IMPROVEMENT THE POSITIONAL ACCURACY OF THE 3D TERRAIN DATA EXTRACTED FROM IKONOS -2 SATELLITE IMAGERY

Jae-Bin Lee [a,*], Yong Huh [a], Byoung-jun Seo[a], Yong-Il Kim[a]
(leejeabin@hanmail.net, hy21262@dreamwiz.com, sttrap@chollian.net, yik@plaza.snu.ac.kr)
[a] School of Civil, Urban & Geo-System Engineering, Seoul National University,
Shillim-Dong, Kwanak-Gu, Seoul, Korea

Commission III, WG III/2

KEYWORDS: IKONOS-2 Satellite Images, RPC(Rational Polynomial Coefficients) Model, 3D terrain data, GCPs, Pseudo_GCPs

ABSTRACT:

This paper reports on the development of an algorithm that can renovate the RPC(Rational Polynomial Coefficients) models using GCPs (Ground Control Points) and Pseudo_GCPs (Pseudo_Ground Control Points) in order to improve the positional accuracy of the 3D ground coordinates extracted from IKONOS-2 satellite images. When 3D ground coordinates are extracted from IKONOS-2 satellite images, their positional accuracy depends on the RPC models. Therefore, in the case where RPC models are renovated by GCPs, the positional accuracy of the extracted ground coordinates can be improved. However, in actual cases, the GCPs are neither distributed evenly on the area of the satellite images nor can be obtained sufficiently. To solve these problems, Pseudo_GCPs, which were calculated from the original RPC models, were used. The RPC models were then renovated using both the GCPs and the Pseudo_GCPs together, and the 3D ground coordinates were extracted using the renovated RPC models. Finally, the validity of the algorithm was demonstrated on the basis of an accuracy evaluation using the check points obtained from the GPS(Global Positioning System) survey and triangulation. In addition, it was demonstrated that the vertical accuracy of the ground coordinates could be improved by using this algorithm.

1. INTRODUCTION

The periodic supply of images over an extensive area has caused the an information revolution. Indeed, satellite images have been used in various industrial and environmental fields. Nevertheless, the use of high-resolution satellite images was limited to military and espionage activities. However, with technological developments industry and its own operation of satellites, the acquisition of high-resolution (approximately 1m) satellite images has become possible for general public use. Worldwide nations and users will be able to make huge profits through the supply of high-resolution satellite images, which will leads to a new information revolution.
As a means to increase the applicable fields of high-resolution satellite images, this paper focuses on the development of an algorithm that can improves positional accuracy of the 3D ground coordinates extracted from the IKONOS-2 satellite images.
For this purpose, a basic algorithm was developed for extracting 3D ground coordinates using the IKONOS-2 satellite images and the RPC (Rational Polynomial Coefficients) models of the images. In addition, an algorithm that can renovate the RPC models with GCPs and pseudo_GCPs was developed. Finally, this study demonstrated the validity of this algorithm on the basis of an accuracy evaluation using check points obtained from a GPS(Global Positioning System) survey and triangulation. Furthermore, it was found that the vertical accuracy of the ground coordinates could be improved by using this algorithm.

2. THEORY

2.1 Extraction of 3D ground coordinates

To extract the 3D ground coordinates from the IKONOS-2 satellite images, an RPC model needs to be analyzed. The RPC model, which represents a relationship between the images and the ground, is extracted from the physical model of the IKONOS-2 satellite. In addition, the physical model is determined by the position of the satellite and it's camera information.
RPC models are provided from a header file of the IKONOS-2 satellite images, which are described as a fractional expression. The fraction is composed of a 3rd polynomial denominator and a numerator about the row and column coordinates of each image. The RPC models for the row and column coordinates of the image can be described as follows.

$$r = \frac{Num_R(u,v,w)}{Den_R(u,v,w)} \quad c = \frac{Num_C(u,v,w)}{Den_C(u,v,w)} \tag{1}$$

where r , c = the normalized row and column coordinates
u, v, w =the normalized coordinates of f, l, h

