

Urban Image True Orthorectification in The National Map Program

Guoqing Zhou and W. Chen

Department of Civil Engineering and Technology, Old Dominion University,
Tel: (757)683-3619; Fax: (757)683-5655; E-mail: zhou@odu.edu

ABSTRACT

The large-scale urban orthoimage generation is being deployed in all level government agencies and private sectors. However, the early procedures and algorithms for digital orthoimage generation in the National Digital Orthophoto Program (NDOP) were based on earlier USGS mapping operations, which have not considered the urban case so that the *Standard for Digital Orthophoto* formulated by USGS has not considered the requirements of large-scale city orthophoto generation. To provide advanced technical basis (algorithms and procedures) and experience needed for national large-scale digital orthophoto generation and the revision of the *Standards for National Large-scale City Digital Orthophoto* in National Digital Orthophoto Program (NDOP), this paper presents a comprehensive study on theories, algorithms, and methods of large-scale urban orthoimage generation. These techniques include DTM-based orthoimage generation, DBM-based orthoimage generation, and their merge for true orthoimage generation, the problems of orthoimage generated using traditional method, building occlusions and compensation, the data structure to model urban buildings for accurately generating urban orthoimage, shadow detection and removal, the optimization of seamline for automatic mosaic, and radiometric balance of neighbor images, street visibility analysis.

KEYWORDS: Orthorectification, urban, DEM, DBM, orthophoto, National Mapping

1. INTRODUCTION

1.1 National Digital Orthophoto Program

Digital orthophotos are a critical component of the National Spatial Data Infrastructure (NSDI) and the National Map (Federal Geographic Data Committee, 1997; Maitra, 1998). The USGS began to produce digital orthophoto quadrangle (DOQ) in 1991 and currently has nearly 50,000 available for distribution. In 2001 the USGS deployed *The National Map*, a digital version of its topographic mapping program, including large-scale digital orthophotos. *The National Map* is the product of a consortium of Federal, State, and local partners who provide geospatial data to enhance America's ability to access, integrate, and apply geospatial data at national and local scales (Zhou *et al.*, 2005). The information layers planned for distribution include structures in urban areas and are listed in the website of <http://nationalmap.usgs.gov>.

The National Digital Orthophoto Program (NDOP) was first proposed in 1990. The primary goal of this program is to ensure the public domain availability of data for the Nation (USGS, Digital Orthophoto Program, 1998). The NDOP was based on quarter-quadrangle-centered aerial photographs (3.75 minutes of longitude and latitude in geographic extent) obtained at a nominal flying height of 20,000 feet above mean terrain with a 6-inch focal-length camera (photo scale = 1:40,000). Additionally, the early procedures and algorithms for digital orthophoto generation were based on earlier USGS mapping operations, such as field control, aerotriangulation (using photogrammetric equations derived in the early 1920's), and 2.5 D digital elevation models.

The procedures and algorithms used in the 1990s are not appropriate for large-scale city orthorectification, because when generating large-scale urban orthophotos using the existing algorithms and methods, many problems, such as incomplete orthorectification, occlusion, ghost image, shadow, etc., have been disclosed. (Zhou *et al.* 2003). The impacts of these problems have significantly influenced the

usefulness of the digital orthophoto in industry because the error of these incompletely rectified large-scale city orthoimage maps no longer can be tolerated when used for updating and planning urban tasks. This is because the early standard has not considered the urban case so that the *Standard for Digital Orthophoto* formulated by USGS has not considered the requirements of large-scale city orthophoto generation. Thus, in order to provide the needed advances of technology of orthorectification in urban area, this paper presents our comprehensive study and in-depth understanding on urban orthophoto generation, including algorithms and data processing procedures via a joint effort between a university and government agency (USGS) at national, state and local-scale as well as private sections for the future national large-scale city orthophoto generation deployment.

1.2 Problems of Classical Orthorectification in Urban Area

With the investigation of urban orthorectification, we produced the orthoimage for the date set described in Section 4 using the classical orthorectification method. From the experiment, the following problems have been discovered for urban images.

