# CALIBRATION AND VALIDATION OF AERIAL PHOTOGRAMMETRIC SYSTEMS WHICH UTILIZE SOLAR IMAGES FOR DETERMINING AERIAL CAMERA TILT ANGLES

U. Ethrog, G. Even-Tzur

Department of Transportation & Geo-Information Eng. Faculty of Civil & Environmental Eng. Technion Israel Institute of Technology, Technion City, Haifa 32000, Israel
cvuzi@techunix .technion.ac.il eventzur@techunix.technion.ac.il

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**ABSTRACT:**

This paper presents an inexpensive, efficient, low-weight airbornern system based on two non-metric cameras together with a GNSS receiver and its antenna, The main camera is oriented towards the ground, and the other, being a solar camera, is oriented towards the sun and used instead of an IMU system to determine the system's tilt angles. The device can be carried by small helicopter, any tiny air carrier, or even an unmanned small aircraft. The system is suitable for large scale photogrammetric mapping of small tracts of difficult terrain of special interest, and allows the recording of small but significant land deformations which occur within a short time span. The photogrammetric measurements are done without any ground control: the images' exterior orientations are determined by the coordinates of the GPS antenna's position at the moment of exposure as well as by the sun's geocentric position and by the location of its image in the solar photo. This paper describes the calibration of such a system.

## 1. INTRODUCTION

The idea for developing this particular photogrammetric method, as described below, came as a result of seeking a method suitable for monitoring the terrain deformations in special hard to reach areas. The ground all around the area that was once at the bottom of a salt water lake is now dry, soft, and dusty and unsuitable for maintaining any permanent ground control point for geodetic or conventional photogrammetric measurements. Furthermore, the terrain is filled with small underground caverns which can collapse at any moment leaving pits that are a few meters in depth. These cause damage to the surrounding roads and houses, and traversing such terrain becomes very dangerous. The geologists who inspect such phenomena try to predict the position of those dangerous places before they collapse, and they therefore need to monitor the

terrain deformations in those places of special concern with care and precision. The deformation measurements in these relatively small areas should be done frequently and within short time spans. Aerial photogrammetry based on GPS and IMU systems rather than ground control is a potentially good solution, but it is too expensive for small areas and the equipment is not always available when needed. Instead, we suggest in this paper the use of an additional non-metric digital fish eye camera equipped with a special optical filter-- as a substitute for the IMU system. This camera is aimed towards the sky and takes photographs of the sunsimultaneously with the earth photographs taken by the main camera. The fish eye camera is used as a solar camera and photographs the sun. Since the direction of the sun at each moment is well-determined, it can be used as a distant control point. A spatial transformation formula transforms the image coordinates in the solar camera into image coordinates at the main camera.

In addition, the device contains a GPS receiver and antenna and two cables from the receiver PPS outlet to the cameras' remote cord connectors. This arrangement ensures that the two cameras' exposures are done simultaneously with the GPS epoch recording. It eliminates the errors in the main camera position caused by interpolation when using the data from an event marker. This equipment, illustrated in Fig.1, is light and can be carried by small helicopter or by a tiny unmanned air carrier, which would make it ideally suited for small areas of special interest.

The idea of using a solar camera in order to help determine the tilt angels of aerial photographs is not new. Schermerhorn (1966) briefly mentions that it was proposed by Finsterwalder in 1916 and that Santoni designed and produced a commercial solar periscope in 1920 and obtained good results, but there was no interest in this system outside of Italy. The big advantage of using the sun as a control point is its good spatial coordinates and its clear image on the digital photograph, so that its image position can be determined by simple procedure within accuracy of 0.1 pixels which is equivalent to 0.05 milliradians, better then most of the IMU systems. The purpose of this paper is to present the calibration procedures for this device.

