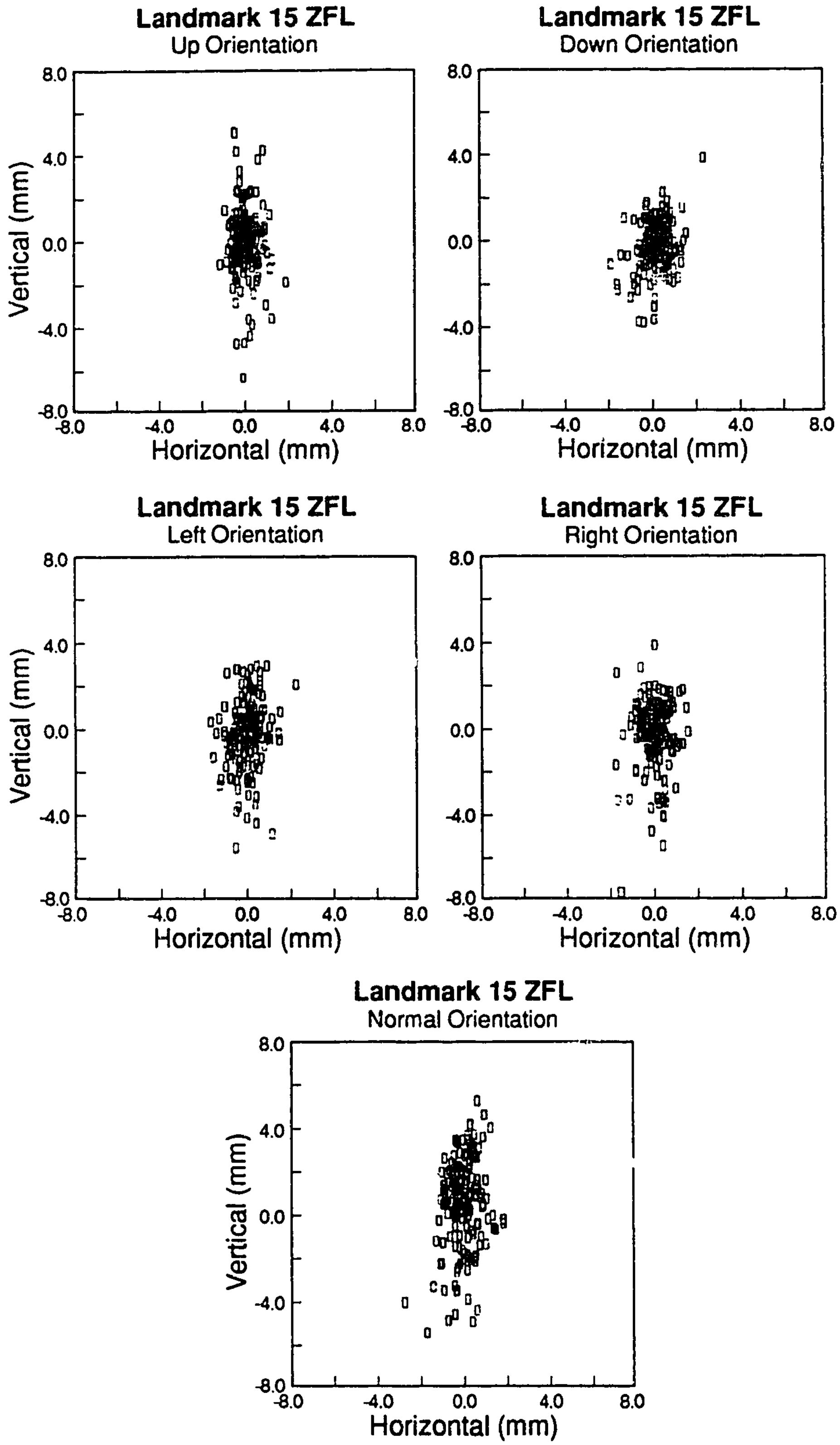


Figure 16. Landmark ZFL in all Orientations

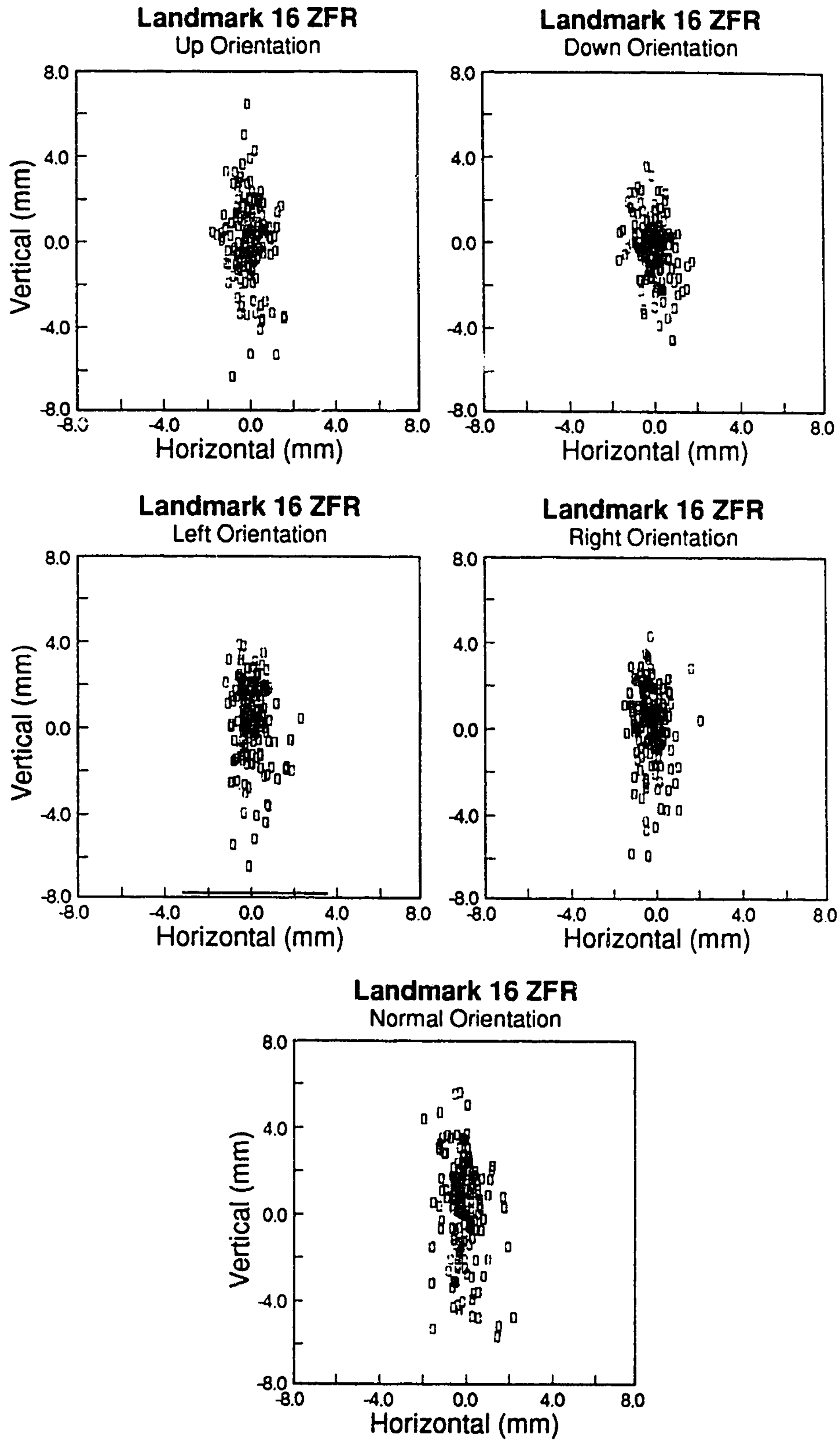


Figure 17. Landmark ZFR in all Orientations

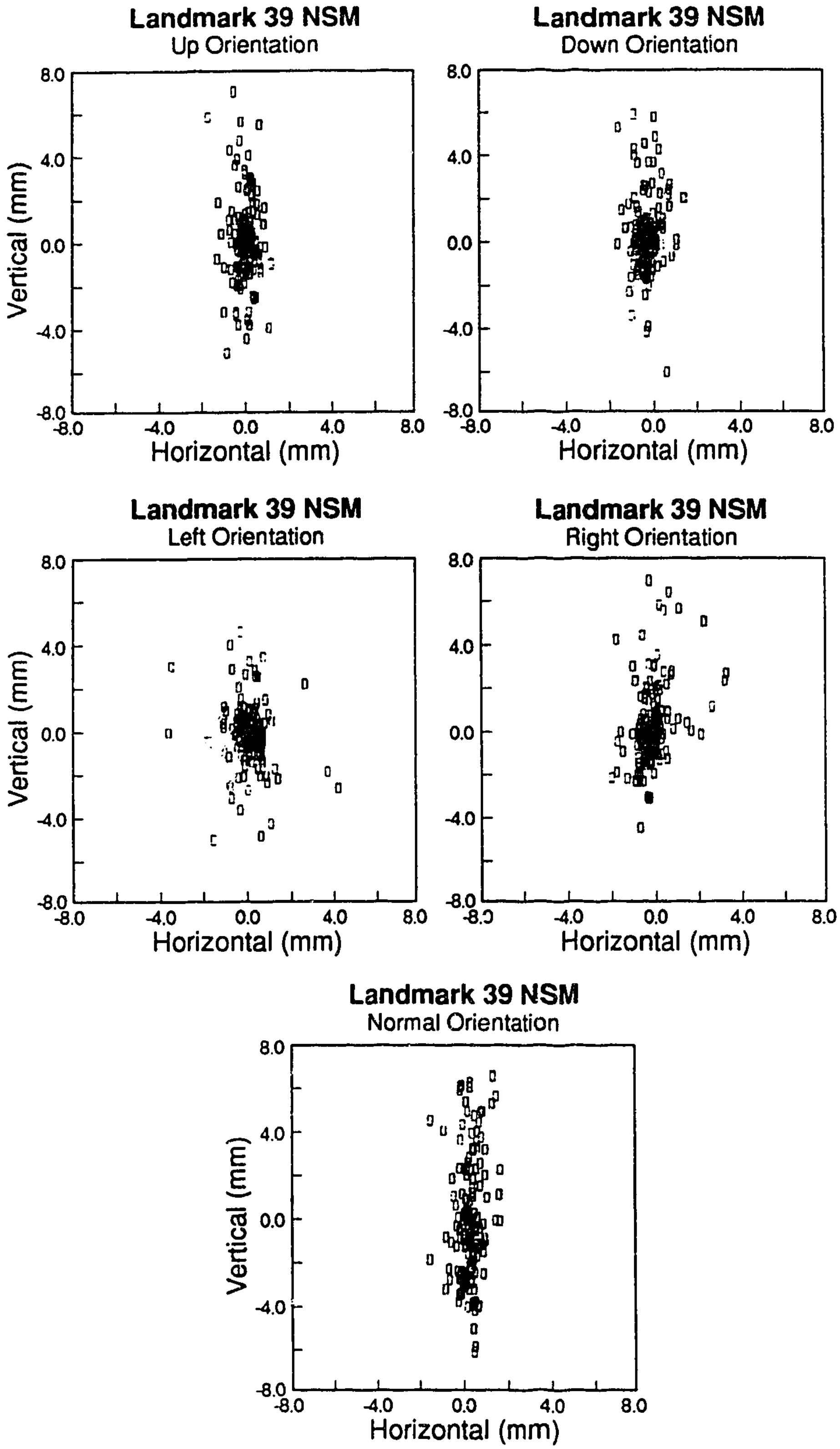


Figure 18. Landmark NSM in all Orientations

The effects of head rotation upon identification error can be explained by the superimposition of structures within the skull upon one another. In some instances the rotation of the head is such that it causes increased superimposition therefore increases the identification error. In other cases the rotation moves the structure into an area where there is less superimposition and makes it easier to identify. If the tables of identification error are exami... closely the trend for greater identification error in the rotated orientations is evident but the instances where this is significant are few. If the size of the sample were increased the number of significant findings may have been larger.

E. Inter-examiner Error

The inter-examiner identification errors showed a wide variance in magnitude in both the horizontal and vertical dimensions. The range of values for the inter-examiner identification error (0.28-3.36) is larger than that exhibited in the intra-examiner portion of the study (0.34-2.06). This difference can be attributed to interpretative differences between operators. These differences were present despite the standardization of conditions prior to initiating digitizing procedures.

In comparison to the results of the study by EL Mangoury et al[29] (0.42-1.74) the range for the same landmarks was larger in this part of the study (0.36-3.36). This can be attributed to the fact that the study by El Mangoury et al utilized only one operator. The study of Baumrind and Frantz[9] utilized multiple operators and the range of identification errors in their study (0.34-3.71) are sim[illegible] to those found for the inter-examiner error(0.28-3.36).

A comparison of the scattergraphs between the inter-examiner and intra-examiner portions reveals that the plots have similar shapes with a generally larger scatter associated with the inter-examiner plots (figures 19-24). The shapes of the plots tend to resemble the contours of the area in which the landmark is located.

There were no significant differences between intra-examiner and inter-examiner identification error in the horizontal dimension. Significant differences between intra-examiner and inter-examiner identification error in the vertical dimension occurred in three instances: landmark Condyle Superior Left (CSL); landmark Condyle Superior Right (CSR); and landmark Centre Condyle Right (CCR).

The fact that these landmarks exhibited significantly greater identification error with four operators may be attributable to the position of these landmarks within the skull as seen in the PA cephalogram. The region of the skull in which these landmarks are located is superimposed over the image of the petrous portion of the temporal bone. This is a very dense osseous structure and makes localization of the condylar process of the mandible difficult. The identification of these structures therefore involves some guesswork on the part of the operator and the result becomes evident for multiple operators.

