Chapters 1 – 11: Overview

- Chapter 1: Introduction
- Chapters 2 – 4: Data acquisition
- Chapters 5 – 11: Data manipulation
  - Chapter 5: Vertical imagery
  - Chapter 6: Image coordinate measurements and refinements
  - Chapters 7 – 10: Mathematical model, bundle block adjustment, integrated sensor orientation, and direct geo-referencing
  - Chapter 11: Digital image matching
- This chapter will cover the generation of map-like images (orthophotos).

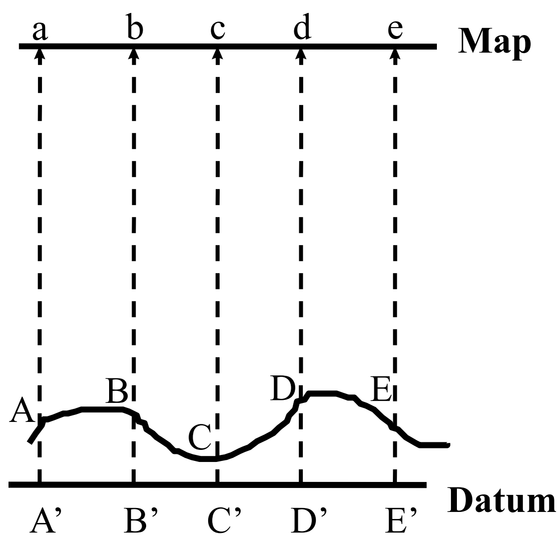
CE 59700: Chapter 12

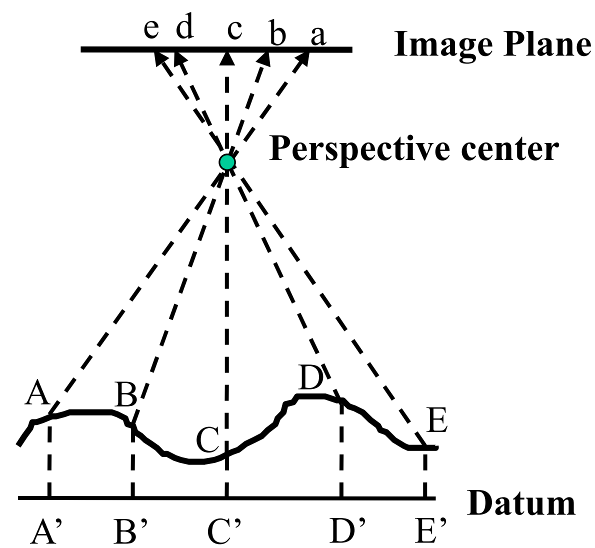
Digital Orthophoto Generation

Overview

- Orthophoto: Introduction
- Tools:
  - Image transformation
  - Image resampling
- orthophoto generation
  - Polynomial rectification
  - Differential rectification
  - Image resampling techniques
  - Stereo orthophotos

Maps & Images

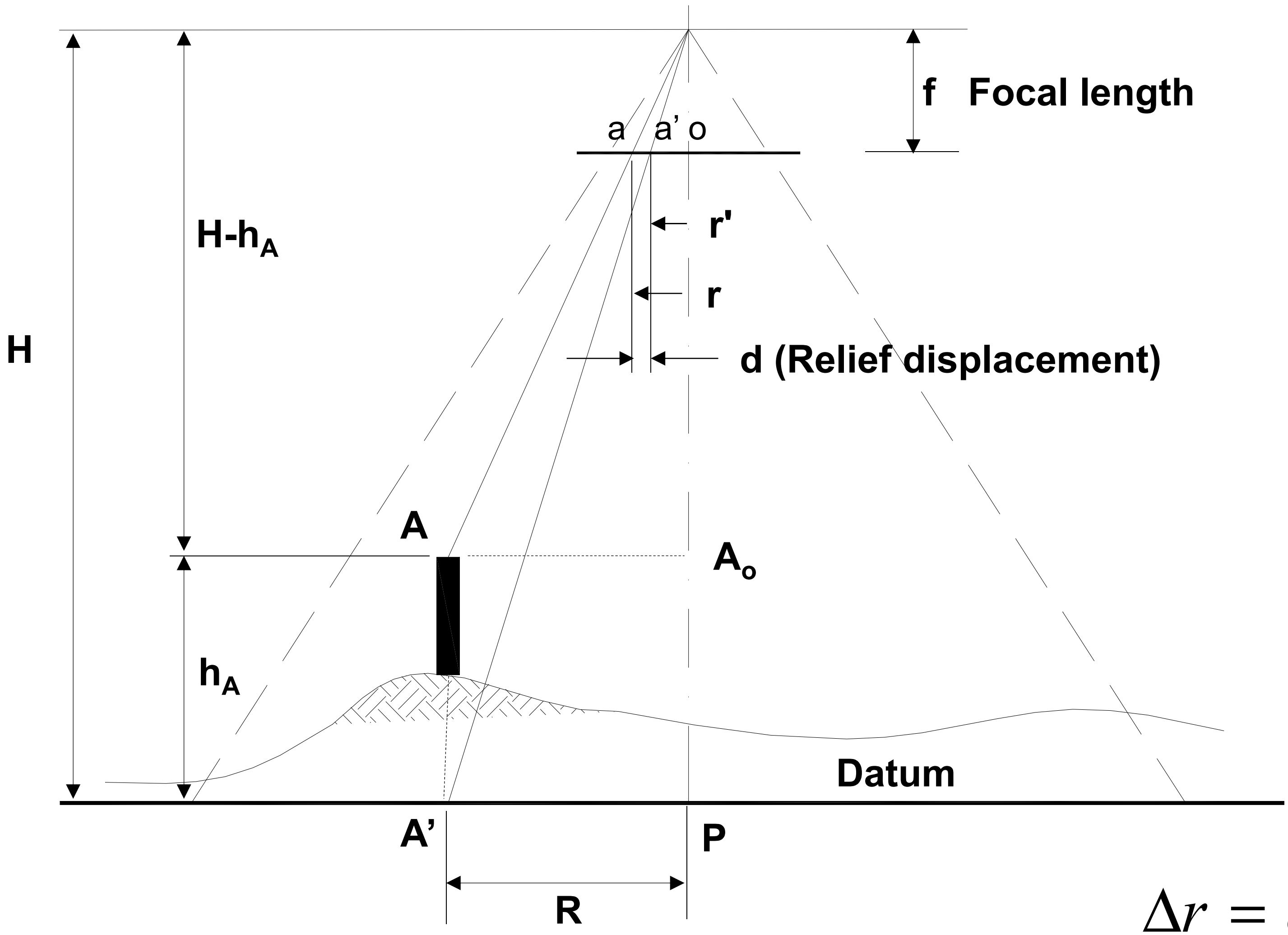




- Orthogonal projection
- Uniform scale
- No relief displacement

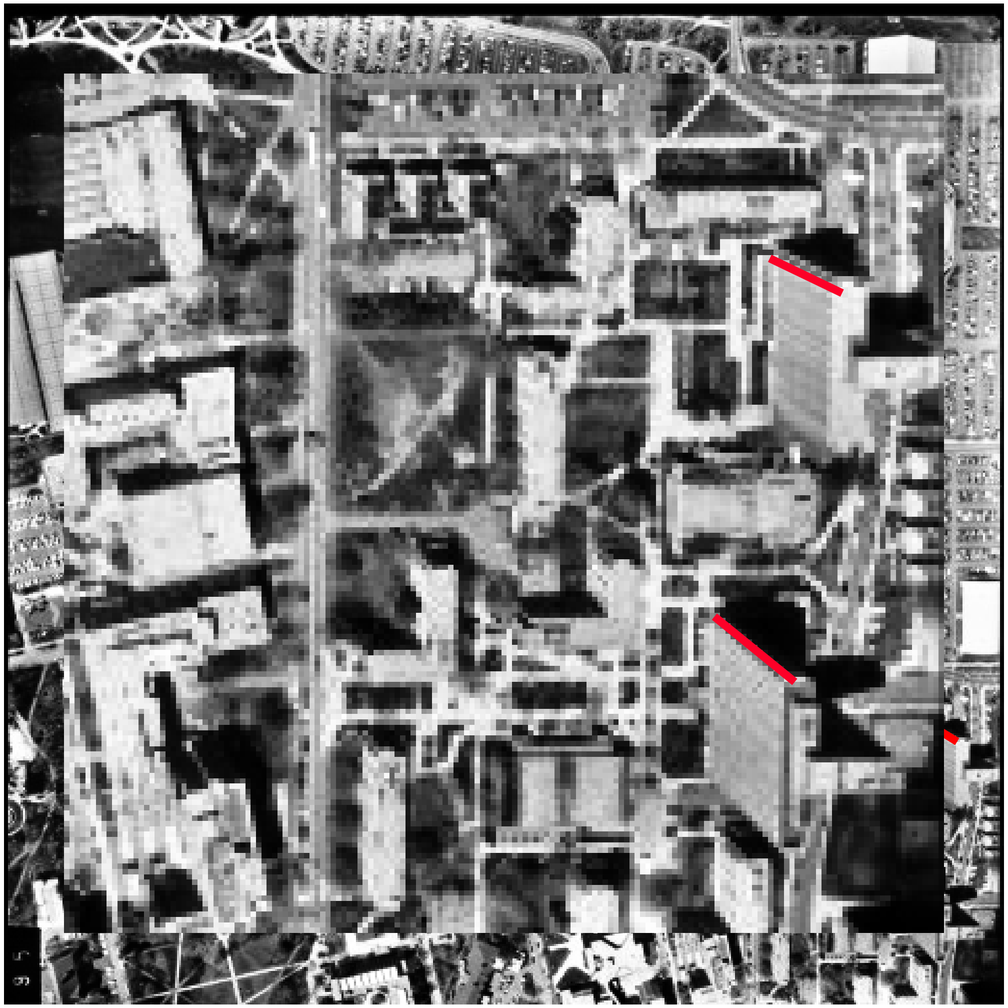
- Perspective projection
- Non-uniform scale
- Relief displacement

Relief Displacement



$$\Delta r = d = \frac{r\ h_a}{H}$$

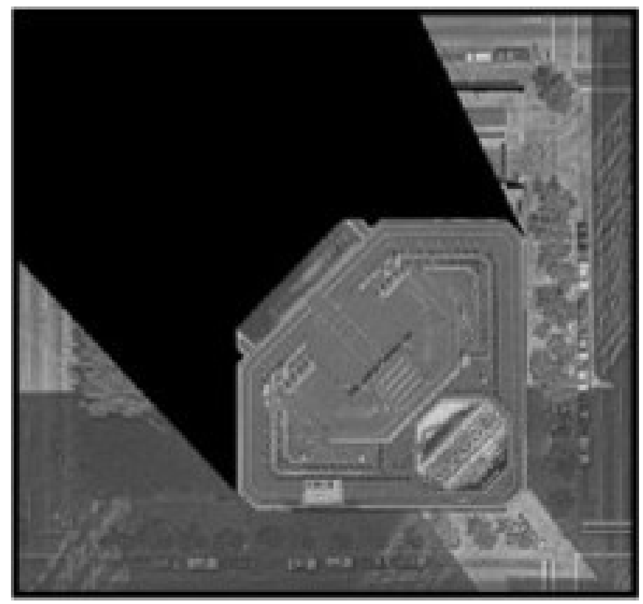
Relief Displacement



Orthophoto

- Orthophoto:
  - Relief displacement free image
  - Image which has the same characteristics of a map
    - Orthogonal (parallel) projection,
    - Uniform scale, and
    - No relief displacement

Perspective Image Versus Orthophoto



Orthophoto

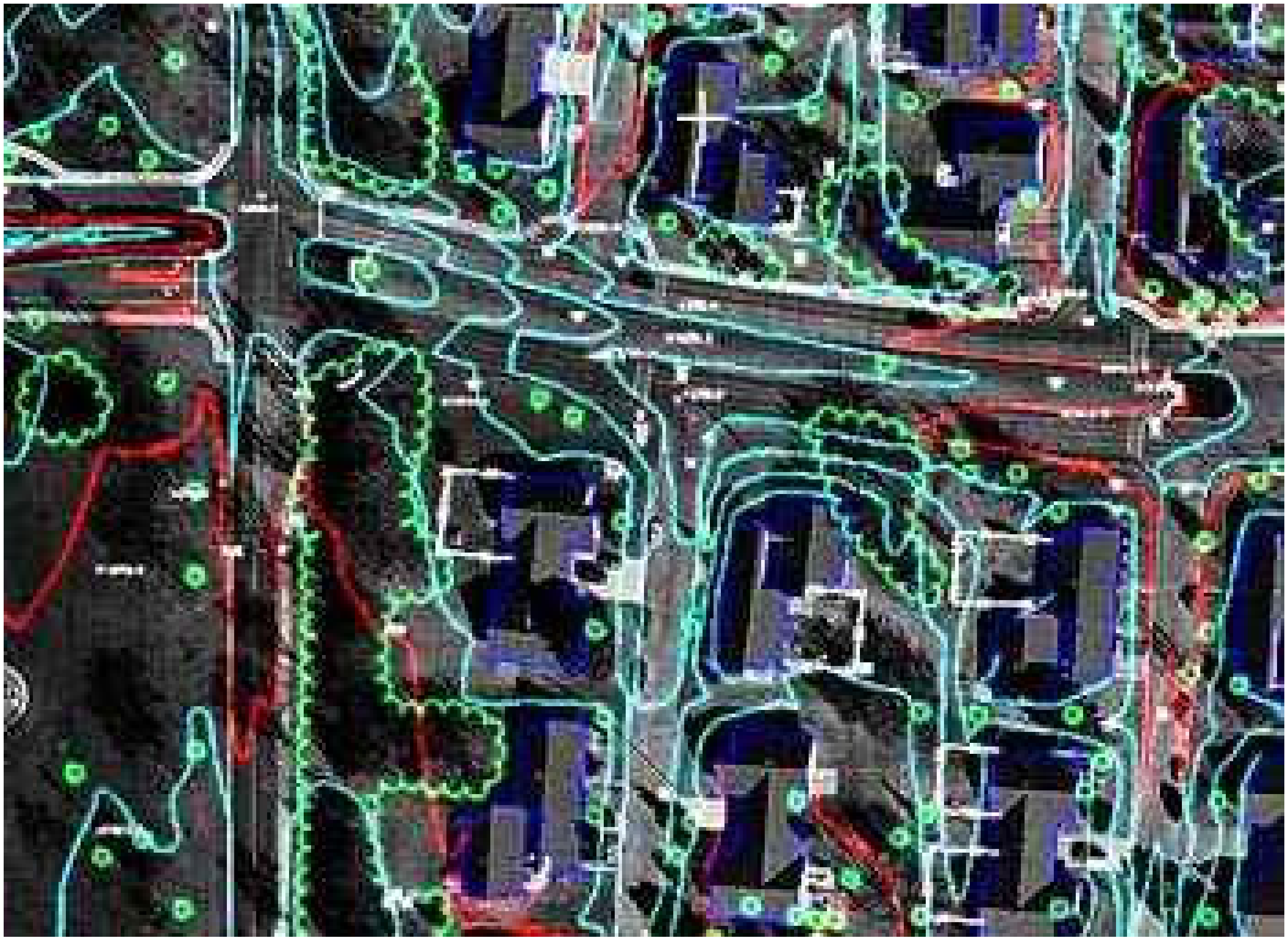
- Advantages:
  - They have the same characteristics of a map but with more features.
  - The user can draw lines and measure distances without the need for stereo-plotters.
  - Cheap alternatives for maps (for developing countries)
  - They can be generated automatically.
  - They constitute a very important layer for GIS databases.

Perspective Image Versus Orthophoto

- Perspective Image
- Orthophoto

Orthophoto Application: Example

Orthophoto Application: Example



Rectification of Digital Imagery

- Aerial imagery and satellite scenes do not show features in their correct locations due to displacements caused by the tilt of the sensor and terrain relief.
- Ortho-rectification transforms the central projection of the photograph into an orthogonal view of the ground, thereby removing the distorting effects of tilt and terrain relief.

