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Photogrammetric Self-Calibration of Scanning Electron Microscopes

Spiral distortion compensation is the key to accurate three-dimensional mapping with scanning electron microscopes.

INTRODUCTION

SINCE THE DISCOVERY of the scanning electron microscope (SEM) several decades ago, microscopists have been trying to develop stereo-photogrammetric techniques for making accurate three-dimensional (3D) angle and distance measurements of SEM specimens from stereo-pairs of SEM micrographs; such measurements are required by industrial, academic, and research organizations from dozens of diverse disciplines throughout the scientific community. While numerous mathematical approaches to microscopic mapping problems have been published in technical literature, many non-rigorous assumptions have

ABSTRACT: *There is a demand from throughout the scientific community for extremely accurate three-dimensional (3D) angle and distance measurements from SEM micrographs. Photogrammetric self-calibration can be used to mathematically model systematic SEM distortions, which amount to many hundreds of micrometers at photo scale, so that a 10- to 100-times improvement over conventional methods can be realized in the accuracy of SEM 3D measurements. Photogrammetric self-calibration also provides the microscopist with his first means for determining the true accuracy of his 3D measurements. The highly significant spiral distortion, resulting from nonlinear electron scanning, is believed to apply as well to airborne sensors which rely upon scanning techniques.*

been made concerning magnifications, distortions, projectivity, tilt and rotation angles, film stability, measurement processes, etc. Furthermore, all currently known procedures share a major common fault: none provides a means for determining or estimating the accuracy of angle or distance measurements resulting from the measurement process. In the absence of such guidance, some microscopists have developed means of their own for estimating the accuracies of their calculations based on the precision (consistency) of repeated measurements; such action has caused these microscopists to overestimate the accuracy of their measurements by as much as 2 to 3 orders of magnitude (100 to 1000 times) because of major systematic errors in basic assumptions. Some of these assumptions, e.g., distortion-free elec-

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tron trajectories, have been long known to be in error; but the nature, magnitude, and/or significance of such errors and appropriate corrective actions have not been known.

In 1972, photogrammetrists from The Ohio State University Department of Geodetic Science were approached by academic and industrial research members of the metallography community who had requirements for extremely accurate microscopic mapping of metallurgical specimens. The metallographers questioned the accuracy of current stereophotogrammetric techniques as used by microscopists, and they stated requirements for three-dimensional angle measurements with accuracies of 1° or better and three-dimensional distance measurements with accuracies of 100 Angstroms or better. They asked, "Are such accuracies possible with a SEM? What magnification would be required? Can a standardized procedure be adopted for performing such measurements? Would the procedure provide a valid indication of the true accuracy of such measurements?" This paper reports on the development of answers to these questions as made possible by the use of photogrammetric self-calibration[1,2] of a Materials Analysis Company Model 700 (MAC 700) SEM provided by The Ohio State University Department of Metallurgical Engineering. Most results are directly applicable to other SEM instruments, and the mathematical model developed for spiral distortion is believed to apply to aerial sensors which rely upon scanning techniques for area coverage.

The Scanning Electron Microscope

No attempt will be made to thoroughly explain the SEM principles of operation since excellent descriptions are readily available[3,4,5,6].

SEM PROJECTIVITY

Figure 1 shows how the SEM projective geometry may be considered a perspective projection. Suppose that an electron beam accelerates down the SEM electron column through a system of electronic lenses. At point o the beam passes between deflection coils which cause it to scan systematically the specimen area in a raster pattern. Angle α is the scan angle, shown exaggerated in the diagram since it is but a few minutes of arc (e.g., 10′ at 2000×, 2′ at 10000×); there is a similar scan angle perpendicular to the plane of the paper. Point o may be considered to be the effective external nodal point of a lens viewing an object or specimen to be photographed. As the electron beam strikes the specimen at thousands of points, one at a time over perhaps a minute of scanning time, secondary electrons are emitted from the specimen and are attracted to the collector which controls the brightness of the signal going to the cathode ray tube (CRT). The scan generator, which controls the deflection coils at point o, and thus generates the raster scan of the specimen, simultaneously controls the deflection coils at o' which cause a synchronized scan to be made in the CRT, with CRT spot brightness at any instant controlled by the electric current from the secondary electron collector. The CRT scan angle β is large enough to scan a CRT approximately 10 cm across. The CRT is photographed by a CRT camera, generally of a Polaroid variety, rigidly attached to the CRT. Both the object distance (d) and the image distance or focal length (c) can be up to several inches in length; the large magnifications are achieved by having α vary as a very small angle with respect to β which is perhaps 100 to 10000 times larger. Point o' can be considered to be the effective internal nodal point of a lens facing the film in the CRT camera.

