Infrastructure Inventory Compilation Using Single High-Resolution Satellite Images

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Overview

- Objective
- Building Inventory Data Structure
- Why Building Inventory?
- Available Building Inventory Databases
- Why Remote Sensing?
- Proposed Algorithm
  - Sensor Models
  - Rational Function Model
  - Image Acquisition Geometry
  - 3D Reconstruction Algorithm
  - Measurement Error
- Implementation (MIHEA)
- Results and Calibration

Objective

To develop a semi-automated method for spatial and structural information extraction from single satellite images to be used in building inventories

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Building Inventory Data Structure

- Address or Lon/Lat
- Age or year of construction
- Height or number of stories
- Footprint Area
- Structural type
- Occupancy type
- Roof type
- Cladding
- Shape irregularity
- Height irregularity

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Why Building Inventory?

Vital information to:

- Decision Makers
- Urban Planners
- Disaster Response
- Loss Estimation
- Portfolio management

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Available Inventory Databases

Sources:

- Tax Assessors files
- Government files (e.g. FEMA, GSA ...)
- Sanborn maps (US only)
- Real estate files
- Insurance portfolios

Problems:

- Not always available in digital format
- Incomplete for many attributes
- Unavailable for many regions (e.g. developing countries)
- Updating only some information

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Why Remote Sensing?

- Remote and hard to reach locations
- Digital formats
- Can augment missing information
- Large Coverage
- Frequent updates
- Eventually will be more cost effective than land survey

Building Inventory Data Structure

- Address or Lon/Lat *
- Age or year of construction
- Height or number of stories*
- Footprint Area*
- Structural type
- Occupancy type
- Roof type*
- Cladding*
- Shape irregularity*
- Height irregularity*

* - information that can be obtained from imagery

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Sensor Models

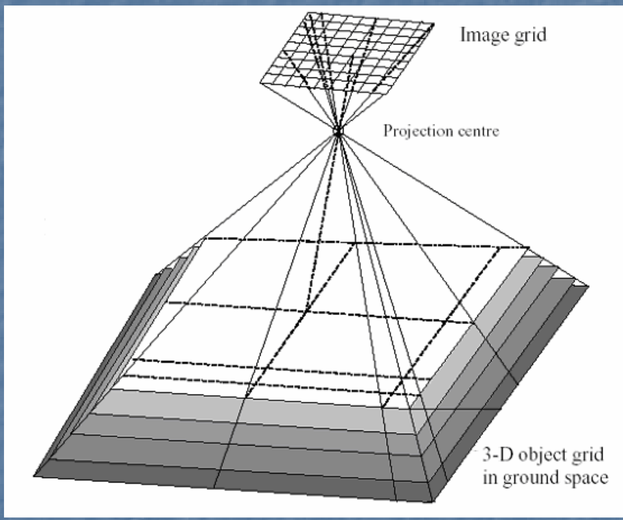
- Physical Sensor Model
  - Sensor dependent
  - Parameters have physical significant
  - Parameters are statistically uncorrelated
  - Rigorous and not always available to users
- Generalized Sensor Model
  - Generic
  - Sensor independent
  - Real-time computation

Rational Function Models (RFMs)

- Describes the image-to-ground relationships.
- Generalization of polynomial models (ratio of two polynomial functions)

$$r_n = \frac{f_1(\phi_n, \lambda_n, h_n)}{f_2(\phi_n, \lambda_n, h_n)}$$

$$c_n = \frac{f_3(\phi_n, \lambda_n, h_n)}{f_4(\phi_n, \lambda_n, h_n)}$$



RFMs cont'd

Rational Polynomial Coefficients (RPCs)

$$f = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3} a_{ijk}\phi^i \lambda^j h^k$$

$$\begin{aligned} f &= a_1 + a_2\lambda + a_3\phi + a_4 h + a_5\lambda\phi + \\ & a_6\lambda h + a_7\phi h + a_8\lambda^2 + a_9\phi^2 + a_{10}h^2 + \\ & a_{11}\phi\lambda h + a_{12}\lambda^3 + a_{13}\lambda\phi^2 + a_{14}\lambda h^2 + \\ & a_{15}\lambda^2\phi + a_{16}\phi^3 + a_{17}\phi h^2 + a_{18}\lambda^2 h + \\ & a_{19}\phi^2 h + a_{20}h^3 \end{aligned}$$