Rectification of Digital Imagery

- Generation of an orthophoto from an aerial photograph requires the knowledge of:
  - The internal characteristics of the camera (IOP),
  - The location of the camera (X_o, Y_o, Z_o),
  - The camera orientation in space (ω, ϕ, κ), and
  - A digital elevation model (DEM).
- If the terrain is flat, then the orthophoto generation does not require the above information.
  - In such situations, orthophotos can be produced by a process called simple (perspective) rectification that only removes the effect of tilt using few control points.

Tilt Effect

Tilted Image

Rectified Image

Necessary Tools

- Direct versus indirect image to image transformation
- Resampling techniques

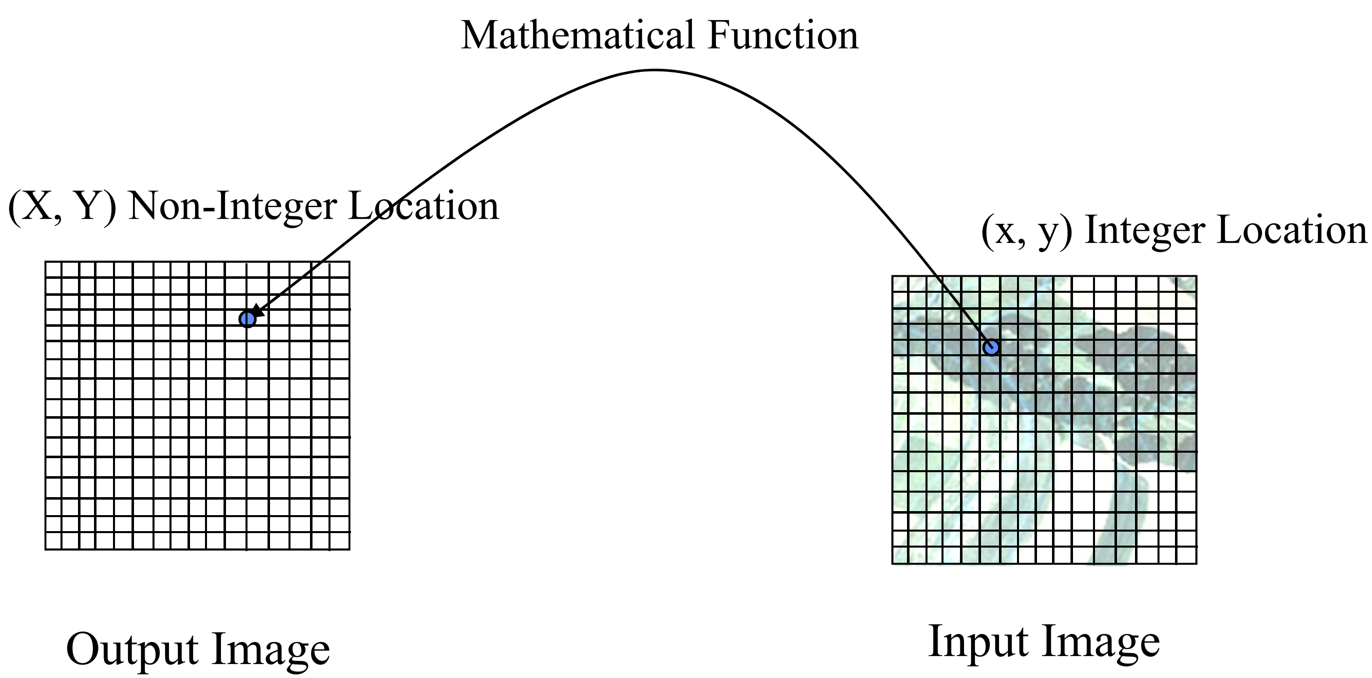
Image-to-Image Transformation

- Given:
  - Input image
  - Blank output image
    - To be generated from the input image
  - A mathematical relationship between conjugate points in the input and the output images
- Required:
  - Fill the blank output image using the input image and the provided mathematical relationship

Image-to-Image Transformation

- Applications:
  - Image rotation
  - Image registration
  - orthophoto generation
  - Normalized image generation
- Image-to-image transformation alternatives:
  - Direct transformation, and
  - Indirect transformation

Direct Transformation

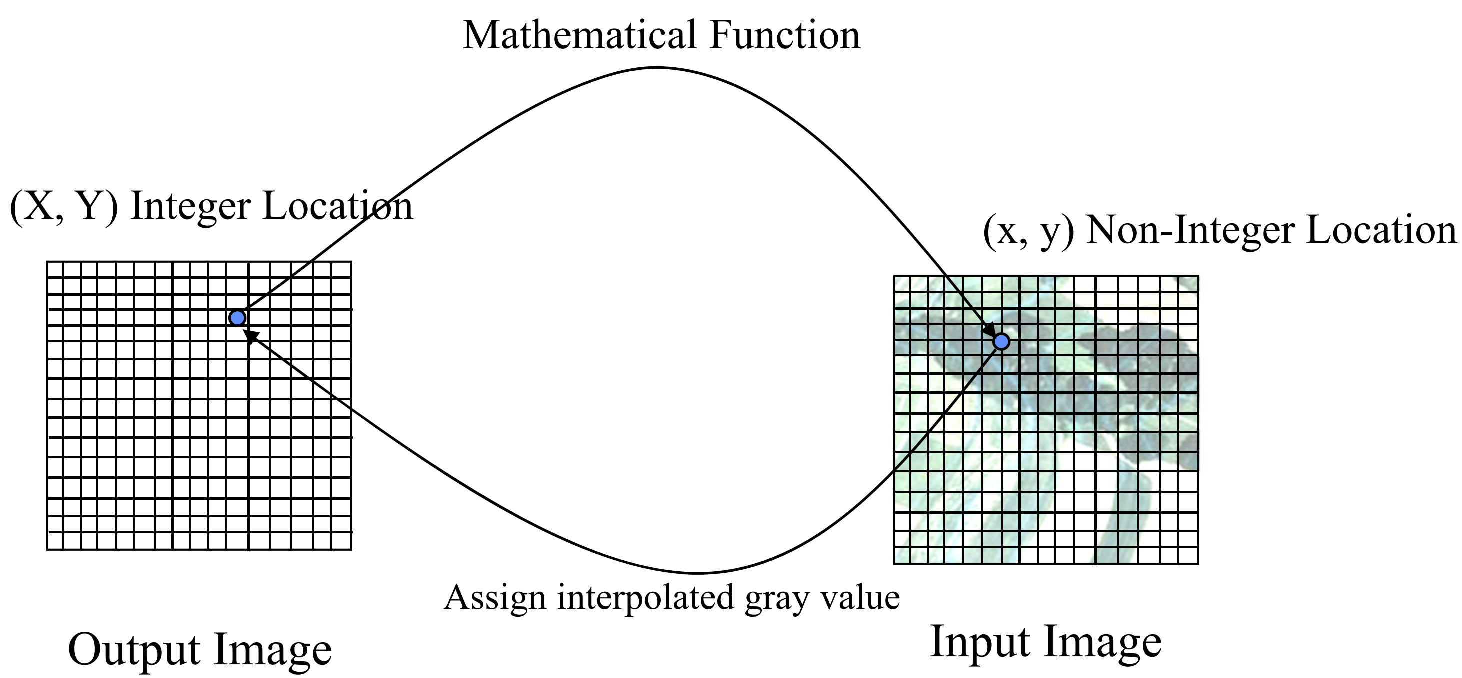


- Assign the pixel gray/color value to the nearest cell in the output image

Direct Transformation

- Transformation from the input image coordinates (x,y) to the output image coordinates (X,Y)
- Assign the pixel gray/color value to the nearest cell in the output image
- Advantages:
  - Gray/color values of the input image will not change
- Disadvantages:
  - Not all the cells in the output image will be assigned a gray value. Therefore their gray values have to be interpolated from neighboring cells.

Indirect Transformation



- Estimate the gray/color value using interpolation / resampling techniques (e.g., nearest neighbor)

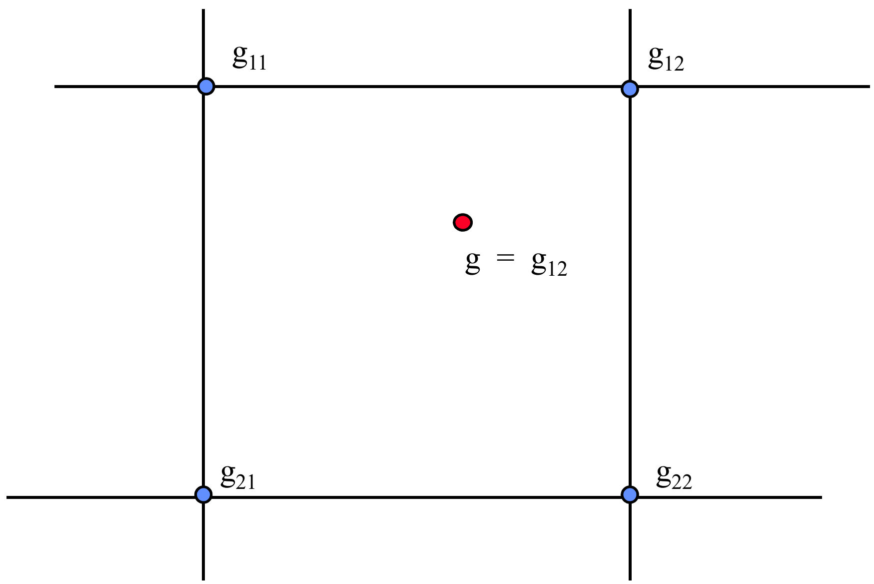
Indirect Transformation

- Transformation from the output image coordinates (X,Y) to the input image coordinates (x,y)
- Estimate the gray/color value using interpolation techniques (e.g., nearest neighbor)
- Assign the interpolated gray/color value to the initial cell in the output image
- Advantages:
  - Every cell in the output image will get a gray value
- Disadvantages:
  - Interpolating the gray value is time consuming.
  - The gray values in the output image might not be the same as those of the original image (due to interpolation).

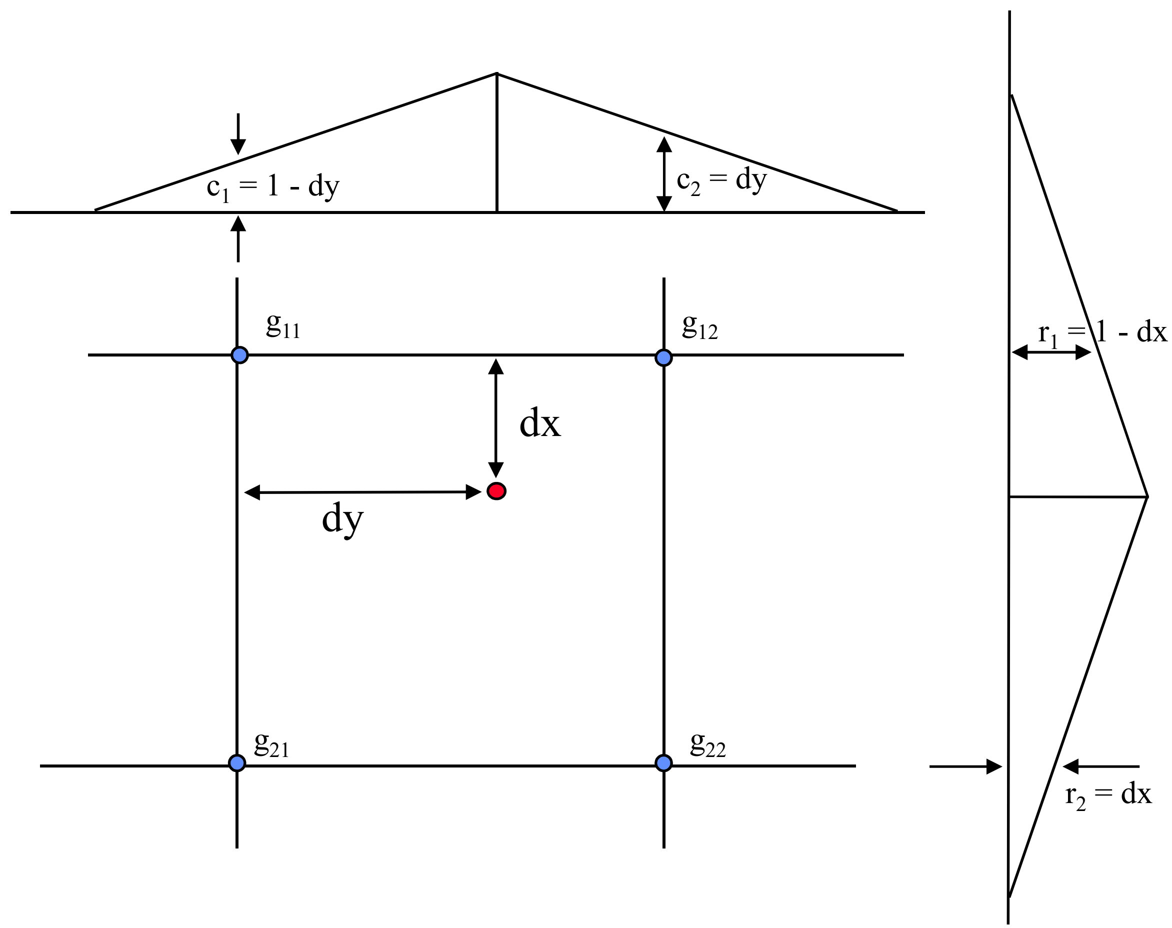
Image Resampling

- Objective:
  - compute $g(x', y')$ for non-integer (x', y')
- Alternatives:
  - Nearest Neighbor algorithm,
  - Bilinear interpolation,
  - Bicubic convolution, …

