PHOTOGRAMMETRIC SCANNING WITH A SQUARE ARRAY CCD CAMERA

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ABSTRACT

Photogrammetric scanning poses the highest requirements on geometric accuracy of scanners. Conventional film scanning devices do not satisfy rigorous accuracy requirements in the conversion of metric photography to digital pixel arrays. There exists therefore the need for separate photogrammetric scanning devices. We describe a new product, the VX3000 precision film scanner which is a device specifically designed to satisfy photogrammetric scanning needs at high accuracy. We express this in terms of pixel size and aim at a scanning accuracy of $\pm$0.1 pixel.

In order to accomplish this accuracy at reasonable cost, the VX3000 scanner avoids a kinematic scanning approach where film and/or sensor dynamically move to assemble a large pixel array. Instead we employ a static square array CCD. Individual square windows of digital imagery are assembled into a large seamless pixel array with the help of an invisible calibration grid or reseau. Radiometric and geometric accuracy are the result of extensive calibrations by software; the product can be denoted as software-leveraged hardware.

1. INTRODUCTION

Acceptance of softcopy (or digital) photogrammetric production systems is contingent upon availability of decentralized capabilities for precision ditgitization of aerial photography. This must not only be accurate to within photogrammetric standards, but also sufficiently inexpensive to not disqualify the cost of digital systems.

A review of alternatives for film scanning reveals that the offering is dominated by devices designed to address the needs of the Graphic Arts and desk-top publishing industries. Geometric accuracy and resolution, radiometric accuracy and resolution, as well as throughput, are optimized for this market with its need for certain pixel sizes at no more than perhaps 600 dots per inch (dpi) equivalent to 40 µm per pixel for desktop publishing, and up to 2000 dpi which is equivalent to 12.5 µm per pixel for color separation. Data formats of 36 mm to 4" x 5" dominate, and file sizes of 16MByte are already considered rather large. Geometric accuracy is of no concern and may be off by $\pm$500µm.

Since the photogrammetric market is small, it is impossible to achieve a specialized photogrammetric equipment offering at low cost by relying on economies of scale and large production lots. Instead, small production lots of specialized solutions must be "smart" to be inexpensive.

We describe in the following the VX3000 photogrammetric precision film scanner which offers photogrammetric accuracies in the micrometer range, geometric resolutions better than 10 µm per pixel, mono-comparator mode and light table operations. This device is available at a cost of less than typical Graphic Arts scanners, and lends itself to easy integration into a photogrammetric production process of both ortho-photos and stereo-softcopy analysis systems.

2. REVIEW OF PREVALENT SCANNING TECHNOLOGIES

2.1 Assembling Large Pixel Arrays

Figure 1 summarizes the major existing scanning technologies; they rely on compiling a large seamless array of digital pixels from

* a single aperture which is scanning in two dimensions over the document;

* a linear arrangement of apertures which then kinematically assembles the pixel array in a one-dimensional sweeping motion over the document;

* a linear arrangement of apertures which moves over the document two-dimensionally in a meandering manner;

* compiling the large square array through assembly of smaller square sub-arrays.

The required motion *typically* includes a rotating drum if the sensor has a single aperture, and a flat bed if the sensor consists of a linear or square array of apertures. Cost is determined by the needed geometric accuracy of the kinematic process. For the Graphic Arts, where geometric accuracy is not a major concern, this cost can be avoided. Instead, cost may be determined in that field by the required throughput: since very little work is done with the digitized images in the Graphic Arts application, throughput must be high.

In photogrammetric mapping, individual photographs are subject to elaborate interactive and batch processing, either for stereo-plotting or for orthophoto-production; therefore the photogrammetric need for decentralized scanning throughput is comparatively relaxed. Instead, geometric accuracy needs are unforgiving, since any error in scanning may be mis-interpreted as stereo-parallax, or as an error of orthophoto-production.

2.2 Scanning Cameras versus Scanning Systems

The concept of *scanning* is implemented in the form of integrated systems with concern for mounting the film (perhaps even a roll of film), keeping it flat, illuminating it carefully and in a controlled fashion, setting up the scan, formatting the pixels and making the resulting digital files available to the user on a local area network.

Scanning can also be thought of as just the process of *imaging*. In this case the camera produces pixels, and by directing the camera at a photograph, imaging equals film-to-pixel conversion. However, the main purpose of digital cameras is not film scanning, but the creation of "natural" digital images of objects in the 3-dimensional world.