(u,v,w) are normalized coordinates, which offset the values and scale factors, and are applied to the coordinates, , of the WGS84 coordinate system. The RPC model is determined independently about each image. Therefore, every scale factor and image offset are different. It is for this reason that the coordinates of the RPC models should be converted to WGS84 coordinates, before the 3D ground coordinates are extracted from the RPC models. The relationship can be described as follows.

$$\begin{aligned} u &= (f - O_f)/SF_f \\ v &= (l - O_l)/SF_l \\ w &= (h - O_h)/SF_h \\ r &= (R - O_R)/SF_R \\ c &= (C - O_C)/SF_C \end{aligned} \tag{2}$$

where O = offset

SF = scale factor

r, c = normalized value of R, C

R, C = Row and Column of images

u, v, w = normalized value of f, l, h

f, l, h = latitude, longitude and height on WGS84 system respectively

There are two equations for the row and column for one image, and there can be 2n RPC equations for n images. Therefore, there can have 2n simultaneous equations with 3 unknown quantities, f, l, h (latitude, longitude, height). By solving these simultaneous equations, the 3D ground coordinates can be extracted from the IKONOS-2 satellite images as follows. The subscript letter denotes the number of images. In addition, $(a_1, \cdots, a_{20})_1$, $(b_1, \cdots, b_{20})_1$, $(c_1, \cdots, c_{20})_1$ $\cdots$ $(a_1, \cdots, a_{20})_n$, $(b_1, \cdots, b_{20})_n$, and $(c_1, \cdots, c_{20})_n$ are coefficients that compose the RPC model of images.

$$
\begin{aligned}
F_1 &= \frac{[1, v, u, w, \cdots, w^3]_1 \times [a_1, a_2, a_3, \cdots, a_{20}]^T{}_1}{[1, v, u, w, \cdots, w^3]_1 \times [c_1, c_2, c_3, \cdots, c_{20}]^T{}_1} = r_1 \\
G_1 &= \frac{[1, v, u, w, \cdots, w^3]_1 \times [b_1, b_2, b_3, \cdots, b_{20}]^T{}_1}{[1, v, u, w, \cdots, w^3]_1 \times [c_1, c_2, c_3, \cdots, c_{20}]^T{}_1} = c_1 \\
&\vdots \\
F_n &= \frac{[1, v, u, w, \cdots, w^3]_n \times [a_1, a_2, a_3, \cdots, a_{20}]^T{}_n}{[1, v, u, w, \cdots, w^3]_n \times [c_1, c_2, c_3, \cdots, c_{20}]^T{}_n} = r_n \\
G_n &= \frac{[1, v, u, w, \cdots, w^3]_n \times [b_1, b_2, b_3, \cdots, b_{20}]^T{}_n}{[1, v, u, w, \cdots, w^3]_n \times [c_1, c_2, c_3, \cdots, c_{20}]^T{}_n} = c_n
\end{aligned}
\qquad (3)
$$

To solve above equations, the function needs to be made linear. The linear equation can be obtained by partial derivatives of the Taylor series as follows.:

$$
\begin{bmatrix}
\frac{\partial F_1}{\partial f} & \frac{\partial F_1}{\partial l} & \frac{\partial F_1}{\partial h} \\
\frac{\partial G_1}{\partial f} & \frac{\partial G_1}{\partial l} & \frac{\partial G_1}{\partial h} \\
\frac{\partial F_2}{\partial f} & \frac{\partial F_2}{\partial l} & \frac{\partial F_2}{\partial h} \\
\frac{\partial G_2}{\partial f} & \frac{\partial G_2}{\partial l} & \frac{\partial G_2}{\partial h} \\
 & \cdots & \\
\frac{\partial F_n}{\partial f} & \frac{\partial F_n}{\partial l} & \frac{\partial F_n}{\partial h} \\
\frac{\partial G_n}{\partial f} & \frac{\partial G_n}{\partial l} & \frac{\partial G_n}{\partial h}
\end{bmatrix}
\times
\begin{bmatrix} df \\ dl \\ dh \end{bmatrix}
=
\begin{bmatrix} r_1 - (F_1)_0 \\ c_1 - (G_1)_0 \\ r_2 - (F_2)_0 \\ c_2 - (G_2)_0 \\ \cdots \\ r_n - (F_n)_0 \\ c_n - (G_n)_0 \end{bmatrix}
+
\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ \cdots \\ v_{2n-1} \\ v_{2n} \end{bmatrix}
\qquad (4)
$$