Nearest Neighbor Resampling

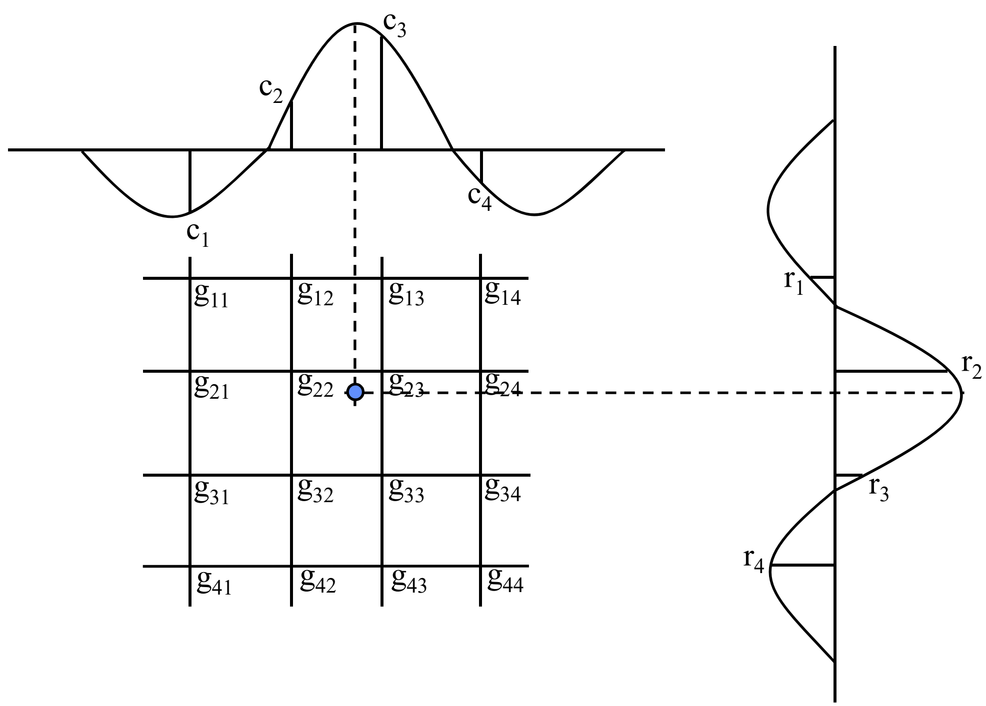


Bilinear Resampling



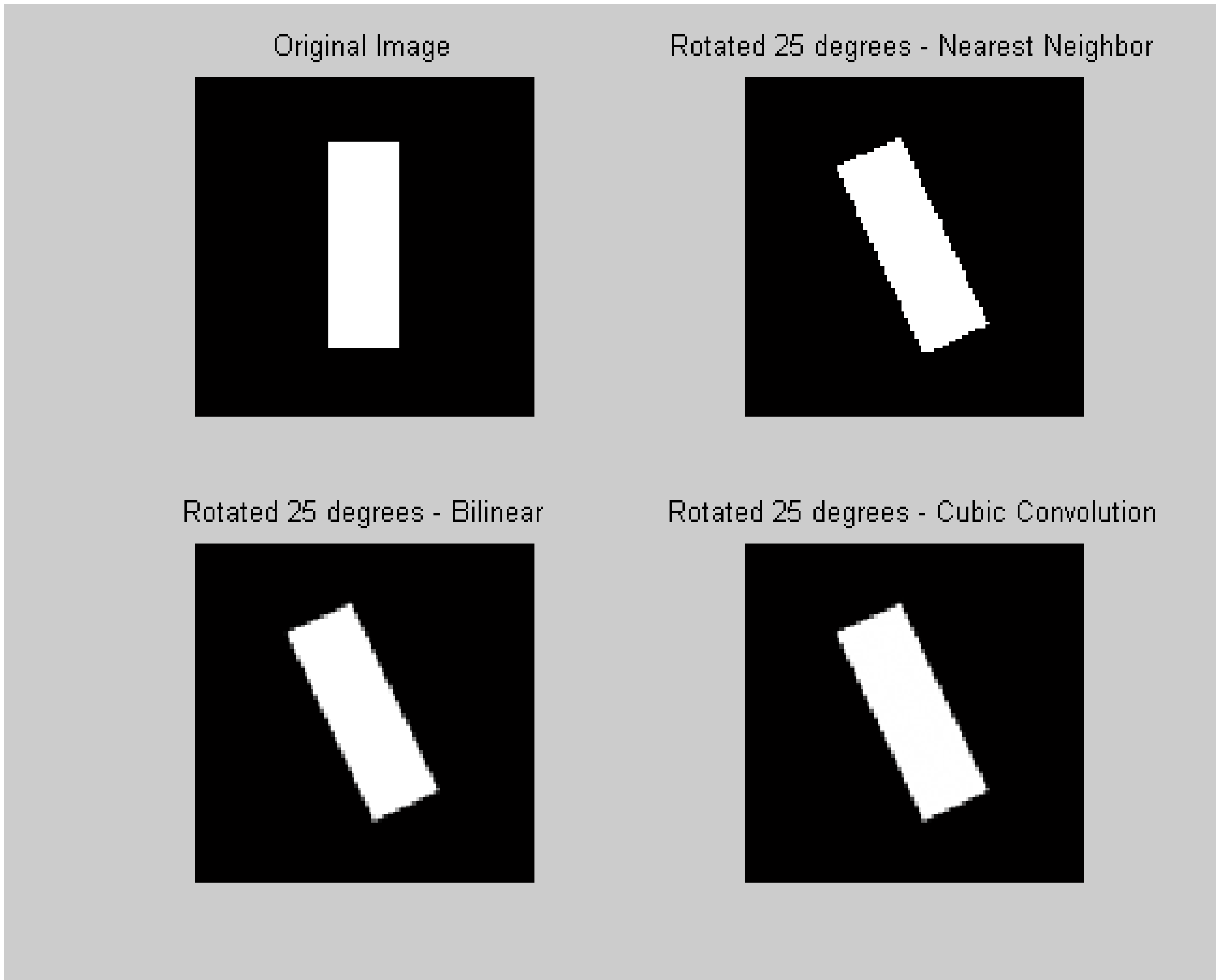
$$g = g_{11}\ r_1\ c_1 + g_{12}\ r_1\ c_2 + g_{21}\ r_2\ c_1 + g_{22}\ r_2\ c_2$$

Cubic Convolution

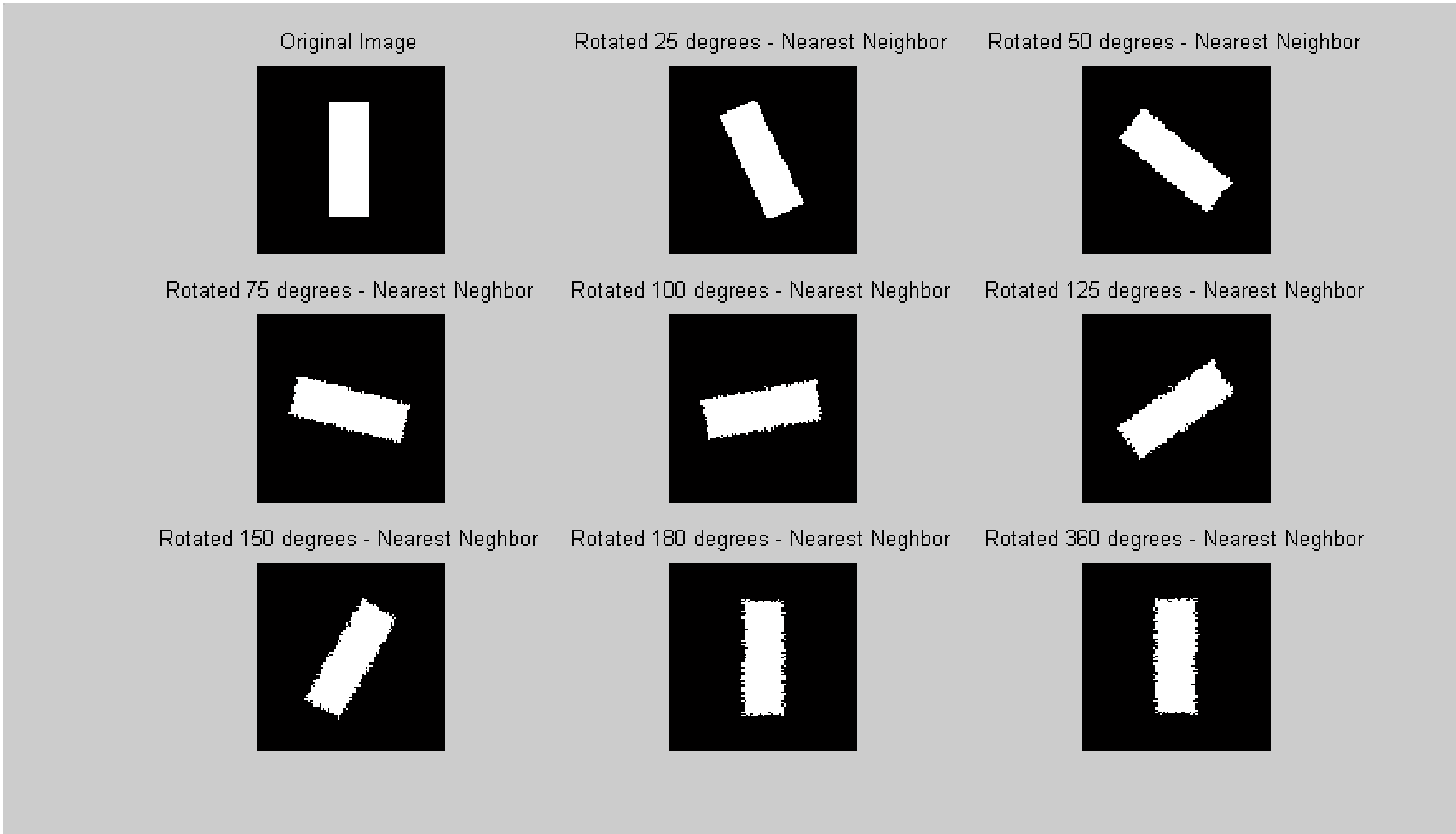


$$\begin{aligned} g = \; & g_{11}\, r_1\, c_1 + g_{12}\, r_1\, c_2 + g_{13}\, r_1\, c_3 + g_{14}\, r_1\, c_4 + \\ & g_{21}\, r_2\, c_1 + g_{22}\, r_2\, c_2 + g_{23}\, r_2\, c_3 + g_{24}\, r_2\, c_4 + \\ & g_{31}\, r_3\, c_1 + g_{32}\, r_3\, c_2 + g_{33}\, r_3\, c_3 + g_{34}\, r_3\, c_4 + \\ & g_{41}\, r_4\, c_1 + g_{42}\, r_4\, c_2 + g_{43}\, r_4\, c_3 + g_{44}\, r_4\, c_4 \end{aligned}$$

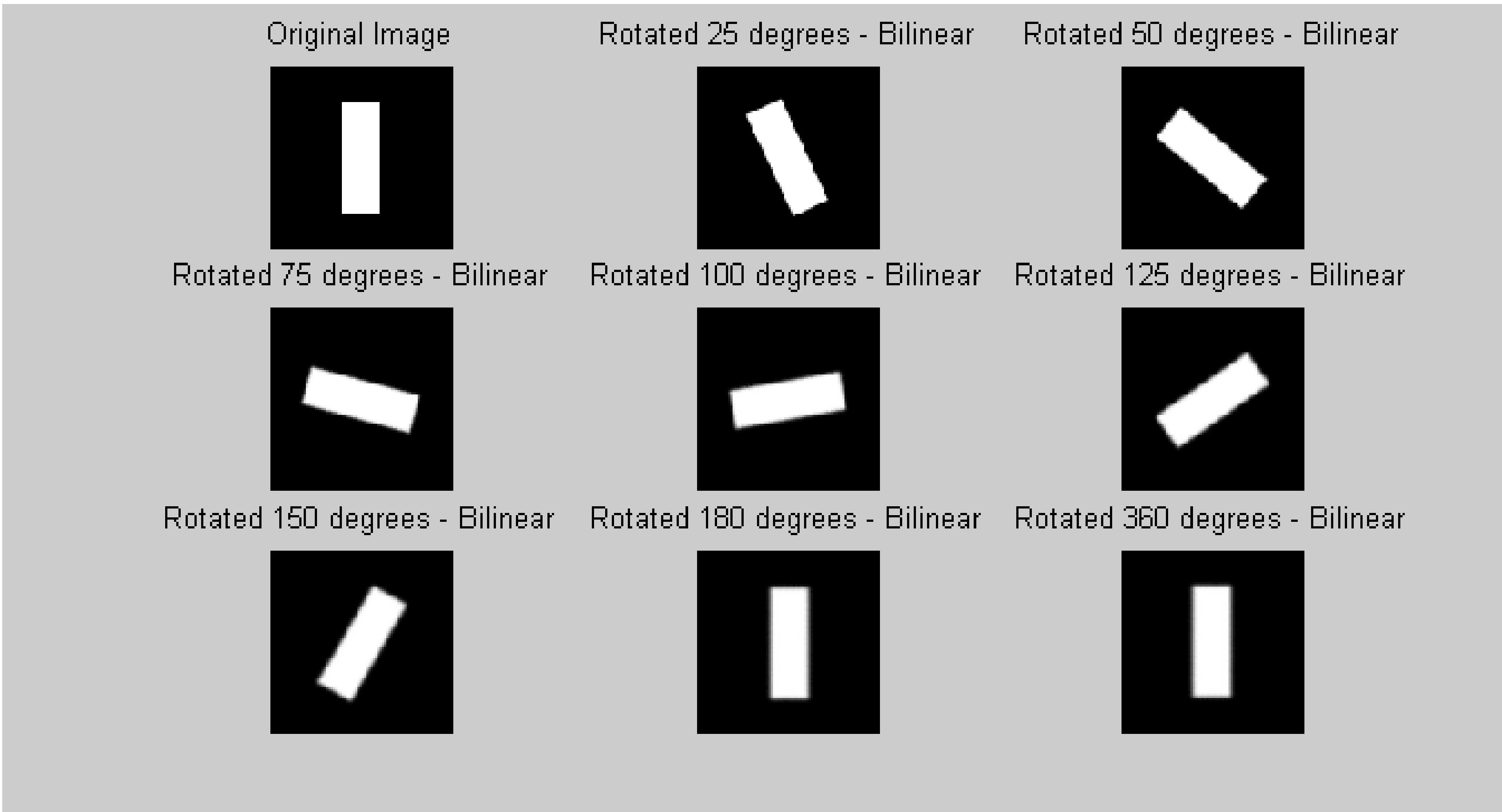
Example (Image Rotation)



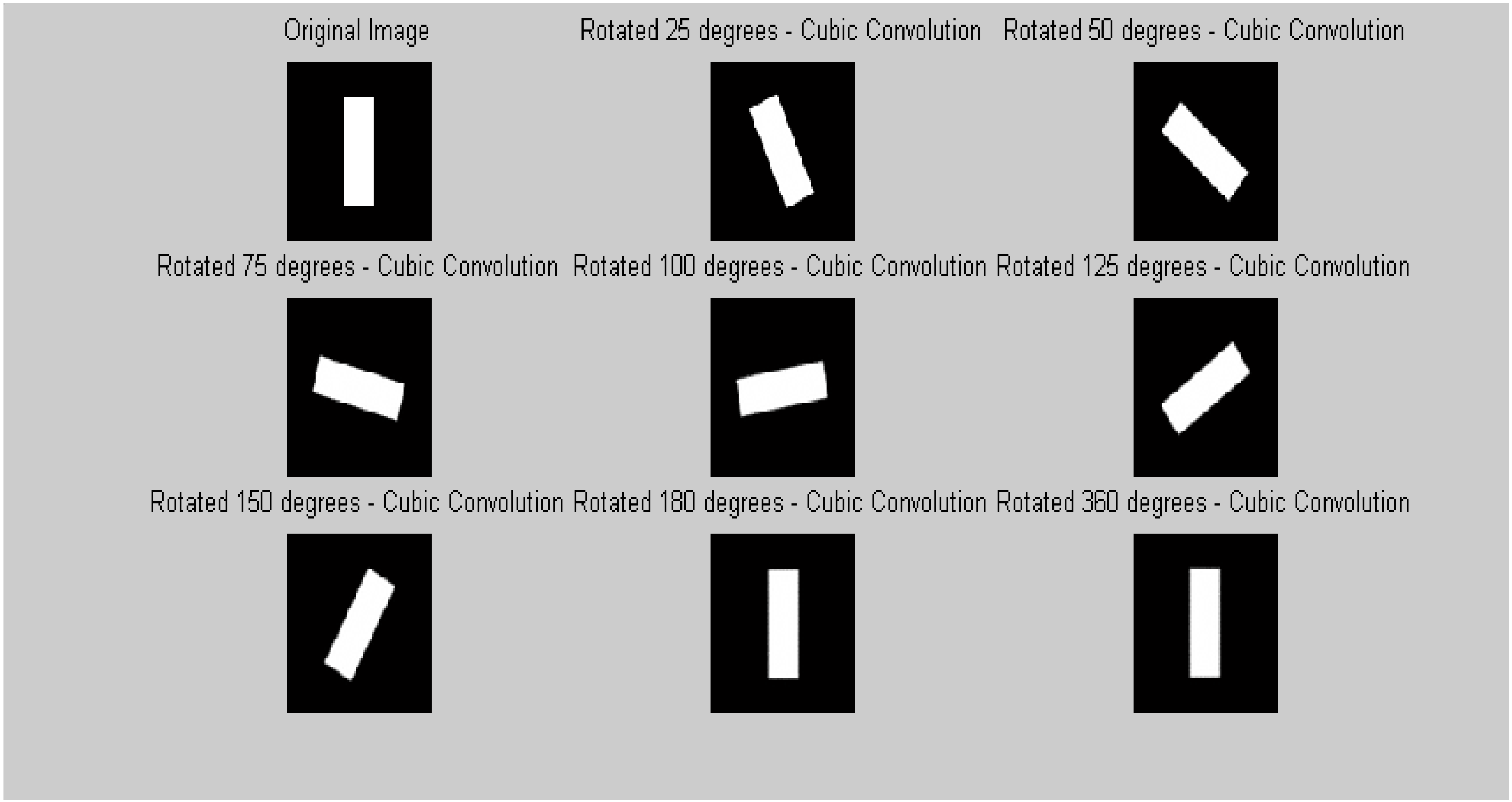
Nearest Neighbor Resampling



Bilinear Resampling



Cubic Convolution



Resampling: Final Remarks

- Geometric Characteristics:
  - Cubic → Best
  - Bilinear → Good
  - Nearest Neighbor → Poor
- Radiometric Characteristics:
  - Cubic → Poor
  - Bilinear → Good
  - Nearest Neighbor → Best
- Execution Time:
  - Cubic → Slow
  - Bilinear → Relatively Fast
  - Nearest Neighbor → Fast

Digital Orthophoto Generation

- Polynomial rectification
- Differential rectification

Digital Orthophoto Generation

- Perspective imagery do not show features in their correct locations due to displacements caused by:
  - Tilt of the of the imaging sensor, and/or
  - Terrain relief.
- Polynomial rectification is suitable for removing the effects of the sensor tilt.
- Differential rectification removes the effects of the sensor tilt and terrain relief.

