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A Production Method for Conversion of Scanned Historic Aerial Imagery into Orthophotos Using the Rational Function Model

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A Major Individual Project submitted in partial satisfaction of the requirements for the degree of Master of Science in Geographic Information Systems

by

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Abstract

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Historical aerial photographs are a valuable resource for the Center for Conservation Biology because they offer land cover and land use data from the past at high spatial resolution. The imagery which the CCB currently holds, however, is not geo-referenced, so finding imagery for a particular site and using it in geographic software is difficult. A method was developed using the rational function model to convert scanned photos into imagery with a spatial reference system, while at the same time correcting for distortions caused by elevation changes. The rational function model uses a digital elevation model and a spatial reference system from USGS DOQQ aerial photographs to reference the historic photographs. In addition, the entire conversion process is documented in an easy to use, step-by-step workflow for use in ArcGIS 10. This will enable the CCB to employ undergraduate assistants to perform the workflow to convert selected collections of historical photographs easily and consistently.

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List of Acronyms and Definitions

CCB – Center for Conservation Biology
UCR – University of California, Riverside
GIS – geographic information systems
USGS – United States Geological Survey
DOQQ – Digital Orthoimagery Quarter Quadrangle
DEM – Digital Elevation Model
TIFF – Tagged Image File Format
NAD – North American Datum
UTM – Universal Transverse Mercator
RMSE – root-mean-square error

Chapter 1 – Introduction

The Center for Conservation Biology (CCB) at the University of California, Riverside (UCR) looks to find new ways to research conservation biology and to respond to existing needs in the field. Historical aerial images are a great resource for conservation studies and are a valuable baseline for performing land change analysis. However, the collection of historical images which the CCB has lacks spatial reference, and as a result they are not useful in a GIS context. Adding to the problem, many of the images cover rough mountain terrain, making them more difficult to geo-reference with high accuracy. The goal of this project was to create a workflow for employees with introductory geographic information systems (GIS) experience to transform the aerial images from their raw state to a data product which can be used in a GIS environment so the researchers can find and use them with ease.

1.1 Client

The client for this project was the Center for Conservation Biology at the University of California, Riverside. The CCB is comprised of researchers working to identify new research areas in conservation biology while still responding to existing needs. Most of the researchers who will use the imagery are not familiar with GIS, or have very limited knowledge of the subject and limited computer skills, as well. In addition to the researchers, the CCB also employs undergraduates to help with research who have only a few months of ArcGIS training. It was important to keep in mind that the CCB is comprised of a group of researchers with varying knowledge and abilities when designing the project. The resulting workflow had to meet the needs of the client, benefiting those who are not familiar with ArcGIS.

Mr. Robert Johnson, Assistant Specialist in GIS, served as a point of contact for technical issues regarding project development. His role was to provide all data and discuss guidelines and expectations. In addition, Mr. Johnson provided additional GIS and project support as needed.

1.2 Problem Statement

The CCB's collection of unprocessed historic aerial photographs lacked spatial reference. In order to be used for spatial analysis, the images needed to be transformed to a spatial reference system. In addition, without any geo-referencing, it was difficult for the researchers to identify which images covered their study site. The problem was that the CCB did not have a method of geo-referencing images accurate enough to meet the National Map Accuracy Standards. They needed a work flow which included a method of referencing images which meet the National Map Accuracy Standards by reducing relief distortion and a method of mosaicking and cropping images to the United States

Geological Survey (USGS) Digital Orthoimagery Quarter Quadrangle (DOQQ) extents to make the search process easier. The creation of a step-by-step workflow beginning with the unprocessed imagery and ending with the cropped mosaic ready to use in a GIS addressed the problem and ensured consistency.

1.3 Proposed Solution

Historical aerial photography has the potential to enhance the CCB's research. The problem was addressed in a two-part approach. The first step was to create a method which would accurately geo-reference the images so that they would meet the National Map Accuracy Standards. The solution for this was to create a tool in ArcMap which orthorectifies the photos using a rational function model. The rational function model approach was a good solution because the model can correct distortions caused by relief changes.

The second step was to create a workflow so that the process of referencing, mosaicking and clipping the images to match the USGS quarter quadrangles could be performed on a large scale. Figure 1-1 shows the general process of the workflow, starting with scanned images and ending with a referenced, mosaicked image with the extent of a DOQQ. The workflow included step-by-step instructions so that the CCB can employ an undergraduate research assistant who will perform the process on selections of the CCB's collection of aerial photographs.

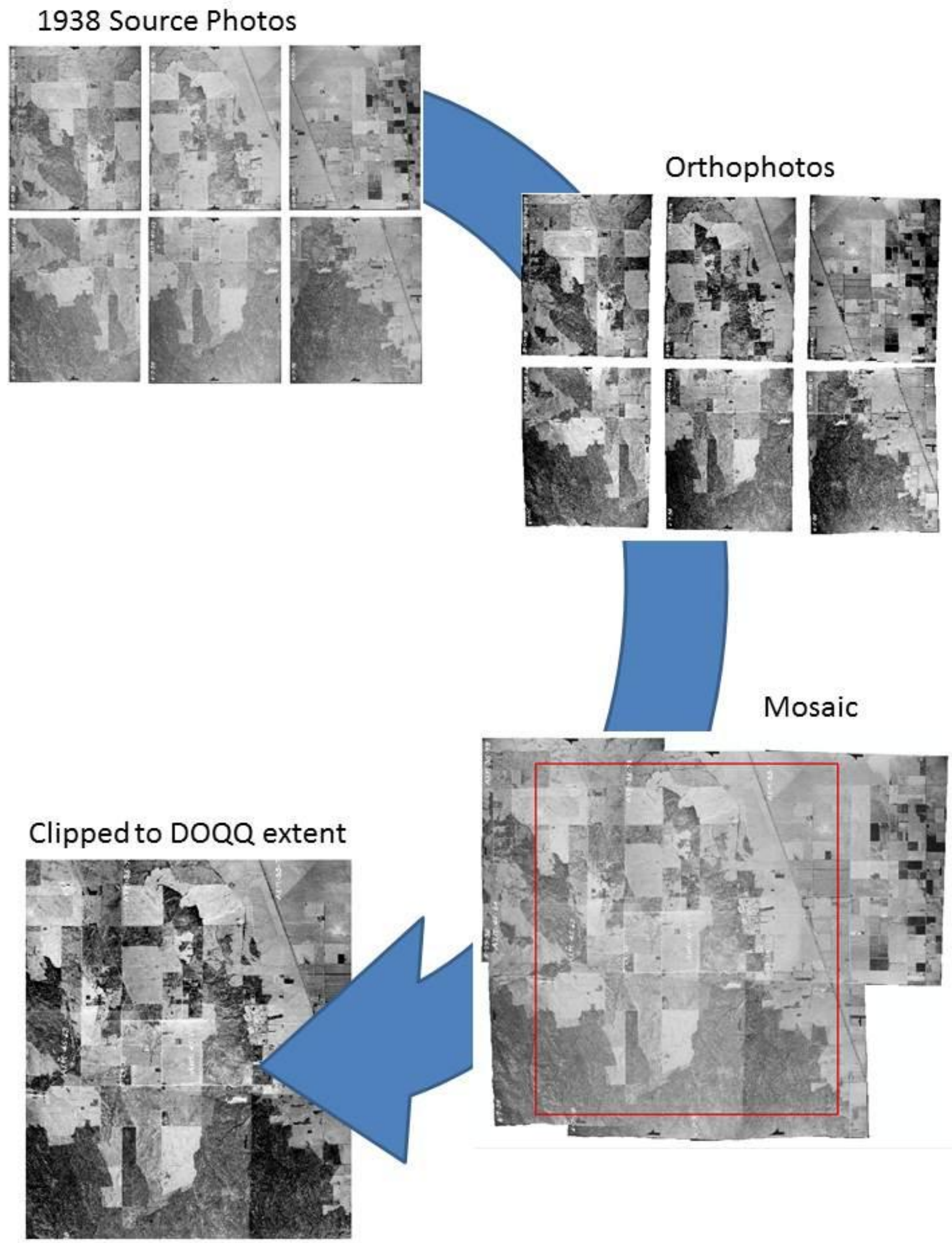


Figure 1-1: Project Workflow

1.3.1 Goals and Objectives

The priority for the project was to develop a method to reference the scanned imagery with an accuracy which meets the National Map Accuracy Standards. The client was unable to find a method which could produce satisfactory results, especially in areas with mountains. After testing the geo-referencing toolbar in ArcMap 10 using a polynomial transformation, this method was ruled out due to its poor accuracy. Because improvements in areas with relief displacement were needed, an orthorectification using the rational function model was appropriate to produce the desired accuracy. A rational function model transforms a point from a 3-dimensional ground coordinate system (X, Y, Z) to a 2-dimensional image coordinate system (x, y) to account for relief displacement on the ground.

Once the method was chosen, the next goal was to implement this method in ArcMap 10, because the client required everything to work within this software platform. A tool was created using Python script. The script calculates the rational function model coefficients using ground control points (X, Y, Z coordinates) and then transforms an image to produce an orthorectified image.

The next goal was to create a workflow to produce geo-referenced images to the extents of USGS DOQQs. The mosaicking was done so that the seams between images are ideally invisible. To do this, the Production Mapping extension to ArcMap was used to create a mass-production type workflow to orthorectify the images, then mosaic and clip them to the extents of DOQQs. The workflow is intended to complete one DOQQ coverage at a time. This enabled the employees who will be using the workflow to mass process the entire set of imagery quickly and consistently.

1.3.2 Scope

Defining the scope at the beginning of the project was important to make sure all requirements were satisfied and it was a safeguard against trying to take on too much. As defined by the scope, the final deliverable of this project was a workflow which will be used by undergraduate research assistants to reference historical aerial imagery which can be easily queried and used by researchers. The project was comprised of two major components. The first component was to create a method to reference the imagery to a sufficiently accurate standard. The second component was to document the workflow, in the form of instructions using the Production Mapping extension, so that undergraduates can easily repeat the process. This workflow would result in the mass production of images with the dimensions of a USGS DOQQ image. The workflow included steps for referencing, mosaicking, and clipping the aerial photographs to match those specified dimensions. Because undergraduates with little GIS experience would use the workflow, background information, such as how to choose ground control points, was also included.

Defining the scope of the imagery and study area were also important. This project used one series of aerial photos, and is meant as a prototype which can be applied to other sets of imagery in the future. The photos, acquired on a 1938 mission in black and white, were scanned at 1200 dots per inch. The images' extent covers most of Riverside County, California, which includes mountainous areas. The diverse terrain was a consideration for the chosen referencing method. All of the imagery, including reference imagery, were either provided by the client or were publically available free data. There was no field data collection and all ground control points were measured from reference imagery; this means that the accuracy of the orthorectification relies on the reference imagery accuracy. This workflow was designed as a prototype that can be applied towards other sets of imagery.

1.3.3 Methods

After setting up a schedule with the client the process began. The client provided Tagged Image File Format (TIFF) files of full resolution scans (1200 dots per inch) of the 1938 imagery which needed to be referenced. Free public downloads of ten meter resolution DEMs and high resolution DOQQ aerial photographs were used to reference the images. Because the client requested the finished product to be in the North American Datum (NAD) 1983, Universal Transverse Mercator (UTM) Zone 11N projected coordinate system, all of the reference data were converted to this coordinate system.

After all of the data was processed, referencing the scanned 1938 imagery began. The client had specified that the work should be done in ArcGIS 10. A tool was built using a Python script to orthorectify the images using a rational function model. This code was a two-step process: the model coefficients were calculated from ground control points, and then image orthorectification was performed based on its established model.

Once this tool was successful and the accuracy of orthorectified images was tested in multiple locations with satisfactory results, a workflow was created to mosaic and clip the images to match the extent of the DOQQs. The workflow included using the Mosaic tool in the Data Management toolset from ArcGIS. This tool allows for some customization so that the seams from the edges of the images which have been mosaicked together are minimal. Additionally, the Clip tool in the Data Management toolset was used to clip the mosaic using a shapefile as the boundary of the DOQQ. The workflow was created using the Production Mapping extension in ArcMap, which enables consistent mass production. The workflow also consisted of step-by-step instructions to walk undergraduate research assistants through the entire process. Included was a set of instructions on how to prepare data and a set of requirements for the tool and workflow to work smoothly. Additionally, an example was included that went through the entire production process step-by-step to provide a user with a demonstration of what each step should look like and what it will do. In the end, a user would reference the 1938 imagery to one DOQQ boundary at a time. It was recommended that multiple employees perform the entire production process using the same data set a few times and compare results to help ensure that each employee is performing quality work and to help standardize the results.

1.4 Audience

This paper is intended to be read by the GIS specialist at the CCB. It discusses an accurate method of referencing images in ArcMap. This paper proposes an alternative method to the standard geo-referencing that ArcMap already has, and therefore may be read by others looking for an alternative to traditional geo-referencing. In this case, the reader would most likely have a background in GIS.

1.5 Overview of the Rest of this Report

Chapter 2 is a literature review of previous research in the field discussing why aerial photography is important in conservation biology research. In addition to examining the use of aerial photography, Chapter 2 also explores various methods of geo-referencing and includes detailed explanation of the rational function model. Chapter 3 is a systems analysis, including an analysis of the project requirements, the system design and the project plan. Next, Chapter 4 explains the database design for the project, from the conceptual model to the implementation of the data. Chapter 5 discusses the implementation process, explaining how everything was done. This is followed up by an explanation of the results in Chapter 6. Lastly, Chapter 7 discusses ideas for the project in the future.

Chapter 2 – Background and Literature Review

Previous research shows how aerial photography is used in conservation biology research and how it can benefit the Center for Conservation Biology. In addition, this chapter examines the differences between geo-referencing and orthorectification, as well as more specifics of the rational function model and why it was a good choice for this project.

2.1 Aerial Photography in Conservation Biology Research

Although historical aerial photography is useful for research in many fields, the particular domain of this project was conservation biology, an important function of the Center for Conservation Biology at UCR.

Previous work shows aerial photography can be used for conservation biology research. In one particular example, studying vegetation changes led to determining the impact of grazing on the landscape and the environment of the Galilee Mountains in Israel (Carmel & Kadmon, 1999). As Carmel and Kadmon express, “The use of image analysis of aerial photographs enabled us to map current and historical vegetation of a relatively large area at a high resolution and high spatial accuracy” (p. 253). In this case, the high spatial resolution and temporal factors made historical aerial photographs a valuable resource for their research.

Historical collections of aerial photography are also useful when studying conservation biology in marine environments. In documenting the deterioration of marine and coastal habitats of Finland, Ekebom and Erkkila (2003) chose to use aerial photography in a remote sensing environment. Further, Ekebom and Erkkila expressed the potential for aerial photography in the study of coastal conservation biology. They explained that high altitude photographs offer good coverage of the Norwegian coast and historical archives were suitable for both regional and national environmental research. Historical collections have proven useful when studying conservation biology both inland and on the coast.

2.2 Rational Function Model

There are many ways that imagery can be referenced and this chapter explores several, focusing on the rational function model. The term “rational function model” is used throughout this document, and this section will explain what the rational function model is and why it was chosen. The differences between geo-referencing and orthorectification are summarized in Table 1.

Table 1. Comparison of geo-referencing and orthorectification approaches

	Geo-Referencing	Orthorectification with Rigorous Sensor Model	Orthorectification with Rational Function Model
Known Physical Sensor Model Required	No	Yes	No
2-Dimensional or 3-Dimensional transformation	2-D	3-D to 2-D	3-D to 2-D
Elevation Data Required	No	Yes	Yes
Ground Control Points Required	Yes	Yes	Yes
Level of Accuracy Achieved	Moderate	Excellent	Good-Great (dependent on GCPs)

2.2.1 Approaches to geo-referencing

There are several approaches to geo-referencing aerial photographs. In discussing geo-referencing techniques of Danish airborne scanner data, two are examined: the regional approach and the local approach. The regional approach uses polynomial distortion models to interpolate transformations from a base map to the input image using ground control points. The regional approach has panoramic and topographic corrections which are applied to each ground control point-image point pair. Elevation data are used to correct for topographic distortion. The local approach uses triangulation modeling that creates a network of triangles based on ground control points and interpolation. The local approach, however, does not account for panoramic or topographic distortion (Jacobsen, Drewes, Stjernholm & Balstrom, 1999).