$$A_{2n\times3} \times X_{3\times1} = L_{2n\times1} + V_{2n\times1} \qquad (5)$$

The following equation can be obtained by using the least square adjustment theory.:

$$X = (A^T A)^{-1} A^T L \qquad (6)$$

As a result, the three dimensional coordinates, (f, l, h), can be solved from the RPC model.

2.2 Renovating RPC model with GCPs and Pseudo_GCPs

A RPC model is determined with information from the orbit and camera model of the IKONOS-2 satellite. In addition, the accuracy of the 3D ground coordinates is limited if the images and original RPC models are only used for the extraction. Therefore, when more accurate 3D ground coordinates are required, the RPC models can be renovated using the GCPs.

To renovate the RPC models, a linear equation is required, and it has RPC coefficients as unknown quantities that are partially differentiated. The following equations represent these processes.

$$
\begin{aligned}
&F_{1_0} + \left(\frac{\partial F_1}{\partial a_{1_1}}\right)_0 d\,a_{1_1} + \cdots + \left(\frac{\partial F_1}{\partial a_{20_1}}\right)_0 d\,a_{20_1} \\
&\quad + \left(\frac{\partial F_1}{\partial b_{1_1}}\right)_0 d\,b_{1_1} + \cdots + \left(\frac{\partial F_1}{\partial b_{20_1}}\right)_0 d\,b_{20_1} = r_1 \\
&\qquad \vdots \\
&G_{n_0} + \left(\frac{\partial G_n}{\partial c_{1_n}}\right)_0 d\,c_{1_n} + \cdots + \left(\frac{\partial G_n}{\partial c_{20_n}}\right)_0 d\,c_{20_n} \\
&\quad + \left(\frac{\partial G_n}{\partial d_{1_n}}\right)_0 d\,d_{1_n} + \cdots + \left(\frac{\partial G_n}{\partial d_{20_n}}\right)_0 d\,d_{20_n} = c_n
\end{aligned}
\qquad (7)
$$

After Taylor' s theory is applied to the RPC models of n images, an observation matrix is constituted as follows:. When a certain GCP appears at each j images, the observation equation for the 3rd polynomial RPC model can be formulated as follows.:

$$
\begin{bmatrix}
a_1^{\,1} & 0 \cdots 0 & \cdots & 0 \cdots 0 & 0 \cdots 0 \\
0 \cdots 0 & a_2^{\,1} & \cdots & 0 \cdots 0 & 0 \cdots 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
0 \cdots 0 & 0 \cdots 0 & \cdots & a_{2j-1}^{\,i} & 0 \cdots 0 \\
0 \cdots 0 & 0 \cdots 0 & \cdots & 0 \cdots 0 & a_{2j}^{\,i}
\end{bmatrix}
\times
\begin{bmatrix} dx_{1,1} \\ dx_{2,1} \\ dx_{3,1} \\ dx_{4,1} \\ \vdots \\ dx_{40i,1} \end{bmatrix}
=
\begin{bmatrix} (r - F_0)_1^{\,1} \\ (c - G_0)_2^{\,1} \\ \vdots \\ (c - G_0)_{2j}^{\,i} \end{bmatrix}
+
\begin{bmatrix} v_1^{\,1} \\ v_2^{\,1} \\ \vdots \\ v_{2j}^{\,i} \end{bmatrix}
\qquad (8)
$$

$$A_{(2ij\times40i)} \times X_{(40i\times1)} = L_{(2ij\times1)} + V_{(2ij\times1)} \qquad (9)$$