Ghost images: The roofs of buildings are superimposed onto the bottom of the buildings and the roofs of buildings appear twice. This phenomenon is called "ghost image" (Rau *et al.* 2002). The reason causing ghost images is due to the fact that when we orthorectify the relief displacement caused by buildings, the roofs of buildings are orthorectified in their upright positions; when we orthorectify the relief displacement caused by occluded objects, the occluding objects are again employed to fill the occluded objects. This kind of processing process leads to the occluding pixels to be doubly employed. Obviously, the classical method of orthorectification will not be able to be used for urban large-scale orthoimage generation.

Occlusion and Building Lean: The orthorectification of the image in urban area shows that the image features are distorted from their true locations. This distortion appears as a tall building leans over a street and occludes features like street, manholes, fire hydrants, and utility poles. Thus, the classical rectification model is not able to identify occlusions and compensates for the occlusions. Based on this point, the standards of national orthophoto program will have to be revised for processing this problem.

Shadow of the buildings: The orthorectified image in urban areas demonstrates that the shadow cannot be removed using the classical rectification model, thus deteriorates the quality of orthoimage. In the revised standards of orthophoto, we need consider the methods, metadata for shadow detection and restore, and radiometric grey standards of removing shadow.

Inaccuracy of DSM: The classical rectification method is based on digital surface model (DSM), which is used to represent and model the buildings. It has been found from our experiments that (1) small objects on top of the building were not completely orthorectified due to the lack of model; (2) the wall of the buildings is incompletely orthorectified due to inaccuracy of the DSM; (3) the boundary of buildings is inaccurately orthorectified due to the inaccuracy of the DSM. It has been demonstrated that the traditional DSM-based orthorectification need to be improved to obtain high-quality orthoimage.

Incomplete Refilling to Occlusion: Traditionally, photogrammetric flying mission used to require an approximately 65% endlap along strip and 35% sidelap cross strip. This specification has had challenges in urban photogrammetry because it is not possible to find sufficient slave orthoimages to completely refill the occluded areas in the master orthoimage. Therefore how we design flight mission, such as endlap, sidelap, flying height, choose a camera with different focal length and IFOV, and the direction of flight need to be investigated in national orthophoto program.

Different Accuracy of Two Orthoimages: It has been found that the geometric accuracy of the two neighbor orthoimages generated using the same method, the same DSM, the same GCPs, and the same iterative number, are different. This phenomenon is probably caused by the incomplete correction of lens distortion because magnitude of the lens distortion is the function of object locations in an image plane. Therefore, the revised standard will consider how to find exact lens distortion model to correct their distortions.

Radiometric Difference of Two Orthoimages: Although the radiometric difference of two adjacent orthoimages also exist s using classical method, the problem in urban area is significant due to occlusion and shadow. The revised standard will need consider how to correct this difference and what is their standard

Overall, the existence of these problems indicates that the conventional orthorectification method is not able to orthorectify the objects into their correct and upright positions for a large-scale urban aerial image. Significant efforts are still needed to improve the methodology for generation of true orthoimages for large-scale aerial images.



(a)



(b)

(c)

Fig.1. (a) Standards, (b) is general and (c) is specifications.

2. METHODS OF ORTHOIMAGE GENERATION

Because the problems mentioned above, the classical method will be impossible to generate a high-quality orthoimage in urban area, thus, the standards of national orthophoto program need to be revised. In the recent several years, a few investigators conducted so-called the generation of true orthoimages for urban images, for example, Skarlatos (1999), Joshua (2001), Amhar *et al.* (1998), Schickler and Thorpe (1998), Mayr (2002), Rau *et al.* (2002), Jauregui *et al.* (2002), Vassilopoulou *et al.* (2002), Siachalou (2004), Passini and Jacobsen (2004), Biason *et al.* (2004).

2.1 Basic Steps of True Orthoimage Generation

In order to orthorectify a building to its correct, upright position, the buildings must be represented as part of the surface to be rectified. Although the DSM can represent the building surface (roof), the orthoimage generated using the DSM cannot achieve satisfactory accuracy (Zhou *et al.* 2003). In addition, in order to compensate for the occluded areas, occlusion detection must be conducted through visible analysis. One of such methods is to trace the imaging rays from the top of the surface back to the projection center of the photograph. Only those objects whose rays do not intersect any other object before arriving at the projection center are not occluded, as a result, leading to a correctly rectified image pixel (Amhar *et al.* 1998).

