PRACTICAL PAPER

Evaluating a Low-Cost, Non-Metric Aerial Mapping System for Waste Site Investigators

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Abstract

This paper examines a complete low-cost aerial mapping system for waste site investigation. Photos taken with a hand-held, standard 35-mm camera are enlarged using a commercial color copier. Stereoscopic and monoscopic measurements are captured with a digitizing tablet using conventional photogrammetric solutions. System development and operating procedures are outlined, followed by three waste site applications. Particular attention is devoted to errors associated with interior orientation.

Introduction

The success of a new system for waste site investigation generally comes by the pull of need rather than the push of technology. Virtually all waste site investigators require time- and geo-referenced information. Time referencing is important because chemical and biological interactions are related to cause-and-effect events. In addition, investigators require data frequently (perhaps several times a month), and they need these data often within days notice. Geo-referencing data implies plotting points in a standard or local coordinate system. Spatial location is important because many chemical and ecological reactions are influenced by topography. Waste site investigators, therefore, require time-related descriptions of a three-dimensional (3D) environment. And, of course, they need to capture these data accurately and efficiently.

Regarding accuracy, keep in mind that there are two types: absolute and relative. *Absolute accuracy* is the exactness of locating the position of a given point to a global coordinate system (e.g., UTM). It is primarily geodetic and it is of particular interest for relating the waste site to a fixed datum. Because many waste sites border shorelines, knowing elevation relative to datum water levels is often imperative.

Relative accuracy compares measured and true differences in locations between points of interest. When investigations focus upon cause-effect relationships within a site, relative accuracy is of greater concern than absolute accuracy. For practical purposes, such as excavation and sampling site dynamics, the relative accuracy requirement is 0.5 to 2 m.

Regarding efficiency, investigators should perform as many of the mapping tasks as possible in-house, without procuring expensive equipment and extensive training. The map data must be in digital form and easily exported to a variety of file formats (e.g., for generating a digital elevation model (DEM) or input to a GIS). Finally, turn-around time from data capture to map analysis should be a matter of days, not weeks.

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Small-Format Aerial Surveys

"Do-it-yourself" small-format (35- and 70-mm) aerial surveys are well suited for waste site investigators because they balance accuracy with economy. During the past decade small-format aerial surveys have matured from experimental designs (e.g., Graham and Read, 1984) to operational systems (e.g., Heimes *et al.*, 1993). Generally speaking, an accurate small-format measurement system relies on a metric camera, because a metric camera has a fixed and constant interior orientation. Although a non-metric (sometimes called "standard") camera can be used for measurement purposes, it is not designed specifically for photogrammetry: its interior orientation is completely or partially unknown and is frequently unstable. Standard cameras are easily identifiable by the lack of fiducial marks, although the availability of fiducial marks *per se* does not render a camera metric. Compared to metric cameras, standard cameras have the following advantages and disadvantages (Karara, 1980). The advantages are

- General availability.
- Flexibility in focusing range.
- Some are motor driven, allowing for quick succession of photographs.
- They are usually smaller in size and lighter in weight.
- They can be easily hand-held and thereby oriented in any direction.
- They use readily available film.
- The price is considerably less than metric cameras.

The disadvantages are

- Lenses are designed for high resolution at the expense of geometric quality, as evidenced by generally large and often irregular distortion.
- Instability of interior orientation.
- Lack of fiducial marks.
- The absence of proper film flattening devices.

With the advent of the computer, a number of analytical data reduction techniques have reduced the effects of the above disadvantages. For example, the direct linear transformation (DLT) approach (Marzan and Karara, 1975) eliminates the need for fiducial marks; and the 11-parameter solution (Bopp and Krauss, 1978) provides on-the-job calibration for standard cameras. Although the two solutions have disadvantages, these and other analytical solutions have solved many of the orientation problems associated with standard small-format photography (Abdel-Aziz and Karara, 1974; Karara, 1980; Kölbl, 1976).

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Figure 1. The Cub offers low stall speed and excellent visibility. A microphone built into the face mask enables the photographer to communicate with the pilot while the window/door is open.

