GEOS 639 – INSAR AND ITS APPLICATIONS

GEODETIC IMAGING AND ITS APPLICATIONS IN THE GEOSCIENCES

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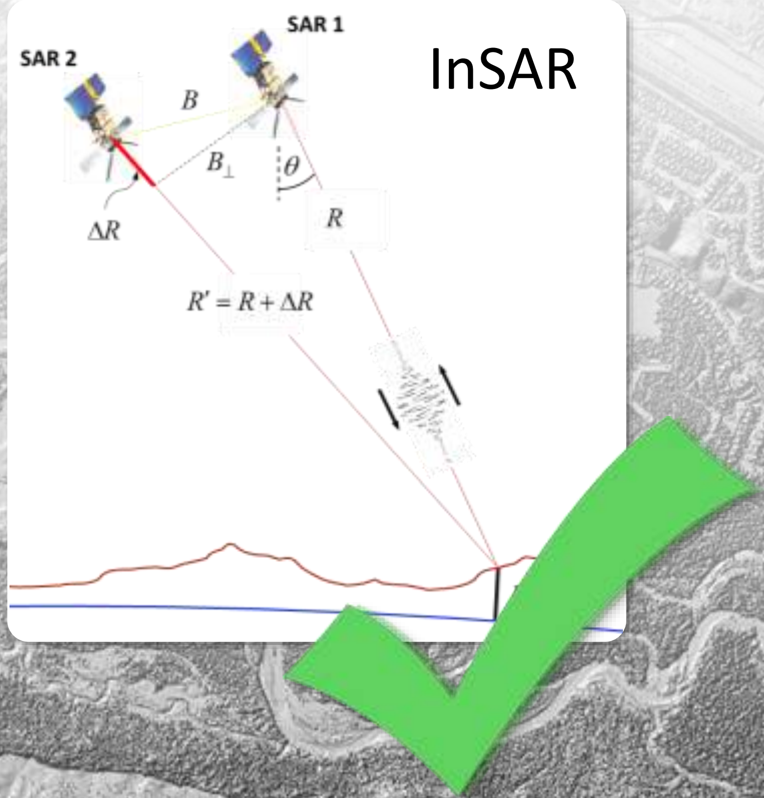
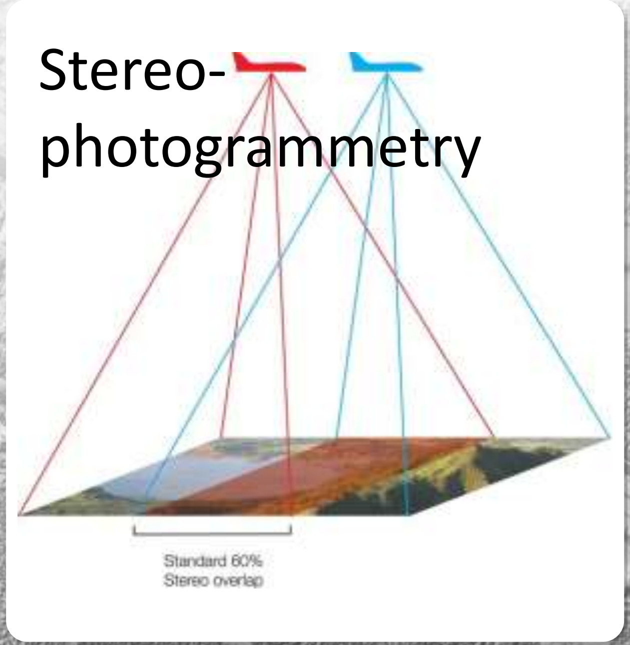
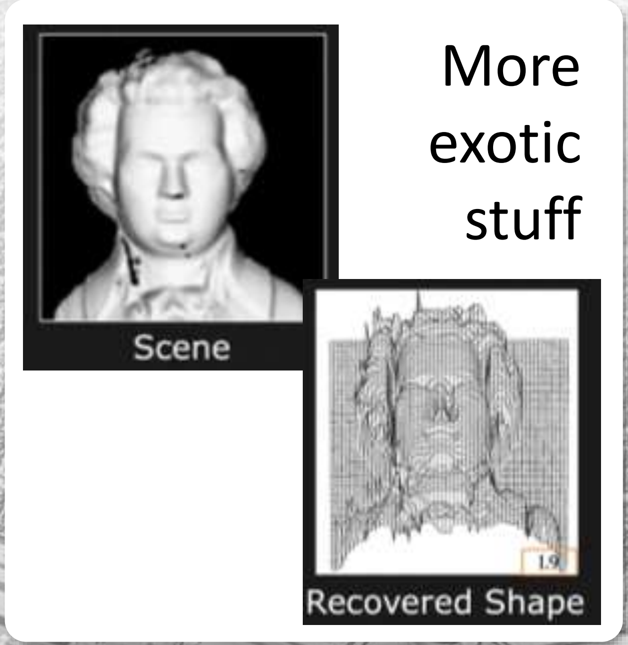
Lecture 7: Stereo Photogrammetry – Creating DEMs from Optical Imagery