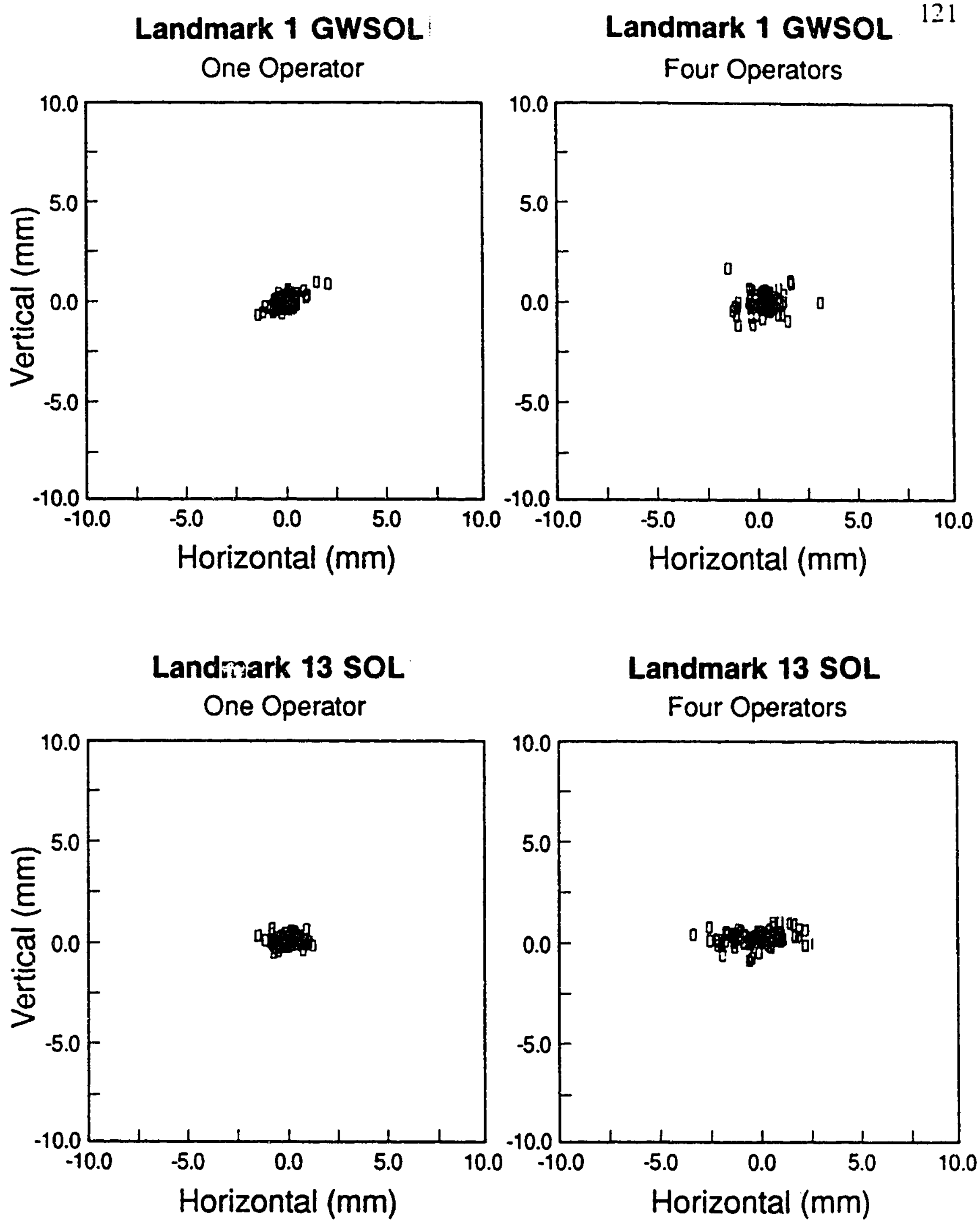


Figure 19. Scattergraphs of Intra-examiner vs. Inter-examiner

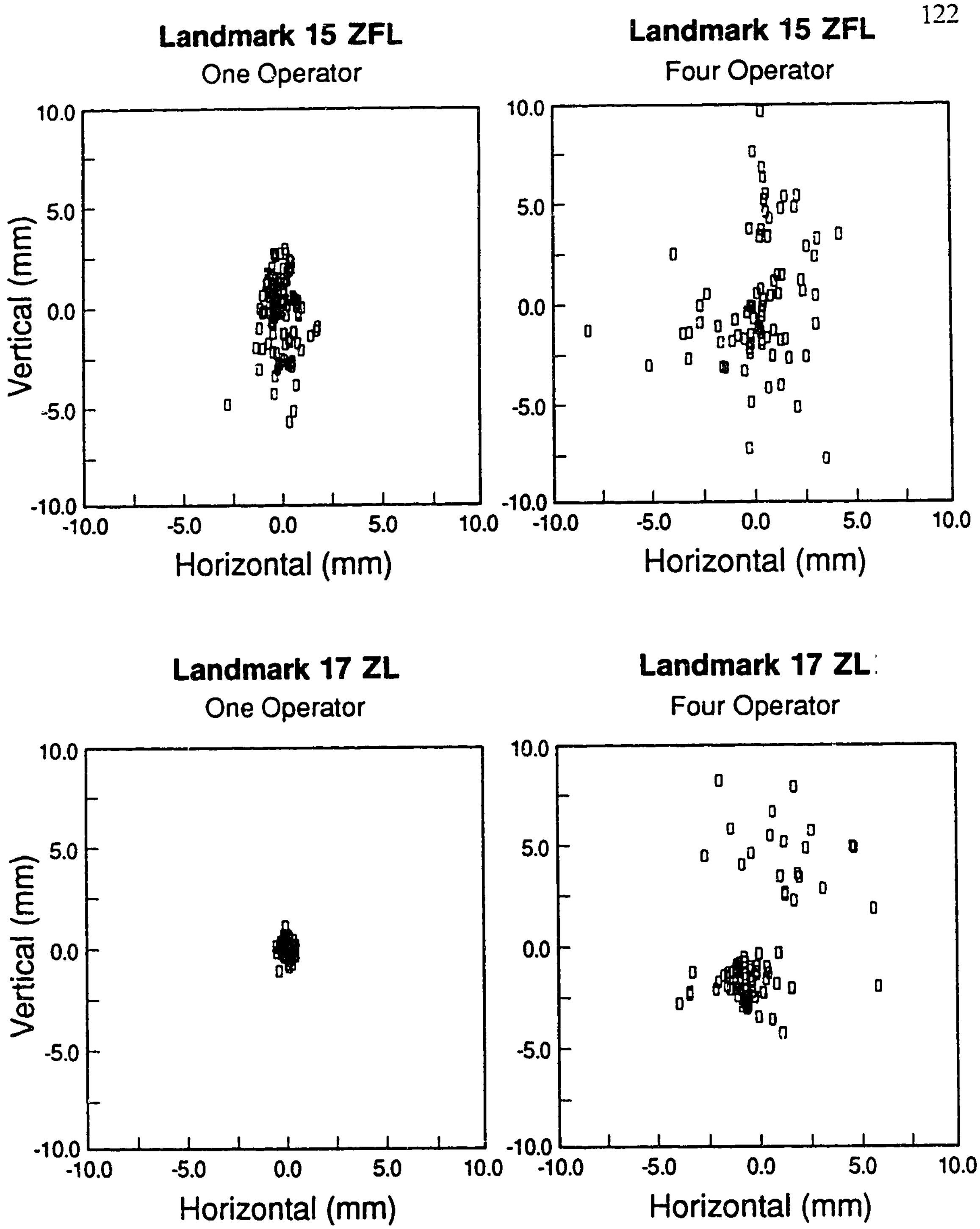


Figure 20. Scattergraphs of Intra-examiner vs. Inter-examiner

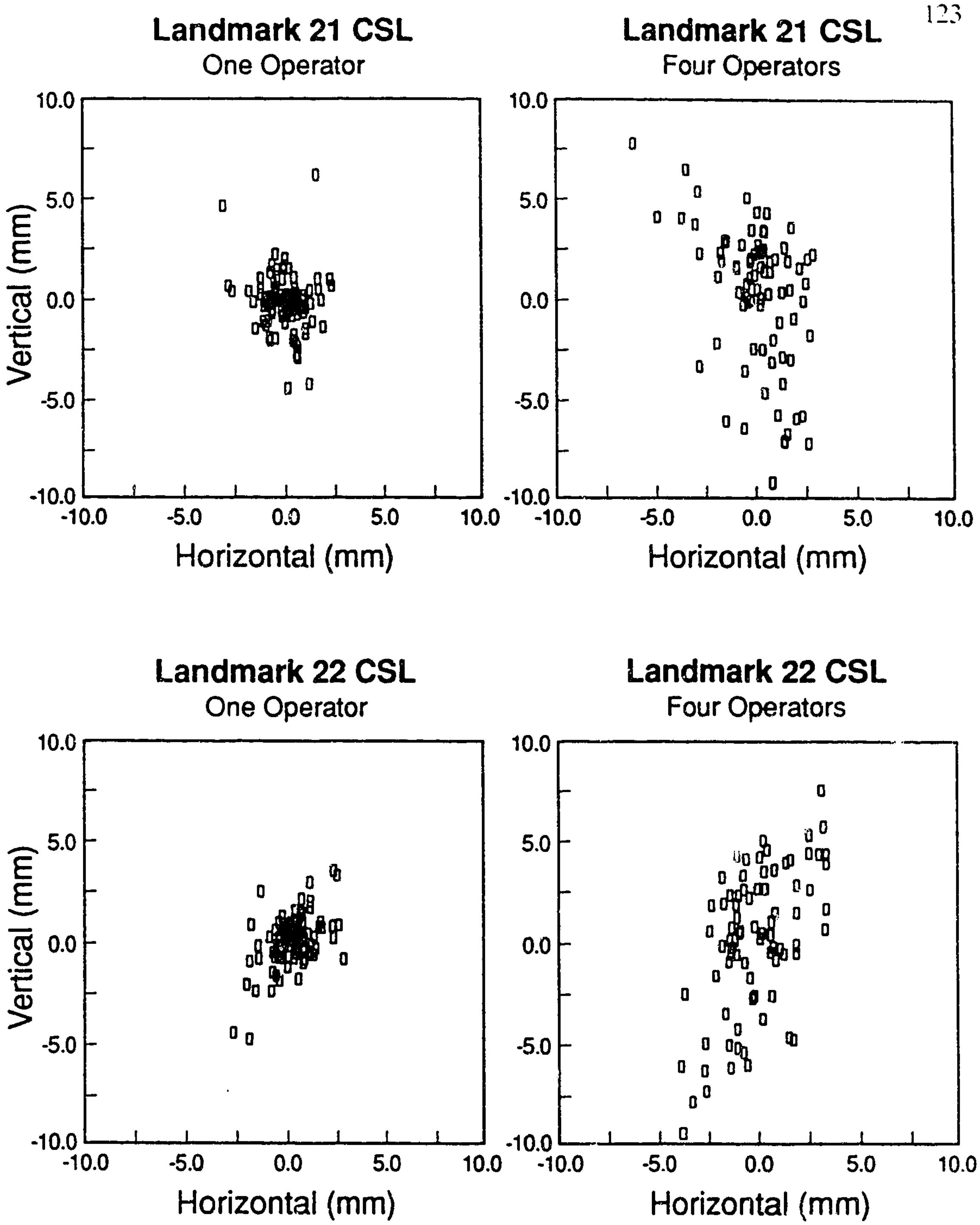


Figure 21. Scattergraphs of Intra-examiner vs. Inter-examiner

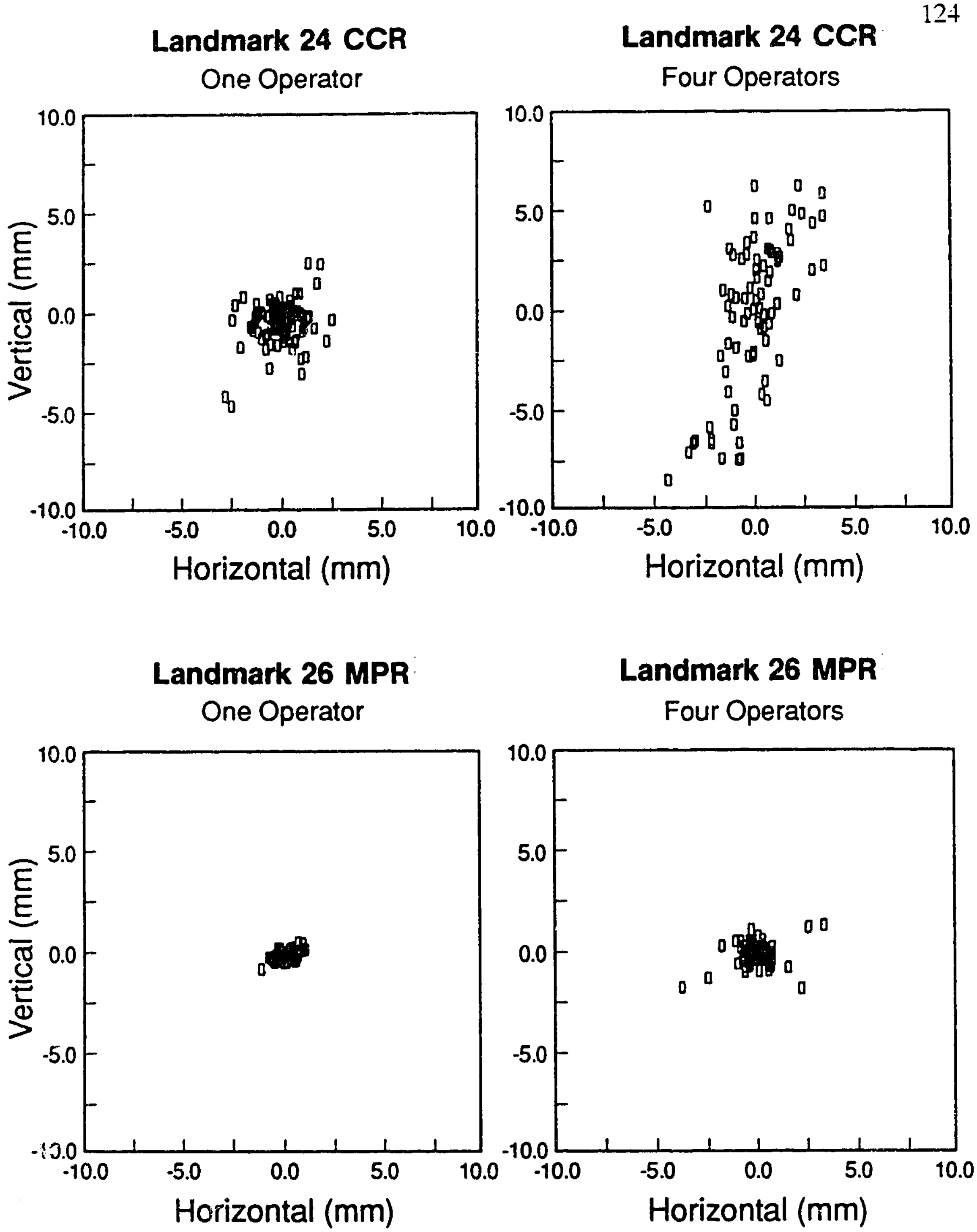


Figure 22. Scattergraphs of Intra-examiner vs. Inter-examiner

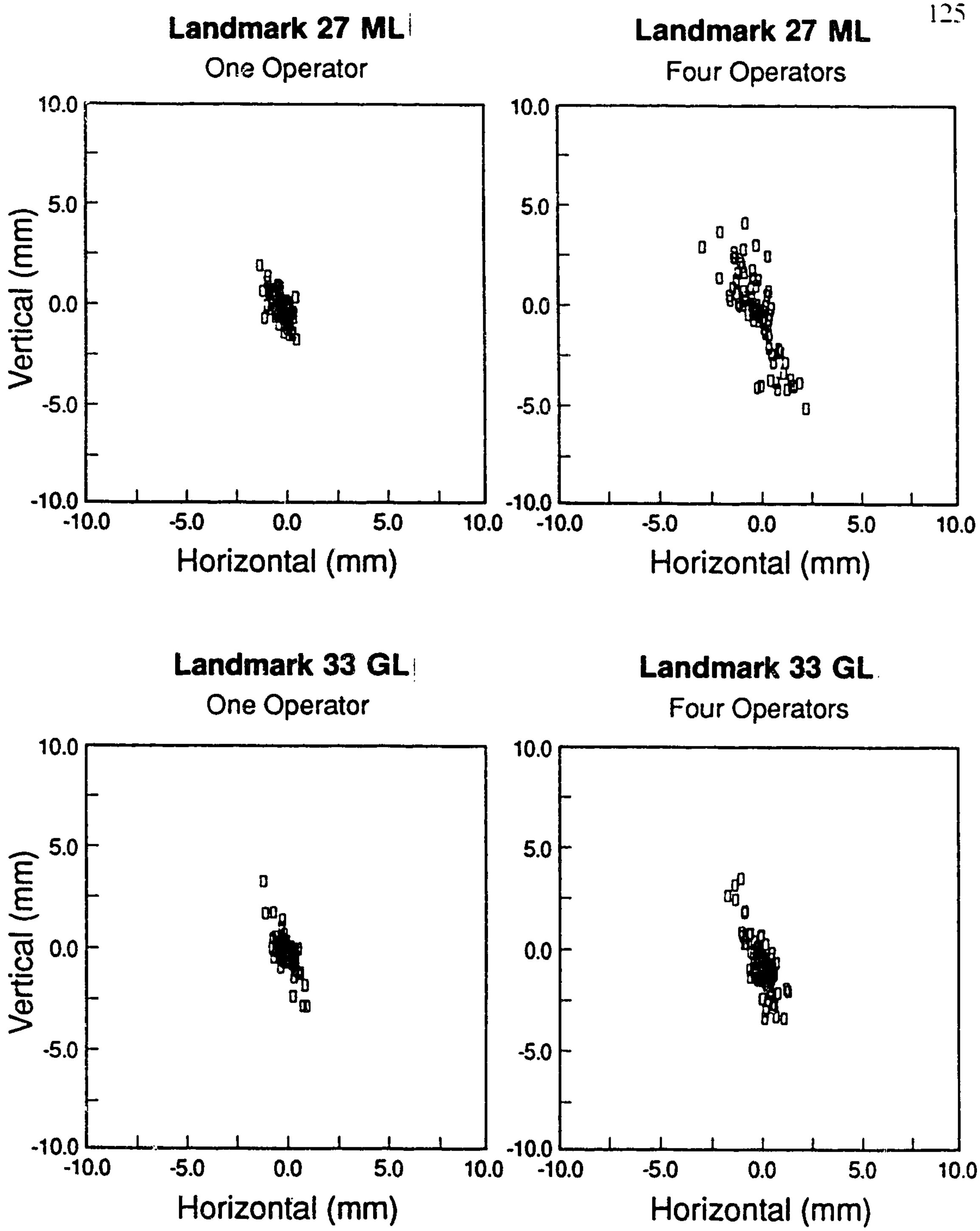


Figure 23. Scattergraphs of Intra-examiner vs. Inter-examiner

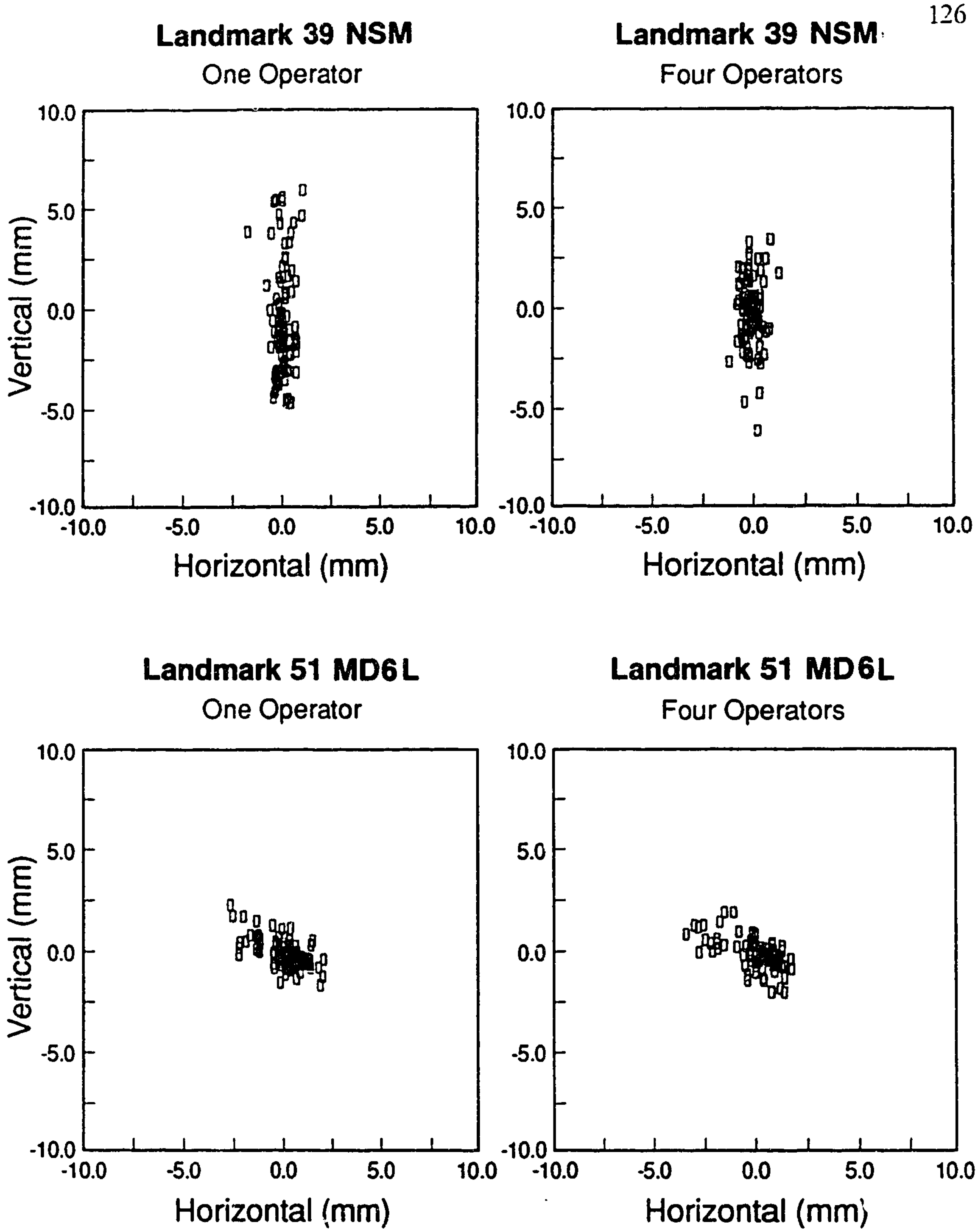


Figure 24. Scattergraphs of Intra-examiner vs. Inter-examiner

F. Reference Planes

The last portion of the study was designed to evaluate the landmarks in the upper facial skeleton and determine, through the use of statistical tests, which landmarks would be best suited to determine independent vertical and horizontal reference planes.

Utilizing PA cephalograms, symmetry of the skull in both the vertical and horizontal dimensions can be evaluated. An ideal analysis of symmetry for the PA cephalogram would enable one to evaluate not only the location of any asymmetry but also give information as to the magnitude of the discrepancy.

The choice of which landmarks to utilize in the construction of these planes should be based upon the location of the landmarks and the error associated with their identification. Those landmarks to be used in the establishment of the vertical reference should also be representative of the true midline of the skull. The landmarks which are the most suitable for establishing a horizontal reference may not be the best for a vertical reference and vice versa. For this reason the establishment of the horizontal and vertical reference planes should be made independently of one another.

The majority of analyses available to the orthodontic profession today have drawbacks which limit their usefulness. Some analyses like the x-line method of Harvold[65] are useful for examining symmetry in the horizontal dimension only.[7,74] Other analyses like the triangle analysis of Butow and Van der Walt[76,77] utilize a vertical reference line to make both horizontal and vertical measurements. While the establishment of the vertical axis is done by constructing horizontal lines through the skull there is no evidence presented to which shows this method of establishing a midline is actually representative of the true midline of the skull.

The analysis by Hewett[58] and Vig and Hewitt[59] utilizes the measurement of area in different regions of the face to compare the differences between sides of the skull. This method while giving an overall assessment of symmetry within the skull does not quantify any asymmetries found.

Chebib and Chamma[75] produced a method in which to examine asymmetry through the use of indices. In this method the horizontal and vertical indices of symmetry were determined relative to two constructed midlines, one for the bilateral landmarks and one for the midline landmarks. Which of these midlines represents the true midline of the skull is unclear and one must therefore question the results.

