Rigorous Model of Panoramic Cameras

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
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Graduate School of The Ohio State University

By

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* * * * *

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2003

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2003
Establishing a rigorous model for non-frame dynamic imaging system requires incorporating the complex geometry of perspective center into the transformation function that connects image space to object space. This research addresses an appropriate transformation method by extending traditional collinearity equations for the sophisticated descriptions of the relationship between the panoramic image space and object space in order to achieve the robustness of reconstructing the object space. Generally, the crucial requirement of the rigorous model for the non-frame satellite sensor is to have the direct measurements of the GPS/INS for determining the satellite trajectory for the image acquisition periods. However, since there were no measurements of Global Positioning System (GPS) and Inertial Navigation System (INS) for the satellite trajectory of panoramic image data used in this research, we unavoidably applied the indirect method for recovering Exterior Orientation Parameters (EOPs) of the panoramic imagery. This indirect method is a suitable method because it is less sensitive to the errors, caused by the incorrect interior orientation parameters, for obtaining less uncertain results of the reconstructing 3D object space. This research proposes the a robust model for panoramic cameras. This model includes extended collinearity equations, space intersection algorithm based on the coplanarity condition, and object reconstructing modules for generating Digital Elevation Model (DEM) and ortho-rectified image. The proposed model is analyzed in terms of its
capabilities for the recovery of the EOPs and the performance of the space intersection by inspecting the statistics of the output. The model is also tested for proving the validity by comparing it with the generic sensor models such as affine transformation, Direct Linear Transformation (DLT), and Rational Function Model (RFM). Experiments performed in this research show that the proposed model is a suitable representation of the panoramic imagery and can produce useful input for the GIS applications.
Dedicated to Mi Young who believes in me
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PUBLICATIONS


**FIELDS OF STUDY**

Major Field: Geodetic Science and Surveying

Digital Photogrammetry

Satellite Sensor Modeling

DEM Generation

Adjustment Theory
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CHAPTER 1

INTRODUCTION

The major aim of photogrammetry is to reconstruct the object space without physical contact from various types of image data. This entails the development of suitable relationships between the image space and object space. With only few pre-knowledge of the object space and its image data, photogrammetry enables one to establish those relationships playing an important role to reconstruct object space. The fundamental component of reconstruction is the registration of the features on image data to the object space (e.g., determination of the locations of the objects, shown in the image data, in the 3D object space).

Recovery of the camera parameters via orientation processes is the pre-requisite for deriving the locations of objects. Generally, two main procedures are performed in the orientation processes. The first is interior orientation (IO) which defines the perspective center with respect to the image plane. This includes all sources of image coordinate perturbations. The second procedure is the exterior orientation (EO) which defines the perspective center with respect to object space in terms of its location and attitude. In photogrammetry, the most common model for representing the relationship between the image space and the object space is the collinearity equation.
Here, image coordinates of points are functions of the interior orientation parameters (IOPs: The image coordinates of the principal point, the principal distance, and the image perturbations resulted from various distortion sources), the exterior orientation parameters (EOPs), and the ground coordinates of the corresponding object points.

This research applies the collinearity model to develop a rigorous model for panoramic cameras. Unlike traditional frame camera, non-frame dynamic sensors pose a challenge to describe the complex geometry of the exterior orientation. This results in estimating numerous sets of EOPs. However, neighboring EOP sets are very similar and it is not required to recover all EOP sets. Thus, many studies performed for the space resection problems of dynamic non-frame sensors have used either polynomial models ((Ebner et al., 1991), (Ebner et al., 1996), (Heipke et al., 1996), (Habib and Beshah, 1997), (Radhadevi et al., 1998), and (Ebner et al., 1999)) or orientation images (Tang, 1993) for estimating the exterior orientation parameters. Hence, we also will explore ways of avoiding the determination of all EOP sets by simplifying the perspective geometry.

Since the image data (CORONA satellite panoramic imagery) used in this research have been acquired in the mid 60’s for reconnaissance purposes, there are no GPS (Global Positioning System) and INS (Inertial Navigation System) measurements available. Hence, we unavoidably focus on applying the indirect method (Schenk, 1999, p. 389-392) for recovering EOPs to develop a rigorous model for the CORONA satellite panoramic imagery. The indirect method is less sensitive to the errors caused by an imperfect IO for the determinations of the 3D locations in object space because
the impacts of incorrect IOPs can be absorbed in the EOPs due to the strong correlations between IOPs and EOPs. On the other hand, direct method using GPS/INS measurements for determining the EOPs does not offer the advantage of cancelling the effects of incorrect IOPs since it decouples the correlations between IOPs and EOPs. As a result, the direct method may introduce larger errors for the reconstruction of object space when IOPs are not correct. In order to achieve a robust relation, a rigorous model should be less sensitive to imperfect IOPs.

The main concern of this research is to establish a rigorous mathematical model which can produce a highly accurate reconstruction of the 3D object space from panoramic imagery. To accomplish this goal, three main tasks will be conducted in this research. The first task will be the estimation of EOPs through a space resection process performed by applying least square adjustments. The second task will be the development of the space intersection algorithm. The third task will be generating DEM (Digital Elevation Model) and ortho-rectified imagery as by-products of the sensor modeling. The proposed research will attempt the following:

1. Development of an appropriate mathematical model for representing the relationship between image space and object space by the establishment of extended collinearity equations for panoramic imagery.

2. Evaluating feasible configurations of the control points for parameter recovery.

3. Development of space intersection algorithms.


5. Generation of ortho-rectified panoramic imagery.
Validation of the suggested rigorous model.

Validations of the proposed method is performed by comparing (in terms of the accuracy of reconstructed object space) it with the generic sensor models such as affine model, DLT (Direct Linear Transformation), and high order RFM (Rational Function Model). The popularity of using the generic sensor models for the non-frame dynamic sensors (Okamoto et al., 1998), (Okamoto et al., 1999), (Wang, 1999), (Tao et al., 2000), (Dowman and Dollof, 2000), and (Yang, 2000)) mainly have lead by the complexity and the rigorousness of the physical modeling of non-frame dynamic sensors. However, using generic sensor models requires the sacrifice of the accuracy of object reconstruction, limits applying within only small area of image coverage, or demands too many control points for recovering parameters. This research also clarifies the limitations of each generic model for applying it to represent the panoramic imagery.

The organization of this research consists of six chapters. The next chapter provides background information for the DISP (Declassified Intelligence Satellite Photographs) and an overview of the non-frame dynamic sensors. This is followed by the explorations of the general aspects of panoramic camera system, the problem statements of CORONA panoramic imagery, and the proposed procedures for the research. Chapter 3 describes generic sensor models and the derivation of a rigorous model of the panoramic imagery, together with the proposed space intersection algorithm. Chapter 4 shows the various experiments using simulation data and real data for estimating the EOPs. This is followed by the analysis of the results of the
comparisons between suggested rigorous model and the generic sensor models. After suggested model is validated, the reconstructing object spaces is performed to generate DEM and ortho-rectified panoramic imagery. Chapter 5 addresses how we apply the suggested rigorous model to the glaciological application. In the Chapter 6, the findings and gains, resulted from the experiences throughout the research, are summarized together with proposals of future studies to extend this research.
CHAPTER 2

BACKGROUND

2.1 Declassified intelligence satellite photographs (DISP)

During the Cold War era, high resolution space borne cameras acquired thousands of reconnaissance images over the targeted countries (or areas). These reconnaissance images were released more than two decades later in the middle of 90’s. The data set of declassified intelligence satellite photographs (DISP) includes all published reconnaissance satellite images acquired between August 1960 and May 1972. Shortly after its release, DISP had the attentions to be used as historic satellite data for earth science applications. In this section, the overall aspects of DISP and their applications are examined. Section 2.1.1 discusses different sensors of DISP and their distinctive characteristics. Section 2.1.2 reviews how DISP have been used in earth science fields.

2.1.1 The characteristics of DISP imagery and sensors

In the early 60’s, the CORONA program was launched as a satellite imaging reconnaissance system. The CORONA program consisted of six sub-programs which were designated as KH-1, KH-2, KH3, KH-4, KH-4A, and KH-4B according to the assigned camera systems. These reconnaissance satellite programs were followed by
ARGON designated as the KH-5 and LANYARD designated as the KH-6. ARGON was a mapping system developed in parallel with CORONA and flew 12 missions between February 17, 1961 and August 21, 1964. LANYARD was an attempt to develop enhanced imaging capability with higher resolutions. The best resolution of LANYARD imagery was approximately 1.8 m (originally, its intended resolution was 0.6 m) (McDonald, 1995).

Compared with the images acquired by the ARGON mapping system, the images acquired by KH-4A system have higher resolution (e.g., the best resolution of KH-4A system: 2.75 m, the best resolution of ARGON: 140 m). In addition, the available coverage of CORONA KH-4A imagery is world-wide. In the KH-4A camera system, dual camera systems (FWD and AFT) were equipped for the acquisition of stereoscopic scenes. With a convergence angle of 30°, FWD camera pointed 16.5° forward from the nadir and AFT camera pointed 13.5° backward from the nadir. Each camera has a lens with a focal length 609.6 mm and a scan angle of 70°. Table 2.1 describes the details of the KH-4A imaging system as compared with other reconnaissance satellite imaging systems (McDonald, 1997, p.306-307).

The KH-4A camera system acquired hundreds of panoramic images from August 1963 to September 1969. Each image has a ground coverage of 17 km × 231 km approximately. During each mission of imaging capturing, neighboring images in a swath overlap by approximately 10 percent, allowing them to be co-registered to adjacent images. However, this configuration leads to the fact that the available images of the same area have different radiometric and geometric characteristics because the
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Table 2.1: Characteristics of CORONA, ARGON, and LANYARD

KH-4A camera system acquired images on different missions that had various attitudes, altitudes, and orbital inclinations according to the desired coverage.

2.1.2 Applications of DISP in earth science

After over 860,000 U.S. photo reconnaissance satellite photographs were declassified and opened to public in 1995, DISP became more and more popular for earth science research, including urban expansion study, ice sheet dynamic study, and change detection of AOIs over time periods. The inexpensive cost of a DISP film, its high resolution, and wide coverage are attractive to use DISP imagery, particularly the high resolution CORONA KH-4A and KH-4B panoramic imagery, for the earth science research. Several studies have demonstrated the feasibility of using DISP for glaciological applications. The first attempt of using DISP imagery in earth science was found in the work conducted by Bindschadler and Vornberger (1998). Compared with two images of Advanced Very High Resolution Radiometer (acquired in 1980...
and 1992) and a series of panchromatic SPOT images (collected between January 1989 and February 1992), the authors used the ARGON images acquired in 1963 to estimate an avecton speed of the ice stream entering the Ross Ice Shelf and Crary Ice Rise. Kim et al. (2001a) have mapped the ice shelf margin and assessed changes in ice shelf margin position and ice sheet shelf area along the coast of Queen Maud Land, Antarctica over time period from 1963 to 1997 by comparing the 1963 ARGON image with the 1973-1976 Antarctic Digital Database (Cooper et al., 1993) and the 1997 RADASAT-1 synthetic aperture radar (SAR) image mosaic. Aforementioned studies using ARGON have reached coarse results of image registrations (e.g., image to image co-registration and geocoding of image) due to a coarse ground resolution of ARGON Imagery. However, Zhou et al. (2002) conducted ortho-rectification of ARGON images by applying bundle block adjustment techniques based on the collinearity model and reported that the accuracy of check point positions reached approximately 155 m.

The limitations of low resolutions of the ARGON imagery are motivating factor for using the high resolution CORONA KH-4A and KH-4B imagery. With time series of space borne and airborne data (e.g., SPOT image collected in 1988, ERS-1 SAR image obtained in 1992, and aerial photo acquired in 1985), Sohn et al. (1998) estimated the changes in position of the grounded ice sheet margins near Jakobshavn Glacier in west Greenland area by using a portion of CORONA KH-4B imagery (acquired in 1962). Ground coverage is approximately 37.5 km × 37.5 km at the starting point. Comparing the skirt of Columbus (OH, USA) derived from Landsat image acquired in 1994, Kim (1999) selected a central portion (its coverage was 17 km × 33 km)
of CORONA panoramic image strip taken in 1965 to derive early the 60's boundaries of Columbus area. The author applied a 2-D linear polynomial function for co-registration of image to object space by using 30 points of control points collected from 1:24,000 Digital Raster Graph maps. By evaluating the residuals of fitting polynomial function, Kim (1999) reported 15 m (5 ∼ 6 pixels: 1 pixel corresponds 7 µm in image space and approximately 3 m in object space) RMS errors in planimetric accuracy. However, this result is far away from taking advantage of the high resolutions of the Conora image since the general acceptance of accuracy of co-registration of image to object space is in the range of a pixel and even better (Schenk, 1999, p. 6-7). Other glaciological studies conducted using CORONA imagery are found in the studies of Csatho et al. (1999) and Thomas et al. (2000) for deriving ice sheet velocity of Kangerdlugssuaq outlet glacier in east Greenland. The authors used affine transformation to rectify CORONA KH-4A images and reported the error analysis rendered $60\sqrt{2}$ m as the accuracy of the geocoded displacement vectors.

The first trial using stereo pairs of CORONA KH-4B satellite images was performed for the generation of Digital Surface Model (DSM) and ortho images (Altmaier and Kany, 2002). The main concept of work done by Altmaier and Kany (2002) was that the accuracy of intersection using two stereo pairs could be acceptable even if it lacks having accurately estimated interior orientation parameters (IOPs) and exterior orientation parameters (EOPs). This was based on the absorption effects between the IOPs and EOPs (e.g., even badly estimated, the location of principal point may lead to shift estimated values of sensor position. However, the collinearity condition still
can be preserved). Except for using photogrammetric method than polynomial transformation to achieve better triangulation results (RMSE: 1.8 m (X) and 2.8 m (Y) for the Northern part of test area, and 13.9 m (X) and 13.7 m (Y) for the Southern part of test area), this approach could not describe the physical characteristics which have the important roles of eliminating systematic errors by mathematical modeling. Another drawback of this approach is based on ERDAS IMAGINE OrthoBASE Pro module, designed for rectification of frame camera imagery and partly scanned portions of images (e.g., image patches) rather than whole strips of CORONA Images. The aforementioned facts would lead authors to be less confident to explain the trend of systematic errors.

