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FIXED-BASE PHOTOGRAMMETRY WITH WING-TIP MOUNTED CAMERAS

Calibration procedure and foresty application

Abstract

This paper deals with a general method of deriving information on forest sample plots from fixed air base photography without extensive control for each plot. The method requires a test area with given control to allow in-flight calibration. Both inner orientation of the two cameras and their outer orientation relatively to a model coordinate system can be derived from photographing the test area. The theoretical accuracy of the method is discussed, and some practical applications with wing-tip mounted cameras are reported.

Introduction

Aerial photogrammetry has become an important means of deriving information about timber resources. Spencer, 1979 considered the possibility of forest-sampling with fixed air-base photographs taken from a helicopter 100 - 500 ft above ground. He reported trials with two identical cameras mounted on a horizontal boom at a fixed distance (16 ft) and aligned to each other and to the boom with their axes vertically adjusted. The boom was oriented either parallel to or perpendicular to the flight direction (longitudinal and transverse orientation). Thus, in principle, no ground control was necessary. However, a significant scale error might occur, due to bending of the boom in transverse orientation or to lack of syncronization in the longitudinal orientation of the boom (Spencer, 1979).

The present study considers the approach of in flight calibration for a numerical determination of those orientation parameters (including unknown inner orientation) which are needed to derive tree parameters.

The practical experiment was initiated by the Norwegian Forest Research Institute. To obtain a sound solution of photogrammetric problems, there has been a close cooperation with the Norwegian Institute of Technology, Division of Geodesy and Photogrammetry.

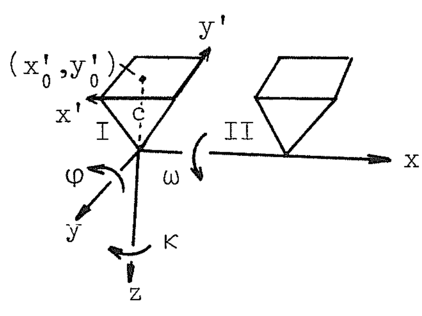

Fig. 1 The model coordinate system

The in-flight calibration

In-flight calibration is practical when ordinary aerial cameras are used (see f. in Anderson, 1975). It should be noted that the method requires a test field with sufficiently large height differences in relation to flying height if an accurate determination of the complete inner orientation is to be obtained.

In the case of fixed air-base photography, the test field photography can be used to estimate both the inner orientation and those parameters describing the positions and rotations of the two cameras. If we choose a model coordinate system as defined in fig. 1, six outer orientation parameters are also defined:

$$x_{0_I} = y_{0_I} = z_{0_I} = y_{0_{II}} = z_{0_{II}} = \omega_I = 0 \tag{1}$$

Thus, the following six residual outer orientation parameters are unknowns to be determined in the calibration process:

$$x_{0_{II}}, \kappa_I, \kappa_{II}, \omega_{II}, \varphi_I, \varphi_{II} \tag{2}$$

If we assume that the two cameras are identical and that each is provided with at least two fiducial points which define the image coordinate system, then the following inner orientation parameters can be introduced as unknowns, see fig. 1:

$$c, x'_0, y'_0 \tag{3}$$

(In the present study, image deformation is not considered.)

The basic formulae for deriving the unknowns (2) and (3) from fixed-base photography over a test field with geodetically measured points and distances are (for sake of simplicity, the indicies I and II are omitted):

$$\left.\begin{aligned} x' &= x'_0 + c\,\frac{a_{11}(x - x_0) + a_{12}(y - y_0) + a_{13}(z - z_0)}{a_{31}(x - x_0) + a_{32}(y - y_0) + a_{33}(z - z_0)} \\ y' &= y'_0 + c\,\frac{a_{21}(x - x_0) + a_{22}(y - y_0) + a_{23}(z - z_0)}{a_{31}(x - x_0) + a_{32}(y - y_0) + a_{33}(z - z_0)} \end{aligned}\right. \tag{4a}$$