The studies by Stabrun[78] and Molstead and Dahl[66] both utilize two reference planes, one horizontal and one vertical, to determine the location and extent of asymmetry within the skull. Both of these methods however use a vertical reference line which is constructed as a perpendicular to the horizontal reference. This method is less than ideal as it does not consider the horizontal and vertical reference planes separately. There is no evidence to indicate that the horizontal and vertical reference lines should be perpendicular to one another.

The study by Grummons and Van de Coppello[3] was the only analysis found which utilized independently determined horizontal and vertical reference lines. This method enables structures to be evaluated independently in the horizontal and vertical dimensions in a quantitative manner. The vertical reference line used in this study must be questioned however, as it utilizes the anterior nasal spine as one of its determining landmarks. This landmark is in the lower facial skeleton and thus may be involved in any facial asymmetry.

None of the analyses examined reported information regarding the reliability of landmarks in determining either the horizontal or vertical reference planes, possibly due to the lack of information currently available especially regarding landmarks in the upper facial skeleton.

In selecting landmarks from which to construct horizontal and vertical reference planes there is one criterion which is common to both reference planes. Any landmarks utilized to evaluate symmetry of the face should be located in a region of the skull which is not subject to the effects of treatment and exhibits a high degree of internal symmetry. The landmarks located in the upper facial skeleton (the region including the anterior cranial base and the orbits) have been shown to be well suited to this purpose.[54-57,66]

i. Horizontal Reference - The specific criteria for landmarks to be used in establishing a horizontal reference plane are based on the fact that the horizontal reference will be used to evaluate vertical symmetry of the skull. These criteria include: minimal deviation of the line through the landmarks from the best horizontal line through the skull; minimal identification error in the vertical dimension; and wide separation of the landmarks horizontally.

Minimal deviation from the best horizontal line through the skull and minimal vertical identification error are both designed to ensure that the chosen reference line is a good approximation of the true horizontal reference plane and will be minimally affected by the difficulty in identifying the landmarks.

The wide separation of the landmarks horizontally is required in order to reduce the effects of the vertical identification error. If the landmarks are close together, a small vertical deviation in one of the landmarks will have a greater effect on the relationship of the line through the landmarks with respect to the true horizontal than if the landmarks are widely separated.

The horizontal deviation analysis which was carried out for the bilateral landmarks showed (table 16) that the landmarks Lateral Orbit (LOR/L), Superior Orbit (SO), Medial Orbit (MO), Zygomatic Frontal (ZF), Orbitale (O), Foramen Rotundum (FR) and Greater Wing Superior Orbit (GWSO) did not exhibit significantly greater variation from the best horizontal line than any other landmarks using all the skulls, all the orientations and one operator. The same landmarks plus landmark Lesser Wing Orbit (LWO) were free from significant differences when only the selected skulls were evaluated (table 17). None of the landmarks exhibited significant differences when orientation was removed, the selected skulls included and multiple operators utilized (table 18). The fact that no significant differences were found in the four operator portion shows that when the orientation of the skull is varied the ability of some landmarks to estimate the best horizontal line was affected. Therefore the remaining testing was carried out using all of the skulls and all orientations.

Thus, based on the deviation of the line through the bilateral landmarks with respect to the best horizontal line through the skull, the landmarks Mastoid Point (MP), Lesser Wing Orbit (LWO), Greater Wing Inferior Orbit (GWIO) and Zygomatic Arch (Z) should not be utilized to establish the horizontal reference plane.

If an arbitrary limit on vertical identification error is set at a standard deviation of one millimetre four landmarks fall under this limit. These are landmarks Superior Orbit (SO) (SD=0.31 mm), Greater Wing Superior Orbit (GWSO) (SD=0.36 mm), Foramen Rotundum (FR) (SD=0.58 mm),and Orbitale (O) (SD=0.94mm).

When the horizontal separation of the landmarks is considered (figure 6) the landmarks with the widest separation are Greater Wing Superior Orbit (GWSO) followed by Superior Orbit (SO) and Orbitale (O) with Foramen Rotundum (FR) being the closest landmarks together. With all the factors taken into account the landmarks Greater Wing Superior Orbit (GWSO) appears to be the best suited for establishing a horizontal reference from which to assess vertical symmetry of the skull.

ii. Vertical Reference - The criteria for the landmarks used to establish a vertical reference plane are based on the requirement of ability to evaluate horizontal symmetry. These criteria include: minimal deviation of the landmarks, either midline landmarks or bisectors of bilateral landmarks, from the best midline through the skull; minimal identification error in the horizontal dimension; and wide separation vertically.

Initially an analysis was performed to examine the deviation of each bilateral landmark and midline landmark with respect to the best midline of the skull. The results of this analysis show (table 21) that the only upper facial landmark which did not exhibit a significantly larger amount of variance than any other landmark was Greater Wing Inferior Orbit (GWIO). All of the other landmarks in the upper facial skeleton exhibited significantly greater variance than at least one other landmark. Since one landmark is insufficient to determine a vertical reference line, only those landmarks exhibiting significantly greater variance than more than one other landmark were deleted from the next part of the study (Zygomatic Arch (Z) and Mastoid Point (MP)).

When an examination was made of the horizontal landmark identification errors, landmark Orbitale (O) exhibited a standard deviation of greater than one millimetre and was therefore deleted (table 8).

Two other landmarks were removed from further testing due to being located close to another landmark on a similar structure and exhibiting a greater horizontal identification error. These were landmarks Lateral Orbit (LO) and

Lesser Wing Orbit (LWO) which were very close to landmarks Zygomatic Frontal (ZF) and Medial Orbit (MO) respectively (figure 5).

The next step in the determination of a vertical reference line involved the testing of the line through pairs of landmarks with respect to the best midline. The results of this portion of the study (table 23) show that rotation about the transverse axis had no significant effects on the variance between the lines through the pairs of landmarks and the best midline.

Rotation of the skull about the vertical axis significantly affected the variance from the best midline for twenty of the twenty-six pairs of landmarks. There were six pairs which were not affected by rotation all of which exhibited relatively large variance from the best midline. The fact that rotation of the head about the vertical axis is significant and rotation about the transverse axis is not, is explainable by the geometry of both the cephalostat and the skull.

The design of the cephalostat places all of the landmarks in the PA cephalometric image closer to the film than the axis of rotation. When a rotation occurs about either the transverse ertical axes, each landmark moves in the same direction in relation to the film. Since each landmark is located at a different distance from the axis of rotation, those landmarks farther from the axis of rotation will move a greater distance on the projected image than those closer to the axis. This will change the relationship of the landmarks to one another on the cephalogram.

Rotation about the transverse axis will affect the relationship of landmarks vertically but not horizontally, as landmarks on both sides of the skull move the same amount. Horizontal symmetry will not be affected as no changes in horizontal relationships take place.

Rotation about the vertical axis has the opposite effect, with horizontal relationships affected while the vertical relationships remain unchanged. This creates problems because the assessment of symmetry for bilateral landmarks involves relating them to a midline reference plane. If the reference plane is constructed from landmarks not located at the same antero-posterior position within the skull, any rotation about a vertical axis will change the relationship between the bilateral landmarks and the midline. Ideally, to eliminate the effects of rotation about a vertical axis, each pair of bilateral landmarks should be measured with respect to a midline reference located at the same antero-posterior position within the skull.

The landmarks used to establish a midline reference are located in the upper facial skeleton for several reasons including: symmetry of the area, stability over time, separation from the areas affected by treatment, and easy identification. It is therefore obvious that the midline reference will not be located at the same antero-posterior position as each bilateral structure of interest. For this reason it will not be useful for assessing horizontal symmetry if rotations about the vertical axis are permitted. Therefore in order to be able to assess horizontal symmetry of the skull, rotation about the vertical axis must be strictly controlled when PA cephalograms are taken. The choice of which two landmarks are utilized to construct a vertical reference plane through the skull must take into account the vertical separation of the landmarks as well as the horizontal identification error and the deviation from the best midline.

In order to maximize vertical separation the choice of landmarks should logically involve one landmark from the supra-orbital region and one from the infra-orbital region of the upper facial skeleton. An examination of the mean variances of deviation from the best midline (table 23) revealed that seven of the ten pairs of landmarks which exhibited the least variation from the best midline contained one landmark from the infra-orbital region. Six of the ten contained landmarks from the supra-orbital region. The four pairs of landmarks which exhibited the least variance from the best midline contained each of the four landmarks in the supra-orbital region in combination with one landmark in the infra-orbital region (Nasal Septum Midpoint (NSM)).

The other landmark in the infra-orbital region which was tested was Foramen Rotundum (FR). From the results, it can be seen that Foramen Rotundum (FR) was contained in three of the ten pairs which exhibited the greatest variance from the best midline. Since these two landmarks are very close to one another vertically the difference between them lies in the magnitudes of their horizontal identification error and deviation from the best midline. Landmark Foramen Rotundum (FR) exhibited both a larger horizontal landmark identification error and a larger variance from the best midline than Nasal Septum Midpoint (NSM).

The decision of which of the four landmarks in the supra-orbital region to use in combination with landmark Nasal Septum Midpoint (NSM) in determining a vertical reference line must be made through an examination of the horizontal identification error (table 8) and the deviation from the best midline (table 21). With these two factors considered, the midpoint between the bilateral landmarks Greater Wing Inferior Orbit Left and Right (GWIOL/R) in conjunction with landmark Nasal Septum Midpoint (NSM) is the best combination to use in establishing a vertical reference plane.

In a situation where the landmark Greater Wing Inferior Orbit (GWIO) was not visible, any of the other landmarks in the supra-orbital region, Greater Wing Superior Orbit (GWSO), Superior Orbit (SO), or Crista Galli (CG), could be substituted for GWIO without affecting the variance from the best midline to a great extent. This shows that the use of Crista Galli as a basis for the vertical reference plane in other analyses[7,55,65,73,78], has some merit.

The analysis of the relationship between the horizontal and vertical reference lines showed that while the magnitude of their difference from perpendicular was small (table 23) it was significant for all the orientations. This emphasizes the fact that the choice of reference planes should be made independently of one another. This analysis also showed that rotation of the head about the vertical axis significantly increases the difference from perpendicular.

The use of two landmarks to construct each reference plane is an attempt to design a simple method of PA analysis which involves a minimal number of measurements. It is quite possible that the combination of a greater number of landmarks may give a better estimation of the best horizontal and vertical lines through the skull, but any such combination would most likely require a computerized method to calculate the reference lines. The object in this case was to produce reference planes which could be used simply and quickly without the need for computers.

G. Summary

In summary the results of the study show that the methodology utilized was very reliable. The differences in the position of the individual landmarks was the greatest contributor to the total variance within the sample.

The magnitude of the identification error in both the horizontal and vertical dimensions was peculiar to each landmark and was relatively unaffected by rotations of the head within the cephalostat. No differences were seen in identification error between the same landmarks on opposite sides of the skull.

Differences between intra-examiner and inter-examiner identification errors were not significant in the horizontal dimension and significant for only three landmarks in the vertical dimension. There were no differences in the error between the same landmarks on opposite sides of the skull for multiple operators.

A horizontal deviation analysis and an examination of the vertical landmark identification errors, revealed that several pairs of bilateral landmarks were significantly better than the rest in estimating the best horizontal line through the skull. Based on this information the Greater Wing Superior Orbit Left and Right were suggested as the most suitable pair of bilateral landmarks for establishing a horizontal reference line.

A vertical deviation analysis and testing of pairs of landmarks for deviation from the best midline showed that rotation of the head about a vertical axis significantly affects the determination of a vertical reference line through the skull. Through an examination of the vertical separation of landmarks in the upper facial skeleton, the horizontal landmark identification errors, and deviation from the best midline, the bisector of landmark Greater Wing Inferior Orbit (GWIO) in combination with the landmark Nasal Septum Midpoint (NSM) were suggested for establishing a vertical reference plane through the skull.

H. Suggestions for Further Study

This study was limited by the fact that it utilized dried skulls as a sample. While this enabled the effects of head rotation to be studied, the identification errors that were found were probably smaller than what would be seen on actual patient radiographs because of the lack of soft tissue. The landmark identification error may be quite different for radiographs of live patients and requires further investigation.

The selection of the sample also limits the study in that it was not random and of limited size. The results could possibly be different with a random an '/or larger sample.

This study was also limited in that it utilized skulls which exhibited very little facial asymmetry. Whether the same reference planes are suitable for skulls which are not symmetric remains unexplored.

Another area which is open to investigation would be the effect of the rotations of the head on both linear and angular measurements made on PA cephalograms. The mathematical model developed by Eliasson et al[49] enables the effects of head rotation on these measurements to be calculated theoretically, but the actual changes which occur when identification error is included may be quite different.

Other areas of investigation might include examination into the fields of digital enhancement of radiographs or computer aided recognition of cephalometric landmarks.[88,89]

There are many areas of study left untouched with respect to postero-anterior cephalometrics and the only limitation is the imagination of the investigators.

VI. CONCLUSIONS

The conclusions which can be drawn from the results of this study are as follows:

1. The identification error for the individual landmarks on the PA cephalogram is specific to each individual landmark. 2. Rotation of the skull by 5^{o} about a vertical axis significantly affects the landmark identification error for two landmarks in the horizontal dimension and five landmarks in the vertical dimension.

3. Rotation of the skull by 5^{o} about the transverse axis significantly affects the landmark identification error for one landmark in the horizontal dimension and six landmarks in the vertical dimension.

4. The identification error for the same landmarks on opposite sides of the skull are not significantly different from one another.

5. There are no significant differences between intra-examiner and inter-examiner identification errors in the horizontal dimension. Significant differences exist between intra-examiner and inter-examiner error for three landmarks in the vertical dimension.

6. There is no difference in identification error between the same landmarks on opposite sides of the skull with four operators.

7. There are differences in the magnitude of deviation from the best horizontal line between pairs of bilateral landmarks.

8. Rotation about the vertical axis by 5^o does not significantly affect the fit of the lines through the bilateral landmarks with the best horizontal li...

9. Rotation about the transverse axis by 5^o does not significantly affect the fit of the lines through the bilateral landmarks with the best horizontal line.

10. There are differences in the magnitude of deviation from the best midline between the various bisectors of bilateral landmarks and midline landmarks.

11. There are differences in the deviation from the best midline between the various selected pairs of upper facial landmarks.

12. Rotation of the head about the transverse axis by 5^o does not significantly affect the fit of the constructed midlines with the best midline.

13. Rotation of the head about the vertical axis 5^o significantly affects the fit of the constructed midlines with the best midline.

14. The landmark which is best suited to establish a horizontal reference plane is the intersection of the superior border of the greater wing of the sphenoid bone with the lateral orbital margin (GWSO).

15. The landmarks which are best suited to establish a vertical reference plane are; the bisector of the line through the intersection of the inferior border of the greater wing of the sphenoid bone and the lateral orbital margin(GWIO), and the midpoint of the nasal septum (NSM).

VII. BIBLIOGRAPHY

1 Broadbent, B H, A new x-ray technique and its application to orthodontia. Angle 1:45-66, 1966.

2 Bergman, R, Practical application of the PA cephalometric headfilm. Orthodontic Review 20-26, March/April 1988.

3 Grummons, D C, Kappeyne, MA, A frontal asymmetry analysis. J Clinical Orthodontics 21(7):448-465, 1987.

4 Brodie, A G, Cephalometric roentgenology: history, techniques, and uses. A J Oral Surg 7:185-198, 1949.

5 Salzman, J A, Limitations of roentgenographic cephalometrics. A J Orthod 50(3):168-188, 1964.

6 Sassouni, V, Diagnosis and treatment planning via roentgenographic cephalometry. A J Orthod 44(6):433-463, 1958.

7 Ricketts, R M, Perspectives on the clinical application of cephalometrics. Angle 51(2):115-150, 1981.

8 Vincent, A, West, V C, Cephalometric landmark identification error. Aust Orthod J 10(2):98-104, 1987.

9 Baumrind, S, Frantz, R, The reliability of head film measurements - 1. landmark identification. A J Orthod 60(2):111-127, 1971.

10 Thurrow, R C, Cephalometric methods in research and private practice. Angle 21:104-116, 1951.

11 Newman, K J, Meredith, H V, Individual Growth in skeletal bigonial diameter during the childhood period from 5 to 11 years of age. A J Anat 157-187, 1956.

12 Adams, J W, Correction of error on Cephalometric roentgenograms. Angle 10(1):3-13, 1940.

13 Bergersen, E O, Enlargement and distortion in cephalometric radiography: compensation tables for linear measurements. Angle 50(3):230-244, 1980.

14 Andrew, F D A, Warren, S L, A study of the distortion in roentgenograms taken at various target-film distances. A J Roent 22:332-338, 1929.

15 Hallett, G E M, Inherent errors in cephalometric films and their reduction. Dent Pract 9(10):163-172, 1959.

16 Wylie, W L, Elasser, W A, Undistorted vertical projections of the head from lateral and postero-anterior roentgenograms. A J Roent 60:414-417, 1948.

17 Vogel, C, Correction of frontal dimensions from head x-rays. Angle 37(1): 1-8, 1967.

18 Franklin, J B, Certain factors of aberration to be considered in clinical roentgenographic cephalometry. A J Orthod 38:351-368, 1952.

19 Halse, A, Hedin, M, May fast screen-film combinations be used for cephalometry. Brit J Orthod 5189-192, 1978.

20 McWilliam, J S, Welander, U, The effect of image quality on the identification of cephalometric landmarks. Angle 48(1): 49-56, 1981.

21 Hurlburt, C E, Faster screen/film combinations for cephalometric radiography. Oral Surg 52(6):661-665, 1981.

22 Kaugars, G, Fatouros, P, Clinical comparison of conventional and rare earth screen-film systems for cephalometric radiographs. Oral Surg 53(3):322-325, 1982.

23 McNichol, A, Stirrups, D R, Assessment of screen/film combinations for cephalometric radiography. Brit J Orthod 12:117-121, 1985.

24 Stirrups, D R, A comparison of the accuracy of cephalometric landmark location between two screen/film combinations. Angle 59(3):211-216, 1988.

25 Stathopoulos, V, Poulton, D R, Evaluation of rare earth intensifying screens in cephalometric radiography. Angle 60(1):9-16, 1989.

26 Margolis, H I, Standardized x-ray cephalographics. A J Orthod 26(8):725-740, 1940.

27 Broadbent, B H Sr, Broadbent, B H Jr, Golden, W H, Bolton standards of dentofacial developmental growth, C V Mosby Co., St. Louis, 1975.

28 Gravely, J F, Benzies, P M, The clinical significance of tracing error in cephalometry. Brit J Orthod 1:95-101, 1974.

29 ElMangoury, E H, Shaheen, S I, Mostafa, Y A, Landmark identification in computerized postero-anterior cephalometrics. A J Orthod 91:57-61, 1987.

30 Ghafari, J, Engel, F E, Lasler, L L, Cephalometric superimposition on the cranial base: a review and comparison of four methods. A J Orthod 91:403-413, 1987.

31 Bambha,J K, Longitudinal cephalometric roentgenographic study of the face and cranium in relation to body height. J A Dent Ass 63:776-799, 1961.

