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PROGRESS IN CARTOGRAPHY, EROS PROGRAM

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INTRODUCTION

During the past 7 years the Interior Department EROS (Earth Resources Observation Systems) program with NASA sponsorship has conducted cartographic research based on high-altitude aerial and space photographs. The research has centered on the direct use of the image and its transformation into so-called photo or image maps. Today the cartographers of the Geological Survey have a real opportunity to apply themselves to making maps from data supplied by a satellite which is dedicated to remote sensing of the Earth.

On July 23, 1972, ERTS-1 (Earth Resources Technology Satellite; the figure 1 indicates the first of a series of proposed flights) was successfully launched into orbit by NASA. Within a few days its Return Beam Vidicon (RBV) cameras and Multispectral Scanner (MSS) were transmitting scenes of the Earth. The RBV cameras were turned off early in the mission because of technical problems in the control system, but the MSS continues to perform nearly flawlessly. The RBV cameras may be turned on again in the future. Two basic products are produced by NASA (Goddard Space Flight Center) from ERTS-1, which are known as bulk (system-corrected) and precision (scene-corrected) imagery. Bulk and precision processing are applied to both RBV and MSS imagery, and since there are three RBV spectral bands and four MSS bands, a variety of image forms can be produced for any one scene. NASA provides transparencies and/or prints at 1:3,369,000 and 1:1,000,000 scale to investigators and cognizant government agencies. The Interior Department, through the EROS Data Center at Sioux Falls, S. Dak., sells ERTS products to the public at nominal cost. ERTS-1 is scheduled to remain in orbit for a full year, but with good luck its effective life may be much longer.

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Cartographers of the Geological Survey have developed a number of ERTS-1 experiments, accepted by NASA, as follows:

Experiment	NASA Proposal
• Photomapping of the U.S.	211
• Map revision	237
• Basic thematic mapping	116
• Polar regions mapping	149
• Mapping from orbital data	150
• Overall cartographic application	233

The principal investigators for these experiments are receiving a wide variety of imagery; in addition, NASA has asked them to take a quick look at selected ERTS-1 imagery and report preliminary findings. The cartographic experiments are unique in that they apply to the development of graphics related to an accepted reference figure of the Earth to some defined degree of accuracy. However, both geometric and perceptional considerations are involved. Although the revision of line maps by means of ERTS materials is one of the more important experiments, the others concentrate on the problem of turning out maps in which the image itself provides the base.

PERCEPTIONAL CONSIDERATIONS

Maps are expected to have an informational content commensurate with their scale. For image-based products, which go under the general name of photomaps, image quality must be adequate for the map user to perceive (detect) and, within reason, identify objects that imagery of the given scale can be expected to portray. Cartographic products are normally lithographed and viewed by the unaided eye, a condition that establishes criteria for the evaluation of the perceptional quality of a photomap. Line maps, on the other hand, are highly interpreted products on which important features are shown and identified regardless of whether they can be seen or identified in imagery of the same scale. For example, major roads and railroads appear on most general-purpose maps of small scale (say 1:1,000,000), but the images of the features are not usually visible at the same scale.

The informational content of an image is based primarily on two factors, spectral and spatial response. Spectral response is measured by monochromatic tone or color differences, and the term *spectral consistency* is used here for evaluation of ERTS imaging forms in relative terms of repetitive spectral response. Line maps are normally compiled from black-and-white aerial photographs in which objects are defined by differences in density, recorded as tones of gray. As long as the density differences enable the map compiler to detect and identify the mappable object, spectral consistency is not of primary concern. But photomaps, which use the image as a base, are highly dependent on the spectral consistency of the image. Since spectral response changes with time, sun angle, and atmospheric conditions, the production of photomaps which normally incorporate more than one image poses a real problem in attaining spectral consistency. The problem is magnified when the parameter of color is introduced, for now one must deal with three spectral responses (normally) rather than one. Automated thematic mapping--or Autographic Theme Extraction, as it is called in the Geological Survey--is based on image density slicing, and here again spectral consistency is the key.