Figure 1 may then be converted to an Effective Central Projection, as shown in Figure 2, where β is forced to equal α so that the collinearity condition of first order photogrammetric theory can apply; instead of having β thousands of times larger than α, we may achieve the same magnification by assuming c to be effectively thousands of times larger than d. If the

Fig. 1. Perspective projection of SEM.

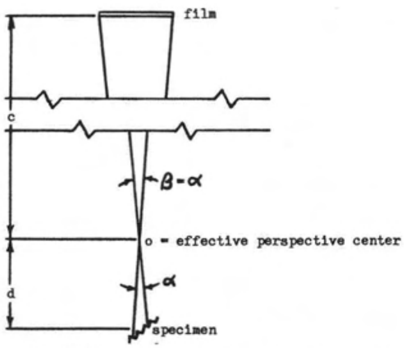


FIG. 2. Effective central projection of SEM.

collinearity condition applies, then the object points on the specimen, their respective image points on the film, and the perspective center would all lie in straight lines. But photogrammetric self-calibration will yield those parameters which describe the systematic distortions in the SEM which prevent the collinearity condition from being strictly applicable.

SEM PHOTOGRAMMETRIC DIFFERENCES

Fundamental differences which prevent the SEM from being treated as a microscopic version of a macroscopic photographic system include the fact that[1] the SEM has (1) unstable or changeable eletronics; (2) a different means of magnification; (3) a near-parallel projection; (4) electron beams with curved trajectories; (5) a sequentially scanned array; (6) more-significant and complex distortions with mathematical representations previously unknown; (7) an object (specimen) coordinate system which tilts, rotates, and translates while the photographic coordinate system remains fixed; (8) an orientation system which does not effectively tilt or rotate about the point of perspectivity as in optical photographic systems; (9) rotation axes which do not intersect each other; and (10) an imaging system which scans the photo format with bands 100 μm wide (called "picture point size" in microscopy literature) recording images to the nearest 100 μm on MAC 700 micrographs (less for newer instruments). Each of these differences must be addressed in the adaptation of general photogrammetric theory for use in SEM photogrammetry.

CURRENT SEM PHOTOGRAMMETRIC TECHNIQUES

CONVENTIONAL METHODS

Using adaptations of elementary photogrammetric formulas, numerous authors[7-12] have published formulas for computing specimen height measurements from parallax measurements made on stereopairs of SEM micrographs. Although many of their calculations are made by electronic computer, their measurement processes are potentially grossly inaccurate because: (1) crude measurement techniques are used (rulers or parallax bars); (2) they assume the collinearity condition applies—which implies that electron beams in the SEM specimen chamber and CRT have undistorted trajectories, when in fact distortions are so large they are often seen by the naked eye; and (3) they use weak angles of tilt differences (6° to 10° generally) in taking the stereo micrographs so as to accommodate viewing with a stereoscope. Such conventional methods are in general use today throughout the microscopy community.

ADVANCED METHODS

Boyde[13] reported the development of a SEM Plotting Device EMPD1 used to plot contour maps from stereo-pairs of SEM micrographs taken with a tilt difference of 10°, a completely new instrument designed specifically for the SEM. Other authors[14-17] used a Zeiss Stereotope, a Wild B8, a Wild A7, and an AS-11A analytical plotter to perform microscopic contouring with SEM micrographs. All of these methods used photogrammetric instrumentation for micrograph measurement and plotting, but none accounted for the significant systematic SEM distortions.

Boyde[18] proposed a procedure in which the CRT superimposes a grid on each micrograph, thereby having a scale for parallax measurements which has the same CRT, camera, and film distortions as the images to be measured. This method has considerable practical merit; however, special instrumentation is required to produce the grid, the grid itself obliterates details to be measured, the grid does not necessarily have the same CRT originated distortions as the specimen image, and the grid does not contain distortions from within the electron column, when in actuality the specimen image has considerable distortion from this source[1].

Boyde[19] proposed a "quantimet image analysis system" which completely eliminates the need for a recording CRT, camera, and even the micrographs themselves, thereby eliminating possible errors from these sources. The system allows direct measurement of features in the visual SEM display by using the variable scale position and size controls to adjust the length of a line to correspond to an x-distance which may be read by eye from the manual digiswitch control. While eliminating several error sources, the procedure appears to introduce new ones, i.e., errors caused by imprecise identification and measurement of points on the visual CRT, and the errors caused by erroneous magnification, tilt differences, and picture-point size. Again, with this method, Boyde neglects the significant distortions within the electron column itself. Boyde[19] himself lists other limiting features of this procedure.

