In-Flight Aerial Camera Calibration from Photography of Linear Features

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ABSTRACT: The calibration of aerial survey cameras in government service in Australia has traditionally been performed in a laboratory environment using a Hilger and Watts goniometer in conjunction with a precisely graduated diagonal grid plate. This technique has yielded a calibrated principal distance and a symmetrical radial lens distortion curve for most common metric aerial cameras. Such a procedure does not, of course, take into account the entire system effects which would include atmospheric refraction, platen flatness, and the optical effects of the aircraft port. This paper describes a simple system of photographing a well defined linear feature with multiple photography to form, if overlayed, a grid pattern of straight lines. After compensating for the theoretical effects of atmospheric refraction, Earth curvature, and dislevelment of the linear feature, a perfect grid should be apparent. This method is an adaptation of the plumbline technique. Here, the deviations from linearity indicate the full model of photographic distortions for an in-flight camera system, including the conventional parameters for radial and decentering lens distortion. Other partial calibration methods using the goniometer have been used as a basis for comparison of this "aerial plumbline" calibration technique.

INTRODUCTION

DISTORTIONS IN CAMERA SYSTEMS must be carefully monitored. A high accuracy in aerotriangulation can only be achieved if all systematic distortions due to lens, camera, and environmental conditions are carefully determined and subsequently modeled in adjustments.

Modern metric aerial cameras have lenses which exhibit small amounts of lens distortions and, consequently, have very little effect on aerotriangulation solutions for small scale mapping. In older cameras, the effect is not inconsiderable as the lenses in these cameras often have large values of radial distortion.

Lens distortions can be determined in the laboratory using a goniometer which measures the angles of incidence to lines on a grid plate located in the focal plane. However, these are not the only distortions present in a typical aerial photograph. Other error sources include refraction, optics of camera ports, effect of differential pressure/temperature within and outside the aircraft, film shrinkage, and platen flatness.

Photographs of well defined linear features with the usual camera set-up (usual aircraft, camera port, film type, flying height, and atmospheric conditions) were used to provide a very strong method for determining the systematic distortions experienced under in-flight situations without the need for extensive ground control surveys.

THE PLUMBLINE METHOD

GENERAL

The plumbline technique was developed by Brown (1971) as a rapid method for determining the distortion in lenses of terrestrial cameras. The technique of self-calibration using bundle adjustments largely superseded the plumbline technique by the late 1970s.

In the mid-1980s a number of factors saw the re-emergence of the plumbline technique for the lens calibration of the large format CRC-1 camera (Brown, 1984). The availability of Kodak Technical Pan 2415 film which has extremely high resolution (400 line pairs/mm) coupled with the development of the very fast, line-following automatic monocomparator Autoset-1 meant that a lens calibration could be completely observed and calculated in one hour (Fryer and Brown, 1986). This compares with a time of approximately two days which was required in the 1970s on a manual monocomparator. The accuracy, using this combination of stable-base film and automated monocomparator, increased by a factor of five to produce RMS values of under one micrometre on the photographic plate.

A collaborative program between the Department of Civil Engineering and Surveying, University of Newcastle, and the Australian Surveying and Land Information Group (AUSLIG), which was formerly the Division of National Mapping, commenced early in 1986 to investigate the possibilities of adapting the plumbline technique to the calibration of aerial survey cameras.

THEORY

For a perfect lens system, any straight line object should project as a straight line on the photographic image. It is usual to erect a set of near vertical plumblines using, say, piano wire and take two approximately horizontal photographs of this object array, one with the camera in a normal position and one with the camera rotated through 90 degrees. Using a simple transformation to the fiducial coordinates, the imaged lines on both photographs may be treated as one gridded set of observations. Observations are made at random along each line and bear no relation to the intersections of the grid.

Any bending of the imaged lines may be attributed to the systematic effects of radial and decentering distortion (see Brown, (1971) for a full exposition of the mathematics of the plumbline technique). Suffice to note here that observation equations are formed which contain nine parameters: two to define each line, three for radial distortion (K_1, K_2, and K_3), two for decentering distortion (P_1 and P_2), and two parameters which relate the principal point on the photograph to the intersection of the fiducial axes (x_p and y_p). The observation equations are independent of focal length and the relative orientations of the object and image planes.

A typical plumbline solution might consist of ten vertical lines and ten rotated lines (horizontal lines) with 30 observations per line. This arrangement would provide 600 observations to solve

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for a total of 47 parameters consisting of 40 to determine the direction and offset distance from the principal point to the plumblines and seven for the various camera constants.