Recap of DEM Mapping Techniques We'll Discuss







Stereo Photogrammetry – A Definition

- Stereo-photogrammetry involves estimating the 3D coordinates of points on an object employing measurements made from two or more photographic images taken from different positions.

- Stereo-photogrammetry is based on the **stereoscopic** principles which allow us to create or enhance the illusion of depth in an image by means of stereopsis for **binocular vision**.

An Example of a Stereo Image Pair

Are these pictures identical or do you see differences?

Kasuga Lantern; Osaka Garden, Jackson Park, Chicago

Let’s Look at This Image Pair a Second Time – But a Bit Differently

And a Third Time – This is Called an Anaglyph

Now Let's Look a bit at the Mathematics of Images

Stereo Pairs

Defining “Photogrammetry”

- Photogrammetry is "the art and science of making measurements from (optical) images."
- Specifically, goal is to measure locations of features in the images (image space) and try to relate them to
  - (a) the position, pointing, and attitude of the camera (called orientation); and
  - (b) the locations of the features in the real world (ground or object space).
- The basic formulation that combines positions is called the **Collinearity Equation** (see next slide).

NOTE: Collinearity is very important in traditional photogrammetry we will talk about collinearity a number of times

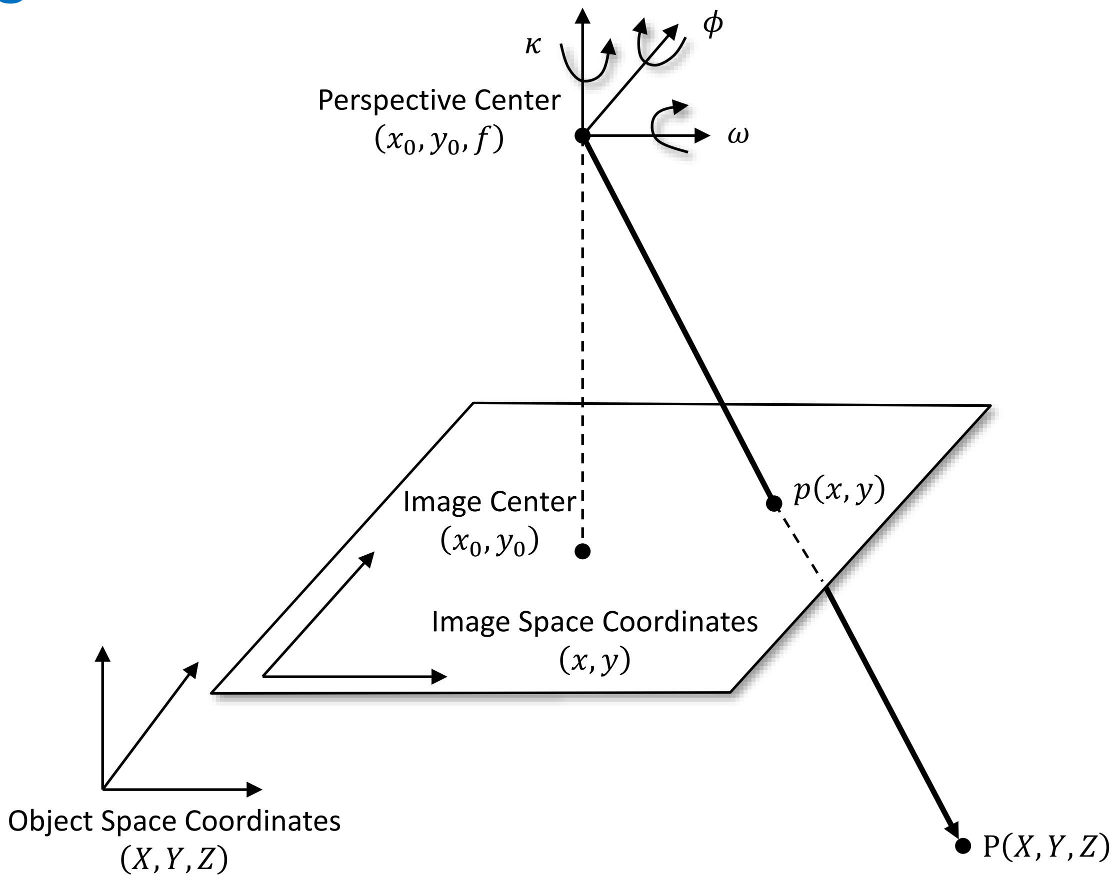
Collinearity Condition

- **Geometrical condition that the camera (the perspective center), the image point, and the corresponding point on the ground, lie on a straight line**

- If information on camera position and camera orientation known → some object space coordinates can be calculated from measured image pixel coordinates.