This method requires an exact digital building model (DBM), which describes the building structure, 3D coordinates, topologic relationship, etc. On the other hand, the relief displacement caused by terrain should be corrected in true orthoimage. For this reason, an exact representation of terrain should be given, i.e., digital terrain

mode (DTM), which does not contain buildings. Therefore, the basic steps of true orthoimage generation contain DTM-based orthoimage generation and DBM-based orthoimage generation as well as the merge of the DTM- and the DBM-based orthoimages (see Figure 2).

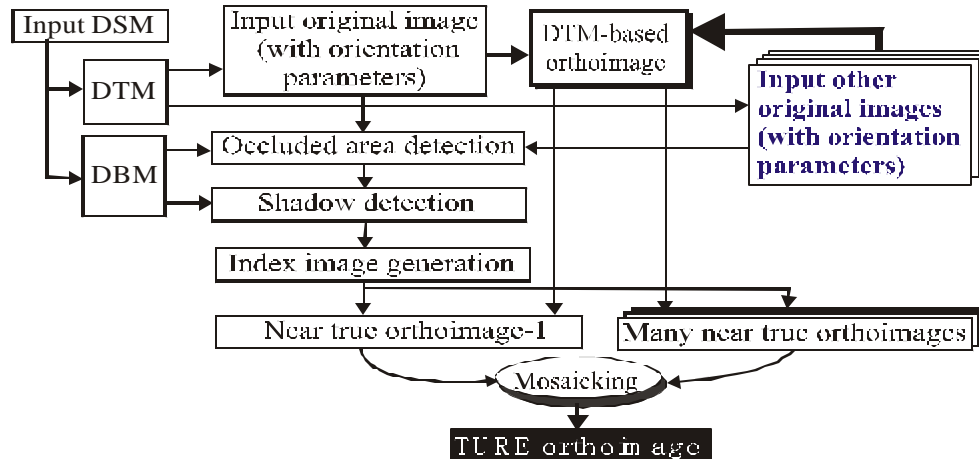


Figure 2. The procedure of true orthoimage generation

2.2 DBM-based orthoimage generation

The process of DBM-based orthoimage generation only orthorectify the displacement caused by buildings without considering displacement caused by terrain. To this end, the occluded buildings need to be detected. At present, an effective and commonly used method for occlusion detection is to apply the DBM to calculate the distance between object surfaces to project center. This distance is called *Z distance*, and the method is called *Z-buffer* algorithm (Amhar *et al.* 1998). In this step, the displacements caused by visible buildings are orthorectified into their upright planimetric position. Additionally, the occluded buildings cannot be orthorectified, consequently holes are left in the orthoimage in this step. We can mark these occluded areas by simply back-projecting the individual DBM into the individual images and marking occluded areas as black. This means that areas occluded by objects need to be filled using other orthoimages, called *slave orthoimage* (Rau *et al.* 2002, Amhar *et al.* 1998). The above generated orthoimage only contains buildings, is thus called *DBM-based orthoimage*.

2.3 DTM-based orthoimage generation

DTM-based orthoimage generation for correcting the relief displacement caused by terrain was traditionally implemented by bottom-up methods. The basic mathematical model of this algorithm is collinearity equation, which requires a DTM and the interior and exterior orientation elements of an image. A detailed description can be found in Zhou and Jezek (2002), Chen *et al.* (1993), Hohle (1996), and Baltasvias *et al.* (2002).

2.4 Near True Orthoimage Generation

Based on the DBM-based and the DTM-based orthoimage obtained above, the orthoimage is created by merging the two types of orthoimages via a very simply operation, called *logical <OR> operation*, which is recommended by

Amhar *et al.* (1998). The resulting orthoimage generated in this step still contains black patches, which represent occluded objects. They therefore need to be filled by using additional orthoimages, called “*slave*” orthoimages. This intermediate orthoimage is therefore called *Near True Orthoimage (NTOI)*.

2.5 Occlusion Compensation

The occlusion compensation is implemented by refilling the occluded areas from neighbor slave orthoimages. This process is implemented by mosaicking. Based on this point, the occluded area must be visible in one, even several slave orthoimages in order to completely refill an occlusion. To reduce the radiometric discrepancy, it is better to use images acquired at the same flight mission due to their similarity in imaging conditions. In addition to necessity of a considerable overlap between aerial images, the following factors would be considered:

- 1) *Optimization of seam lines*: The boundary might fall on ground features not modeled in the DBM such as trees, cars or shadows, which probably have different brightness values in the individual NTOI images. Therefore, new method will have to be developed in the urban orthoimage generation.
- 2) *Optimization of orthoimage patches*: The qualities of orthorectification of the identical ground object in different NTOIs are different. An algorithm to automatically ‘pick up the best’ orthoimage patch from the “slave” NTOIs for compensation of occluded areas should be developed.