Spatial response is measured by the minimum size of objects (of uniform response) that are uniquely recorded under certain conditions and can be identified as real scene objects rather than system noise. The term *object detectability* is used here to evaluate ERTS forms for spatial response. The term *resolution* is normally employed as a measure of spatial response for photographic products, but it relates to the minimum observable spacing between two like objects, such as stars in the sky or targets on the ground. With electro-optical systems such as TV or optical scanners, the relationship between resolution and minimum object size (detectability) is different than with photographic systems. Object detectability depends on edge sharpness or acutance as well as resolution, and the term is used in preference to resolution even though methods of quantifying detectability are not fully developed. (Rosenberg, 1971.) Both spectral consistency and object detectability are related to recorded contrast, which in turn depends on the differences in spectral response, atmospheric conditions, and image processing.

The following table evaluates the various types of ERTS imagery with respect to spectral consistency and object detectability and also indicates maximum practical printing scales for the imagery:

Perceptional Relative Image Quality

Image type	Spectral consistency	Object detectability	Maximum printing scale
RBV bulk	Poor to fair	Good	1:500,000
MSS bulk	Good	Good	1:250,000
RBV precision	Poor to fair	Fair	1:500,000-1:1,000,000
MSS precision	Poor to fair	Fair	1:500,000

We acknowledge that many ERTS-1 images have particular features that can be effectively enlarged to scales of 1:100,000 or larger; high-contrast land-water interfaces are good examples. On the other hand, objects of equal size but lower contrast become indistinguishable at the larger scales. Therefore, the maximum printing scales are rated as appropriate for maximum information content as viewed by a normal unaided eye at reading distance.

Resolution would also be a useful indicator of image quality, and the Geological Survey has asked NASA to install sizable targets on the ground for definitive resolution analysis. In the meantime, image edge analyses and similar techniques are being applied, but it is not known how well they can relate to resolution as photographically recorded in terms of target response.

The table given above is significant in that only one type, MSS bulk, exhibits image quality (perceptional) suitable for 1:250,000-scale mapping. However, conclusions about map products should not be drawn until the geometric properties have been fully examined.

GEOMETRIC CONSIDERATIONS

A major goal of the Interior Department is to map the country at various scales and with accuracy as defined by the U.S. National Map Accuracy Standards (NMAS). For planimetry the standards require, in effect, that 90% of well-defined features should be in error by no more than 0.02 inch (0.5 mm), measured on the publication scale. The 90% accuracy value is therefore ∿500 m (on the ground) at 1:1,000,000 scale, ∿250 m at 1:500,000, and ∿125 m at 1:250,000. Map errors may not be normally distributed, but for practical purposes the root mean square (rms) error of position for points tested should be less than 300 m at 1:1,000,000 scale, 150 m at 1:500,000, and 75 m at 1:250,000 scale to meet NMAS. Until recently it was considered impractical (or impossible) to make maps of scales smaller than ∿1:100,000 that met or even approached NMAS because oversize symbolization of features and other cartographic treatments require sizable positional displacement on small-scale maps. Photomaps, unless extensively annotated, do not contain displacement due to symbolization, and there is no reason why a photomap of small scale cannot meet NMAS as long as the image is geometrically sound and adequate control is available.

A prime consideration in attaining or analyzing map accuracy is the internal geometry of the imaging system. The desirable image is one that has a minimum of internal distortion. The ERTS image data processing system has unique capability, in the computer processing and electron beam recording, to system-correct many distortions. If the system were stable and if all sensor distortions and spacecraft motions were completely calibrated, the result could be an image of high internal geometric quality. At present, good calibration is available for the RBV system, and a mathematical model of the distortions has been developed (Wong, 1972). The MSS system is not suited to similar calibration, and moreover it fully incorporates (in the recorded image) the effects of small but continuous attitude changes of the spacecraft.

