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AN EXPOSÉ ON PHOTOGRAPHIC DATA ACQUISITION SYSTEMS IN CLOSE-RANGE PHOTOGRAMMETRY

by

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ABSTRACT

The purpose of this paper is to convey to users and potential users of photogrammetry, as well as to photogrammetrists, the photogrammetric potentials of non-metric cameras vis-à-vis metric cameras. A listing of practically all currently available metric cameras (single and stereometric) is given, together with some of their pertinent characteristics. The role of non-metric cameras in close-range photogrammetry is outlined. The precautions to be taken in connection with the use of non-metric cameras are stressed, and some of the data reduction schemes for non-metric photography are discussed. Conclusions from theoretical studies are mentioned, and results of experimental research and practical works are referred to.

1. INTRODUCTION

Many engineers and scientists in numerous disciplines could, but are not availing themselves of the obvious economical and technical advantages of photogrammetry. Some of the reasons for this unfortunate situation appear to be:

a - metric cameras suitable for the particular project under consideration are not available,

b - in some cases, available metric cameras are considered too expensive to be used by the economy-minded engineer or scientist, particularly in cases of projects with limited budgets,

c - information about the photogrammetric potentials of readily available and rather inexpensive non-metric* cameras has not

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*The terms "non-metric," "simple," "off-the-shelf," "amateur" cameras are used interchangeably throughout this paper.

been given wide enough circulation and thus has not reached many scientists and engineers,

d - some traditional photogrammetrists still think in terms of metric cameras only, and do not consider non-metric cameras as a viable alternative in data acquisition.

The purpose of this paper is to convey to users and potential users of photogrammetry, as well as to photogrammetrists, the photogrammetric potentials of non-metric cameras vis-à-vis metric cameras. It is realized that some traditionally-thinking photogrammetrists may still find it difficult to accept non-metric cameras as components of photogrammetric systems. It is hoped, however, that we can convince these colleagues that if photogrammetry is to be applied on a much larger scale than heretofore, one has to reconsider the stand "metric or none" which is being adhered to rather rigorously by some of them.

As will be illustrated in this paper, highly accurate results can be achieved using non-metric cameras for data acquisition, in combination with an appropriate analytical data reduction scheme.

2. OVERVIEW OF DATA ACQUISITION SYSTEMS

After having limited the scope of this paper to photographic data acquisition only, thereby excluding sensors for radiation other than visible light, it appears proper to distinguish between metric and non-metric cameras.

2.1 Metric Cameras

Under this heading, all cameras specifically designed for photogrammetric purposes are included. Without going into details, it can be stated that metric cameras have a stable interior orientation, referenced with fiducial marks, whose parameters remain constant over extended periods of time, and therefore can be determined by calibration prior to or after the photogrammetric mission.

Tables 1 and 2 list practically all the metric cameras (single and stereometric) currently (1979) available, together with some of their pertinent characteristics. These tables were published in the Handbook of Non-Topographic Photogrammetry (ASP, 1979) and are based, in part, on information from an article by Carbonnell (1973).

2.2 Non-Metric Cameras

Although various types of metric cameras are available, there is an ever-increasing use for off-the-shelf simple cameras as tools for data acquisition in close-range photogrammetric projects with various levels of accuracy requirements.

In this context, a non-metric camera is simply a camera not designed specifically for photogrammetric purposes. According to Faig (1975a), a non-metric camera is a camera whose interior orientation (spatial position of the projection center with respect to the photographic image) is completely or partially unknown and frequently unstable. All "off-the-shelf" or "amateur" or "simple" or "non-metric" cameras belong to this category, and are perhaps easily identified by the lack of fiducial marks, although the availability of fiducial marks *per se* does not render a camera metric.