3. OTHER MAIN TECHNIQUES OF URBAN ORTHORECTIFICATION

3.1 3D urban model for orthorectification

As described above, DBM-based orthoimage generation requires an effective representation of urban buildings. The geospatial data to be operated for true orthoimage generation includes (1) digital terrain data, (2) images, and

(3) spatial objects. How to select an effective data structure, which is capable of precisely representing the ground surface for urban orthorectification? The generation of a 3D urban (building) model is a rather challenging task, from both a practical and a scientific points of view, because different applications (e.g., city planning, communication system design, control and decision making, tourism, pollution distribution, military security operation, visualization, etc.) require different data types and manipulation functions. Many models have been proposed, e.g., Breunig (1996), Graz (1999), Grün *et al.* (1998), Zhou *et al.* (2000), and Zlatanoca (2000). It has been demonstrated that the maintenance and administration of this huge amount of urban data to be well organized need an all-powerful 3D urban model which may be impossible to realize because realistic presentation of the real world and the description of surface properties and material parameters are quite difficult (Grün *et al.* 1998). For the purpose of true orthoimage generation, the data structure to be developed in this paper requires:

- To generate the DBM - based high - quality orthoimage,
- To easily create, store, design, analyze and query city objects for orthoimage-based urban applications.

To the end above, we need investigate the 3D urban model, which include

- *Data Structure*: an effective data structure to represent the urban geospatial data.
- *Topological Relationship*: The topological relationships between geometrical elements should be effectively defined by the data structure, and
- *Implementation*: The data structure defined should be able to be implemented by an effective technology, such as object-oriented data structure, relational database structure. In addition, other techniques, such as the query of a geometrical description for a type of object, etc.

3.2 City street Visibility Analysis

The traditionally flight planning usually requires an approximate 65% endlap for adjacent two photographs along flight strip, and 30% sidelap across flight strips. It has been demonstrated that, from an orthoimage generation point of view, these early specifications for urban photogrammetric mission have encountered challenges due to impacts of the occlusions, deep discontinuities, and shadows. So, we should investigate and analyze the relationship between occlusion and building height, street width, flying height, AFOV (angular field of view) of camera. For example, as illustrated in Figure 3, to ensure that the street is fully visible for occlusion compensation using the two contiguous images along a flight strip, We should have

$$W_1 \cos \theta_1 + W_2 \cos \theta_2 \leq W \quad (1)$$

where W_1 and W_2 are the projected length for Building 1 and Building 2 on the ground, and θ_1 and θ_2 are the angles between street line and the ground radial of Building 1 and Building 2 from ground nadir points, respectively.

3.3 Shadow Detection and Restoration

Shadow detection: Urban large-scale orthoimage generation requires detecting and removing shadow. Many

efforts for detection and restoration of the shadowed areas from aerial images have been made in the past years, e.g., Salvador *et al.* (2001), Peng *et al.* (2004), Liow *et al.* (1990), Noronha *et al.* (2001), Stauder *et al.* (1999), Irvin *et al.* (1989), Jiang *et al.* (1992), Jaynes *et al.* (2004), Salvador *et al.* (2004), Gonzalez *et al.* (2003), Tsai *et al.* (2003). Most of these efforts did not consider the self-shadow, and typically focused the attention on umbra, considering the penumbra as a particular case of umbra. Moreover, they only took advantages of the image gray information and 2D object geometric shapes when detecting the shadowed areas. How to makes full use of digital building model (DBM) data for building shadow detection will be investigated for urban orthorectification.

Shadow Restore : After shadow is detected, the following step will be restore the shadowed areas. We used histogram adjustment algorithm to change the mean and variance of the shadowed areas via matching the mean and variance of the image with no shadows. The mathematical model can be written as:

$$Y = \sigma_l / \sigma_s * (X - \mu_s) + \mu_l \quad (2)$$

where Y is the output of original pixel, X , in the shadowed areas after histogram adjustment, σ and μ are the standard deviation and mean; and the subscripts l and s stand for non-shadow and shadowed areas, respectively.