The available RBV frames, though limited in number, are enough for comparison of the reseau coordinates with calibrated preflight values. At ground scale the internal distortion ranges from a minimum of 42 m to a maximum of 100 m on the images evaluated. The average rms distortion for all RBV images is 65 m and is generally a random distribution, representing images of high geometric quality and probably the practical limit for the ERTS RBV. The figures cited represent only the internal distortions of the sensor system. In practice, internal sensor distortions are combined with external distortions, such as topographic relief, earth curvature, sensor attitude, and the map projection. External distortions have been previously analyzed (Colvocoresses, 1970). When control-point image coordinates are compared with map coordinates, both external and internal distortions are effective, and the comparisons are true tests of images for mapping purposes.

Selected well-defined features on several RBV images have been compared with established Universal Transverse Mercator (UTM) coordinates. The number of points has been densified at selected sites to 15 or 20 points per image. The ability of an observer to identify and measure a ground control point varies, but for well-defined points it is between 15 and 25 m. The tested RBV frames fit the UTM coordinates with a maximum rms error of position of 150 m and a minimum of 100 m, determined by a least-squares four-parameter fit using x and y translation, rotation, and scale change. Additional adjustment allowing for tilt rectification produced a slight improvement but, as expected with a near-vertical, narrow-angle system, not enough to justify additional processing.

Many more MSS images have been measured and compared with ground control points. The MSS does not have a reseau, and preflight calibration data are not available. Since the internal and external errors cannot be separated, the only approach is to measure image points and attempt to identify and isolate specific errors. The MSS image is subject to certain microdistortions or anomalies that occur at regular intervals. In addition, some images have lines obviously omitted or displaced during processing. One anomaly is illustrated in figure 1, which is derived from a 1:100,000-scale enlargement of the Golden Gate bridge obtained from frame 1021-18172-6. The stair-step pattern is apparent; it follows a periodic cycle of 6 lines or one mirror scan. The offset is a function of the angle between the scan lines and the feature and may amount to over 100 m. The anomaly can be observed on airport runways, coastlines, and other linear features in other frames. NASA has recently indicated that the anomaly is one that they believe can be eliminated, or at least reduced, and that corrective action will be undertaken.

Early MMS images fitted to ground control had rms distortions up to 1000 m, always larger than 300 m. Best results to date were obtained with frame 1080-15192-5, showing Chesapeake Bay. Figure 2 shows a vector plot of residuals for that frame, for which rms = 192 m. Systematic error, such as changes in mirror speed and spacecraft attitude, can be corrected, so that MSS geometric quality can be further improved.

Measurements have been made on 70-mm third-generation and 24-cm (9.5-in.) fourth-generation transparencies. Some first-generation images were also measured, with results identical with those obtained with a third-generation copy of the same scene. It does not appear that image duplication, enlargement, or processing is introducing any significant distortion even though target scales, such as 1:1,000,000, may not be exact.

Separate spectral bands of the same MSS scene have been measured and compared. The results indicate excellent register between bands, with maximum differences of only 10 to 20 m. Multispectral analysis of a single MSS scene is therefore subject to a negligible geometric error.

The bulk-image scenes are positioned by orbital data. The latitude and longitude coordinates for the midpoint of the scene given in the data block are subject to some errors, as are those for the edges of the frame. Frame 1080-15192 of Chesapeake Bay has center coordinates approximately 5 km in error. Some frames may have greater errors, but scenes processed since November 1972 are reported to be of better accuracy. However, sequential scenes cannot be registered by reference to indicated positions.

Both bulk and precision images of scene 1002-18131, Lake Tahoe, have been evaluated for geometric accuracy. The scene is available in all seven bands from the RBV and MSS and is the only one for which measurements have been made on precision-processed products. The measurements indicate an rms of 140 m for the RBV (precision) and 170 m for the MSS (precision). Since the scene was the first so processed and included unusual problems relative to terrain and control, the indicated rms values are considered to be high. The following summary contains a somewhat lower range of expected values and is based on the finding that most bulk images measured have exhibited less distortion than the Lake Tahoe scene.