The notion of mapping with a standard 35-mm camera is not new. More than a decade ago Welch and Jordan (1983) captured image measurements on positive film enlargements with a cartographic digitizer (25-μm resolution). Although a digitizer is used primarily for the measurement of points, lines, and areas from map data, it also can be used to measure points on enlarged photographs to sufficient precision and accuracy for analytical adjustments. With enlarged film transparencies, the precision at negative scale is computed by dividing measurement precision by the enlargement factor. For instance, Welch and Jordan's (1983) close-range measurement precision of x, y coordinates averaged ± 0.03 mm on the enlarged image (1:61) scale, or ± 1.8 mm on the ground. "When reduced to the original negative scale, this precision is equivalent to approximately ± 4 μm, which is approaching the precision of a photogrammetic comparator" (Welch and Jordan, 1983).

A Low-Cost, Non-Metric Aerial Mapping System

Three years ago JORDFORSK (Norway's Center for Soil and Environmental Research) began developing a "do-it-yourself" aerial mapping system designed for those with no photogrammetric experience. The objective was to create a system in which photos taken from a hand-held standard camera could be used for mapping and measuring with standard office equipment. This resulted in enlarging 35-mm photos with a Canon color laser-scanned copier, and capturing measurements with a digitizer driven by Carto MDSD software. The principal aim in developing the complete aerial mapping system was to create maps quickly, inexpensively, and with acceptable accuracy.

Accuracy

Point location accuracy is influenced by several factors: accuracy of the measurement system, print quality and size, geometric quality of the camera and its position and attitude, landscape characteristics (terrain variation), quality of control points (distribution and accuracy of ground coordinates), method of photo measuring (mono- or stereoscopic), and, of course, human error. The combinations make it difficult to state expected measurement accuracy at ground scale; however, it is possible to state key accuracy factors for the three major components of system described in this paper.

- Radial lens distortion of the standard 35-mm camera used in this study is ± 55 μm. Although the camera is calibrated (Ø. Andersen, unpublished report, 1990), I use nominal values for frame-edge corners (based upon a 36- by 24-mm format) for interior orientation, and a nominal focal length value of 35 mm for exterior orientation. Later, I explain why calibrated data are not used.
- The digitizing tablet has a (manufacturer) stated accuracy of 100 μm. Its calibrated accuracy is ± 87 mm (Warner and Carson, 1991).
- Image deformation of enlarged prints from the Canon CLC200 color copier are relatively small. A dense array of targets on transparencies were measured and compared with corresponding measurements on enlargements: least-squares affine coordinate transformations showed RMS errors of 12 to 16 μm at original photo scale, and skewness and stretch of about 1 mm at 12 × enlargement scale (Warner and Andersen, 1992).

Cost

Like accuracy, cost is difficult to pinpoint. But assuming one has a standard 35-mm camera, PC-driven digitizing tablet, laser printer, and access to a color laser-scanned copier, it is possible to examine the basic expenses of the complete system: from taking the aerial photography to issuing a map.

Based upon personal experience, the cost of small-format aerial photography generally runs around US $100/hour (including light-aircraft rental with pilot (Figure 1)), which averages to US $300 per mission for our waste site investigations. Generally, the greatest expense of the total mission is the flying time between the airport and the waste site.

Film is developed at a commercial laboratory, and transparencies are enlarged using a commercial, color laser-scanned copier. Costs vary world-wide, but in Norway laser-scanned copying is 10 to 20 percent of conventional photographic enlarging.

Carto MDSD software costs US$ 2500 and does not require specialized hardware. The programs execute on the full range of IBM-PC compatible equipment—PC/AT, 386, and 486 machines (with a math co-processor)—and interface with most digitizing tablets. Photo data are exported to Golden Software's MapViewer (US$ 249) where text and symbols are added and a map is issued. For creating a DEM or computing volumes, data are exported to Golden Software's SURFER (US$ 499). Although mapping costs depend on the scale of the projects, I have found that most waste sites can be mapped within a few hours.

Operating Procedures

Although the MDSD software enables one to measure from a single photograph or a stereopair, I shall focus attention upon the former. Monoplotting uses space resection by collinearity, which is purely a mathematical method that simultaneously yields all six elements of exterior orientation. It is a versatile method that determines the rotational elements (ω, φ, κ) and the camera perspective center. It also permits the use of redundant ground control information. Hence, least-squares computational techniques can be used to determine most probable values for the six elements. MDSD monoplotting is based upon an exterior orientation program

Figure 2. Left photo of overlapping photography. Original photo scale about 1: 9300 (27°ω and 4°ϕ).

developed for the Carto AP190 analytical plotter (Carson, 1987).