32 Ford, E R H, Growth of the human cranial base. A J Orthod 44:498-506, 1958.

33 Melsen, B, The cranial base. Acta Odont Scand 32(supp 62), 1974.

34 Van Aken, J, Geometric errors in lateral skull x-ray projections. Neder T Tand 70:18-30, 1963.

35 Krogstad, O, Kvam, E, Geometric errors in measurements on x-ray films. Acta Odont Scand 29:187-196, 1971.

36 Rossman, K, Wiley, B E, The central problem in the study of radiographic image quality. Radiology 96:113-118, 1970.

37 Ishiguro, K, Krogman, W, Mazaheri, M, Harding, R, A longitudinal study of morphological craniofacial patterns via PA x-ray headfilm in cleft patients from birth to six years of age. Cleft Palate 13:104-126, 1974.

38 Savara, B S, Tracy, W E, Miller, P A, analysis of errors in cephalometric measurements of three dimensional distances on the human mandible. Archs Oral Biol 11:209-217, 1966.

39 Bergin, R, Hallenberg, J, Malmgren, O, Computerized cephalometrics. Acta Odont Scand 36:349-357, 1978.

40 Cohen, A M, Uncertainty in cephalometrics. Brit J Orthod 11:44-48, 1984.

41 Sandler, P J, Reproducibility of cephalometric measurements. Brit J Orthod 15(2):105-110, 1988.

42 Sekiguchi, T, Savara, B S, Variability of cephalometric landmarks used for growth studies. A J Orthod 61(6):603-618, 1972.

43 Mattila, K, Haataja, J, On the accuracy of determining certain reference points in cephalometric radiography. Odont T 76:249-259, 1976.

44 Midtgard, J, Bjork, G, Linder-Aronson, S, Reproducibility of cephalometric landmarks and errors of measurements of cephalometric distances. Angle 44(1):55-61, 1974.

45 Broch, J, Slagsvold, O, Rosler, M, Error in landmark identification in lateral radiographic headplates. Europ J Orthod 3:9-12, 1981.

46 Stabrun, A E, Danielsen, K, Precision in cephalometric landmark identification. Europ J Orthod 4:185-196, 1982.

47 Ahlqvist, J, Eliasson, S, Welander, U, The effect of projection errors on cephalometric length measurements. Europ J Orthod 8:141-148, 1986.

48 Ahlqvist, J, Eliasson, S, Welander, U, The effect of projection errors on angular measurements in cephalometry. A J Orthod 10:353-361, 1988.

49 Eliasson, S, Welander, U, Ahlqvist, J, The cephalometric projection: part I general considerations. Dentomaxillofac Radiol 11:117-122, 1982.

50 Ahlqvist, J, Eliasson, S, Welander, U, The cephalometric projection: part II principles of image distortion in cephalometry. Dentomaxillofac Radiol 12:101-108, 1983.

51 Richardson, A, A comparison of traditional and computerized methods of cephalometric analysis. Europ J Orthod 3:15-20, 1981.

52 Richardson, A, An investigation into the reproducibility of some points, planes, and lines used in cephalometric analysis. A J Orthod 52(9):637-651, 1966.

53 Kvam, E, Krogstad, O, Variability in tracings of lateral headplates for diagnostic orthodontic purposes. Acta Odont Scand 27:359-369, 1969.

54 Woo, T L, On the asymmetry of the human skull. Biometrika 22:324-352, 1931.

55 Letzer, G M, Kronman, J H, A postero-anterior cephalometric evaluation of craniofacial asymmetry. Angle 37(3):205-211, 1967.

56 Shah, S M, Joshi, M R, An assessment of asymmetry in the normal facial complex. Angle 48(2):141-148, 1978.

57 Jain, K K, Jain, B K, Asymmetry in the skull. Acta Anat 104:349-352, 1979.

58 Hewett, A B, A radiographic study of facial asymmetry. Brit J Orthod 2·37-40, 1975

59 Vig, P S, Hewett, A B, Asymmetry of the human facial skeleton. Angle 45(2):125-129, 1975.

60 Farkas, L G, Cheung, G, Facial asymmetry in healthy north American Caucasians. Angle 51(1):70-77, 1981.

61 Greene, D, Asymmetry of the head and face in infants and children. A J Dis Child 41:1317-1326, 1931.

62 Mulick, J F, An investigation of craniofacial asymmetry using the serial twin study method. A J Orthod 51(2):112-129, 1965.

63 Thompson, J R, Asymmetry of the face. J A D A 30:1859-1871, 1943.

64 Cheney, E A, Dentofacial asymmetries and their clinical significance. A J Orthod 47(11):811-829, 1961.

65 Harvold, E, Cleft lip and palate, morphologic studies of the facial skeleton. A J Orthod 40:493-506, 1954.

66 Molsted, K, Dahl, E, asymmetry of the maxilla in children with complete unilateral cleft lip and palate. Cleft Palate 27(2):184-192, 1964.

67 Broadway, E S, Two unusual cases of facial asymmetry. Dent Practit 15(4):145-148, 1964.

68 Kaban, L B, Milliken, J B, Murray, J E, Three-Dimensional approach to analysis and treatment of hemifacial microsomia. Cleft Palate 18(2):90-99, 1981.

69 Arvystas, M G, Antonellis, B S, Justin, A F, Progressive facial asymmetry as a result of early closure of the left coronal suture. A J Orthod 87:240-246, 1985.

70 Bjork, A, Bjork, L, Artificial deformation and cranio-facial asymmetry in ancient Peruvians. J Dent Res 13(3):353-362, 1964.

71 Scott, J H, Growth in width of the facial sutures A J Orthod 43:336-371, 1957.

72 Scott, J H, The analysis of facial growth II The horizontal and vertical dimensions. A J Orthod 44:585-589, 1958.

73 Harvold, E P, Trugue, M, Viloria,J O, Establishing the median plane in Posteroanterior Cephalometrics. In Roentgenographic Cephalometrics Editor J A Salzman 2nd Ed, J B Lipincott Co., Philadelphia PA, 1959.

74 Svanholt, P, Solow, B, Assessment of midline discrepancies on the postero-anterior cephalometric radiograph. Trans Europ Orthod Soc 261-277, 1977.

75 Chebib, F S, Chamma, A M, Indices of craniofacial asymmetry. Angle 51(3):214-226, 1981.

76 Butow, K W, Van der Walt, P J, The "Stellenbosch"-triangle analysis of the postero-anterior and basilar cephalographs. J Dent Ass South Africa 36:461-467, 1981.

77 Butow, K W, Van der Walt, P J, The use of triangle analysis for cephalometric analysis in three dimensions. J Maxillofac Surg 12:62-70, 1984.

78 Stabrun, A E, Mandibular morphology and position in juvenile rheumatoid arthritis. A study on postero-anterior radiographs. Europ J Orthod 7:288-298, 1985.

79 Winer, B J, Statistical Principles in Experimental Design. McGraw-Hill Book Co. New York, N Y, 1962.

80 Milliken, G A, Johnson, D E, Analysis of Messy Data. Van Nostrand Reinhold Co. New York, N Y, 1984.

81 Yen, P K J, Identification of landmarks in cephalometric radiographs. Angle 30(1):35-41, 1960.

82 Potter, G D, Gold, P R, Radiographic analysis of the skull. Dent Radiol and Photog 49(2):27-41, 1976.

83 Sassouni, V., Position of the maxillary first permanent molar in the cephalofacial complex. A J Orthod 43(7):477-510, 1957.

84 Baumrind, S, Miller, D M, Computer-aided head film analysis: the University of California San Francisco method. A J Orthod 78(1):41-65, 1980.

85 Houston, W J B, Maher, R E, McElroy, D, Sherriff, M, Sources of error in measurements from cephalometric radiographs. Europ J Orthod 8:149-151, 1986.

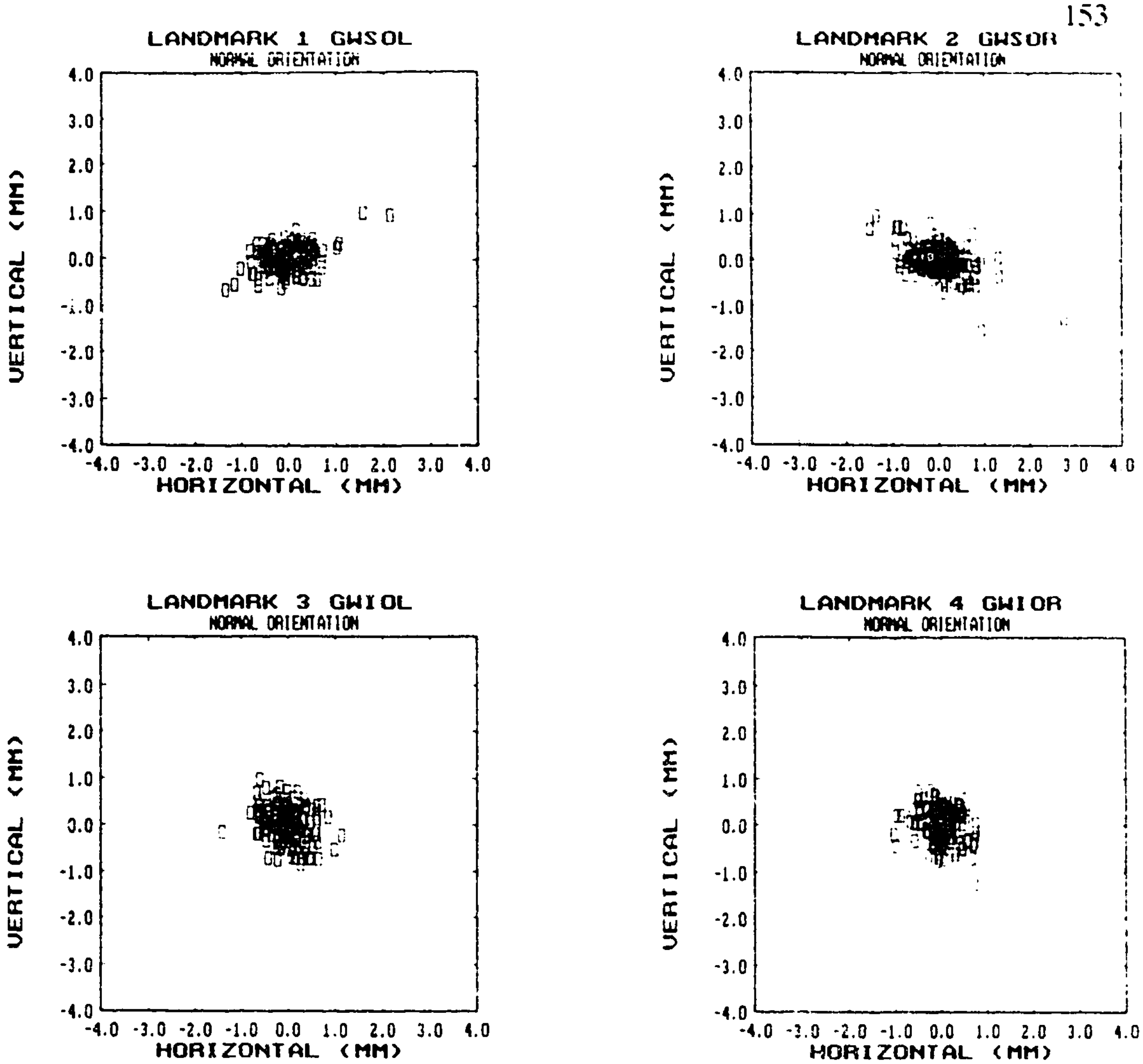
86 Houston, W J B, The analysis of errors in orthodontic measurements. A J Orthod 83(5):382-390, 1983.

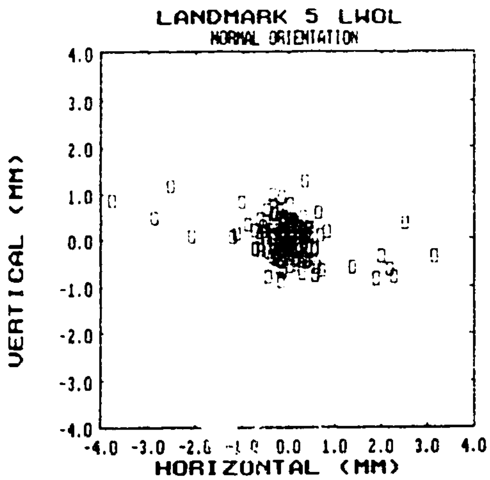
87 McWilliam, J S, Orientation of orthogonal coordinate systems used for registration of cephalometric landmarks. Scand J Dent Res 90:145-150, 1982.

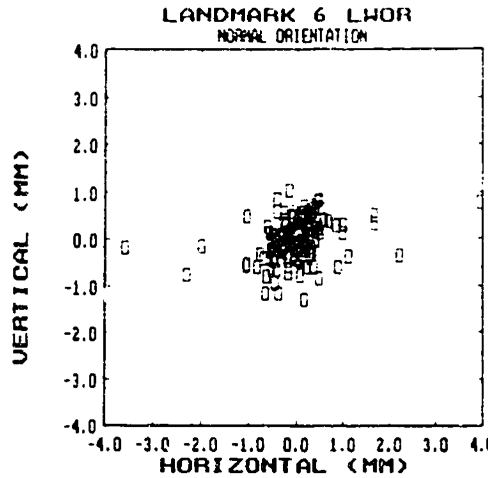
88 Cohen, A M, Ip, H H S, Linney, A D, A preliminary study of computer recognition and identification of skeletal landmarks as a new method of cephalometric analysis. Brit J Orthod 11:143-154, 1984.

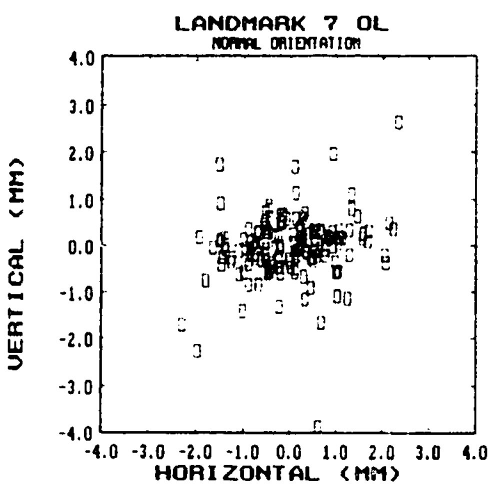
89 Oka, S W, Trussel, H J, Digital enhancement of cephalograms. Angle 48(1):80-84, 1978.

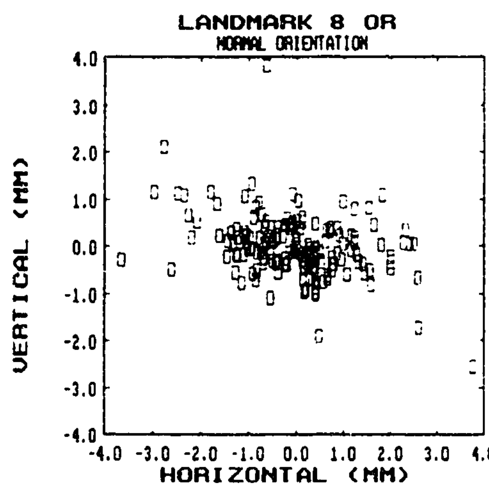
VIII. APPENDIX 1 - Scattergraphs intra-examiner

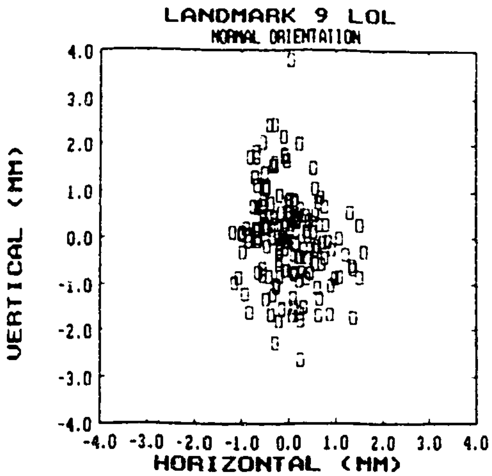

LANDMARK 1 GWSOL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 2 GWSOR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 3 GWIOL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 4 GWIOR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