The majority of these studies have not applied robust and rigorous panoramic camera sensor model. This fact causes considerable errors in image to image co-registration as well as geocoding of panoramic image. Csatho et al. (1999) reported that RMS error in image space was 0.09 mm and resulted from the approximation of camera model by affine transformation. Hence, we will develop a robust model which describes the physical panoramic sensor characteristics and assures the robustness of reconstructing object space.

2.2 CORONA KH-4A panoramic imagery

Since CORONA KH-4A panoramic camera acquired imagery with dynamic nature of sensor (e.g., platform movements, swing of lens, and so on), it is essential
to explore the fundamentals of imaging formation of various dynamic sensors (Section 2.2.1). This is followed by detail descriptions of panoramic camera system in Section 2.2.2 and statements of problems associated with CORONA KH-4A Imagery in Section 2.2.3.

2.2.1 Overview of dynamic imaging devices

Since panoramic camera is a member of dynamic imaging devices, it is better to explore the other types of dynamic sensors to figure out the common (or different) features of dynamic imaging devices. In both airborne and space borne, the most different feature of dynamic imaging devices from static imaging devices is whether a time variable should be considered in the image formation. According to the configurations of sensor alignment the dynamic imaging devices can be classified into four categories as panoramic cameras, push broom scanners, three line scanners and whisk broom scanners. In this section three types of dynamic sensors, push broom scanners, three line scanners, and whisk broom scanners are discussed. The panoramic camera system will be continued in Section 2.2.2 and Section 2.2.3.

Push broom scanners, also called linear CCD cameras or line scan devices, acquire one dimensional image at a time. Unlike panoramic cameras, push broom scanners have a linear array which is perpendicular to the flight direction. By the movements of scanners along the flight direction, push broom scanners acquire two dimensional image consisting of a combination of one dimensional image lines which have their
own perspective centers (Lee, 2002). Figure 2.1 depicts the image acquisition mechanism of push broom scanners. A well-known example of a push broom scanner is SPOT, which has a linear array consisting 6000 sensing elements (CNES, 1987).

![Image formation of push broom scanners](image)

Figure 2.1: Image formation of push broom scanners

A stereo scene of push broom scanners can be obtained when two images of the same area are acquired on different days with different orbits. This causes a time lapse between two images. In order to avoid this problem, three line scanners are introduced. The principle of three line scanners is the same as push broom except that triple linear arrays are arranged for nadir looking, forward looking, and backward looking (Lee, 2002). Figure 2.2 illustrates the configuration of imaging system of three line scanners.
There are numerous studies being conducted by using push broom imagery and three line scanner imagery such as SPOT, IKONOS, MOMS (Modular Optoelectronic Multi-spectral/Stereo Scanner), IRS (Indian Remote Sensing Satellite), HRSC (High Resolution Stereo Camera), and WAOSS (Wide Angle Optoelectronic Stereo Scanner).

Since SPOT was launched in 1986, many studies have been conducted to improve the accuracy of the positioning module of SPOT imagery. Gugan (1987) incorporated the inverse collinearity equations in transformation of image space to object space for dynamic satellite imagery by using a real time loop algorithm. Kratky (1989) proposed an approach which saves computing time by fitting polynomial functions for transformation. Baltsavias and Stallmann (1992) also applied polynomial functions for transformation and assessed the geometric accuracy of them. Chen and Lee (1993)
proposed a rigorous model based on the collinearity equations for the rectification of SPOT imagery. Orun and Natarajan (1994) modified a traditional bundle block algorithm for SPOT imagery. El-Manadili and Novak (1996) generated a rectified SPOT image by implementing a modified direct linear transformation (DLT) with self calibration method. Ono et al. (2000) reported on the 2D affine transformation method which can be a substitute for the rigorous transformation method for rectification of small area. A robust algorithm for the indirect method of orientation for linear push broom imagery was proposed by Kim et al. (2001b). This algorithm solved the transformation procedure iteratively with an initial estimate of the 2D image point coordinates without any rigorous steps to determine a good initial estimate.

Another type of push broom sensor is IKONOS which was commercially launched in 1999. The most distinctive feature of the IKONOS scene is its high resolution (e.g., ground resolution: 4 m of stereo and 1 m of mono). There is no significant robust modeling of the IKONOS sensor because the sensor parameters are not published. This is the main reason that the majority of research using IKONOS scenes applied Rational Function Model (RFM) for modeling the sensor. Tao et al. (2000), Dowman and Dollof (2000) performed the feasibility studies of using RFM as generic sensor model which are independent on sensor platforms as well as sensor types. The feasibilities were entailed in the work of Di et al. (2000) who applied RFM for deriving shorelines from simulated IKONOS satellite images. The research performed by Di et al. (2000) explicitly described the form of upward (object space to image space transformation) and downward (image space to object space transformation) RFM.
Similarly, Zhou and Li (2000) assessed the accuracy of space intersection results from RFM model applied for IKONOS scenes.

Many recent studies dealing with three line scanners (e.g., MOMS, IRS, HRSC, and WAOSS) have been conducted to develop a robust sensor model. The design issues, camera configurations (Albertz et al., 1992), and the mechanism of stereoscopic image acquisition of three line camera can be found in the works of Murai et al. (1995), Sandau and Eckert (1996). There were also a few efforts to estimate pose parameters (i.e., parameters describing positions and orientations of camera) of three line cameras. Tang (1993) applied the orientation image method for pose estimation of HRSC and WAOSS. Radhadevi et al. (1998) proposed the time dependent polynomial functions, which were incorporated into collinearity equations, for estimation of pose parameters of IRS-1C PAN imagery. In the same fashion, Ebner et al. (1999) adopted polynomial models for estimating EOPs of MOMS-02/D2 imagery and MOMS-2P/PRIRODA imagery. Recently, more intensive study for estimation of pose parameters of three line cameras was performed by Lee (2002) who applied straight line constraint as uses of the straight line features and the free form curved features for recovering pose parameters of three line cameras.

Whisk broom scanners employ a single detector (rather than linear array) with narrow fields of view sweeping the terrain to acquire an image (Sabins, 1997, p. 14-19). The mechanism of the whisk broom imaging system is basically the same as cross-track scanners. In the cross-track scanners, a faceted mirror of which rotation axis is aligned parallel to the flight direction (i.e. the mirror sweeps across the
ground space with normal to the flight direction). Unlike typical cross-track scanners that have the mirror sweeping to one way of direction, whisk broom scanners have a mirror which sweeps terrain in two directions as illustrated in Figure 2.3. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is the typical sensor equipped with whisk broom scanners (Clark et al., 1998) (Green et al., 1998).

![Figure 2.3: Image formation of whisk broom scanners](image)

### 2.2.2 General of panoramic cameras

The basic mechanism of panoramic principle employs the rotation of lens its second nodal point with cylindrical focal plane to keep the image of distant object not move (e.g., during scanning process, only lens and scan arm move while the film remains
stationary). Figure 2.4 illustrate the schematic diagram of panoramic principle as applied in the HYAC (McDonald, 1997, p.111-120) (Itek-Laboratories, 1961).

Figure 2.4: Panoramic principle applied in the HYAC

Since the principle of panoramic imaging system was proposed, there have been various mechanical approaches for the design of panoramic camera systems. These approaches were mainly categorized into three classes as: (a) direct scanning cameras with swinging lenses (e.g., Fairchild KA-81 and Fairchild KA-82); (b) cameras that scan by means of rotating mirror or prisms (e.g., Fairchild KB-29A and Perkins-Elmer KS-69A); and (c) optical-bar-type cameras with folded, rotating optics and moving film (e.g., Itek 5776, Itek KA-80A, and Fairchild KA-94A) (Slama, 1980, p.197-207).
Although the aforementioned types of panoramic cameras applied different mechanism of imaging system, the design of the panoramic camera focuses on achieving high resolution and wide swaths with one camera. The details of objects can be imaged with narrow lens field of view so that the amounts of distortions resulting from the optics are in the range of only few micrometers. However, there are possible distortion sources, which impact the geometric fidelity panoramic imagery, that are not found in frame imagery. These types of distortions cause the displacement of the images of the ground points from their expected perspective positions and are mainly divided into four categories as follows (Slama, 1980, p. 196-207):

- Panoramic distortion: Caused by the cylindrical shape of the negative film surface and the scanning action of the lens.

- Scan positional distortion: Caused by the forward motion of the camera during scanning process.

- Image motion compensation distortion: Caused by film or camera motion for compensation of image motion during the exposure time.

- Tipped panoramic distortion: Caused by tipping of the scan axis within the vertical plane of the flight path.

In addition, other sources of distortion can be found in the attitude instability of the platform. Roll, pitch, and yaw result in geometric distortions which cause the sampled image to be projected in the incorrect places in the reconstructed image. These types of distortion sources are more prevalent in the airborne panoramic camera than in the space borne panoramic camera since the trajectory of space borne

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camera less affected by the attitude instability (e.g., the trajectory of space borne camera is usually assumed to be smooth plane). More details of attitude instability and estimation procedures of them would be found in the section of pose estimation of the line camera in the work of Lee (2002).

Based on the exploration of the possible distortion sources that cause the bias in perspective geometry of the panoramic camera imagery, the acquired panoramic imagery may appear different from the expected imagery. Hence, it is essential to model all possible distortion sources in the estimation process of exterior orientation parameters of panoramic camera and eliminate them from the imagery acquired.

2.2.3 Problem of CORONA KH-4A panoramic imagery

Although the effects of the attitude instability could be small enough to be neglected in imagery acquired by the space borne panoramic camera system like KH-4A, there are still problems associated with panoramic imagery. These problems are mainly result from the scanning mechanisms, dynamic sensor characteristics, and interplay between instabilities of image acquisition components (Richards, 1993, p.51-56) (Lillesand and Kiefer, 1994, p.393-404). As offsprings of problems defined above, the distortions are smeared in the acquired panoramic images even though the images are shown as continuous representations of features on the ground.

In addition to distortion, there are another problem that arises in using KH-4A panoramic imagery for photogrammetric applications. The lack of ephemeris data
describing sensor dynamics, such as ground velocity of platform and scan rate of sensor play an important role for reconstructing image geometry. This leads to the complexity in estimation of the sensor parameters (e.g., these parameters are treated as unknowns and to be estimated or solved rather than used as prior knowledge of sensor). Unlike traditional frame camera imagery, the IOPs (e.g., the photo coordinates of principal points and fiducial marks) of KH-4A panoramic imagery are not available. This fact hinders conducting traditional image orientation procedures, such as steps of deriving three dimensional information of objects. However, the impacts of the lack of IOPs can be alleviated by performing the self calibration procedures.

Another important issue of using KH-4A imagery is on how to handle the numerous EOPs. The field of view of KH-4A panoramic cameras is parallel to the flight direction and rotates about a perspective center with preset swing angle. Figure 2.5 illustrates how the perspective center changes its location during the image formation process of the vertical panoramic camera system. For the total scan time denoted as T [second], the perspective center moves along the flight direction and rotates from the first look position to the next look position. After completing a period of scan time, panoramic cameras acquire images of a series of sub-swaths over the area of coverage.

As shown in the Figure 2.5, a panoramic scene consists of numerous image swaths where each swath has its own EOPs at the exposure time. Based on this fact, we can induce that there are too many EOPs to be estimated and they are highly correlated to each other (especially, between neighboring EOPs) so that the system of parameter
estimation would be fallen into singular. Hence, we have to reduce the number of involved EOPs by setting up an appropriate model for the locations of the perspective center at different exposure time.

2.3 Proposed procedures for this research

The aim of this research is to develop a rigorous and robust sensor model for panoramic cameras. The following outline presents the essential steps to be underlined by the proposed research:
Step 1 - Collection of sensor information

1A. Overall examination of sensor characteristics (Section 2.1.1): The identification of available ephemeris data of image frame and sensor platform should be accomplished.

1B. Analysis of panoramic imaging formation (Section 2.2.2 and Section 2.2.3): The concept of panoramic imaging formation is clarified and the possible distortion sources with their impacts on the scene are identified and described.

Step 2 - Design and development of the mathematical model

2A. Identify and classify parameters: This part entails the effects of dynamic motion of the sensor platform on EOPs. Also, it is necessary to clarify what parameters are unknown and estimable (or not estimable).

2B. Set hypothesis: Since not every phenomenon and details (e.g., the perturbations of sensor EOPs at every moment during exposure time) of all camera systems can be incorporated into mathematical model, it will simplify some conditions with reasonable assumptions (For example, it is possible to assume the satellite trajectory as 2nd order polynomial since the orbit surface of satellite platform is smooth).

2C. Develop the mathematical model for geometry of the imaging system: Descriptions of all geometric features of the imaging system would be made in this part. Furthermore, the relationships between the parameters are set up. Incorporating all unknown parameters into extended collinearity equations would be addressed.
Step 3 - Implementation

3A. Simulation: Based on the developed mathematical model of panoramic imaging system, panoramic images and their foot prints can be generated from extended collinearity equations with assumed parameters and synthetic DEM data. In addition, overall investigations of simulated imagery and its foot prints must be carried out in order to check whether the suggested mathematical model looks reasonable by comparing it with the results of past research. In this part, the unknown EOPs of the sensor are estimated throughout the adjustment process and checked by comparing assumed (or input) values.

3B. Preparing software and hardware: For measuring image coordinates of certain points, it is better checking the available software and hardware (e.g., Adobe photoshop, ERDAS Imagine, Soft copy workstation, scanner, and analytical plotter, and etc).

3C. Collection of ground control points: Suppose that the digital format of panoramic images are available at this stage. This part determines the sources of control points to be collected (e.g., digital line graphs, aerial photos, and so on). In addition, it is crucial to check the spatial accuracy of control points.

3D. Programming: Programs include the modules of space resection for estimation of the EOPs for the sensor, space intersection for determination of object coordinates of tie points, ortho photo generation, and quality control.

3E. Analysis of the testing results of each program module: It is possible to evaluate the performance of each program module by checking the statistics computed in
each module (e.g., simulation panoramic image module, parameter estimation module, space intersection module, and ortho-rectification module).