Operating procedures consist of two basic steps: photo orientation and photo measurement. The first step transforms digitized coordinates of the enlargement to the original photo-coordinates, followed by orienting the photograph to the ground. The second step digitally records a two-dimensional point (x,y) from the print and queries a DEM for elevation. From a collection of two-dimensional photo coordinates (x,y) and the associated elevation (z) supplied by the DEM, line length, area, slope, and azimuth can be computed to ground coordinates in near real-time. Data can be read-out in a variety of formats (e.g., Auto/Cad, Erdas, ARC/INFO, Golden Software SURFER, and MapViewer). The following summarizes the actual tasks:

Photo Orientation

Interior orientation transforms the digitizer coordinates of the photograph to the measurement system, and accounts for any scale change due to film shrinkage or stretch during development. The procedure consists of taping an enlargement to the digitizing tablet and digitizing the four frame-edge corners. The software then matches digitizer coordinates to the camera coordinates and computes an affine transformation. Because the enlarging process crops the original image, calibrated frame-edge corners are useless. Interior orientation errors caused by the enlarging process are discussed later.

Exterior orientation scales and levels the photograph to the ground, then determines photo accuracy. Six or more well-distributed control points assure a robust fit. Exterior orientation generally requires a calibrated focal length for scaling purposes. However, considering all the systematic errors associated with this mapping method, a nominal focal length value appears adequate. An explanation is in order. A wrong focal length usually does not influence the accuracy of points on the ground very much because parameters of the interior and exterior orientation are correlated. For example, errors in the focal length and flying height are highly correlated. Therefore, errors in the focal length are "compensated" by a (wrong) flying height.

Photo Measurement

The software's *point collection* mode ties the oriented photo to a DEM and transforms (x,y) photo coordinates into (X,Y,Z) ground coordinates. In other words, as the digitizer cursor moves to a point on the photo, the software queries the DEM for elevation (Z) and computes the point's three-dimensional Cartesian coordinates in near real-time.

A critical issue with monoplotting is the DEM that supplies elevation data (Warner *et al.*, 1993a). The DEM can be generated from different sources. If the landscape is relatively flat, a DEM is created internally from control points. If the landscape has substantial terrain variation, thus causing relief displacement, a DEM is imported from an external source. Unfortunately, DEMs often do not exist, or those provided by mapping authorities are too crude for large scale imagery. Under these conditions, a DEM is created from photogrammetric height measurements captured from two overlapping photographs.

To collect elevation data with the MDSD, the measurement system is switched to stereo-mode: two enlargements are mounted side by side on the digitizing tablet, and the model is oriented following the conventional procedures of interior, relative, and absolute orientation. Next, in stereo measurement mode, a ground object (point) on the left photo is digitized, followed by recording the same ground object (point) on the right photo, and object height is computed (in near-real time). After sufficient elevation points are recorded, the data are exported to Golden Software's SURFER program and a DEM is generated.

Waste Site Applications

The system has proven moderately successful for waste site investigation in Norway. The following is a summary of three