TABLE 1 CHARACTERISTICS OF SINGLE METRIC CAMERAS

Manufacturer	Model	Format* of Photographic Material (cm)	Nominal Focal Length (mm)	Total Depth of Field (m)	Tilt Range of Camera Axis & Number of Intermediate Tilt Stops	Photographic Material	Comments
Galileo	Verostat	9 × 12 U	100		0→±90° (2)	glass plates or cut film	variable principal distance (in steps)
Galileo	FTG-1b	10 × 15 H	155	10→∞	0→±36° (continuous)	glass plates	variable principal distance (in steps)
Hasselblad	MK70 (Biogon lens)	6 × 6	60	0.9→∞	unlimited$^{\Delta}$	70mm film	Δ hand held or on tripod. variable principal distance (continuous mode) single frame exposure or sequence exposure
Hasselblad	MK70 (Planar lens)	6 × 6	100	15→∞$^{\nabla}$	unlimited$^{\Delta}$	70mm film	∇ fixed focus at ∞ (upon request fixed focus at desired distances down to 2m). Δ hand held or on tripod. motor driven; single frame exposure or sequence exposure.

TABLE 1 CHARACTERISTICS OF SINGLE METRIC CAMERAS *(continued)*

Manufacturer	Model	Format* of Photographic Material (cm)	Nominal Focal Length (mm)	Total Depth of Field (m)	Tilt Range of Camera Axis & Number of Intermediate Tilt Stops	Photographic Material	Comments
Jenoptik Jena	UMK 10/1318 FP UMK 10/1318 NP	13 × 18 UH	99	1.4→∞	−30°→+90° (7)	glass plates	Lamegon 8/100 lens with distortion <12μm for object distances ∞→3.6m. Lamegon 8/100 N lens with distortion <12μm for object distances 4.2→1.4m.
Jenoptik Jena	UMK 10/1318 FF UMK 10/1318 NF	13 × 18 UH	99	1.4→∞	−30°→+90° (7)	190mm roll film & glass plates (with adapter)	Lamegon 8/100 lens with distortion <12μm for object distances ∞→3.6m. Lamegon 8/100 N lens with distortion <12μm for object distances 4.2→1.4m.
Jenoptik Jena	19/1318 Phototheodolite	13 × 18 H	190	25→∞	none[δ]	glass plates	δ lens can be shifted vertically (+30→−45mm) in snap-in steps of 5mm.
Kelsh	K-470	10.5 × 12.7 UH	90	2→∞	none	cut film, roll film, glass plates.	image format offset from the optical axis of the lens by 13mm.

Sokkisha	MK165	12 × 16.5 U	165	10→∞	0→±30° (2)	glass plates	variable principal distance (in steps).
Wild	P32	6.5 × 9 UH	64	0.6→∞	on T1, T16 or T2: 0→±40° (continuous) on GW 1: 0→±30° (continuous)	glass plates, cut film, roll film	variable principal distance (in steps—interchangeable spacers).
Wild	P31	10.2 × 12.7 UH (4″ × 5″)	100	6.6→∞ (f/22) 12.4→∞ (f/5.6)	0→±30° (3) also +90°	glass plates & cut film	variable principal distance (in steps—interchangeable spacers)—wide-angle lens.
	″	″	45	1.5→∞ (f/22) 3.6→∞ (f/5.6)	″	″	Super-wide-angle lens.
	″	″	200	18→640 (f/22) 26→53 (f/5.6)	″	″	Normal-angle lens. Standard focusing 35 m; adapter rings on request; minimum distance 8m.
Zeiss (Oberkochen)	TMK-6	9 × 12 UH	60	5→∞	0→±90° (2)	glass plates	6 close-up lenses are available for object-distances of 0.5m, 0.6m, 0.75m, 1m, 1.5m, and 2.5m.
Zeiss (Oberkochen)	TMK-12	9 × 12 UH	120	20→∞	0→±90° (2)	glass	