Orthorectification can be more accurate than geo-referencing because it uses a DEM to correct for relief displacement. Both geo-referencing and orthorectification correct for tilt and radial displacement, but orthorectification also corrects for relief displacement. Geo-referencing is a 2-dimensionsal transformation which is suitable in flat areas. Geo-referencing can account for both a slope in an evenly sloping area where the slope is constant as well as tilt from the plane. Geo-referencing is not appropriate in areas with high relief displacement. For areas of high relief displacement, orthorectification should be used because elevation data correct for relief distortions. Orthorectification is a more complicated transformation, transforming 3-dimensional ground positions into 2-dimensional image positions. Orthorectification uses camera geometry to produce extremely accurate referencing. When the camera geometry is not available, ground control points can be used to calculate the camera geometry. With well selected ground control points, the camera geometry can be derived with high accuracy (Rossiter & Hengl, 2002).

When studying long-term plant ecology in the Mt. Carmel region of Israel, historical aerial photographs were orthorectified using the physical camera model. The process corrected tilt, radial, and relief distortions. Seven ground control points were chosen for each photo to calculate the physical model. The resulting images were resampled to a resolution which was applicable to the field observations for the vegetation research. For the use of plant ecology, orthorectification using the physical model is the most accurate method (Kadmon & Harari-Kremer, 1999).

2.2.2 Orthorectification

Orthorectification is often used in photogrammetry to reference images with a high degree of accuracy. Orthorectification is performed using a sensor model to represent the relationship between an object's 3-dimensional coordinates in real space and its 2-dimensional coordinates in an image (Hu, Tao, & Croitoru, 2004). There are two types of sensor models which can be used: a rigorous physical sensor model and the generalized sensor model.

The rigorous physical sensor model produces a higher degree of accuracy because physical parameters such as the position and orientation of the sensor are used. In addition, calibration parameters are added to address any known effects. The main downside to the rigorous sensor model is that the sensor parameters are often unclear, have never been collected, may have been lost in the handling process, or are simply unavailable for proprietary or security reasons. This is why the generalized sensor model is often used.

The generalized sensor model, although not always able to produce as accurate results, is still much more accurate than geo-referencing. It also allows the sensitive sensor parameters to be kept hidden from the user, and can be used when these parameters are not known. The generalized sensor model works by using mathematical functions to represent the relationship between object space and image space and can be faster to compute (Tao & Hu, 2000).

The rational function model is a more recent approach used in photogrammetry. In the late 1990s the rational function model became widespread in the U.S. intelligence community as an alternative to using a rigorous sensor model (Open GIS Consortium, 1999). The rational function model grew in popularity because private companies, such as IKONOS, can release the coefficients for the function without releasing the specific details about the sensor. That being said, it means that it can also be used when that sensor information is unknown. A rational function is a ratio of two polynomials. Ground control points are used to develop such a model, which approximates the rigorous sensor model with high accuracy. With carefully selected ground control points, the rational function model can produce very accurate results (Hu and Tao, 2002).

There are two approaches to calculating the rational function coefficients: the terrain-independent approach and the terrain-dependent approach. Figure 2-1 shows the strategy used when choosing which approach to develop.

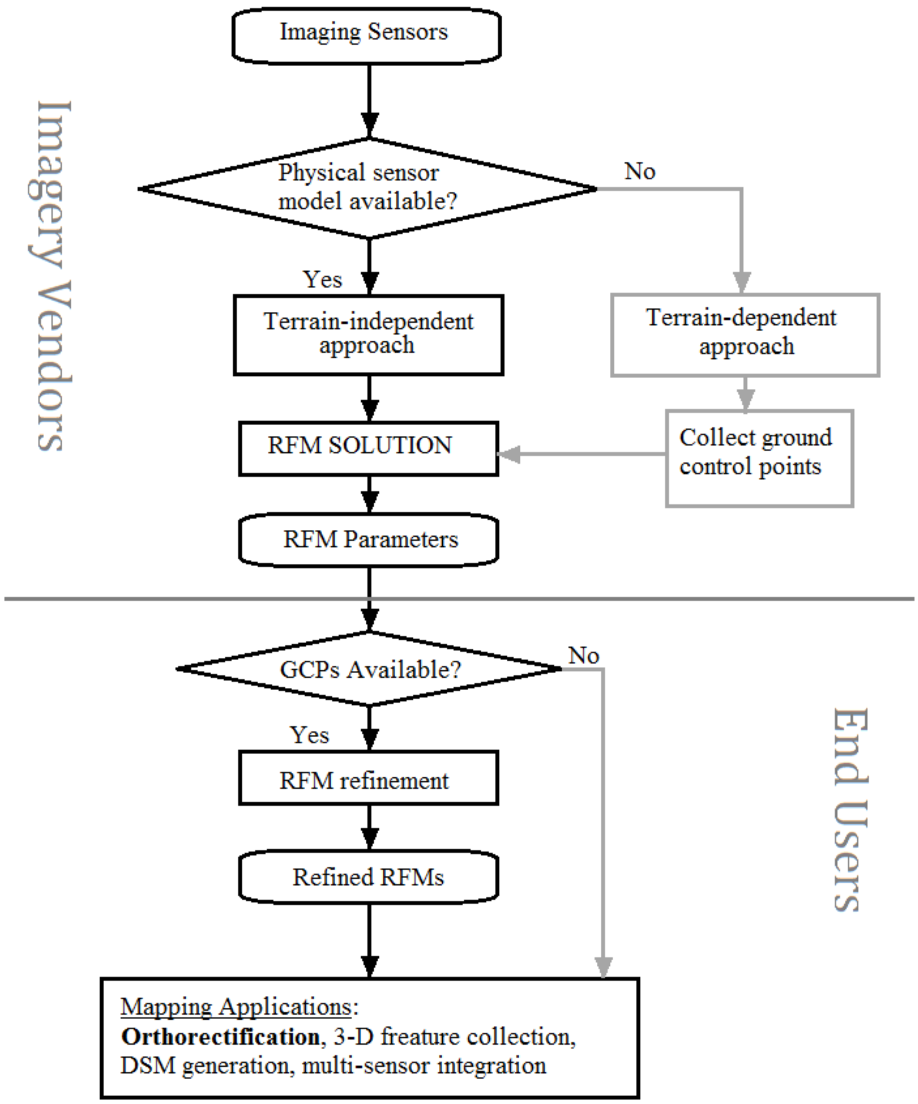


Figure 2-1: The strategy of developing the rational function model, adapted from Hu, Tao, & Croitoru, 2004.

The terrain-independent approach develops the rational function coefficients using the physical sensor model and can produce very high approximation accuracy. The terrain-independent approach is capable of achieving a very high accuracy of approximating the physical sensor model, so often times this method of releasing just the rational function coefficients is chosen over releasing the physical sensor information (Hu, Tao, & Croitoru, 2004).

The terrain-dependent approach is not as common as the terrain-independent approach, but has the advantage that it can be developed by a user when the physical sensor model is unknown. The terrain-dependent model approximates the image geometry using many polynomial terms. The accuracy of this method is dependent on the quality and quantity of the ground control points. There must be a large number of ground control points and they must be well distributed across entire area of the image. Without satisfying these high ground control point requirements, the terrain-dependent model may not provide a suitable level of accuracy. However, if sensor model information is unknown, and careful consideration is given to ground control point collection, the terrain-dependent approach to the rational function model can provide a better alternative to the 2-dimensional polynomial transformation geo-referencing uses (Hu, Tao, & Croitoru, 2004).

2.3 Summary

Aerial photography, especially historical aerial imagery, is a great resource for conservation biology research. It has been shown that they can be beneficial for both coastal and inland conservation research. Developing a method which will accurately reference the imagery is important. The 2-dimesnioal polynomial geo-referencing transformation cannot achieve the desired accuracy. Thus a rational function model was developed to orthorectify images. Because the sensor geometry was unknown in the case of this project, the terrain-dependent approach was used to develop the rational function model.

Chapter 3 – Systems Analysis and Design

This chapter articulates the process of accurately referencing imagery in mountainous areas and how to create a workflow to orthorectify imagery on a large scale. The design addresses the problem the CCB had. Section 3.1 examines the problems which this project has attempted to resolve. Section 3.2 analyzes the requirements for the system and data, explaining both the functional and non-functional requirements. Section 3.3 explains the design of the system, showing how all of the major components fit together. Section 3.4 gives a description of the original project plan and how it was updated throughout the project.

3.1 Problem Statement

Historical aerial imagery is a great resource for conservation biology especially when studying change over time. However, the CCB's collection of historical aerial photographs was simply scanned prints with no spatial reference. Without that these images could not be used for any GIS-based analyses. The CCB needed a method to reference the set of 1938 aerial imagery, taking into account distortions caused by elevation changes in mountainous areas. The client had previously tried various methods for referencing the imagery, including the geo-referencing tools in ArcGIS. However, the results were not accurate enough. A tool or method was needed to reference the imagery more accurately, to meet the National Map Accuracy Standards for imagery at a scale of 1: 20,000. Because the collection of scanned imagery is large, a workflow needed to be created to process the images consistently and accurately by undergraduate assistants. So in general, the problem was that the CCB had a collection of scanned historical aerial photographs and wanted referenced imagery which matched the USGS DOQQs.

3.2 Requirements Analysis

The functional and non-functional requirements for the data and the workflow processes are outlined in Table 2. The GIS lab at the CCB had already begun a process for standardizing all of its data, and for that reason the data requirements matched the existing CCB standards. All data had to be in the NAD 83 UTM Zone 11 North coordinate system, and the extent of all final images had to match the extent of the USGS DOQQs.

Table 2. System requirements

System Requirement	Functional/Non-Functional	Required/Optional
Data required to be consistent with the CCBs collection of GIS data	Non-Functional	Required
Use Esri ArcGIS Desktop version 10.0 for all processes.	Non-Functional	Required
Use the rational function model for orthorectification to reference the imagery to meet the National Map Accuracy Standards	Functional	Required
Script the orthorectification tool in Python	Functional	Required
Use the Production Mapping extension to ArcGIS version 10 for generating the workflow	Non-functional	Optional

The main non-functional requirement for the entire process was that everything had to run in ArcGIS Desktop Version 10 for several reasons. Most importantly, the CCB currently has this version of the software running on their computers. They do not have a version of ERDAS Imagine installed, which could have also been used. Another reason was that the workflow is going to be used by undergraduate research assistants who will have only taken one GIS class with version 10. Using the version of the software they are familiar with was important so that further training would not be required.

Another non-functional requirement was to generate the workflow using the Production Mapping extension for ArcGIS Version 10. Production Mapping has the Task Assistant Manager which creates a step-by-step process to run in ArcMap. The workflow generated by this extension shows instructions for each step and automatically opens the tool needed to perform the function for that step of the process. The benefits of using Production Mapping was that it helped to standardize and streamline the mass processing of the imagery, and, it helped to decrease the production time. However, this was not required and the workflow could have taken a different form, such as a written manual in Microsoft Word.

The main functional requirement of the system was to find a method to reference the imagery with an accuracy which met National Map Accuracy Standards. The rational function model was chosen because it orthorectifies images to correct relief displacement distortion. There is no pre-built tool for performing this process from ground control points so it needed to be scripted. Because the entire process was required to work in ArcGIS Version 10, the script for performing the orthorectification had to be compatible with this version of the software. ArcGIS Version 10 works well with Python, and the software package comes with Python and a few Python extensions built in. Not only was this essential for creating the tool in ArcGIS, but it also made the process easier.

3.3 System Design

The system was designed to address the problem of creating a workflow to process the historical aerial imagery. The main components of the design were a tool to orthorectify the images, a workflow using the Production Mapping extension, and data storage. All components of the system were designed to work together to minimize processing time and to take advantage of the skill level of the user.

The first aspect of the design was to create a tool to orthorectify the images. Since the built-in geo-referencing methods in ArcGIS version 10.0 were unable to reference the images to the desired accuracy, a new method was designed to work in ArcMap to reference the images to the National Map Accuracy Standards. The method was to orthorectify the images using the rational function model, which is often used to reference high spatial resolution satellite images. Since the camera geometry for the scanned images was not known, the coefficients for the rational function model had to be calculated from ground control points. The design for this approach was to have the user generate ground control points from reference imagery – DOQQs and DEMs in this case – and then run a script to calculate the coefficients. Once the coefficients were calculated, a script was written to transform the imagery to generate orthophotos.

The orthorectification method was implemented in ArcGIS so that the user could perform the function easily. A tool was created from the script that runs in ArcMap. Figure 3-1 shows the user interface that was designed to make the tool easy to understand and use by undergraduate assistants. The tool has three inputs and one output field. The inputs include a ground control points file, the image which needs to be referenced, and a DEM. The output is the name and location of the new orthorectified image. The Help documentation for each section of the tool was provided to ensure that the proper formats for the inputs and outputs are used. Help documents are used for all tools developed in this project.

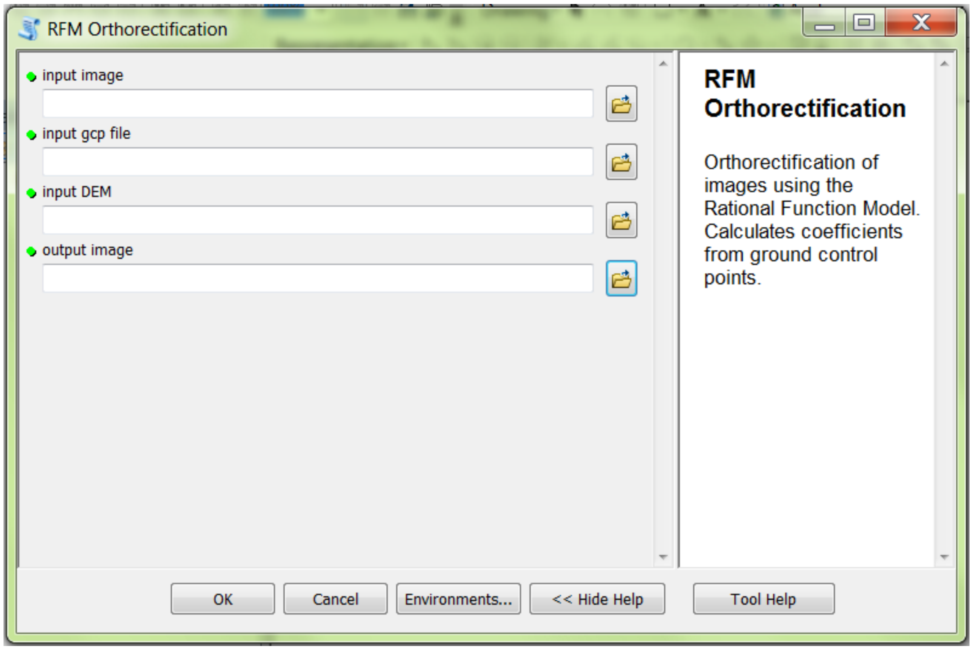


Figure 3-1: Rational function model orthorectification tool

As part of the design of the tool, the ground control points file was designed as a text file. A sample ground control points file and a template file were provided to ensure that the ground control points file had the correct format. Using the right file format was crucial for the tool to work, as it reads the ground control points in a specific format from such a file to calculate rational function models.

The workflow had several components: collecting ground control points, using the tool to orthorectify the images, mosaicking the images, and clipping the images to the extent of a DOQQ. The workflow was designed to bring all of the components together in a logical progression that would walk users through each step. The design was meant to not only meet the needs of the client, but also to work well with the skill level of the user. Because the CCB plans to employ undergraduate assistants to use the workflow and perform the processing, it was important to keep in mind that the users would have only limited GIS skills. To address this, the workflow was created in Task Assistant Manager from the Production Mapping extension, which made it possible to integrate instructions and a step-by-step guide into the process. The resulting workflow automatically opens related tools when a user reaches a step, so that the user does not need to worry about using the wrong tool or where to find it.