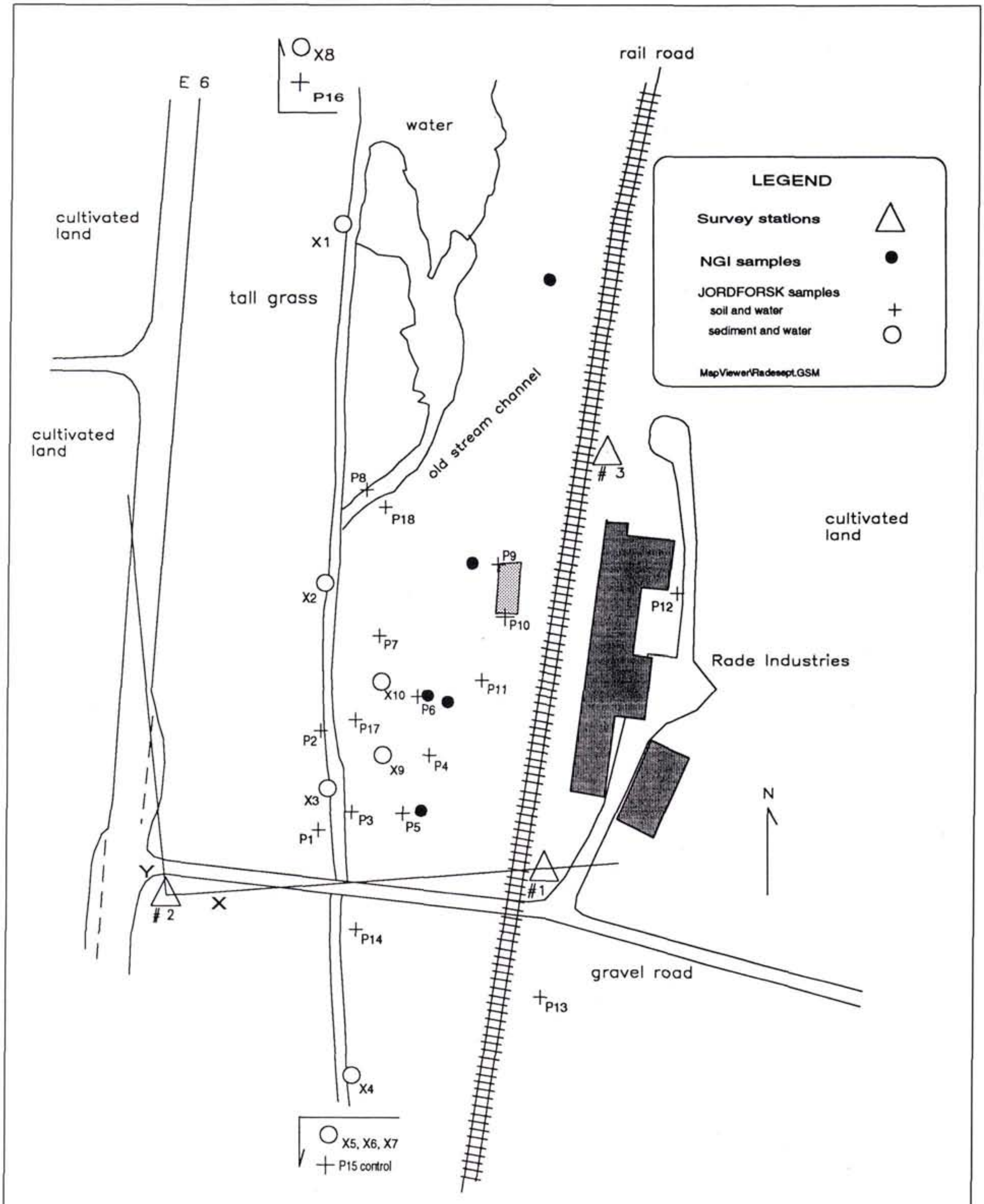

Figure 3. Map created from Figure 2. Road (partially obscured by aircraft wheel) and buildings were edited in MapViewer to make them orthogonal.

applications. In all cases, photography was taken with the hand-held, standard 35-mm camera, fitted with a 35-mm lens.

In the first case, the objective was to plot in the field five points marked on an enlargement of a near-vertical photo (1:

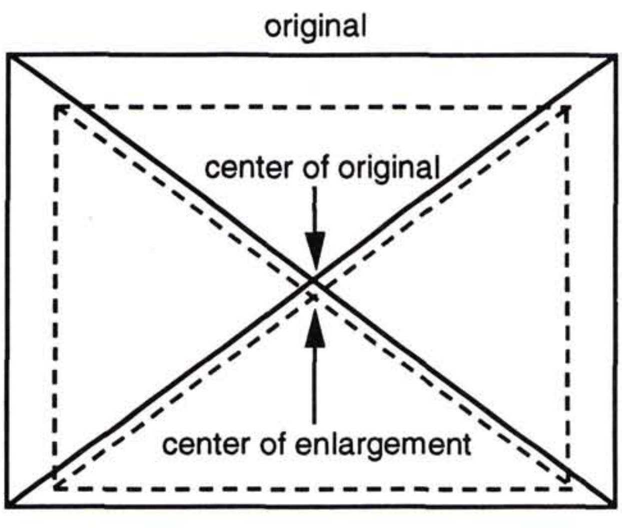

Figure 4. Interior orientation error: center of enlargement and principal point might not coincide.

5187 original photo scale). The five points were proposed locations for monitoring instruments (based upon buried waste and potential pollutant pathways identified from large-format historical photographs). A DEM was created by measuring 50 elevation points from an oblique stereopair (1:12,000 original photo scale, with about 28°ω). Warner *et al.* (1993b) details the procedures. With this DEM supplying elevation data for the near-vertical photo, I measured three distances from each instrument location to reference points (e.g., manholes). These distances were then triangulated in the field with a measuring tape (a 35-minute operation). In addition, eight line-lengths measured on the photo and compared with field measurements showed the accuracy of monoscopic measurements to be within ± 0.43 m.