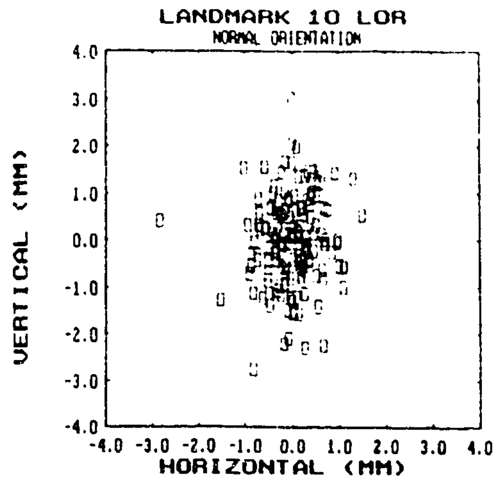

LANDMARK 5 LWOL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

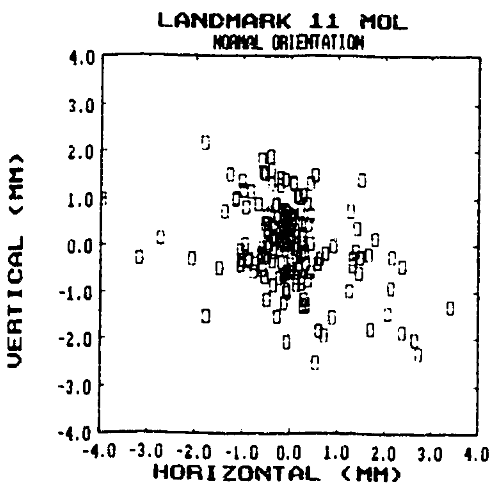

LANDMARK 6 LWOR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

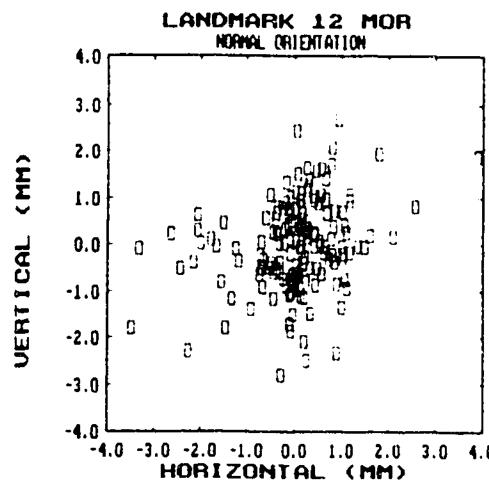

LANDMARK 7 OL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

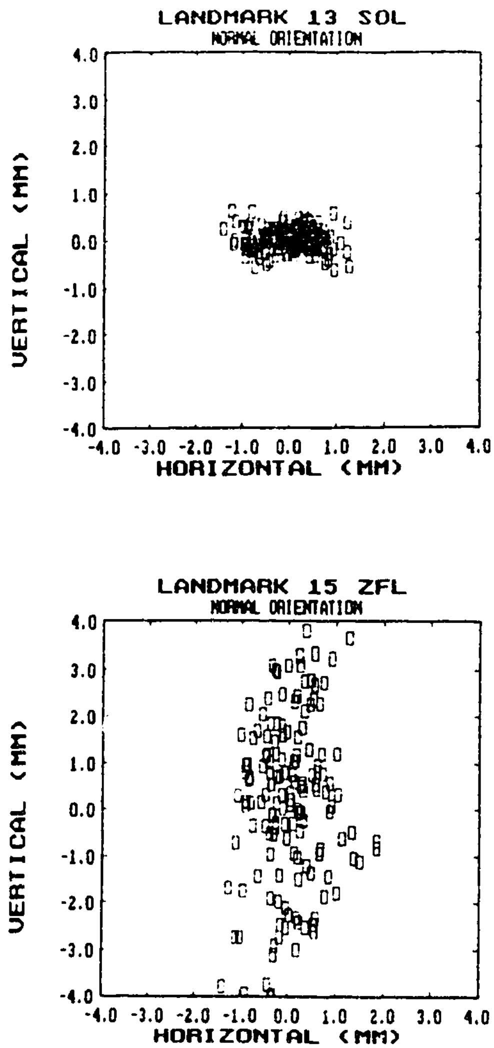

LANDMARK 8 OR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

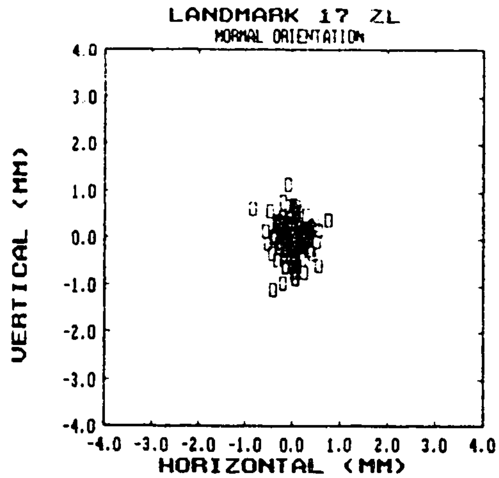

LANDMARK 9 LOL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

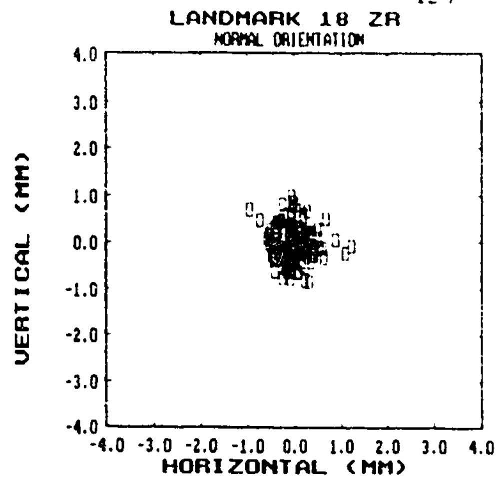

LANDMARK 10 LOR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

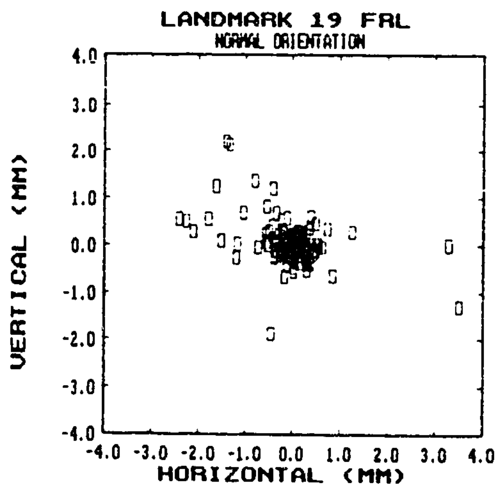

LANDMARK 11 MOL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

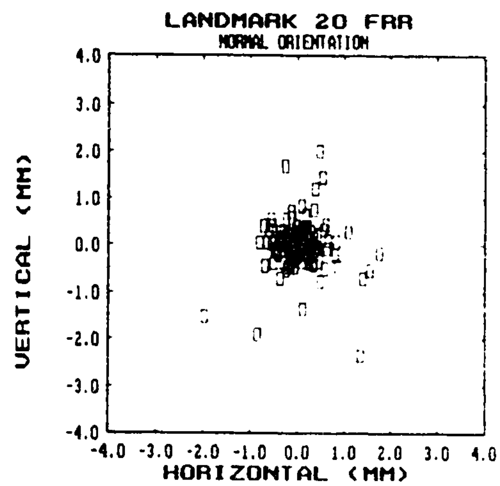

LANDMARK 12 MOR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

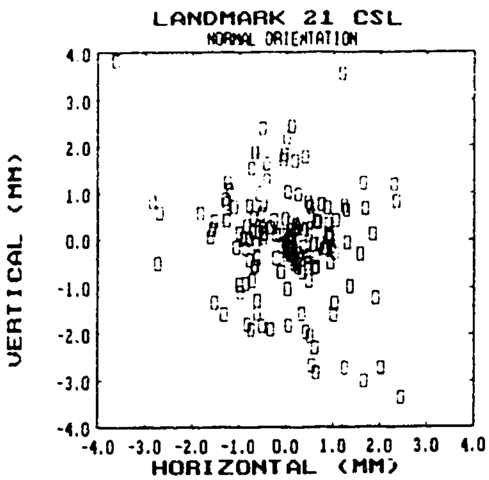

LANDMARK 13 SOL
NORMAL ORIENTATION
LANDMARK 14 SOR
NORMAL ORIENTATION
LANDMARK 15 ZFL
NORMAL ORIENTATION
LANDMARK 16 ZFR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

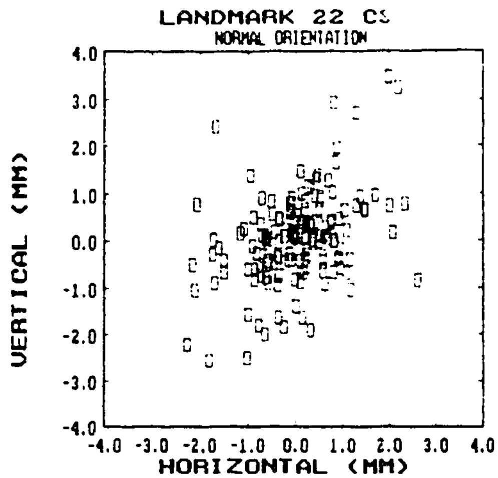

LANDMARK 17 ZL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

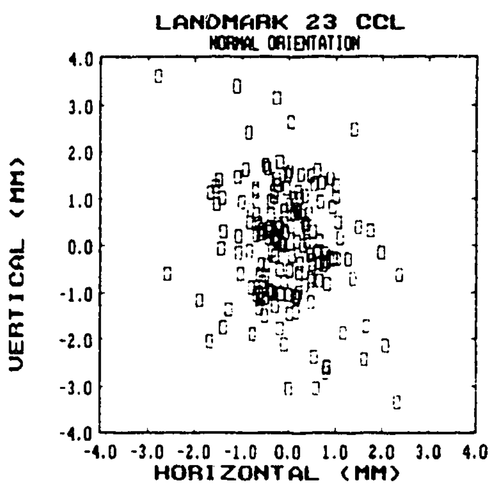

LANDMARK 18 ZR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

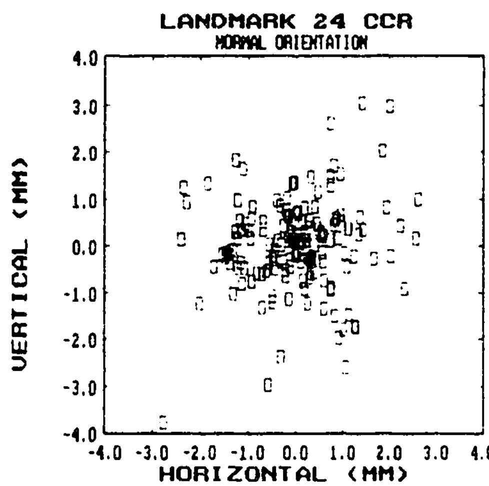

LANDMARK 19 FRL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

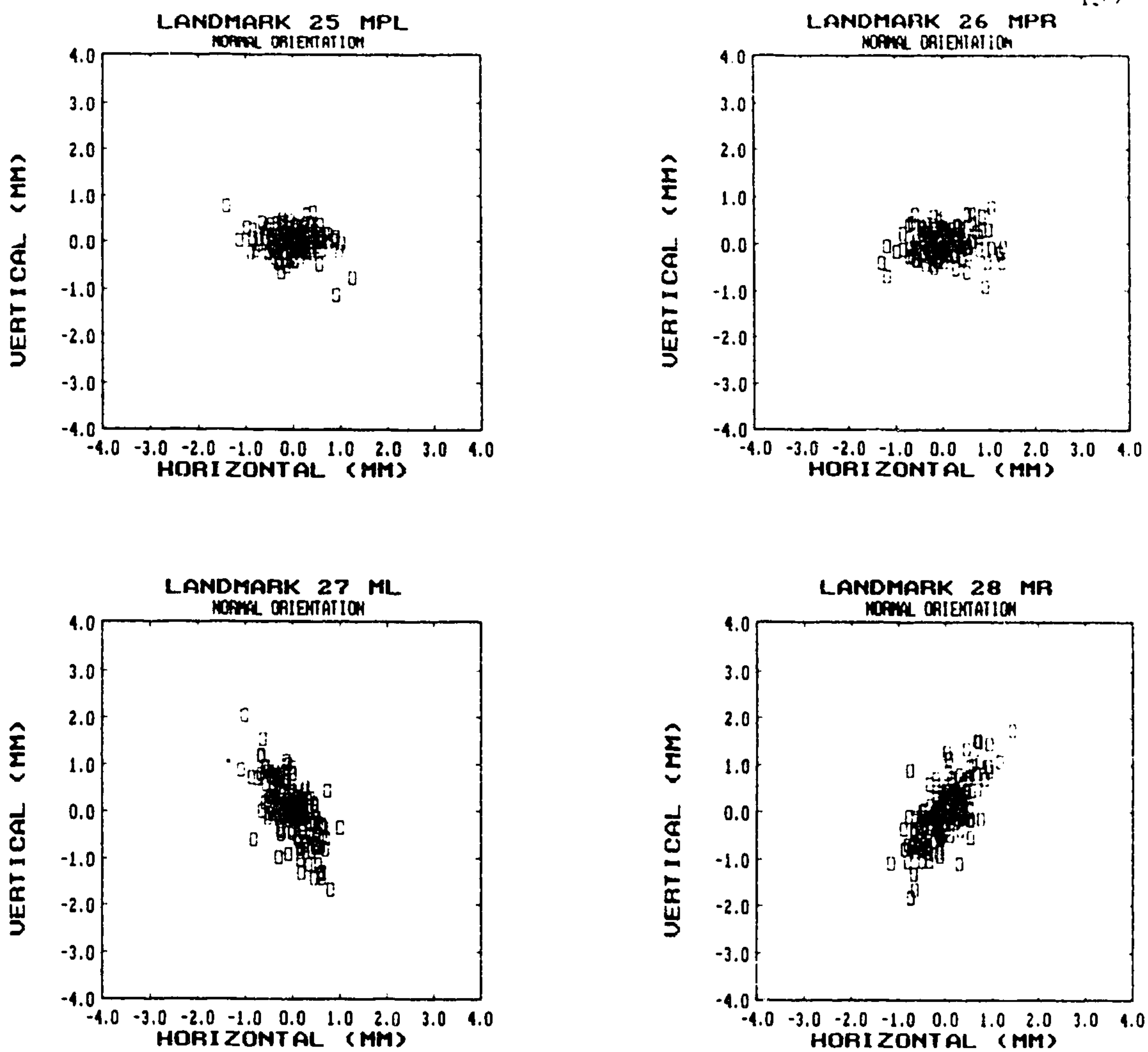

LANDMARK 20 FRR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

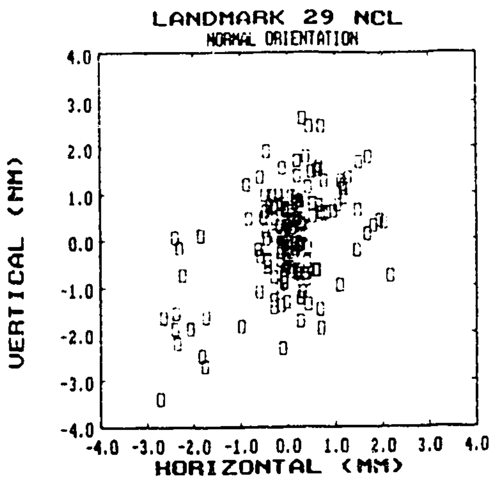

LANDMARK 21 CSL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

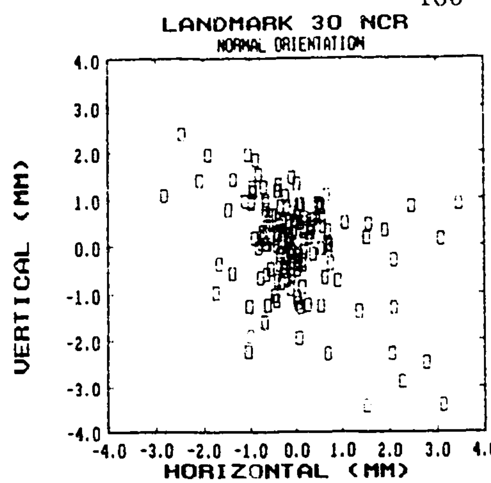

LANDMARK 22 C
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

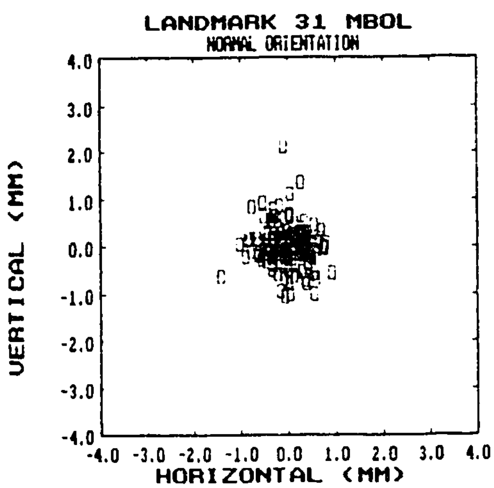

LANDMARK 23 CCL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

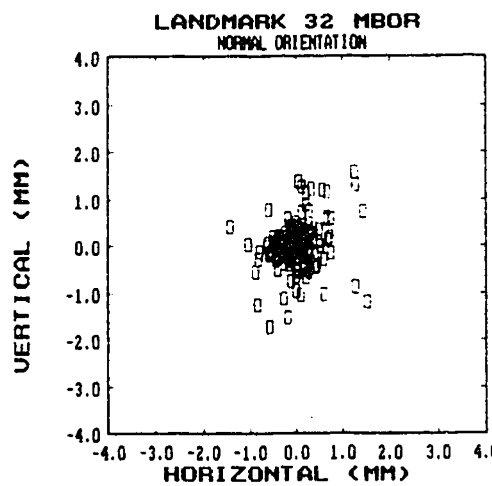

LANDMARK 24 CCR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

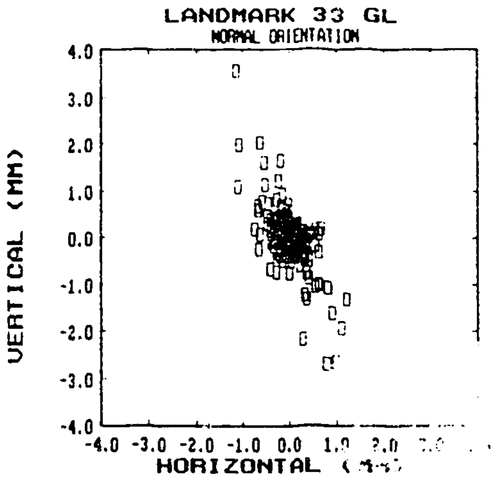

LANDMARK 25 MPL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0
LANDMARK 26 MPR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 27 ML
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 28 MR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