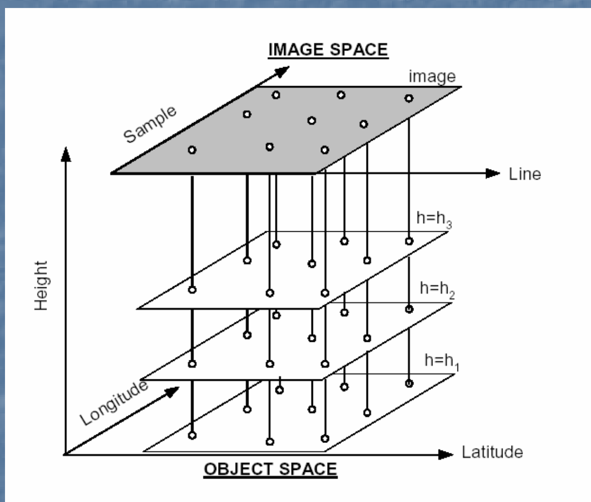


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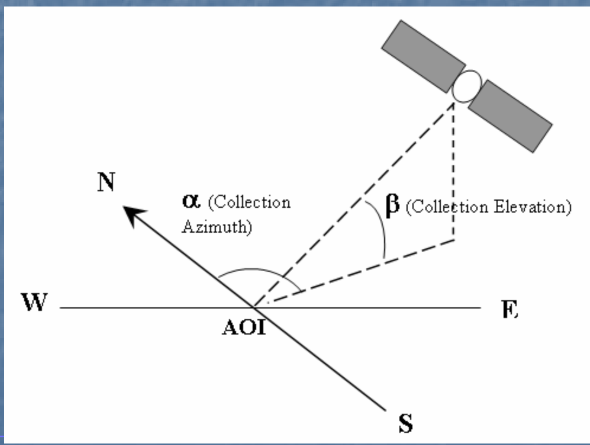
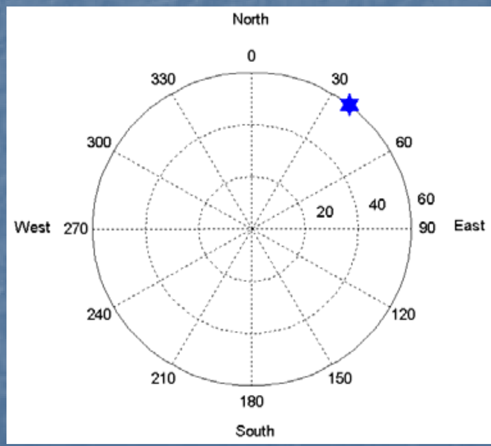
Image Acquisition Geometry

Approximate image acquisition geometry and satellite orientation can be described by sensor's <u>elevation</u> and <u>azimuth</u> angles





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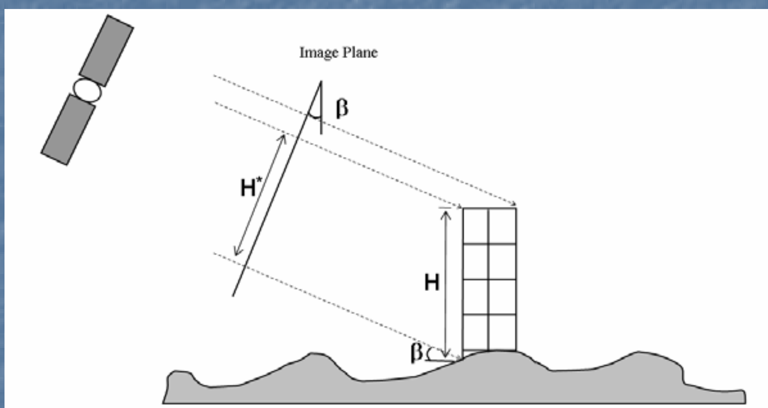
Height Metrology