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \mathbb{R} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} + \begin{Bmatrix} X_0 \\ Y_0 \\ Z_0 \end{Bmatrix} \tag{4b}$$

$$D_{PQ} = \sqrt{(x_P - x_Q)^2 + (y_P - y_Q)^2 + (z_P - z_Q)^2} \tag{4c}$$

where X,Y,Z: given field coordinates

D_{PQ} : given field distance between points P and Q

x,y,z: unknown model coordinates

x',y': image coordinates

a_{ij} : elements of orthogonal matrices derived from φ,ω,κ (Schwidewsky, et al., 1976)

$\mathbb{R}$: orthogonal matrix expressing the rotation of the model system relative to the field system.

X_0, Y_0, Z_0: shift parameters

(4) are the basic equations for a least squares solution. (4a) are the condition equations with x', y' as observations (weights = 1) and with x, y and z and the parameters (2) and (3) as unknowns. (4b) and (4c) are additional constraints. (4b) constrains the given field coordinates into the solution with $\Phi, \Omega, K, X_0, Y_0, Z_0$ as added unknown parameters, while (4c) constrains the given field distances. In the computation program, (4b) and (4c) can be interpreted as condition equations with large weights (variances equal zero).

Due to non-linearity, the unknowns must be solved iteratively with linearized equations. This procedure requires initial approximate values. Assuming such values of the parameters (2) and (3) (e.g. $\kappa_I \approx \kappa_{II} \approx \varphi_I \approx \varphi_{II} \approx \omega_{II} \approx 0$), we can derive initial values of the model coordinates x, y, z from the formulae for space intersection (Anon., 1979). (The solution is particularly simple with the chosen model coordinate system, fig. 1).

With n field points, a total number of $15 + n \cdot 3$ unknowns is involved in equations (4). However a more favourable computational technique than simultaineous solution of all the unknowns can be developed and the calibrations performed on a simple computer, e.g. a micro-computer. (Anon., 1972 and Hådem, 1980).

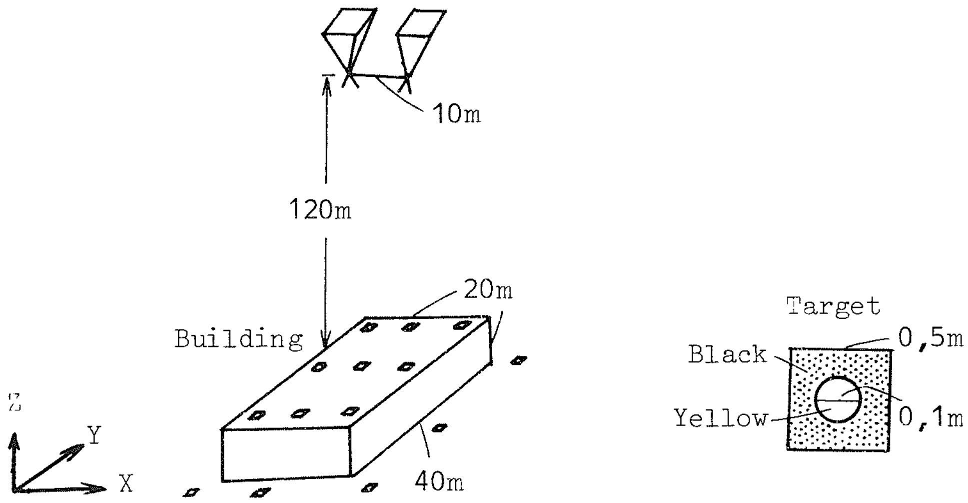

Fig. 2 The test field

The control points of the test field should be signalized to make their identification and measurement on the photos simple, and they should have a favourable distribution. The use of a building as a "test field" usually gives a sufficiently good three-dimensional distribution. However, it might be necessary to use additional points (can be unknown) to strengthen the relative orientation of the two cameras. If the inner orientation is known, the given control can theoretically be restricted to one measured distance.