## 2. MODEL RECONSTRUCTION

The exposure point location is determined by the transformation matrix from the earth geocentric coordinates system to the main camera coordinates system and by the vector from the main camera exposure point to the GPS antenna. It is given by the equation:

$$\begin{pmatrix} e_X \\ e_Y \\ e_Z \end{pmatrix} = R \begin{pmatrix} X_{GPS} - X_C \\ Y_{GPS} - Y_C \\ Z_{GPS} - Z_C \end{pmatrix} \qquad (1)$$

where, $e_X,e_Y,e_Z$ is the vector from the exposure point to the GPS antenna at the main camera coordinates system,
R is the unknown transformation matrix from the geocentric coordinates system to the main camera coordinates system,

$X_{GPS},Y_{GPS},Z_{GPS}$ are the coordinates of the GPS antenna at the moment of exposure in the earth geocentric coordinates system,
$X_C,Y_C,Z_C$ are the coordinates of the camera's exposure point in the earth geocentric coordinates system.

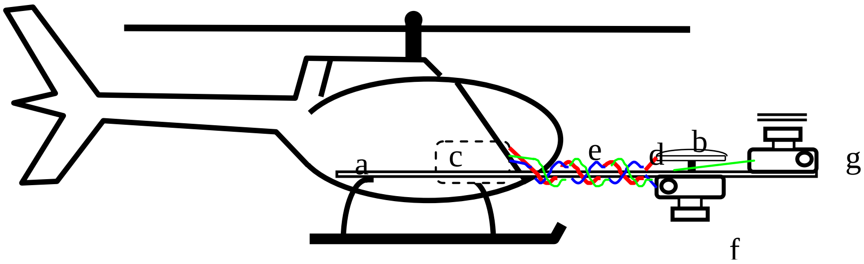


Figure.1 The proposed system

**THE APPARATUS**:

a. A solid frame to which everything is rigorously attached
b. A GPS Antenna
c. A GPS receiver which has three tasks:
  to records the position of the GPS antenna at each exposure,
  to cause simultaneous exposures of the two cameras at the moment of any GPS epoch recording at fixed time intervals,
  to be used as an accurate chronometer
d. A Cable connecting the antenna to the receiver
e. Two cables from the PPS outlet to the cameras' remote cord connectors which transmit electrical signals from the receiver to the two cameras (f and g) and cause simultaneous exposures when a GPS epoch is recorded
f. A non-metric 3000x2000 pixel camera with 20 mm lens which is the main camera and is oriented towards the earth to take images of the terrain
g. A non-metric 3000x200 pixels camera with 15 mm fish eye lens oriented towards the sky to take images of the sun

The GPS system provides exposures at accurate times in which the position of the sun at any moment of exposure is determined by its known values of declination δ and Greenwich Hour Angle G.H.A., both corrected for the air refraction and the sun parallax. They are transformed to the solar camera coordinate system by the transformation equation, Eq.2.

$$\begin{pmatrix} V_X \\ V_Y \\ V_Z \end{pmatrix} = QR \begin{pmatrix} \cos(G.H.A.)\cos\delta \\ \sin(G.H.A.)\cos\delta \\ \sin\delta \end{pmatrix} \tag{2}$$

where, $V_X,V_Y,V_Z$ are the components of a unit vector of the sun's direction at the solar fisheye camera,
R is the unknown transformation matrix from the geocentric coordinates system to the main camera coordinates system,
Q is the transformation matrix from the main camera coordinates system to the solar camera coordinates system.

Kumler J. & Bauer M .(2000) ,Schwalbe E. (2005) and Tzung-Hsien Ho, Christopher C.Davis, & Stuart D. Milner(2007) present several mathematical models for fisheye projection. The most suitable for our fisheye lens (Sigma) is also the simplest: r=Kθ, in which r is the distance between an image point and the photo's principal point, and θ is the angle between the camera's axis and the vector from the camera's exposure point to the corresponding object. K is a constant. Therefore, the sun's coordinates at the solar fisheye camera are:

$$\begin{aligned} x &= x_h + dx + V_X \frac{K}{\sqrt{V_X^2+V_Y^2}} \arctan\left(\frac{\sqrt{V_X^2+V_Y^2}}{V_Z}\right) \\ y &= y_h + dy + V_Y \frac{K}{\sqrt{V_X^2+V_Y^2}} \arctan\left(\frac{\sqrt{V_X^2+V_Y^2}}{V_Z}\right) \end{aligned} \tag{3}$$

where, x,y are the coordinates in the fisheye image,
$x_h,y_h$ are the coordinates of the image principal point,
dx,dy are corrections for radial distortions,
K is a constant,
and $V_X,V_Y,V_Z$ are as in Eq. 2.