- Image coordinates for the corner of a building at ground level (r_{ground}, c_{ground}), and its corresponding roof-point coordinates (r_{roof}, c_{roof})
- Sensor's collection azimuth angle



$$H = \frac{H^*}{\cos(\beta)}$$

$$H^* = GSD \times \sqrt{(r_{ground} - r_{roof})^2 + (c_{ground} - c_{roof})^2}$$

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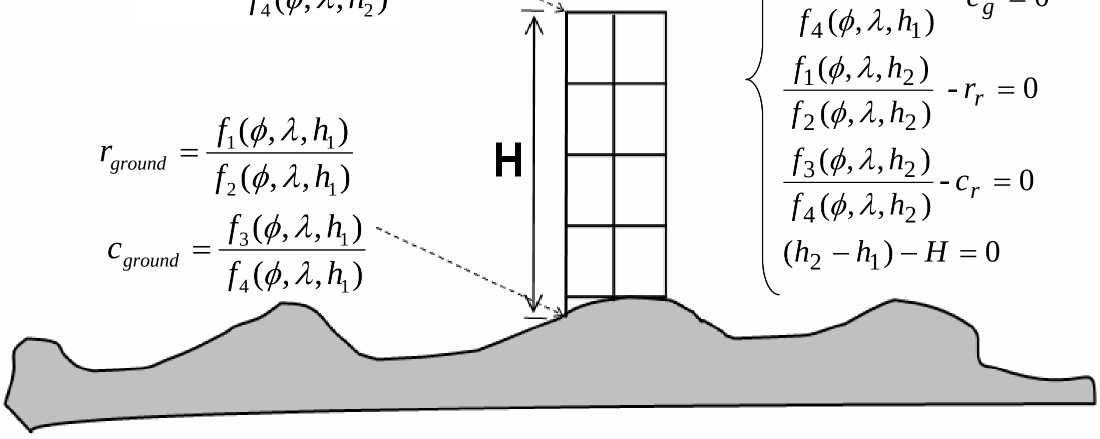
3D Reconstruction Algorithm

$$r_{roof} = \frac{f_1(\phi,\lambda,h_2)}{f_2(\phi,\lambda,h_2)}$$

$$c_{roof} = \frac{f_3(\phi,\lambda,h_2)}{f_4(\phi,\lambda,h_2)}$$

$$r_{ground} = \frac{f_1(\phi,\lambda,h_1)}{f_2(\phi,\lambda,h_1)}$$

$$c_{ground} = \frac{f_3(\phi,\lambda,h_1)}{f_4(\phi,\lambda,h_1)}$$



$$\begin{cases} \dfrac{f_1(\phi,\lambda,h_1)}{f_2(\phi,\lambda,h_1)} - r_g = 0 \\ \dfrac{f_3(\phi,\lambda,h_1)}{f_4(\phi,\lambda,h_1)} - c_g = 0 \\ \dfrac{f_1(\phi,\lambda,h_2)}{f_2(\phi,\lambda,h_2)} - r_r = 0 \\ \dfrac{f_3(\phi,\lambda,h_2)}{f_4(\phi,\lambda,h_2)} - c_r = 0 \\ (h_2 - h_1) - H = 0 \end{cases}$$

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3D Reconstruction Algorithm - cont'd

- Homogeneous
- Nonlinear
- Over-determined

Solution: Trust-Region Dogleg Method

$$\begin{aligned} &\frac{f_1(\phi,\lambda,h_1)}{f_2(\phi,\lambda,h_1)} - r_g = 0 \\ &\frac{f_3(\phi,\lambda,h_1)}{f_4(\phi,\lambda,h_1)} - c_g = 0 \\ &\frac{f_1(\phi,\lambda,h_2)}{f_2(\phi,\lambda,h_2)} - r_r = 0 \\ &\frac{f_3(\phi,\lambda,h_2)}{f_4(\phi,\lambda,h_2)} - c_r = 0 \\ &(h_2 - h_1) - H = 0 \end{aligned}$$