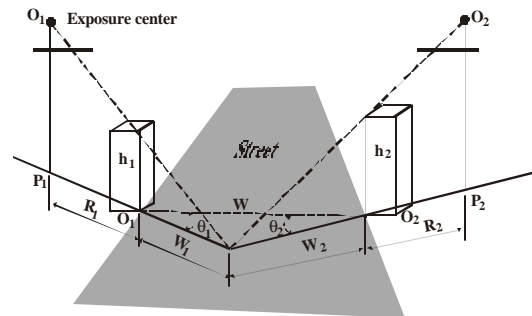


Fig. 3. The geometric configuration of street visibility analysis

4. EXPERIMENTS AND ANALYSIS

4.1 Data Set

The experimental field is located in downtown Denver, Colorado, where the highest buildings reach 125 m, and many buildings are around 100 m. The six original aerial images from two flight strips were acquired using an RC30 aerial camera at a focal length of 153.022 mm on April 17, 2000. The flying height was 1650 m above the mean ground elevation of the imaged area. The aerial photos were originally recorded in film and later scanned into digital format at a pixel resolution of 25 μ m. Figure 4 illustrates the configuration of the photogrammetric flight mission and the available digital surface model (DSM). Two of the six aerial images (DV1119 and DV1120) covered the downtown area. The endlap of the images is about 65%, and the sidelap is approximately 30%. A digital surface model (DSM) in the central part of the downtown, Denver is available (Figure 4). The accuracy of planimetric coordinate and vertical coordinate in the DSM are

approximately 0.1m and 0. 2m respectively. The horizontal

datum is GRS 1980, and the vertical datum is NAD83.

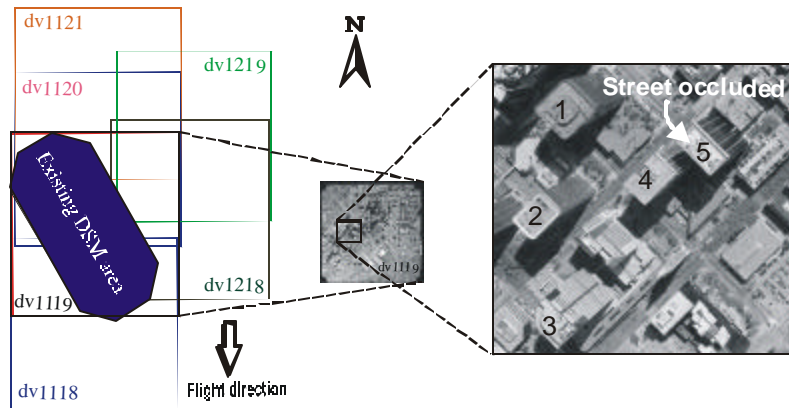


Figure 4. Six aerial images from two strips and digital surface model (DSM covering Downtown Denver, CO. The heights of the five numbered buildings are 100 m, 103 m, 125 m, 100 m, and 107 m, respectively.

4.2 True Orthoimage Generation

After the above procedures are implemented, a true orthoimage can be created. Figure 5b depicts the results of a true orthoimage that is generated using our method. For the comparison purpose, Figure 5a is an orthoimage generated by the conventional differential model. As seen in Figure 5a, the occlusions of buildings still exist in the resulting orthoimage as evidenced by the ‘doubling’ of the building roofs. The building occlusions in Figure 5b have been completely removed and refilled. The buildings are correctly orthorectified in their true planimetric positions, and the shadows of buildings have been removed.

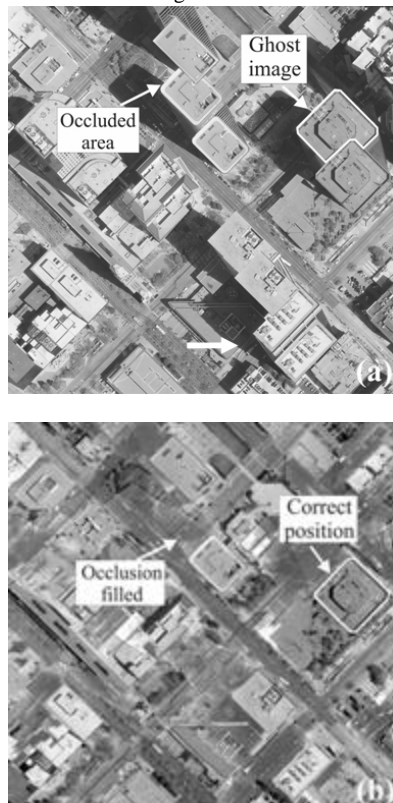


Figure 5. The comparison of orthorectified large-scale aerial images by (a) traditional method, and (b) our method