Polynomial Rectification

- Mainly used for relatively flat terrain (to remove the effect of the sensor tilt)
- Polynomial rectification could be applied using either direct or indirect transformation.
- It uses Ground Control Points (GCP^s) to relate the orthophoto and the image coordinate systems.
- The degree of the polynomial depends on the number of the GCP^s and the nature of the terrain.
- More GCP^s yield more accurate rectified imagery.

Polynomial Rectification

- Polynomial rectification is completely independent from the geometry of the image.
  - Therefore, it can be used for both satellite and aerial images.
- It is more often used for satellite images due to the following reasons:
  - Satellite image geometry and distortions are sometimes difficult to model, and
  - The relief displacement due to the topography of the Earth is relatively small compared to the flying height of the satellite.

Polynomial Rectification

$$x = \sum_{i=0}^{N} \sum_{j=0}^{N-i} a_{ij} X^i Y^j$$

$$y = \sum_{i=0}^{N} \sum_{j=0}^{N-i} b_{ij} X^i Y^j$$

$$x = a_{00} + a_{10} X + a_{01} Y + a_{20} X^2 + a_{11} XY + a_{02} Y^2$$
$$= a_0 + a_1 X + a_2 Y + a_3 X^2 + a_4 XY + a_5 Y^2$$

$$y = b_{00} + b_{10} X + b_{01} Y + b_{20} X^2 + b_{11} XY + b_{02} Y^2$$
$$= b_o + b_1 X + b_2 Y + b_3 X^2 + b_4 XY + b_5 Y^2$$

Polynomial Rectification

- Advantages:
  - Easy to implement
  - Distortions of the image (due to sensor geometry, terrain relief, etc.) are corrected simultaneously.
- Disadvantages:
  - The accuracy is limited.
  - Does not correct for relief displacement
  - We do not consider the geometric model of the imaging system (e.g., collinearity).

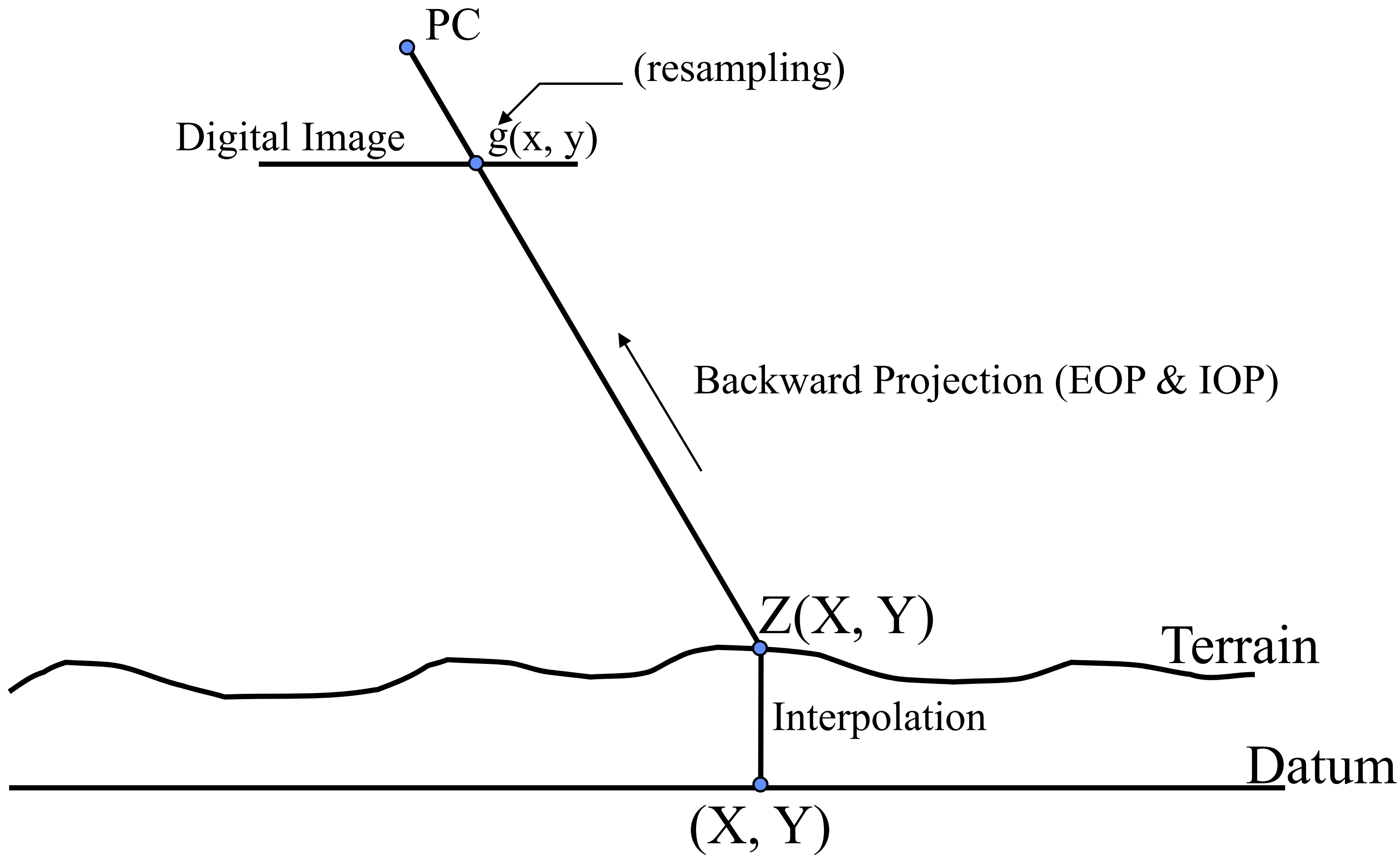
Differential Rectification

- The objective of differential rectification is the assignment of gray values from the image (usually aerial image) to each cell within the orthophoto.
- After the rectification, both the elevation and the gray/color values are stored at the same location along the datum.

Differential Rectification

- Input:
  - Digital image,
  - EOP of that image,
  - IOP of the used camera, and
  - Digital Elevation Model
- Output:
  - Digital image which has the same characteristics of a map (orthophoto)

Differential Rectification

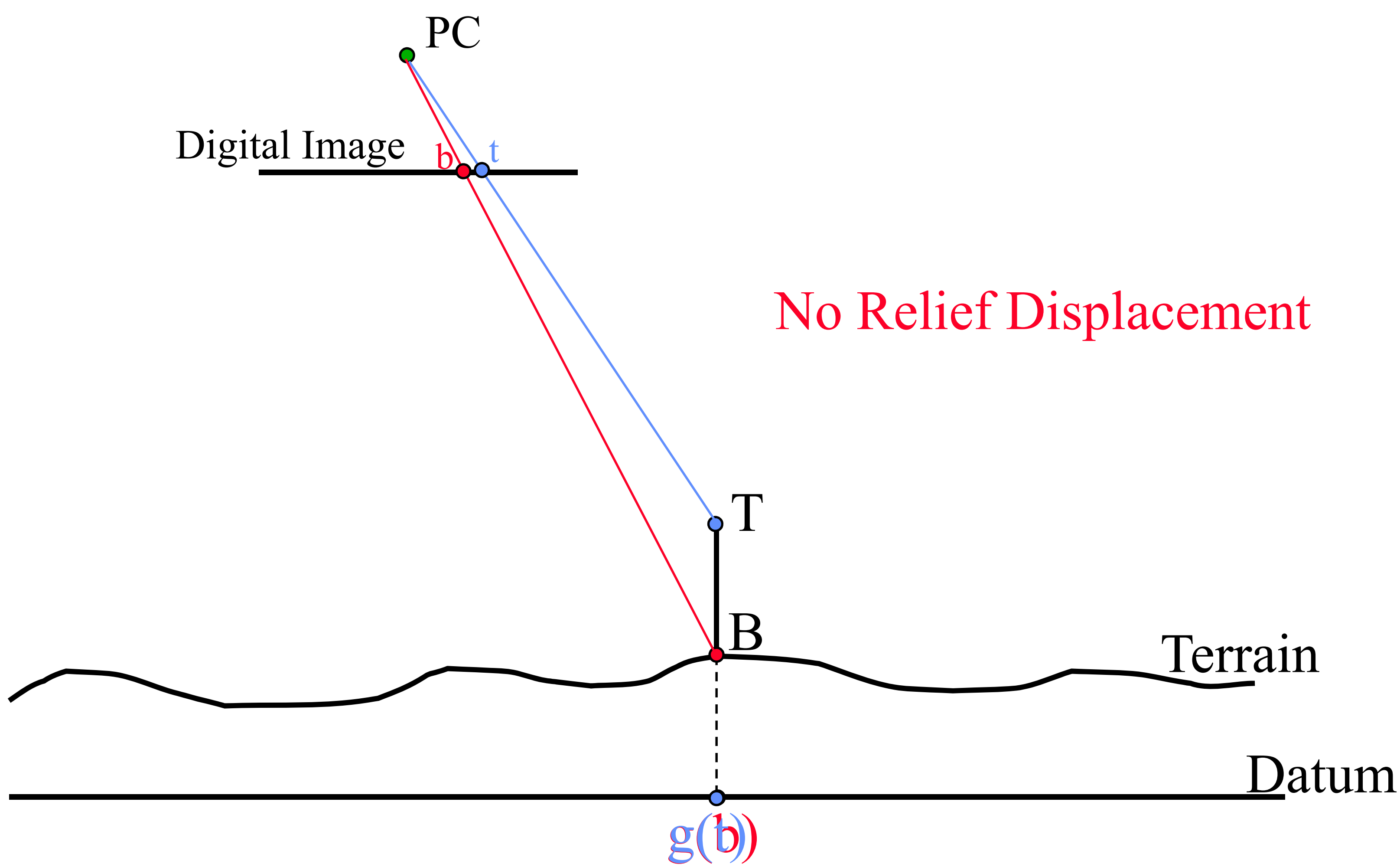


G(X, Y) = g (x, y)

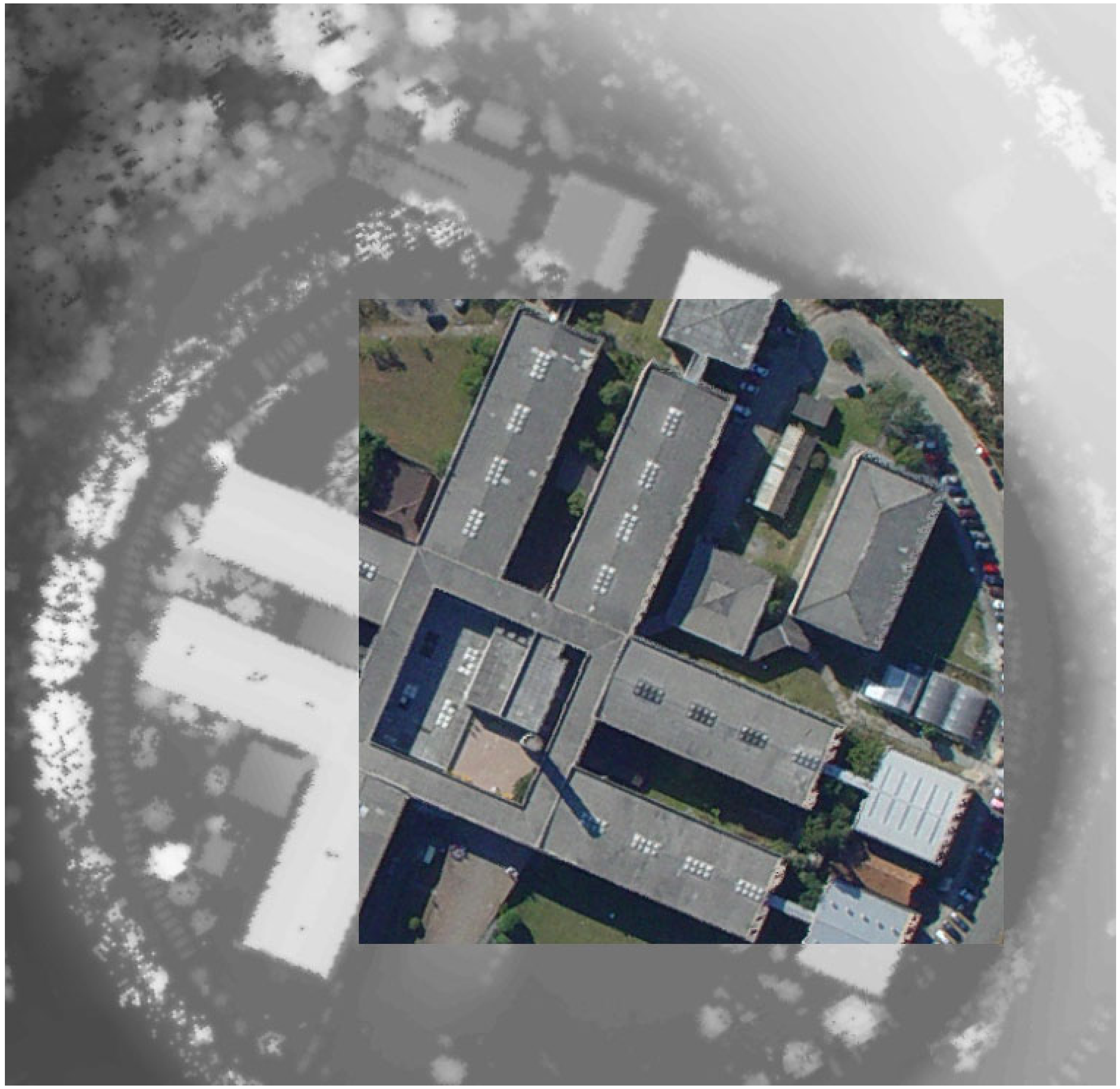
Differential Rectification

- Procedure:
  - Define a uniform grid over the orthophoto plane (datum)
  - For each grid element (X, Y) in the orthophoto plane, interpolate for the corresponding elevation → Z(X, Y)
  - Using the EOP and IOP together with the collinearity equations, find the corresponding image point (x, y)
  - Find g(x, y) using one of the resampling techniques
  - G(X, Y) = g(x, y)
  - Repeat the above procedure for all the pixels in the orthophoto plane