*U/H: format Upright/Horizontal; UH: format Upright or Horizontal

TABLE 2 CHARACTERISTICS OF STEREOMETRIC CAMERAS

Manufacturer	Model	Format* of Photographic Material (cm)	Nominal Focal Length (mm)	Base Length (cm)	Operational Range (m)	Tilt Range of Optical Axes and Number of Intermediate Tilt Stops	Photographic Material	Comments
Galileo	Veroplast	13 × 18 H	150	56	1.6→∞	0→±90° (continuous)	glass plates	variable principal distance (in steps)
Galileo	Veroplast	13 × 18 H	150	200	5→∞	0→±90° (continuous)	glass plates	variable principal distance (in steps)
Galileo	Veroplast	9 × 12 U	100	120	2→∞	0→±90° (continuous)	glass plates or cut film	variable principal distance (in steps)
Galileo	Technoster A	6.5 × 9 H	75	16→70	0.5→6	0→±18° (continuous)	roll film	variable base length; convergence of individual cameras possible (o→13°); variable principal distance (in steps)
Galileo	Technoster B	23 × 23	150	30→70	2→5	−45°→+5° (continuous)	glass plates	variable base length
Jenoptik Jena	SMK-5.5/0808	8 × 8	56	40	1.5→10	0→±90° (5)	glass plates	
Jenoptik Jena	SMK-5.5/0808	8 × 8	56	120	5→∞	0→90° (5)	glass plates	
Jenoptik Jena	IMK-10/1318	13 × 18 UH	99	35 − 160	1.4→∞	0→−45 (common ω continuous)	glass plates or 190mm film	variable base length; individual ϕ tilt (0→11°); common ω (0→−45°)

Kelsh	K-460	10.5x 12.7 U	90→ 120	23.7→ 92.0 (14.2 →50.0 for table model)	0.36→∞	None	cut film, roll film glass plates	variable principal distance (continuous); variable base length (continuous); 2 models
Nikon	TS-20	6.5 × 9 H	64	20	0.9→5	0→±90° (2)	glass plates or cut film	
Nikon	TS-40	9 × 12 U	60	40	2.5→10	0→±90° (2)	glass plates	
Nikon	TS-120	9 × 12 U and 6.5 × 9 U	60	120	5→50	0→±90° (2)	glass plates	
Sokkisha	B-45	12 × 16.5 H	121	45	1→5	None	glass plates	designed primarily for bio-medical applications; variable principal distance (in steps)
Sokkisha	SKB-40	6.5 × 9 H	67	40	2.5→10	0→±45° (continuous)	glass plates	
Sokkisha	SKB-120	6.5 × 9 H	67	120	5→∞	0→45° (continuous)	glass plates	
Sokkisha	KSK-100	12 × 16.5 U	90	30→100$^{\Delta}$	1→∞	0→±15° (continuous)	glass plates	variable principal distance (in steps) $^{\Delta}$ base length settings: 30, 50 and 100cm

TABLE 2 CHARACTERISTICS OF STEREOMETRIC CAMERAS *(continued)*

Manufacturer	Model	Format* of Photographic Material (cm)	Nominal Focal Length (mm)	Base Length (cm)	Operational Range (m)	Tilt Range of Optical Axes and Number of Intermediate Tilt Stops	Photographic Material	Comments
Sokkisha	V-3	12 × 16.5 H	121	25→50$^{\Delta}$	0.5→5	0→±27° (continuous)	glass plates	variable principal distance (in steps) $^{\Delta}$ base length settings: 25, 35 and 50cm
Wild	C 40	6.5 × 9 H	64	40	1.5→7 0.9→9	0→±90° (4)	glass plates	standard equipment special
Wild	2P 32's with Base-Bar	6.5 × 9 UH	64	40,30, 20	0.6→2.5	horizontal only	glass plates, cut film roll film	
Wild	C 120	6.5 × 9 H	64	120	2.7→∞	0→±90° (4)	glass plates	
Zeiss (Oberkochen)	SMK-40	9 × 12 U	60	40	2.5→10	0→±90° (2)	glass plates	6 attachable close-up lenses are available for object distances of 0.5m, 0.6m, 0.75, 1m, 1.5m, and 2.5m
Zeiss (Oberkochen)	SMK-120	9 × 12 U	60	120	5→∞	0→±90° (2)	glass plates	