Step 4 - Validation

4A. Model validation: This is the final part of modeling procedure and can be conducted by the comparing the space intersection results of suggested approach with those of other transformation methods (e.g., Affine transformation, DLT, RFM).
CHAPTER 3

MATHEMATICAL MODEL

Though there are many types of cameras, there are two main categories of sensor models such as rigorous sensor models and generic sensor models for the description of relationship between image space and object space.

As represented by collinearity equations based on the perspective relationship between image and object space, the rigorous model depicts the sensor physical characteristics as forms of parameters (e.g., attitude, location, and movement of the perspective center during the exposure time). The generic sensor models have the form of ratios of polynomials which do not explicitly (or directly) described in the estimated parameters. The examples of these generic sensor models are the ratios of higher order polynomials (higher than first order polynomials), direct linear transformation (first order polynomial in both denominator and numerator), and affine model (first order polynomial in numerator and zero order polynomial in denominator).

This chapter introduces all mathematical models used in this research. Section 3.1 presents the generic models with their mathematical forms, advantages, and disadvantages. Section 3.2 addresses the rigorous model which describes the geometry
of panoramic imaging formation. Section 3.3 explores the space intersection algorithm, modified from traditional space intersection algorithm for frame images, for panoramic images.

3.1 Generic sensor models

3.1.1 Ratios of higher order polynomials

Since OpenGIS® Consortium (OGC) proposed the higher order polynomials (or rational function model: RFM) as one of the Earth image geometry model (OGC, 1999), several studies including the work of Tao et al. (2000), Dowman and Dollof (2000), Di et al. (2000), and Yang (2000) reported the feasibility of using ratios of higher order polynomials for photogrammetric resection and intersection problems. The majority of these studies argue that acceptable accuracies are achieved in their application results.

Ratios of polynomials

This generic sensor model uses a ratio of two polynomial functions to compute a row location and a similar ratio to compute a column location in an image of object points. All four polynomials are functions of ground coordinates. Generally, each polynomial has 20 coefficient terms. In the equations representing the relationship between image coordinates and ground coordinates of points, the coordinates are normalized coordinates which have a range of -1 to 1 over an image segment that is a pre-defined segment of a large image (OGC, 1999). For each image segment, the ratios of polynomials are defined as follows:
\[ r_n = \frac{p_1(X_n, Y_n, Z_n)}{q_1(X_n, Y_n, Z_n)} \]
\[ c_n = \frac{p_2(X_n, Y_n, Z_n)}{q_2(X_n, Y_n, Z_n)} \]

where \( r_n \) and \( c_n \) denote the normalized pixel coordinates (row, column) of a point; \( X_n, Y_n, \) and \( Z_n \) are the normalized object coordinates (easting, northing, height) of a point; \( p_1, q_1, p_2, \) and \( q_2 \) indicate the polynomials that are functions of \((X_n, Y_n, Z_n)\).

The polynomials described in Eq. 3.1 can be defined as:

\[
\begin{align*}
p_1 &= \sum_{i=0}^{m_1} \sum_{j=0}^{m_2} \sum_{k=0}^{m_3} a_{ijk} X_n^i Y_n^j Z_n^k \\
p_2 &= \sum_{i=0}^{m_1} \sum_{j=0}^{m_2} \sum_{k=0}^{m_3} c_{ijk} X_n^i Y_n^j Z_n^k \\
q_1 &= \sum_{i=0}^{m_1} \sum_{j=0}^{m_2} \sum_{k=0}^{m_3} b_{ijk} X_n^i Y_n^j Z_n^k \\
q_2 &= \sum_{i=0}^{m_1} \sum_{j=0}^{m_2} \sum_{k=0}^{m_3} d_{ijk} X_n^i Y_n^j Z_n^k
\end{align*}
\]

where \( m_1, m_2, \) and \( m_3 \) indicate the power of ground coordinates of \( X, Y, \) and \( Z, \) respectively; \( a_{ijk}, b_{ijk}, c_{ijk}, \) and \( d_{ijk} \) are the polynomial coefficients.

For uses of polynomials, the maximum power of each ground coordinate is limited to 3. Also, the total power of all three ground coordinates is limited to 3 (i.e., polynomial coefficients are to be zero whenever \( i + j + k > 3 \)).

With the aforementioned limitation of powers, Eq. 3.1 can be rewritten as follows:
where \((a_0, a_1, \ldots, a_{19})\) denote the polynomial coefficient in the \(p_1\) polynomial; \((b_1, \ldots, b_{19})\) denote the polynomial coefficient in the \(q_1\) polynomial; \((c_0, c_1, \ldots, c_{19})\) denote the polynomial coefficient in the \(p_2\) polynomial; and \((d_1, \ldots, d_{19})\) denote the polynomial coefficient in the \(q_2\) polynomial.

In general, the ratio of first order terms represents the distortions caused by optical projection. the ratio of second order terms indicates the corrections for atmospheric refraction, lens distortions, and earth curvatures while the ratio of third order terms is compensation for unknown distortions (Tao et al., 2000). Eq. 3.3 delineates the projection of a point from object space to image space and is called upward RFM. Similarly, the inverse form of upward RFM (also called downward RFM) can be written as follows (Di et al., 2000):

\[
X_n = \frac{p_3(r_n, c_n, Z_n)}{q_3(r_n, c_n, Z_n)} = \frac{(1, r_n, c_n, Z_n, \ldots, r_n^3, c_n^3, Z_n^3) \cdot (e_0, e_1, \ldots, e_{19})^T}{(1, r_n, c_n, Z_n, \ldots, r_n^3, c_n^3, Z_n^3) \cdot (1, f_1, \ldots, f_{19})^T} \tag{3.4}
\]

\[
Y_n = \frac{p_4(r_n, c_n, Z_n)}{q_4(r_n, c_n, Z_n)} = \frac{(1, r_n, c_n, Z_n, \ldots, r_n^3, c_n^3, Z_n^3) \cdot (g_0, g_1, \ldots, g_{19})^T}{(1, r_n, c_n, Z_n, \ldots, r_n^3, c_n^3, Z_n^3) \cdot (1, h_1, \ldots, h_{19})^T}
\]
where \((e_o, e_1, ..., e_{19})\) denote the polynomial coefficient in the \(p_3\) polynomial; \((f_1, ..., f_{19})\) denote the polynomial coefficient in the \(q_3\) polynomial; \((g_o, g_1, ..., g_{19})\) denote the polynomial coefficient in the \(p_4\) polynomial; and \((h_1, ..., h_{19})\) denote the polynomial coefficient in the \(q_4\) polynomial.

**Normalization of coordinates**

The normalization steps of image coordinates and ground coordinates of points are presented in this section. The ground coordinates are offset and scaled to fit the range of -1 to 1 for each image segment. The normalized ground coordinates are computed as follows (OGC, 1999):

\[
\begin{align*}
X_n &= \frac{X_u - X_{ofs}}{X_s} \\
Y_n &= \frac{Y_u - Y_{ofs}}{Y_s} \\
Z_n &= \frac{Z_u - Z_{ofs}}{Z_s}
\end{align*}
\]  

(3.5)

where \(X_n, Y_n,\) and \(Z_n\) are normalized ground coordinates of a point; \(X_u, Y_u,\) and \(Z_u\) are unnormalized ground coordinates of a point; \(X_{ofs}, Y_{ofs},\) and \(Z_{ofs}\) are offset values for ground coordinate system; and \(X_s, Y_s,\) and \(Z_s\) are scale values for ground coordinate system.

In the same fashion, the image coordinates can be normalized as:

\[
\begin{align*}
r_n &= \frac{r_u - r_{ofs}}{r_s} \\
c_n &= \frac{c_u - c_{ofs}}{c_s}
\end{align*}
\]  

(3.6)
where \( r_n \) and \( c_n \) are normalized image coordinates of a point; \( r_u \) and \( c_u \) are unnormalized image coordinates of a point; \( r_{ofs} \) and \( c_{ofs} \) are offset values for image coordinate system; \( r_s \) and \( c_s \) are scale values for image coordinate system.

In spite of its sensor independence that facilitates real time and simple implementation, RFM has some drawbacks associated with following facts:

- When applying the third order polynomials, it is necessary to have at least 39 ground control points to solve the 78 parameters for each image segment (e.g., if a whole scene consists of four image segments, the number of control points needed are \( 4 \times 39 = 156 \)).

- The uses of this model are limited only on image segments which are divided from original scene to achieve desired accuracy.

- It would have potential failure due to zero denominator.

- Since there are too many parameters (possibly, highly correlated to each other) in this model, the normal matrix of linear system for solving parameters is not stable. This is the reason that this model would implement a regularization process to make normal matrix be stable and solution can be obtained throughout iterative process.
3.1.2 Direct linear transformation

Direct linear transformation (DLT) model was developed by Abdel-Aziz and Karara (1971) to establish the relationship between stage coordinate system and object coordinate system without transformation of stage coordinates into photo coordinates. There were several studies that reported the significant results of applied DLT for geometric correction or transformation from object space to image space of dynamic sensor imagery. As mentioned in Chapter 2, El-Manadili and Novak (1996) performed the rectification of SPOT imagery using DLT with self calibration approach. With assumptions that during the image acquisition time the velocity variations in the orbit could be neglected and the rotations of orbital frame as well as fluctuations of orientation with respect to this frame are negligible. Gupta and Hartley (1997) developed linear transformation model (which is the same as DLT) for push broom camera and compared it with a rigorous model with respect to the results of the transformation from object space into image space. Based on the comparisons, the authors reported the acceptable accuracy of DLT (e.g., RMSE of DLT is 0.80 pixel while RMSE of rigorous model is 0.73 pixel) and proposed the use of DLT as an alternative of a push broom camera model. Savopol and Armenakis (1998) applied DLT to model IRS-1C pan stereo imagery. In the same fashion, Wang (1999) extended the uses of DLT with self calibration algorithm for the triangulation of IRS-1C imagery and argued that the accuracy of triangulation is acceptably high.

As mentioned earlier in this section, DLT relates measured stage coordinates on comparator directly to ground coordinates. DLT can be derived by combining the affine transformation and the collinearity equations together:
\[\begin{align*}
x_a &= x_p - c_x \left( r_{11}(X - X_o) + r_{21}(Y - Y_o) + r_{31}(Z - Z_o) \right) \\
y_a &= y_p - c_y \left( r_{12}(X - X_o) + r_{22}(Y - Y_o) + r_{32}(Z - Z_o) \right)
\end{align*}\] (3.7)

where \(x_a\) and \(y_a\) are the metric image coordinates of point \(a\); \(c_x\) and \(c_y\) are the principal distance with respect to \(x\) and \(y\) directions, respectively; \(x_p\) and \(y_p\) are metric image coordinates of the principal point; \(X, Y,\) and \(Z\) are the ground coordinates of a point corresponding image point \(a\); \(X_o, Y_o,\) and \(Z_o\) are the ground coordinates of the perspective center at the exposure time; \((r_{11}, ..., r_{33})\) are the elements of rotation matrix.

As shown in the Eq. 3.7, there are two principal distances \((c_x, c_y)\), which are different from regular collinearity equations. These two principal distances compensate for two scale factors. The coordinates of the principal point \((x_p, y_p)\) compensate the shift terms of the affine transformation. In addition, the rotation are compensated by the \(\kappa\) rotation which is the rotation angle with respect to \(Z\)-axis of ground coordinate system. Eq. 3.7 can be rewritten as follows:

\[\begin{align*}
x_a &= \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1} \\
y_a &= \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1}
\end{align*}\] (3.8)

where \(L_1, L_2, ..., L_{11}\) are the DLT coefficients denoting the relationships between parameters as defined in following equations:
\[ L_1 = \frac{x_p r_{13} - cx r_{11}}{L} \]
\[ L_2 = \frac{x_p r_{23} - cx r_{21}}{L} \]
\[ L_3 = \frac{x_p r_{33} - cx r_{31}}{L} \]
\[ L_4 = x_p + c_x \frac{r_{11}X_o + r_{21}Y_o + r_{31}Z_o}{L} \]
\[ L_5 = \frac{y_p r_{13} - cy r_{12}}{L} \]
\[ L_6 = \frac{y_p r_{23} - cy r_{22}}{L} \]
\[ L_7 = \frac{y_p r_{33} - cy r_{32}}{L} \]
\[ L_8 = y_p + c_y \frac{r_{12}X_o + r_{22}Y_o + r_{32}Z_o}{L} \]
\[ L_9 = \frac{r_{13}}{L} \]
\[ L_{10} = \frac{r_{23}}{L} \]
\[ L_{11} = \frac{r_{33}}{L} \]
\[ L = -(r_{13}X_o + r_{23}Y_o + r_{33}Z_o) \]

Eq. 3.8 can be easily linearized with respect to unknown parameters. This could be done by rewriting Eq. 3.8 as follows:

\[ x_a = XL_1 + YL_2 + ZL_3 + L_4 - x_a XL_9 - x_a YL_{10} - x_a ZL_{11} + e_{x_a} \quad (3.9) \]
\[ y_a = XL_5 + YL_6 + ZL_7 + L_8 - y_a XL_9 - y_a YL_{10} - y_a ZL_{11} + e_{y_a} \]

where \( e_{x_a} \) and \( e_{y_a} \) denote the errors associated with the observations of \( x_a \) and \( y_a \), respectively.
In order to solve the unknown coefficients, it is necessary to have at least 6 points. Hence, we establish 12 equations for 11 unknown parameters to be solved. Those equations can be solved by applying the least square adjustment process. After the 11 parameters have been estimated, the EOPs and IOPs can be computed by using Eq. 3.10:

\[
L_d = \frac{1}{\sqrt{L_9^2 + L_{10}^2 + L_{11}^2}} \\
x_p = (L_1L_9 + L_2L_{10} + L_3L_{11})L_d^2 \\
y_p = (L_5L_9 + L_6L_{10} + L_7L_{11})L_d^2 \\
c_x = \sqrt{(L_1^2 + L_2^2 + L_3^2) - x_p^2} \\
c_y = \sqrt{(L_5^2 + L_6^2 + L_7^2) - y_p^2} \\
\phi = \arcsin(L_9L_d) \\
\omega = \arctan\left(\frac{L_{10}}{L_{11}}\right) \\
\kappa = \arccos\left(\frac{r_{11}}{\cos\phi}\right) \\
r_{11} = L_d x_p L_9 - L_1 \\
\begin{bmatrix}
X_o \\
Y_o \\
Z_o
\end{bmatrix} = - \begin{bmatrix}
L_1 & L_2 & L_3 \\
L_5 & L_6 & L_7 \\
L_9 & L_{10} & L_{11}
\end{bmatrix}^{-1} \begin{bmatrix}
L_4 \\
L_8 \\
1
\end{bmatrix}
\]

If we explore Eq. 3.7 and Eq. 3.8, we find that 10 parameters \((x_p, y_p, ..., Y_o, Z_o)\) in Eq. 3.7 are replaced by 11 parameters \((L_1, ..., L_{11})\) in Eq. 3.8. The additional parameter can be regarded as compensation for the non-orthogonality between x and y-axis of the affine transformation. The general remarks of the DLT can be summarized as follows:
• The equations are linear so that it is not necessary to compute partial derivatives. Also, approximations for the unknowns are not required.