Summary of expected image distortion
after best fit to ground control

Type	Error (rms, in meters)
RBV bulk	100-150
MSS bulk	200-450
RBV precision	100-150
MSS precision	100-150

Relating scales to errors through the NMAS, we might assume from the tabulated errors that maps of 1:500,000 scale could be made from RBV bulk, RBV precision, and MSS precision images whereas 1:1,000,000 would be the largest acceptable scale for MSS bulk. If the indicated errors were purely random, the deductions would probably hold, but systematic error is present and accuracy can be improved in cartographic processing. Specifically, it should be possible to improve the geometry of the bulk imagery through application of corrections determined from control-point comparison in precision processing. The procedure requires individual computations for each scene as well as a second printing with the electron beam recorder. NASA is not yet prepared to undertake custom processing routinely, but has indicated that engineering tests of the concept will be undertaken. If the evidence indicates that custom processing will reduce distortion in bulk MSS imagery to perhaps half of present values, processing of ERTS imagery may be eventually modified to incorporate these geometric corrections.

However, it should also be noted that some types of cartographic products do not need to meet NMAS but may be useful even though their rms error is about twice the allowable NMAS error. Nevertheless, the basic conflict between perceptional and geometric qualities of the ERTS RBV and MSS images poses a real challenge to the mapmaker.

ANALYSIS OF THE MAPPING PROBLEM

With ERTS imagery, the mapping problem can be divided into two distinct categories, depending on whether identifiable ground control is or is not available. For the better mapped areas of the world, such as Europe and the United States, photoidentifiable control is readily available and permits the precise geometric evaluation and fitting of ERTS imagery to the Earth's figure. It also provides the basis for NASA's precision processing, in which the image is transformed and fitted to a recognized (UTM) map projection. In areas where ground control is not available, mapping must depend on orbital (and sensor) data by methods and techniques that are the subject of a specific ERTS investigation that is still in its early stages. The image of an RBV is a perspective projection, like the image of a conventional frame camera, and therefore mapping with RBV imagery by reference to either ground control or orbital data is a matter of well-understood, established procedures. The MSS, an optical scanner, creates a continuous image made up of a large number of independent picture elements (pixels), each representing a small segment of the Earth's surface. If printed out in raw form, the image would have such complex geometry that the mapmaker would find it all but impossible to use. To overcome the problem, NASA applies no less than 14 geometric corrections to the MSS imagery (noted on page G-18 of the ERTS Data Users Handbook prepared by General Electric for NASA). The curved Earth surface cannot be depicted on a plane without some distortion, but since the MSS image ray is always within 5.78° of the nominal vertical and the curvature of the Earth across the scene is less than 2°, the image approximates an orthographic view. The printed MSS image is a montage of sequentially produced thin projections and therefore lacks the internal geometric fidelity of the instantaneous frame image of an RBV. (See table of distortions presented earlier.)

Precision processing was defined as a system that correlates ERTS imagery to photoidentifiable ground control, rescans the image, and fits it to a specified projection. Unfortunately, precision processing involves considerable degradation of image quality that limits its application although the geometric improvement of the MSS imagery is highly significant for the mapmaker.

Regardless of availability of identifiable control and type of image used, the problem of map format is critical. The simplest format is that of a single ERTS scene whereas conventional geographic quadrilaterals or States normally require a mosaic made from several scenes. Using single scenes is relatively simple, and producing cartographic products from them is referred to as *First Phase Mapping.* Producing standard quads or State base maps is far more complex and is referred to as *Second Phase Mapping.*

FIRST PHASE MAPPING--IMAGE OR SCENE FORMAT

The first phase involves the processing of a single ERTS scene which by any of three methods has been brought to a specific scale and form and related to the figure of the Earth. Mapmakers are loath to use an image to define map boundaries, but in the case of ERTS the scenes are of sufficient size and repeatability for use in defining a series of maps. (The extent to which the system will be accepted by map users is not known.) The three methods of processing a single scene are as follows:

- Precision processing by NASA, which applies geographic (latitude and longitude) or plane coordinate (UTM) ticks to the image as transformed to the UTM projection. An agency such as USGS can then add a fine-line grid and lithograph in either black-and-white or color. The orthophotoimage of Lake Tahoe reproduced in color is a sample product; 1:1,000,000 is the only publication scale used to date, and the precision processing imposes image-quality limitations that may preclude publication at large scales. It is important to note that any ERTS image precision processed by NASA is a cartographic product. Suitable control throughout the U.S. is being identified by the U.S. Geological Survey and furnished NASA. The precision-processed images so far produced of the U.S. do meet NMAS at the 1:1,000,000 scale, and accuracy can undoubtedly be maintained wherever suitable control is available.

- A bulk ERTS MSS image can be rectified and scaled to a defined projection and a geodetic grid. At 1:1,000,000 scale the products should meet NMAS, but at 1:500,000 the error may be about twice the tolerance of NMAS. An RBV bulk image should meet NMAS at 1:500,000 and still present an image of acceptable quality in monochromatic printing.

- The third method is to bring an ERTS image as close as possible to a predetermined scale and fit a grid that has been generated from image-identified control points. The grid-fitting method is particularly applicable to bulk MSS imagery, and the products should meet NMAS at 1:500,000 scale. It should be noted that the image has not been controlled to an accepted map projection and the grid lines theoretically do not form perfect squares. However, the departure from the perfect square is so small that it is not measurable in individual grid units. At present, this procedure is the only one of the three that promises to produce a 1:500,000-scale map of good image quality at NMAS.

SECOND PHASE--QUADRANGLE OR STATE FORMAT

A 1:250,000-scale standard geographic quad extends 1° in latitude by 2° in longitude and may be covered by only 2 ERTS scenes. A 1:1,000,000-scale quad extends 4° in latitude by 6° in longitude and may contain 30 or 40 ERTS scenes. USGS 1:500,000-scale maps are now State maps rather than quadrangle maps, and therefore vary greatly in size and shape. Second phase maps at 1:250,000, 1:500,000, and 1:1,000,000 are in various stages of compilation; we hope that they will be lithographed and placed on public sale by USGS in the near future.

APPLICATIONS AND FINAL FORM

There are several cartographic applications of ERTS imagery. Revising line maps is one in which the image is not retained, but the other applications defined to date retain the image or a derivative of the image as follows:

- *Monochromatic orthophoto.*--normally derived from one spectral band and portrayed in gray tones. Colors may be assigned as a function of density, but the basic input at some stage is a single gray-tone image.

- *Polychromatic orthophoto.*--the color image application; with ERTS, normally gives a false-color rendition that includes the near-infrared.

- *Autographic theme extraction.*--a derivative application that isolates one or more basic themes, such as water, snow and ice, or infrared reflective vegetation.

Final form depends on the reproduction process used and results in photographic, diazo, or lithographic prints. The choice of final form is generally determined by the expected demand. However, diazo is now limited to a single color whereas the photo and lithographic form may be either in black-and-white or in color.

At this stage of investigation, it is impossible to say what combinations of the characteristics described will result in optimum products. All indications are that out of ERTS will develop one or more series of maps that will be of real value to this country and to the world as a whole.

REFERENCES

Colvocoresses, A. P., 1970, ERTS-A Satellite Imagery, *Photogrammetric Engineering*, v. 36, no. 6, p. 555-560.

Rosenberg, Paul, 1971, Resolution, Detectability and Recognizability, *Photogrammetric Engineering*, v. 37, no. 12, p. 1255-8.

Wong, K. W., 1972, Geometric Analysis of the RBV Television System (Phase II), September 1972; report available from National Technical Information Service, Springfield, Virginia 22151.