Differential Rectification

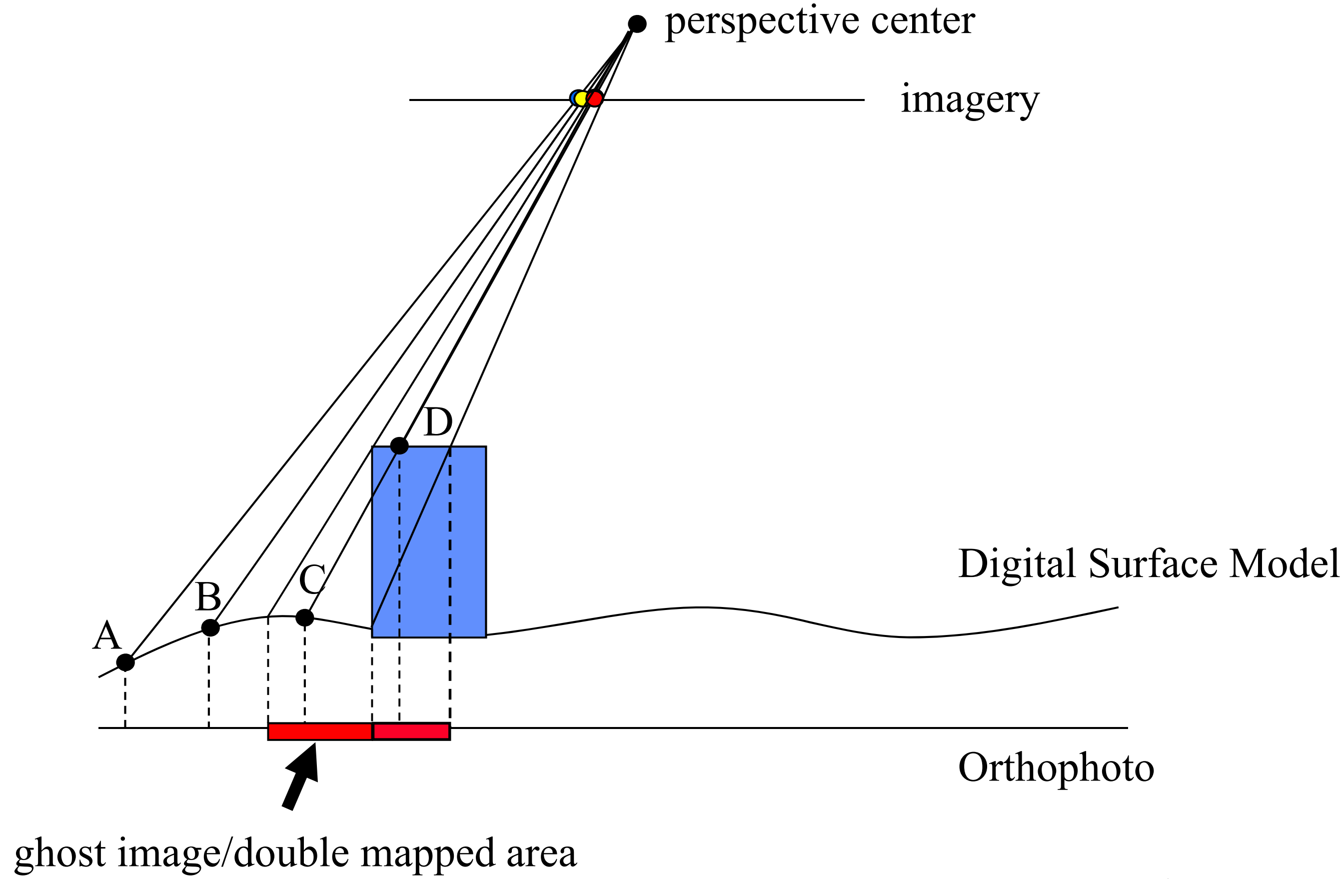


Orthophoto & DEM



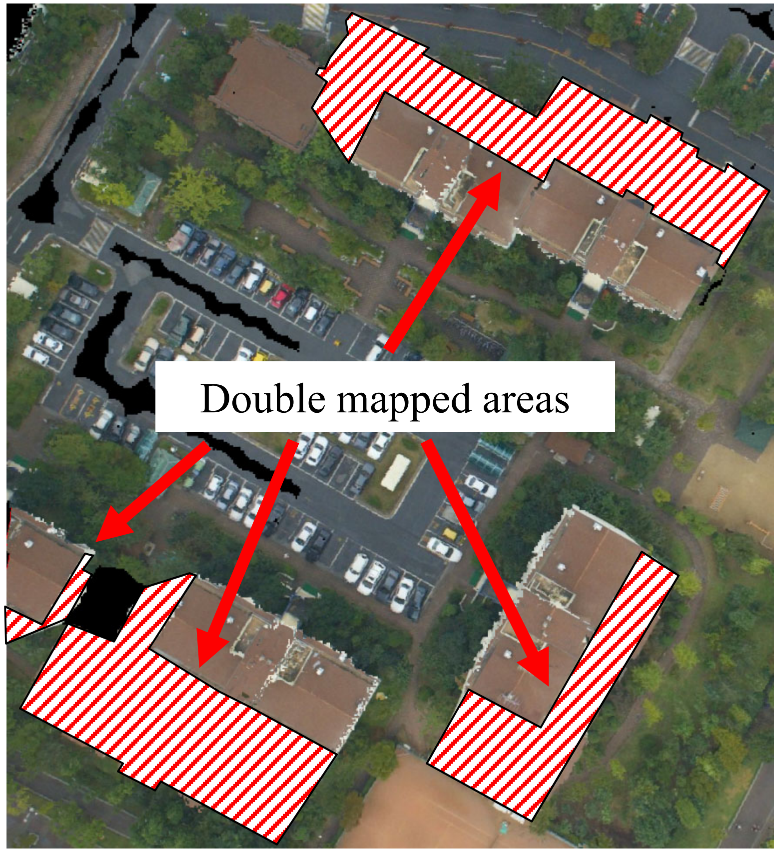
Differential Rectification

Ghost images / Double Mapping Problem



Differential Rectification

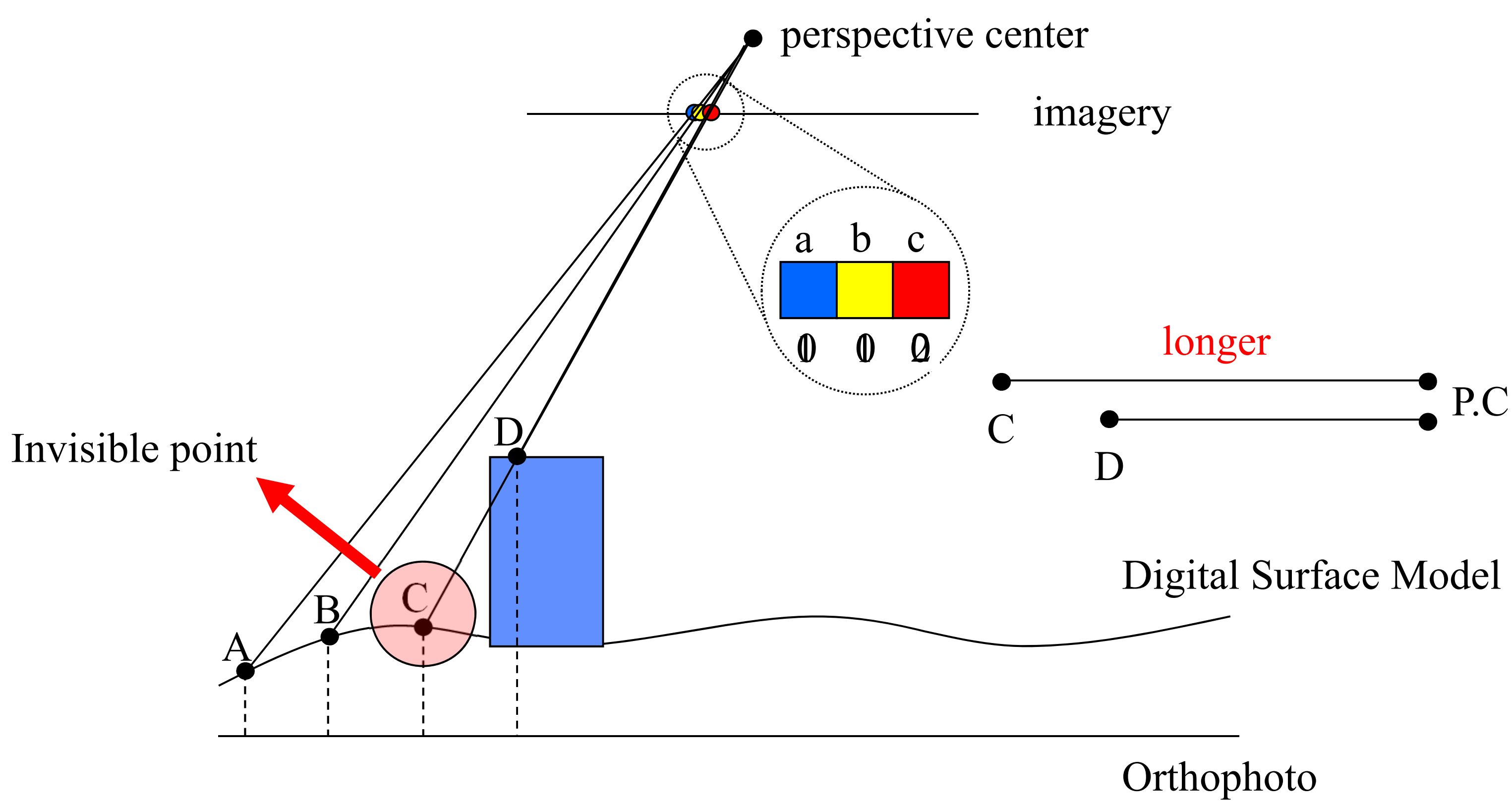
Original Imagery



Generated Orthophoto

True Orthophoto Generation

Z-Buffer Method



True Orthophoto Generation

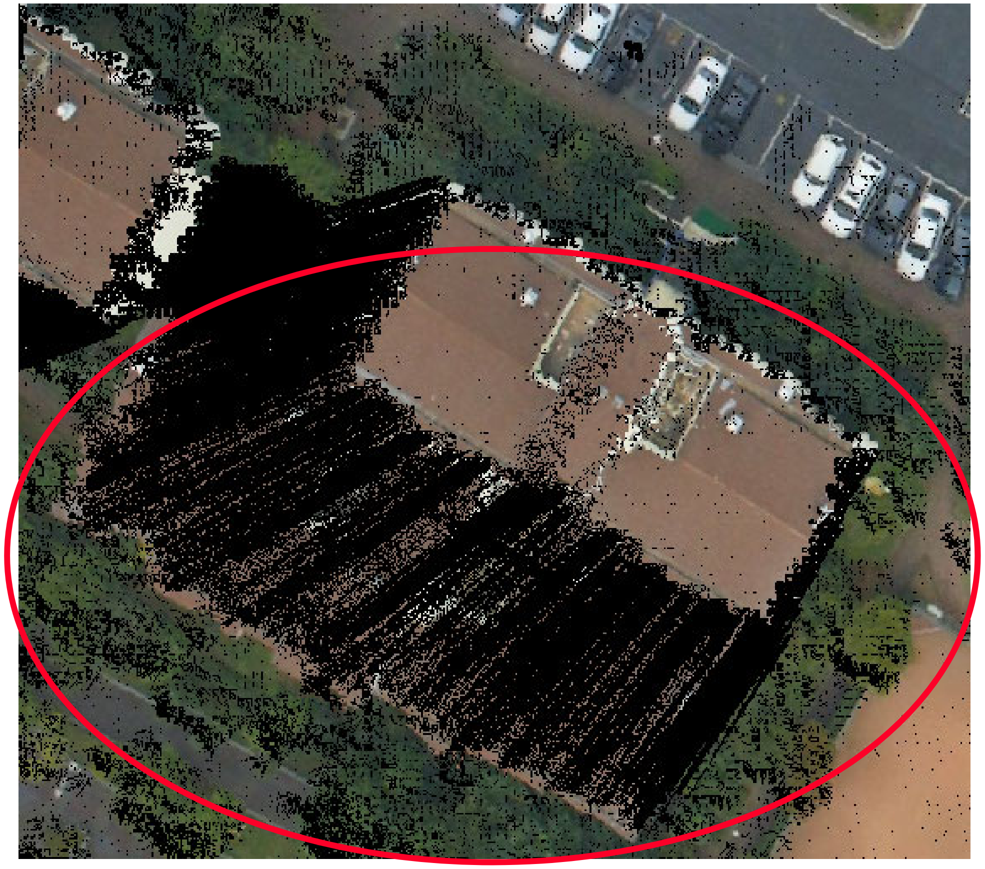
Z-Buffer Method

Original Imagery

Generated True Orthophoto

True Orthophoto Generation

Z-Buffer Method

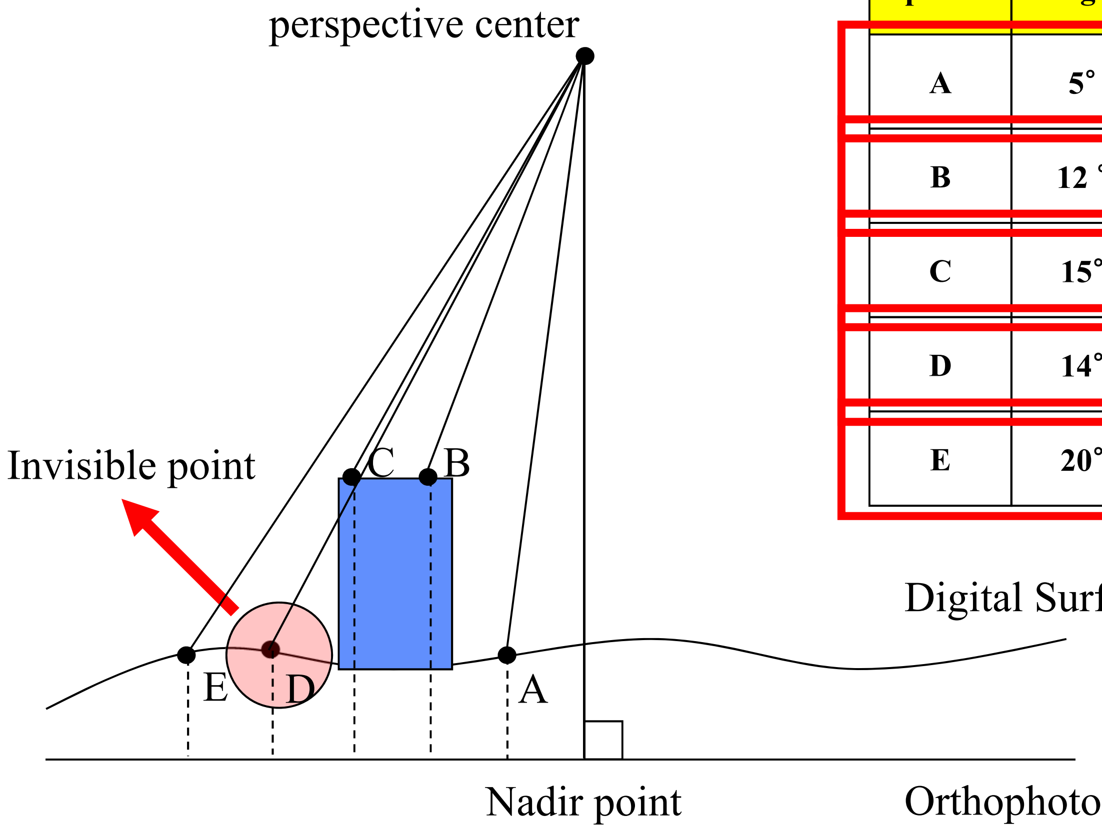


Generated True Orthophoto

True Orthophoto Generation

Angle-based Method

point	angle	comparison	max angle	visible / hidden
A	5°	>	0°	visible
B	12 °	>	5 °	visible
C	15°	>	12°	visible
D	14°	<=	15°	invisible
E	20°	>	15°	visible



True Orthophoto Generation

existing method

adaptive radial sweep method

spiral sweep method

- Adaptive radial sweep and spiral sweep are two implementation strategies of the angle-based method for true orthophoto generation.