Photogrammetric Self-Calibration Concepts

CALIBRATION STANDARD

Until recently, it was virtually impossible to perform a photogrammetric SEM calibration because of the absence of a suitable microscopic calibration standard with targets accurately positioned in three dimensions. But, with the advent of self-calibration[20], it is necessary to have only a single accurate measurement for scale control, while utilizing multiple convergent photographs of numerous uncontrolled targets to provide geometric means for solution of the various calibration parameters.

Diffraction grating replicas, with as many as 2160 lines/mm in crossed directions, are available commercially[21]. Although the manufacturer specifies the grid spacing to be 2160 lines/mm within a very close tolerance, there is no absolute guarantee that the replica lines are flat, evenly spaced, parallel, or perpendicular. Since self-calibration has no requirement for such a guarantee, the diffraction grating replica is an ideal standard for SEM calibration because it does provide accurate overall scale control as well as hundreds of easily identifiable targets (grid intersections). Examples of annotated micrographs of diffraction grating replicas used in SEM calibration are given in Maune[1,2].

CALIBRATION TECHNIQUES

Calibration can be of value in SEM photogrammetry provided that it is possible to calibrate the magnification, tilt and rotation angles, and distortion parameters in such a way that results are directly applicable to application micrographs, i.e., the calibration procedure must be conducted under the operational conditions in which the results will be applied, and the operational circumstances must be randomly sampled until a "state of statistical control" is achieved[22,23]. In order to do these things, it is necessary for the SEM to remain stable (perform consistently) over the period of time for which calibration results are to be applied. Since current SEMs have numerous unstable characteristics[1], it is presently necessary to take extraordinary precautions which includes recalibration of the instrument every time a new batch of specimens is to be measured. (Such actions are "extraordinary" only in the field of microscopic photogrammetry; DBA Systems Inc., for example, uses self-calibration techniques to recalibrate their cameras every time they make parabolic surface conformity measurements of large radio reflectors[24], a case where the measurement significance clearly warrants application of rigorous photogrammetric theory.) The SEM community has been informed[2] of those actions required to design future instruments so that necessary parameters are resettable for future retrieval of settings used in calibration, as well as other design changes necessary for compatibility with calibration requirements (addition of *reseau* marks, fiducials, etc.). If SEM manufacturers can comply with these recommendations, to a reasonable extent, then one-time calibrations can be used thereafter for three-dimensional measurements with significantly improved accuracies.

In the meantime, however, it is necessary to take action to stabilize the performance of existing SEMs. Experience with the MAC 700 pilot calibration indicated that the dial normally used to electronically refocus the instrument causes a 3-4 percent change in magnification. Other changeable settings were similarly suspect because of actual or possible unacceptable changes in magnification or distortion parameters. For these reasons, the established step-by-step calibration procedure[1,2] includes requirements that the electronic focus, and certain other dials, be taped or otherwise secured in place during calibration so as to prevent inadvertent movement. This implies that focusing must be performed entirely by specimen translation, requiring minor retraining of the SEM operator.

The concept of SEM calibration utilized in this research involves the mounting of a calibration standard on the SEM specimen stub along with all specimens to be measured at a specific magnification. The concept requires two to eight application micrographs to be taken of each specimen with SEM settings (magnification, tilt, rotation, etc.) identical to two to eight of the eight calibration micrographs to be made of the calibration standard (using four rotations, nominally 90° apart for each of two tilt angles selected so as to obtain the strongest ray intersections on the application micrographs[2]); with this method, calibration parameters derived from processing of the calibration micrographs can be applied to the application micrographs taken under identical circumstances. This approach would not really be necessary if the specimen to be measured has perhaps 50 identifiable "targets" visible from numerous orientations so that the hundreds of observations necessary for self-calibration can be made on the micrographs of the actual specimen[20]; if this is possible, all but one of the calibration micrographs could be eliminated completely, and a single self-calibration adjustment would yield the necessary three-dimensional specimen coordinates. Unfortunately, few SEM specimens actually exhibit the characteristics necessary for pure self-calibration, and the modified form of self-calibration explained herein would be more generally applicable.

DATA REDUCTION SOFTWARE

In addition to the hardware requirements for calibration[1,2], the user would need to develop three computer programs, such as the following programs, Fortran listings of which appear in Maune[1]:

The *Coordinate Refinement Program* is a computer program which uses a measurement algorithm to obtain accurate photo coordinates for the image centers of the calibration standard grid intersections which generally appear blurry and much larger than the measuring marks of comparators used to perform the photographic measurements. This program also translates and rotates photo coordinates into the fiducial coordinate system and scales the x and y coordinates to account for the linear effects of film stretch or shrinkage.