Although seven camera parameters appear in the observation equations, the offsets to the principal point from the intersection of the fiducial axes are directly correlated with the parameters of decentering distortion (see discussion in Fryer and Fraser, (1986)). It is permissible to artificially hold, by weighting, the offsets to the principal point to zero. Due to projective compensation, the parameters of decentering distortion will reflect both misalignment of the lenses along the optical axis and any offset of the principal point from the intersection of fiducial axes.

As the observation equations are independent of camera orientation, it is permissible to take multiple photographs of one linear object from several different camera positions. By transfering all images to the one set of fiducial coordinates, a pattern of vertical and horizontal "plumblines" are derived from the multiple images of the same line.

This paper details the extension of the plumbline technique from the usual close-range photogrammetric situation of photographing piano wires to actual aerial photography of a 20-km long section of surveyed railway line.

TEST PROCEDURES

Feature Selection

Suitable linear features such as roads, piers, and airstrips were investigated and it was decided to use a straight section of railway line as an object for the test. Though many such sections of nominally 20-km length exist in Australia, a section just southeast of Bourke, New South Wales (latitude 30°S, longitude 146°E) was selected. This straight section of railway line is level for 10 km and has gentle grades for the next 10 km. No sections of railway line which are completely level for a full 20 km could be found.

Ground control points were set out at known chainages and offsets to the surveyed railway profile. They were targeted to provide scale and a datum to correct observations for the varying railway grades. The sleepers and gravel between the rails were targeted with white paint at intervals of 500 metres for the first 10 km and every one km for the undulating 10-km section to provide high contrast on the image. A total of 30 points were marked along the 20 km of the railway line (see Figure 1).

Software Modifications

Software was developed to reduce raw observations from multiple photographs to a common datum based on calibrated fiducial coordinates and to compensate for the effects of

- film shrinkage;
- atmospheric refraction, which is significant is typical flying heights;
- Earth curvature, which recognizes that a surveyed level line on the ground is actually curved; and
- relief displacement effects along the undulating 10-km section of railway line.

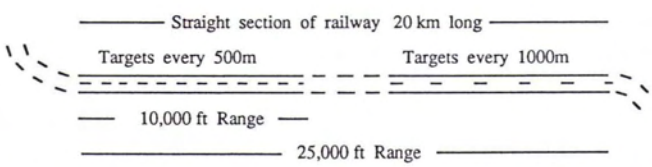

FIG. 1. Straight 20-km section of railway line near Bourke, New South Wales, Australia. Targets placed every 500 meters along section for 10,000-feet photography and every one km along section for 25,000-feet photography.

Photography

Photography with 90 percent overlap was flown (see Figure 2) across the railway with the camera in its normal configuration and then rotated through 90 degrees. This gave a total of 20 observable photographs which, if overlayed, formed a gridded pattern. This photography was taken both at 10,000 feet over the completely level section of railway and at 25,000 feet over the entire length of surveyed railway line. The 10,000-feet photography represented the largest possible section of railway where correction was not necessary for dislevelment of the line, while the photography at 25,000 feet represented typical flying altitudes for aerial survey work.

Reduction of Observations

The fiducials and as many targeted points as possible were observed on both sets of photography using a Zeiss Stecometer comparator to obtain sets of x,y coordinates. The coordinates were reduced to a form suited to the plumbline calibration program using the software described earlier. The results obtained for the parameters of lens distortion and their error budgets are presented in the next section.

RESULTS

Aerial Plumblines

The distortion curves shown in Figures 3 and 4 were obtained from the aerial plumbline calibration of RC10 camera No. SAG II 2018 fitted with a super-wide angle lens whose nominal principal distance was 88 mm. The radial and decentering distortion curves were derived from photography at 10,000 and 25,000 feet. Root mean square errors for both sets of photography were below three micrometres. The differences between the radial

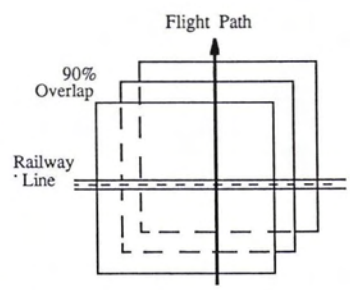

FIG. 2. 90 percent overlap photography taken across the railway line.