Data storage was not a main component of the project but it needs to be addressed. All of the data are already on the client's computer and are set up in a database designed to CCB specifications, and this project was meant to preserve the same consistency. Three output databases were needed for storage for this process: one which contains the outputs from the orthorectification, one which stores the mosaics, and one which stores the final output images which have been cropped to the DOQQ extents. For consistency, the design of the data and the databases matched the current CCB specifications.

3.4 Project Plan

The project changed slightly from what was originally outlined in the project plan. The initial goals were to create a method of geo-referencing and to create a workflow to streamline the process. To address the problem of improving the accuracy of geo-referencing, the original project plan had a different approach than what ended up being implemented. In the original project plan, the first method tried was a simple polynomial transformation using just a few ground control points in the corners and several in the middle. Realizing that this would most likely produce accurate results in flat areas but not in the mountains, other methods were considered, including dividing the image into sections and transforming the mountain areas separate from the flat areas. This method, however, could have produced its own set of challenges which would have needed to be addressed at the time. Overall, developing a method to geo-reference images accurately was designated as the biggest challenge and the most important step of the project. It was recognized that it would be a process of trial and error and would require further training to learn additional techniques.

In fact, none of the proposed methods of geo-referencing were used. Further instruction was sought and the rational function model was proposed. Using this method required additional research and advising, but in the end, it proved to be an accurate and implementable solution to the referencing problem.

The other main goal outlined in the initial project plan was creating a documented workflow so that the work can be performed by undergraduate research assistants to eventually geo-reference all of the CCB imagery. This goal addressed the problem of consistency and time effectiveness, as the process will be performed on a mass scale. The workflow ensures that the same process is applied to each image, creating consistent results and providing a way for undergraduate employees to perform the work. The workflow was designed to use the ArcGIS Production Mapping extension. It also included information on how to choose appropriate reference data and good ground control points to assure that the results are as accurate as possible.

The original plan called for regular meetings with the client to ensure that the project was progressing according to plan and to keep everyone on the same page. Setting up regular meetings, or at least establishing good communication from the start was very important. Fully understanding the client’s problem and his expectations from the start provided a good basis for the planning phase and helped prevent the scope from expanding over time. In reality, this lesson was learned the hard way. In the beginning the client laid out some very specific requirements for what he was looking for, and somehow these were accidentally overlooked. However, because of regular meetings and email updates, the client was quick to point these out, so necessary changes were made early on. These included simple things such as using Production Mapping for the workflow and changing the output extent and format for images once they were referenced.

3.5 Summary

The solution for developing a method for accurate imagery geo-referencing and creating a well-designed workflow was addressed by the planning and design of the system. The system was designed to address key requirements including using Production Mapping for documenting the workflow, using tools in ArcGIS such as Mosaic and Clip, and coding a new tool in Python to orthorectify the images. Together these tools worked to transform the scanned imagery frames to accurately referenced imagery with the dimensions of the DOQQs. In addition, the workflow was designed in a way that is easily implemented by users with entry level GIS skills. It also includes instructions for updating the script to work with other sets of imagery in the future.

Chapter 4 – Database Design

Chapter 4 discusses the database design for the project, as well as where the data came from and how it was prepared. Data is the heart of any GIS project and without quality data and good database management a GIS project cannot be successful. For this particular project, integrating with the client's data and creating a database management system for the client were out of scope. Instead, a sample database was created and used to test the functionality and accuracy of the tool and workflow generated. This chapter includes a discussion of the conceptual model and then explains how that came into being with the logical model. It is followed by the discussion of the data and what were made to it for the project purposes.

4.1 Conceptual Data Model

The conceptual data model is an abstract representation of the database and the relationships between essential components of it. Figure 4-1 shows the concept model of the database in a general sense.

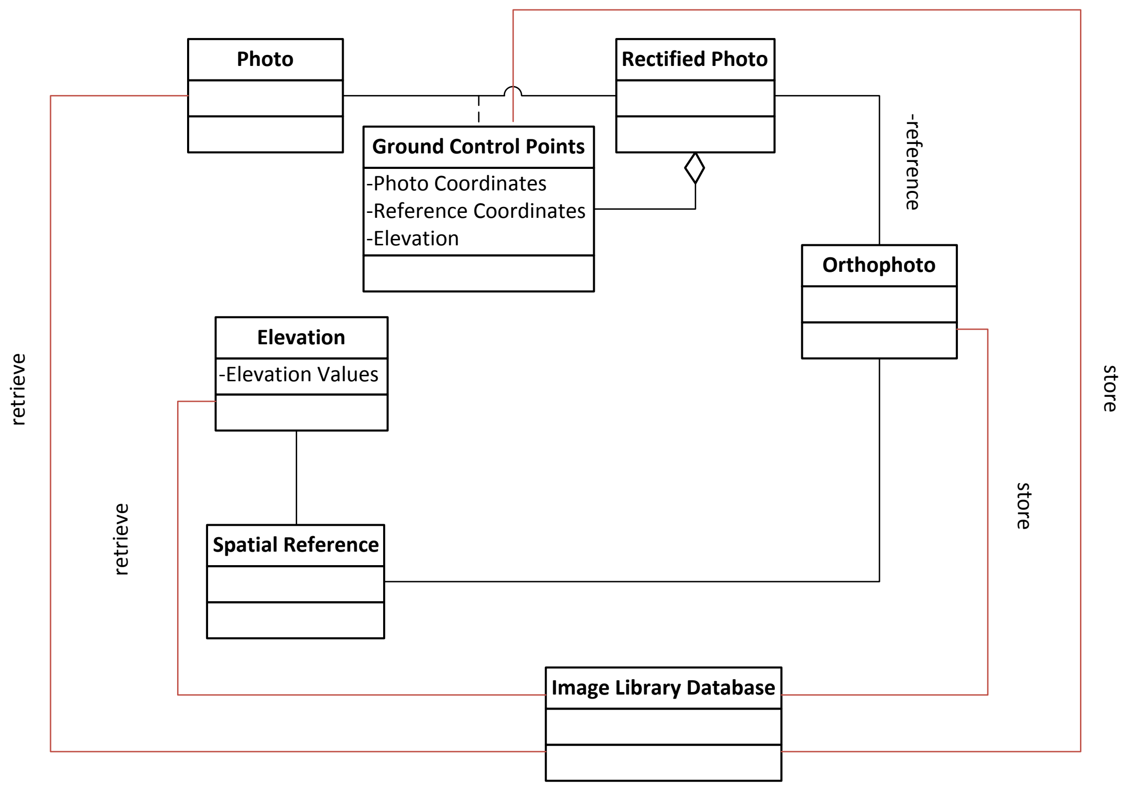


Figure 4-1: Conceptual model UML diagram

The generalized concept of the project was to take a photo and put it in the correct location on the ground. For this particular project the database resided on the client's computer, as well as copies on external drives. A new database management system was out of the scope of the project. The contents of the database and data produced were be read and written to the database through a user interface. The red lines in Figure 4-1 represent which files were read from and which were written to the database. The aerial photographs and the digital elevation models were read from the database and the produced orthophotos were then written to the database, as were the ground control points which were used to reference the photos.

The conceptual model also shows the relationship between the various components of the database. The basic flow to the model can be read from left to right. The aerial photographs were just a compilation of gray pixel values. Ground control points were used to establish a transformation from the ground coordinate system to the image coordinate system. The spatial reference from the DEM, NAD83 UTM 11 North, was added to the rectified orthophoto. The orthophoto was then stored back into the database.

Three sets of orthophotos were actually generated in this project. The first was just an orthophoto version of its source photo, which is referred to as the source orthophoto. The second was a mosaic of several source orthophotos, which were also stored in the geodatabase. The third type of orthophoto generated was a clip of the mosaic. Figure 4-2 shows the relationship of the three types of orthophotos. One mosaic can be comprised of several source orthophotos. A clipped orthophoto is just the mosaic orthophoto which was clipped to a DOQQ's extent.

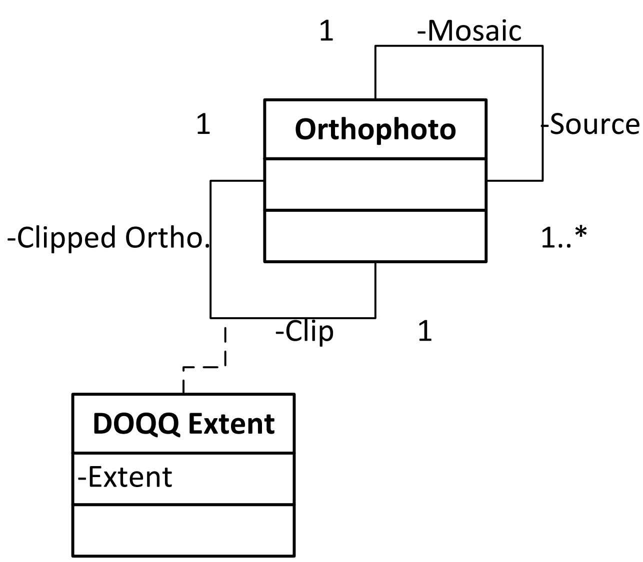


Figure 4-2: A more detailed look at the conceptual model of the orthophoto

The ground control points were another important component to this project. Figure 4-3 shows a more detailed look at what comprises the ground control point file. The ground control point files were comprised of a set of coordinates which were used to transform scanned photos into rectified photos. This is the process of rearranging the pixels to their correct places on the ground. Figure 4-3 shows that the same spatial reference system is shared for the DOQQ and the DEM; it is the reference system used in this project. A ground control point file gets its spatial reference information – the northing and easting (x and y) – from the DOQQ's spatial reference, and the elevation data (z) from the DEM.

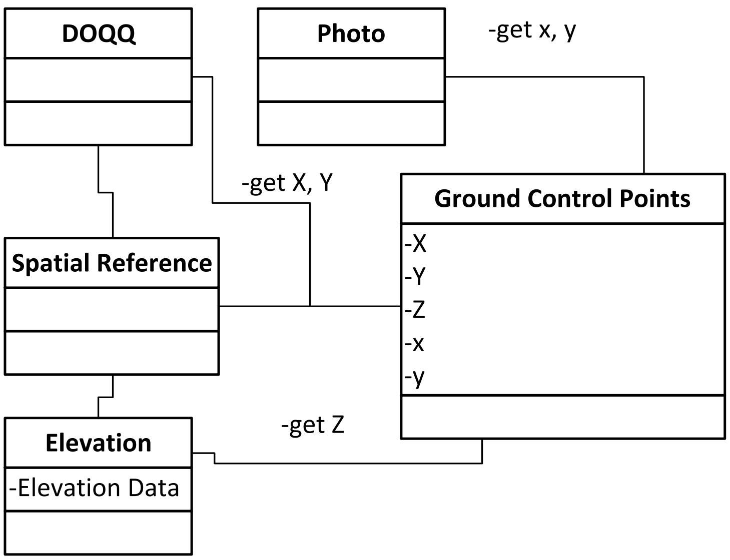


Figure 4-3: A more detailed look at the conceptual model for ground control points

4.2 Logical Data Model

The project began with database design and standardization of data. However, the database used was a sample database for testing purposes only. The client maintains an image library and database management system. The tool created is flexible and can handle various data formats, but has only been tested with the sample geodatabase created for this project, which was a collection of folders stored and managed in ArcCatalog. Figure 4-4 shows the design of the database.

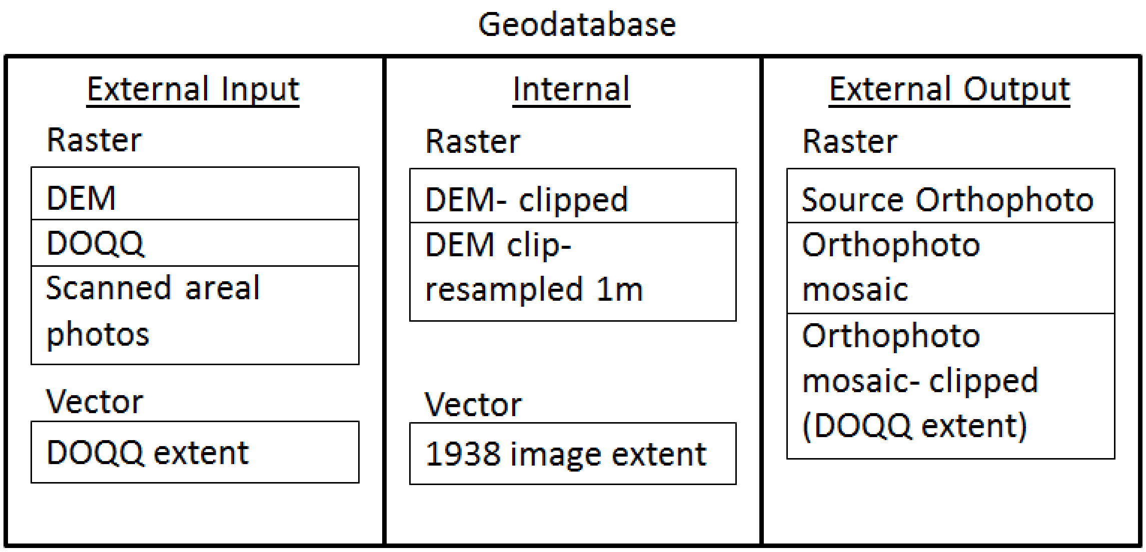


Figure 4-4: Logical model

The database had three components: external inputs, internal components and external outputs. The external inputs were inputs that were stored in the sample geodatabase that were taken from other image libraries. The internal components were outputs that were created during the process but were discarded when the workflow was completed. The internal components were just used as intermediary steps to create the final outputs. The external outputs were stored in the sample database and transferred back the client's image library.

The tool used the extent and resolution of the DEM in the creation of the source orthophotos. For this reason, the DEMs, which originally covered a very large area with a 10 meter resolution, were clipped to the extent of the 1938 image which was being orthorectified and the DEM was resampled to 1 meter resolution. Because the 1938 images had not been referenced yet, shapefiles of their extents needed to be created in order to clip the DEMs to their extents. These steps were intermediary steps and so they were discarded after the orthorectification was completed successfully.

To create the orthophotos, the rational function model tool was created to run in ArcMap. This tool inputs the ground control points which had the image reference coordinates for the 1938 scanned imagery and its corresponding spatial reference from the DOQQs, as well as the elevation data from the DEMs. The tool rearranged the pixels to their correct places on the ground. The output images were assigned the same spatial reference as the DEM. The output images were stored in Geo-TIFF format as the source orthophotos in the geodatabase.

Once several source orthophotos were generated, usually six to eight to cover an entire DOQQ area, these images were mosaicked and stored in an orthophoto mosaic folder in the geodatabase. The extent of a DOQQ was stored as a shapefile, which was then used to clip the mosaic so that the clipped image would have the extent of the

DOQQ. The resulting output image was stored in a different folder in the geodatabase. The clipped mosaic is the final product of the production workflow created for the client, and thus is an external output. The source orthophotos and the pre-clipped orthophoto mosaics were external outputs because they could be used for other projects, and could offer varying extents.

4.3 Data Sources

The data used for this project included: the scanned aerial photographs, the DOQQs, the DEMs, and the DOQQ extent shapefile. The aerial photographs were provided by the client, and are held in the imagery library at the University of California, Riverside. The aerial photographs are black-and-white scanned photographs from the AXM-1938 flight. The photos were acquired in 1938 and cover most of Riverside County. Figure 4-5 provides a reference of where Riverside County is in California. Each frame was scanned at 1200 dots per inch and has a scale of 1:20,000. The format is 7.25 inches by 9.25 inches and there is a 60 percent end lap along a flight line and 20 percent side lap between flight lines.

Figure 4-5: Map of Riverside County, CA

The DEMs, DOQQs, and DOQQ boundary shapefile were all acquired from the Cal Atlas Clearinghouse. The DEMs are from the National Elevation Dataset, 2010 collection, and were downloaded in GRID format with a resolution of 1/3 arc second, or about ten meters, located with geographic coordinates on the North American Datum of 1983. The DOQQs are high resolution orthophotos with a spatial resolution of one meter. Both the 1993 black-and-white photos and the 1998 color infrared orthophotos from USGS were used with a spatial reference of the NAD 1983 UTM Zone 11 North. The DOQQ extent shapefile was downloaded separately and was not extracted from the DOQQ imagery. The shapefile contains only the extents of each DOQQ and the name of that quarter quadrangle. Like the DOQQ imagery, the shapefile had the NAD 1983 datum and UTM Zone 11 North projected coordinate system.