In the absence of appropriate scanning systems the user may be tempted to employ a digital camera on a copy stand, looking at the film image mounted on a light box. This approach has a certain tradition in remote sensing and is therefore addressed here. Digital cameras create large pixel arrays by kinematic assembly from a linear arrangement of detectors, or by using a square array CCD. However, the current limitations are:

* the lack of control over the illumination, and the inability to meaningfully calibrate illumination;

* the limits on the geometric resolution since the number of sensor elements typically defines the number of pixels that can be resolved;

* the limits on geometric accuracy due to the undefined relationship between the camera and object;

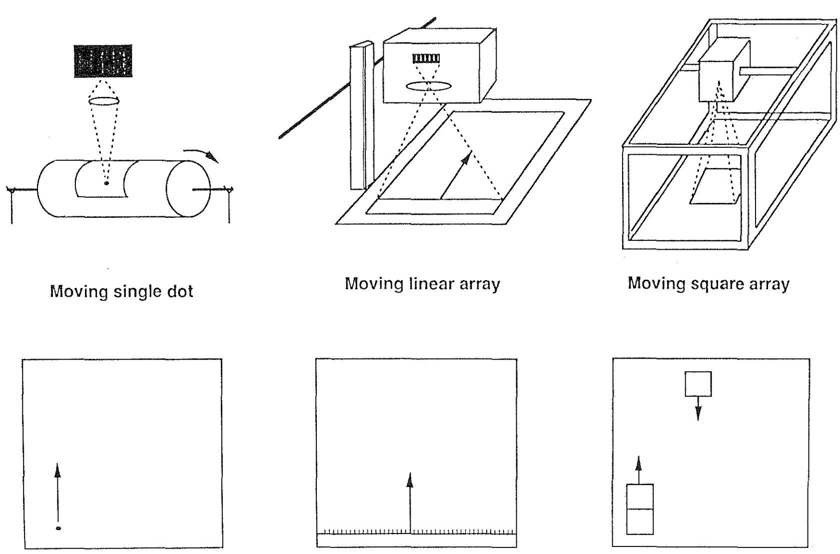

Figure 1: Major scanning technologies using photo-detectors, linear CCD arrays and square array CCDs.

* the optical field of view that is provided by a single lens, and the inability to cover both a large field of view and obtain a large pixel array.

3. GEOMETRIC RESOLUTION AND ACCURACY IN PHOTOGRAMMETRY

3.1 Resolution of Mapping Photography

Mapping photography typically is taken with a geometric resolution of perhaps 30 line-pairs per millimeter (lp/mm). In the event where forward motion compensation is applied, this resolution is said to improve at times towards 60 lp/mm (Meier, 1984).

At times one might hear a discussion of even higher resolutions in photo-interpretation. However, this might not be a discussion of original mapping photography, but of imagery obtained by recording orginially digital electro-optically sensed data onto film at a *selected* pixel size and resolution. Such recordings can be at resolutions in excess of 100 lp/mm.

3.2 Point Positioning Accuracies

Mapping photography supports geometric point positioning accuracies of ±2 µm in the image. It provides stereoanalysis with a sensitivity to stereo-parallax differences in the range of ±2µm, although more typically *dynamic* stereo accuracies (not resolution!) are at times ±10 µm to ±15µm or 1 part in 10,000 (at a camera focal length of 152 mm, this represents an accuracy of ±15µm). Note should be taken, however, of the increasing accuracies in our field; most recently, accuracies of 1 part in 1 million were reported (Fraser, 1992).

3.3 Orthophoto Accuracies and Resolution

The least demands on geometric accuracies traditionally have been coming from the orthophoto. Since this is an analogon of the planimetric map, accuracy does not need to be any greater than that in traditional maps; this is defined in planimetry by the "graphical accuracy" or the ability to draw accurately by hand, to symbolize objects by line weights, and by the generalization of certain mapped objects if not enough room exists at presentation scale for the various symbols needed. Orthophoto accuracy does not need to be any greater than ±0.2 mm at presentation scale, and since micro-detail is not ortho-rectifiable (trees, buildings etc.), accuracies of ±0.5mm to ± 1.0mm have been found to be acceptable. The required scanning accuracy depends therefore on the enlargement between original photograph and orthophoto: at a 5 x enlargement, an accuracy of ±20µm to ±40µm could be acceptable.