where i = number of GCPs

j = number of overlapping images

dx = amount of adjustment

$$\alpha_{2j-1}{}^{i} = [\frac{\partial F_j^i}{\partial a_{1_j}} \frac{\partial F_j^i}{\partial a_{2_j}} \frac{\partial F_j^i}{\partial a_{3_j}} \cdots, \Big| \frac{\partial F_j^i}{\partial a_{20_j}} \frac{\partial F_j^i}{\partial b_{1_j}} \frac{\partial F_j^i}{\partial b_{2_j}} \frac{\partial F_j^i}{\partial b_{3_j}} \cdots, \frac{\partial F_j^i}{\partial b_{20_j}}]$$

$$\alpha_{2j}{}^{i} = [\frac{\partial F_j^i}{\partial c_{1_j}} \frac{\partial F_j^i}{\partial c_{2_j}} \frac{\partial F_j^i}{\partial c_{3_j}} \cdots, \Big| \frac{\partial F_j^i}{\partial c_{20_j}} \frac{\partial F_j^i}{\partial d_{1_j}} \frac{\partial F_j^i}{\partial d_{2_j}} \frac{\partial F_j^i}{\partial d_{3_j}} \cdots, \frac{\partial F_j^i}{\partial d_{20_j}}]$$

3. EXPERIMENTS

3.1 Specification of image

The southern part of Seoul city was selected as a test area because of the thick cloud that existed in other areas of the original image. Table 1. shows the resources of the IKONOS 2 satellite image data. In addition, Figure 1 shows the left and right image extracted from the original images for this research.

	Left Image	Right Image
Producer	Space Imaging inc.	Space Imaging inc
Sensor	IKONOS-2	IKONOS-2
Acquisition Date	2000-07-02 02:02	2000-07-02 02:03
Project Name	Seoul Level 2 Pan/MSI (4 bands) stereo 11 bits TIFF	Seoul Level 2 Pan/MSI (4 bands) stereo 11 bits TIFF
Band used	Panchromatic	Panchromatic
Stereo Position	Left	Right
Resolution	1m	1m
Datum	WGS84	WGS84
Image Size	13252*10264	13252*10264

Table 1. Specification of Images

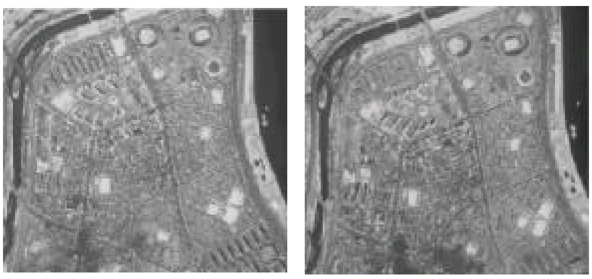

Figure 1. Left and Right image

3.2 Estimation of renovated RPC model.

The algorithm to renovate the RPC model is described above. However, in practical cases, there is something that needs to be considered in renovating RPC models with the previous algorithm.
The RPC model of the IKONOS-2 satellite image in this research has 59 coefficients for one image. Therefore, there are a total of 118 coefficients for the stereo-pair image, which has a left and right image. Table 2. shows the necessary number of GCPs used to renovate the RPC models.

Order of polynomial	Number of coefficients	Number of GCPs to be used
1st order	22	6
2nd order	58	15
3rd order	118	30