The derivation of tree parameters

This derivation is based on the in-flight calibrated values of the orientation parameters (2) and (3) assuming that those parameters remain stable during flight. To check this stability, the test field could be photographed several times during one flight. The model coordinates x, y, z of the points that define crown diameters and tree heights can be found by intersection in space (see Anon., 1979). This intersection is based on data of the image coordinates x',y', and the known orientation of the two cameras relative to the introduced model coordinate system of fig. 1. The crown diameters and the tree-heights are then derived as distances (4c).

However, it might be more convinient to derive a tree height as the height difference between the top of the tree, P_t, and a ground point with the same height as the root of the tree, Pg. In this case, we have to consider a rotation between the model system x,y,z and field system X,Y,Z (Z = vertical) with two parameters Φ,Ω involved, see fig. 3. Assuming that the values of Φ and Ω are small, we can use the following formula to derive Z:

$$Z = z + x\Phi - y\Omega$$

Thus, a tree height is derived as:

$$\Delta h = Z_g - Z_t = z_g - z_t + (x_g - x_t)\Phi - (y_g - y_t)\Omega$$

On the basis of determining two points $P_1(x_1,y_1,z_1)$, $P_2(x_2,y_2,z_2)$ on a tree stem (which is vertical), Φ and Ω can be derived as:

$$\Phi = \frac{x_1 - x_2}{z_1 - z_2} \qquad \Omega = -\frac{y_1 - y_2}{z_1 - z_2}$$

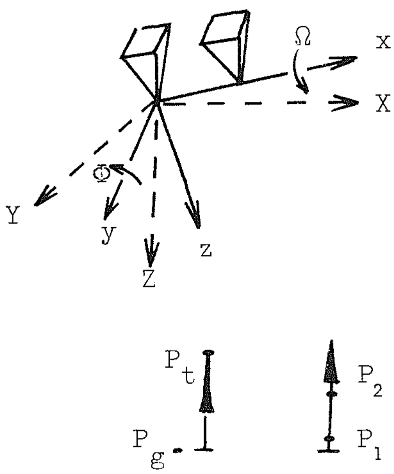

Fig. 3 Absolute orientation in height

Accuracy

Errors in the photogrammetric determination of crown diameters and tree heights, using a fixed air-base system calibrated in flight, are mainly dependent upon

a) errors in the calibration parameters due to errors in the given test field control and in the identification and measurement of image points on the calibration photos;

b) instability of the calibration condition during flight: important are changes in the bending of the air-base and lack of syncronization (see Spencer, 1979);

c) errors in identification and measurement of points on the forest photos.

We will in the following discuss in a little more detail the influence of these sources of errors on the accuracy of tree height determination.

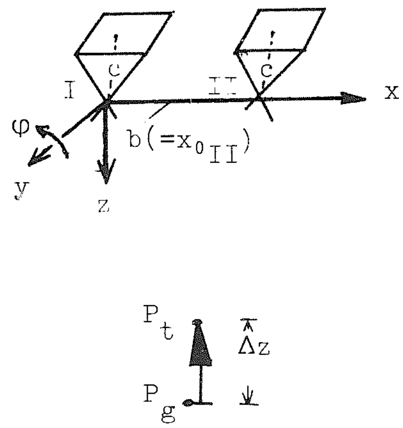

Fig. 4 Geometry of tree height determination

Assuming the normal situation, such as fig. 4, the following formula expressing the error in the z-coordinate in terms of errors in the inner and outer orientation (the calibration parameters) can be derived as (Hådem, 1968):

$$dz = z[\frac{dc}{c} + \frac{dx_{0_{II}}}{b} - \frac{z}{b}(d\varphi_1 - d\varphi_2)] + \text{terms independent on } z$$

Thus, the error in a height difference $\Delta z = z_g - z_t$ is:

$$d\Delta z = dz_g - dz_t = \Delta z[\frac{dc}{c} + \frac{dx_{0_{II}}}{b} - 2\frac{z_m}{b}(d\varphi_1 - d\varphi_2)] \qquad (5)$$

where $z_m = (z_g + z_t)/2$, z_g = ground height, z_t = height of tree top.