*U/H: format Upright/Horizontal; UH: format Upright or Horizontal

Essentially all amateur cameras could be used in close-range photogrammetric projects, provided that sufficient object-space control is utilized, and an appropriate *analytical* data reduction system is available. It should be pointed out, that because of the relatively large and often irregular lens distortions and film deformations generally associated with most non-metric cameras, the use of an analogue approach in data reduction from non-metric photography is often not feasible, if reasonably accurate results are desired.

The list of non-metric cameras reported as having been used in close-range photogrammetric projects is impressive and represents a wide variety resembling the display of a well-stocked photographer's store. Among these cameras are simple and inexpensive ones, such as Kodak Instamatic 154, most of the medium-priced ones, such as Asahi Pentax ME, Minolta XG-7, Rolleiflex SL66, and the more expensive ones such as Linhof Technica and Hasselblad 500 EL.

3. THE ROLE OF NON-METRIC CAMERAS IN CLOSE-RANGE PHOTOGRAMMETRY

The main reason for the use of non-metric cameras in close-range photogrammetry is the unavailability of metric cameras suitable for the particular project at hand. In addition, even though suitable metric cameras may be available, they are often prohibitively expensive for projects with limited budgets.

Compared to metric cameras, non-metric cameras have the following advantages and disadvantages:

Advantages:

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

Disadvantages:

- 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 orientation aids, such as level vials, and orientation provisions precludes the precise orientation of the camera along desired directions,
- the absence of a proper film flattening device.

Concentrated research and development efforts in North America and Europe, aimed at the elimination (or at least the reduction) of the effects of the above listed disadvantages, have resulted in the development of a number of analytical data reduction approaches particularly suitable for non-metric photography. The key to the success of these schemes is combining the calibration and evaluation phases using newly developed techniques, as outlined in detail by Faig (1975a).

4. DATA REDUCTION FROM NON-METRIC PHOTOGRAPHY

In view of the relatively large and often irregular lens distortions and film deformations generally associated with non-metric cameras, the analytic approach has exclusively been used in photogrammetric data reduction from non-metric photography for precise applications.

Because non-metric cameras are not usually equipped with fiducial marks, special data reduction approaches not requiring fiducial marks were successfully devised. Among these unique approaches are the following:

a. The Direct Linear Transportation (DLT) solution (Abdel-Aziz and Karara, 1971, 1974; Karara and Abdel-Aziz, 1974; Marzan and Karara, 1975),

b. The 11-Parameter solution (Bopp and Krauss, 1977, 1978a, 1978b),

c. The UNB Self-Calibration Method (Faig & Moniwa, 1973; Faig, 1974; Faig 1975b; Moniwa, 1976 & 1977; El Hakim, 1979).

5. OBJECT SPACE CONTROL

The amount of object-space control is directly related to the calibration approach selected (partial, self-, or on-the-job calibration, for details see Faig, 1975a), and the degree of refinement undertaken in correcting for systematic errors.

For example, in the DLT approach, the following mathematical model is used to correct for symmetrical and asymetrical lens distortions:

$$\Delta x = x' \, (K_1 r_1^2 + K_2 r^4 + K_3 r^6 + \dots) + P_1 (r^2 + 2x'^2) + 2P_2 x'y',$$

$$\Delta y = y' \, (K_1 r^2 + K_2 r^4 + K_3 r^6 + \dots) + P_2 (r^2 + 2y'^2) + 2P_1 x'y',$$

where

$x' = x - x_0$, $y' = y - y_0$

x_0, y_0 coordinates of the principal point, referred to the comparator coordinate system,

x, y coordinates of observed imaged point, referred to the comparator coordinate system,