The *SEM Calibration Program* utilizes hundreds of micrograph observations (up to 50 points measured on each of eight calibration micrographs) processed by the Coordinate Refinement Program, combined with calibration standard grid spacing information, plus *a priori* SEM parameter estimates (object distance, magnification, tilt and rotation angles, etc.) all collectively termed as "observations" with variable weights. Mathematical models, including all calibration parameters, have been developed and tested by the author to describe the SEM projectivity. (These projective equations are described in the next section.) The least squares adjustment incorporates accepted analytical calibration techniques[20,25]. The output are the calibration data used as input data for the next program, the SEM Intersection Program; these data include the calibrated magnification, specimen tilt and rotation angles, plus all distortion parameters—plus a full covariance matrix for all of these terms—all of which apply to the application micrographs just as validly as they apply to the calibration micrographs.

The *SEM Intersection Program* combines the calibration parameters, plus covariance matrix, with weighted micrograph observations from two or more micrographs made of the specimen(s) to be measured, these new photo observations also having been processed by the Coordinate Refinement Program. The SEM Intersection Program is similar to the SEM Calibration Program except that now there are no calibration standard observations; the calibration parameters have high weights (full covariance matrix); only two parameters (X_o and Y_o) unique for each application micrograph are unknowns solved by the adjustment; and the primary output is a list of three-dimensional coordinates with a full covariance matrix for as many points as were measured on the micrographs of the specimen being studied[1]. From this information, it is easy to compute distances and angles along with their variances and covariances by standard error propagation[26].

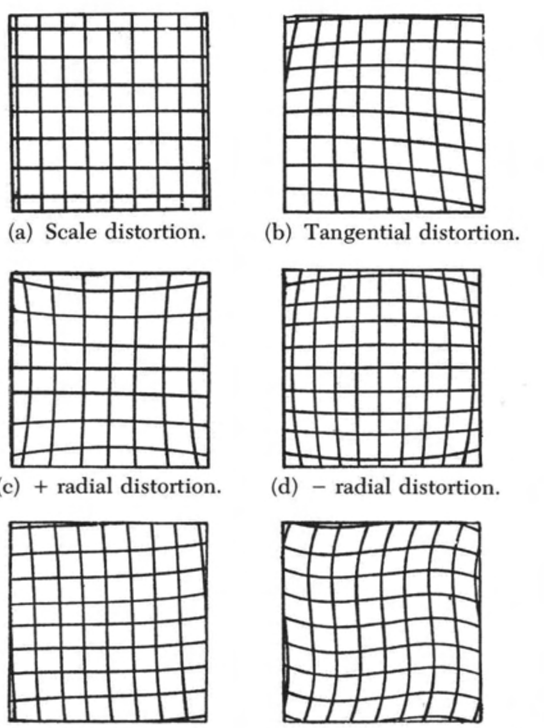
PROJECTIVE EQUATIONS

The projective equations found to best describe the projective geometry of the MAC 700 SEM are explained on the next few pages. Note that the "effective point of tilt," explained in detail by Maune[1], is the innovation developed to overcome facts (7), (8) and (9) in the previous section entitled "SEM Photogrammetric Differences." Figure 3 illustrates the general nature of scale, tangential, radial, and spiral distortion modelled by the projective equations, assuming a square grid pattern to be undistorted.

$$F(x) = F(K)\cdot\bar{x}_{ij} + F(P)\cdot[P_1(r_{ij}^2 + 2\bar{x}_{ij}^2) + P_2(2\bar{x}_{ij}\bar{y}_{ij})] - F(S)\cdot\bar{y}_{ij} - c_x \frac{\Delta Xr_{ij}}{\Delta Zr_{ij}} = O, \text{ and}$$

$$F(y) = F(K)\cdot\bar{y}_{ij} + F(P)\cdot[P_2(r_{ij}^2 + 2\bar{y}_{ij}^2) + P_1(2\bar{x}_{ij}\bar{y}_{ij})] + F(S)\cdot\bar{x}_{ij} - c_y \frac{\Delta Yr_{ij}}{\Delta Zr_{ij}} = 0, \text{ where}$$

x_{ij} and y_{ij}	are the photographic coordinates of the jth specimen point on the ith photograph;
x_p and y_p	are the photographic coordinates of the principal point in a fiducial centered coordinate system; these may be constrained equal to zero because of the near-parallel projection if the fiducial center is near the image location of the principal electron axis;
$\bar{x}_{ij}$	$= x_{ij} - x_p$;
$\bar{y}_{ij}$	$= y_{ij} - y_p$;
r_{ij}	$= (\bar{x}_{ij}^2 + \bar{y}_{ij}^2)^{1/2}$
f-scale	is the scale distortion factor by which the focal length in the y-direction is a scalar multiple of the focal length in the x-direction, primarily caused by improper CRT deflection amplitude settings. (See (a) of Figure 3);
P_1 and P_2	are the correction coefficients for tangential (nonsymmetric radial) distortion[27]. (See (b) of Figure 3);