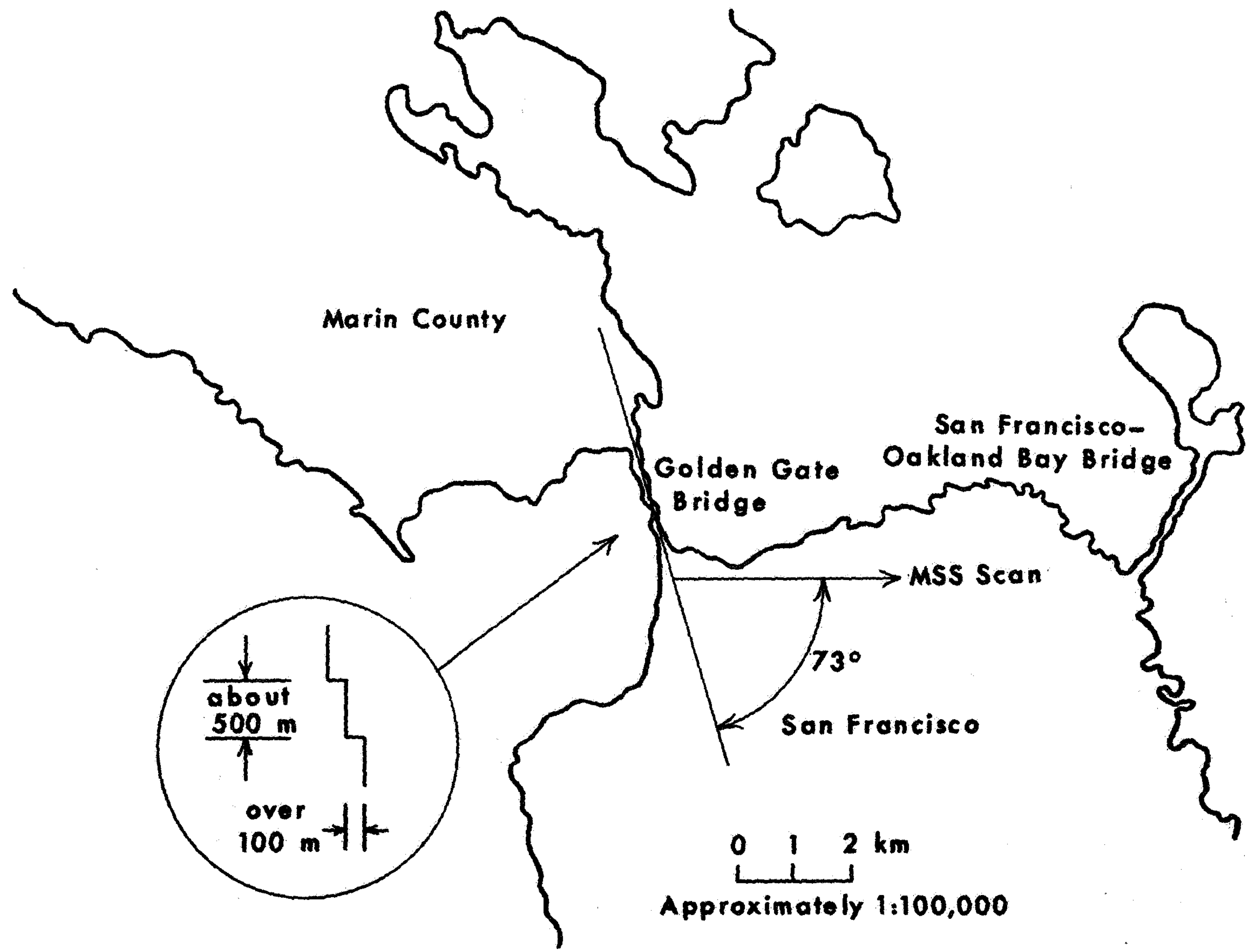

Figure 1. -- MSS line-scan anomaly.