Table 2. Necessary umber of GCPs

The values for the coefficients of the RPC model range from 1.0×10^{00} to 1.0×10^{-04} for the 1st order, from 1.0×10^{-02} to 1.0×10^{-06} for the 2nd order, and from 1.0×10^{-04} to 1.0×10^{-09} for 3rd order polynomial RPC model. Therefore, when RPC model coefficients with the offset and scale factor are utilized, the accuracy of the 3D ground coordinates is nearly dependent on the 1st order polynomial coefficients of the RPC model rather than the 2nd or 3rd order polynomial coefficients. Because of these properties of the RPC model, only the 1st order polynomial RPC model coefficients are used to renovate a RPC model with the GCPs.
There are 4 observation equations for one GCP, because a RPC model of two images has 2 equations for each the row and column.
This means that in order to renovate the 1st order polynomial RPC models, which have 22 coefficients, more than 6 GCPs are needed. However, if only 6 GCPs are used, these GCPs cannot explain the properties of the entire image. In addition, there is a weakness in that the accuracy of the renovated RPC models is sensitive to the accuracy of the GCPs. However, in actual cases, it is almost impossible to obtain GCPs that are evenly distributed over an image to explain the properties of the entire image.
In this research, pseudo_GCPs, which were calculated from the original RPC models, were used to supplement the insufficient GCPs to renovate the RPC model. Moreover, the pseudo_GCPs could solve not only the problem where the number of GCPs is insufficient, but can also solve the problem where the GCPs are not distributed over an entire image evenly.
Thirty pseudo_GCPs, which are evenly distributed on the image, were selected. Figure 2. shows the distribution of the pseudo_GCPs.

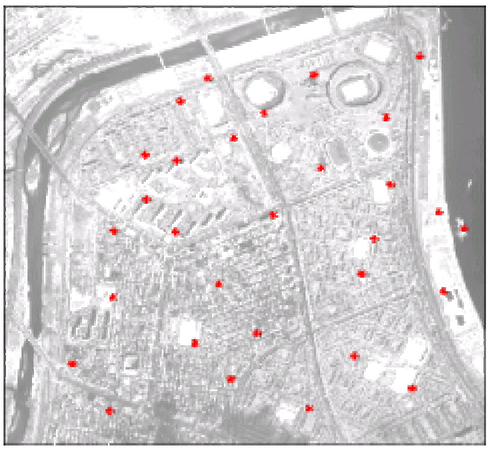

Figure 2. Distribution of psuedo GCPs

In this study, in order to evaluate the validity of the algorithm, 12 check points obtained from the GPS survey and triangulation were used. Table 3. shows the coordinates of the check points.

Number	ϕ	λ	h (m)
1	37° 31′03.96723″	127°05′10.77296″	36.804
2	37°31′05.02695″	127°05′10.63802″	37.683
3	37°31′05.16130″	127°05′12.80288″	35.975
4	37°31′04.10909″	127°05′12.92584″	37.360
5	37°31′03.26052″	127°05′07.53028″	34.381
6	37°31′04.31666″	127°05′07.41002″	34.841
7	37°30′54.90677″	127°05′23.16001″	51.565
8	37°30′53.93981″	127°05′18.82358″	54.416
9	37°30′50.09336″	127°05′16.57182″	49.977
10	37°30′51.95914″	127°05′18.34125″	50.010
11	37°30′51.91517″	127°05′19.34490″	52.036
12	37°30′26.02947″	127°05′01.80163″	56.123

Table 3. The coordinates of check points

The result showed that the more GCPs used for the algorithm the more the RMSE and mean value of the errors in the longitude, latitude and height were reduced.

However, a statistical verification of the renovating algorithm is necessary to show the validity. The t-test was used to verify the validity of the algorithm, and for this purpose, the error distribution of the extracted 3D ground coordinates was examined according to the number of GCPs. Result of the t-test shows that algorithm is meaningless for a change in the longitude and latitude error, but if more than 3 GCPs are used, the vertical accuracy of the extracted points from this algorithm is improved with a confidence level > 95%.

Therefore, it can be concluded that the error in the height is adjusted with a previous algorithm. Moreover, in the case of using renovating RPC models with 4 GCPs, the RMSE and mean error of the height are reduced to 0.66197m and 1.45489m.

Figure 3. and 4 show the variation in the RMSE and the mean value of the height according to the number of GCPs to be used.