(a) Scale distortion. (b) Tangential distortion.
(c) + radial distortion. (d) − radial distortion.
(e) S_1 spiral distortion. (f) S_1 and S_2 spiral distortion.

FIG. 3. SEM distortion patterns.

$F(P)$ $= 1 + P_3 r_{ij}^2 + P_4 r_{ij}^4 + \ldots$
= function of tangential distortion[27] which may be solved only when non-zero estimates for P_1 and P_2 are used. A separate set of these parameters through P_4 were found to be significant for each tilt used. This distortion is probably caused by effects of the tilted specimen on spiral distortion;

$F(K)$ $= 1 + K_1 r_{ij}^2 + K_2 r_{ij}^4 + K_3 r_{ij}^6 + \ldots$
= function of symmetric radial distortion[28]. One set of these parameters through K_3 were found to be significant and apply equally to all micrographs. Some coefficients are positive and reflect pincushion distortion ((c), Figure 3), while others are negative and reflect barrel distortion ((d), Figure 3). Positive and negative distortions can both be present, each dominating at different distances from the center of the micrographs;

$F(S)$ $= S_1 r_{ij} + S_2 r_{ij}^2 + S_3 r_{ij}^3 + S_4 r_{ij}^4 + S_5 r_{ij}^5 + S_6 r_{ij}^6 + \ldots$
= function of spiral distortion, derived in this research. A separate set of coefficients through S_6 was found to be quite significant for each tilt used. This distortion is caused by the spiralling or nonlinear trajectory of electrons in the SEM column (specimen chamber) as well as in the CRT. Examples of the first two spiral distortion parameters are shown in (e) and (f) of Figure 3.

c_x is the effective focal length in the x-direction, assumed constant for all micrographs.

c_y is the effective focal length in the y-direction, assumed constant for all micrographs $= f\text{-scale} \cdot c_x$

$$\begin{bmatrix} \Delta X r_{ij} \\ \Delta Y r_{ij} \\ \Delta Z r_{ij} \end{bmatrix} = \begin{bmatrix} ROTATE_i \end{bmatrix} \begin{bmatrix} Xs_j - Xo_i \\ Ys_j - Yo_i \\ Zs_j - Zo_i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ d \end{bmatrix}$$

$ROTATE_i = 3 \times 3$ rotation matrix for photo i

$$= \left[\begin{bmatrix} CK & SK & 0 \\ -SK & CK & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & CO & SO \\ 0 & -SO & CO \end{bmatrix} \begin{bmatrix} CP & 0 & -SP \\ 0 & 1 & 0 \\ SP & 0 & CP \end{bmatrix} \right]^T$$

SK and CK = sine and cosine, respectively, of κ_i, the rotation angle of the specimen holder for photo i.

SO and CO = sine and cosine, respectively, of ω_i, the x-tilt of the specimen holder for tilt group including photo i.

SP and CP = sine and cosine, respectively, of ϕ_i, the y-tilt of the specimen holder, constrained equal to zero[1].

d = object distance between the effective perspective center and the effective point of tilt, constrained constant for all photos[1].

Xs_j, Ys_j, Zs_j = coordinates of the jth specimen point in the specimen coordinate system[1].

Xo_i, Yo_i, Zo_i, = coordinates of the effective point of tilt for photo i in the specimen coordinate system. The Zo values are functionally constrained[1], but the Xo and Yo terms are free parameters, estimated from the following:

$$\begin{bmatrix} Xo_i \\ Yo_i \\ Zo_i \end{bmatrix} = \begin{bmatrix} ROTATE_i \end{bmatrix}^T \begin{bmatrix} -x_{i,1}/\text{Mag-}x \\ -y_{i,1}/\text{Mag-}y \\ 0 \end{bmatrix}$$

Mag-x = Magnification in the x-direction $= c_x/d$.

Mag-y = Magnification in the y-direction $= c_y/d$.

$x_{i,1}$ and $y_{i,1}$ = photo coordinates of the first specimen point on the ith photo. The first specimen point is selected as that point to be measured which appears closest to the aiming point[1,2] (nominally the center of each micrograph).