• It is a special case of RFM of which two numerators and one common denominator have the first order polynomials.

• It requires at least six well-distributed control points in 3D space and the solution is very sensitive to the configuration of the control points in the object space.

• Since DLT does not consider the dynamic characteristics of sensor, it is less accurate than collinearity based rigorous model when it is applied for the images acquired by dynamic sensors.

3.1.3 Affine model

Some studies have presented that acceptable accuracy of results could be achieved for rectification of dynamic sensed image using 2D affine model. The extended form of 2D affine model, which is also referred to linear polynomials (OGC, 1999), used for 3D analysis of linear scanner imagery can be expressed as follows (Okamoto et al., 1998):

\[
\begin{align*}
    x_i &= a_o + a_1 X_i + a_2 Y_i + a_3 Z_i \\
    y_i &= b_o + b_1 X_i + b_2 Y_i + b_3 Z_i
\end{align*}
\] (3.11)
where \( x_i \) and \( y_i \) denote the image coordinates of a point \( i \); \( X_i, Y_i, \) and \( Z_i \) are the ground coordinates of a point \( i \); and \((a_0, ..., b_6)\) are the affine parameters.

Practical implementation of the affine model has been intensively conducted using both stereo SPOT images and MOMS-2P imagery ((Okamoto et al., 1998), (Hattori et al., 2000), (Ono et al., 2000)). With less than 10 ground control points, the authors reported that the planimetric accuracy of triangulation reached up to sub-pixel level (6-8 m) over 60 × 40 km test area. However, this result was only valid to the small coverage of flat area. With expansion of 2D affine model, some studies have shown that the use of a lower-order polynomial 3D model can be an alternative of a rigorous model for rectifying dynamic sensed images even in hilly and mountainous areas ((Pala and Pans, 1995), (Okamoto et al., 1999)). The expanded lower order polynomial 3D model can be expressed as follows:

\[
\begin{align*}
    x_i &= a_o + a_1 X_i + a_2 Y_i + a_3 Z_i + a_4 X_i Y_i + a_5 X_i Z_i + a_6 Y_i Z_i \\
    y_i &= b_o + b_1 X_i + b_2 Y_i + b_3 Z_i + b_4 X_i Y_i + b_5 X_i Z_i + b_6 Y_i Z_i
\end{align*}
\]  

(3.12)

where \((a_o, ..., b_6)\) are the polynomial coefficients.

The only distinctive difference Eq. 3.12 from Eq. 3.11 is whether model incorporates three more convolved order terms derived from the multiplications of ground coordinates (e.g., \(X_i Y_i\), \(X_i Z_i\), and \(Y_i Z_i\)) in both equations of \(x_i\) and \(y_i\). The general aspects of affine model (or expanded lower order polynomial 3D model) can be described as follows:

- The model has a simple form and is easy for implementation.
• It is independent to the physical characteristics of a sensor.

• It is only applicable when the relief displacement is negligible. In other words, the ground undulations may cause the larger errors.

• Though the expansion of order of polynomial improves the fitting results so that the residuals are small, it also means more ground points needed to estimate the polynomial parameters.

• In general, the accuracy (w.r.t. transformation results) of this model can not reach the accuracy of rigorous model due to the modeling error (e.g., affine parameters are not sufficient to describe the relationship between image space and object space).

3.2 Rigorous model

This section addresses the details about the components and the procedures of establishing a rigorous mathematical panoramic camera model for KH-4A camera system. Starting from the explanation of the coordinate systems used in the mathematical model (Section 3.2.1), the parameters involved in scanning system (Section 3.2.2). This is followed by the descriptions of assumptions made for simplifying the physical phenomenon of camera system. In addition, the extended collinearity equations applied to the panoramic camera model are presented (Section 3.2.3).
3.2.1 Coordinate systems

The KH-4A camera system acquired imagery by a sequence of scanning object through telescope. To explain the relationship between image points and object points, three different coordinate systems are defined by the telescope coordinate system, the camera coordinate system, and the ground coordinate system. Each coordinate system has its own sign convention and origin. Figure 3.1 shows the relationship between three coordinate systems (Habib and Beshah, 1997). The notations used in this research are as follows:

- \((x, y, z)_T\) is the telescope coordinate system (e.g., \(x_T\), \(y_T\), and \(z_T\) are axes of telescope coordinate system).
- \((x, y, z)_c\) is the camera coordinate system (e.g., \(x_c\), \(y_c\), and \(z_c\) are axes of camera coordinate system).
- \((X, Y, Z)_G\) is the ground coordinate system (e.g., \(X_G\), \(Y_G\), and \(Z_G\) are axes of ground coordinate system).
- \(PC_t\) denotes the perspective center at scan time, \(t\).
- \((X_{ot}, Y_{ot}, Z_{ot})_G\) are the ground coordinates of the perspective center at scan time, \(t\).
- \(\alpha_t\) denotes the scan angle at scan time, \(t\).

The coordinate systems used in developing a rigorous model for KH-4A camera system are defined as follows:

- The telescope coordinate system \((x, y, z)_T\) has its origin at the perspective center of the lens when the lens is looking nadir (z-axis is vertical).
The camera coordinate system \((x, y, z)_c\) is the coordinate system defined by \(y_c\) being in the flight direction and \(x_c\) being in the scan direction. The scan arm rotates about the \(y_c\)-axis with an angular measurement \(\alpha\) which is zero occurred at the nadir looking. The origin of the this coordinate system is the same as telescope coordinate system.

The ground coordinate system \((X, Y, Z)_G\) is a user defined coordinate system (e.g., 3D cartesian coordinate system, UTM with heights, and etc.). The relationship between the camera and the ground coordinate system is defined through the three rotation angles

Rotation angles (Azimuth, Pitch, and Roll): Azimuth \((-\kappa)\) is the primary rotation angle around \(Z_G\). Pitch \((\omega)\) is the secondary rotation angle around \(X_{GA}\)-axis (rotated \(X_G\)-axis after applying azimuth). Roll \((\phi)\) is the tertiary
rotation angle around $Y_{GAP}\text{-axis}$ (rotated $Y_G\text{-axis}$ after applying azimuth and pitch).

### 3.2.2 Scan angle, scan arc, and scan time

Since KH-4A panoramic camera applied scanning system to acquire imagery, it is necessary to define parameters which describe the scanning system. The parameters involved in scanning system are defined as (Figure 3.2):

![Figure 3.2: Scan angle, scan arc, and scan time](image)

(1) Scan angle ($\alpha_t$) is the measurement of the rotation angle from vertical $z_c\text{-axis}$ (nadir looking) to oblique $z_c\text{-axis}$ at scan time, $t$ in the camera coordinate system. The total scan angle ($\alpha_T$) is an angular measure from the starting scan time to end time of scan. At an arbitrary scan time, the scan angle ($\alpha_t$) [radian] can be computed as:

$$\alpha_t = -\frac{x_c}{f}$$  \hspace{1cm} (3.13)
where \( x_c \) is the \( x \)-image coordinates (in camera coordinate system) of a point captured at scan time \( t \). The sign convention of \( \alpha_t \) is defined as positive when the \( x \)-image coordinates of a point is negative.

(2) The total length of scan arc \( (L_s) \) is the multiplication of the total scan angle [radian] and the focal length.

\[
L_s = f \cdot \alpha_T
\]  
(3.14)

where \( \alpha_T \) is the total scan angle [radian].

(3) Scan time \( (t) \) is the fraction of total scan time. The scan time at an arbitrary time \( t \) can be computed by:

\[
t = \left( \frac{x_c}{L_s} + 0.5 \right) \cdot T
\]  
(3.15)

where \( t \) denotes an arbitrary scan time; and \( T \) is total scan time.

### 3.2.3 Collinearity equations for panoramic imagery

The concept of collinearity condition on light ray is that the object point, the perspective center, and the corresponding image point lie on a straight line. In other words, the vector from an image point to the perspective center is the same as the vector from the perspective center to the object point except the scale difference.

A couple of assumptions are made for deriving the appropriate mathematical model for KH-4A panoramic camera model as:
In the telescope coordinate system, the coordinates of the principal point (PP) are \((0, 0, -f)_T\) for the positive focal plane.

Based on the assumption of smooth trajectories of satellite, the satellite attitude does not change during one scan.

In order to derive the extended collinearity model that can be applied for KH-4A panoramic imagery, we start to define the perspective geometry in the telescope coordinate system as shown in Figure 3.3. In the telescope coordinate system, the coordinates of the perspective center can be expressed in Eqs. 3.16.

![Figure 3.3: The location of the perspective center in telescope coordinate system](image)

\[
\begin{bmatrix}
  x_{pc} \\
  y_{pc} \\
  z_{pc}
\end{bmatrix}_T = \begin{bmatrix}
  x_p \\
  y_p \\
  0
\end{bmatrix}_T
\] (3.16)
In the telescope coordinate system, the coordinates of image point $a$ can be expressed as Eq. 3.17 (if and only if x coordinates of image point with respect to the telescope coordinate system is equal to zero).

\[
\begin{bmatrix}
  x_a \\
y_a \\
z_a
\end{bmatrix}_T = \begin{bmatrix}
  0 \\
y_a \\
-f
\end{bmatrix}_T
\]  
(3.17)

where $[x_a, y_a, z_a]_T$ are the image coordinates (in the telescope coordinate system) of a point captured at scan time $t$.

The vector from the perspective center to an image point in the telescope coordinate system can be obtained by follows:

\[
\begin{bmatrix}
  x_a - x_p \\
y_a - y_p \\
-f
\end{bmatrix}_T = \begin{bmatrix}
  0 \\
y_a \\
-f
\end{bmatrix}_T
\]  
(3.18)

Also, we can define the relationship between the telescope coordinate system and the camera coordinate system through the rotation matrix with respect to scan angle at time $t$ (refer to Figure 3.1). Thus, the vector from perspective center to image point in the camera coordinate system can be expressed as follows:

\[
V_C = R_{\alpha_t} \cdot V_T
\]  
(3.19)

where $R_{\alpha_t}$ is rotation matrix with respect to scan angle $\alpha_t$ at time $t$, which can be represented as:

\[
\begin{bmatrix}
  \cos(\alpha_t) & 0 & \sin(\alpha_t) \\
  0 & 1 & 0 \\
-\sin(\alpha_t) & 0 & \cos(\alpha_t)
\end{bmatrix}
\]
The vector from the perspective center to object point $A$, captured as image point $a$, with respect to the ground coordinate system could be expressed in Eq. 3.20. The location of perspective center in object space (ground coordinate system) can be defined as shown in Figure 3.4.

\[
\mathbf{V}_G = \begin{bmatrix}
X_A - X_{ot} \\
Y_A - Y_{ot} \\
Z_A - Z_{ot}
\end{bmatrix}_G
\]  

(3.20)

where $[X_A, Y_A, Z_A]_G$ are the ground coordinates of the object point $A$ and $[X_{ot}, Y_{ot}, Z_{ot}]_G$ are the ground coordinates of the perspective center at time $t$.

Figure 3.4: The location of perspective center in ground coordinate system
Vector $V_G$ can be rewritten as multiplying $V_C$ by a scale factor and the rotation matrix of azimuth ($\theta_A$), pitch ($\theta_P$), and roll ($\theta_R$). Thus, the collinearity equation for an arbitrary scan time $t$ can be written as follows:

$$V_G = \lambda \cdot R_{\theta_A \theta_P \theta_R} \cdot V_C = \lambda \cdot R_{\theta_A \theta_P \theta_R} \cdot R_{\alpha_t} \cdot V_T$$ (3.21)

where $\lambda$ is scale factor and $R_{\theta_A \theta_P \theta_R}$ is rotation matrix with respect to azimuth, pitch, and roll.

Substituting Eqs. 3.18, 3.19, and 3.20 into Eq. 3.21 and placing the vector $V_T$ in left side of Eq. 3.21 yield the collinearity equation as follows:

$$\begin{bmatrix} 0 \\ y_a \\ -f \end{bmatrix}_T = \frac{1}{\lambda} \cdot R_{\alpha_t}^T R_{\theta_A \theta_P \theta_R} \cdot \begin{bmatrix} X_A - X_{ot} \\ Y_A - Y_{ot} \\ Z_A - Z_{ot} \end{bmatrix}_G = \frac{1}{\lambda} \cdot R_{tot} \cdot \begin{bmatrix} X_A - X_{ot} \\ Y_A - Y_{ot} \\ Z_A - Z_{ot} \end{bmatrix}_G$$ (3.22)

where $R_{tot}$ denotes the $R_{\alpha_t}^T \cdot R_{\theta_A \theta_P \theta_R}$.

The resulting (extended) collinearity equations are given by:

$$F_x = 0 = -f \frac{r_{11}(X_A - X_{ot}) + r_{12}(Y_A - Y_{ot}) + r_{13}(Z_A - Z_{ot})}{r_{31}(X_A - X_{ot}) + r_{32}(Y_A - Y_{ot}) + r_{33}(Z_A - Z_{ot})}$$

$$F_y = y_a = -f \frac{r_{21}(X_A - X_{ot}) + r_{22}(Y_A - Y_{ot}) + r_{23}(Z_A - Z_{ot})}{r_{31}(X_A - X_{ot}) + r_{32}(Y_A - Y_{ot}) + r_{33}(Z_A - Z_{ot})}$$ (3.23)

where $F_x$ and $F_y$ are the functional descriptions of collinearity equations.