Perspective Image

Orthophoto with Ghost Images

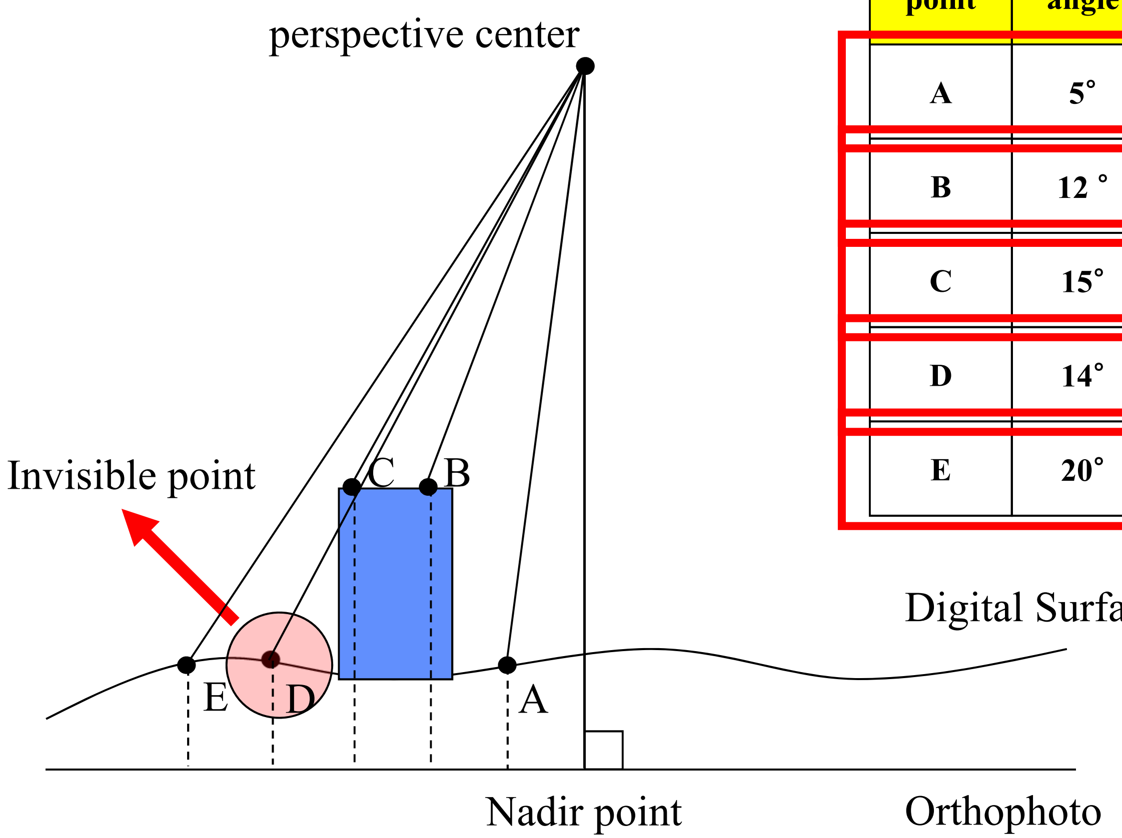
True Orthophoto without Ghost Images

True Orthophoto After Occlusion Filling

Occlusion Extension

Angle-based Method

point	angle	comparison	max angle	visible / hidden
A	5°	>	0°	visible
B	12 °	>	5 °	visible
C	15°	>	12°	visible
D	14°	<=	15°	invisible
E	20°	>	16°	visible