5. CONCLUSIONS

A methodology for the generation of true orthoimages from large-scale aerial images in urban areas has been investigated in this paper. The core technique of the methodology involves four key parts: (1) a DBM and a DTM that accurately models the urban buildings and terrain, (2) DTM-based and DBM-based orthoimages and their merging, (3) automatic detection of shadowed areas and occluded areas, restore and compensation of the lost information, (5) radiometric differences of scene-to-scene. All of the procedures and algorithms will be used for revision of the standards of national orthophoto program. The formulation of standards is leading by Old Dominion University via funds of national science foundation in collaboration with two USGS centers.

ACKNOWLEDGEMENT

The project was funded by the US National Science Foundation (NSF) under contract number of NSF 0131893. The authors sincerely thank Wolfgang Schickler for his kindly providing aerial images, building data, and DSM of Denver, CO. We also would like to thank the project administrators at the City and County of Denver for granting permission to use their data.

REFERENCES

- Amhar, F., J. Josef, and C. Ries (1998). The generation of true orthophotos using a 3D building model in conjunction with a conventional DTM, *International Archives of Photogrammetry and Remote Sensing*, vol. 32, Part 4, pp. 16-22.
- Breunig, M. (1996). *Integration of spatial information for geo-information systems*, Springer Corp. Berlin.
- Cameron, A.D, D. R. Miller, F. Ramsay, I. Nikolaou and G. C. Clarke (2000), Temporal measurement of the loss of native pinewood in Scotland through the analysis of orthorectified aerial photographs. *Journal of Environmental Management*, 58: 33-43.
- Chen, L.C. and J.Y. Rau (1993). A unified solution for digital terrain model and orthoimage generation from SPOT stereopairs, *IEEE Trans. on Geoscience and Remote Sensing*, vol. 31, no. 6, pp. 1243-1252.