At the same time there is the issue of legibility of image detail. One finds references in the literature that a viewer will not be able to take advantage of more than 8 pixels per millimeter at presentation scale, or 125µm per pixel. With an enlargement of 5 x, 25µm pixels should be adequate.

3.4 Choosing Pixel Size

Traditional measures of resolution are in terms of linepairs per millimeter at a certain contrast or by *"granularity"* of the emulsion. Measures of accuracy are in terms of root mean square errors of point position at photo scale, in µm. Pixel size relates to *"interpretability"* of the image and to *"geometric positioning"* of an object.

"Resolution" must be translated into pixel sizes for digital photogrammetry. Some research has been reported on this subject. Examples include the work by Funkhouser (1978), Konecny et al. (1979), Makarovic and Tempfli (1979), Doyle (1982), Hempenius et al. (1986), Trinder (1987 and 1989).

(a) Resolving Detail. A straightforward relationship is at times quoted which argues that one line-pair needs to imaged into 2 pixels, simply because a line pair consists of a white and a black line , i.e. of at least two image elements (Funkhouser, 1978). However, if pixels were to cover half of the black line, half the white line, the two lines would not be resolved. Therefore 2.8 pixels are suggested to resolve the two lines (e.g. Konecny, et al., 1979).

Makarovic and Tempfli (1979) employ modulation transfer functions to assess the fidelity of certain spatial frequencies as they get sampled in a digitizing process and conclude that 3.3 pixels are needed for each line-pair.

Some considerations ignore the fact that the binary line-pair is imaged into 8-bit pixels with gray values between 0 and 255. Hempenius et al. (1986) persuasively argue with the help of granularity, resulting in pixel sizes relaxed to less than 2.8 per line pair; typically 25 µm are recommended. However, the authors are discussing interpretative content, not geometric pointing accuracy.

(b) The issue of geometric pointing. Trinder (1987) reports on research to find the statistics of positional errors from manual measurements of symmetric features, like fiducial marks, as a function of pixel size. He found that positional error of 0.18 * pixel size must be expected from manually centering on a point. For scans with 25 µm pixels, ±4 µm errors will be expected for symmetric fiducial marks. Such errors propagate into the stereo-model setup; furthermore, stereo-parallaxes get additionally contaminated by such errors so that a height error of ±9.4 µm will be introduced just from a 25 µm pixel size. Trinder (1987) therefore concludes that:

> "pixel sizes of 10 µm or smaller must be considered as necessary for photogrammetric operations".

The topic is thus still shrouded in some "fog", therefore we determine that geometric resolution is to be expressed as pixel size p in micrometers (µm) as a function of n lp/mm in a range as follows:

$$1000/(3.3 * n)\ \mu m < p < 25 * (granularity/20)\ \mu m$$

At 30 line-pairs per millimeter, or a granularity of 20, this translates into:

$$10\ \mu m < p < 25\ \mu m,$$

and at 60 lp/mmm:

$$5\ \mu m < p < 12.5\ \mu m.$$

Trinder (1987) suggested that centering a (manual) measurement on a symmetric target like a fiducial mark in a digitized image may be in error by 0.18 of the pixel size. Then, to accomplish a ±1.5µm or ±2µm accuracy of (manual) pointing, pixels should be 8.5 µm to 11 µm.

However, it has been demonstrated by Fraser (1992) that automated centering does not suffer from this limitation. Subsequent work by Trinder (1989) therefore assesses the same accuracy issue, but for a specific *automated* centering algorithm. In this case, and with 8 bits per pixel, centering errors become negligibly small at ±0.1 pixel diameter.

(c) A Guide to Selecting a Pixel Size. While published studies provide some guidance to select a pixel size, there remains uncertainty as requirements of image interpretation need to be weighed against issues of geometric accuracy.

3.5 Conclusion

A balanced photogrammetric system will require that the scanning function satisfy the demands of resolving the image content, of point positioning and of stereo-measurement. However, initial uses of digital photogrammetric systems are for orthophoto generation; since orthophotos follow their own relaxed accuracy standards, users have initially been led to live with relaxed scanning accuracies and resolution.