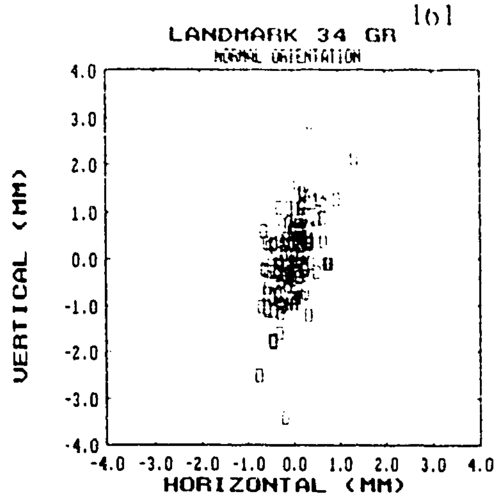

LANDMARK 29 NCL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

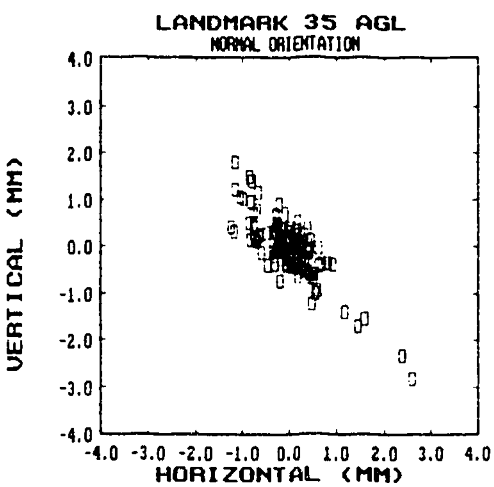

LANDMARK 30 NCR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

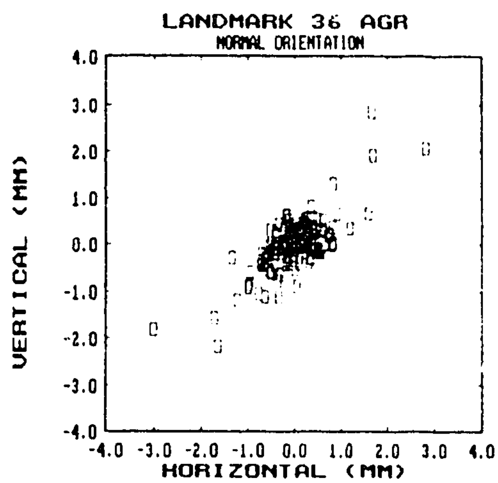

LANDMARK 31 MBOL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

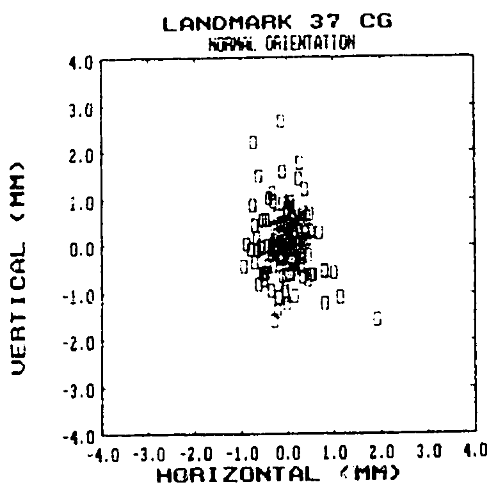

LANDMARK 32 MBOR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

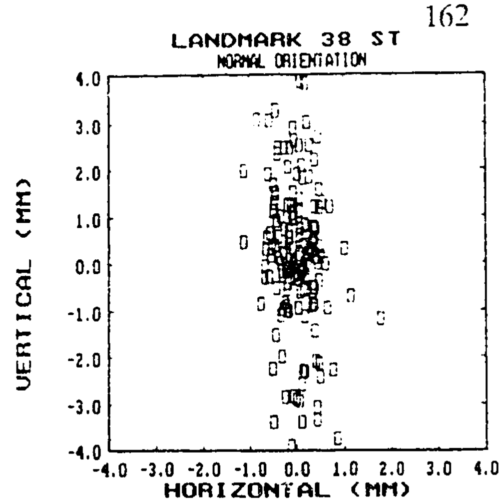

LANDMARK 33 GL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

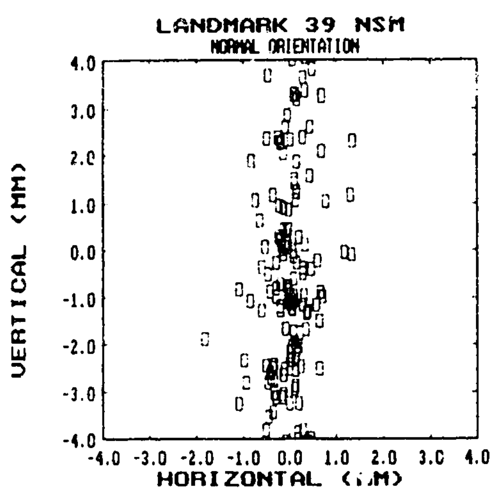

LANDMARK 34 GR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

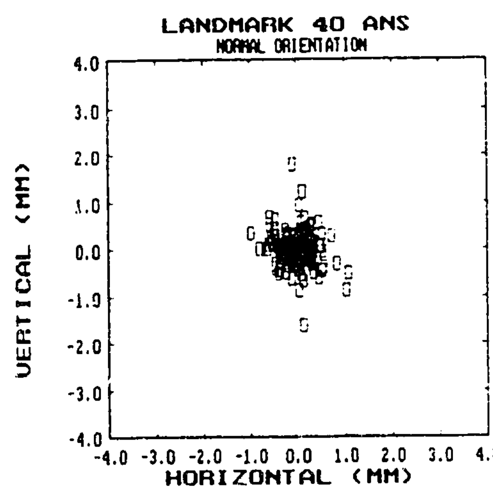

LANDMARK 35 AGL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

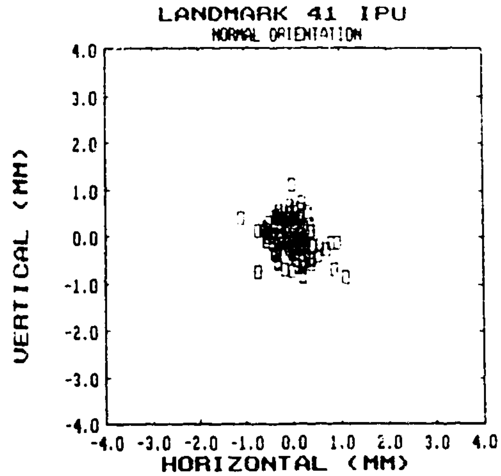

LANDMARK 36 AGR
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)

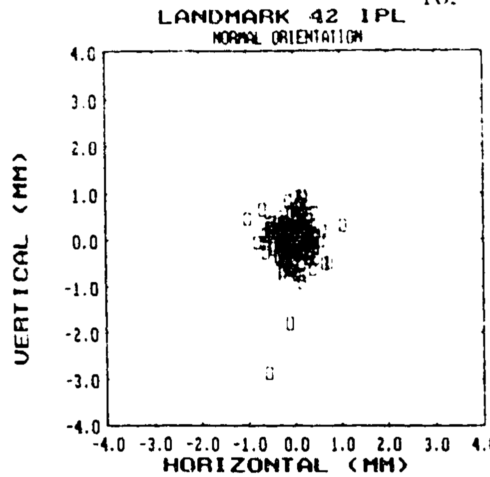

LANDMARK 37 CG
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

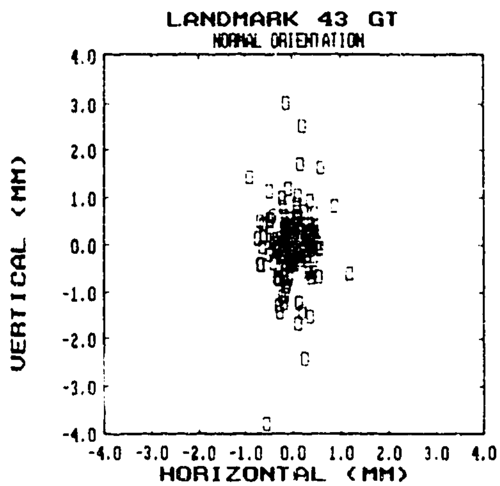

LANDMARK 38 ST
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

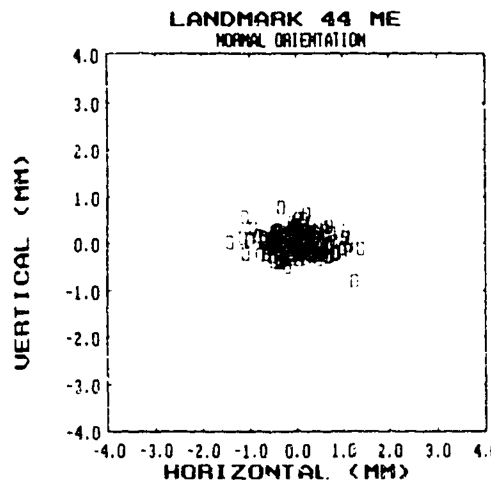

LANDMARK 39 NSM
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

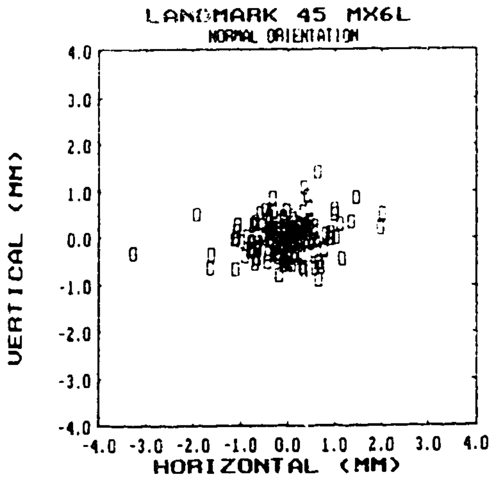

LANDMARK 40 ANS
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

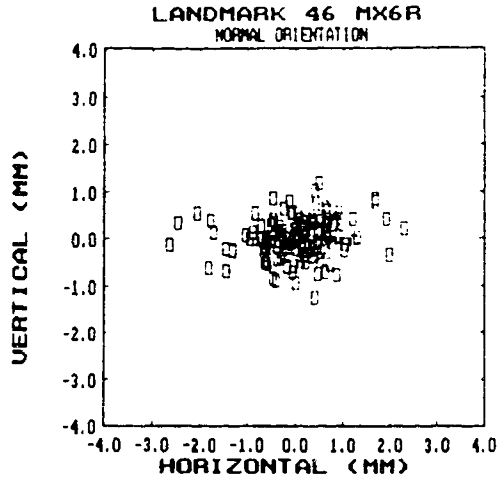

LANDMARK 41 IPU
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

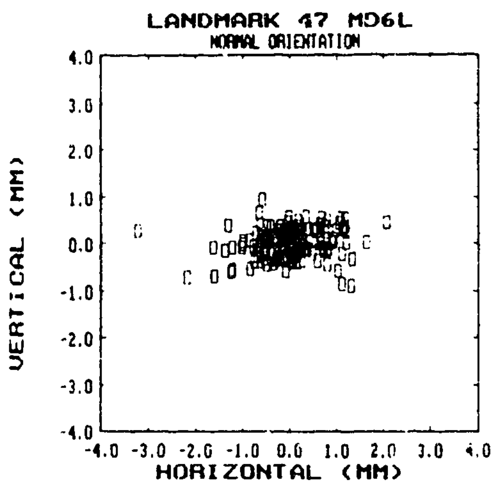

LANDMARK 42 IPL
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

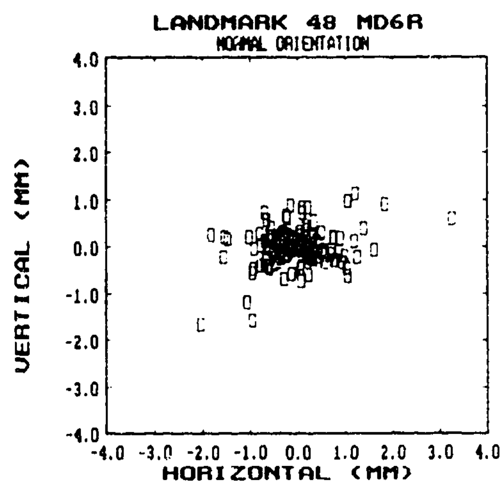

LANDMARK 43 GT
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

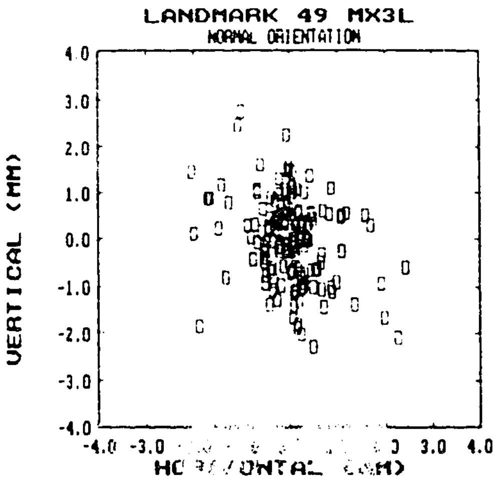

LANDMARK 44 ME
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

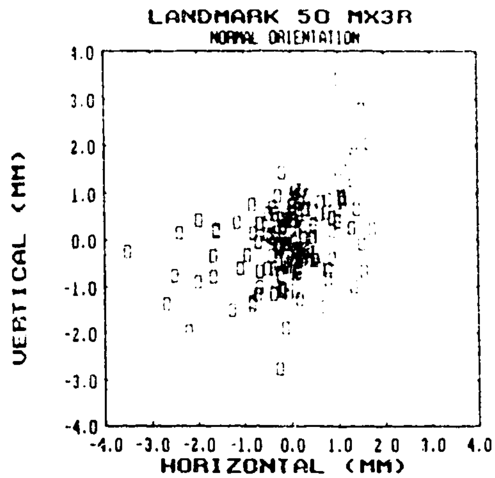

LANDMARK 45 MX6L
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

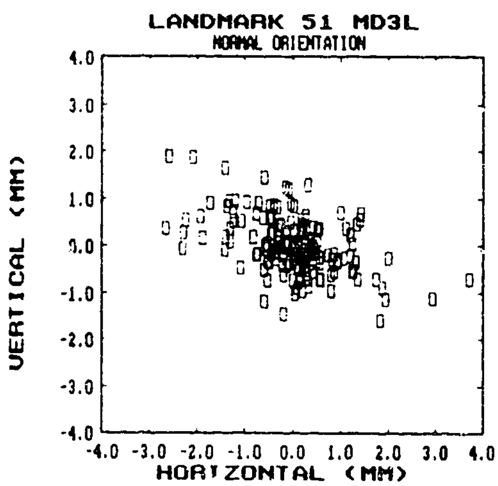

LANDMARK 46 MX6R
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

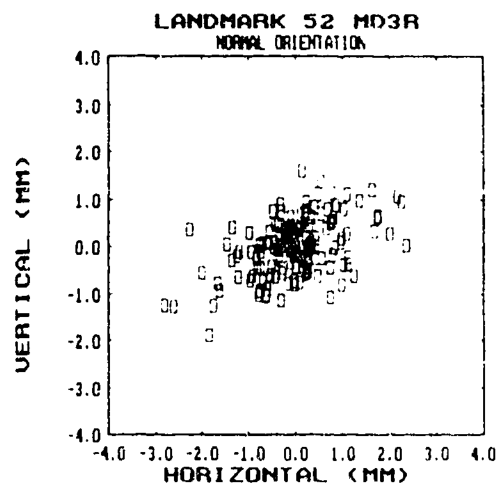

LANDMARK 47 MD6L
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0


LANDMARK 48 MD6R
NORMAL ORIENTATION
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

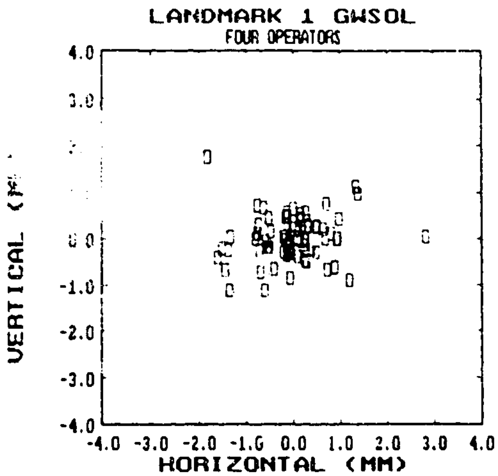

LANDMARK 49 MX3L
NORMAL ORIENTATION
VERTICAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0
3.0 4.0
HORIZONTAL (MM)

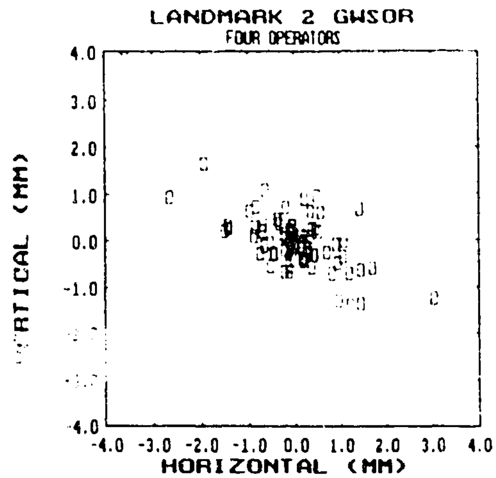

LANDMARK 50 MX3R
NORMAL ORIENTATION
VERTICAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0
HORIZONTAL (MM)

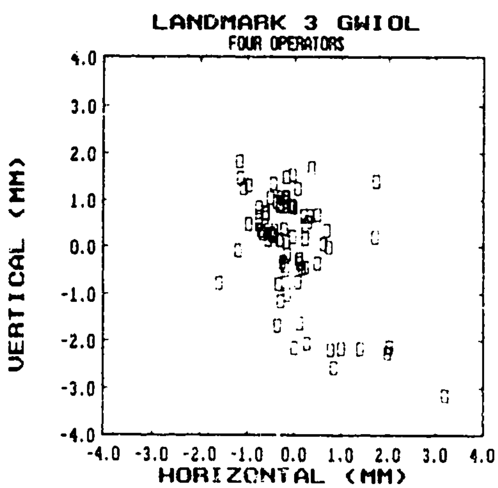

LANDMARK 51 MD3L
NORMAL ORIENTATION
VERTICAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0
HORIZONTAL (MM)

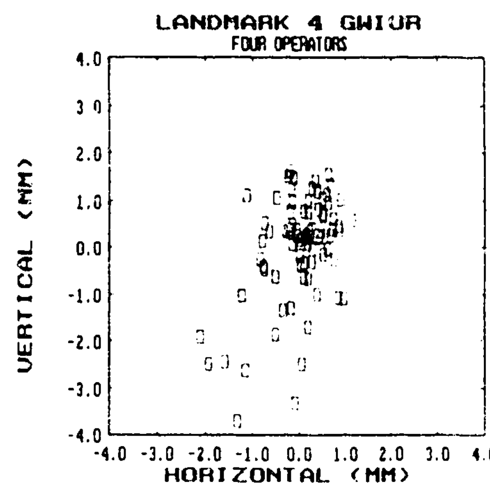

LANDMARK 52 MD3R
NORMAL ORIENTATION
VERTICAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0
HORIZONTAL (MM)

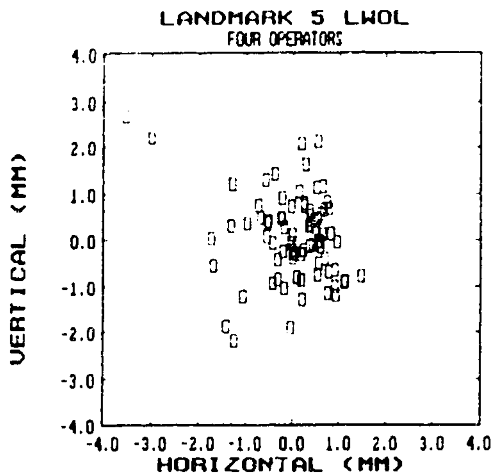
IX. APPENDIX 2 - Scattergraphs inter-examiner