4.4 Data Scrubbing and Loading

The data scrubbing ensured uniform data and that the sample data were representative of the client's data and expectations. The client had specified that the final output images, needed to be in the NAD 83 datum with the UTM Zone 11 North projected coordinate system. Before using any of the data for the project, the first step was to make sure all the data were transformed to this coordinate system. The project raster tool in ArcGIS was used to create new raster images with the specified coordinate system. This was applied to all the DEMs which were used for collecting ground control point information.

In addition to re-projecting, the DEMs needed some further pre-processing to work properly with the developed orthorectification tool. Four DEMs, which collectively covered the entire flight area for the AXM-1938 imagery, were downloaded and re-projected. These four DEMs were then mosaicked together to ensure that each 1938 image had a DEM which covered its entire area. Then, for each photo which was being processed in the orthorectification tool, the DEM was clipped to roughly the same extent as the source photo. This was done by visual interpretation and giving a buffer for room for error. It was important to ensure that a DEM covered the entire area of a source photo, so they were clipped to a slightly larger extent than the source photo. Clipping the DEMs was important for two reasons: it improved processing speed for the tool, and it reduces the size of the output orthophoto. The tool required that the DEM be resampled to one meter resolution from its original ten meter resolution. Because the output extent of a source orthophoto was actually based off the extent of the input DEM, a clipped DEM would greatly reduce processing time and output storage space.

4.5 Summary

Data management is crucial for the proper functioning of any geographic information system. In this case, creating a new database was unnecessary because the client already had an image library and management system in place. The standards set by the client's existing data model were followed, such as projection and spatial extent of the imagery.

From conception to implementation, the model took advantage of the data provided, and the new tool works well in the geodatabase. The proper organization of data and data processing provided a good foundation for the project.

Chapter 5 – Implementation

The main focus of the project was to develop a method to accurately reference the collection of 1938 scanned aerial images of Riverside County. As an initial test, the geo-referencing toolbar in ArcGIS 10 was explored. However, it was confirmed that the results did not meet the National Map Accuracy Standards as the client required. This did, however, provide a base point for comparison when exploring other methods.
The rational function model was chosen to orthorectify the images. However, unlike with the satellite systems which the rational function model is commonly used for, key camera operational models are not known, so the coefficients for the rational function model had to be calculated from ground control points. The basic equation of the rational function model used in this project is as follows:

$$x = \frac{a_0 + a_1 * X + a_2 * Y + a_3 * Z}{c_0 + c_1 * X + c_2 * Y + c_3 * Z}$$

$$y = \frac{b_0 + b_1 * X + b_2 * Y + b_3 * Z}{c_0 + c_1 * X + c_2 * Y + c_3 * Z}$$

In the equation, X, Y, and Z are ground coordinates from ground control points measured from a DEM and orthophotos; the a's, b's, and c's are coefficients to be calculated; and x and y are the image coordinates.

5.1 Ground Control Points

Ground control points were used to calculate the rational function model because the camera geometry was unavailable. Ground control points, here, refer to points taken from reference imagery in a ground coordinate system, in this case UTM. Although the reference images have an accuracy of 20 feet or less, the points taken from the reference imagery are considered ground truth, and the quality of the transformation is measured to the accuracy of the reference image.

The accuracy of the orthophoto relied heavily on the quality and quantity of ground control points. Each image used between twenty and thirty ground control points, which were evenly distributed throughout the image. The transformation works pixel by pixel so it was important to have ground control points covering the entire area. If one corner or section of the image did not have ground control points that section of the image would not be accurately transformed. In addition to making sure that the ground control points were evenly distributed, all four corners needed ground control points to help ensure the edges were correctly rectified. Figure 5-1 shows one of the images with its ground control points. Note that the ground control points are distributed fairly evenly throughout the image.

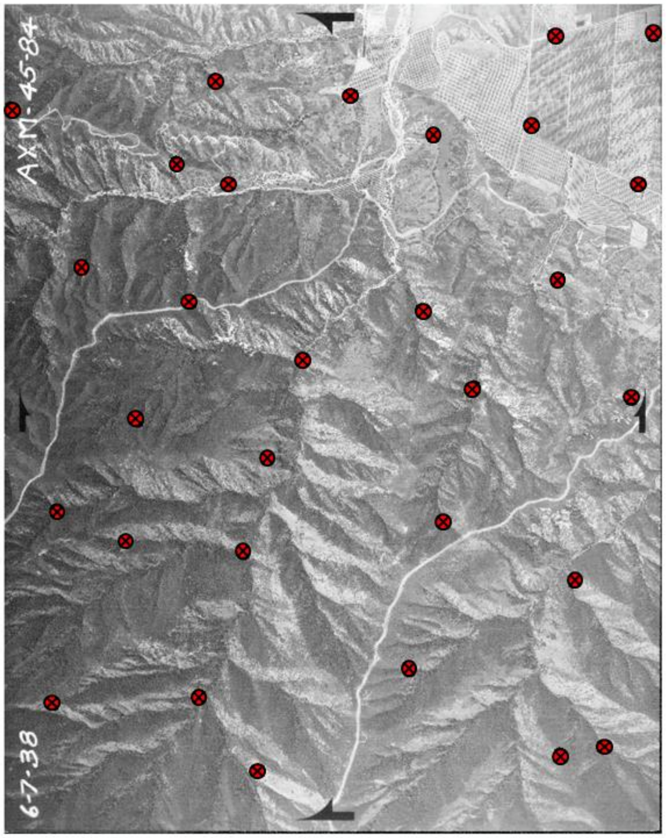
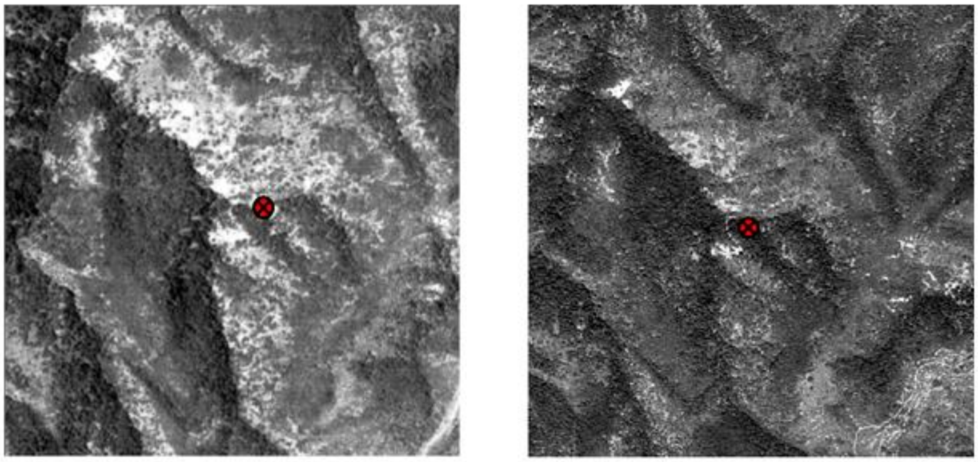


Figure 5-1: Ground control point distribution

There were different approaches to choosing ground control points based on the location of the images. In urban areas residential street intersections worked well. Residential streets were better to use than main streets because they are narrower so the intersection is smaller and more precise. Residential streets, if there were some from the 1938 image in the DOQQ images, were also less likely to have changed in size than main streets. In mountain areas the intersections of mountain ridges were often used as ground control points because the ridges formed easily identifiable lines, and the intersection of two ridges formed points which were easy to identify in both areas. Figure 5-2 shows an example of a good ground control point used from a mountainous area. In this example the intersections of two ridges was chosen. Sharp turns in mountain roads also provided good points for ground control points.



1938 Scanned Aerial Photo DOQQ Reference Photo

Figure 5-2: Ground control point in mountainous area

One especially difficult problem that occurred during the collection of ground control points in the mountains was that shadows created by the sun angle shift with the time of day. If the 1938 image and the reference image were taken at different times of day, then the sun angle would be different. Different sun angles make the shadows from the mountains have different shapes and directions, which made it difficult to differentiate between ridges and valleys along the same mountain. Figure 5-3 shows an example of a mountain area where the sun angles were different in the 1938 image and the reference DOQQ image.

1938 Source Imagery DOQQ Reference Imagery

Figure 5-3: Different shadow angles make it difficult to find good ground control points

The ground control points were collected using the Identify tool in ArcMap. Two ArcMap documents were open at the same time: one with a 1938 image loaded and one with a DEM and a DOQQ loaded. The DOQQ was the top layer because it was used as the reference imager, but the Identify tool was set to read the information from the DEM, which had the elevation data. The same spot would be located and coordinates from both the 1938 image and the DOQQ image would be recorded, along with the elevation value from the DEM at that location. These values were stored in the ground control point file in text file format. The format of the file had to be very specific because the developed script reads the values from the file with a strict sequence. For this reason an example file and a template file were created for future users to refer to. Figure 5-4 shows an example ground control point file. The text file format was used since it is easy to read in Python. Notice that values are delimited by a comma and tab (",   "). This is how the Python code extracts the values from the file. The word "end" is used twice on the two lines following the end of the ground control points. This was used as a break in the loop for the code to stop reading the file.

```
Image 053_092
Image Center
xc,             yc,             X,              Y,
3.6065,         4.617,          498432.816,     3759183.053
Ground Control Points:

ximag,          yimage,         X,              Y,              Z
2.027,          0.524,          497658.55,      3757078.79,     742.683838
1.061,          0.421,          497152.59,      3757013.28,     732.510559
3.432,          0.492,          498381.06,      3757072.22,     753.482117
5.644,          2.047,          499488.94,      3757886.13,     786.29834
3.67,           3.642,          498467.58,      3758680.45,     773.716003
3.647,          2.074,          498473.22,      3757878.82,     760.670715
2.101,          3.669,          497669.35,      3758679.48,     746.706177
6.824,          1.796,          500088.63,      3757754.82,     788.10498
6.958,          4.406,          500120.40,      3759095.08,     825.469727
4.916,          3.636,          499105.25,      3758685.45,     796.847534
2.092,          2.095,          497674.95,      3757884.87,     749.754456
3.986,          0.795,          498657.48,      3757229.85,     755.924377
1.074,          2.667,          497153.44,      3758155.83,     732.336487
1.079,          4.789,          497124.85,      3759220.68,     730.611267
6.52,           3.62,           499912.77,      3758691.20,     803.661316
1.394,          8.537,          497265.25,      3761134.77,     792.87384
5.993,          7.839,          499566.24,      3760777.32,     931.710449
4.799,          8.383,          498990.19,      3761056.65,     893.161438
4.519,          6.65,           498858.42,      3760192.24,     908.16272
6.389,          6.64,           499783.54,      3760194.07,     918.490234
1.353,          7.671,          497248.97,      3760709.65,     766.972534
1.471,          6.469,          497337.16,      3760094.83,     815.400085
4.534,          5.528,          498885.90,      3759635.73,     856.007446
6.787,          5.887,          499996.58,      3759830.89,     874.897949
3.162,          5.154,          498203.38,      3759439.07,     811.121399
2.137,          8.242,          497646.18,      3760996.30,     791.510437
3.084,          6.85,           498151.94,      3760279.27,     880.355774
5.693,          6.422,          499445.90,      3760084.65,     921.098999
5.327,          1.127,          499339.33,      3757412.92,     781.331665
5.754,          4.427,          499507.36,      3759093.54,     845.98999
end
end
```

Figure 5-4: Example ground control points text file

5.2 Rational Function Model Tool

The rational function model was coded in Python to calculate the coefficients. NumPy was used to perform matrix math and other mathematical functions. Since rational function models are nonlinear functions, they need to be linearized. The linearization requires the coefficients to be estimated first. The parameters needed from the 1938 imagery to calculate the initial rational function coefficients include the focal length, fly height, and scale, all of which are provided in the metadata for that series of imagery, which are in turn specified in the code.

The script first reads the input ground control points file and builds a matrix out of these values. The script included adjusting the 1938 ground control points so that the origin of the image coordinate system was in the center of the image. The origin for the image units defaults to the lower left corner in ArcMap, so the script included code to change the origin of the image coordinate system to the center of the image.

Once the ground control points have been read and stored in a matrix, a series of matrix operations are performed to calculate the coefficients using the Gauss-Markov model. The coefficients were used to perform the transformation, transforming the ground positions to image positions.

The next step was to generate orthophotos. Determining how to read a raster file in Python was the first challenge in using this method. Originally the Geospatial Data Abstraction Library (GDAL) extension for Python was installed. This extension was very difficult to install and configure correctly, and required further instruction and research on how to use it. While researching methods on how to use GDAL it was discovered that the ArcGIS version 10 software came with the ArcPy extension, which included the needed capabilities. So GDAL was abandoned and ArcPy was used. ArcPy can open a raster as a NumPy array. This meant that only the NumPy and ArcPy extensions were needed, and both came with the installation of ArcGIS version 10.

The Python script worked by taking the spatial reference from the DEM and the pixel values from the image to rebuild the image pixel by pixel in its correct ground location. The script performed the following process:

1. Open both the 1938 image and the DEM as arrays in memory. A third array was created with the exact same dimensions as the DEM and would eventually become the orthophoto.
2. Iterate through every pixel in the DEM, extracting the ground coordinates and elevation for that pixel and converting them to image coordinates using the rational function model previously calculated.
3. Find the corresponding location in the 1938 image array and copy the pixel value.
4. Take that pixel value and put it in the newly created array at the location of ground coordinates from the DEM.

The DEM was clipped to be slightly larger than the 1938 photo which meant that some pixels from the DEM would not be found in the 1938 image. To deal with this, the output orthophoto array was given the extent of the DEM, and if the pixel could not be found in the 1938 image that cell in the output image was given a value of -1. This created a border of -1 values surrounding the 1938 image in the orthophoto, which was accounted for when the array was converted back to a raster. The orthophoto generated array was converted back to a raster using ArcPy functions and given the same projected coordinate system as the DEM. A value of -1 was set to represent no data, so that this area would not be visible in the final orthophoto. Figure 5-5 shows an example 1938 scanned image and its corresponding orthophoto created using this method. It is clear that the original scanned photo and the orthophoto version of the same frame have a different shape.

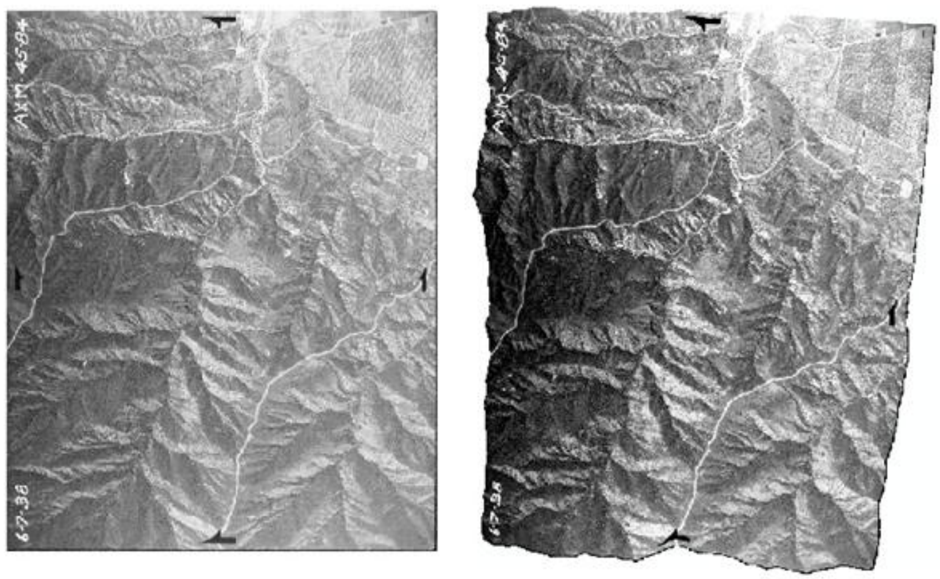


Figure 5-5: Comparison of scanned photo versus orthophoto

5.3 Generating Mosaic Orthophotos

After the source orthophotos were generated, they were mosaicked and clipped to match the extent of the corresponding DOQQ. At the start of the project the client provided a Google Earth Document which had the centers of each 1938 imagery frame pinned. The DOQQ boundary shapefile was exported to XML format to use in Google Earth. The XML file showed which frames would be needed to cover the extent of a DOQQ.