Starting point for the iterative solution: by linearizing RFM

$$r_g = \frac{a_1 + a_2\lambda + a_3\phi + a_4 h_1}{b_1 + b_2\lambda + b_3\phi + b_4 h_1} + \varepsilon_1,\quad c_g = \frac{c_1 + c_2\lambda + c_3\phi + c_4 h_1}{d_1 + d_2\lambda + d_3\phi + d_4 h_1} + \varepsilon_2$$

$$r_r = \frac{a_1 + a_2\lambda + a_3\phi + a_4 h_2}{b_1 + b_2\lambda + b_3\phi + b_4 h_2} + \varepsilon_3,\quad c_r = \frac{c_1 + c_2\lambda + c_3\phi + c_4 h_2}{d_1 + d_2\lambda + d_3\phi + d_4 h_2} + \varepsilon_4$$

$$A \cdot \mathbf{x_0} = b$$

$$A = \begin{bmatrix} r_g b_2 - a_2 & r_g b_3 - a_3 & r_g b_3 - a_3 & 0 \\ c_g d_2 - d_2 & c_g d_3 - d_3 & c_g d_3 - d_3 & 0 \\ r_r b_2 - a_2 & r_r b_3 - a_3 & 0 & r_r b_3 - a_3 \\ c_r d_2 - d_2 & c_r d_3 - d_3 & 0 & c_r d_3 - d_3 \end{bmatrix},\quad \mathbf{x_0} = \begin{bmatrix} \phi^* \\ \lambda^* \\ h_1^* \\ h_2^* \end{bmatrix},\quad b = \begin{bmatrix} a_1 - r_g b_1 \\ c_1 - c_g d_1 \\ a_1 - r_r b_1 \\ c_1 - c_r d_1 \end{bmatrix}$$

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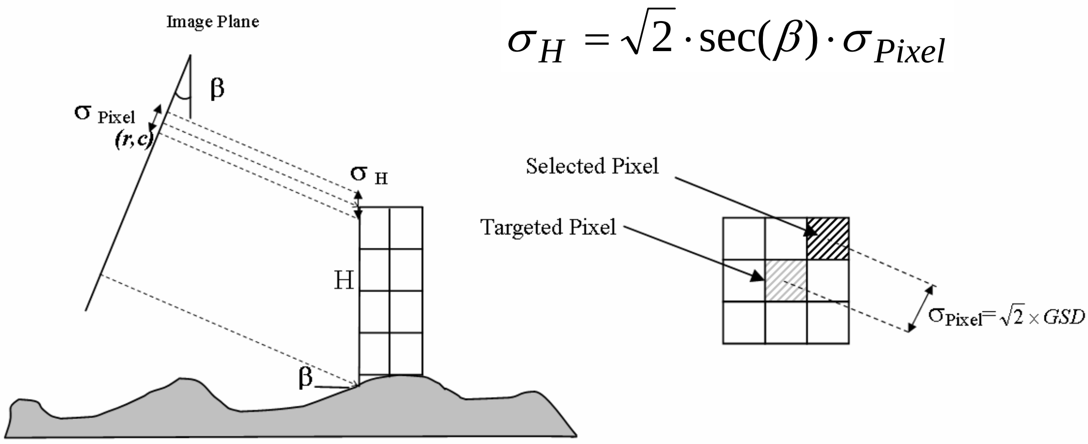
Measurement Error

- Image dependent (shadows and obstacles along the line of sight)
- User (operator) dependent



$$\sigma_H = \sqrt{2} \cdot \sec(\beta) \cdot \sigma_{Pixel}$$

Sensor	Altitude (Km)	Off-Nadir (degree)	Collection Azimuth (β - degrees)	GSD @ off-nadir	σ_{Pixel} (m)	σ_H (m)
IKONOS	681	26	64	1.0 m	1.41	4.56
QuickBird	450	25	65	0.72 m	1.02	3.23