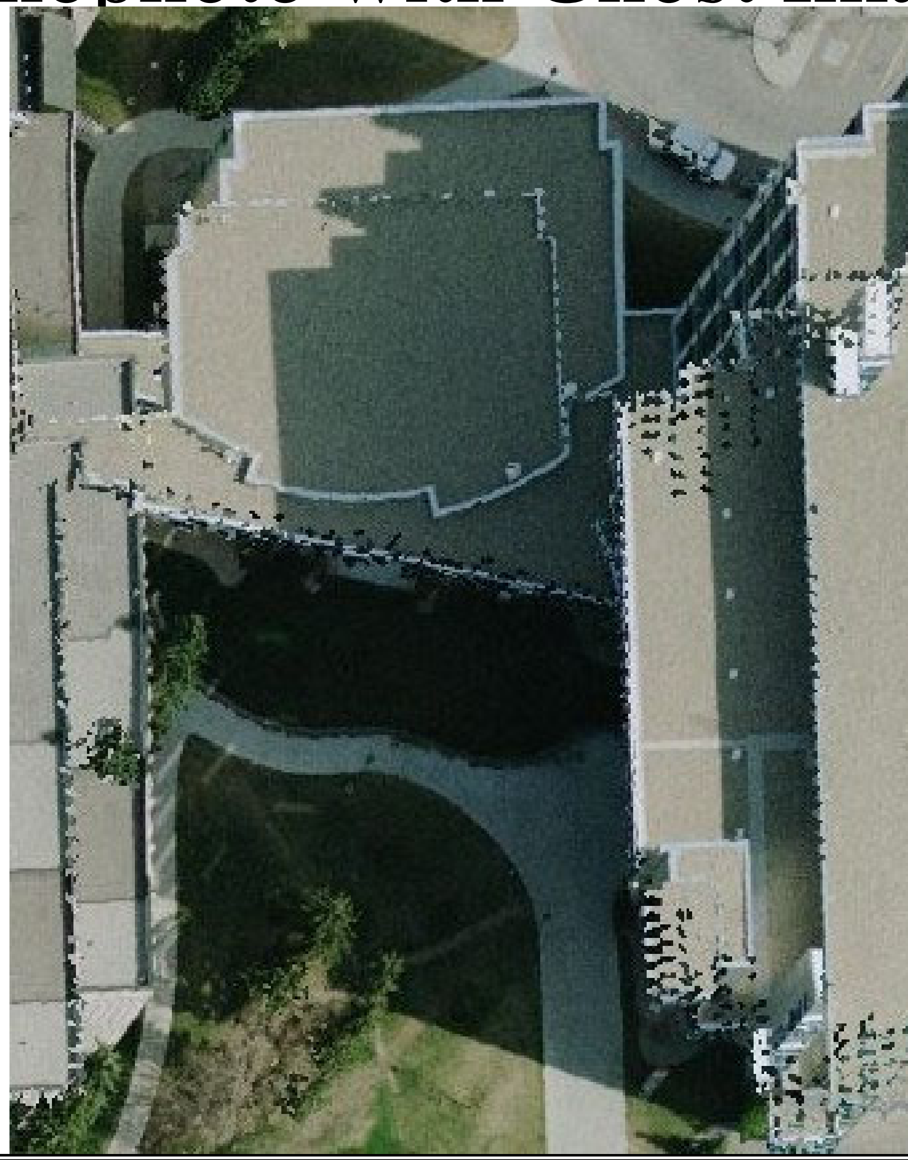


True Orthophoto After Occlusion Filling

True Orthophoto After Occlusion Extension

True Orthophoto After Boundary Enhancement

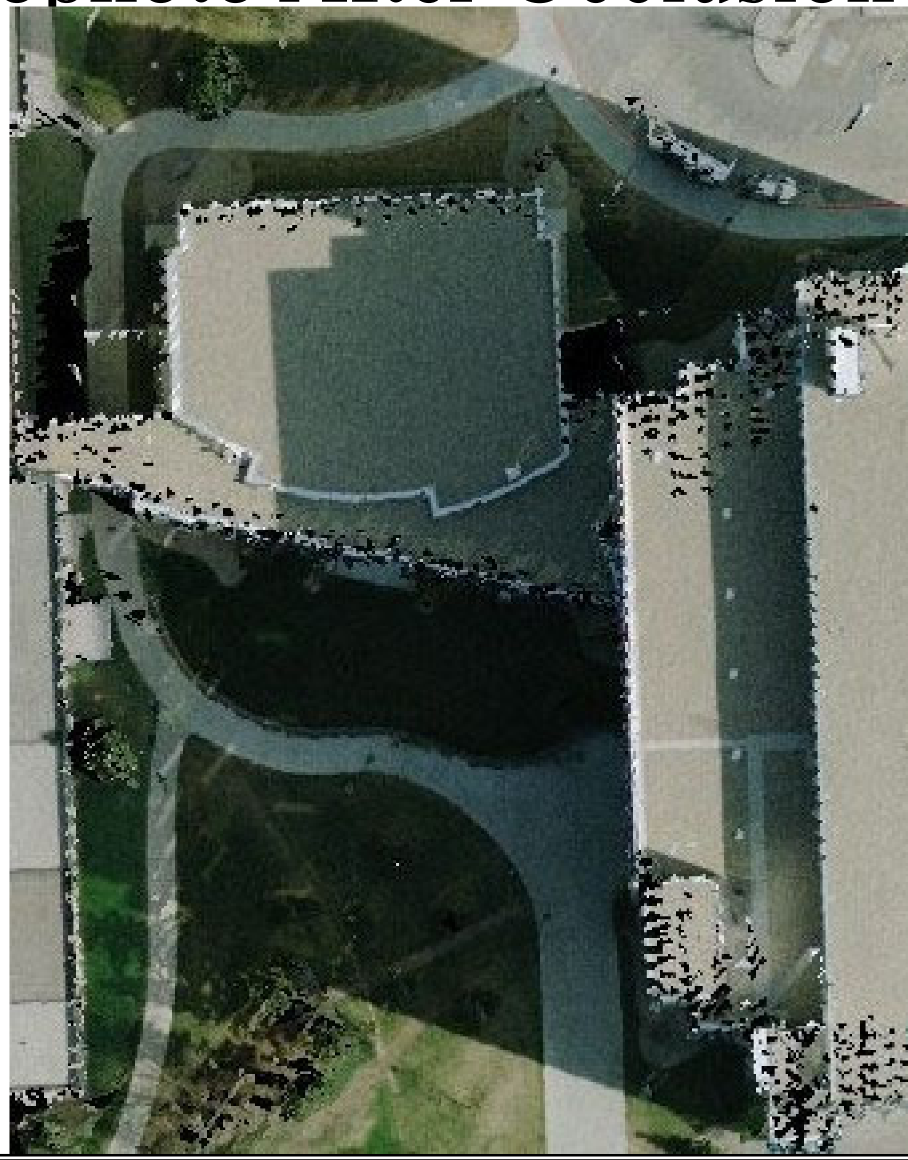
Orthophoto with Ghost Images



True Orthophoto without Ghost Images

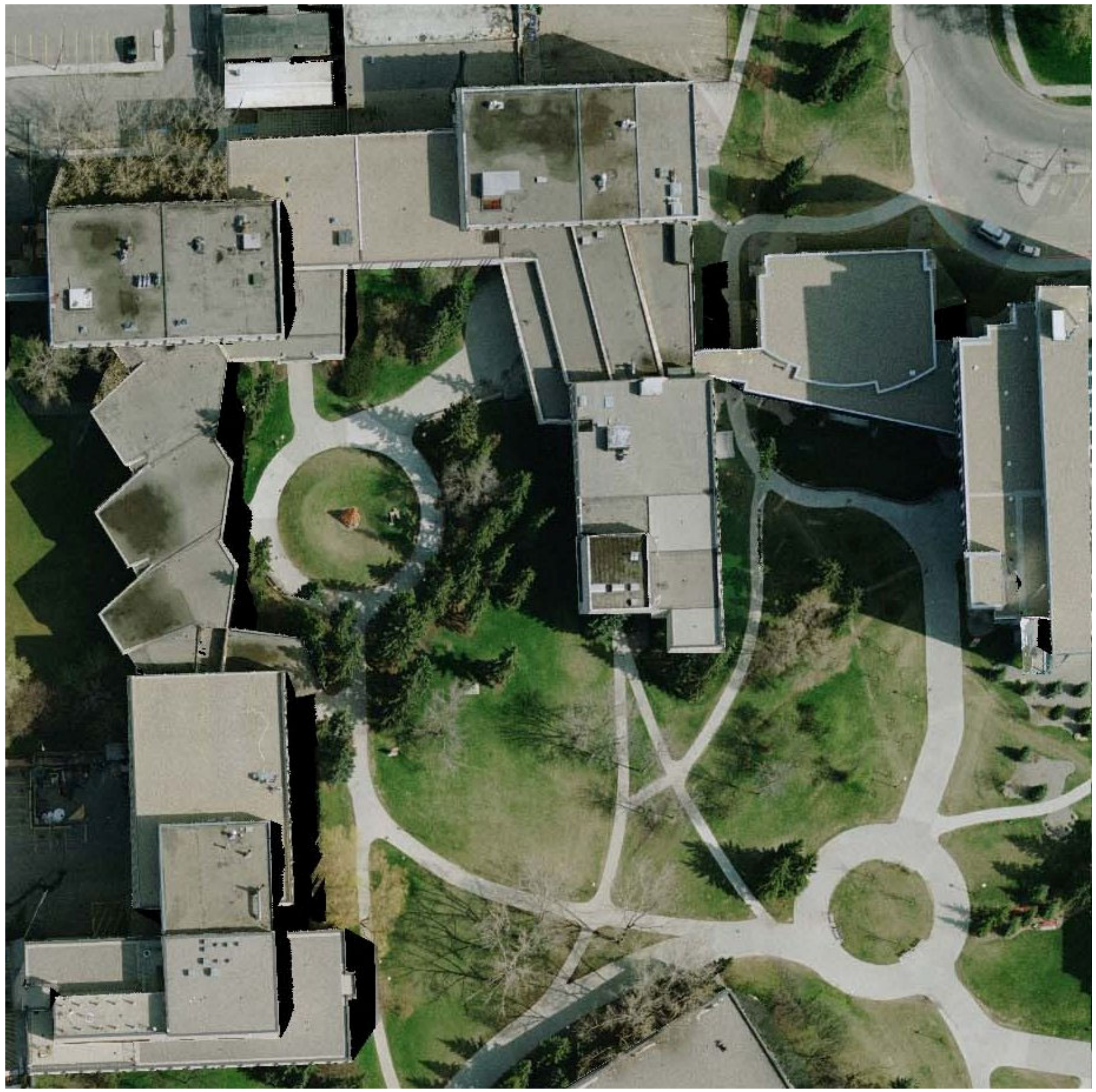
True Orthophoto After Occlusion Filling

True Orthophoto After Occlusion Extension



True Orthophoto After Boundary Enhancement

Orthophoto

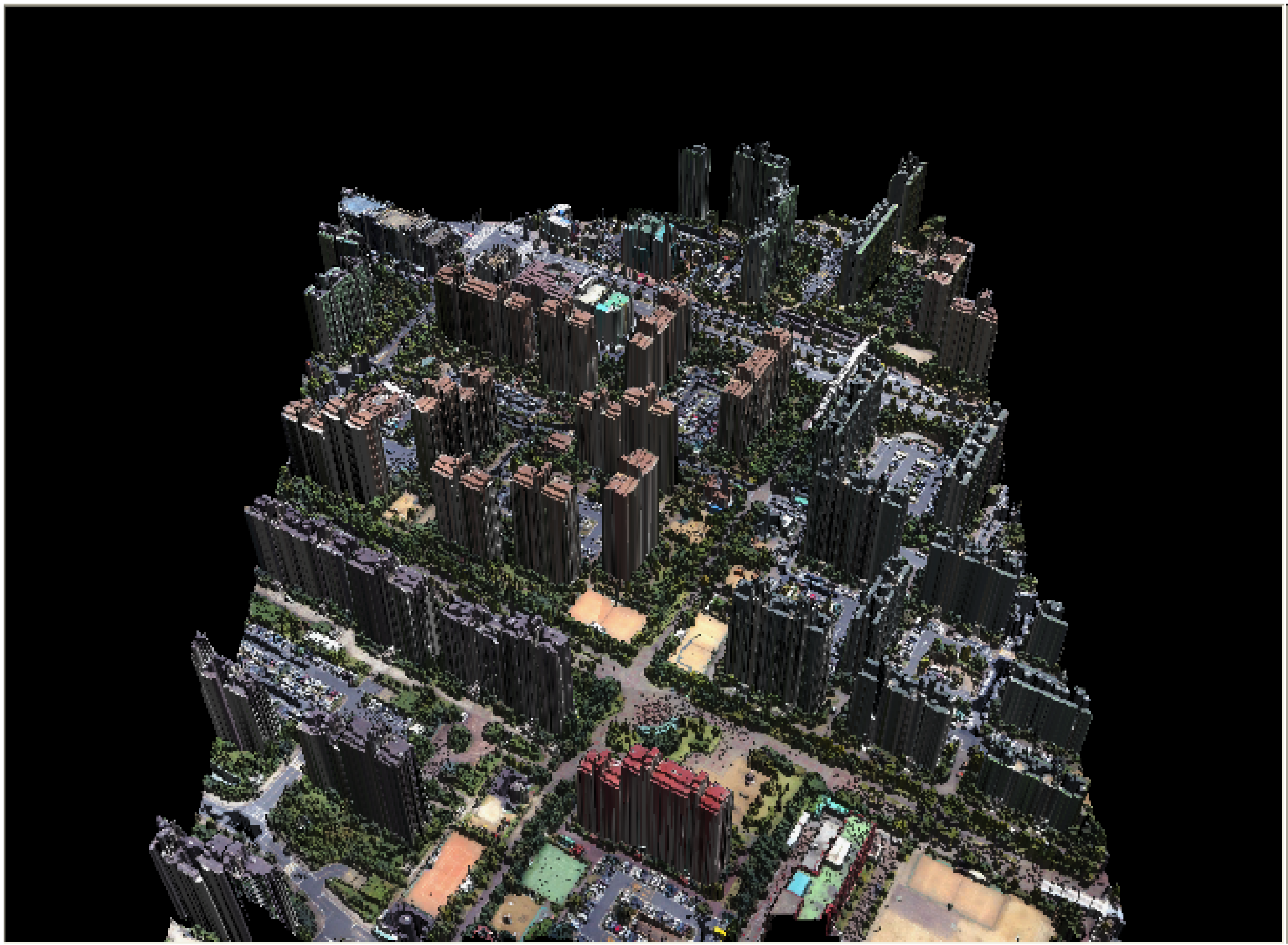


Beyond Orthophotos: 3D Realistic Views

(X, Y, Z): 1122.23 m, 3251.53 m, 72.03m

(R, G, B): 23, 136, 69

Beyond Orthophotos: 3D Realistic Views



Digital Orthophoto Generation

- Image + DTM + Differential Rectification:
  - Buildings and tree relief still exist.
- Image + DSM + Differential Rectification:
  - Buildings and tree relief is removed.
  - Ghost images are present.
- Image + DSM + True Orthophoto Generation:
  - Buildings and tree relief is removed.
  - No ghost images
  - Irregular building boundaries
- Image + DSM + DBM + True Orthophoto Generation:
  - Buildings and tree relief is removed (trees might look strange).
  - No ghost images
  - Regular building boundaries
- Image + DTM + DBM + True Orthophoto Generation:
  - Buildings relief is removed.
  - Tree relief still exist (trees will look OK?).
  - No ghost images
  - Regular building boundaries

True Orthophoto: DSM + DBM

True Orthophoto: DTM + DBM

True Orthophoto: DSM + DBM

True Orthophoto: DTM + DBM

True Orthophoto: DSM + DBM

True Orthophoto: DTM + DBM

True Orthophoto: DSM + DBM

True Orthophoto: DTM + DBM

True Orthophoto: DSM + DBM

True Orthophoto: DTM + DBM

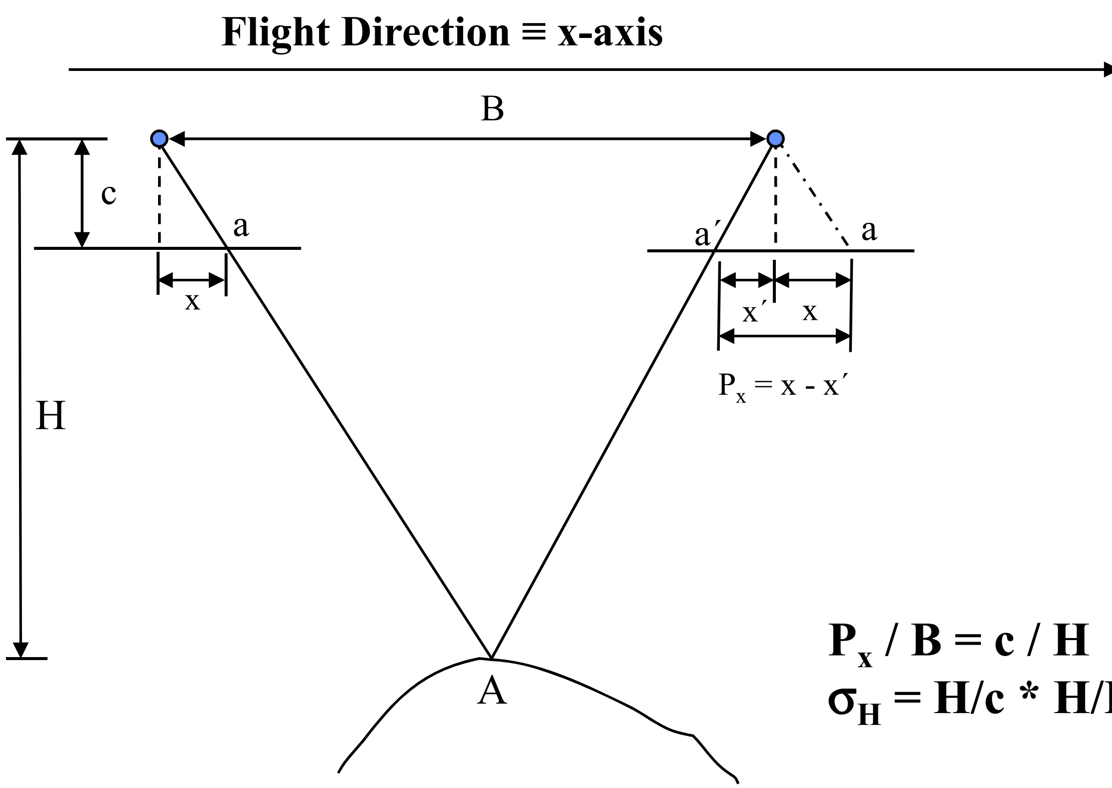
Digital Orthophoto Generation

- Factors that affect the accuracy of the final orthophoto:
  - Distortions in the original image,
  - Errors associated with the EOP and the IOP of the involved images and cameras, and
  - Errors associated with the DEM:
    - Errors arising from the discrete representation of the Earth surface by a grid, and
    - Interpolation errors

Digital Orthophoto Generation

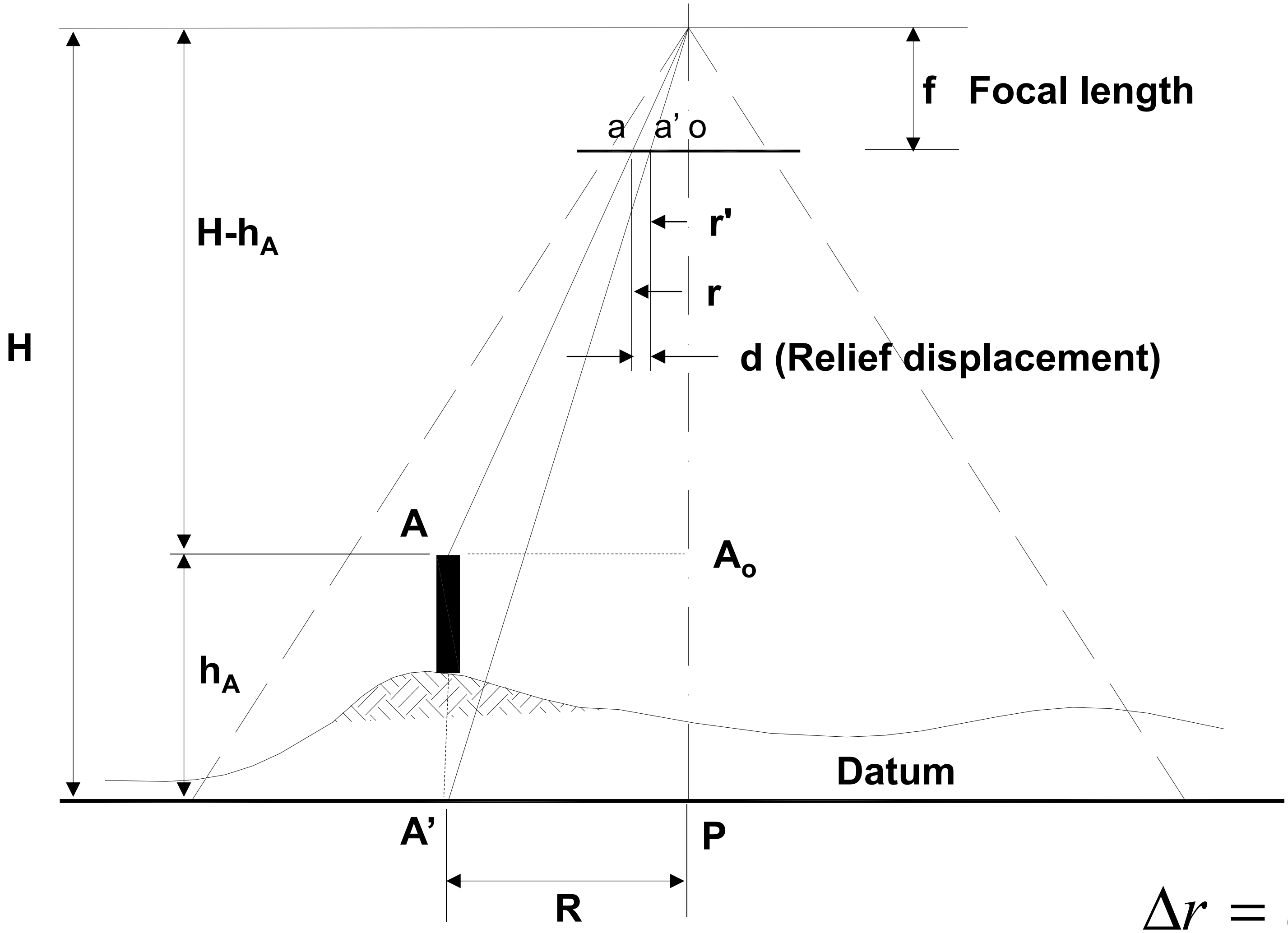
- One way of reducing the errors in the final orthophoto:
  - Use wide angle camera to produce the DEM
    - $\sigma_Z = H/C * H/B \;\; \sigma_{px}$
    - Good DEM
  - Use normal angle camera to produce the orthophoto
    - $\Delta r = r * h/H$
    - Less relief displacement/occlusions

Height Accuracy



$$P_x / B = c / H$$
$$\sigma_H = H/c * H/B * \sigma_{px}$$

Relief Displacement



$$\Delta r = d = \frac{r\ h_a}{H}$$

Stereo-Orthophoto Generation

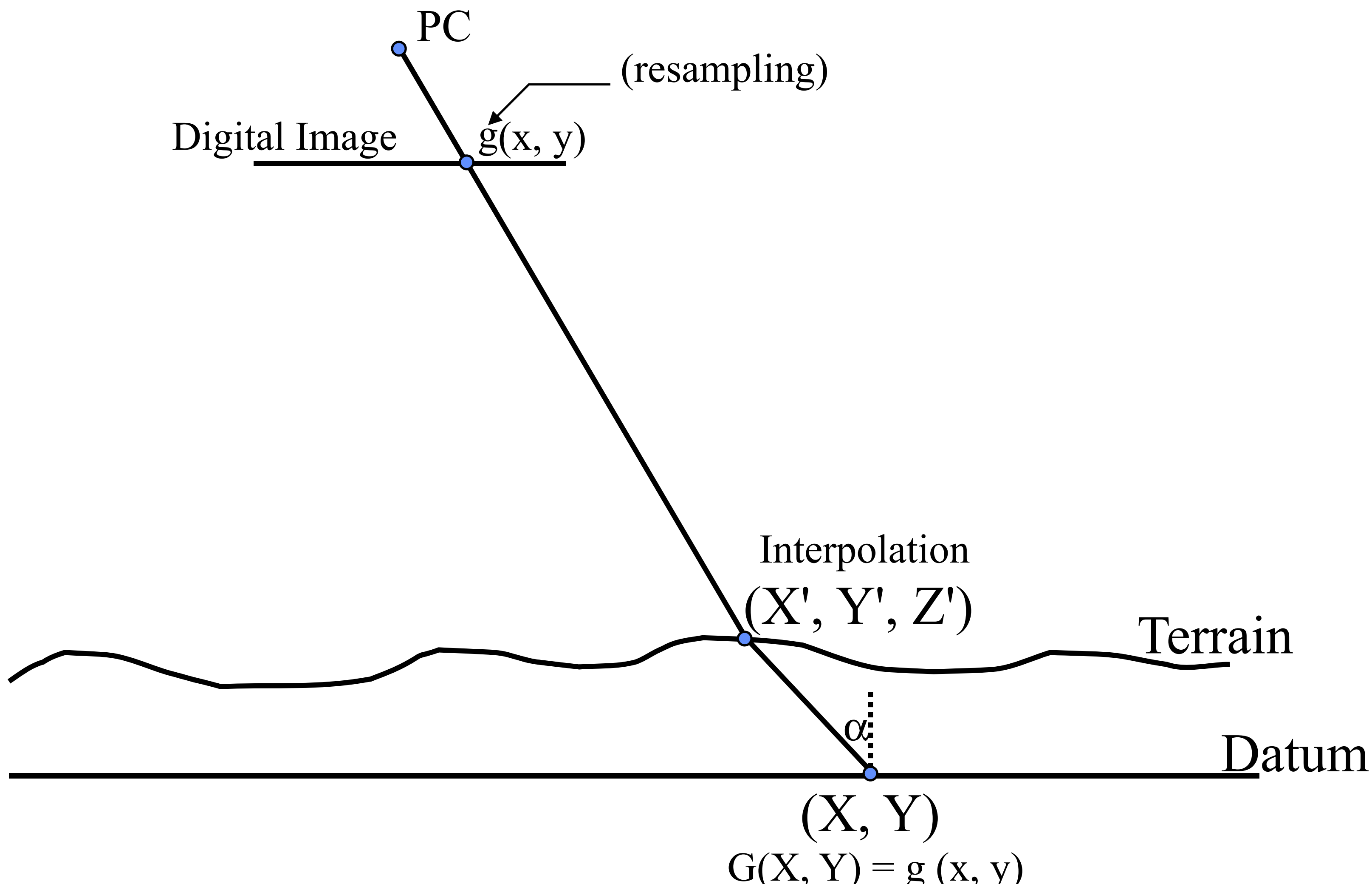
Stereo Orthophoto

- Conditions for stereo-scopic viewing:
  - Two images covering the same area from two different locations,
  - There is no y-parallax, and
  - There is x-parallax that is proportional to the elevation.
- Objective of stereo orthophoto:
  - Generate a stereo-mate that can be used in conjunction with the orthophoto for 3-D viewing of the involved area without the need for photogrammetric plotters
  - In other words, conjugate entities in the orthophoto and the stereo-mate have:
    - No y-parallax, and
    - X-parallax is proportional to the elevation of such entity.