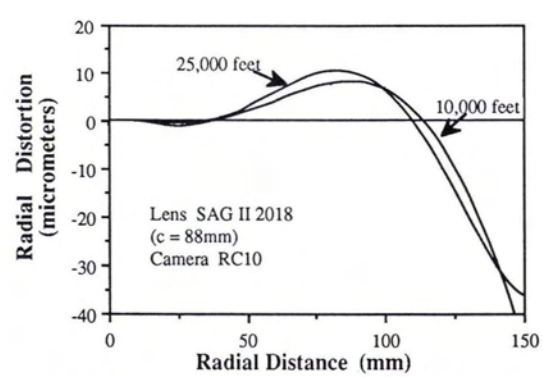

FIG. 3. Radial distortion curves for a super-wide angle lens, Wild RC 10 camera, at 10,000 and 25,000 feet. Multiple photographs of a straight railway line and the plumbline calibration technique for calculation were used.

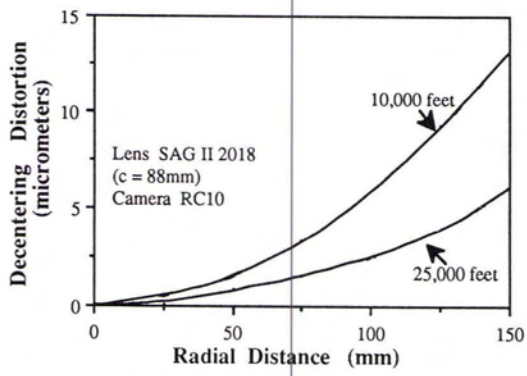

FIG. 4. Decentering Distortion Curves for a super-wide angle lens, Wild RC 10 Camera, at 10,000 and 25,000 feet. Multiple photographs of a straight railway line and the plumbline calibration technique for calculation were used.

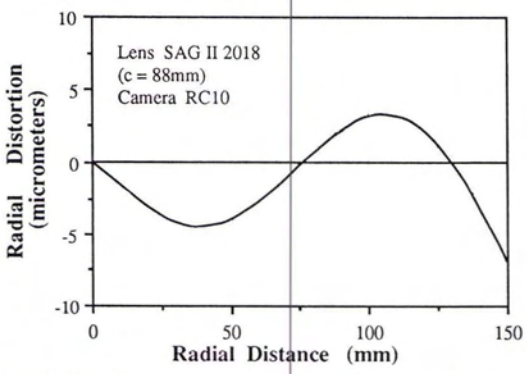

FIG. 5. Radial distortion curve for a super-wide angle lens, Wild RC 10 Camera, using a goniometer under laboratory conditions.

distortion curves for the two altitudes were minimal, while the slight discrepancy between the decentering curves was not statistically significant.

Goniometer Calibration

A conventional vertical goniometer solution for radial lens distortion was conducted under laboratory conditions for the above camera and lens. Figure 5 shows the resulting curve. No solution for decentering distortion was available using the Hilger and Watts goniometer at the AUSLIG laboratory.

Discussion

A comparison of results from the aerial plumbline calibration using the railway line with those from the standard laboratory calibration indicates a marked difference between the curves for the radial lens distortion at all radial distances. The aerial plumbline curve shows more positive distortions close to the center and larger negative values near the edge of the format area.

The small root mean square errors resulting from the tests indicated that the observations were more than adequate to define the radial distortion. The logic of all the programs used in the calibrations was validated using sets of "theoretical" test data. It was therefore concluded that the results, as presented, truly represented the actual situation.

The differences in the results for the laboratory and aerial plumbline solutions must be attributable to other distortions inherent in a complete camera system calibration rather than to those parameters determined from a simple lens calibration. These distortions would include camera port optics, platen flatness, atmospheric conditions, and film shrinkage.

Platen flatness was further examined as being the most likely source of the differences in the calibration results. A dial gauge was used to measure it and a contour map was drawn. The contours were reasonably symmetrical about the principal point so a model of platen flatness was formed by taking the mean of the contour value for a particular radial distance along each diagonal. Figure 6 shows this deformation of the platen.

Curvature of the platen produces radial distortions similar to those of radial lens distortion. The components of radial distortion, δr, which can be attributed to a bowl-shaped platen such as shown in Figure 6 can be represented by

$$\delta r = z.r/c$$

where z is the separation of the platen from the position of the calibrated focal plane, r is the radial distance from the principal point, and c is the calibrated principal distance.

A radial distance of 105 mm was selected as the point where the calibrated focal plane intersected the film, held by vacuum, on the platen. This radial distance was selected because the area of a circle of radius 105 mm is approximately equal to the area of the annulus between circles of radii 105 mm and 150 mm. In this manner, approximately half of the imaged area will be positively affected and the other half will receive a negative influence. The radial distortion attributable to the platen is also illustrated in Figure 6.

The radial distortion due to the curved platen was added to the goniometer results for radial lens distortion to produce Figure 7. The similarities between the aerial plumbline calibration shown in Figure 3 and Figure 7 clearly indicate the need for a method of total system calibration for aerial survey cameras. Calibration of the lens only is not sufficient.