For one scan ($T$), the perspective center of the panoramic camera has moved from its initial location to the final location. Theoretically, there are infinite number of
EOPs. Recovering unlimited number of EOPs is not needed because neighboring EOPs are similar to each other. Herein, with the assumption of smooth surface of satellite trajectories we establish an analytical function between the location of the perspective center at starting scan time and the location of the perspective center at scan time $t$ (shown in Figure 3.5). This function enables one to predict all EOPs (for one scan) by recovering one EOPs.

![Figure 3.5: Movements of perspective center during panoramic image acquisition](image)

For an scan period (from the starting scan time to scan time, $t$), the displacement of the perspective center occurs due to camera motion. This displacement occurs along the $y$-axis of the camera coordinate system. Since the relationship between the ground coordinate system and the camera coordinate system can be established through the rotation matrix $(R_{\theta_A\theta_P\theta_R})$, the displacement of the perspective center with respect to the ground coordinate system can be obtained from the multiplication of the rotation matrix by the displacement with respect to the camera coordinate system.
Therefore, the location of the perspective center at scan time, \( t \), can be computed as follows:

\[
\begin{bmatrix}
X_{ot} \\
Y_{ot} \\
Z_{ot}
\end{bmatrix}_G = \begin{bmatrix}
X_o \\
Y_o \\
Z_o
\end{bmatrix}_G + R_{\theta_A \theta_P \theta_R} \begin{bmatrix}
0 \\
v \cdot t \\
0
\end{bmatrix}_C + R_{\theta_A \theta_P \theta_R} \begin{bmatrix}
X_o \\
Y_o \\
Z_o
\end{bmatrix}_G + R_{\theta_A \theta_P \theta_R} \begin{bmatrix}
0 \\
D \cdot \left( \frac{x_c}{L_s} + 0.5 \right) \\
0
\end{bmatrix}_C
\]

where, \([X_o, Y_o, Z_o]_G\) is the location of the perspective center at the starting scan time.

### 3.3 Space intersection

After we estimated six EOPs and flight distance, we could reconstruct ground coordinates of ground points. The planimetric ground position \((X_A, Y_A)\) of an object point could be calculated from the following formula (Kraus, 1992, pp.15-16):

\[
X_A = X_{ot} + (Z_A - Z_{ot}) \frac{r_{11}(x_a) + r_{21}(y_a) - r_{31}}{r_{13}(x_a) + r_{23}(y_a) - r_{33}}
\]

\[
Y_A = Y_{ot} + (Z_A - Z_{ot}) \frac{r_{12}(x_a) + r_{22}(y_a) - r_{32}}{r_{13}(x_a) + r_{23}(y_a) - r_{33}}
\]

Eq. 3.25 shows that there are infinitely many possible object points corresponding to each image point. Hence, it is impossible to reconstruct the ground coordinates of object points from a single photo. This is the reason why we must have either a stereo pair of photographs or pre-knowledge of \( Z \) of object points (e.g., all points locate on the plane with known elevation) (Kraus, 1992). In this research, we have used a stereo pair of photographs to reconstruct the ground positions of object points. The concept of space intersection by using stereo pairs is illustrated in Figure 3.6.
Suppose we have conjugate image points identified on the left and the right image. The vector from the perspective center of the left image to the perspective center of the right image with respect to the ground coordinate system can be easily defined as:

\[
\mathbf{B} = \begin{bmatrix}
X_{rot}^r - X_{rot}^l \\
Y_{rot}^r - Y_{rot}^l \\
Z_{rot}^r - Z_{rot}^l
\end{bmatrix}_G
\]

(3.26)

where \([X_{rot}^r, Y_{rot}^r, Z_{rot}^r]_G\) are the ground coordinates of the perspective center of the right image and \([X_{rot}^l, Y_{rot}^l, Z_{rot}^l]_G\) are the ground coordinates of the perspective center of the left image.

As we defined in Eq. 3.18, the vector from the perspective center to image point of the right image in the telescope coordinate system could be set by:

\[
\mathbf{P}_r = \begin{bmatrix}
0 \\
y_{a'} \\
-f
\end{bmatrix}_T
\]

(3.27)
In the same fashion, we can compute the vector from the perspective center to the image point of the left image in the telescope coordinate system as:

\[
P_l = \begin{bmatrix} 0 \\ y_a \\ -f \end{bmatrix}_T \tag{3.28}
\]

Now, we convert the vectors of \( P_r \) and \( P_l \) with respect to ground coordinate system as follows:

\[
P_{rG} = \lambda_r \cdot R_{\theta_A}^{\theta_r} \cdot R_{\alpha_l} \cdot P_r \tag{3.29}
\]

\[
P_{lG} = \lambda_l \cdot R_{\theta_l} \cdot R_{\alpha_l} \cdot P_l \tag{3.30}
\]

As shown in Figure 3.6, the triangle \( O_lO_rA \) is a closed polygon. Thus, we can define the coplanarity condition as:

\[
B + \lambda_1 \cdot P_{rG} - \lambda_2 \cdot P_{lG} = 0 \tag{3.31}
\]

where \( \lambda_1 \) and \( \lambda_2 \) are scale factors to be estimated.

Hence, the observation equations for estimation of \( \lambda \) and \( \mu \) can be rewritten as:

\[
\begin{bmatrix}
X_{ot}^r - X_{ot}^l \\
Y_{ot}^r - Y_{ot}^l \\
Z_{ot}^r - Z_{ot}^l
\end{bmatrix}_G = \lambda_2 \cdot R^l \cdot \begin{bmatrix} 0 \\ y_a \\ -f \end{bmatrix}_T - \lambda_1 R^r \begin{bmatrix} 0 \\ y_a' \\ -f \end{bmatrix}_T \tag{3.32}
\]

where \( R^l \) denotes \( R_{\theta_A}^{\theta_r} \cdot R_{\alpha_l} \) and \( R^r \) denotes \( R_{\theta_r}^{\theta_r} \cdot R_{\alpha_l} \).

After estimating two unknown parameters of \( \lambda_1 \) and \( \lambda_2 \), we can compute the ground coordinates of an object point based on Eqs. 3.33 and 3.34.
\[
\begin{bmatrix}
X_A \\
Y_A \\
Z_A
\end{bmatrix}_G = \begin{bmatrix}
X_{ot}^r \\
Y_{ot}^r \\
Z_{ot}^r
\end{bmatrix}_G + \lambda_1 \cdot R^r \begin{bmatrix}
0 \\
y_{a'} \\
-f
\end{bmatrix}_T
\] (3.33)

\[
\begin{bmatrix}
X_A \\
Y_A \\
Z_A
\end{bmatrix}_G = \begin{bmatrix}
X_{ot}^l \\
Y_{ot}^l \\
Z_{ot}^l
\end{bmatrix}_G + \lambda_2 \cdot R^l \begin{bmatrix}
0 \\
y_a \\
-f
\end{bmatrix}_T
\] (3.34)

By using two sets of \([X_A, Y_A, Z_A]_G\) computed by Eqs. 3.33 and 3.34, we can determine the ground coordinates of tie points identified on a stereo pair from the average of two \([X_A, Y_A, Z_A]_G\) sets.
CHAPTER 4

EXPERIMENTS

Experiments were conducted using simulation data and real data primarily focused on achieving the following objectives:

- Determine the required parameters to sufficiently describe the panoramic camera system.

- Figure out the optimal configuration of control point distributions for the improvement of checkpoint accuracy.

- Compare the performance of the suggested rigorous camera model to those of various transformation methods (e.g., RFM, DLT, affine transformation).

- Explore the accuracy of the reconstructed object space using estimated parameters.

4.1 Simulation

Simulations were performed to verify the fidelity of the suggested rigorous panoramic camera model and the algorithm of parameter recovery. The synthetic panoramic image coordinates were generated with the following input parameters:
• Interior orientation parameters \((x_p, y_p, f)_T\) are known and fixed.

• Exterior orientation parameters \(([X_o, Y_o, Z_o]_G, (\theta_A, \theta_P, \theta_R))\) and velocity of satellite are assumed and to be estimated.

• Initial scan angle \((\alpha_o)\).

• Amounts of increment of scan angle per second \((\alpha_i)\).

• Total scan time \((T)\) for capturing one whole panoramic scene.

• Synthetic digital elevation model (DEM).

In the simulation process of generating synthetic panoramic image coordinates, it should be recognized that panoramic camera can capture the object points if and only if the \(x\) coordinates of the image points with respect to the telescope coordinate system is equal to zero. Following is a summary of the steps of the simulations:

(1) Step 1: Compute rotation matrix with respect to azimuth, pitch, and roll.

(2) Step 2: Compute planimetric position of points at the starting time of scan, \(t = 0\).

(3) Step 3: Compute planimetric position of points at the end time of scan, \(t = T\).

(4) Step 4: Derive exposure time and compute image coordinates of points \((x_a, y_a)\) in the telescope coordinate system.

In order to derive exposure time, it is necessary to select approximate exposure time, \(t_o\). Then, we compute scan angle \((\alpha_{t_o})\) and satellite position \([X_{t_o}, Y_{t_o}, Z_{t_o}]_G\) at the approximate exposure time. These allow to compute panoramic image coordinates
of points with respect to the telescope coordinate system. Once the approximate exposure time is chosen, the exposure time can be determined when \( x \) panoramic image coordinates with respect to telescope coordinate system are equal to zero. The step of estimating exposure time can be formulated using the Newton-Raphson method as follows (Rice, 1993, p.327-331) (Habib and Beshah, 1997):

\[
t_e = t_o - \frac{x_t(t_o)}{\frac{\partial x_t(t)}{\partial t}|t_o} \tag{4.1}
\]

\[
\frac{\partial x_t(t)}{\partial t}|_{t_o} = \frac{x_t(t_o + dt) - x_t(t_o)}{dt} \tag{4.2}
\]

where \( t_e \) is the estimated time of exposure; \( t_o \) is the approximated time of exposure; \( x_t(t_o) \) is the panoramic image coordinates of a point at the approximate time of exposure; and \( dt \) is the amount of time increment.

### 4.1.1 Simulation of panoramic image coordinates and footprints

Based on the suggested panoramic camera model, the panoramic image coordinates with respect to the telescope coordinate system (or camera coordinate system) and the corresponding footprint of the panoramic image are simulated. To do so, a flat surface with constant elevation is assumed and the parameters of camera attitude (azimuth, pitch, and roll) are set at zero to simulate a vertical panoramic image for discerning distortion patterns. The details of the simulation parameters for the panoramic camera system are summarized in Table 4.1.

The panoramic image coordinates (with respect to camera coordinate system) are simulated and shown in the Figure 4.1. The grid shape of the panoramic image
Simulation parameters | Specification
---|---
Image coordinates of principal point \((x_p, y_p)\) | \((0,0)\) [mm]
Focal length \((f)\) | 300 [mm]
Initial scan angle \((\alpha_t)\) | 45 [deg.]
Scan rate | −30 [deg./sec.]
Scan time | 3 [sec.]
Azimuth, pitch, and roll \((\theta_A, \theta_P, \theta_R)\) | \((0,0,0)\) [deg.]
Sensor position \((X_o, Y_o)\) | \((0,0)\) [m]
Flight height \((Z_o)\) | 4000 [m]
Flight distance \((D)\) | 600 [m]

Table 4.1: Panoramic camera specification for simulation

coordinates has a wave form which is a symmetric shape only with respect to the diagonal directions.

Figure 4.1: Simulated panoramic image coordinates
The corresponding footprints of panoramic images are acquired by back projecting of assumed DEM onto image plane through collinearity equations using given parameters. Figure 4.2 shows the footprint of the panoramic image.

### 4.1.2 Recovery of the required parameters by using simulation data

To test the algorithm for estimating required parameters (six EOPs and flight distance), we simulated oblique panoramic image coordinates by projecting synthetic DEM (Figure 4.3) on the image plane by using collinearity equations with the assumed parameters. In order to analyze the noise effects on the estimated parameters, we added the noises approximately 6 \( \mu m \) for the image coordinate measurements.
and approximately 10 cm for the ground coordinates of control points, respectively.

Table 4.2 summarizes the simulation parameters of oblique panoramic image coordinates. As a sequence, 210 pairs of panoramic image coordinates were generated in this simulation.

![Figure 4.3: 3D view of synthetic DEM used in simulation of oblique panoramic image coordinates](image)

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image coordinates of principal point ((x_p, y_p))</td>
<td>((0, 0) [mm])</td>
</tr>
<tr>
<td>Focal length ((f))</td>
<td>300 [mm]</td>
</tr>
<tr>
<td>Initial scan angle (\alpha_{v0})</td>
<td>45 [deg.]</td>
</tr>
<tr>
<td>Scan rate</td>
<td>-30 (\text{deg. sec.})</td>
</tr>
<tr>
<td>Scan time</td>
<td>3 [sec.]</td>
</tr>
<tr>
<td>Azimuth, pitch, and roll ((\theta_A, \theta_P, \theta_R))</td>
<td>((-45, 10, 10) [deg.])</td>
</tr>
<tr>
<td>Sensor position ((X_o, Y_o))</td>
<td>((0, 0) [m])</td>
</tr>
<tr>
<td>Flight height ((Z_o))</td>
<td>2000 [m]</td>
</tr>
<tr>
<td>Flight distance ((D))</td>
<td>600 [m]</td>
</tr>
</tbody>
</table>

Table 4.2: Camera specification for simulation of oblique panoramic image coordinates
Frequently, the acquisition of well-distributed control points is not an easy task and requires significant effort in terms of time and economical matters. Therefore, the optimal configuration (or at least feasible configuration) of the control points should be determined not only to obtain better accuracy of space intersection results but also to reduce the economical effort for collecting control points. Hence, we carried out several experiments for recovering required parameters. These experiments are designed by the distribution of the control points appearing at different locations on the image space (denoted as Type L - left, Type M - middle, Type R - right, and Type E - entire). Figure 4.4 shows the distributions of control points set up.

