Geolocation of CAMBOT imagery from Operation IceBridge surveys

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1 CAMBOT Description

CAMBOT is a digital image acquisition system that supports analysis of laser altimeter data collected by the Airborne Topographic Mapper (ATM). The CAMBOT images provide a qualitative assessment of the surface structure and lower atmospheric conditions sensed by the ATM. CAMBOT is a passive instrument that uses sunlight as the source of illumination.

The CAMBOT raw images are collected by an Allied Vision Prosilica GT4905C camera. The Prosilica GT4905C, a 16 MP machine vision camera designed for extreme environments, operates over ethernet via the GigE command interface. The camera is fitted with a Zeiss Distagon 28 mm f/2 ZF.2 lens to yield an image width below the aircraft that is marginally wider than the ATM wide-scan lidar swath. The camera is rigidly mounted in each science aircraft platform above a down-looking optical window (either glass or acrylic) to provide nadir imagery of the surface below. Finally, the camera is connected to three components: a power supply, an acquisition/control computer, and an intervalometer. The CAMBOT data acquisition and control computer is a SuperLogics Microbox PC that provides an ethernet connection to the camera for transferring data and managing the camera settings. Custom software is used to set up the camera, transfer images, display QA thumbnails, and organize collected images into 1-minute duration tar files. The intervalometer used to trigger the CAMBOT image collection is a Javad Delta/Sigma GPS receiver set to output two pulses per second (PPS). The 2 PPS signal is delivered on every half second, which provides accurate timing of each image acquired.

The ancillary data used to create this data product include an Applanix-smoothed best estimate of trajectory (SBET) and a range-to-surface measurement provided by the ATM lidar. The Applanix SBET is a post-processed PPP solution created from the GPS/IMU data collected by an Applanix POS AV 610 sensor, which provides the position (latitude, longitude, altitude) and attitude (pitch, roll, yaw) of the camera. The ATM lidar instruments measure the time-of-flight of laser pulses that are transmitted from the instrument to the ground surface below and back. Once calibrated and averaged, an estimated range, corrected for off-nadir pointing angle, is provided for each image. The combination of these two data sets determines the origin, direction, and magnitude of each pixel vector.

2 Geolocation procedure

This section describes the geolocation procedure for each image pixel recorded by the CAMBOT sensor. Since the sensor is mounted on an aircraft which is constantly in motion a series of coordinate transformations are applied to convert position and attitude as measured by the GPS/IMU systems to obtain the geolocation for each recorded image pixel. In this procedure the camera orientation is here assumed that if the airplane is traveling due north the image $(0, 0)$ pixel is assumed to be in the upper left (northwest) corner of the image.

2.1 Lens distortion

To account for lens distortion effects prior to flight operation, a checkerboard calibration target was imaged with the CAMBOT camera in a laboratory to determine the lens radial and tangential distortion coefficients. The sizes of the checkerboard squares were measured with a ruler and the calibration target was imaged at different orientations. The images were analyzed using the “Caltech Calibration Toolbox” (Bouget, 2016) software package to determine the lens distortion coefficients. An inverse model was then applied to convert between the actual image pixel position (x_i, y_i) and the effective pixel position (x_{ip}, y_{ip}) after lens distortion.

2.2 Geolocation procedure for the camera sensor

For each image, differential GPS and aircraft attitude measurements are synced with the camera time stamp. To determine the position of the camera sensor from this information, the spatial distance between the CAMBOT camera and GPS antenna, $\mathbf{r}_{ant}$, is measured prior to each Operation IceBridge campaign using a North, East, Down (NED) coordinate system. The following coordinate transformations are then applied to correct for the camera offset from the GPS antenna location and determine the camera sensor location.

The GPS antenna latitude, longitude, and altitude are first converted to Earth-Centered Earth-Fixed (ECEF) coordinates, $\mathbf{p}_{ECEF}$ using standard formula. Coordinate transformations are then created using the aircraft pitch, p, roll, r, and heading, d, to determine the camera position in ECEF coordinates following Harpold et al., 2016. The $\mathbf{T}(p,r,d)$ transformation brings the camera's position coordinates into the aircraft NED coordinate system

$$\mathbf{T}(p,r,d) = \begin{bmatrix} cos\,d\,cos\,p & cos\,d\,sin\,p\,sin\,r - sin\,d\,cos\,r & cos\,d\,sin\,p\,cos\,r + sin\,d\,sin\,r \\ sin\,d\,cos\,p & sin\,d\,sin\,p\,sin\,r + cos\,d\,cos\,r & sin\,d\,sin\,p\,cos\,r - cos\,d\,sin\,r \\ -sin\,p & cos\,p\,sin\,r & cos\,p\,cos\,r \end{bmatrix} \tag{1}$$

The $\mathbf{R}(\alpha,\beta)$ transformation brings the camera location to the ECEF coordinate system using the GPS antenna geodetic latitude, α, and geodetic longitude, β

$$\mathbf{R}(\alpha,\beta) = \begin{bmatrix} -sin\alpha cos\beta & -sin\beta & -cos\alpha cos\beta \\ -sin\alpha sin\beta & cos\beta & -cos\alpha sin\beta \\ cos\alpha & 0 & -sin\alpha \end{bmatrix} \tag{2}$$

The camera position in ECEF coordinates, $\mathbf{C}_{ECEF}$, is then determined as

$$\mathbf{C}_{ECEF} = \mathbf{p}_{ECEF} + \mathbf{r}_{ant}\mathbf{TR} \tag{3}$$

Lastly, the camera position in ECEF coordinates is converted to the camera sensor latitude, α_C, longitude, β_C and altitude, a_C using a fixed point iteration method (Bowring, 1976).