The total number of calibration parameters are of three types: (1) There are six parameters common to all points and photos; they are d, c_x, f-scale, K_1, K_2, and K_3; (2) there are eleven parameters common to each tilt used; they are P_1 through P_4, S_1 through S_6, and ω_i; and (3) there are three photo parameters for each micrograph used; they are κ_i (rotation angle) plus Xo_i and Yo_i (coordinates of the effective point of tilt of the specimen for photo i.) Xo_i and Yo_i are the only calibration parameters which do not apply to the application micrographs.

Calibration with four micrographs (at 0°, 90°, 180°, and 270° rotation angles) for each of two tilts would entail a minimum of $6 + (2 \times 11) + (8 \times 3) = 52$ calibration parameters. When 50 grid intersections are selected at random over the grid area photographed, their three-dimensional specimen coordinate system coordinates can be computed theoretically and given light weights (since the replica may be warped slightly from its original shape, and because it may have been mounted in a non-horizontal position); it is necessary that some weight be given to control the overall scale of the solution[1]. These 150 coordinates are thus lightly weighted "observations" as well as "unknowns" solved by the calibration as a useless byproduct. In addition to the 150 specimen coordinates, the observations would normally include weighted values for object distance (d), magnification, two tilt angles, eight rotations, and 800 x and y photo-coordinate observations of the 50 points appearing on eight micrographs. Therefore, the degrees-of-freedom would normally number 760 (962 observations − 202 unknowns).

Research Results

A pilot calibration was performed at 5000× which enabled the preparation of specified step-by-step procedures[1,2] for the remaining calibrations. The system was then recalibrated at 2000×, 5000×, and 10000×, with additional micrographs taken of the diffraction grating replica used in lieu of actual specimens for theoretical studies because of the abundance of clearly defined targets that the diffraction grating replica provides.

Pilot Calibration Results

The pilot calibration yielded four major findings: (1) Utilizing electronic refocus, the magnification of each micrograph varied by 3-4 percent from the average magnification for the entire set; in order to retain magnification consistency, therefore, it is necessary that each micrograph be refocused by specimen translation only. (2) Although the CRT x and y amplitude deflection potentiometers were adjusted in accordance with the Operator's Manual for the MAC 700, the magnification in the x-direction was 12.4 percent different from the y-direction magnification; a single parameter (f-scale) can account for this scale distortion, but the CRT was balanced prior to subsequent calibrations. (3) Prior to the introduction of distortion parameters, the standard deviation of photocoordinate observations was approximately 1500 μm. (4) It is the nature of SEM imagery that some images may provide clearer targets for "pointing" than others. It was decided that an *a priori* weighting scheme for photo coordinate observations is necessary so as to determine, at the time of measurement, the relative expected weights to be applied to degraded images with respect to perfectly clear images. This author gave unit weights to clear images and weights as low as 0.5 to blurry or irregular images.

Final Calibration Results

After the CRT x and y deflection potentiometers were balanced, the MAC 700 was calibrated at 2000×, 5000×, and 10000×, using tilts of 22.5 and 45°. Prior to the introduction of distortion parameters, the adjustment required photo coordinate observations to have artificial *a priori* standard deviations of 565 μm in order for the least squares solution to indicate an *a posteriori* variance of unit weight of unity. Obviously, such discrepancies were caused by an inadequate mathematical model, and not by actual observational errors of that magnitude.

Trial and error with various distortion parameters, and significance testing[29] for each, yielded the mathematical model listed in the section entitled "Projective Equations." In addition to a small amount of residual scale distortion, corrected by the "f-scale" parameter, the following distortions were found to be significant: (1) A separate set of spiral distortion coefficients through S_6 were found to be very significant for each tilt used, accounting for approximately 320 μm of systematic errors. At least 100 μm of this amount was caused by distortions within the specimen chamber because it required $S_1 - S_6$ for 22.5° tilt separate from $S_1 - S_6$ for 45° tilt to account for the final 100 μm of systematic errors which otherwise could have been removed by a single set of parameters had all spiral distortion been caused by the CRT. The modelling of this distortion is probably the most significant finding of this research. (2) A separate set of tangential distortion coefficients through P_4 were similarly found to be significant for each tilt used, accounting for approximately 80 μm of systematic errors. (3) One set of symmetric radial distortion coefficients through K_3 were found to be significant and apply equally to all micrographs, regardless of tilt. These parameters accounted for approximately 50 μm of systematic errors. Both positive and negative radial distortions exist.