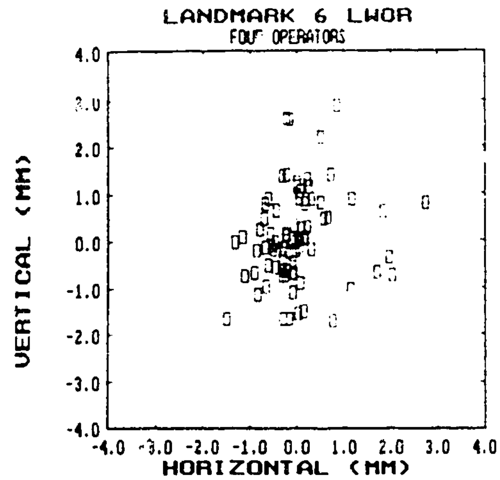

LANDMARK 1 GWSOL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

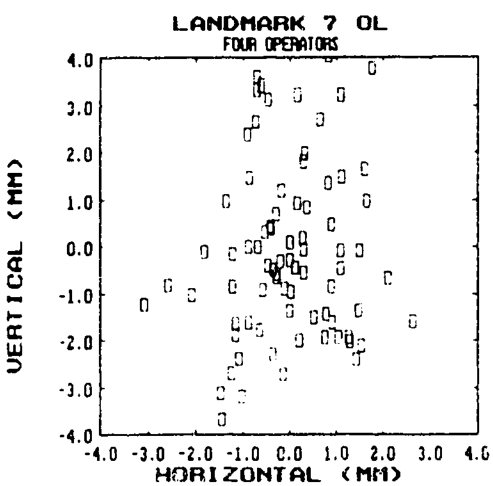

LANDMARK 2 GWSOR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

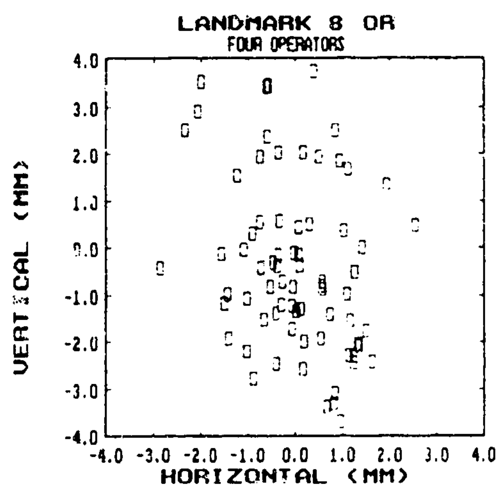

LANDMARK 3 GWIOL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

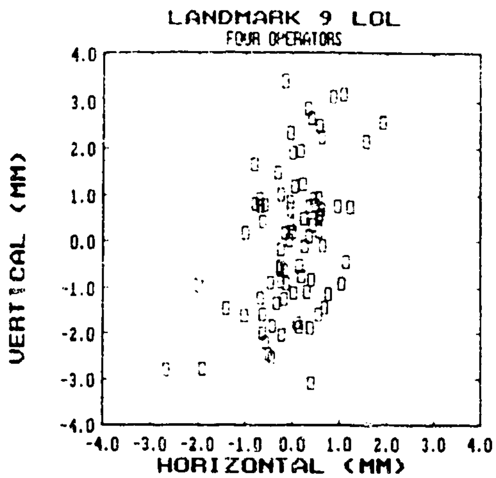

LANDMARK 4 GWIOR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

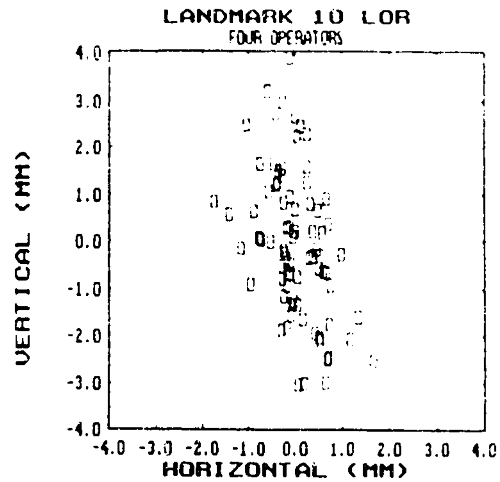

LANDMARK 5 LWOL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

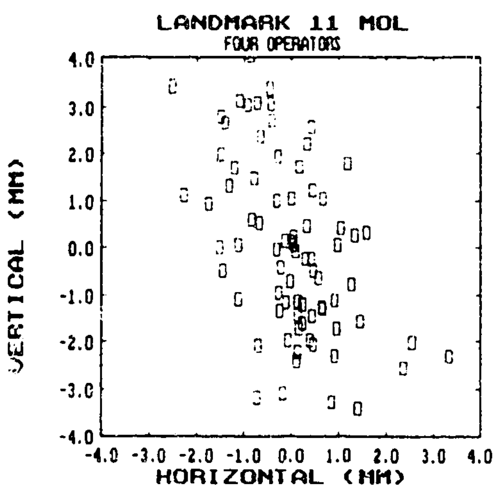

LANDMARK 6 LWOR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

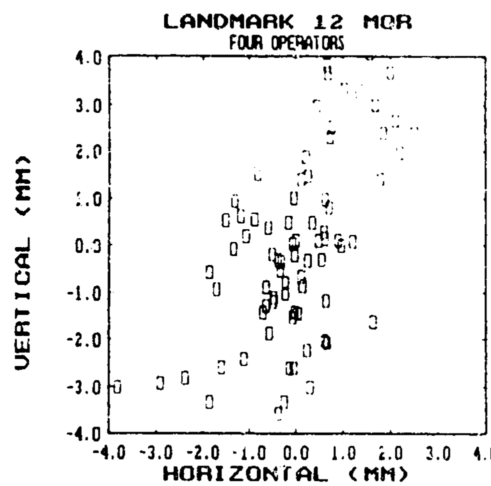

LANDMARK 7 OL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

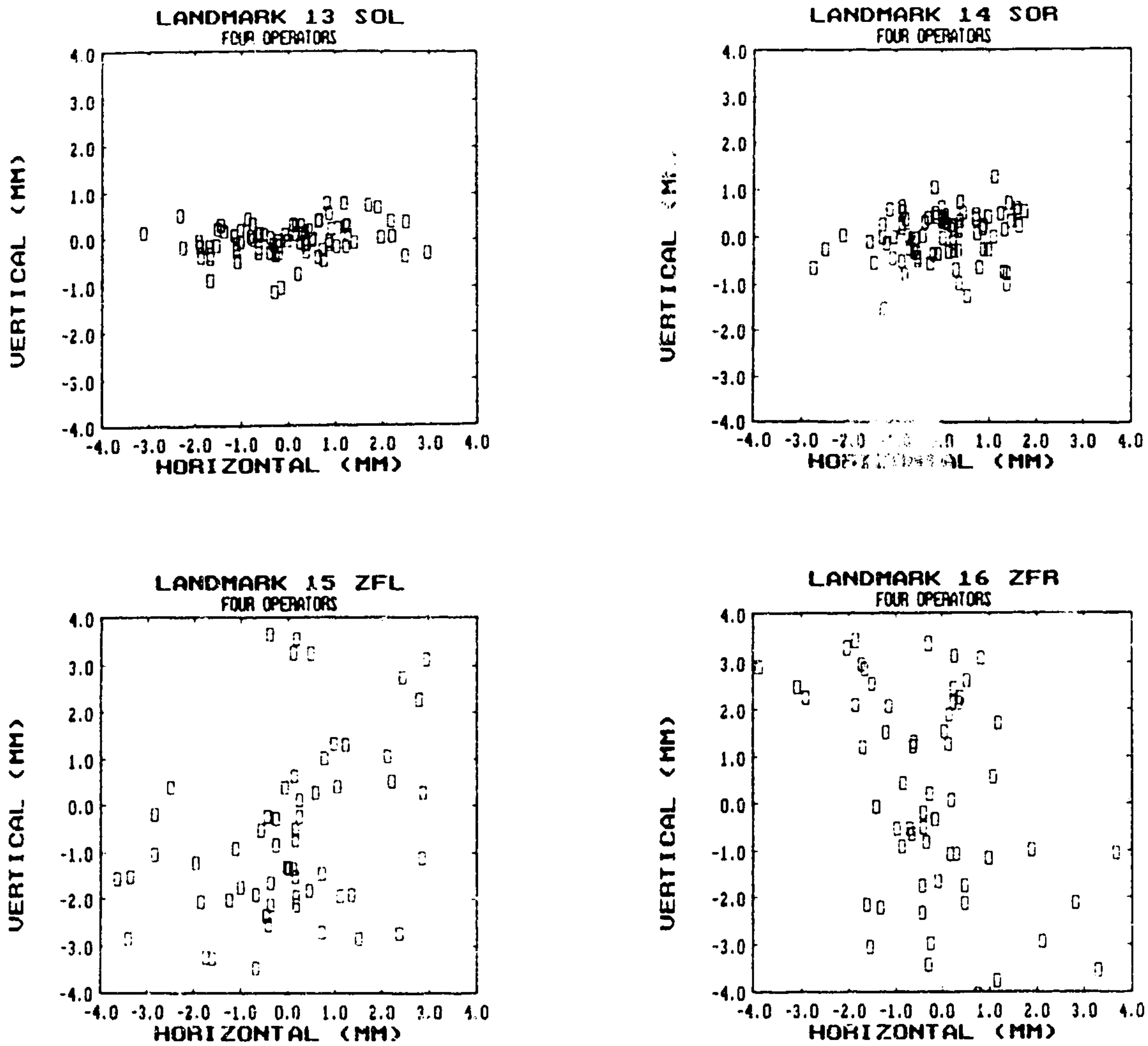

LANDMARK 8 OR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

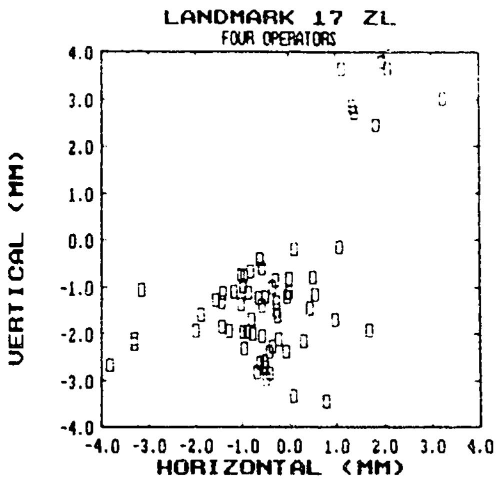

LANDMARK 9 LOL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

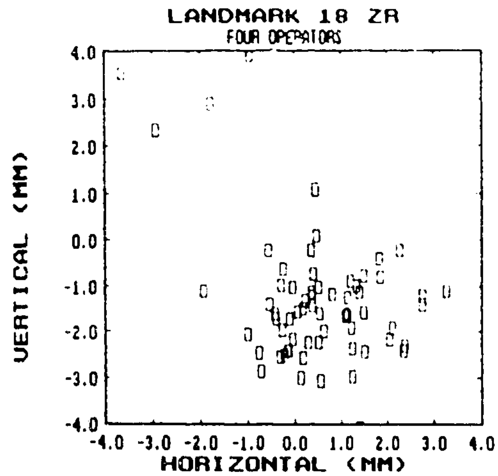

LANDMARK 10 LOR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

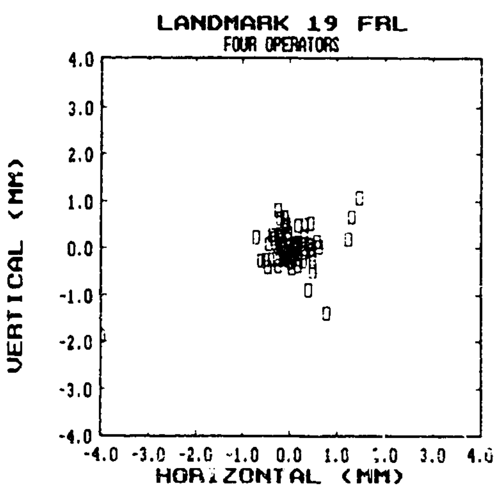

LANDMARK 11 MOL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

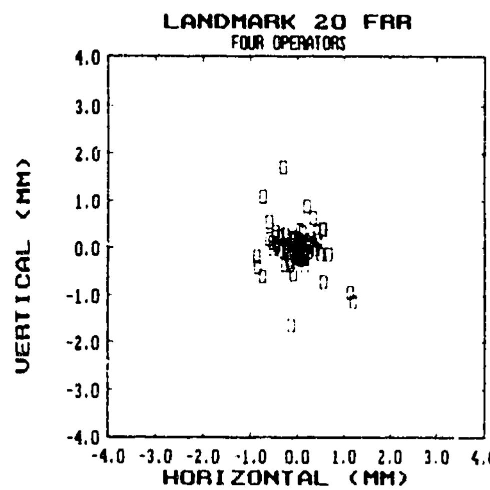

LANDMARK 12 MOR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

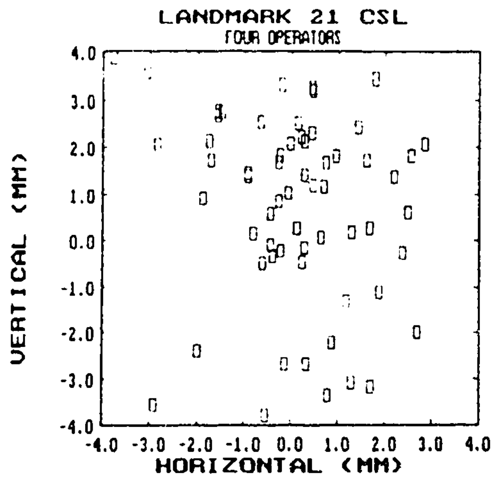

LANDMARK 13 SOL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 14 SOR
FOUR OPERATORS
LANDMARK 15 ZFL
FOUR OPERATORS
LANDMARK 16 ZFR
FOUR OPERATORS

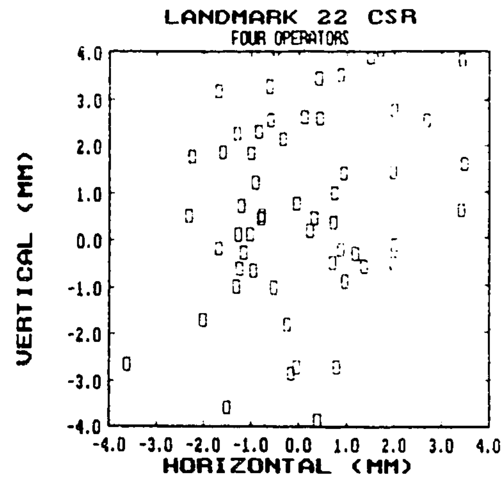

LANDMARK 17 ZL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

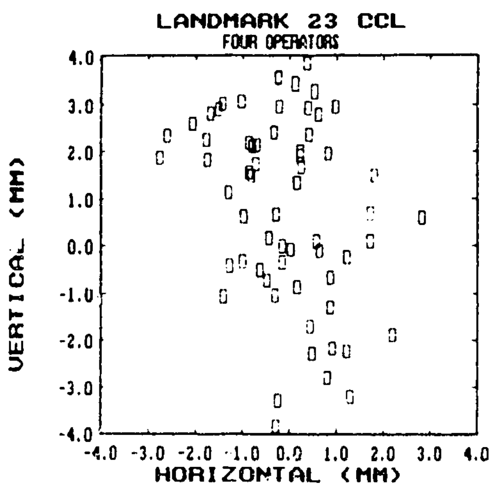

LANDMARK 18 ZR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

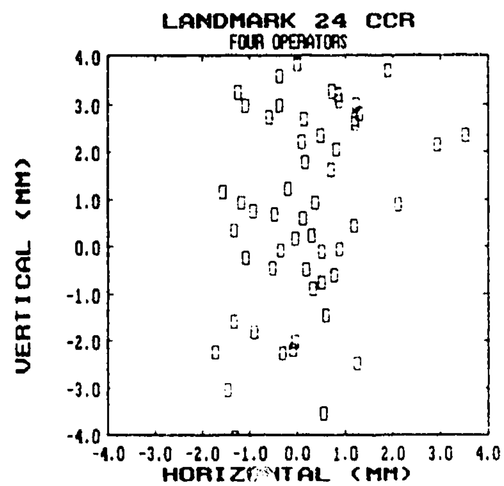

LANDMARK 19 FRL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

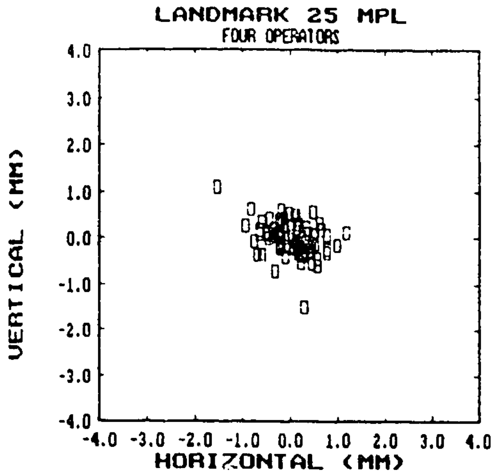

LANDMARK 20 FRR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

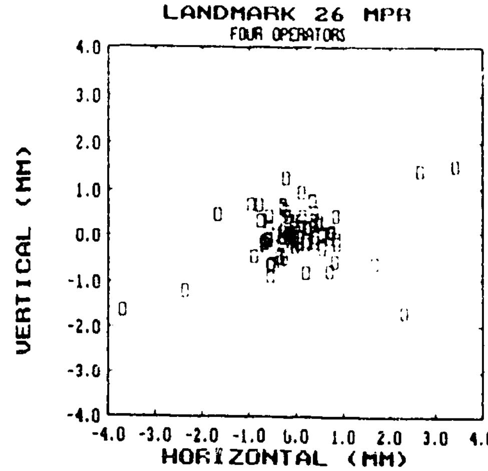

LANDMARK 21 CSL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

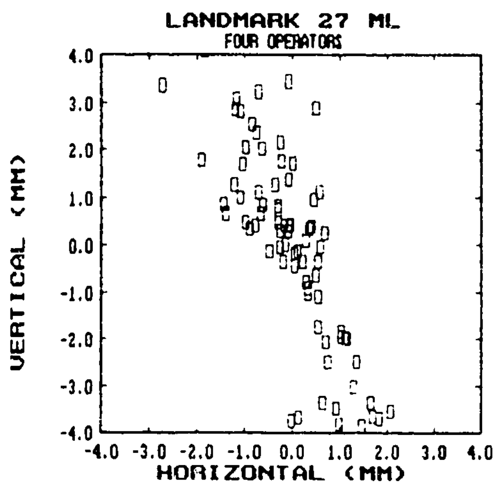

LANDMARK 22 CSR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

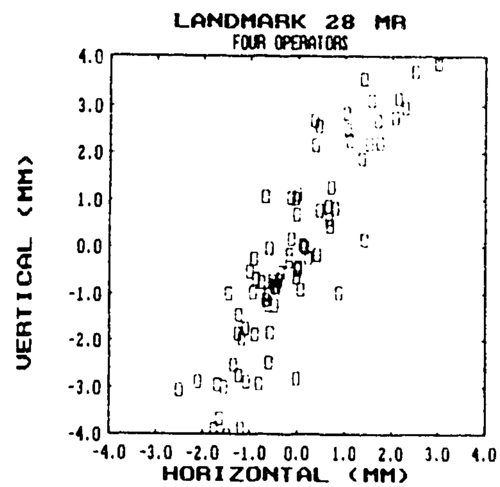

LANDMARK 23 CCL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

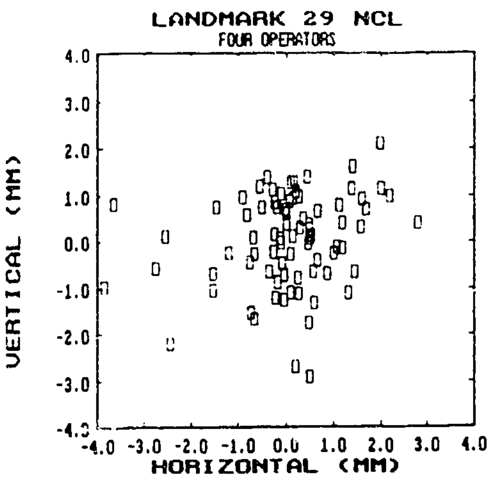

LANDMARK 24 CCR
FOUR OPERATORS
VERTICAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