If the entire suite of photogrammetric operations needs to be supported on a softcopy digital mapping system, then pixel sizes may have to be available of up to 8.5 µm, although some arguments can be made that 20 µm to 25 µm are sufficient.

4. THE VX3000 PRECISION FILM SCANNER

4.1 Principle of Operation

As previously described by Leberl (1989, 1992) and Rosengren (1990), the VX3000 is based on the use of a moving digital camera with a square array CCD to digitize a *window of imagery* of about 512 x 512 pixels in a stationary mode. Motion of the camera is discontinuous, i.e. the camera is stationary at the time of imaging, but is being displaced into a new position after a window has been digitized. A large image is formed from combining many smaller image windows or "tiles".

Figure 2 illustrates the flow of the digitizing process: two images are taken at each position of the camera, one being of a calibration grid, the other of the actual film image segment in the field of view. High image quality is obtainable from

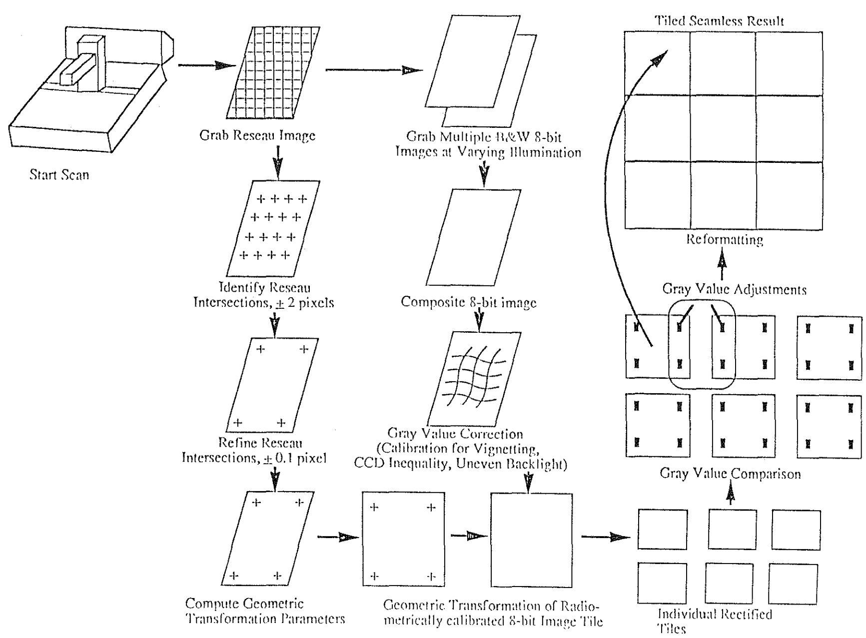

Figure 2: Flow of digitizing process implemented in the VX3000 precision film scanner.

averaging multiple image windows at each position of the stationary camera, and by carefully modeling and controlling the illumination system. The image of the calibration grid or reseau serves to provide the geometric transformation parameters for the film image window.

4.2 Major Functions

(a) Setting up a Scan. Figure 3 presents the graphical X-Windows/Motif user interface of the VX3000 and thereby illustrates the functionality. The user defines an "area of interest" to be scanned, and selects this area interactively in the light table mode, together with the pixel size and file name for the resulting pixel array.

(b) Scanning into a Fiducial Coordinate System. If the area or region of interest (ROI) is smaller than the area defined by the fiducial marks, then the user can enter into the "comparator mode" and measure the scanner reference coordinates of individual fiducial marks using the scanner itself as the measuring device. Subsequent scanning is into a coordinate system defined by the measured fiducials. Alternatively, the scan is into the table coordinate system, but the header of the scan file contains the coordinates of fiducials in the table system for the user to employ.

4.3 Performance

Table 1 contains the elements of a typical acceptance test which is being routinely performed upon delivery of a VX3000. It is largely self-explanatory. Several elements may deserve separate examination.

(a) Geometric Resolution. We employ a geometric resolution target reproduced at different resolutions of 40 µm, 20 µm , 12 µm and 10 µm. Inspection of the target on a screen reveals that the following line-pairs per millimeter can be resolved:

40 µm ....14 lp/mm.....1.8 pixel/lp;

20 µm.....................28 lp/mm.....1.8 pixel/lp;

12 µm.....................40 lp/mm.....2.1 pixel/lp;

10 µm.....................45 lp/mm.....2.2 pixel/lp.