$r^2 = x'^2 + y'^2$,

K_1, K_2, K_3 coefficients of symmetrical lens distortion,

P_1, P_2 coefficients of asymmetrical lens distortion

The number of unknowns to be involved in the solution, and thus the minimum number of spatial (X,Y,Z) object-space control points required, depends on the degree of sophistication desired in the solution, as shown in the following Table 3 (Marzan and Karara, 1975):

Table 3. Correction of Systematic Errors in the DLT Solution

Systematic Errors Corrected	Unknowns in DLT Solution	Number of Unknowns	Minimum Number of Spatial (X,Y,Z) Control Points
Linear components of film deformation, lens distortion, and comparator errors.	ℓ_1 thru ℓ_{11}	11	6
Linear components as above, and symmetrical lens distortion (first term only)	ℓ_1 thru ℓ_{11} K_1	12	6
Linear components as above and symmetrical lens distortion (first 3 terms only)	ℓ_1 thru ℓ_{11} K_1, K_2, K_3,	14	7
Linear components as above, symmetrical lens distortion (3 first terms and asymmetrical lens distortion.	ℓ_1 thru ℓ_{11}, K_1, K_2, K_3, P_1, P_2	16	8

The above listed number of object-space control points represent the minimum requirements for unique solutions in the various cases. A healthy redundancy in object space control would be highly desirable to increase the realiability of the solution. If all the control points lie in or near one plane, the solution becomes indetermined because of an ill-conditioned normal equation system. Therefore, as much deviation from the planar pattern, as can be allowed by depth of field considerations, is highly recommended. It is important that control points be selected in such a way as to avoid extrapolation. In other words, control points should surround the object of interest and, as much as possible, be well distributed throughout the object-space.

Self calibration approaches, e.g. UNBASC (Moniwa, 1977) can provide good results with the minimum number of control points, namely 7 known coordinates, such as two planimetric and three vertical control points. The only disadvantage may be in areas of extrapolation. It is therefore recommended to have control points at the four corners surrounding the object. There is, however, no need to have full control points (X, Y, and Z). Independent of the number of unknown parameters for modelling systematic effects, e.g. lens distortion, this approach does not require additional control. All that is needed are point images that can be identified in overlapping photographs.

5.1 Alternative Parameters for Object-Space Control

Object-space control need not always be established in terms of coordinates of control points. Wong (1975) discussed a number of alternative parameters for object-space control, including:

Table 4. Alternative Parameters for Object-Space Control

Parameter	Minimum Requirements
Spatial (X,Y,Z) points in object-space	3 points
Distances in object space	2 distances
Distances between camera stations and object-space points	3 distances (from 3 camera stations)
Distances and their azimuths in object-space	1 distance and its direction
Lengths along plumblines in object-space	3 plumblines, a distance on each

The above tabulated minimum numbers of parameters refer to the usual fully analytical solution using collinearity equations. Wong (1975c) also discussed the mathematical formulations of the solutions involving the various alternatives in object-space control parameters.

Providing object-space control in terms of distances in object-space is perhaps the most attractive among the alternatives listed in Table 4, especially as far as the required manpower is concerned. Among the available computer programs using this alternative is program CRABS (Close-Range Analytical Bundle Solution) developed by Kenefick (1978). El Hakim's (1979) approach also can utilize geodetic measurements instead of coordinates of control points. An extension of the DLT solution to handle distances as object-space control is well underway and is expected to be published shortly.