Once all source photographs were transformed into orthophotos, a mosaic was created. The mosaic was created by first generating an empty raster in ArcCatalog in the Mosaic Database. Then the Mosaic tool in the Data Management toolset was used to mosaic all of the source orthophotos; the empty raster was designated as the target layer to output the mosaic. In order to create a seamless look to the mosaic, the lines at the edges of frames are smoothed using various parameters. In the end, it was found that by setting the Mosaic Operator to Maximum, the black border that is found on some of the frames due to the scanning process disappear. Setting the Mosaic Colormap Mode to Last helped smooth the transitions between frames. Figure 5-6 shows an example of the mosaic created as an example for the client.

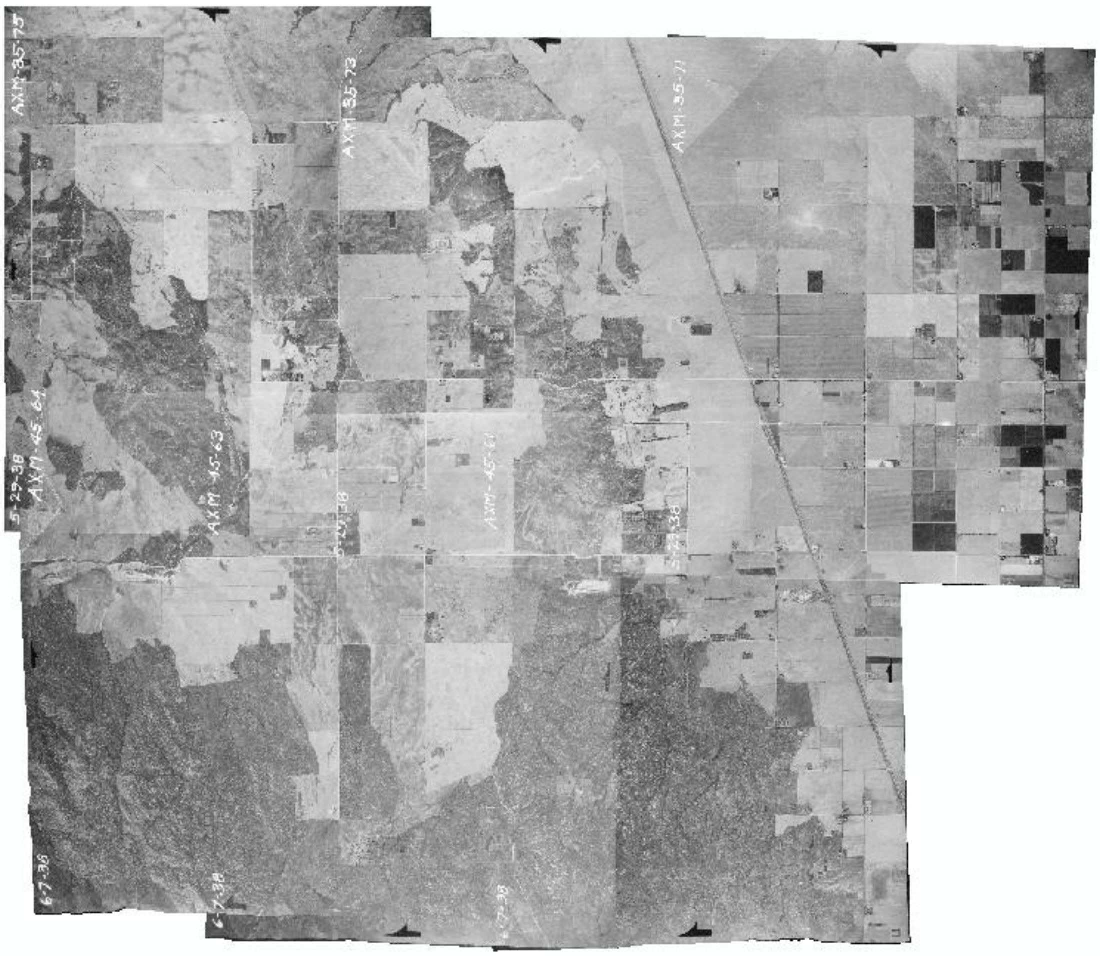


Figure 5-6: Example mosaic

The Select Layer by Rectangle was then used to select the necessary individual DOQQ boundary. This selection was turned into a layer stored in the map document, but not in the geodatabase. The Clip tool in the Data Management toolset was used to clip the mosaic orthophoto to the DOQQ extent, using the DOQQ boundary layer. This output was then stored in a new geodatabase. This final orthophoto, which has the extent of a DOQQ and is comprised of multiple source images, is the final product generated. Figure 5-7 shows an example of the final product. Using the developed methods, the entire collection of images from the AXM-1938 flight can be turned into orthophotos with DOQQ extents.

Figure 5-7: Orthophoto after mosaicked and clipped to DOQQ extent

5.4 Creating the Workflow

The workflow tied together all the production steps necessary to convert the scanned un-referenced imagery into mosaicked orthophotos with the dimensions of the DOQQ. To create the workflow, the Task Assistant Manager Toolbar from the Production Mapping Extension of ArcMap was used. Task Assistant Manager has a designer and user mode. The designer mode allows the creation of a step-by-step production workflow. For each step in the workflow a set of instructions was written to guide the user through the process and specify data requirements for that step. Figure 5-8 shows what the workflow looks like in Task Assistant Manager, with the instructions highlighted in a red box. Each step also specified the needed geoprocessing tool or command such as creating a new feature class. The result of specifying the tool for each step is that when a user gets to a particular step in the workflow the specified tools will automatically appear. This means that a user does not have to figure out which tool to use or where it is located. This was ideal since the user of the workflow is going to have limited GIS skills.

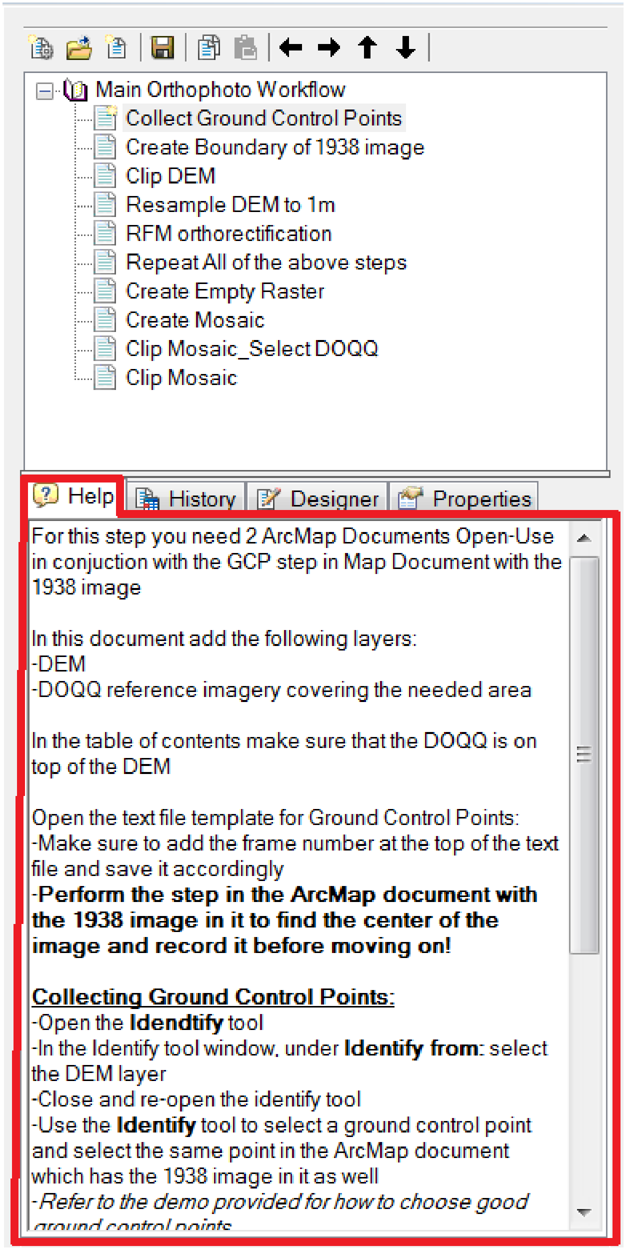


Figure 5-8: Task Assistant Manager workflow

The ground control point selection part of the workflow used two windows; this meant that two Task Manager workflows had to be created. One workflow was created to run in the ArcMap document which had the source 1938 imagery. The other workflow was the main workflow which used the DOQQ and DEM for referencing and contained all of the other steps. The two workflows were written to work together, so that the instructions indicate which step in the main workflow corresponds to which step in the secondary workflow. The secondary workflow with the source 1938 imagery is only to be used for the ground control point collection steps phase.

The workflow was designed to include all of the steps which a user would use. It starts with the ground control point selection and includes steps on clipping the DEM for use in the rational function model tool. Then the rational function model tool is used to create orthophotos. These steps are all repeated as many times as needed to generate all of the orthophotos, which cover the entire area of a DOQQ. The workflow then has steps to mosaic and clip the data to the DOQQ extent. The workflow includes all of the small steps between major steps, as well. One such example is that it includes a step on how to select the extent DOQQ shapefile, and how to create a new layer to be used for clipping.

Once the workflow was generated, an example was created as additional instruction and reference for users. It was also used to test the workflow. The Steele Peak NE DOQQ was chosen and every corresponding image was orthorectified and mosaicked using the workflow. Each step was additionally documented in a Word document with screenshots of each tool with the proper inputs. This helped to ensure that a user uses each tool as it is intended to produce the correct results. Also included were screenshots of the output from each step to help a user make sure each step is correct. In the end, the example and workflow helped ensure that the process worked correctly to orthorectify the entire collection of images from the RE-AXM-1938 mission.

Chapter 6 – Results and Analysis

The accuracy of the referencing was especially important for this project. The client's requirement for the project specified that the method chosen should produce results which meet the National Map Accuracy Standards; that 90 percent of all points tested must be within one-fiftieth of an inch on the map. At a scale of 1:20,000, one-fiftieth of an inch on the map would be 33.33 feet or 10.16 meters on the ground. To assess the image accuracy, check-points were collected the same way that the ground control points were selected. Using Excel, the differences in the values for the same point in the orthophoto and the DOQQ reference imagery were calculated. Table 3 shows the accuracy assessment using the checkpoints for one of the images. The root mean square error (RMSE) was calculated for each of the 15 check points as well as the total for all of the points.

Table 3. Frame 045-084 accuracy assessment

RE-AXM-38 Frame 045-084 RFM Orthophoto (meters)		DOQQ Reference Image (meters)		Residual (meters)		RMSE(meters)
X	Y	X	Y	X	Y	Total RMSE: 7.87
445,641.36	3,744,611.05	445,643.01	3,744,611.07	1.65	0.02	1.65
445,120.14	3,740,622.28	445,127.84	3,740,618.47	7.71	-3.81	8.60
442,741.94	3,741,051.02	442,745.13	3,741,046.80	3.19	-4.21	5.29
442,766.93	3,744,445.39	442,757.00	3,744,448.33	-9.93	2.94	**10.36**
444,911.43	3,744,400.02	444,914.51	3,744,394.83	3.08	-5.20	6.04
445,496.74	3,741,701.46	445,505.38	3,741,705.25	8.64	3.79	9.44
442,770.99	3,743,675.44	442,779.27	3,743,676.43	8.28	0.98	8.34
445,644.30	3,742,858.10	445,643.50	3,742,856.80	-0.80	-1.30	1.52
446,002.14	3,744,346.95	446,001.79	3,744,344.82	-0.36	-2.12	2.15
444,385.85	3,742,746.26	444,387.25	3,742,754.33	1.41	8.07	8.19
445,586.68	3,740,800.79	445,594.69	3,740,798.11	8.01	-2.69	8.45
443,599.22	3,744,835.43	443,606.58	3,744,839.80	7.36	4.37	8.56
442,982.99	3,742,381.79	442,986.39	3,742,389.80	3.40	8.01	8.70
445,607.07	3,744,916.36	445,608.48	3,744,926.30	1.42	9.94	10.04
443,750.66	3,743,803.48	443,757.05	3,743,808.41	6.39	4.93	8.07

To meet the accuracy standards, 90 percent of the points had to be within 33.33 feet or 10.16 meters. The coordinates were measured in UTM with a distance unit of meter. Table 3 shows that all of the points except one were more accurate than 10.16 meters. This means that 14 of 15 (93 percent) were within one-fiftieth of a map inch. The accuracy met the National Map Accuracy Standard.

The accuracy was also evaluated for the six frames used to create a clipped mosaic orthophoto. These frames covered the area of Steele Peak NE DOQQ. Table 4 shows the assessment results of these six orthophotos created using the rational function model tool designed for this project.

Table 4. Accuracy assessment of example Images

Image	RMSE (m)	% < 10.16m
045-061	5.39	100
045-063	5.93	100
045-064	5.43	93.3
035-071	7.29	93.3
035-073	7.81	93.3
035-075	6.67	93.3

Each image's accuracy was assessed using 15 check points. Table 4 shows the overall RMSE and the percentage of check points with a RMSE smaller than 10.16 meters, which is the National Map Accuracy Standard for images with a scale of 1:20,000. In this assessment, all six images tested were well within the National Map Accuracy Standards. Appendix B shows the complete assessment tables with all of the check points used to calculate the RMSEs for the six additional photos. Each photo has greater than 90 percent of the points within the 10.16m mark.

A comparison was conducted to see the difference between orthorectification and 2-dimensional geo-referencing using ArcGIS built-in methods. The exact same 30 ground control points used for calculating a rational function model were used to perform the geo-reference. Figure 6-1 shows the resulting images from the geo-reference and the rational function model orthorectification tool. Visually, there is a significant difference between the two images. The orthorectification tool actually changes the outlook of the image, whereas the geo-reference only shears the image slightly.

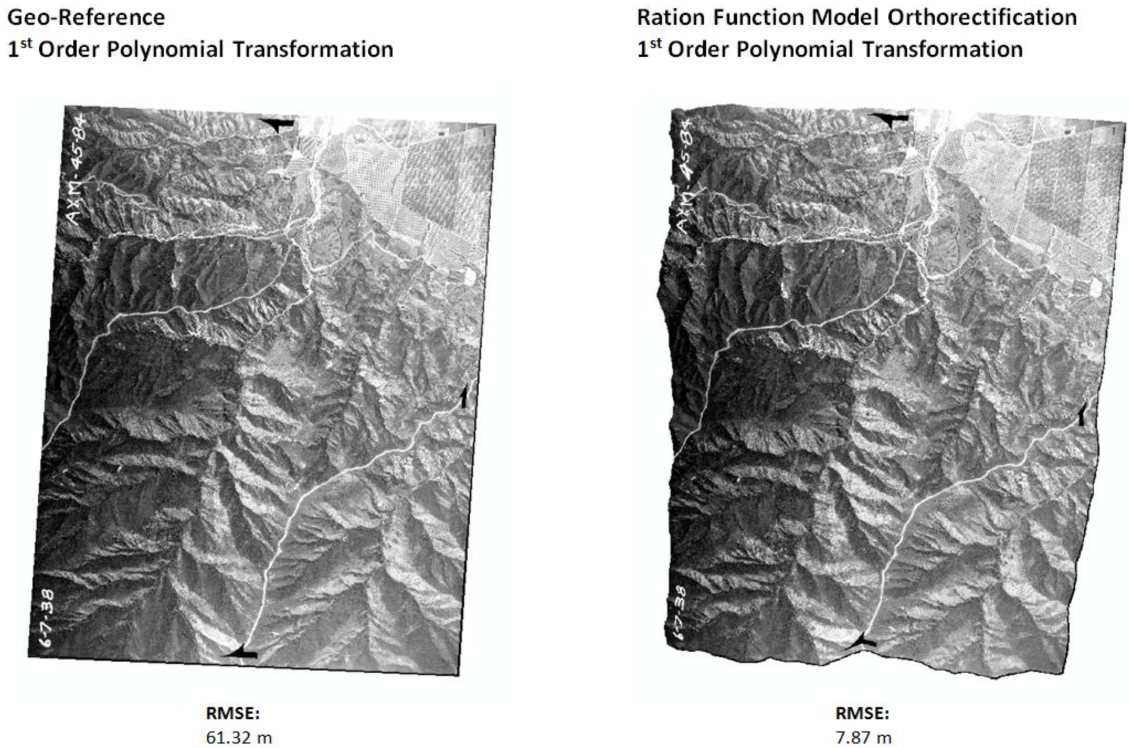


Figure 6-1: Orthorectification versus geo-reference

Figure 6-2 illustrates the RMSE of the geo-reference and orthorectification by displaying several of the check points. The green dots represent the coordinates from the DOQQ and the red dots represent the coordinates of the check points from the geo-referenced image or the orthorectified image. This figure shows that the error in the geo-reference check points is much larger than the error from the orthorectified image check points. Figure 6-3 is another comparison of the rational function model orthorectification versus the geo-reference. Figure 6-3 shows a digitized road from the DOQQ photo, the rational function model orthophoto and the geo-referenced photo. This once again shows that greater accuracy of the rational function model orthorectification.