(b) Radiometric Accuracy. To assess radiometry, we use several tests. Figure 5 is a curve showing the mean radiometric value observed by the scanner at various locations on the backplane. We find confirmed that the radiometric variation is less than ± 2 digital numbers (DNs).

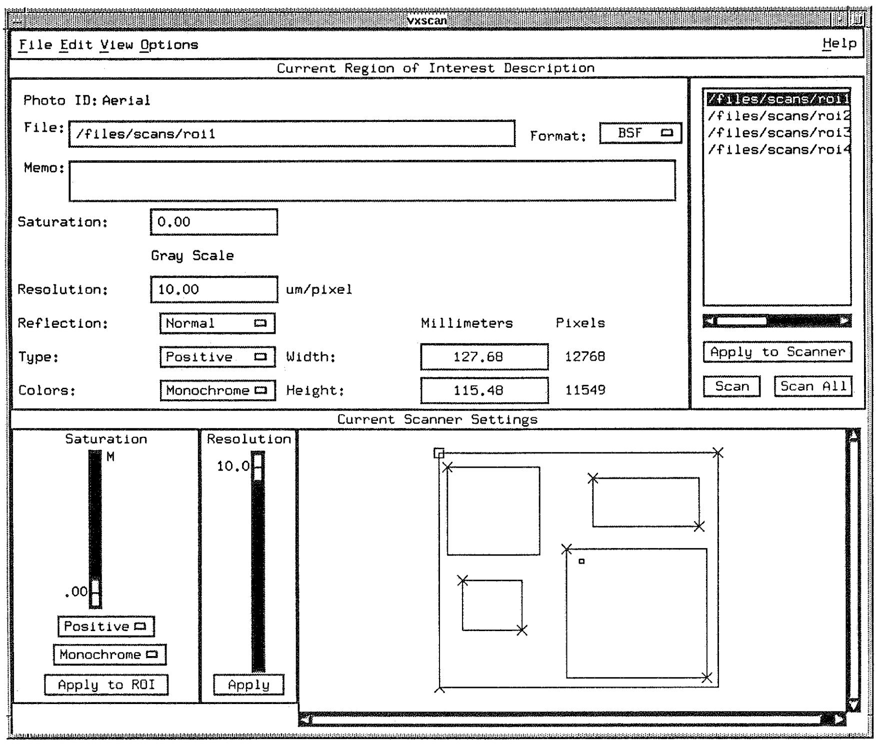

Figure 3: Graphical user interface of the VX3000.

(c) Multiple Regions of Interest. A photograph may contain more than one region of interest, or the scanner may hold more than one photograph. This can be accomodated by defining several ROIs for one scan job to be completed. These scans can be at different resolutions, and can overlap arbitrarily.

(d) Selection of Resolution and Saturation. In the interactive mode, the user can preview any pixel size between the extremes of 165 µm and 8.5 µm, and can set the gray value sensitivity. Upon satisfying the review of the expected appearance of the image, the scan would be started.

(e) Black and White, Color, Negatives. Scanning of positives and negatives is supported, as well as of black and white and of color images.

(c) Geometric Accuracy. The principle of scanning is self-verifying as far as geometric accuracy is concerned. Any small geometric error in positioning the camera would be noticeable in the seams of individual tiles.

However, in order to verify geometric accuracy, we have used a mylar test grid with 1 mm x 1 mm rectangular crosses. This grid was scanned at 30 µm to create an output image of 2050 x 2050.

The analysis of this image was performed using an interactive digitizer program. The points were gathered by placing a cursor over the crosses and manually digitizing them. A total of 1342 points were collected. A linear conformal transformation of coordinates reveals an RMS discrepancy of