From the mathematical model of the calibration, see (4), we can derive the error properties of the calibration parameters and thereby also the accuracy of Δz, by applying the law of propagation of errors. It should be mentioned that the accuracy also depends on a proper design of the test field control.

An important practical problem seems to be how to keep the calibrated system stable during flight (Spencer, 1979). If a transverse air-base is assumed, the instability is mainly due to bending of the air-base. If this bending occurs as illustrated in fig. 5, the following relation exists between the vertical movement t of the two cameras, and their φ-rotations:

$$d\varphi_1 = - d\varphi_2 = 4t/b$$

This introduced into (5) gives

$$d\Delta z = -\Delta z \cdot 16 \cdot \frac{z_m}{b} \cdot \frac{t}{b} \qquad (6)$$

To give a numerical example, we assume that

$z_m = 150$ m, $b = 10$ m (fixed wing air craft).

This introduced into (6), gives

$$\frac{d\Delta z}{\Delta z} 100\% = [-2,4 \cdot t(\text{in mm})]\% \qquad (7)$$

It is of interest to compare the influence of bending of the air-base with the influence of observational errors (see (c) above). The error dz in the z-coordinate depends on observational errors dx'_I and dx'_{II} in corresponding image points in two photos I, II, through (Hådem, 1968):

$$\delta z = -\frac{z^2}{b \cdot c}(dx'_I - dx'_{II})$$

If dx'_I and dx'_{II} are expressed as standard errors $m_{x'_I} = m_{x'_{II}} = m_{x'}$, we can derive the corresponding standard error m_z in z and also the standard error in a height difference, $m_{\Delta z} = \sqrt{2} \cdot m_z$. Assuming further:

$c = 100$ mm, $\Delta z = 20$ m, $z = 150$ m, $m_{x'} = 0{,}03$ mm

we get

$$\frac{m_{\Delta z}}{\Delta z} \cdot 100\% = 7\%$$

The example illustrates that the accuracy in height determination is sensitive to bending of the air-base.

The influence of lack of syncronization, which effects dx_0 (see (5)), is not significant when using transversal air-base (Spencer, 1979).

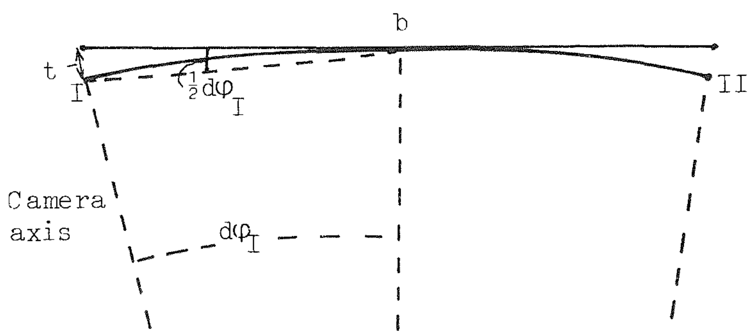

Fig. 5 Bending of the air-base

Practical experiment

The photographic equipment consisted of two Hasselblad EL 500 cameras with Planar 100 mm objectives, mounted with nearly vertical axes on the wing tips of an acrobatic aircraft with particulary stiff wings. Stereopairs covering sample plots were taken over a forest area. Within each sample plot, the tree heights were measured both directly in the field (with hypsometer) and photogrammetrically to determine the accuracy of the photogrammetric method. A test field, fig. 2, for in-flight calibration was established with 18 geodetic measured points (X,Y,Z) which were identified by painted targets. Four stereopairs were taken over the test field during one flight.