Projective equations for a central projection (including distortion parameters) were found to be a slightly better representation of SEM projectivity than are equations for a parallel projection (which require the same distortion parameters). However, the distinction between the two projections was not statistically significant at the magnifications used, and probably would not be significant except at very small magnifications.

Calibrations at nominal magnification settings of 2000×, 5000×, and 10000× determined the actual magnifications to be 1997×, 4585×, and 8873× respectively, indicating very poor magnification control by the MAC 700 used.

APPLICATION RESULTS—METHOD COMPARISON

Measuring 50 points on each of eight calibration micrographs and 25 points on each of eight application micrographs (of the same calibration standard), the *identical* observations were processed by three different means so that a comparison could be made of the methods, as listed in Table 1.

Equivalent Conventional Method. The eight calibration photos plus two application photos (0° rotation, 22.5 and 45° tilts) were processed by the SEM calibration and intersection programs using *no* distortion parameters in the projective equations, forcing the projective equations to comply with the collinearity condition. This method is considered[1] equivalent to the very best possibly achievable by conventional methods now in use and is, therefore, referred to as the "equivalent conventional method." Row one of Table 1 shows the resulting standard deviation of height coordinates to be on the order of 2650 nanometers (1 nm = 10^{-9}m = 10 Angstroms), primarily caused by the 565 μm standard deviation in photo coordinate observations (see "Final Calibration Results") and resulting "wobble" in intersecting rays.

Calibration + 2-Photo Method. The same measurements of the same ten micrographs, as used in the previous methods, were then processed by the SEM calibration and intersection programs using all empirically derived distortion parameters. As shown by the second row of Table 1, there was an approximate 8.5 times improvement in the accuracy of z-coordinates. This method would be approximately equivalent to a conventional method if the SEM were distortion-free. The 108 μm standard deviation of photo coordinate observations is approximately the best that could be expected from a system where images are recorded to the nearest 100 μm at photo scale—number (10) from "SEM Photogrammetric Differences."

Calibration + 8-Photo Method. The same measurements of the eight calibration micrographs, plus measurements of all eight application micrographs, were then processed by the SEM calibration and intersection programs with all distortion parameters. Row three of Table 1 shows that this multi-photo method produced heighting accuracies approximately seven times more accurate than the stereo-method in row two of Table 1, a factor much more significant in SEM photogrammetry (where photo coordinates are precise approximately to the nearest 100 μm) than it would be in aerial photogrammetry (where photo coordinates are precise approximately to the nearest 5 μm). Furthermore, this method produced an approximate 60-time improvement in heighting accuracy over conventional (equivalent) techniques. Because of the conservative nature of the equivalent conventional versus actual conventional techniques[1] (use of a CRT already corrected for x-y scale distortion, use of more

TABLE 1. COMPARISON OF METHODS.

Mag.	Solution Method	σ (μm) Photo	σ (nm) Planimetry	σ (nm) Height
5000X	Eq. Conventional	565	325–2340	~ 2650
5000X	Cal. + 2-Photo	108	168–243	329–332
5000X	Cal. + 8-Photo	108	26–44	43–50

TABLE 2. COMPARISON OF MAGNIFICATIONS.

Mag.	Solution Method	σ (μm) Photo	σ (nm) Planimetry	σ (nm) Height
2000X	Cal. + 8-Photo	84	37–62	126–137
5000X	Cal. + 8-Photo	108	26–44	43–50
10000X	Cal. + 8-Photo	123	11–16	18–20

accurate photogrammetric measurement and data adjustment techniques, stronger angles of convergence, etc.), it is possible to expect a 100-time improvement over actual conventional techniques.

APPLICATION RESULTS—MAGNIFICATION COMPARISON

Table 2 compares the Calibration + 8-Photo solution accuracies achieved with magnifications of 2000×, 5000×, and 10000×. The results are generally self-explanatory. The better standard deviations of photo coordinate observations at smaller magnifications is due to the fact that grid intersections provide better targets for precise measurement at smaller magnifications, while grid intersections at larger magnifications appear so large that precise pointing is more difficult.

ACCURACY OF ANGLE AND DISTANCE MEASUREMENTS

Using a 6-point method[2] for computing two planes and the angle between them, numerous theoretical calculations were made of the accuracy of angle measurements to be expected for three-dimensional angles from 30° (= 150°) to 90°, by propogating average variance/covariance values resulting from the computer programs used to obtain the results of Tables 1 and 2. For all angles and magnifications, the standard deviations were in the ranges shown in Table 3, depending on distance, orientation assumptions, etc. The results are primarily dependent upon the accuracies or inaccuracies of the z-coordinates used. It can be seen that calibration does enable angles to be determined with accuracies within the 1° tolerance level specified by the micrographers (see "Introduction").