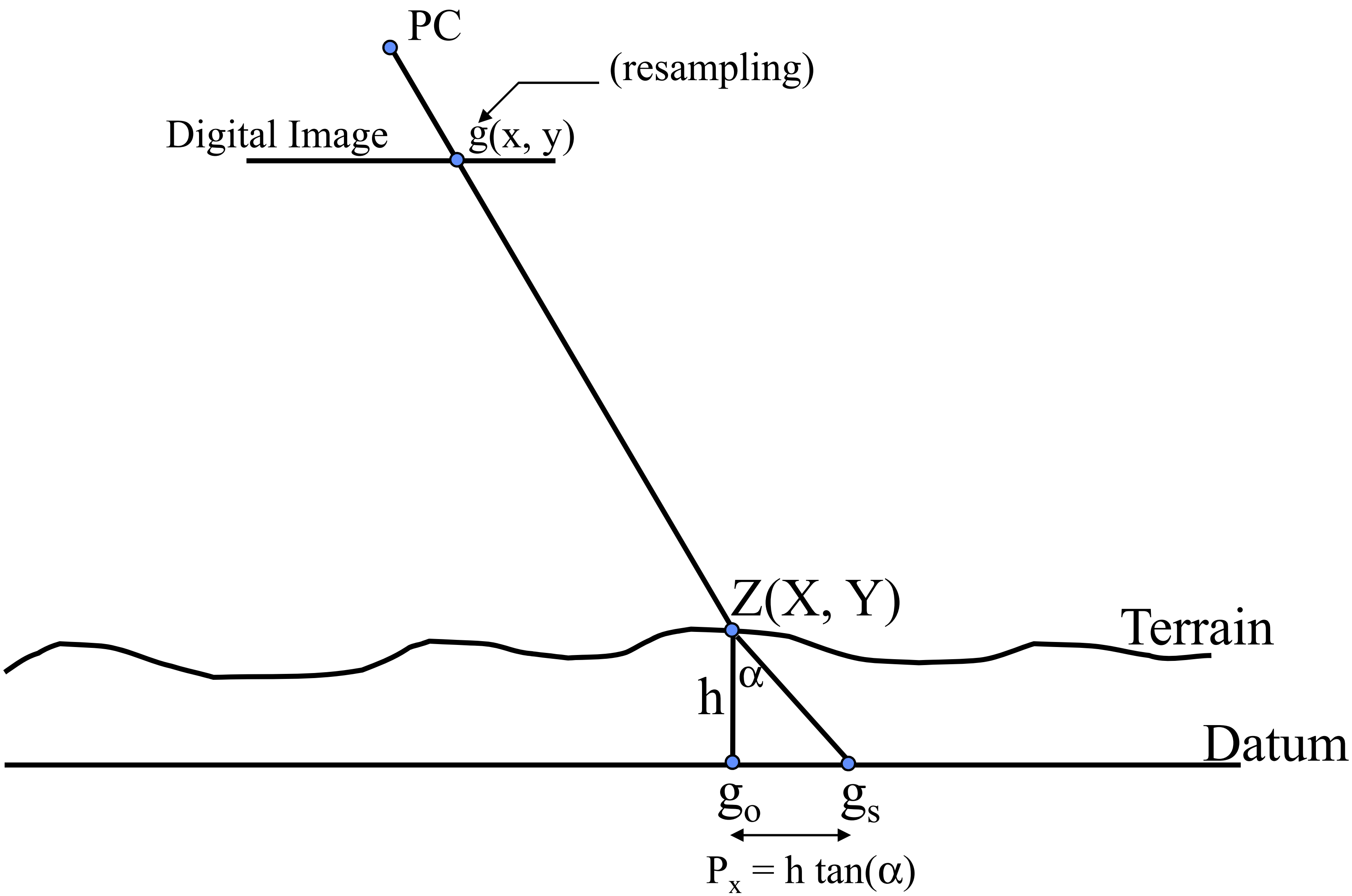
Digital Stereo-Mate Generation

- Procedure:
  - Define a square grid in the XY-plane (datum)
  - Project the grid points along oblique parallel rays in the XZ-plane to the DEM surface $\Rightarrow$ (XYZ)
  - Transform the XYZ coordinates of the intersection points into the image space using the collinearity equations $\Rightarrow$ (xy)
  - Apply one of the resampling techniques to get the gray value at the corresponding image location
  - The resampled gray values are stored at the corresponding locations along the defined grid.

Digital Stereo-Mate Generation



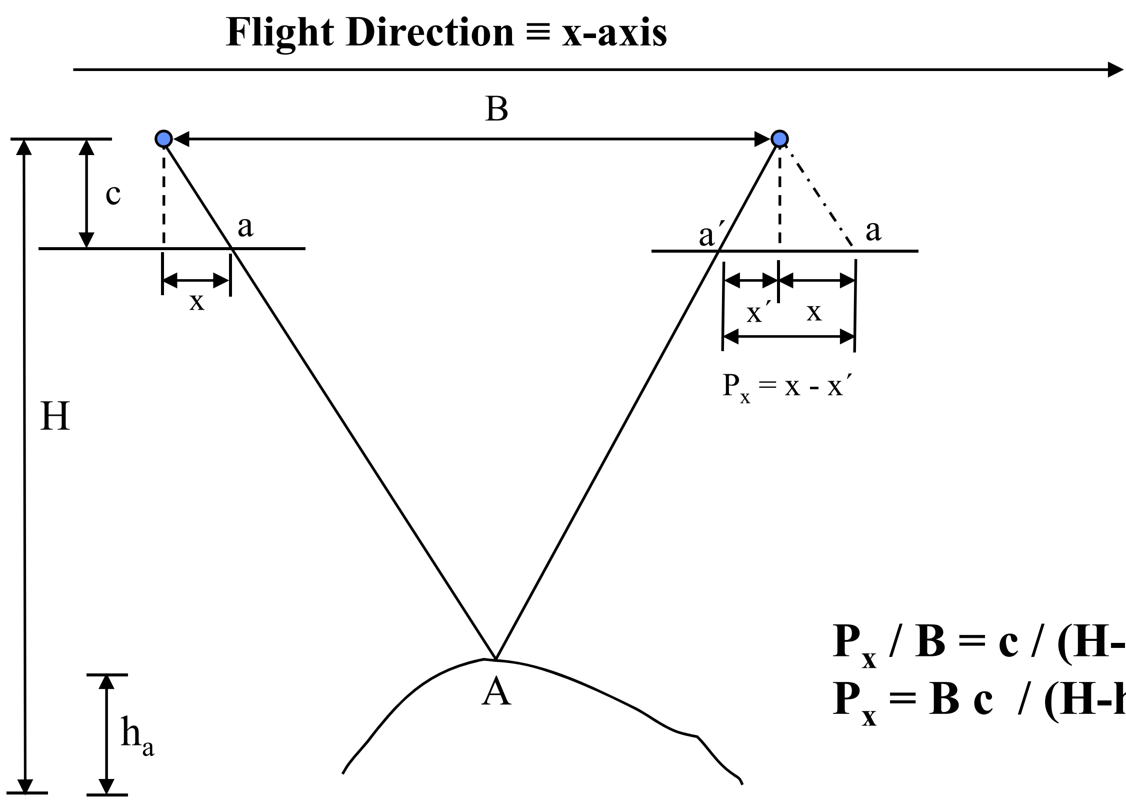
Introduced X-Parallax



Introduced X-Parallax

- Note: The oblique parallel projection is applied in the XZ-plane $\Rightarrow$ only X-parallax is introduced.
- The introduced X-parallax = h tan(α)
  - Where α is the projection direction of the oblique projection.
- Therefore, the introduced X-parallax is proportional to the elevation of the point above the datum.
- Question: How can we choose the parallel projection direction (α)?

Parallel Projection Direction (α)



$$P_x / B = c / (H-h_a)$$
$$P_x = B\,c / (H-h_a)$$

Parallel Projection Direction (α)

$$P_x = \frac{B\ c}{H - h_a} = \frac{B\ c}{H\ (1 - h_a / H)}$$

$$P_x \approx \frac{B\ c}{H} (1 + h_a / H)\ \{\text{Image Space}\}$$

$$P_x \approx B + B / H\ h_a\ \{\text{Object Space}\}$$

$$P_x \approx \text{constant} + B / H\ h_a \approx B / H\ h_a$$

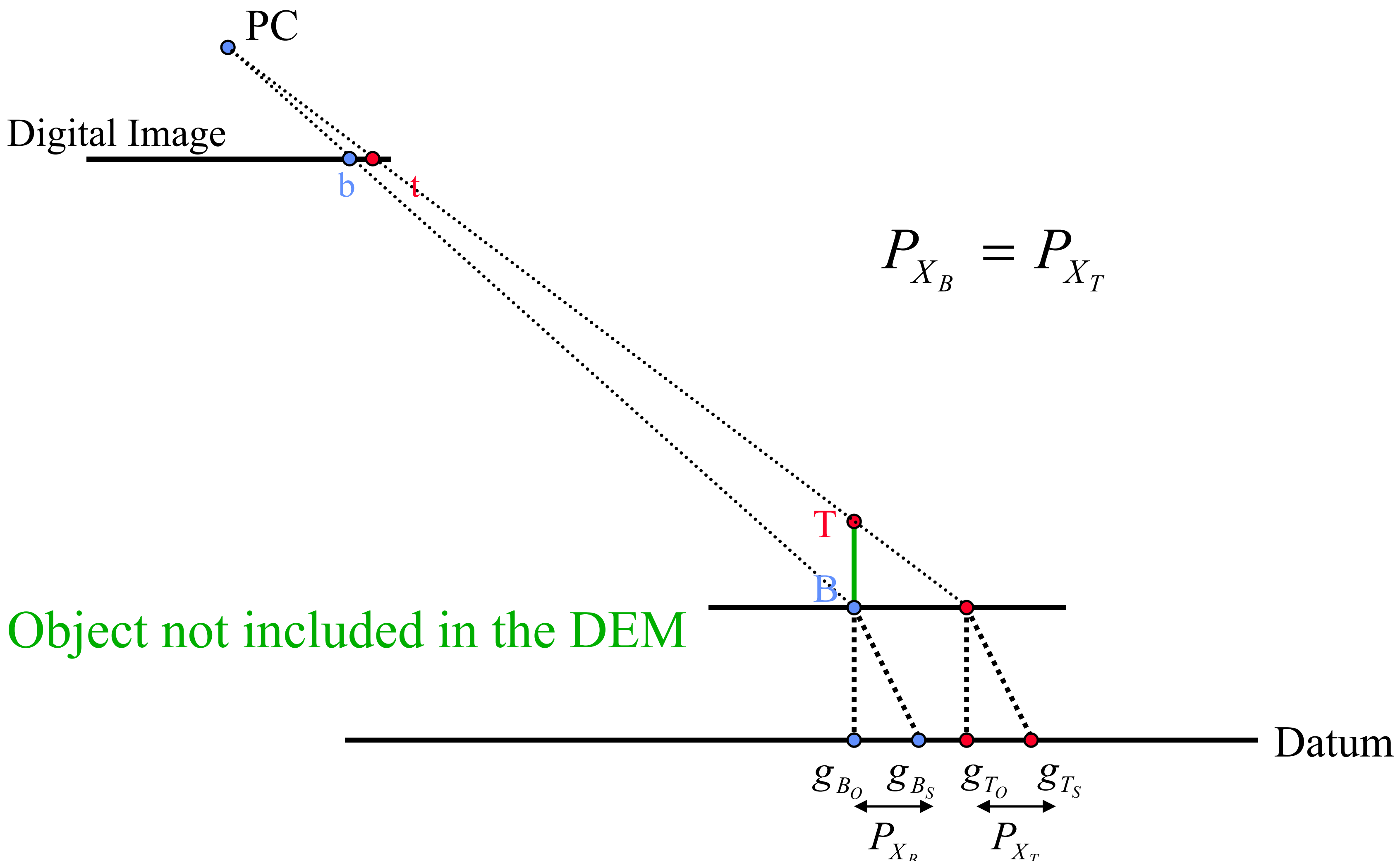
$$P_x \approx B / H\ h_a$$

$$\tan(\alpha) = B / H$$

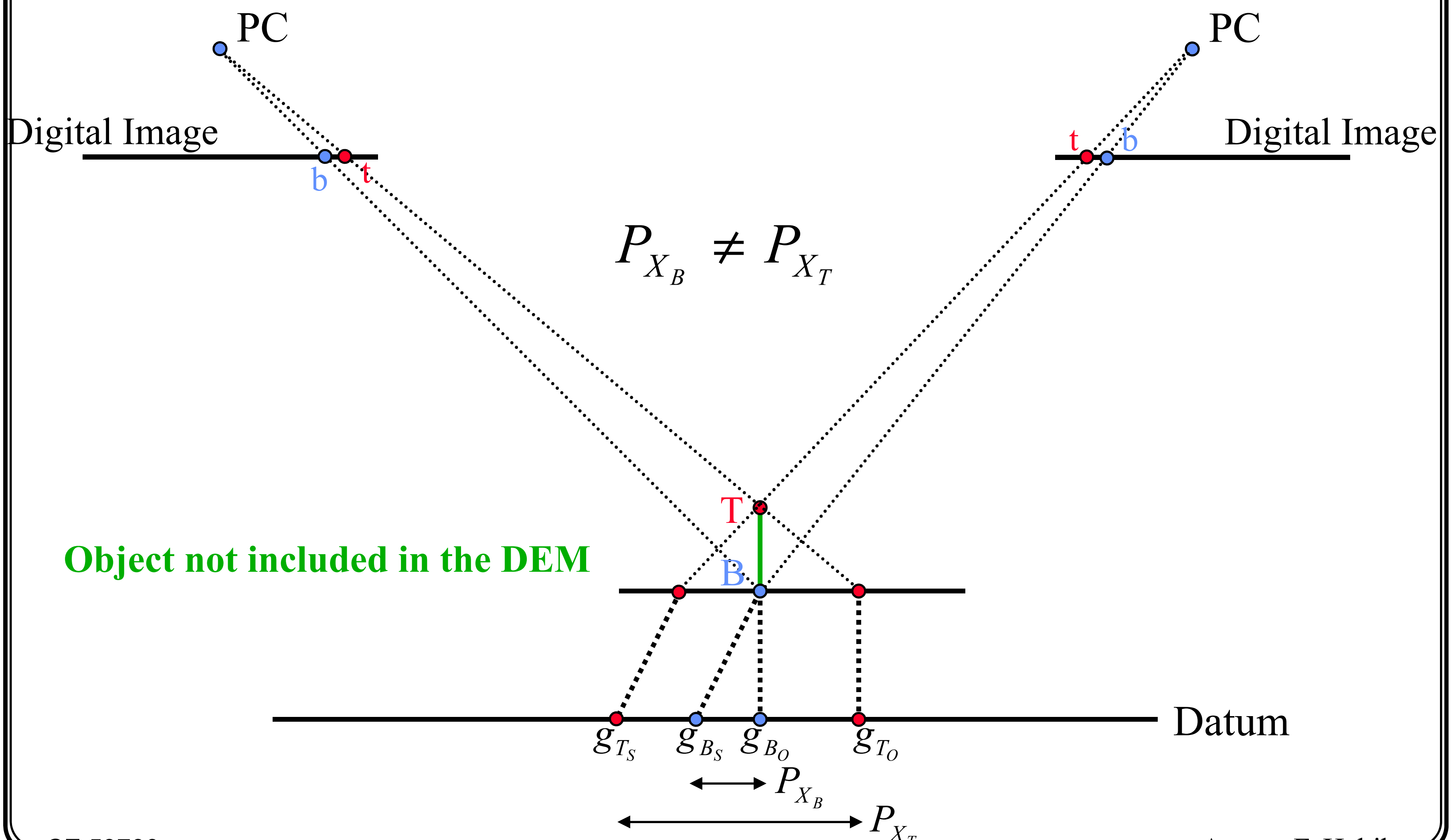
Digital Stereo-Mate Generation

- Now, we would like to study the impact of having some objects not included in the DEM in case of:
  - Using the same image for generating the orthophoto and the stereo-mate, or
  - Using two images of a stereo-pair for generating the orthophoto and the stereo-mate.
- Note: in the stereo-mate, we generate an X-parallax (artificial parallax) using the oblique parallel projection.

Using One Image



Using a Stereo-Pair



Digital Stereo-Mate Generation

- If we use the same image to generate the orthophoto and the stereo-mate:
  - Objects not included in the DEM will appear lying on the terrain surface.
- If we use a stereo-pair to generate the orthophoto and the stereo-mate:
  - Objects not included in the DEM will appear above the terrain surface.
  - The introduced parallax is known as natural parallax.

Chapters 1 – 12: Overview

- Chapter 1: Introduction
- Chapters 2 – 4: Data acquisition
- Chapters 5 – 7: Data manipulation
  - Chapter 5: Vertical imagery
  - Chapter 6: Image coordinate measurements and refinements
  - Chapters 7 - 10: Mathematical model, bundle block adjustment, integrated sensor orientation, and direct geo-referencing
  - Chapter 11: Digital image matching
  - Chapter 12: Production of map-like images (orthophotos)