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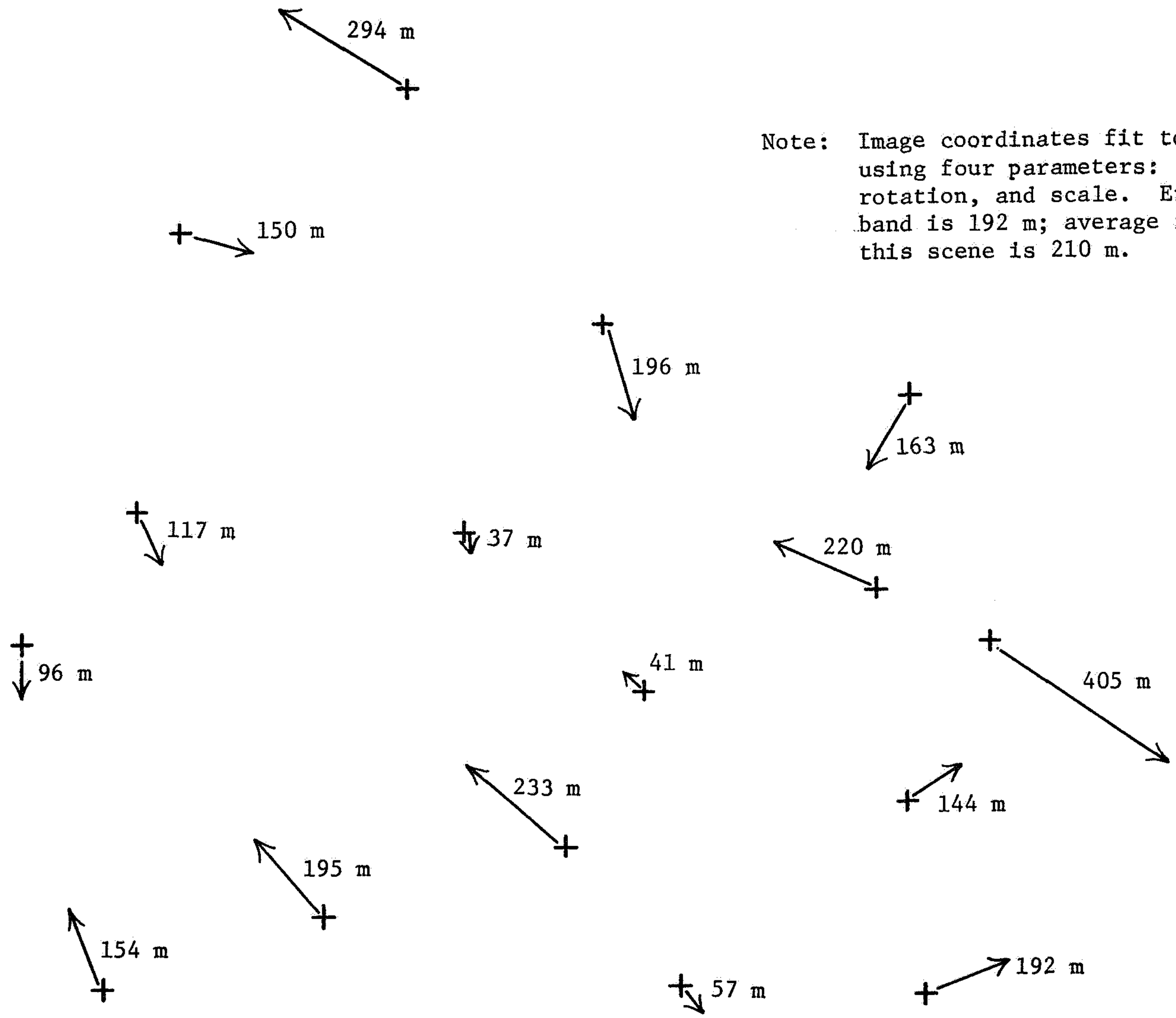

Note: Image coordinates fit to UTM coordinates using four parameters: X and Y translation, rotation, and scale. Error (rms) for this band is 192 m; average for the 4 bands of this scene is 210 m.

Figure 2.--MSS bulk-image distortion (meters); frame 1080-15192-5, Chesapeake Bay area.