Using distances at a 45° oblique angle to the vertical axis, theoretical calculations were made in a similar fashion to determine the accuracies which might be expected from distance measurements. The results are also indicated in Table 3, and are seen to be both magnification and method-dependent. The best distance accuracy obtained was 220 Angstroms at 10000×. One can extrapolate that the 100 Angstrom accuracy goal (see "Introduction") could be achieved if a 20000× calibration technique was used (appropriate calibration standard not known to be commercially available) or perhaps at 10000× if a 50 μm resolution SEM (now commercially available) were calibrated and used with at least an 8-photo solution.

CONCLUSIONS

The primary conclusions of this research are that: (1) Photogrammetric self-calibration provides the SEM microscopist with his first means for assessing the true accuracy of his three-demensional coordinate, angle, and distance measurements.
(2) Theoretical studies have proven that SEM specimen three-dimensional angle measurements can be made with a standard deviation less than 0.5° at magnifications tested (2000X to 10000X), and three-dimensional distance measurements can be made which approach a

TABLE 3. STANDARD DEVIATION OF THREE DIMENSIONAL ANGLES & DISTANCES.

Solution Method	σ angles (deg) All Magnifications	σ distances (nanometers) 2000X	5000X	10000X
Eq. Conventional	23.6–28.0°	3960 nm	2900 nm	1180 nm
Cal. + 2-Photos	2.65–3.40°	842 nm	361 nm	147 nm
Cal. + 8-Photos	0.38–0.48°	122 nm	55 nm	22 nm

standard deviation of 200 Angstroms at 10000X. These accuracies, obtained with a MAC 700 SEM, are one, to two, orders of magnitude (10 to 100 times) more accurate than accuracies that would be obtainable (with the same instrument) from stereo-photogrammetric techniques now in use, throughout the microscopy community, which do not account for the significant systematic distortions present in SEMs.
(3) After the MAC 700 CRT deflection potentiometers were correctly balanced, the following systematic distortions were modelled at photo scale: spiral distortion ($\approx 320\ \mu m$), tangential distortion ($\approx 80\ \mu m$), and radial distortion ($\approx 50\ \mu m$). Prior to the CRT adjustment, the total systematic distortions had been on the order of 1400 μm at photo scale (1 sigma standard deviation) in spite of the fact that the instrument had been adjusted in accordance with the specifications of the MAC 700 Operator's Manual. It is believed that SEMs produced by other manufacturers would have similar distortion characteristics, the significance of which remain generally unknown to SEM users.
(4) Although extremely valuable for a few critical SEM measurements, photogrammetric self-calibration is currently too costly to be practical for general use; this is caused primarily by the fact that SEMs are not currently engineered for stable (consistent) performance, and calibrations have to be repeated whenever new batches of specimens are to be measured. The microscopy community has been informed[2] of actions necessary to make their instruments more suitable for photogrammetric calibration.

Recommendations

While waiting for the SEM community to improve their instruments, there is significant research[1] still required by the photogrammetric community in order to simplify and optimize procedures for practical application. Can reasonable accuracies be achieved with two, three, or four micrographs at a single tilt? What is the correlation between coordinate accuracies and the number of photos, their orientations, and the number of points measured on each? Under what circumstances can the calibration micrographs be disposed of completely so that pure self-calibration can be used with specimen micrographs only? Can the projective equations be improved upon? Can simple, semi-automated procedures be developed for SEM photogrammetric calculations which incorporate calibration data? Can analytical plotters be programmed to account for SEM calibration data? Under what circumstances can conventional analog plotters be used for continuous mapping with SEM micrographs? How can requirements for photogrammetric expertise be minimized so that non-photogrammetrists can afford to use accurate photogrammetric techniques? These are but a few of the questions which the author recommends for research by the photogrammetric community.

In addition, it is felt that the spiral distortion portion of the projective equations may be directly usable by aerial photogrammetrists who utilize panoramic photography (with inherent S-curve errors) or other sensors (such as the Multispectral Scanning Subsystem of the Earth Resources Technology Satellite) which rely upon electronic scanning. It is recommended that the spiral distortion mathematical model, which served so well to account for SEM electron spiral and/or nonlinear scanning, be tested for relevance in the calibration of other sensor systems which operate on scanning principles.

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Note: for information on the annual SEM symposium and/or proceedings, contact Dr. Om Johari, Director, Annual SEM Symposia, IIT Research Institute, 10 West 35th Street, Chicago, Ill. 60616, or phone (312) 225-9630, Ext. 4843.