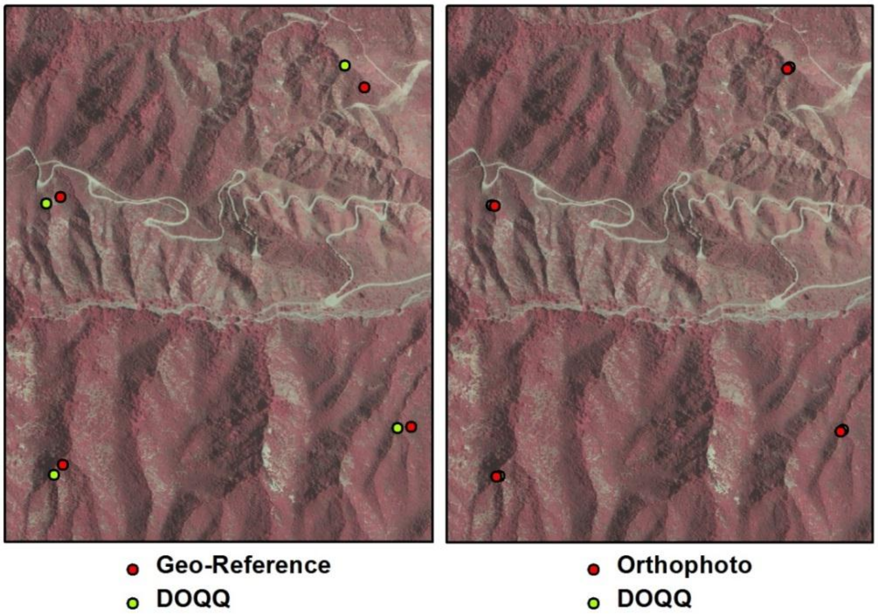


Figure 6-2: Accuracy of RFM orthorectification and geo-reference

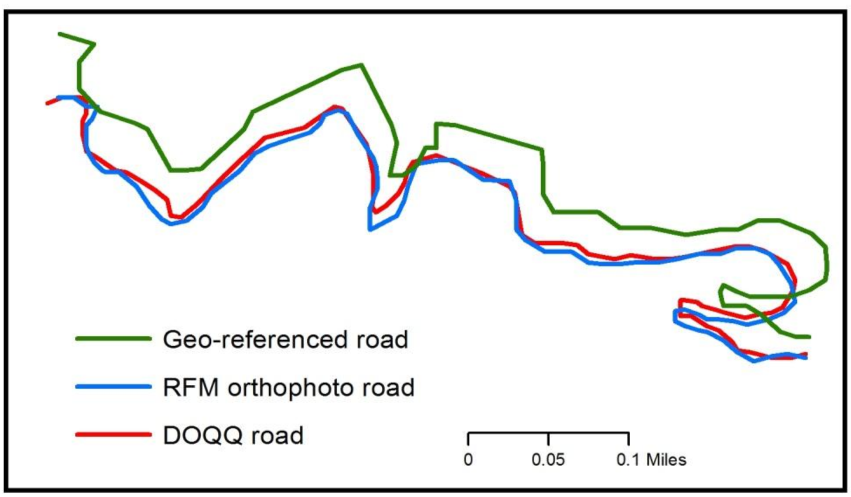


Figure 6-3: Digitized roads comparing RFM orthorectification and geo-referencing

The visual difference between the results of the two processes are striking, but when looking at the math it is clear that the rational function model orthorectification tool produced much more accurate results than the geo-referencing tool did. For the comparison the exact same 15 check points were used to calculate the accuracy of each image. The RMSE for the geo-referenced image was 61.32 meters, and thus did not meet the National Map Accuracy Standards. The rational function model orthophoto had an RMSE of 7.87 meters. The tool is capable of producing results which meet the National Map Accuracy Standards, as illustrated previously in Table 4. Tables 5 and 6 show the RMSE calculations for the geo-referenced image and the rational function model orthophoto, respectively.

Table 5. RMSE of the geo-referenced image

RE-AXM-38 Frame 045-084 Geo-referenced (meters)		DOQQ Reference Image (meters)		Residual (meters)		
X	Y	X	Y	X	Y	RMSE (m)
445,599.35	3,744,574.04	445,643.01	3,744,611.07	43.66	37.02	57.25
445,154.47	3,740,607.75	445,127.84	3,740,618.47	-26.63	10.72	28.71
442,669.27	3,740,963.82	442,745.13	3,741,046.80	75.86	82.99	112.43
442,797.26	3,744,466.24	442,757.00	3,744,448.33	-40.26	-17.91	44.07
444,916.57	3,744,393.61	444,914.51	3,744,394.83	-2.05	1.22	2.39
445,492.74	3,741,767.53	445,505.38	3,741,705.25	12.64	-62.28	63.55
442,804.34	3,743,704.86	442,779.27	3,743,676.43	-25.06	-28.43	37.90
445,660.27	3,742,927.99	445,643.50	3,742,856.80	-16.77	-71.19	73.14
445,943.44	3,744,336.38	446,001.79	3,744,344.82	58.35	8.44	58.96
444,401.33	3,742,788.16	444,387.25	3,742,754.33	-14.08	-33.84	36.65
445,633.89	3,740,798.74	445,594.69	3,740,798.11	-39.20	-0.63	39.21
443,662.62	3,744,778.63	443,606.58	3,744,839.80	-56.04	61.17	82.96
442,949.73	3,742,398.49	442,986.39	3,742,389.80	36.67	-8.69	37.69
445,562.46	3,744,856.39	445,608.48	3,744,926.30	46.02	69.91	83.70
443,795.03	3,743,812.52	443,757.05	3,743,808.41	-37.98	-4.11	38.20
					Overall RMSE	
					Meters	61.32
					Feet	201.12

Table 6. RMSE of the rational function model orthophoto

RE-AXM-38 Frame 045-084 RFM Orthophoto (meters)		DOQQ Reference Image (meters)		Residual (meters)		
X	Y	X	Y	X	Y	RMSE
445,641.36	3,744,611.05	445,643.01	3,744,611.07	1.65	0.02	1.65
445,120.14	3,740,622.28	445,127.84	3,740,618.47	7.71	-3.81	8.60
442,741.94	3,741,051.02	442,745.13	3,741,046.80	3.19	-4.21	5.29
442,766.93	3,744,445.39	442,757.00	3,744,448.33	-9.93	2.94	10.36
444,911.43	3,744,400.02	444,914.51	3,744,394.83	3.08	-5.20	6.04
445,496.74	3,741,701.46	445,505.38	3,741,705.25	8.64	3.79	9.44
442,770.99	3,743,675.44	442,779.27	3,743,676.43	8.28	0.98	8.34
445,644.30	3,742,858.10	445,643.50	3,742,856.80	-0.80	-1.30	1.52
446,002.14	3,744,346.95	446,001.79	3,744,344.82	-0.36	-2.12	2.15
444,385.85	3,742,746.26	444,387.25	3,742,754.33	1.41	8.07	8.19
445,586.68	3,740,800.79	445,594.69	3,740,798.11	8.01	-2.69	8.45
443,599.22	3,744,835.43	443,606.58	3,744,839.80	7.36	4.37	8.56
442,982.99	3,742,381.79	442,986.39	3,742,389.80	3.40	8.01	8.70
445,607.07	3,744,916.36	445,608.48	3,744,926.30	1.42	9.94	10.04
443,750.66	3,743,803.48	443,757.05	3,743,808.41	6.39	4.93	8.07
					Overall RMSE	
					Meters	7.87
					Feet	25.82

For the comparison, a first-order polynomial transformation was used for both the geo-referencing and the orthorectification. However, there are other algorithms to choose from in the pre-built geo-referencing tool. An additional comparison was done using the Adjust algorithm, which transforms the image in sections. Overall this method produced a smaller RMSE but it also produced undesirable effects to the image. Table 7 shows the RMSE table for the Adjust algorithm from the geo-referencing tool. Again, this geo-reference was performed using the same 30 ground control points and checked using the same 15 check points as the first order polynomial transformation geo-reference and the rational function model orthorectification. Using this algorithm the geo-reference produced an overall RMSE of 22.02 meters, and 40% of the check points had and RMSE of less than 10.16 meters. This was an improvement over the first order polynomial geo-reference, but it still does not meet National Map Accuracy standards.

Table 7. RMSE of geo-reference using the Adjust algorithm

Geo-reference Adjust algorithm (meters)		DOQQ Reference Image (meters)		Residual (meters)		
X	Y	X	Y	X	Y	RMSE
445,642.28	3,744,611.89	445,643.01	3,744,611.07	1.10	1.10	1.10
445,108.95	3,740,643.01	445,127.84	3,740,618.47	30.97	30.97	**30.97**
442,768.20	3,741,048.15	442,745.13	3,741,046.80	23.12	23.12	**23.12**
442,756.67	3,744,453.45	442,757.00	3,744,448.33	5.13	5.13	5.13
444,915.33	3,744,400.32	444,914.51	3,744,394.83	5.55	5.55	5.55
445,496.52	3,741,720.37	445,505.38	3,741,705.25	17.53	17.53	**17.53**
442,768.39	3,743,672.67	442,779.27	3,743,676.43	11.52	11.52	**11.52**
445,643.85	3,742,874.32	445,643.50	3,742,856.80	17.52	17.52	**17.52**
446,004.60	3,744,346.31	446,001.79	3,744,344.82	3.18	3.18	3.18
444,359.86	3,742,752.61	444,387.25	3,742,754.33	27.44	27.44	**27.44**
445,568.13	3,740,846.92	445,594.69	3,740,798.11	55.57	55.57	**55.57**
443,592.87	3,744,826.97	443,606.58	3,744,839.80	18.78	18.78	**18.78**
442,991.37	3,742,379.57	442,986.39	3,742,389.80	11.37	11.37	**11.37**
445,607.08	3,744,916.75	445,608.48	3,744,926.30	9.65	9.65	9.65
443,749.28	3,743,807.87	443,757.05	3,743,808.41	7.79	7.79	7.79
					Overall RMSE	
					Meters	22.02
					Feet	72.23

Although the Adjust algorithm produced a lower RMSE than the first order polynomial geo-reference, it also produced artificial linear features and blurred areas, making it a less desirable option for referencing. Figure 6-4 shows both a liner feature and a blurred area produced using the Adjust algorithm.

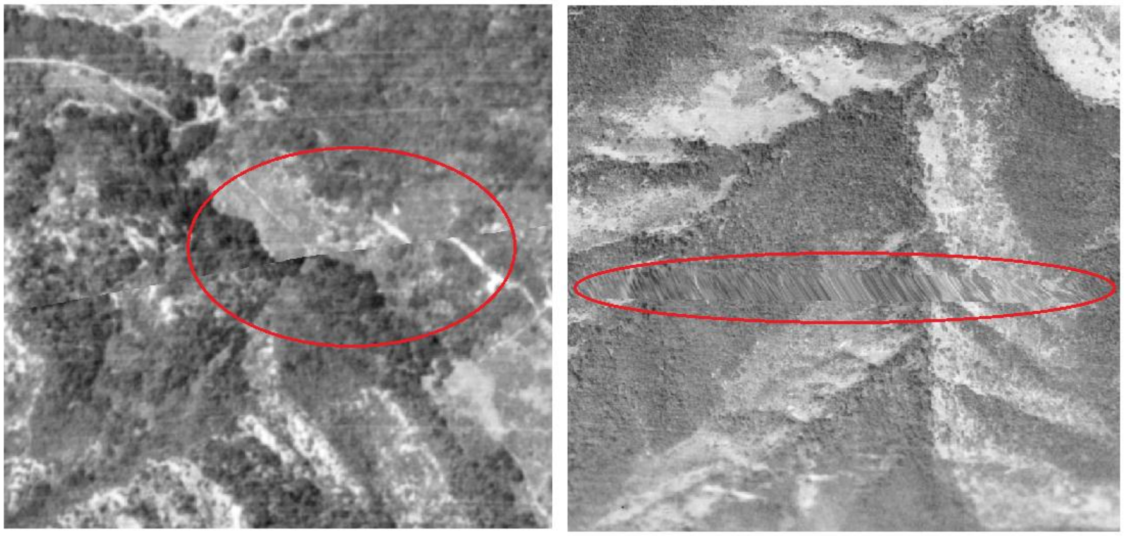


Figure 6-4: Effects caused by the Adjust algorithm

From the examples it is clear that the rational function model produces more accurate results than using any of the geo-reference algorithms. Although the examples used to test the tool produced accurate results, this does not mean that every time the tool is used it will produce the same results. The accuracy of the rational function model is highly dependent on ground control points. There are three variables to the ground control points which can greatly affect the accuracy: the quantity, distribution, and quality of the ground control points. The more ground control points used, the more likely the tool is to generate accurate results because one poorly chosen ground control point would weigh insignificantly if a lot of ground control points were used. The distribution is important, as well. If ground control points are missing from one section of an image the accuracy could vary across the image, being less accurate in the section where there were no ground control points. The quality of the ground control points is the most important. In mountainous areas where the control points have low accuracy, a large number of control points should be used.

Chapter 7 – Conclusions and Future Work

The Center for Conservation Biology at the University of California, Riverside, has a large collection of aerial photographs for research, including the AXM-1938 flight of Riverside County. In order to use these images for spatial analysis in a GIS, the images needed to be referenced to a standard coordinate system with specific accuracy. The CCB wanted a process developed to reference the images accurately within ArcGIS 10 software. In addition, they wanted these images to be mosaicked and clipped to the extents of DOQQs, consistent with the rest of data in their database.

The project was to be a prototype, meaning the developed work process could be implemented by undergraduate assistants in the future to process the entire set of imagery. To address the problem, a tool was created to run in ArcMap to orthorectify the aerial photographs. The rational function model was used as the method of orthorectification to reduce relief displacement distortion. Orthorectification requires a transformation from the ground 3-dimensional space to the 2-dimensional image space. The terrain-dependent approach to the rational function model was chosen as a trial method because the physical camera model for the 1938 imagery was unknown. The terrain-dependent rational function model approach uses ground control points (X, Y, Z) to approximate the physical camera model. The following is the rational function model used to transform from 3-dimensional ground space to 2-dimensional image space.

$$x = \frac{a_0+a_1*X+a_2*Y+a_3*Z}{c_0+c_1*X+c_2*Y+c_3*Z}$$

$$y = \frac{b_0+b_1*X+b_2*Y+b_3*Z}{c_0+c_1*X+c_2*Y+c_3*Z}$$

Once the coefficients are calculated, they are then used in the above equation to orthorectify the image. The 3-dimensional coordinates of the DEM are transformed pixel by pixel to the 2-dimensional image space to find the corresponding image pixel for that location.