- Federal Geographic Data Committee (1995). Development of a National Digital Geospatial Data Framework, April, 1995, <http://www.fgdc.gov/framework/framdev.html>.
- Federal Geographic Data Committee (1997). Fact sheet: National Digital Geospatial Data Framework: A Status Report, Federal Geographic Data Committee, July 1997, 37p. <http://www.fgdc.gov/framework/framdev.html>, July, 1997.
- Gonzalez, J. A., M. L. Docampo, I. C. Guerrero, (2004). Detection of buildings through automatic extraction of shadows in Ikonos imagery, in *Proceedings of The International Society for Optical Engineering: Image and Signal Processing for Remote Sensing IX*, Sep 9-12 2003, Barcelona, Spain, vol. 5238, 2004, pp. 36-43
- Graz, M. Gruber, (1999). Managing Large 3D Urban Databases, *Photogrammetric Week*, Stuttgart University, 1999 pp. 341-349.
- Gruen, A. and X. Wang (1998). CC-Modeler: a topology generator for 3-D city models, *ISPRS Journal of Photogrammetry & Remote Sensing*, vol. 53, pp. 286-295.
- Hohle, J. (1996). Experiences with the production of digital orthophotos, *Photogrammetric Engineering and Remote Sensing*, vol. 62, no. 10, pp. 11189-1194.
- Irvin, R.B. and D.M. McKeown Jr., (1989). Methods for exploiting the relationship between buildings and their shadows in aerial imagery, *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 19, pp. 1564-1575.
- Jauregui, M., J. Vilchez, and L. Chacón (2002). A procedure for map updating using digital monoplottting. *Computers & Geosciences*, 28(4): 513-523.
- Jaynes, C., S. Webb, R. Steele, (2004). Camera-Based Detection and Removal of Shadows from Interactive Multiprojector Displays, *IEEE Transactions on Visualization and Computer Graphics*, vol. 10, no. 3, May/June, pp. 290-301
- Jiang, C. and M.O. Ward, (1992) Shadow identification, in *Proceedings of IEEE Int'l Conference on Computer Vision and Pattern Recognition*, pp. 606-612.
- Joshua, G., 2001. Evaluating the accuracy of digital orthophotos quadrangles (DOQ) in the context of parcel-based GIS, *Photogrammetric Engineering & Remote Sensing*, vol. 67, no. 2, pp. 199-205.
- Liow, Yuh-Tay, Pavlidis Theo, (1990). Use of shadows for extracting buildings in aerial images, *Computer Vision, Graphics, and Image Processing*, vol. 49, no. 2, Feb, pp. 242-277
- Mayr, Werner (2002). True Orthoimages, *GIM International*, vol. 37, April, pp. 37-39.
- Noronha, S., Nevatia, R., (2001). Detection and modeling of buildings from multiple aerial images, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, v 23, n 5, May, pp. 501-518
- Passini, R. and K. Jacobsen, 2004. Accuracy Analysis of digital orthophotos from very height resolution imagery, *International archives of the photogrammetry, remote sensing and spatial information sciences*, edited by Orthan Altan, vol. XXXV, July 12-23, 2004, DVD
- Rau, J.Y., N.Y. Chen, and L.C. Chen (2002). True Orthophoto Generation of Built-Up Areas Using Multi-View Images, *Photogrammetric engineering and Remote Sensing*, vol. 68, no. 6, June, pp. 581-588.
- Schickler, W., and A. Thorpe (1998). Operational procedure for automatic true orthophoto generation, *International Archives of Photogrammetry and Remote Sensing*, vol. 32, Part 4, pp. 527-532.
- Seto, Y., K. Homma, F. Komura (1991). Geometric correction algorithms for satellite imagery using a bi-directional scanning sensor, *IEEE Geoscience and remote sensing*, vol. 29, no. 2, pp. 292-299.
- Siachalou, S. (2004). Urban orthoimage analysis generated from IKONOS data. *International archives of the photogrammetry, remote sensing and spatial information sciences*, edited by Orthan Altan, vol. XXXV, July 12-23, 2004, DVD
- Skarlatos, D. (1999). Orthophotograph production in urban areas, *Photogrammetric Record*, vol. 16, no. 94, pp. 643-650.
- Stauder, J., R. Mech, and J. Ostermann, (1999). Detection of moving cast shadows for object segmentation, *IEEE Transactions on Multimedia*, vol. 1, no. 1, pp. 65-76, Mar. 1999.
- Tsai, J.D. (2003). Automatic Shadow Detection and Radiometric Restoration on Digital Aerial Images, *International Geoscience and Remote Sensing Symposium (IGARSS): Learning From Earth's Shapes and Colours*, Toulouse, France, July 21-25, 2003, vol. 2, pp. 732-733.
- USGS (1998). Digital Orthophoto Program, <http://mapping.usgs.gov/www/ndop/index.html>, U.S. Department of the Interior, U.S. Geological Survey,
- USGS (1996). Digital Orthophoto Standards, *National Mapping Program-Technical Instructions*, Part I, General; Part II, Specifications. US Department of the Interior, U.S. Geological Survey, National Mapping Division. <http://rmmcweb.cr.usgs.gov/public/nmpstds/doqstds.html>, December 1996.
- Zhou, G., Z. Qin, S. Benjamin, and w. Schickler, 2003. Technical Problems of Deploying National Urban Large-scale True Orthoimage Generation, *the 2nd Digital Government Conference*, Boston, May 18-21, 2003, pp. 383-387
- Zhou, G., K. Jezek, W. Wright, J. Rand, and J. Granger (2002). Orthorectifying 1960's declassified intelligence satellite photography (DISP) of Greenland. *IEEE Geoscience and Remote Sensing*, vol. 40, no. 6, pp. 1247-1259.
- Zhou G., Ming Xie and J. Gong, 2000. Design and implementation of Attribute Database Management System for GIS (GeoStar), *Int. Journal of Geographic Information Science*, vol. 6, no. 2, pp. 170-180.
- Zlatanova, Siyka (2000). 3D GIS for Urban Development, ISBN: 90-6164-178-0, ITC Dissertation Number 69. Doktor der technischen Wissenschaften an der Technischen Universitate Graz.