The image points were measured in Wild A7 used as a stereocomparator.

A simultaneous adjustment of the four calibration stereopairs was performed with the base length (b) and inner orientation (c, x'_0, y'_0) as unknowns. Further, the outer orientation parameters $(\varphi_I, \varphi_{II}, \omega_{II}, \kappa_I, \kappa_{II})_i$, $i = 1 \ldots 4$ (see fig. 1), were introduced as unknowns, to examine the variation in their values among the stereopairs. The final orientation was computed as $\bar{\varphi}_I = \Sigma\varphi_{I_i}/4$, etc., and those values together with the calibrated inner orientation values were used in the computation of tree heights and crown diameters from the photos taken of the forest.

Because the photos had no fiducial marks, the photo corners were measured as reference points defining an image coordinate system x',y', to which the measured image coordinates were transformed (rotated and shifted).

The following result of the in-flight calibration is of special interest for evaluating the accuracy of tree height determination (conf. (5)):

$m_0 = 0.015$ mm (the standard error of unit weight),

$m_c = 0.25$ mm (0.25‰ · c), $m_b = 0.03$ m (0.3‰ · b)

$m_{\Delta\bar{\varphi}} = \underline{1{,}^c0}$ $\Delta\bar{\varphi} = \Sigma(\varphi_I - \varphi_{II})_i/4$ is the mean of the convergency values of the four calibration stereopairs. From variation in $\Delta\varphi_i = (\varphi_I - \varphi_{II})_i$ among those stereopairs, a corresponding standard error in $\Delta\bar{\varphi}$ was derived as

$$m'_{\Delta\bar{\varphi}} = \sqrt{\Sigma(\Delta\varphi_i - \Delta\bar{\varphi})^2/3 \cdot 4} = 4{,}^c0$$

which includes also errors in $\Delta\varphi_i$ due to unstabel calibration conditions.

To evaluate the influence of such errors on tree height determination, the following relation can be derived from (5) with b = 10 m and $z_m = 150$ m:

$$\frac{d\Delta z}{\Delta z} 100\% = [-0.5 \cdot \Delta\varphi(\text{in } ^c)]\%$$

No significant variation in $(\kappa_I, \kappa_{II}, \omega_{II})_i$ among the stereopairs was found.

The absolute accuracy of height determination was computed from two stereopairs (plots) with satisfactory photoquality and where the ground level was easy to distinguish. The systematic error, dM, was derived for each stereopair from

$$1 + dM = \Sigma\Delta z_{ge}/\Sigma\Delta z_{ph}$$

with Δz_{ge} as geodetically and Δz_{ph} as photogrammetrically determined tree heights. The result was (18 trees in each stereopair):

$dM_1 = 0.005$ (0.5%), $dM_2 = 0.027$ (2.7%)

When this systematic error was eliminated, the following accuracy within the stereopairs was derived (36 trees):

$$m_{\Delta z} = \sqrt{\Sigma[\Delta z_{ge} - \Delta z_{ph}(1 + dM)]^2/36} = \underline{0{,}35 \text{ m}}$$

= 2% of mean tree height (= 18 m).

Conclusion: The calibration was considered to be sufficiently accurate. The main source of error seemed to be the instability in the convergency of the camera axes.

It should be remarked that in stead of using the relative orientation from calibration, an analytical relative orientation could have been performed for each stereopair of the forest. This alternative has not been examined.

The photo quality of the forest photos, in particular the ability to distinguish ground level, obviously has a significant influence on accuracy. The above results, which are considered satisfactory, are based on suitable stereopairs where measurements could be done very precisely. In addition, there were several stereopairs taken where dark shadows made it difficult to locate the ground level clearly enough. This was due to the fact that the photographs were taken late in autumn with extremely low sun inclination. If the terrain becomes accidented the accuracy of height determination is rapidly lowered. The experimental work will continue, so that we can gain more practical experience and can draw more reliable conclusions about the accuracy of the method.

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