The sun provides only one single vector from the solar camera to the sun. It is not enough for determining the image roll, pitch and yaw. Therefore we need at least two tie points at each photogrammetric model in order to determine the third tilt angle of each photograph.

## 3. TESTING AND CALIBRATION PROCEDURES

The system can provide accurate photogrammetric models only if the following conditions are fulfilled:

a. the two cameras are calibrated,
b. the relative orientation of the two cameras, obtained by the matrix Q in Eq. 2 is well known,

c. the position of the GPS antenna in the main camera coordinates system, (the vector $e_x, e_y, e_z$ in Eq. 1) is likewise well-determined,
d. The two exposures are done simultaneously at the moment of the GPS epoch recording.

### 3.1. Single Camera calibration

This is done by the conventional "test field" method. The test field consists of four rows of targets on the fronts of two neighboring buildings standing opposite one other. Some of them are well-defined "natural" points like point A in Fig 3, the others are marked on the walls. The geocentric coordinates of these targets are determined. For single camera calibration we need only two rows. Four photos of these targets are taken as shown in Fig 2. Using the collinearity equations, we find the camera's interior orientation and the polynomial of its radial distortions.


Figure 2. A half of a test field for camera calibration. (The other half is behind)

### 3.2 Determining the relative orientation of the two cameras and vector between the main camera and the GPS antenna

For this we use the test field as shown in Fig 2. The system is put somewhere inside of this field. The position of the GPS antenna is recorded simultaneously with the two exposures that are taken with the two calibrated cameras. The exterior orientation of each camera is determined separately using Eq. 4 and Eq.5 for the central perspective and fisheye cameras.

$$\begin{pmatrix} x_M \\ y_M \\ f_M \end{pmatrix} = \frac{1}{\lambda_M} R_M \begin{pmatrix} X_G - X_M \\ Y_G - Y_M \\ Z_G - Z_M \end{pmatrix} \quad (4)$$

$$R_S \begin{pmatrix} X_G - X_S \\ Y_G - Y_S \\ Z_G - Z_S \end{pmatrix} = \lambda_S \begin{pmatrix} x_S \\ y_S \\ \dfrac{\sqrt{x_S^2 + y_S^2}}{\tan\left(\dfrac{\sqrt{x_S^2 + y_S^2}}{K}\right)} \end{pmatrix} \quad (5)$$

Where, $x_M, y_M, x_S, y_S$ are image coordinates in the main and solar photos relative to the principal points and corrected for radial distortions,

$f_M$,K are the principal distance and the corresponding constant for the main and solar photos,

$R_M, R_S$ are the transformation matrix from the geocentric coordinates system to the main and solar images,

$X_G, Y_G, Z_G$ are the geocentric coordinates of a control Point,

$X_M, Y_M, Z_M$ and $X_S, Y_S, Z_S$ are the geocentric coordinates of the main and solar cameras exposure points point.

The matrix Q and the the vector $e_x, e_y, e_z$ in equations 2 and 1 are determined by:

$$Q = R_M^{-1} R_S \quad (6)$$

$$\begin{pmatrix} e_X \\ e_Y \\ e_Z \end{pmatrix} = R_M^{-1} \begin{pmatrix} X_{GPS} - X_M \\ Y_{GPS} - Y_M \\ Z_{GPS} - Z_M \end{pmatrix} \quad (7)$$

where, $X_{GPS}, Y_{GPS}, Z_{GPS}$ are the geocentric coordinates of the GPS antenna,

$X_M, Y_M, Z_M$ are the geocentric coordinates of the main camera exposure point.