2.3 Geolocation procedure for image pixels

In order to determine the geolocation of each camera pixel the vector between an image pixel and the surface is calculated using a simple projection camera model in a similar manner to the methodology described in Barber et al., 2006 but with modifications to account for the measurement system used on the IceBridge aircraft.

Two transformation matrices to account for aircraft motion and mounting biases are constructed using homogeneous coordinates. The $\mathbf{T_{ac}}(p,r,d)$ transformation accounts for the tranformation from the aircraft to the camera frame and is written as

$$\mathbf{T}_{ac}(p,r,d) = \begin{bmatrix} cos\,d\,cos\,p & sin\,d\,cos\,p & sin\,p & 0 \\ cos\,d\,sin\,p\,sin\,r - sin\,d\,cos\,r & sin\,d\,sin\,p\,sin\,r + cos\,d\,cos\,r & -cos\,p\,sin\,r & 0 \\ -cos\,d\,sin\,p\,cos\,r - sin\,d\,sin\,r & cos\,d\,sin\,r - sin\,d\,sin\,p\,cos\,r & cos\,p\,cos\,r & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

To account for mounting biases of the camera, a transformation matrix $\mathbf{T}_M(u,v,w)$ is calculated in an equivalent manner to equation 4 but using u, v, and w, which correspond to the bias in the camera pitch, roll, and heading, respectively. The procedure for determining the mounting biases is described below.

Next, let the point $\boldsymbol{q} = (x_i, y_i, 1, 1)^T$ correspond to the homogeneous projection of the point $p^c_{obj} = (p_x, p_y, p_z, 1)^T$ onto the image plane in pixels, where p^c_{obj} is the location of an object p relative to the center of the camera. The distance in pixels in the image frame for both x and y components is calculated as

$$x_p^{dist} = x_{ip} - N_c \tag{5}$$

$$y_p^{dist} = y_{ip} - N_r \tag{6}$$

where x_{ip} and y_{ip} are the image pixel indices after correcting for lens distortion, N_r is the number of image rows, N_c is the number of image columns.

The conversion factor from pixels to meters is determined using the physical size of the camera sensor, x_s and y_s, and is calculated as

$$S_x = \frac{x_s}{2N_c} \tag{7}$$

$$S_y = \frac{y_s}{2N_r} \tag{8}$$

The camera calibration matrix, $\boldsymbol{C}$, provides the mapping of the 3-dimensional world points to the 2-dimensional image points

$$\boldsymbol{C} = \begin{bmatrix} 0 & -f/S_x & -x_p^{dist} & 0 \\ f/S_y & 0 & -y_p^{dist} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

where f is the focal length.

The tranformation from the inertial to aircraft frame is written in an NED coordinate system as

$$\boldsymbol{S}_m = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -a_c \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

From equations 4, 9, and 10 the position vector between the camera pixel and the object location in the inertial frame is then determined from the following relation

$$\boldsymbol{q_i^{obj}} = \begin{pmatrix} x^i_{obj} \\ y^i_{obj} \\ z^i_{obj} \\ 1 \end{pmatrix} = (\boldsymbol{C}\boldsymbol{T}_M\boldsymbol{T}_{ac}\boldsymbol{S}_m)^{-1}\,\boldsymbol{q} \tag{11}$$

To obtain the true object location a scale factor, λ, must be used to stretch the position vector by a scale factor dependent on the distance along the optical axis to the object in the image. This scale factor is defined from the vertical distance between the two locations as

$$\lambda = \frac{h_{surf} - a_c}{z^i_{obj} - a_c}$$

where h_{surf} is the surface elevation where the optical axis intersects the terrain. For sea ice and ocean surfaces h_{surf} is taken to be the EGM08 geoid value at that location. For land ice surfaces an iterative approach is used to determine the first point where h_{surf} intersects a DEM.

The position vector of the object in NED coordinates is then determined by applying the scale factor to the positition vector determined in equation 11 as

$$\boldsymbol{p}_c^I = \begin{pmatrix} 0 \\ 0 \\ a_c \\ 1 \end{pmatrix} \tag{12}$$

$$\boldsymbol{p}_{obj}^I = \boldsymbol{p}_c^I + \lambda \left(\boldsymbol{q}_i^{obj} - \boldsymbol{p}_c^I \right) \tag{13}$$

The image pixel location in ECEF coordinates is then calculated in a similar manner as equation 3 but now using the camera and object positions

$$\mathrm{p}_{ECEF} = \boldsymbol{C}_{ECEF} + \mathbf{R}\boldsymbol{p}^{\mathbf{I}}_{\mathbf{obj}} \tag{14}$$

Lastly, the image pixel position in ECEF coordinates is converted to latitude and longitude values from the same fixed point iteration method used for the camera position.

2.4 Mounting bias determination

Mounting biases for airborne data used on IceBridge are determined through the use of surveyed targets on or near aircraft ramps which are used by the IceBridge ATM laser altimeter system for calibration. The image pixels of the survey targets are identified in a series of images and the mounting biases were found by an iterative method to adjust the camera pitch, roll, and heading, and timing biases to minimize the error in the distance between the known and calculated locations.

3 References

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