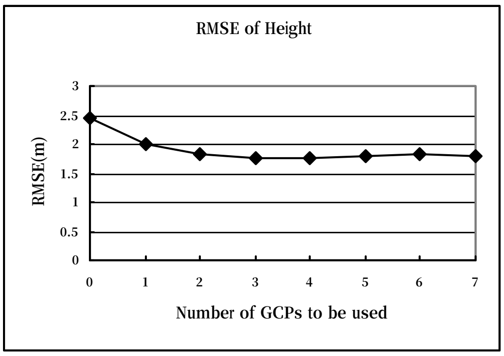

Figure 3. Variation of RMSE

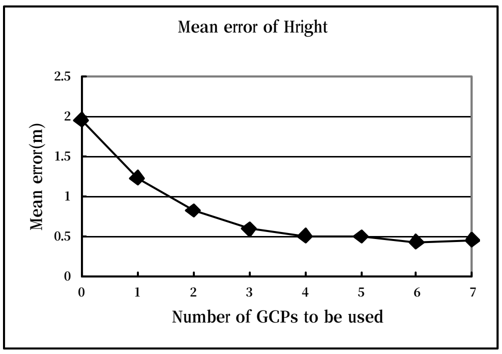

Figure 4. Variation of mean error

4. CONCLUSIONS

The 3D ground coordinates extracted from stereo pairs of an IKONOS-2 satellite image and original RPC models each had a RMSE in the longitude, latitude, and height of 0.17144sec, 0.13514sec, 2.97914m, respectively, and mean errors of 0.05029sec, 0.03554sec, 1.25971m, respectively.

This algorithm was used to renovate RPC models with GCPs and pseudo_GCPs. When the satellite image is rectified with the GCPs, a sufficient number of evenly distributed GCPs are necessary in order to represent the properties of an entire image. However, it is impossible to obtain a sufficient number of GCPs tothat can completely explain the properties of an entire image. Therefore, both GCPs and pseudo_GCPs were used to overcome these problems, and an algorithm was developed that can renovate the RPC models of the IKONOS-2 satellite image.

The accuracy of the 3D ground coordinates extracted from the renovated RPC models and stereo pair of the IKONOS-2 satellite image was estimated. In the case where 4 GCPs were used to renovate the RPC models, the RMSE and the mean error in the height was reduced by 0.662m and 1.455m compared to the case using the original models. As a result, the vertical accuracy of the 3D ground coordinates extracted through this algorithm was improved.

The 3D ground coordinates were extracted from the renovated RPC models using various numbers of GCPs with reasonable accuracy. When 4 GCPs and 7 GCPs were used to renovate the RPC models, the difference in the adjusted amount between them was only 0.03368m and 0.05882m for the RMSE and mean error, respectively. This means that more than a certain number of GCPs does not further improve the accuracy of the 3D ground coordinates.

Reference

Paul R. Wolf & Bon A. Dewitt, 2000. *ELEMENTS OF PHOTOGRAMMETRY With Applications in GIS 3rd edition.* McGraw-Hill Companies, Inc.

Paul R. Wolf & Charles D. Ghilani, 1997. *ADJUSTMENT COMPUTATIONS: Statistics and Least Squares in Surveying and GIS.* John Wiley & Sons, Inc.

Frank Gerlach, 2000. Characteristics of Space Imaging's One-Meter Resolution Satellite Imagery Products. *IAPRS*, Vol. ⅩⅩⅩⅢ, Part B1, pp.128-140

C. Vincent TAO & Yong HU & J. Bryan MERCER & Steve SCHNICK & Yun ZHANG, 2000. Image Rectification Using A Generic Sensor Model-Rational Function Model. *IAPRS*, Vol. ⅩⅩⅩⅢ, Part B3, pp. 874-881

Guo-Jin Wang & Thomas W. Sederberg & Falai Chen, 1997. On the Convergence of Polynomial Approximation of Rational Functions. *JOURNAL of APPROXIMATION THEORY* 89, pp. 267-288

Kaichang Di & Ruijin Ma & Ron Li, 2001. Deriving 3-D Shorelines from High Resolution IKONOS Satellite Images with Rational Functions. *ASPRS Annual Conference*

Joseph H. Silverman, 1996. Rational Function with a Polynomial Iterate. *JOURNAL of ALGEBRA*, 180, pp.102-110

Ian Dowman & John T. Dolloff, 2000. An Evaluation of Rational Functions for Photohrammetric Restitution. *IAPRS* Vol. ⅩⅩⅩⅢ, Part B3, pp.254-266