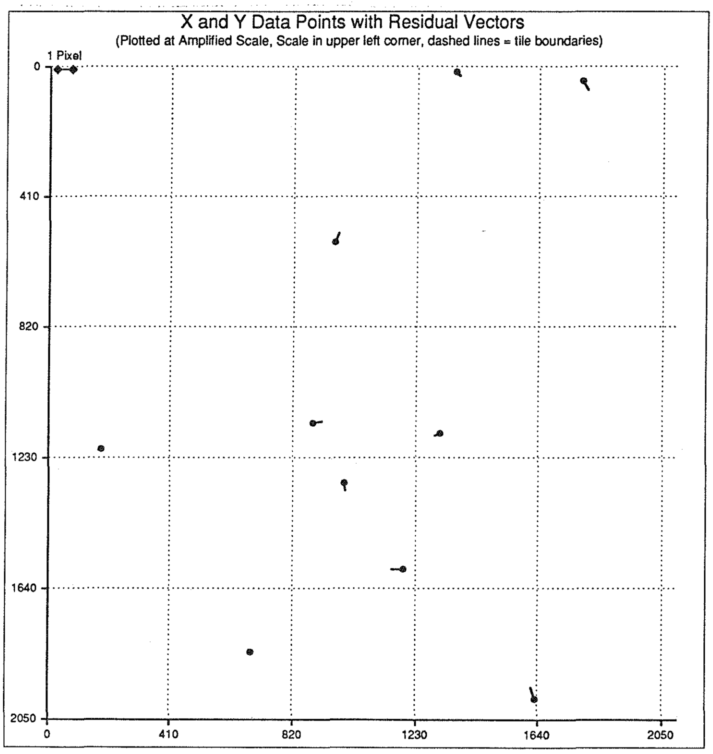

Figure 4: Geometric accuracy plot, obtained by manually measuring 10 randomly located points on a 2050 x 2050 pixel area. Pointing was to the nearest pixel only (no sub-pixel pointing). R.M.S. differences between known coordinates coordinates measured on the scanned image are ± 0.4 pixels.

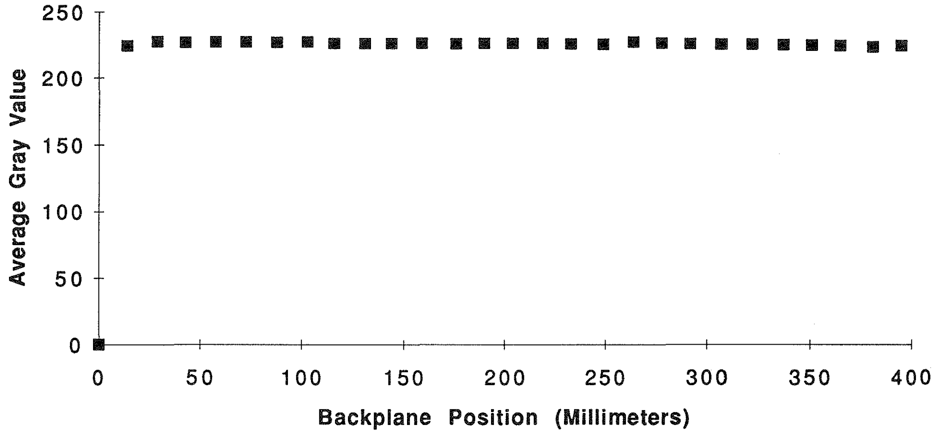

Figure 5: Mean radiometric value observed by the VX3000 of a uniform object at various locations on the film carrier. Ordinate: Digital Number (DN); Abscissa: Millimeters along the backplane. R.M.S. variation is ± 1.5 DN.

VX3000 ACCEPTANCE TEST ELEMENTS

Characteristic	How Performed
Interactive control	Demonstration
Resolution range	Examine resolution target
Region of interest - scanning	Demonstration target
Radiometric uniformity	Scan uniform background Analyze with software
Geometric accuracy	Scan known test target

Table 1: Elements of a scanner acceptance test.

.42 pixels for x and .44 pixels for y. Figure 4 shows the distribution of these errors over the image.

Since the manual measurement technique used only the "nearest neighbor", we must implement an automatic centering algorithm to find the actual accuracy of the scanner.

(d) Throughput. An entire 23 cm x 23 cm aerial photograph will currently be scanned at a resolution of 25 μm per pixel in 45 minutes of wall clock time. This time includes the setup and transfer of the scan result onto a user's disk via Ethernet.

5. CONCLUSION

We report on the new VX3000 scanner for photogrammetric decentralized precision film scanning. We discuss various scanning principles which are currently in use by various vendors. We explain the operations and functionality of the new VX3000 and present a set of performance numbers to include radiometry and geometry.

We believe that the VX3000 satisfies the requirements for a photogrammetric precision scanner for use in orthophoto production, photogrammetric point positioning and routine stereo data extraction.

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