This solution addressed the problem well by producing results which met the National Map Accuracy Standards. It also met with the client's needs by using a Python script to run in ArcMap. In addition, the entire process of orthorectifying, mosaicking, and clipping was brought together in a documented workflow using the Task Assistant Manager tool from the Production Mapping extension in ArcGIS 10. This addressed the requirement that the workflow created should be easily implementable by undergraduate assistants who only have limited GIS skills. The workflow created in the Task Assistant Manager is a step-by-step style production workflow. When a user gets to a given step, a set of instructions in the Help window will open and the tool needed for that particular step will pop up. This means that users should not accidentally use the wrong tool, or have difficulty finding the right tools in ArcMap. Overall this documented workflow should make the task much easier for users and make the process more efficient. All functional and non-functional requirements laid out by the client were met to produce accurate results using an efficient workflow.

7.1 Future Work

Although all of the requirements were met for the project, there are additional areas which could be developed in the future. The most valuable future work on this project would be to develop a user interface for collecting ground control points. The workflow is currently designed to use the Identify tool in ArcGIS to select control points and record values in a text file. This is time consuming and subject to human errors when copying and pasting the values into the text file. Although it works for the task needed, it would be very helpful to develop a user interface for control point collecting.

ArcMap version 10 features a user interface for collecting ground control points when using its geo-referencing tool. This user interface is designed specifically for the polynomial two-dimensional transformation, and for that reason it does not collect any elevation information. A user interface similar to the one for the geo-referencing would be useful. The user interface would record the x and y coordinates of the source image and then the x and y coordinates from the reference image in UTM, as well as the elevation at that point from the DEM. The user interface would be designed to work with the existing tool to orthorectify images, similar to how the text control point file works now. This future development would make the collection of ground control points easier and speed up the process, improving the efficiency.

The focus of this project was to work on the AXM-1938 aerial photographs of Riverside County. The script was customized to work to orthorectify this particular set of imagery. However, it may not necessarily apply towards other sets of aerial photographs. Another area where this project could be continued would be to make the tool more flexible so that it could work for different sets of aerial photographs, from different years and areas. Different cameras result in varying scales and sizes of the imagery. In addition, the photographs were scanned into a computer and the digital versions are the ones to be referenced. This means that there are also variations in scanning, such as varying resolution. A more flexible script would mean that all types of images could be used, regardless of the resolution or flight height. This would be particularly useful for the Center for Conservation Biology. By having a more flexible tool, the CCB could implement the workflow to orthorectify even more of its imagery, creating a larger database for researchers to use.

Several options can be considered when developing such a tool. For instance, the code for the tool needs information such as the scale and plane altitude for calculating the transformation. This information could probably be stored in a metadata file which would be read as an input. Alternatively, each of these fields could be manually entered by the user as inputs in a user interface. Creating a more flexible tool would also provide the opportunity to assess the accuracy and appropriateness of the rational function model orthorectification for various types of terrain by applying it to other sets of imagery. Applying the rational function model in more varying terrain with extreme elevation differences such as the Sierra Nevadas, or really flat areas such as Kansas, might provide insight on where the tool is appropriate to use. In certain instances it might not make sense to go through the longer process of the orthorectification if the geo-referencing can provide the same results with less time and effort.

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Appendix A. Python Script for RFM Orthorectification Tool

```
#Import Arcpy
import arcpy
#Import NumPy
import numpy


#opne GCPs ASCII file
arcpy.AddMessage("setting local variables...")
input_GCP_file=arcpy.GetParameterAsText(1)
arcpy.AddMessage("reading file...")
f=open(input_GCP_file, 'r')

#Parameters
arcpy.AddMessage("calculating rational function coefficients...")
#focal length (inches)
fl= 8.25
#fly height (feet)
h=13750
#scale
scale=1/20000
#Average Grid Elevation (meters)
#Average of Z values from GCPs for a frame
f.seek(0)
i=0
list2=[]
while i >=0:
    line=f.readline()
    if i<=6:
        i=i+1
    elif line=="end\n":
        break
    else:
        list=line.split(",\t")
        z=float(list[4])
        list2.append(z)
        i=i+1

avgZ=sum(list2)/len(list2)
omega=.18962
phi=.58904
kappa=10
```

```
#X and Y of image center (UTM)
f.seek(0)
p=0
while p<4:
    line=f.readline()
    p=p+1
list=line.split(",\t")
X0=float(list[2])
Y0=float(list[3])
#X and Y of image center (image coordiantes)
imgcx=float(list[0])
imgcy=float(list[1])

#Z0= Fly Height (converted to meters)+Avg Elevation
Z0=h*.3048+avgZ

#Create Z-axis matrix for photo
zAxis=numpy.matrix(numpy.zeros(shape=(3,3)))
zAxis[0,0]=numpy.cos(numpy.radians(kappa))
zAxis[0,1]=numpy.sin(numpy.radians(kappa))
zAxis[1,0]=zAxis[0,1]*-1
zAxis[1,1]=zAxis[0,0]
zAxis[2,2]=1


#Create Y-axis matrix for photo
yAxis=numpy.matrix(numpy.zeros(shape=(3,3)))
yAxis[0,0]=numpy.cos(numpy.radians(phi))
yAxis[2,0]=numpy.sin(numpy.radians(phi))
yAxis[0,2]=yAxis[2,0]*-1
yAxis[2,2]=yAxis[0,0]
yAxis[1,1]=1


#Create X-axis matrix for photo
xAxis=numpy.matrix(numpy.zeros(shape=(3,3)))
xAxis[1,1]=numpy.cos(numpy.radians(omega))
xAxis[1,2]=numpy.sin(numpy.radians(omega))
xAxis[2,1]=xAxis[1,2]*-1
xAxis[2,2]=xAxis[1,1]
xAxis[0,0]=1


#Create R Matrix = zAxis*yAxis*xAxis
rMatrix=(zAxis*yAxis)*xAxis
```

```
#Initial Coefficients from EO
a0=fl*(rMatrix[0,0]*X0+rMatrix[0,1]*Y0+rMatrix[0,2]*Z0)
a1=-fl*rMatrix[0,0]
a2=-fl*rMatrix[0,1]
a3=-fl*rMatrix[0,2]
b0=fl*(rMatrix[1,0]*X0+rMatrix[1,1]*Y0+rMatrix[1,2]*Z0)
b1=-fl*rMatrix[1,0]
b2=-fl*rMatrix[1,1]
b3=-fl*rMatrix[1,2]
c0=0-(rMatrix[2,0]*X0+rMatrix[2,1]*Y0+rMatrix[2,2]*Z0)
c1=rMatrix[2,0]
c2=rMatrix[2,1]
c3=rMatrix[2,2]



#Loop through process 100 times

u=0
while u<101:
    #create Matrix for A,B,C, xc', yc', dx, and dy from GCPs
    #Table Columns as follows:
    #xc,yc,X,Y,Z,A,B,C,xc',yc',dx,dy
    N=numpy.matrix(numpy.zeros(shape=(i-7,12)))
    f.seek(0)
    i=0
    while i >=0:
        line=f.readline()
        if i<=6:
            i=i+1
        elif line=="end\n":
            break
        else:
            list=line.split(",\t")
            xc=round((float(list[0])-imgcx),6)
            yc=round((float(list[1])-imgcy),6)
            X=float(list[2])
            Y=float(list[3])
            Z=float(list[4])
            A=(a0+a1*X+a2*Y+a3*Z)
            B=(b0+b1*X+b2*Y+b3*Z)
            C=(c0+c1*X+c2*Y+c3*Z)
            N[i-7,0]=xc
            N[i-7,1]=yc
            N[i-7,2]=X
```

```
        N[i-7,3]=Y
        N[i-7,4]=Z
        N[i-7,5]=A
        N[i-7,6]=B
        N[i-7,7]=C
        N[i-7,8]=A/C
        N[i-7,9]=B/C
        N[i-7,10]=xc-(A/C)
        N[i-7,11]=yc-(B/C)
        i=i+1


#create D matrix
#Columns as follows:
#dV,da0,da1,da2,da3,db0,db1,db2,db3,dc0,dc1,dc2,dc3
length=len(N)
D=numpy.matrix(numpy.zeros(shape=(length*2,13)))
a=0
while a<(length*2):
    if a<length:
        D[a,0]=N[a,10]
        D[a,1]=1/N[a,7]
        D[a,2]=N[a,2]/N[a,7]
        D[a,3]=N[a,3]/N[a,7]
        D[a,4]=N[a,4]/N[a,7]
        D[a,5]=0
        D[a,6]=0
        D[a,7]=0
        D[a,8]=0
        D[a,9]=0-(N[a,5]/(N[a,7]*N[a,7]))
        D[a,10]=0-(N[a,5]*N[a,2]/(N[a,7]*N[a,7]))
        D[a,11]=0-(N[a,5]*N[a,3]/(N[a,7]*N[a,7]))
        D[a,12]=0-(N[a,5]*N[a,4]/(N[a,7]*N[a,7]))
        a=a+1

    else:
        D[a,0]=N[a-length,11]
        D[a,1]=0
        D[a,2]=0
        D[a,3]=0
        D[a,4]=0
        D[a,5]=1/N[a-length,7]
        D[a,6]=N[a-length,2]/N[a-length,7]
        D[a,7]=N[a-length,3]/N[a-length,7]
        D[a,8]=N[a-length,4]/N[a-length,7]
        D[a,9]=0-(N[a-length,6]/(N[a-length,7]*N[a-length,7]))
```

```
        D[a,10]=0-(N[a-length,6]*N[a-length,2]/(N[a-length,7]*N[a-length,7]))
        D[a,11]=0-(N[a-length,6]*N[a-length,3]/(N[a-length,7]*N[a-length,7]))
        D[a,12]=0-(N[a-length,6]*N[a-length,4]/(N[a-length,7]*N[a-length,7]))
        a=a+1


#Refinement Matrix
    from numpy.linalg import inv
    lenD=len(D)

RM=(inv((numpy.transpose(D[0:lenD,1:13])*D[0:lenD,1:13])))*(numpy.transpose(D[0:l
enD,1:13])*D[0:lenD,0])
#Re-defined coefficients
    a0=a0+RM[0]
    a1=a1+RM[1]
    a2=a2+RM[2]
    a3=a3+RM[3]
    b0=b0+RM[4]
    b1=b1+RM[5]
    b2=b2+RM[6]
    b3=b3+RM[7]
    c0=c0+RM[8]
    c1=c1+RM[9]
    c2=c2+RM[10]
    c3=c3+RM[11]

    u=u+1

f.close()
arcpy.AddMessage("orthorectifying image...")
a0=float(a0)
a1=float(a1)
a2=float(a2)
a3=float(a3)
b0=float(b0)
b1=float(b1)
b2=float(b2)
b3=float(b3)
c0=float(c0)
c1=float(c1)
c2=float(c2)
c3=float(c3)

from arcpy.sa import *
arcpy.env.outputCoordinateSystem = "Coordinate Systems/Projected Coordinate
Systems/UTM/NAD 1983/NAD 1983 UTM Zone 11N.prj"
```

```
dem=arcpy.GetParameterAsText(2)
img=arcpy.GetParameterAsText(0)
output=arcpy.GetParameterAsText(3)

imgMatrix=numpy.matrix(arcpy.RasterToNumPyArray(img))

#Get upper left corner coordinates
arraydem=arcpy.RasterToNumPyArray(dem)
ext=arcpy.Describe(dem).Extent
ULx=ext.Xmin
ULy=ext.Ymax
#lower left corner
lowerleft=ext.lowerLeft
#DEM resoluiton
res=arcpy.Describe(dem).meanCellWidth
#number of rows
height=ext.height
#number of columns
width=ext.width
#extent of image
size=arcpy.Describe(img).Extent
#distace from top left to center
imgxc=(size.width)/2
imgyc=(size.height)/2
imgheight=size.height
#1938 image dimensions
imgshape=numpy.array(imgMatrix.shape)
imgmaxY=imgshape[0]
imgmaxX=imgshape[1]

Matrix=numpy.matrix(arraydem)
NewImg=numpy.matrix(arraydem)
arcpy.AddMessage("creating new image...")
c=0
r=0
while r<height:
    while c<width:
        X=ULx+(c*res)
        Y=ULy-(r*res)
        Z=Matrix[r,c]
        A=a0+(a1*X)+(a2*Y)+(a3*Z)
        B=b0+(b1*X)+(b2*Y)+(b3*Z)
        C=c0+(c1*X)+(c2*Y)+(c3*Z)
        x=int((imgxc+(A/C))*1200)
        y=int((imgyc-(B/C))*1200)
        if 0<=x<imgmaxX and 0<=y<imgmaxY:
```

```
            pv=imgMatrix[y,x]
        else:
            pv=-1
        NewImg[r,c]=pv
        c=c+1
    c=0
    r=r+1
newarray=numpy.array(NewImg)
newRaster=arcpy.NumPyArrayToRaster(newarray,lowerleft,"","",-1)
newRaster.save(output)
arcpy.AddMessage("done!")
```

Appendix B. Accuracy Spreadsheets

RFM Orthophoto		DOQQ		Residual		
X	Y	X	Y	X	Y	RMSE
477,439.28	3,744,957.35	477,443.97	3,744,952.65	-4.70	4.70	6.64
476,638.99	3,745,354.23	476,637.98	3,745,356.58	1.01	-2.35	2.56
475,810.33	3,744,563.38	475,804.02	3,744,557.98	6.31	5.41	8.31
474,404.59	3,744,327.61	474,401.15	3,744,327.62	3.43	-0.01	3.43
476,618.74	3,743,367.57	476,616.13	3,743,364.96	2.61	2.61	3.69
477,446.84	3,743,678.75	477,443.06	3,743,674.97	3.78	3.78	5.35
474,826.20	3,743,264.95	474,824.98	3,743,264.95	1.22	0.00	1.22
473,997.52	3,743,628.78	474,003.39	3,743,625.25	-5.88	3.53	6.86
475,909.62	3,742,599.95	475,905.06	3,742,601.47	4.56	-1.52	4.81
477,427.53	3,741,248.93	477,430.42	3,741,250.38	-2.89	-1.44	3.23
475,335.15	3,741,959.32	475,331.22	3,741,961.94	3.93	-2.62	4.72
474,446.22	3,741,138.48	474,444.04	3,741,136.30	2.18	2.18	3.08
475,831.09	3,740,813.83	475,826.86	3,740,814.89	4.23	-1.06	4.36
475,422.39	3,742,410.18	475,418.32	3,742,411.54	4.07	-1.36	4.29
475,594.04	3,743,958.55	475,597.22	3,743,950.09	-3.17	8.47	9.04
Image:	**045_061**	National Map Accuracy Standard:			Overall RMSE	
			Meters:	10.16	Meters	5.39
			Feet:	33.33	Feet	17.68

RFM Orthophoto		DOQQ		Residual		
X	Y	X	Y	X	Y	RMSE
472,986.31	3,744,808.04	472,988.18	3,744,817.28	-1.87	-9.25	9.43
473,794.81	3,744,964.12	473,791.41	3,744,958.18	3.40	5.94	6.85
474,186.83	3,744,149.75	474,188.32	3,744,152.73	-1.49	-2.99	3.34
473,382.86	3,742,532.01	473,388.05	3,742,530.28	-5.19	1.73	5.47
472,597.53	3,741,721.84	472,593.05	3,741,725.20	4.48	-3.36	5.60
472,244.73	3,742,646.45	472,243.59	3,742,649.88	1.14	-3.43	3.62
471,365.47	3,743,587.53	471,368.15	3,743,590.87	-2.67	-3.34	4.28
472,180.70	3,744,935.34	472,177.16	3,744,937.11	3.54	-1.77	3.96
474,182.69	3,743,340.41	474,186.15	3,743,349.04	-3.45	-8.63	9.30
474,758.14	3,742,496.07	474,760.43	3,742,494.93	-2.29	1.15	2.56
474,923.26	3,741,470.65	474,921.93	3,741,469.32	1.34	1.34	1.89
473,669.48	3,741,051.34	473,667.62	3,741,054.14	1.87	-2.80	3.36
472,874.00	3,743,329.87	472,881.60	3,743,330.63	-7.60	-0.76	7.64
472,498.97	3,742,125.29	472,495.17	3,742,124.53	3.80	0.76	3.87
472,707.58	3,744,138.79	472,714.34	3,744,141.97	-6.76	-3.18	7.47
Image:	**045_063**	National Map Accuracy Standard:			Overall RMSE	
			Meters:	10.16	Meters	5.93
			Feet:	33.33	Feet	19.45