In the second case, the objective was to map existing instrument locations at a swamp-like site that was not suitable for a field survey. First, with a theodolite, seven permanent features (e.g., telephone poles) surrounding the 400- by 300-m site were surveyed. I then placed targets at 25 instrument locations and photographed the site at about 400 m above ground level. From two overlapping oblique photos (about 25°ω), the expected accuracy of the stereomodel was about 0.5 m. I measured the X,Y,Z coordinates of 25 points and created a DEM for monoplotting. In the monoplotting mode, buildings, roads and waterways were registered from Figure 2. Data were exported to Golden Software's MapViewer, where labels and a legend were added and a map was issued (Figure 3). Excluding the time it took to commercially develop the film, the entire mapping project (surveying control points, photographing the site, and issuing a map) took less than 24 working hours.

In the third case, the objective was to map five filtration lagoons—newly constructed at the base of a rural waste site—and measure their surface areas. The absolute accuracy requirement was 2 m. Although the area of interest was about 400 by 250 m, an area about twice that size was photographed in order to pick up control points. Control points were digitized from a 1:5000-scale map, with 5-m elevation contours. Expected planimetric accuracy of the oblique photo (about 40°ω and 4°φ) was X 2.27 m and Y 2.10 m. Because water surfaces were level, for every lagoon I fixed Z at an elevation read from the 1:5000-scale map. Turn around time—from the moment the aircraft took-off to when the final map and measurements were delivered—took less than three days.

Interior Orientation Errors

This small-format mapping technique holds promise for waste site investigators who need to capture geo-referenced data quickly. But at this time waste site investigators need evaluation more than enthusiasm. As noted, location accuracy is influenced by numerous factors, not the least of which is the quality of the DEM when monoplotting with an oblique (Warner *et al.*, 1993a). Greater concerns, however, are the errors associated with interior orientation—errors that often yield affine transformation residuals > 100 µm.

Interior orientation is one of the most troublesome aspects of the system for two reasons. First, to enlarge a transparency with the color copier, the original image must be mounted in a frame holder: this crops the original image. Second, the color copier crops the frame-held image. The net result is that 20 to 22 percent of the original image is cropped (Warner and Andersen, 1992). Consequently, enlarging a framed-mounted image introduces two uncorrected errors:

- The measurement system assumes the center of the enlargement is the principal point. It is impossible, however, to assure that the center of the (cropped) enlargement and the principal point will coincide (Figure 4).
- The affine transformation enlarges the cropped image to fit the original. That should be (but is not) followed by enlarging the focal length.

In addition, enlarging 35-mm film also enlarges its inherent errors (e.g., interior orientation, film shrinkage, lack of film flatness, lens distortion, etc.). The accumulative effect of these inherent errors combined with the 100-µm accuracy of a standard digitizing tablet can never produce an interior orientation solution equal to original photography measured with an analytical plotter.

Recommendations

There are sources of error in any photogrammetric method, including the most sophisticated. But when a digitizing tablet is used to capture measurements from enlarged imagery—taken with a hand-held, standard 35-mm camera—errors are abundant. It is foolish to assume that the technique described herewith can provide reliable, metric measurements. To do so, either the camera, the enlarging process, or the measurement system—or all three—need to be altered. The price for improving accuracy, however, is not small.

For instance, a camera fitted with a réseau (a calibrated array or grid of points in the focal plane) would improve interior orientation. And a calibrated focal length would provide a more accurate solution for exterior orientation. For example, Rollei manufactures two 35-mm cameras fitted with a réseau. The Rollei 35 is a semi-metric, fixed focus camera with aperture or shutter speed priority (US$ 2500). The more versatile Rollieflex 3003 metric offers a variety of interchangeable lenses, built-in motorized film transport for fast sequence shooting, interchangeable magazine facility, etc. (US$ 5400).

Instead of using a color laser-scanned copier, one could enlarge original imagery with a calibrated optical enlarger.

Commercial enlarging is not recommended for three reasons: (1) 10 by 20 percent of the original 35-mm image is cropped, (2) distortion caused by the enlarger lens system introduces systematic error, and (3) enlarging may change the tip and tilt orientation imparted to the original image if the planes of the film and the photographic paper (onto which the enlarged image is projected) are not parallel (Needham and Smith, 1984). Using a calibrated optical enlarger, however, does not eliminate the inherent errors of a standard camera.