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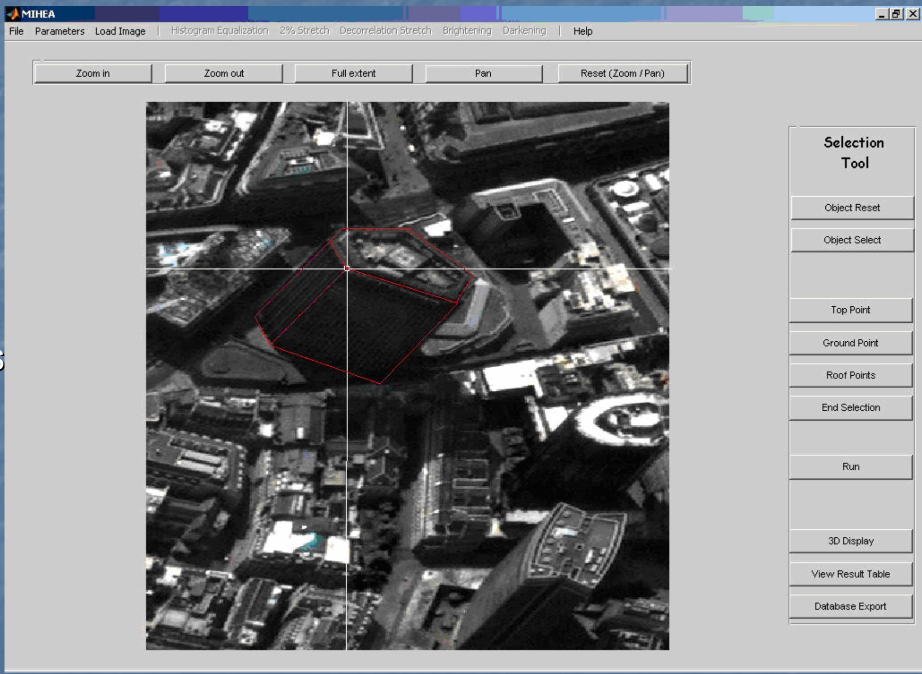
MIHEA

(Mono-Image Height Extraction Algorithm)

- Image Processing Package
- Compatible with IKONOS and QuickBird camera models
- Export results to database



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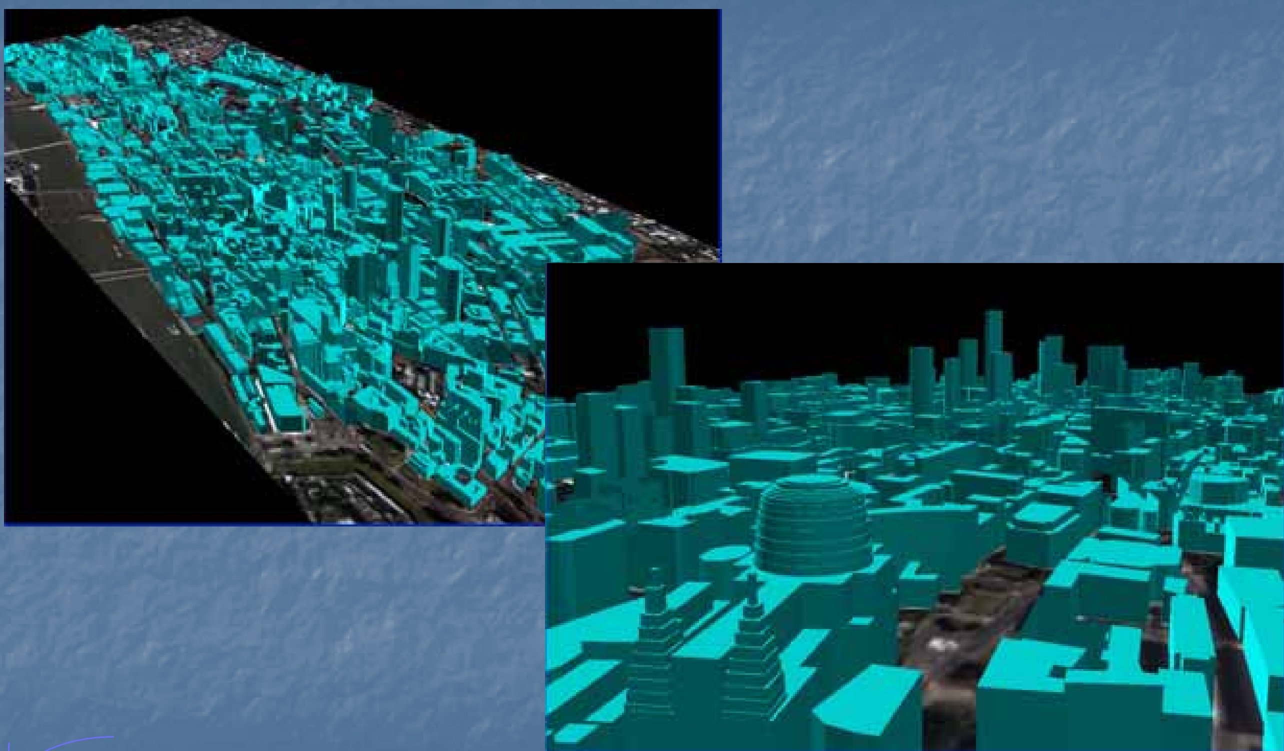
MIHEA cont'd