6. ATTAINABLE ACCURACY WITH SYSTEMS USING NON-METRIC CAMERAS

Theoretically and experimentally, it has been shown that photogrammetric systems using non-metric cameras yield essentially the same level of accuracy attained by systems utilizing metric cameras. For example, Kölbl (1976) concludes the following from a solid theoretical investigation he undertook: "In general, about the same measuring precision can be reached with metric and non-metric cameras. The data processing for photographs taken with non-metric cameras is practically bound to analytical methods, and sophisticated computer programs are needed. Pictures taken by metric cameras can be restituted with analog plotters. Therefore it is more a question of the restitution method than a matter of precision whether metric or non-metric cameras should be used."

In the report of ISP Working Group V-2 (1972-76), Faig (1976) wrote: "The non-metric camera/computer evaluation combination has reached its fullest potential, and accuracies reaching the photogrammetric noise level have been achieved. It often depends on the individual project, whether the low cost camera/expensive evaluation system or the metric approach is more suitable or financially advantageous, which leaves the decision to the user. Often project arrangements require versatility and light weight which can only be met by non-metric cameras, and with the progress that has been made in the evaluation phase this option now can be a high precision approach. The photogrammetric potentials of non-metric cameras are indeed very high."

Interested readers are referred to the following articles which discuss results obtained with photogrammetric systems using non-metric cameras: Adams (1978), Aicher et al (1974), Altan et al (1978), Beattie & Lozowski (1976), Böck & Zoll (1973), Brandow et al (1976), Cheffins (1975) Chiat (1977), Döhler (1971), Hallert (1971), Karara (1972 & 1974), Kölbl (1975), Müller (1977), Rhody (1974), Sabey & Lupton (1967), Schwidefsky (1970), Wellford (1974), van Wijk & Ziemann (1976), Wolf and Loomer (1975), Wong and Vonderohe (1978), among others.

7. IMPROVING THE ACCURACY OF ANALYTICAL SOLUTIONS

Hottier (1976) has shown that the accuracy of analytical solutions in close-range photogrammetry can be significantly improved by increasing image redundancy through using: a) multiple settings per image point, b) multiple neighboring targets to define an object point, and c) multiple frames per camera station. He reported (Hottier 1976) that an accuracy gain in the order of 50% is attainable using an optimum combination of settings, targets, and frames, and that this is independent of the base-height ratio.

8. CONCLUDING REMARKS

Although this paper may give that impression, we do not believe hat non-metric cameras will replace metric cameras in close-range photogrammetry, as each of these types of cameras has its advantages and disadvantages.

However, we do believe that non-metric cameras can successfully be used even for applications previously thought unsuitable for photogrammetry, and thus play an important role in expanding the use of photogrammetric techniques. On the basis of numerous theoretical and experimental studies, as well as reports on practical applications, we are convinced of the suitability of non-metric cameras for photogrammetric work, provided that appropriate data reduction schemes and the necessary software are available to the user, and that they are properly utilized, depending on the accuracy requirements.

There is, of course, an accuracy limit, but this applies to images from both metric and non-metric cameras, and this determines whether or not photogrammetry is suitable at all for a project at hand.

One secondary question on which type of camera should be used, depends on many factors, both physical and economical, considering the scope of the whole project. Once the feasibility of photogrammetry has been established, the inavailability of a suitable metric camera is not critical any more, as non-metric cameras have established their place within photogrammetric systems.

9. REFERENCES

Abbreviations used:

ASCE: American Society of Civil Engineers
ACSM: American Congress on Surveying and Mapping
ASP: American Society of Photogrammetry
BSFP: Bulletin de la Société Française de Photogrammétrie
BSIFET: Bulletino della Societá Italiana di Fotogrammetria e Topografia
BuL: Bildmessung und Luftbildwesen
DGK: Deutsche Geodätische Kommission
ISP International Society for Photogrammetry
PE: Photogrammetric Engineering
PE&RS: Photogrammetric Engineering & Remote Sensing
PR: The Photogrammetric Record
SPIE: Society of Photo-Optical Instrumentation Engineers
UI: University of Illinois at Urbana-Champaign
UNB: University of New Brunswick, Fredericton, N.B., Canada

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