The aforementioned seven parameters are recovered by the least squares adjustment process. Comparing the estimated values of parameters with true values of parameters (input parameters for simulation) as well as inspecting the adjustment statistics allows to judge what is the most favorable configuration of control point distribution and whether the suggested algorithm of the parameter estimation is valid. Table 4.3 shows the estimated parameters with adjustment statistics for each experiment.

After comparing the differences between the true values of the parameters (Table 4.2) and estimated parameters (Table 4.3), all types of control point distributions correctly recover the required parameters so that those designed configurations of control points are feasible to be used for estimating parameters. However, Type E shows better performance than other experiments in the parameter recovering process. This is more obvious when we explore not only the difference between the true
values of parameters and estimated parameters but also the adjustment statistics (Table 4.4). For instance, when we compare the estimated variance component (which implies the accuracy of the measurement or goodness of fit between the observation and the estimated parameters via the given model) for each experiment, Type R uses the control points which have a better accuracy of measurement than other experiments. However, the best case of accuracy of estimated parameters (which can be
induced from the standard deviations of parameters which indicate the accuracy of parameters) occurred in results of Type E which has the smallest standard deviations for all estimated parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type L</th>
<th>Type M</th>
<th>Type R</th>
<th>Type E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_o [m]$</td>
<td>-0.02029</td>
<td>-0.05779</td>
<td>0.19795</td>
<td>0.01162</td>
</tr>
<tr>
<td>$Y_o [m]$</td>
<td>-0.00158</td>
<td>-0.02665</td>
<td>0.10405</td>
<td>0.01957</td>
</tr>
<tr>
<td>$\theta_A [deg.]$</td>
<td>-44.99927</td>
<td>-45.00083</td>
<td>-44.99801</td>
<td>-44.99933</td>
</tr>
<tr>
<td>$\theta_P [deg.]$</td>
<td>10.00036</td>
<td>9.99977</td>
<td>9.99924</td>
<td>9.99992</td>
</tr>
<tr>
<td>$\theta_R [deg.]$</td>
<td>9.99882</td>
<td>9.99969</td>
<td>10.00063</td>
<td>9.99969</td>
</tr>
<tr>
<td>$D [m]$</td>
<td>599.96839</td>
<td>600.10261</td>
<td>599.71300</td>
<td>599.93615</td>
</tr>
</tbody>
</table>

Table 4.3: Estimated parameters from the different types of control point configurations

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Type L</th>
<th>Type M</th>
<th>Type R</th>
<th>Type E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{X_o} [\pm m]$</td>
<td>0.00114</td>
<td>0.00070</td>
<td>0.00088</td>
<td>0.00037</td>
</tr>
<tr>
<td>$\sigma_{Y_o} [\pm m]$</td>
<td>0.00097</td>
<td>0.00069</td>
<td>0.00077</td>
<td>0.00032</td>
</tr>
<tr>
<td>$\sigma_{Z_o} [\pm m]$</td>
<td>0.00108</td>
<td>0.00058</td>
<td>0.00044</td>
<td>0.00022</td>
</tr>
<tr>
<td>$\sigma_{\theta_A} [\pm sec.]$</td>
<td>0.06534</td>
<td>0.06527</td>
<td>0.04318</td>
<td>0.02624</td>
</tr>
<tr>
<td>$\sigma_{\theta_P} [\pm sec.]$</td>
<td>0.06472</td>
<td>0.04710</td>
<td>0.03054</td>
<td>0.02170</td>
</tr>
<tr>
<td>$\sigma_{\theta_R} [\pm sec.]$</td>
<td>0.06236</td>
<td>0.05129</td>
<td>0.03082</td>
<td>0.01839</td>
</tr>
<tr>
<td>$\sigma_{D} [\pm m]$</td>
<td>0.00264</td>
<td>0.00272</td>
<td>0.00123</td>
<td>0.00059</td>
</tr>
<tr>
<td>Variance component</td>
<td>0.00931</td>
<td>0.00983</td>
<td>0.00821</td>
<td>0.00882</td>
</tr>
</tbody>
</table>

Table 4.4: Adjustment statistics of the estimated parameters from the different types of control point configurations
In the following experiments, we examine the effects of the different control point distributions on the results of the reconstructed object coordinates of checkpoints. Three different checkpoint configurations (designated as Type I, Type II, and Type III) are tested. The image space of these configuration is shown in Figure 4.5. Twelve experiments were conducted according to the combinations of the configuration of the control point and the checkpoints. The experiments are summarized in Table 4.5.

Figure 4.5: Distribution of checkpoints: (a) Type I (b) Type II (c) Type III

For the reconstruction of planimetric object coordinates of the checkpoints, we use the known height information of checkpoints for the projection of image coordinates.
Table 4.5: The combinations of the control point distribution and the checkpoint distribution for the twelve experiments

<table>
<thead>
<tr>
<th>Control point type</th>
<th>Exp.1</th>
<th>Exp.2</th>
<th>Exp.3</th>
<th>Exp.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (83 points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II (24 points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III (46 points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

onto the surface by applying the collinearity equations (Eq. 3.25). Reconstructed planimetric object spaces using different configurations of the control points and the checkpoints have been compared through root mean square error (RMSE) analysis.

Table 4.6: RMSE of the reconstructed object spaces of the checkpoints

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$RMS_X$ [m]</th>
<th>$RMS_Y$ [m]</th>
<th>$RMS_T$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>0.08952</td>
<td>0.10654</td>
<td>0.13916</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.10204</td>
<td>0.10463</td>
<td>0.14615</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.10010</td>
<td>0.13346</td>
<td>0.16683</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>0.09255</td>
<td>0.10319</td>
<td>0.13861</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>0.07267</td>
<td>0.05121</td>
<td>0.08891</td>
</tr>
<tr>
<td>Experiment 6</td>
<td>0.06874</td>
<td>0.05823</td>
<td>0.09009</td>
</tr>
<tr>
<td>Experiment 7</td>
<td>0.08086</td>
<td>0.06758</td>
<td>0.10538</td>
</tr>
<tr>
<td>Experiment 8</td>
<td>0.06399</td>
<td>0.05386</td>
<td>0.08364</td>
</tr>
<tr>
<td>Experiment 9</td>
<td>0.08617</td>
<td>0.09667</td>
<td>0.12950</td>
</tr>
<tr>
<td>Experiment 10</td>
<td>0.07893</td>
<td>0.07760</td>
<td>0.11069</td>
</tr>
<tr>
<td>Experiment 11</td>
<td>0.07324</td>
<td>0.07855</td>
<td>0.10740</td>
</tr>
<tr>
<td>Experiment 12</td>
<td>0.06198</td>
<td>0.07881</td>
<td>0.10026</td>
</tr>
</tbody>
</table>

By comparing the results of each group of experiments (e.g., Group1: Experiment 1 through Experiment 4, Group 2: Experiment 5 through Experiment 8, and Group
Experiment 9 through Experiment 12), we observed that there is no significant variation between each experiment. However, the cases of well-distributed control points over the entire image (Experiment 4, Experiment 8, and Experiment 12) allow more accurate results of the reconstructed object space of checkpoints. Hence, one can argue that the recovered parameters throughout the suggested algorithm represent the camera geometry effectively within the entire range of the panoramic image without the significant problem of localization.

4.2 Real data descriptions

For this research, we have chosen a stereo pair of panoramic images consisting of a FWD image and a AFT image. These images cover urban areas in Ohio (U.S.A.) ensuring convenience of identification of the control points. The panoramic images used in this research were acquired by the CORONA mission 1026-1. Table 4.7 summarizes the CORONA KH-4A images used for testing the performance of the suggested rigorous panoramic camera model. Figure 4.6 shows an browse image and enlarged sub-image of panoramic image (DS1026-1014DA011).

<table>
<thead>
<tr>
<th>Mission</th>
<th>1026-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>DS1026-1014DF005 (FWD)</td>
</tr>
<tr>
<td></td>
<td>DS1026-1014DA011 (AFT)</td>
</tr>
<tr>
<td>Date</td>
<td>October 29, 1965</td>
</tr>
<tr>
<td>Ground coverage</td>
<td>17 km × 231 km</td>
</tr>
<tr>
<td>Type</td>
<td>B/W positive film</td>
</tr>
</tbody>
</table>

Table 4.7: Description of CORONA KH-4A images used for testing the suggested algorithm
Those selected images are scanned by the photogrammetric scanner which has a maximum image resolution of 12 $\mu m$ and the scan dimension of 23 cm $\times$ 23 cm. However, since the dimension of the panoramic images (approximately, 55.4 mm $\times$ 757 mm) exceeds the scan dimension of the scanner, we scanned the entire panoramic image by five image patches with approximately 50 percent overlap between two successive image patches. Then, the scanned image patches are stitched by first order polynomial transformation using the tie points identified on the overlapped
image spaces. The transformation of image patches and the resampling process of image patches are performed by using ERDAS Imagine\textsuperscript{TM} 8.4 software (ERDAS, 1999, p.350-359).

Digital raster graphs (DRG, scale 1:24,000 and 7.5 minute quadrangle grid) of Ohio state topographic maps are used as the reference maps for collecting the ground control points. All DRGs were available from the U.S. Geological Survey web site (\url{http://mcmcweb.er.usgs.gov/drg/free_drg.html} - Last visited on July 30, 2002). For ensuring well-distributed control points on the entire panoramic image, we need to used forty sheets of DRG, approximately. According to National Map Accuracy Standards (NMAS), the accuracies of the ground control points identified on the DRG of 1:24,000 scale are 7.44 m for the location and 0.9 m (0.3 \times contour interval of 3 m) for the elevation (Light, 1993).

4.3 Conversion of the ground coordinate system

Before estimating the required parameters of the KH-4A panoramic camera, it is necessary to convert the map coordinates from a geographic coordinate system (latitude/longitude) to a three-dimensional rectangular coordinate system (e.g., 3D local topocentric coordinate system) for the ground points identified on the maps. This conversion step allows to avoid modeling the earth curvature effects into the extended collinearity equations. Figure 4.7 illustrates the geometrical relationship between the ground coordinate systems (e.g., geographic coordinate system, geocentric coordinate system, and 3 D local topocentric coordinate system). The relationship between the
geographic coordinate system and the geocentric coordinate system, which was originally derived by Heiskanen and Moritz (1967), can be depicted as follows (Torge, 1991, p.44-49):

\[
\begin{bmatrix}
X_{GC} \\
Y_{GC} \\
Z_{GC}
\end{bmatrix} = \begin{bmatrix}
(N_r + h)\cos(\phi_L)\cos(\lambda_L) \\
(N_r + h)\cos(\phi_L)\sin(\lambda_L) \\
\left(\frac{b_r^2}{a_r^2}\right)N_r + h)\sin(\phi_L)
\end{bmatrix}
\]

where \([X_{GC}, Y_{GC}, Z_{GC}]\) are the geocentric coordinate system; \(\phi_L, \lambda_L, h\) are the ellipsoidal latitude, longitude, and height, respectively; \(N_r\) is the radius of curvature in prime vertical; and \(a_r\) and \(b_r\) are the semi-major and the semi-minor axis of the ellipsoid.

The inverse conversion from \([X_{GC}, Y_{GC}, Z_{GC}]\) to \([\phi_L, h]\) is solved only by iteration with the approximation of \(\phi_L\). From Eq. 4.3, we can compute the inverse relationship between the geographic coordinate system and the geocentric coordinate system as
follows (Bowring, 1985):

\[ h = \frac{\sqrt{X_{GC}^2 + Y_{GC}^2}}{\cos(\phi_L)} - N_r \]  

\[ \phi_L = \arctan \frac{Z_{GC}}{\sqrt{X_{GC}^2 + Y_{GC}^2}} \left( 1 - e_c^2 \frac{N_r}{N_r + h} \right)^{-1} \]

\[ \lambda_L = \arctan \frac{Y_{GC}}{X_{GC}} \]

where \( e_c \) is the eccentricity of ellipsoid.

After obtaining the geocentric coordinate system, we can transform it into a 3D local topocentric coordinate system by using follow equations:

\[
\begin{bmatrix}
E_s \\
N_t \\
H_t
\end{bmatrix} = R_{\theta_X \theta_Z} \begin{bmatrix}
X_{GC} - X_{GC_o} \\
Y_{GC} - Y_{GC_o} \\
Z_{GC} - Z_{GC_o}
\end{bmatrix}
\]

where \( [E_s, N_t, H_t] \) is the 3D local topocentric coordinate system (easting, northing, and heights, respectively); \( R_{\theta_X \theta_Z} \) is the rotation matrix considering the rotation angles between two coordinate systems; \( \theta_X \) is the rotation angle with respect to \( X_{GC} \); \( \theta_Z \) is the rotation angle with respect to \( Z_{GC} \); and \( [X_{GC_o}, Y_{GC_o}, Z_{GC_o}] \) is the origin of the 3D local topocentric coordinate system (user defined).

### 4.4 Estimation of the KH-4A panoramic camera parameters

As mentioned in the previous chapter, the collinearity equations are the nonlinear function so that we need to input the initial (or approximate) values of parameters for
the adjustment process of the parameter estimation. The initial approximate values of parameters are obtained by the following steps:

- Approximations of $X_o$ and $Y_o$ are computed from the average of the ground coordinates of the four corner points described in the CORONA KH-4A panoramic image meta-data published by the USGS EROS data center.

- Satellite altitude $H$ could be used as the approximate value of $Z_o$.

- Conducting the 2D similarity transformation between the panoramic image coordinates and the ground coordinates of the points allows to obtain an initial approximation of the azimuth.

- Approximation of pitch was extracted from the configuration of the CORONA KH-4A camera system (i.e., using the convergence angle between the FWD camera and the AFT camera).

- The approximate value of roll is assumed to be zero.

- The approximation of flight distance, which is the hardest part to get a good approximation, is assumed by trial and error until the solution converges.

Based on the results of the optimal configuration of control points discussed in the simulation part, the KH-4A parameters are estimated by using well-distributed control points. The number of control points used in the estimation of the parameters are 33 points for DS1026-1014DF005 (FWD image) and 31 points for DS1026-1014DA011 (AFT image). Figure 4.8 shows the distribution of the control points and the check-points in the object space.
With the aforementioned configurations of control points, all required parameters are recovered. Table 4.8 and Table 4.9 show the estimated parameters and the adjustment statistics, respectively.