RFM Orthophoto		DOQQ		Residual		
X	Y	X	Y	X	Y	RMSE
470,373.10	3,744,759.24	470,377.78	3,744,759.24	-4.68	0.00	4.68
471,170.06	3,745,475.10	471,172.46	3,745,476.31	-2.41	-1.20	2.69
472,580.94	3,744,683.00	472,584.90	3,744,672.83	-3.96	10.17	**10.91**
473,398.33	3,745,091.69	473,395.31	3,745,086.66	3.02	5.03	5.86
472,876.36	3,743,331.14	472,877.95	3,743,326.35	-1.59	4.79	5.04
471,770.63	3,743,729.47	471,767.37	3,743,731.10	3.26	-1.63	3.64
472,243.94	3,742,643.63	472,245.38	3,742,649.39	-1.44	-5.77	5.94
470,890.48	3,741,885.19	470,890.48	3,741,883.12	0.00	2.06	2.06
470,962.51	3,743,586.23	470,965.41	3,743,586.23	-2.90	0.00	2.90
469,953.65	3,743,716.24	469,959.31	3,743,717.65	-5.66	-1.41	5.83
470,497.24	3,741,682.39	470,500.44	3,741,680.26	-3.20	2.13	3.85
471,671.47	3,741,839.52	471,671.47	3,741,842.43	0.00	-2.90	2.90
473,041.26	3,741,229.18	473,042.22	3,741,236.88	-0.96	-7.71	7.77
473,404.53	3,741,476.56	473,401.16	3,741,478.80	3.37	-2.25	4.05
473,052.33	3,742,628.88	473,049.85	3,742,630.54	2.48	-1.65	2.98
Image:	**045_064**	National Map Accuracy Standard:			Overall RMSE	
			Meters:	10.16	Meters	5.43
			Feet:	33.33	Feet	17.80

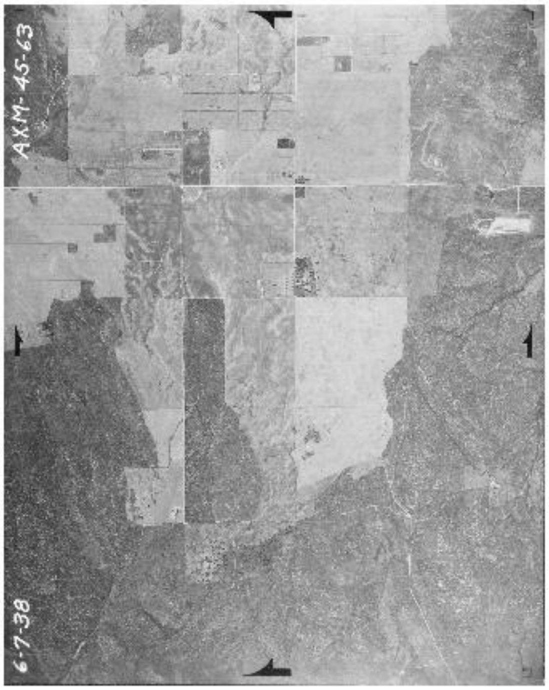
RFM Orthophoto		DOQQ		Residual		
X	Y	X	Y	X	Y	RMSE
476,632.57	3,746,960.04	476,637.50	3,746,953.17	-4.94	6.88	8.46
479,083.32	3,748,179.06	479,089.49	3,748,182.15	-6.17	-3.09	6.90
477,886.08	3,747,576.47	477,880.35	3,747,573.20	5.73	3.28	6.60
477,472.72	3,748,188.86	477,467.99	3,748,193.59	4.73	-4.73	6.69
479,090.07	3,746,965.49	479,088.65	3,746,964.08	1.42	1.42	2.00
475,810.15	3,745,373.43	475,811.17	3,745,364.45	-1.01	8.99	9.04
476,634.16	3,746,168.26	476,636.92	3,746,159.98	-2.76	8.27	8.72
477,456.14	3,747,376.95	477,456.14	3,747,376.95	0.00	0.00	0.00
479,089.40	3,746,149.39	479,094.31	3,746,154.30	-4.91	-4.91	6.95
477,889.46	3,746,563.04	477,880.52	3,746,570.71	8.95	-7.67	**11.78**
475,800.35	3,744,566.48	475,800.35	3,744,558.21	0.00	8.28	8.28
477,443.75	3,744,955.41	477,446.51	3,744,949.89	-2.76	5.52	6.17
479,079.70	3,744,544.84	479,085.19	3,744,550.33	-5.49	-5.49	7.76
478,284.79	3,745,755.91	478,281.53	3,745,753.73	3.26	2.17	3.92
476,637.25	3,745,967.86	476,635.13	3,745,967.86	2.12	0.00	2.12
Image:	**035_071**	National Map Accuracy Standard:			Overall RMSE	
			Meters:	10.16	Meters	7.29
			Feet:	33.33	Feet	23.90

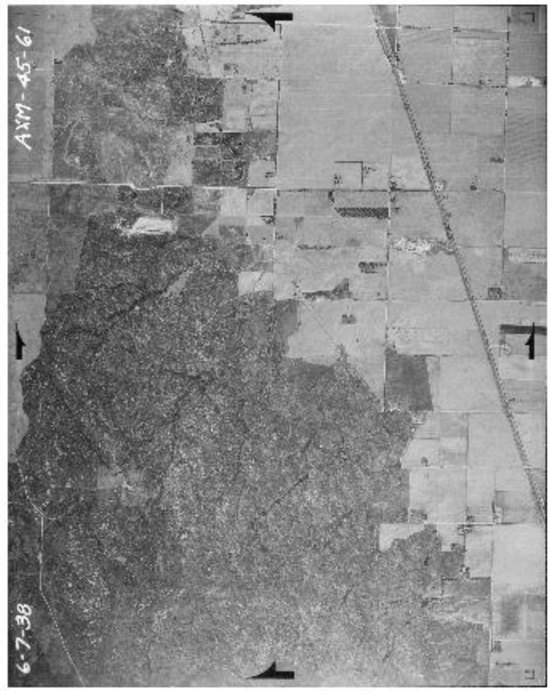
RFM Orthophoto		DOQQ		Residual		
X	Y	X	Y	X	Y	RMSE
472,587.79	3,747,327.59	472,590.66	3,747,321.84	-2.87	5.75	6.42
476,242.92	3,747,365.85	476,238.39	3,747,360.13	4.53	5.72	7.29
475,512.57	3,748,380.73	475,517.50	3,748,383.20	-4.93	-2.46	5.51
474,209.28	3,747,335.34	474,209.28	3,747,337.80	0.00	-2.46	2.46
474,097.42	3,748,539.17	474,089.64	3,748,546.95	7.78	-7.78	**11.00**
472,594.85	3,746,516.61	472,588.35	3,746,516.61	6.51	0.00	6.51
473,797.71	3,746,262.89	473,797.71	3,746,257.73	0.00	5.16	5.16
474,709.06	3,747,074.32	474,709.06	3,747,068.26	0.00	6.06	6.06
475,292.25	3,746,732.35	475,288.46	3,746,727.29	3.79	5.06	6.32
476,250.47	3,747,364.33	476,241.62	3,747,363.07	8.85	1.26	8.94
472,992.15	3,744,952.59	472,986.43	3,744,952.59	5.72	0.00	5.72
472,581.90	3,744,269.77	472,577.24	3,744,278.01	4.66	-8.23	9.46
474,188.12	3,745,100.94	474,195.71	3,745,095.52	-7.59	5.42	9.33
475,797.37	3,744,566.70	475,797.37	3,744,558.23	0.00	8.47	8.47
474,471.88	3,744,385.72	474,477.60	3,744,377.71	-5.72	8.01	9.84
Image:	**035_073**	National Map Accuracy Standard:			Overall RMSE	
			Meters:	10.16	Meters	7.81
			Feet:	33.33	Feet	25.63

RFM Orthophoto		DOQQ		Residual		
X	Y	X	Y	X	Y	RMSE
472,593.78	3,747,327.46	472,590.32	3,747,324.00	3.46	3.46	4.90
472,355.60	3,749,158.06	472,352.39	3,749,156.45	3.21	1.60	3.59
469,752.35	3,748,100.13	469,760.76	3,748,100.13	-8.41	0.00	8.41
470,971.30	3,748,123.42	470,967.48	3,748,121.51	3.83	1.91	4.28
472,592.71	3,746,516.41	472,592.71	3,746,520.21	0.00	-3.80	3.80
471,791.13	3,747,320.78	471,781.93	3,747,316.54	9.20	4.25	10.14
470,970.93	3,747,324.17	470,965.44	3,747,314.11	5.49	10.06	**11.46**
469,762.22	3,747,032.22	469,759.99	3,747,035.20	2.24	-2.98	3.73
471,090.99	3,746,597.18	471,088.02	3,746,597.18	2.97	0.00	2.97
472,597.40	3,746,517.49	472,593.46	3,746,516.51	3.94	0.98	4.06
472,983.90	3,744,953.08	472,987.45	3,744,951.30	-3.55	1.77	3.97
471,782.64	3,745,995.34	471,778.75	3,746,000.54	3.90	-5.20	6.50
471,229.80	3,744,827.74	471,228.28	3,744,821.68	1.52	6.06	6.25
470,325.26	3,745,042.00	470,319.47	3,745,038.09	5.79	3.92	6.99
471,041.50	3,745,432.16	471,033.72	3,745,433.72	7.78	-1.56	7.93
Image:	**035_075**	National Map Accuracy Standard:			Overall RMSE	
			Meters:	10.16	Meters	6.67
			Feet:	33.33	Feet	21.87

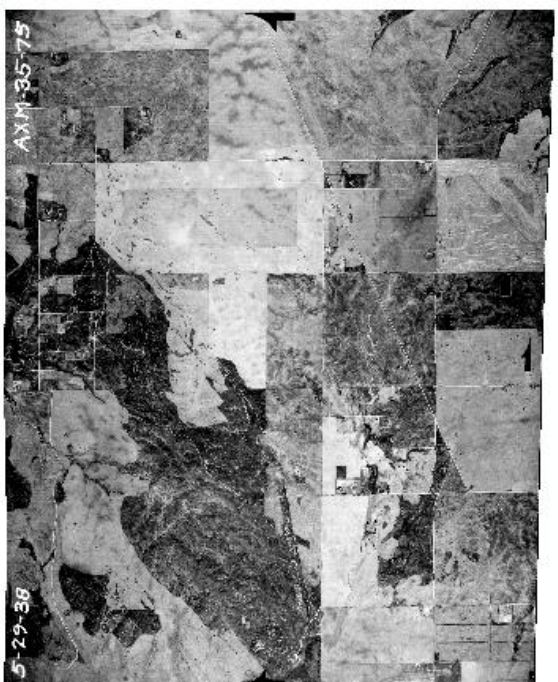
Appendix C. Example Data – Steele Creek NE Quarter Quadrangle

Original 1938 Scanned Photos

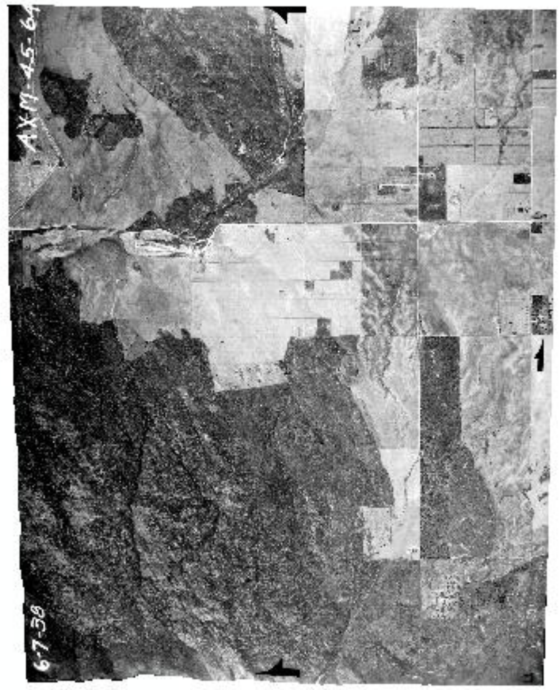




Orthophotos



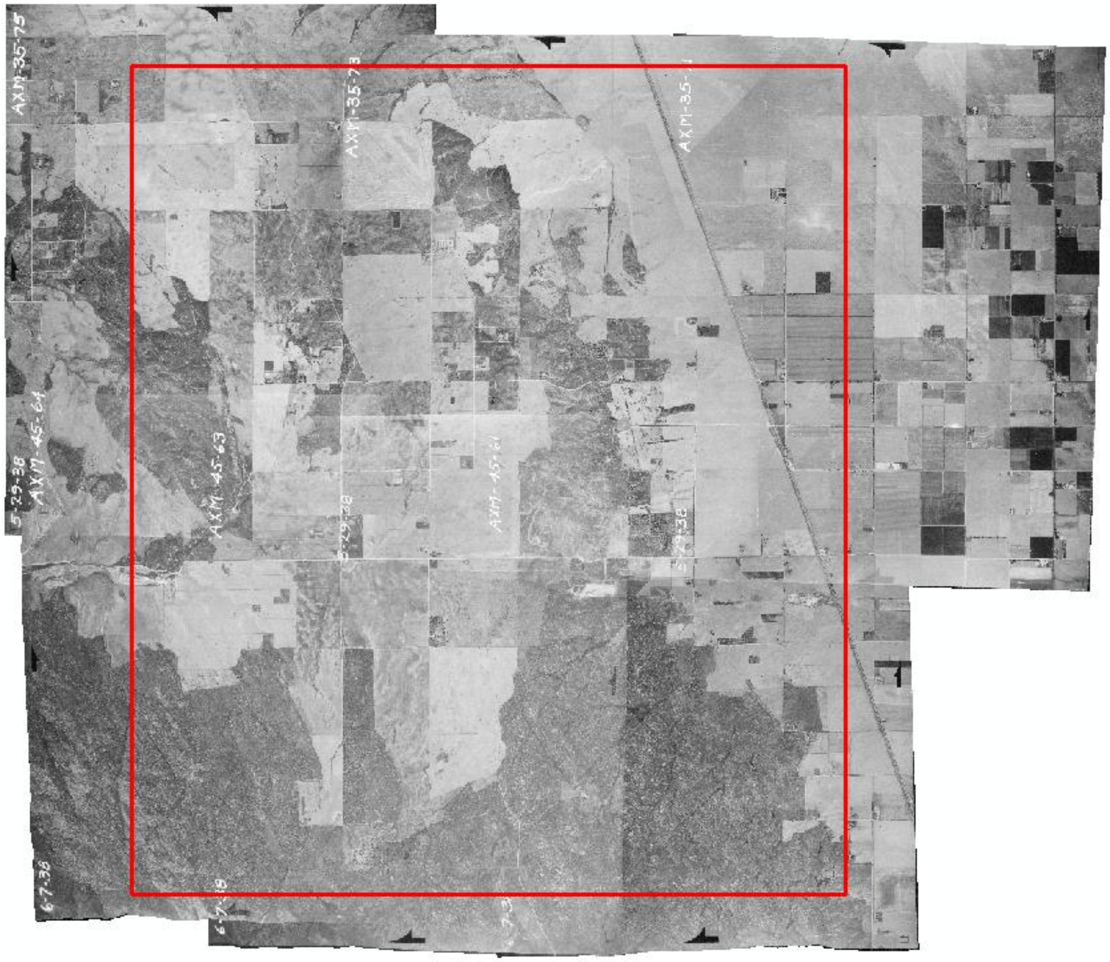

AXM-35-71
5-29-38


AXM-45-64
6-7-38


AXM-45-63
6-7-38


AXM-45-61
6-7-38

Mosaic



Final Product-Clipped to Steele Peak NE Quarter Quadrangle