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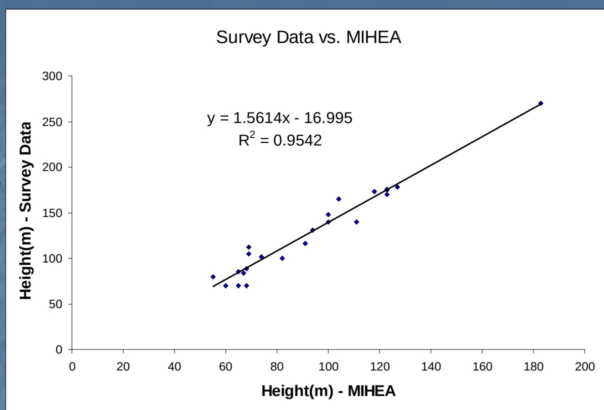
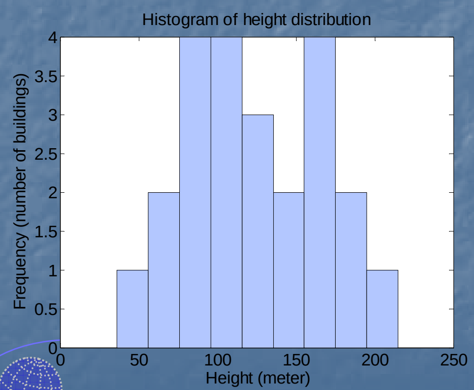
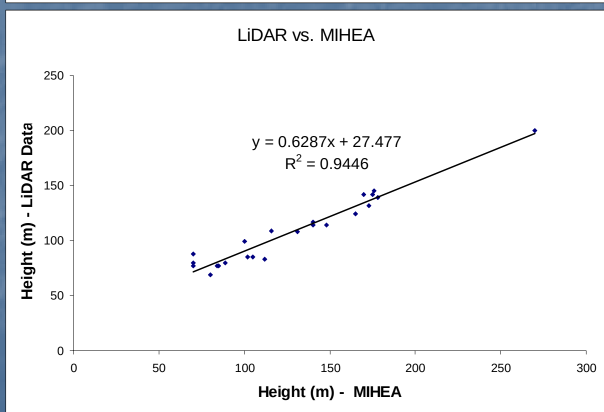
Results and Calibration

- Sensor: QuickBird Image
- Test Area: City of London
- Date: July 28, 2002
- Off-nadir viewing angle: 24.6º
- Validation sources: LiDAR and independently derived survey data
- Validation set: 23 buildings selected from 3D model







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Questions?