As a part of the analysis of the adjustment statistics, we also calculated the correlations between the estimated parameters. The most highly correlated parameters are the azimuth ($\theta_A$) and the flight distance ($D$). The correlations between those parameters are 0.99743 and 0.99705 for the FWD image and for the AFT image, respectively. Decoupling of these two parameters would bring more stable results. However, there is seldom a chance to decouple these parameters since the pre-knowledge of these
### Table 4.8: Estimated parameters of KH-4A images

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DS1026-1014DF005</th>
<th>DS1026-1014DA011</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_o$ [m]</td>
<td>-16432.20247</td>
<td>14148.26418</td>
</tr>
<tr>
<td>$Y_o$ [m]</td>
<td>37321.89139</td>
<td>-62495.86719</td>
</tr>
<tr>
<td>$Z_o$ [m]</td>
<td>197562.69347</td>
<td>195474.03596</td>
</tr>
<tr>
<td>$\theta_A$ [deg.]</td>
<td>200.12767</td>
<td>200.56609</td>
</tr>
<tr>
<td>$\theta_P$ [deg.]</td>
<td>14.50355</td>
<td>-16.37591</td>
</tr>
<tr>
<td>$\theta_R$ [deg.]</td>
<td>0.44168</td>
<td>0.58261</td>
</tr>
<tr>
<td>$D$ [m]</td>
<td>329.16751</td>
<td>184.93537</td>
</tr>
</tbody>
</table>

### Table 4.9: Adjustment statistics of the estimated parameters of KH-4A images

<table>
<thead>
<tr>
<th>Statistics</th>
<th>DS1026-1014DF005</th>
<th>DS1026-1014DA011</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{\sigma}_{X_o}$ [$\pm m$]</td>
<td>0.75003</td>
<td>0.47629</td>
</tr>
<tr>
<td>$\hat{\sigma}_{Y_o}$ [$\pm m$]</td>
<td>1.79360</td>
<td>1.35206</td>
</tr>
<tr>
<td>$\hat{\sigma}_{Z_o}$ [$\pm m$]</td>
<td>0.49309</td>
<td>0.41100</td>
</tr>
<tr>
<td>$\hat{\sigma}_{\theta_A}$ [$\pm \text{sec.}$]</td>
<td>0.64512</td>
<td>0.60624</td>
</tr>
<tr>
<td>$\hat{\sigma}_{\theta_P}$ [$\pm \text{sec.}$]</td>
<td>1.85610</td>
<td>1.40417</td>
</tr>
<tr>
<td>$\hat{\sigma}_{\theta_R}$ [$\pm \text{sec.}$]</td>
<td>0.26178</td>
<td>0.26219</td>
</tr>
<tr>
<td>$\hat{\sigma}_{D}$ [$\pm m$]</td>
<td>0.75588</td>
<td>0.70829</td>
</tr>
<tr>
<td>Variance component</td>
<td>0.01460</td>
<td>0.01403</td>
</tr>
</tbody>
</table>

parameters is not available.

After the parameters are estimated and available, we can verify whether the estimated parameters are acceptable to determine the ground coordinates of the image points. To do so, Eq. 3.25 are used to project the control points and the checkpoints on the image space into the object space. In addition, the differences between the observed values and the computed values of the ground coordinates of the control

70
points and the checkpoints are explored. To compute the planimetric location of the control points and checkpoints, we use known heights of the control points and the checkpoints. Table 4.10 summarizes the results of space intersection in terms of RMSE.

<table>
<thead>
<tr>
<th>Type of point</th>
<th>RMSE</th>
<th>DS1026-1014DF005</th>
<th>DS1026-1014DA011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Point</td>
<td>$RMS_X$ [m]</td>
<td>5.37908</td>
<td>4.67027</td>
</tr>
<tr>
<td>(33 points - F005)</td>
<td>$RMS_Y$ [m]</td>
<td>4.67647</td>
<td>4.78202</td>
</tr>
<tr>
<td>(31 points - A011)</td>
<td>$RMS_T$ [m]</td>
<td>7.12769</td>
<td>6.68428</td>
</tr>
<tr>
<td>checkpoint</td>
<td>$RMS_X$ [m]</td>
<td>8.76801</td>
<td>8.55433</td>
</tr>
<tr>
<td>(20 points - F005)</td>
<td>$RMS_Y$ [m]</td>
<td>8.82165</td>
<td>8.34583</td>
</tr>
<tr>
<td>(20 points - A011)</td>
<td>$RMS_T$ [m]</td>
<td>12.43782</td>
<td>11.95112</td>
</tr>
</tbody>
</table>

Table 4.10: RMSE of space intersection when using known heights of the control points and the checkpoints

### 4.5 Validation of the rigorous panoramic camera model

The aim of this section is the validation of the suggested rigorous panoramic camera model. For the validation, the accuracy of transformation from image space to object space is assessed for the generic models and the rigorous model. This entails the evaluation of the capability of each model by checking the RMSE of the control points and the checkpoints since it is the most fundamental process to illustrate how models appropriately describe the relationship between image space and model space. All involved parameters for each model are estimated by the least square adjustment. Table 4.11 summarizes the number of parameters involved in each model and the
required number of control points (with assumption of no rank deficiency of normal matrix) to recover (unique solution) of parameters.

<table>
<thead>
<tr>
<th></th>
<th>Affine Model</th>
<th>DLT</th>
<th>RFM $(q_1 \neq q_2)$</th>
<th>Rigorous Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>$8 \times n$</td>
<td>$11 \times n$</td>
<td>$38 \times n$</td>
<td>$78 \times n$</td>
</tr>
<tr>
<td>Control point</td>
<td>$4 \times n$</td>
<td>$6 \times n$</td>
<td>$19 \times n$</td>
<td>$39 \times n$</td>
</tr>
</tbody>
</table>

$n$: The number of image segments divided from an entire image

Table 4.11: The number of parameters and the minimum number of control points for recovering of parameters

For testing how each model describes the relationship between the object space and the panoramic image space, the comparisons are conducted with the control points collected on the entire ground coverage of the FWD image and the AFT image. Figure 4.9 shows the distribution of the control points and the checkpoints used in the comparisons. For this experiment conducted with the entire part of image, we applied second order RFM $(q_1 \neq q_2)$ as well as third order RFM $(q_1 \neq q_2)$. The control points used for the comparisons of each model are 42 points for each image. We also used 34 checkpoints for the FWD image and 28 checkpoints for the AFT image to measure the transformation capability of each model.

When we estimate the RFM coefficients, it is necessary to manipulate the normal matrix by adding the multiplication of the identity matrix and the regularization coefficient ($\varepsilon$) since the normal matrix is unstable, which causes the singularity in the adjustment system, resulting from the sparsity or the overparameterization in RFM.
The following equation describes the regularization of the normal matrix:

\[(N + \varepsilon I)\hat{\xi} = A^T P y\]  \hspace{1cm} (4.6)

where \(N\) is the normal matrix; \(\varepsilon\) is the regularization coefficient (experimental range of coefficient is \(4 \times 10^{-7} - 6.4 \times 10^{-3}\) (Tao et al., 2000)); and \(I\) is the identity matrix.

The regularization coefficient \(\varepsilon\) is determined by the iterative process. The criteria of selecting \(\varepsilon\) is that the variance component is getting smaller and converged before \(\varepsilon\) is diverged (if it reaches the limitation of convergence, \(\varepsilon\) is diverged). Figure 4.10 shows the change in the variance component according to the iteration (iteration...
starts at 0.0001 of $\varepsilon$ and ends at 0.000005 of $\varepsilon$).

Figure 4.10: Estimated variance component according to the iterations: (a) Second order RFM (applied to FWD image) (b) Second order RFM (applied to AFT image) (c) Third order RFM (applied to FWD image) (d) Third order RFM (applied to AFT image)

Table 4.12 and Figure 4.11 show the transformation results of each sensor model applied to the entire image.

As one can see, the suggested rigorous model has the best performance to depict the relationship between the object space and the image space. In spite of using a relatively coarse scanned image resolution of 12 $\mu m$ rather than that (7 $\mu m$) used in a
Table 4.12: The transformation results of the sensor models (applied to entire image with corresponding large area of ground coverage)

![Table 4.12](image)

Figure 4.11: The transformation results of the sensor models applied to entire image corresponding to large area of ground coverage: (a) FWD image case (b) AFT image case

previous study (Kim, 1999), the suggested model shows the excellence of representing the relationship between the panoramic image space and the object space. The worst case occurred when an affine model was applied. The results of the affine model are too big to be compared to other models. From this fact, it is proved that applying the affine model should be confined in a small part of the image patch, which covers small ground as mentioned in past studies. The second worst case can be found in the DLT. Even though DLT can be regarded as a type of generic model (e.g., first order RFM
coefficients with \( q_1 = q_2 \), DLT does not have enough RFM coefficients to reflect the panoramic image characteristics into the transformation from the object space to the image space. However, the second order and the third order RFM can be a candidate for substituting the suggested rigorous model for the applications which require only a certain level of accuracy. The results summarized in Table 4.12 shows that third order RFM reaches approximately 20.5 m - 27 m of the checkpoint RMSE in the object space. However, it should always be kept in mind that third order RFM requires at least 39 control points for recovering the RFM coefficients, while the suggested rigorous model requires only four control points. In addition, if we explore the transformation results in more detail, one can find that the RMSE of the second order RFM is worse than that of the third order RFM even though the variance component of the second order RFM is smaller than that of the third order RFM. This is caused by the number of redundancies. In fact, the number of redundancies for the second order RFM is forty six while the number of redundancies of the third order RFM is only six.

The next experiments intend to test the transformation capability of the affine model and the DLT when those are applied to the image patches with corresponding small areas of interest (AOI). Thus, two AOIs (herein, called AOI A and AOI B) are selected. AOI A appears on the side part of the panoramic image and AOI B appears on the nearly central part of the panoramic image. These configurations are designed to figure out how an affine model and DLT can appropriately reflect distortion patterns which are different according to the image parts. For each AOI, two image patches are prepared from each FWD image and AFT image. The areas of ground coverage are approximately 50 km \( \times \) 16 km for AOI I and 30 km \( \times \) 16 km.
for AOI II. Basically, the general acceptance of applying an affine model is confined within the relatively small and flat area of coverage corresponding to a certain part of the image. Hence, this experiment aims to figure out the applicable size of the area of coverage for the affine transformation and the DLT. Figure 4.12 shows the distribution of the control points and the checkpoints used to these experiments. Tables 4.13, 4.14, and Figure 4.13 show the transformation results of the sensor models (affine model, DLT, and rigorous model) applied to the small area of ground coverage. The reason for showing RMSE in ground coordinate unit [m] is to have more clear comparison with previous study results. The affine model has the trend of a smaller RMSE as the area of coverage gets smaller but it has still coarse transformation results. However, the DLT that requires only six control points for recovering eleven parameters shows the potential of the transformation method which can be used as an alternative to the rigorous model. From the results of DLT, we can infer that the higher order RFM would have acceptable accuracy of transformation between a partial image and the relatively small area of ground coverage. But it requires too many control points.
Figure 4.12: The distribution of the control points and the checkpoints used to compare the performance of the sensor models applied to partial image corresponding to small area of ground coverage: (a) AOI A (b) AOI B
<table>
<thead>
<tr>
<th>Model</th>
<th>Image type</th>
<th>$\sigma_0$ [m]</th>
<th>Control point RMSE [m]</th>
<th>checkpoint RMSE [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$RMS_x$</td>
<td>$RMS_y$</td>
<td>$RMS_T$</td>
</tr>
<tr>
<td>Affine</td>
<td>FWD</td>
<td>118.1803</td>
<td>104.5037</td>
<td>93.4365</td>
</tr>
<tr>
<td></td>
<td>AFT</td>
<td>138.7472</td>
<td>95.2689</td>
<td>129.6176</td>
</tr>
<tr>
<td></td>
<td>AFT</td>
<td>3.7119</td>
<td>3.8530</td>
<td>2.6981</td>
</tr>
</tbody>
</table>

Table 4.13: The transformation results of the sensor models applied to image patches with corresponding small area of ground coverage - AOI A

<table>
<thead>
<tr>
<th>Model</th>
<th>Image type</th>
<th>$\sigma_0$ [m]</th>
<th>Control point RMSE [m]</th>
<th>checkpoint RMSE [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$RMS_x$</td>
<td>$RMS_y$</td>
<td>$RMS_T$</td>
</tr>
<tr>
<td>Affine</td>
<td>FWD</td>
<td>62.8407</td>
<td>61.5286</td>
<td>38.4678</td>
</tr>
<tr>
<td></td>
<td>AFT</td>
<td>87.2019</td>
<td>69.4112</td>
<td>34.6576</td>
</tr>
<tr>
<td>Rigorous</td>
<td>FWD</td>
<td>4.9667</td>
<td>4.6438</td>
<td>3.8404</td>
</tr>
<tr>
<td></td>
<td>AFT</td>
<td>5.0050</td>
<td>4.6438</td>
<td>5.0669</td>
</tr>
</tbody>
</table>

Table 4.14: The transformation results of the sensor models applied to image patches with corresponding small area of ground coverage - AOI B

Even within the small area of ground coverage, the suggested rigorous model shows robustness which is superior to the affine model and the DLT in terms of the performance of space intersection. Also, the suggested rigorous model shows the consistency without area-dependent locality problems as reported in the work of Altmaier and Kany (2002). Throughout this research, we insist that the sensor model should have the better transformation (especially, space intersection) accuracy using the least number of control points. Therefore, we may argue that the suggested rigorous model can be regarded as the most robust sensor model.
4.6 Reconstruct the object spaces

After recovering the EOPs of the cameras, we can reconstruct the object space information (especially, 3D ground coordinates) of tie points identified on a stereo pair of the panoramic images by using the space intersection algorithm explained in Section 3.3. This section addresses two components of reconstructing the object spaces. The first is generating DEM from a stereo pair of panoramic images. The second is generating ortho-rectified images of panoramic images.
4.6.1 DEM generation

DEM is the one of the useful by-products in photogrammetry applications because DEM is used in a wide range of applications in the geosciences and in geographic information systems. In this research, we generate the DEM using a stereo pair of panoramic images and the space intersection algorithm. The following Figure 4.14 briefly summarizes the steps of generating the DEM conducted in this research.