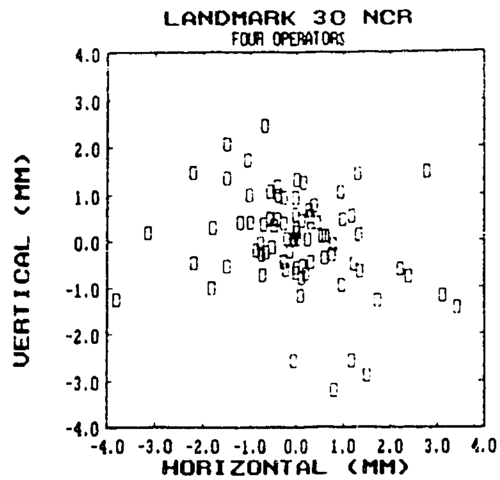

LANDMARK 25 MPL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

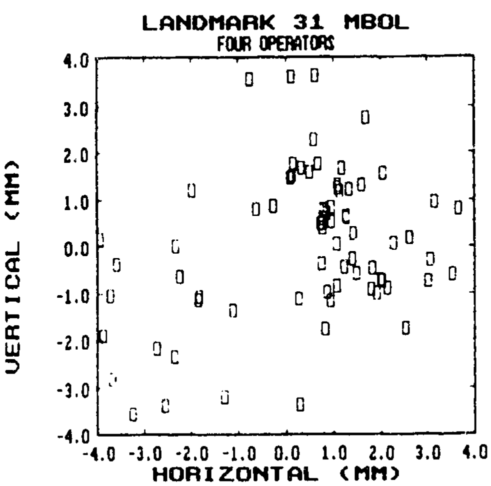

LANDMARK 26 MPR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

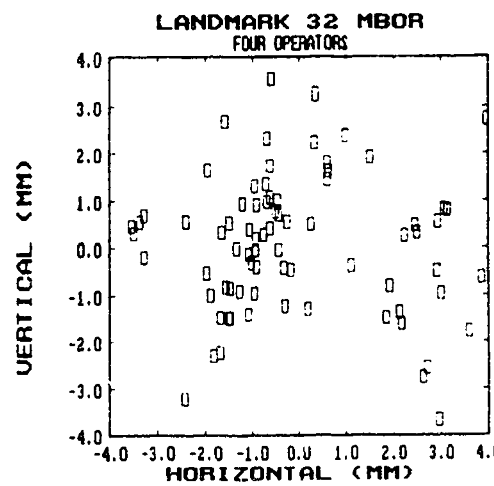

LANDMARK 27 ML
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

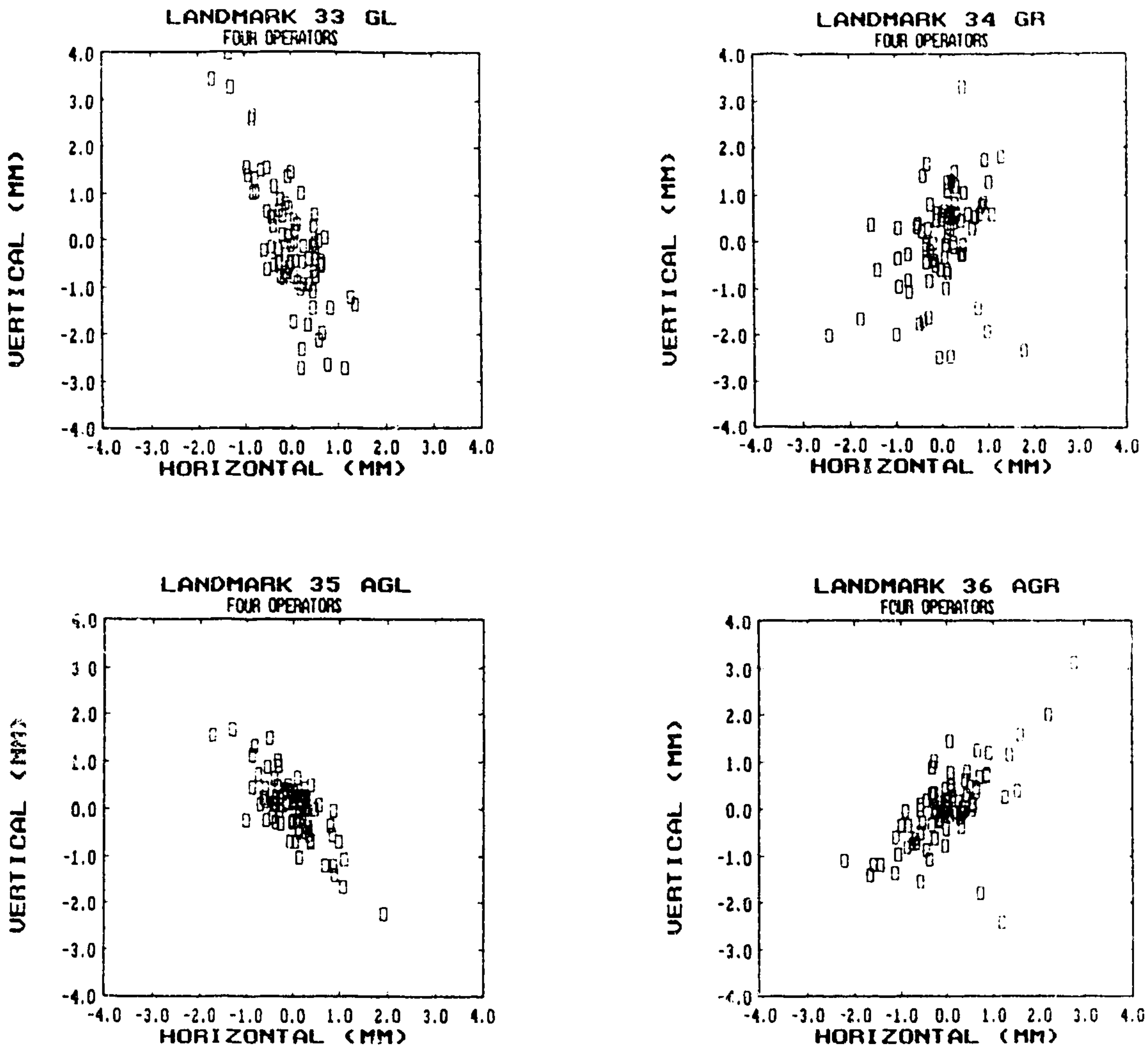

LANDMARK 28 MR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0

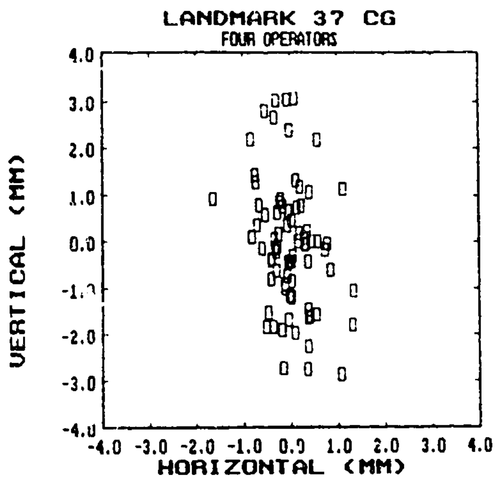

LANDMARK 29 NCL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

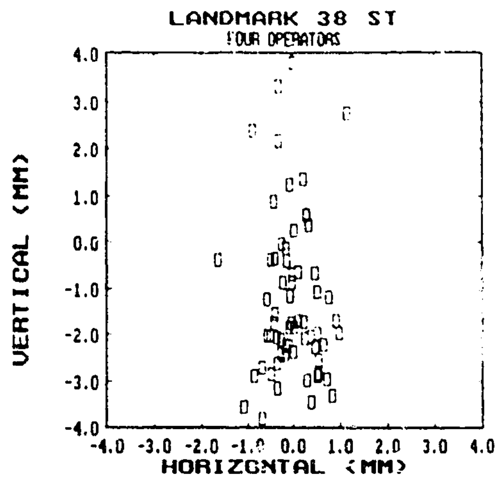

LANDMARK 30 NCR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

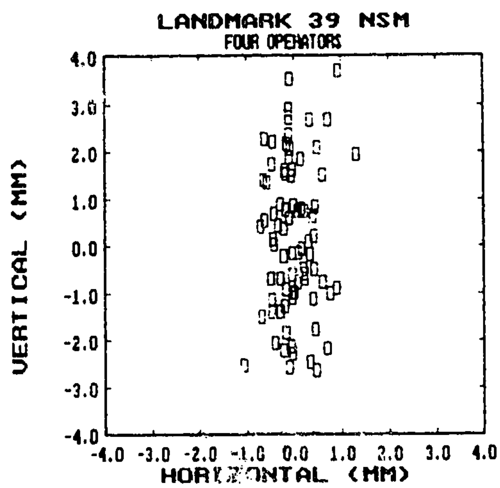

LANDMARK 31 MBOL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

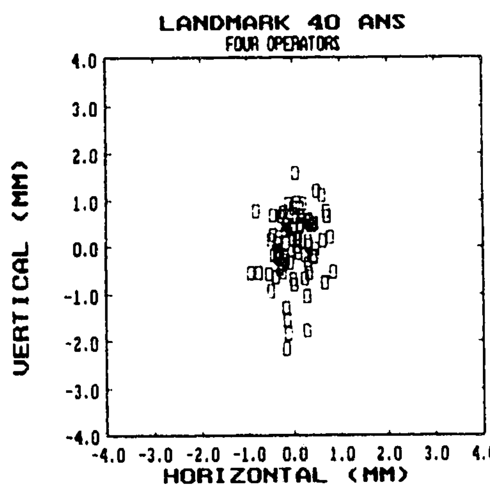

LANDMARK 32 MBOR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

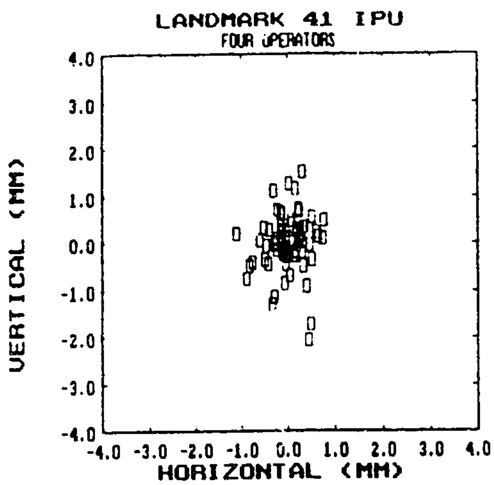

LANDMARK 33 GL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 34 GR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 35 AGL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
LANDMARK 36 AGR
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

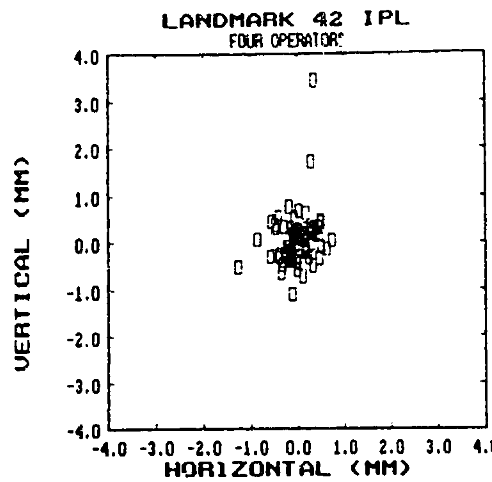

LANDMARK 37 CG
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

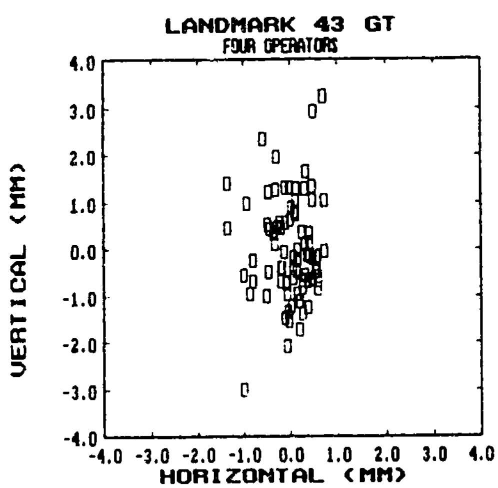

LANDMARK 38 ST
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

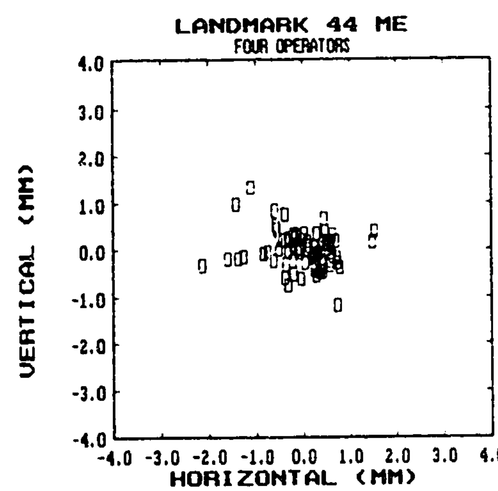

LANDMARK 39 NSM
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

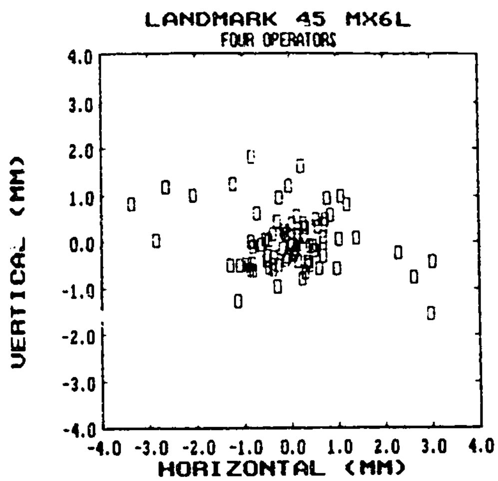

LANDMARK 40 ANS
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)

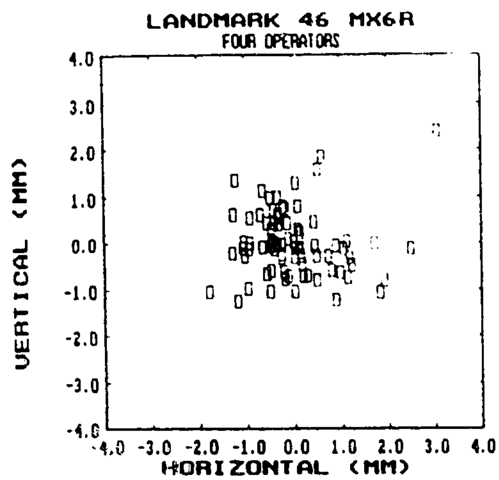

LANDMARK 41 IPU
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

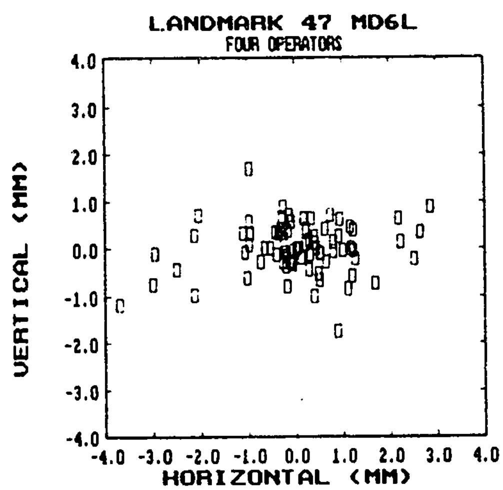

LANDMARK 42 IPL
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

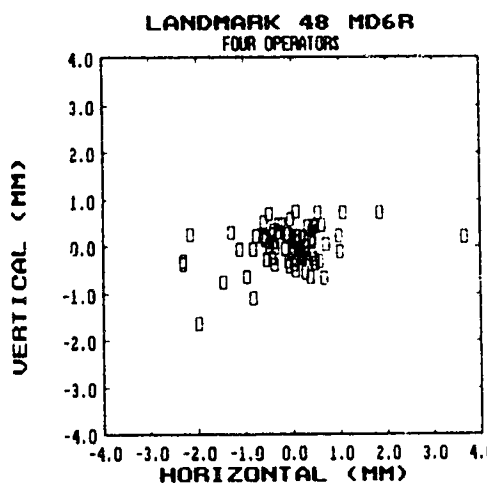

LANDMARK 43 GT
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

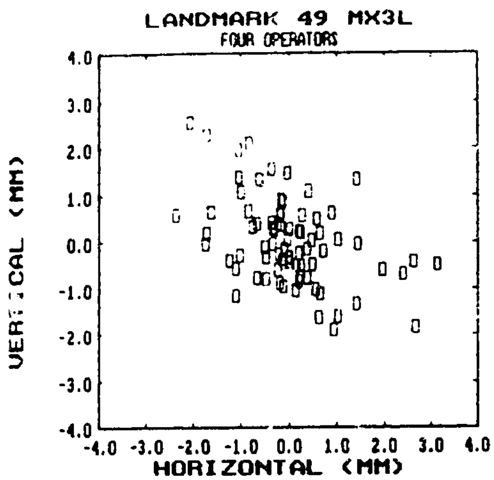

LANDMARK 44 ME
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

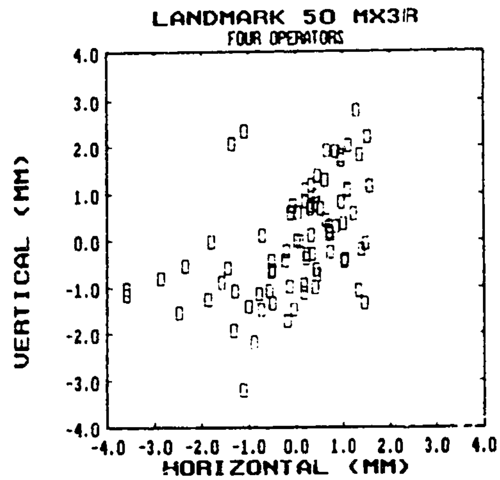

LANDMARK 45 MX6L
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

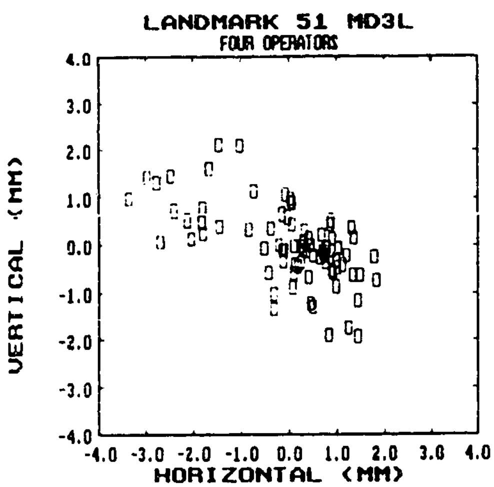

LANDMARK 46 MX6R
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0

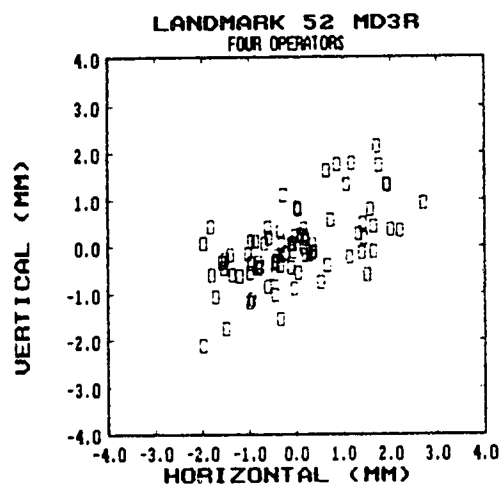

LANDMARK 47 MD6L
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0


LANDMARK 48 MD6R
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0


LANDMARK 49 MX3L
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0


LANDMARK 50 MX3R
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0


LANDMARK 51 MD3L
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0


LANDMARK 52 MD3R
FOUR OPERATORS
VERTICAL (MM)
HORIZONTAL (MM)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0