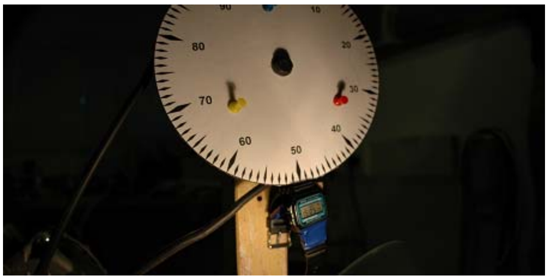

Figure 3. The rolling wheel

### 3.3. Testing the two cables connecting the receiver's PPS outlet with the cameras' remote cord connectors

The GPS receiver should cause simultaneous exposures in both cameras--the whole concept of the method is based on it!. Although we cannot adjust it, it is nonetheless important to check for. For this purpose, we have to simultaneously photograph the same event using both cameras. We could start by photographing a stop watch as its digits change; however, since its digits change only once in one hundredth of a second, it is not sufficiently accurate. Hence, we use the cameras operated by the GPS receiver to photograph a rolling wheel with scale graduation (shown in Fig.3). The rolling speed of the wheel is known, so that the difference in the graduation of the two photos indicates the time difference between the two exposures. After several tests we conclude that the time difference in the two cameras' reactions is almost zero with standard deviation of about 4 milliseconds, which means that there is a small potential error in each exposure time, hence the location and orientation of the main camera determined by the GPS receiver and the solar camera contain small potential errors which can cause unavoidable deformations in the photogrammetric models

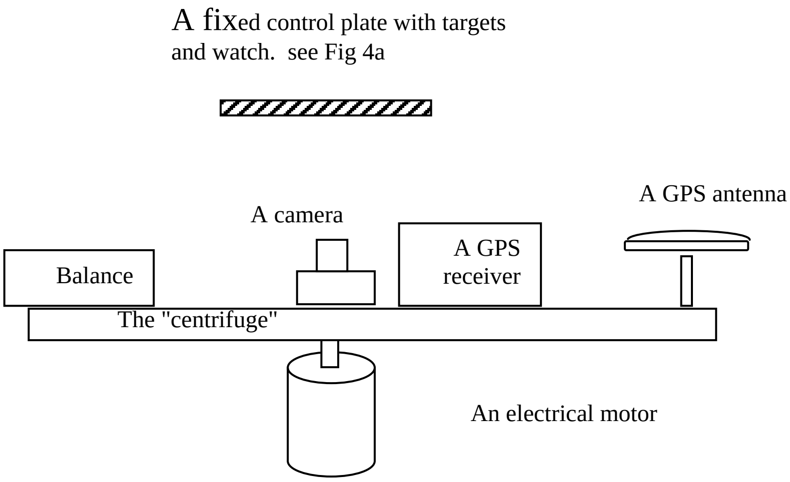


Figure 4a. The control plate and the watch

Fig. 4 Schematic diagram of apparatus for adjusting the electrical signal from the GPS receiver to the cameras

### 3.4. Adjusting the exposure time to the epoch recording time

It takes the camera's shutter a few hundredths of a second to react to the electrical signal from the GPS and make an exposure. Therefore, the time of launch for a signal should be adjusted to the epoch recording. For this purpose, we use the apparatus shown in Fig 4.

The "centrifuge" is held fixed, a GPS epoch is recorded and a camera exposure of the control plate targets is made. The image coordinates of the control points are measured, and the angle of yaw is determined. Then the electrical motor is switched on and brought to a constant angular speed. Additional epoch recordings and additional corresponding exposures are made. The difference in the GPS antenna positions at the two epochs divided by the centrifuge radius is the real angular distance that the centrifuge has passed. The image's angle of yaw using the new image is determined. The difference between the two yaw angles is termed "apparent" angular distance. The difference between the real and apparent angular distances divided by the angular speed is the time delay which we are have been seeking.

## 4. SUMMARY

In this paper we have described a few simple techniques for the calibration of an inexpensive and low-weight mobile system producing large scale digital photogrammetric strips and models. The system is based on no more than two amateur digital cameras and a GPS receiver and antenna. The data acquisition can be done without any control point. The system is different from other similar systems in two aspects that improve its accuracy and make it cheaper and easier to use. One is that the cameras' exposures that are done simultaneously with the GPS epoch recording. It is done by a signal coming from the GPS PPS outlet. The other aspect is the use of a solar camera--an old technique that was used almost a century ago and since then has been almost forgotten.

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