![Figure 4.14: Steps of DEM generation](image.png)
We choose the AOI A as the study site and use the parameters estimated from the configuration of control points shown in Figure 4.12 (a). For each FWD image and AFT image, 11 control points are used to estimate the parameters. A total of 1800 tie points are identified on a stereo pair by using the ERDAS Imagine tie point collection module, and their ground coordinates are determined by using the space intersection algorithm. The ground coordinates of these irregularly distributed points are used as input for generating a regular grid of DEM.

In order to check the effectiveness of the space intersection algorithm, a total of 20 checkpoints are identified on a stereo pair and intersected in this experiment (see Figure 4.15 for the ground coordinates of the checkpoints located in the inside of the boundary of the DEM).

Figure 4.15: The boundary of DEM and the checkpoints
Tables 4.15 and 4.16 summarize the space intersection results. In the Table 4.15, $(X_{obs}, Y_{obs}, Z_{obs})$, $(X_{comp}, Y_{comp}, Z_{comp})$, and $(X_{d}, Y_{d}, Z_{d})$ denote the observed (from DRG) ground coordinates of the tie points, the computed ground coordinates of the tie points, and the differences between the observations and the computed values, respectively.

When we compare the results of space intersection using known heights (Table 4.13) and the results of space intersection estimating heights (Table 4.16), there...
are no significant differences in the planimetric RMSE. The results shown in Table 4.15 and Table 4.16 give credibility to conduct DEM generation by applying the suggested space intersection algorithm. Figure 4.16 shows the contour lines and the shaded reliefs of the resultant DEM. The DEM spacing is 150 m for the easting and the northing.

Figure 4.16: Generated DEM
4.6.2 Ortho-rectification of panoramic image

After we estimate sensor parameters and generate the DEM, the ortho-rectification process can be conducted with raw images. The general purpose of ortho-rectification is to correct the topographic effects (mainly, height effects of the features in object space) on the images and to register raw images to the object space. In this research, we do not discuss the rectification steps in detail (one may refer to the principles and details of digital image rectification addressed in the work of Novak (1992)). However, the graphical concept of ortho-rectification as illustrated in Figure 4.17 and a summary of essential steps are presented.

Figure 4.17: Diagram of the ortho-rectification
In the rectification process, the following steps are conducted:

(1) Determination of the four corner points of the DEM.

(2) Determination of the minimum and the maximum coordinates ($X_{max}$, $X_{min}$, $Y_{max}$, and $Y_{min}$) of the DEM.

(3) Determination of the size of grid space ($\Delta X$ and $\Delta Y$) of the DEM.

(4) Gridding.

(5) Computation of the size of the ortho plane.

$$
Col = \frac{X_{max} - X_{min}}{\Delta X}
$$

$$
Row = \frac{Y_{max} - Y_{min}}{\Delta Y}
$$

(6) Projection of DEM grid onto the image space using estimated EOPs. The correspondence between the image grid and/or ortho plane grid is established at this step.

(7) Assignment of the gray level from the image grid to the ortho plane grid.

For the rectification, a sub-image patch is sampled from the FWD panoramic image. The grid space of the ortho plane is 25 m for the X and the Y directions. Figure 4.18 shows a raw image patch before ortho-rectification and Figure 4.19 displays the ortho-rectified sub-image patch shown in the local ground coordinates (topocentric coordinate system).
Figure 4.18: A raw sub-image patch
Figure 4.19: Ortho-rectified sub-image patch
CHAPTER 5

GLACIOLOGICAL APPLICATION

5.1 Motivations and the description of test site

The glaciology society uses the time repeat remote sensing data in order to derive surface velocities of the larger ice sheets. The CORONA KH-4A and the KH-4B images have attracted the attention of glaciologists to be used for deriving early baseline for assessing the surface velocities of ice sheets because those images, together with their high resolution, cover nearly entire of Greenland ice sheets for most of 1960s. However, no previous study is conducted by using a rigorous model when panoramic images are used. Herein, we apply our rigorous model to generate precise photogrammetric products which can improve the accuracy of derived velocities of ice sheets.

Kangerdlugssuaq glacier in southeastern Greenland is one of the fast moving glaciers with surface velocity of approximate 5 km/year (Dwyer, 1995). Many studies have reported its large changes of mass balance derived from various remote sensing data ((Davis et al., 1998), (Krabil et al., 1999), and (Csatho et al., 1999)). Figure 5.1 shows the test site selected for the glaciological application of the suggested model.
Figure 5.1: Test site: Kangerdlugssuaq glacier in southeastern Greenland
5.2 Data description, data processing, and results

For the glaciological application, we have selected two panoramic images which have about 3 month gaps of acquisition time. The panoramic images used in this application were acquired by the CORONA mission 1034-1 and 1035-1. Table 5.1 summarizes the CORONA KH-4A images used for glaciological application. Figure 5.2 shows the browse image, enlarged sub-image of panoramic image (DS1034-1027DF006) and sub-image of aerial photo.

<table>
<thead>
<tr>
<th>ID</th>
<th>DS1034-1027DF006 (FWD)</th>
<th>DS1035-1059DF008 (FWD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>June 23, 1966</td>
<td>September 24, 1966</td>
</tr>
<tr>
<td>Ground coverage</td>
<td>17 km × 231 km</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>B/W positive film</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Description of CORONA KH-4A images used for glaciological application

Figure 5.2: (a) Browse image of panoramic image (b) Sub-image of aerial photo (c) Sub-image of panoramic image (DS1035-1059DF008)
Since the large scale of topographic map is not available in the Kangerdlugssuaq glacier area, we have performed bundle adjustment using aerial photographs covering Kangerdlugssuaq glacier for the collection of control points that are used to estimate EOPs of the DS1034-1027DF006 (denoted as 027DF006) image and the DS1035-1059DF008 (denoted as 059DF008) image. The aerial photos at a scale of 1:150,000. Each photo covers the area of 35 km × 35 km approximately. For this application, we have used three aerial photographs (Photo IDs: 674, 676, and 678 which are acquired by August 1, 1981), from Kort & Matrikelstyrelsen in Denmark, including the coordinates of ground control points. Figure 5.3 shows the distribution of control points and tie points. The identified tie points will be used as control points to estimate the EOPs of the 027DF006 image and the 059DF008 image.

Figure 5.3: The distribution of the control points and the tie points of the aerial photos
As results of bundle adjustments of aerial photographs, the computed tie points have the RMS errors of 0.51 m and 0.60 m for the X ground coordinates and the Y ground coordinates, respectively.

Using the tie points obtained from the aerial photos, we can conduct the estimation of the EOPs of panoramic images. Figure 5.4 shows the distribution of the control points used for the estimating the EOPs of panoramic images covering Kangerdlugssuaq glacier area.

![Figure 5.4: The distribution of the control points used for the estimation of the EOPs of the 027DF006 image and the 059DF008 image](image)

As shown in Figure 5.4, the control points are not favorably distributed. However, current configuration of the control points is still acceptable to estimate EOPs if we
recall the results of previous experiments dealing with the panoramic images covering the Columbus area. Total 9 control points are used for estimating the EOPs of each panoramic image. Table 5.2 and Table 5.3 show the estimated parameters and the adjustment statistics, respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>027DF006</th>
<th>059DF008</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_o [m]$</td>
<td>41969.64948</td>
<td>-11427.56441</td>
</tr>
<tr>
<td>$Y_o [m]$</td>
<td>109783.05229</td>
<td>66011.84927</td>
</tr>
<tr>
<td>$Z_o [m]$</td>
<td>248132.74483</td>
<td>218969.35549</td>
</tr>
<tr>
<td>$\theta_A [deg.]$</td>
<td>210.01441</td>
<td>194.45472</td>
</tr>
<tr>
<td>$\theta_P [deg.]$</td>
<td>14.83732</td>
<td>15.14685</td>
</tr>
<tr>
<td>$\theta_R [deg.]$</td>
<td>-0.94844</td>
<td>-0.89209</td>
</tr>
<tr>
<td>$D [m]$</td>
<td>460.93911</td>
<td>756.05634</td>
</tr>
</tbody>
</table>

Table 5.2: Estimated parameters of KH-4A images covering Kangerdlugssuaq glacier

<table>
<thead>
<tr>
<th>Statistics</th>
<th>027DF006</th>
<th>059DF008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stdev.of $X_o [\pm m]$</td>
<td>7.72415</td>
<td>8.80799</td>
</tr>
<tr>
<td>Stdev.of $Y_o [\pm m]$</td>
<td>7.36993</td>
<td>2.80626</td>
</tr>
<tr>
<td>Stdev.of $Z_o [\pm m]$</td>
<td>8.75715</td>
<td>0.88045</td>
</tr>
<tr>
<td>Stdev.of $\theta_A [\pm sec.]$</td>
<td>5.99999</td>
<td>2.30256</td>
</tr>
<tr>
<td>Stdev.of $\theta_P [\pm sec.]$</td>
<td>7.81214</td>
<td>2.52117</td>
</tr>
<tr>
<td>Stdev.of $\theta_R [\pm sec.]$</td>
<td>10.81985</td>
<td>8.59018</td>
</tr>
<tr>
<td>Stdev.of $D [\pm m]$</td>
<td>9.53545</td>
<td>2.84389</td>
</tr>
<tr>
<td>Variance component</td>
<td>0.00939</td>
<td>0.01069</td>
</tr>
</tbody>
</table>

Table 5.3: Adjustment statistics of the estimated parameters of KH-4A images covering Kangerdlugssuaq glacier
As one can see the adjustment statistics of the estimated parameters, the standard deviations of parameters are worse than the previous experiments using the panoramic imagery covering urban area. This situation is probably caused by the quality of the measurements of the conjugate points between the panoramic images and aerial photos even though we have used more accurate control points derived from aerial photos than those from Digital Rater Graphs. Since there is a significant gap between the CORONA panoramic images and the aerial photo acquisition time, it is hard to obtain well identified conjugate points between those two different image types. In addition, the statistics of the estimation parameters implies that the geometric strength of the control points is weak (i.e., the distribution of control points is not well distributed even in the small area of coverage). However, this is not the all about geological application of our model. In order to judge the robustness of model, we must test our rigorous model with respect to its capability of reconstructing the object space information correctly. Hence, we conduct space intersection with known height values of control points. This is performed by comparing rigorous model with affine model in terms of RMS error analysis. Table 5.4 shows the results of the transformation from image space to object space. In addition, it is proved that the suggested model has significant better results than affine model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Image ID</th>
<th>$RMS_x$ [m]</th>
<th>$RMS_y$ [m]</th>
<th>$RMS_T$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affine</td>
<td>027DF006</td>
<td>39.75624</td>
<td>30.78404</td>
<td>50.28137</td>
</tr>
<tr>
<td></td>
<td>059DF008</td>
<td>38.83983</td>
<td>37.79936</td>
<td>54.19709</td>
</tr>
<tr>
<td>Rigorous</td>
<td>027DF006</td>
<td>3.22258</td>
<td>3.66369</td>
<td>4.87931</td>
</tr>
<tr>
<td>Model</td>
<td>059DF008</td>
<td>2.09292</td>
<td>3.93101</td>
<td>4.45344</td>
</tr>
</tbody>
</table>

Table 5.4: The transformation results between the affine model and the rigorous model applied to Kangerdlugssuaq glacier area
For the rectification, we have used the DEM derived from aforementioned aerial photos. A sub-image patch is sampled from 027DF006. The grid space of ortho plane of CORONA KH-4A image is 10 m for the X and the Y directions. Figure 5.5 displays ortho-rectified image patches generated from three different types of image data (CORONA KH-4A panoramic image, aerial photo, and LANDSAT-7 ETM+ (panchromatic)). The coordinate system of ortho-rectified images is UTM zone 25 (WGS84).

Figure 5.5: Ortho-rectified image patches (a) CORONA KH-4A image (June 23, 1966) (b) Aerial photo (August 01, 1981) (c) LANDSAT-7 ETM+ (July 03, 2001)
DISP are another good sources for the remote sensing and the GIS applications. Among DISP, the CORONA panoramic images (especially, images acquired by the KH-4A camera system and the KH-4B camera system) have the high photo resolution as well as the wide areas of the coverage. However, the complexity of panoramic sensor modeling leads people to use rather generic sensor models than a rigorous model for the registration of the CORONA panoramic image into object space. This causes the coarse approximate results derived from the CORONA panoramic imagery without the benefits of the high resolution. Thus, it was necessary to develop the rigorous model of the panoramic imagery to unveil its potential. This research proposes a rigorous model of panoramic imagery that promises to bring the better accuracy of the image registration and the object reconstruction than generic models. The suggested model was analyzed in terms of its capabilities of the recovering sensor parameters and the space intersection. In addition, the model was tested with real panoramic images and evaluated by comparing various transformation results of generic models. This evaluation demonstrates the supremacy of the suggested model which requires also fewer number of control points to estimate sensor parameters than other models. The suggested model and algorithms have the following advantages:
• The model has the better results of the transformation from image space to object space. Also, it shows the consistency when it has been applied in the small area of coverage or the large area of coverage of image.

• The model requires fewer number of control points so that the time and the cost for collecting control points can be saved.

• Recovering only six EOPs and one additional parameter is enough to describe the panoramic sensor system.

• It has the capabilities of producing highly accurate DEMs and ortho-rectified images.

• Providing the DEM and ortho-rectified images offers an effective tool to study the change detection occurred on the topography for the certain area of interest.

• The overall merit of the suggested model is that it provides opportunity of using CORONA satellite imagery for the mapping purpose.

This study mostly focused on recovering the EOPs of the panoramic imagery and achieving higher accuracy of the space intersection. Future work will concentrate on the elaborated testing for the recovering interior orientation parameters of the panoramic imagery. In addition, we will explore to identify other distortion sources and to establish additional distortion models to figure out whether they can describe the panoramic imagery more effectively, and will build a complete system of the bundle adjustment with self calibration modules for panoramic imagery. Finally, certain investigations will be conducted to determine how the output of the suggested
model is to be incorporated in the GIS applications such as the change detection of
the surface and the urban area over a period of time.