Use of Goniometer as a Pseudo-Collimator

As a result of the close agreement between the aerial plumbline and the goniometer plus platen correction calibrations, a test was conducted using the goniometer as a pseudo-collimator. Light was shone back through the eyepiece of the goniometer at predetermined angles onto aerial film. In this manner the goniometer was made to act like a bank of collimators. The radial distances of the resulting cross-hair images were measured on the film. The results for radial distortion from this test include the distortions arising from irregular film shrinkage and unflatness of the platen. Figure 7 displays the resulting curve for radial

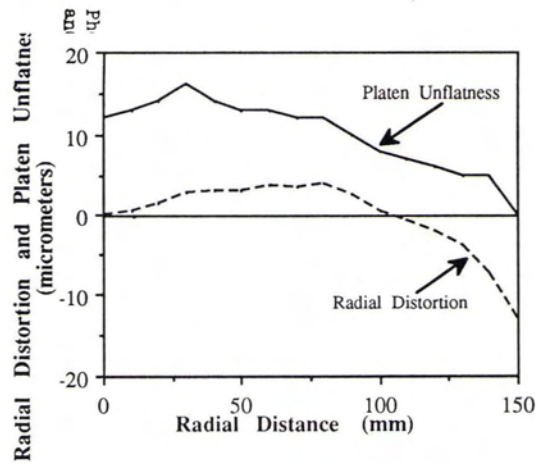

FIG. 6. Unflatness of the platen in a Wild RC 10 Camera, and the resulting radial distortion.

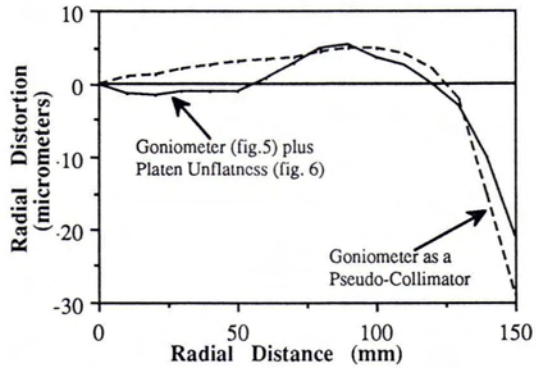

FIG. 7. Accumulated radial distortion from goniometer lens calibration (Figure 5) and platen unflatness (Figure 6) compared to the Radial Distortion curve resulting from the use of the goniometer as a pseudo-collimator.

distortion, which again confirms the results from the in-flight "total system" calibrations.

Comparisons of the curves in Figure 7 with Figure 3 demonstrate that laboratory calibrations should include a consideration of platen unflatness. A simple laboratory calibration for lens distortion is not representative of the situation at the instant of actual aerial photography. In-flight calibration, such as that using a linear feature and the plumbline technique of calculation, can account for all error sources.

CONCLUSION

A simple lens calibration does not take into account whole system effects. By compensating for platen flatness, laboratory results for radial distortion are improved and approximate those experienced under actual flying conditions.

The aerial plumbline calibration, using a straight targeted railway line as the object, provided a solution to system calibration under operational conditions. The results achieved from the aerial plumbline include distortions arising from all sources. The value of the root mean square error was less than three micrometres. The differences between this technique and a conventional goniometer calibration highlight the effects of aircraft ports, atmospheric conditions, irregular film shrinkage, and platen flatness.

To have confidence in any calibration, it is essential that the objects or targets should be easily and definitely distinguishable. Advantages of the aerial plumbline system over a full bundle self-calibration test range of 100 or more points targeted on the ground include the ease of establishing and maintaining only 30 or so targets along a straight railway, road, or aerodrome. Observations are simple to make as neither target numbering nor specific point identification is required. All observations are taken along the one linear feature.

A disadvantage of the system is that no value for the calibrated principal distance is obtained. The operator must also set up 20 separate photographs for observation. These two disadvantages are really not very significant as most test-field calibrations do not yield highly accurate values for the calibrated principal distance unless convergent photography is flow or the test field contains a large amount of relief. Slight uncertainties in the principal distance are of little consequence in aerotriangulation and mapping where the height range is small to moderate. Also, the time taken to prepare the photographs for observation is offset by the speed of actually making those observations.

Importantly, atmospheric effects apart, the aerial plumbline method does not necessarily need photography to be taken at normal photographic altitudes. For any country or mapping organization without *any* calibration facilities, all that is required is to survey and mark a straight line on, say, an airfield for two or more kilometres and to fly overlapping photography at a scale which encompasses this line on the images.

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