To capture reliable measurements from standard cameras, the MDSD should add to its suite of software a calibration program for non-metric cameras: several are described by Karara (1980). An alternative is to replace the digitizer with an analytical plotter that calibrates original imagery. For instance, the Adam Technology MPS-2 has a precision of 4 µm at the scale of the photo, provides self-calibration for standard cameras, compensates for lens distortion, handles oblique and vertical photography, and can be used as a monoplotter (US$ 35,000). Another alternative is to digitize (scan) the original imagery, run a combined adjustment which includes interior and exterior orientation parameters, and use the monitor to digitize locations. This would add flexibility in terms of zooming in and out, and would eliminate the enlarging process.

Conclusion

In the final analysis, even an amateur will admit there are limitations to the outlined mapping technique; however, given the operational demands of many waste site investigators, the system is suitable for investigations during the exploratory phase. Our litigious society demands that a map must meet (U.S.) National Map Accuracy Standards for intensive or routine investigations. However, these standards apply only to well-defined points: How well defined is the surface stain of a gradational feature such as a gasoline spill? Keep in mind, for most initial waste site investigations, maps are used primarily for illustration and planning where even a 3-m error might be acceptable if the target source is poorly defined (due to surface disturbance, staining, etc.). Generally speaking, real field locations, such as actual boring sites, are surveyed to a network using conventional field methods. Considering the need for fast, low-cost maps, which may not necessarily meet National Mapping Standards, the advantages of do-it-yourself aerial mapping are many. And, provided that quality is not sacrificed through shoddy performance, it is certain that such systems will become an accepted part of waste site investigation.

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References

Abdel-Aziz, Y.I., and H.M. Karara, 1974. *Photogrammetric Potentials of Non-Metric Cameras*, Civil Engineering Studies, Photogrammetry Series No. 36, University of Illinois, Urbana, 120 p.

Bopp, K., and H. Krauss, 1978. Extension of the 11-parameter solution for on-the-job calibration of non-metric cameras, *International Archives of Photogrammetry*, 22(5):7–12.

Carson, W.W., 1987. Development of an inexpensive analytical plotter, *Photogrammetric Record*, 11(65):525–541.

Graham, R. W., and R.E. Read, 1984. Small format aerial surveys from light and microlight platforms, *Journal of Photographic Science*, 32(3):100–110.

Heimes, F.J., P. Poole, R. Brechtken, and R. Puruckherr, 1993. *LEO: Local Earth Observation*, unpublished paper, International Symposium, "Operationalization of Remote Sensing," ITC, Enschedes, The Netherlands, 19–23 April 1993.

Karara, H.M., 1980. Non-Metric Cameras, *Developments in Close Range Photogrammetry* (K.N. Atkinson, editor), Applied Science Publishers, London, pp. 63–80.

Kölbl, O., 1976. Metric or non-metric cameras, *Photogrammetric Engineering & Remote Sensing*, 42(1):103-113.

Marzan, G.T., and H.M. Karara, 1975. A computer program for direct linear transformation solution of collinearity condition, and some applications of it, *Close-Range Photogrammetric Systems*, American Society of Photogrammetry, Falls Church, Virginia, pp. 420–476.

Needham, T.D., and J.L. Smith, 1984. Consequences of enlarging 35-mm aerial photography, *Photogrammetric Engineering & Remote Sensing*, 50(8):1143–1144.

Warner, W. S., and Ø. Andersen, 1992. Consequences of enlarging small-format imagery via a color copier, *Photogrammetric Engineering & Remote Sensing*, 58(2): 353-355.

Warner, W.S., W.W. Carson, and K. Bjørkelo, 1993a. Relative accuracy of monoscopic 35-mm oblique photography, *Photogrammetric Engineering & Remote Sensing*, 59(1):101–105.

Warner, W.S., S. Andersen, and S. Særland, 1993b. Surveying a waste site with 35 mm oblique aerial photography: monoplotting with a digitising tablet, *Cartography and Geographical Information Systems* 20(4):237-243.

Warner, W.S., and W.W. Carson, 1991. Errors associated with a standard digitizing tablet, *ITC Journal*, 1991–2:82–85.

Welch, R., and T.R. Jordan, 1983. Analytical non-metric close-range photogrammetry for monitoring stream channel erosion, *Photogrammetric Engineering & Remote Sensing*, 49:367-374.

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