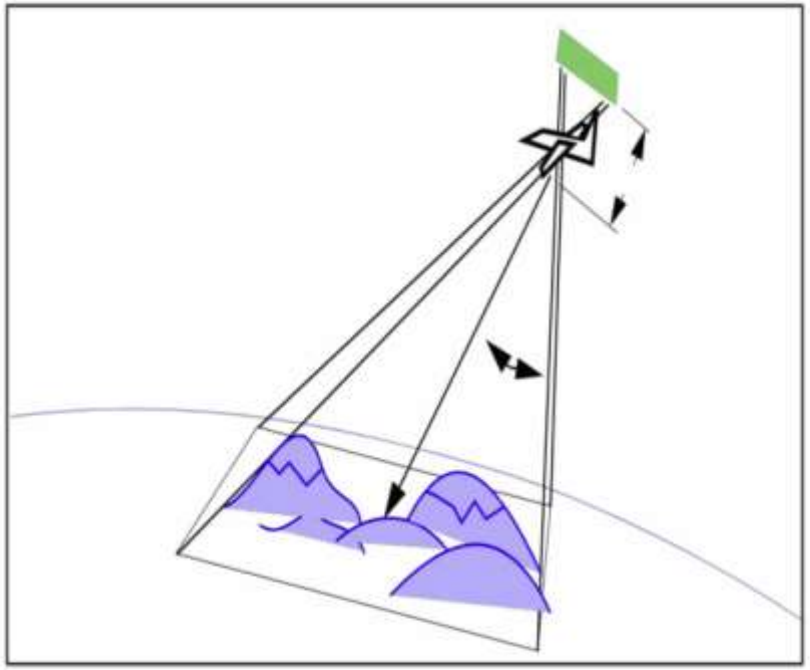
- **Note: Lens distortions violate the collinearity condition**

  → in stereo-processing lens distortions are either assumed negligible or assumed known and corrected

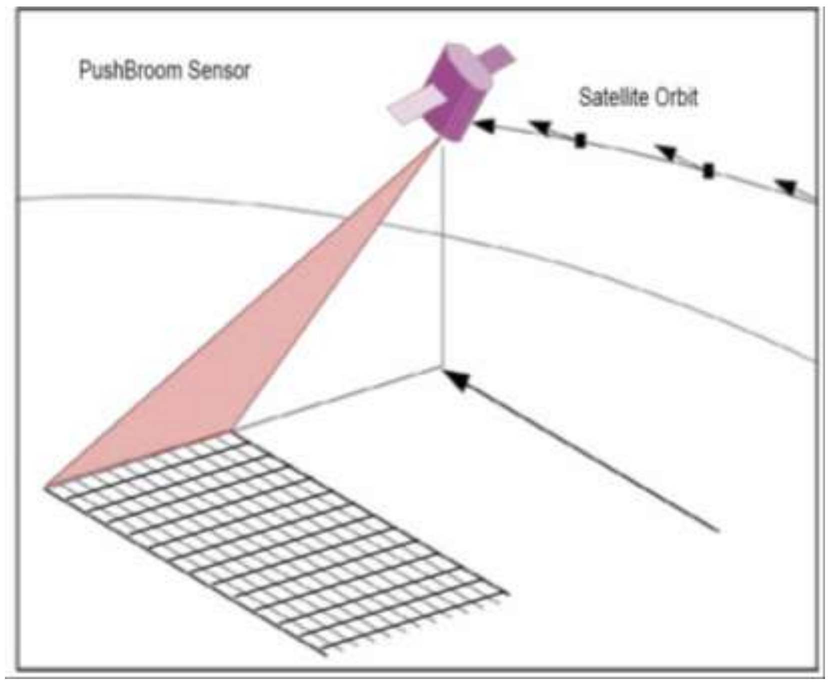


Sensor Models Define the Geometry of the Collinearity Lines

- **Sensor models define mathematical connection between measured image pixel coordinates $p(x, y)$ and object space coordinates $P(X, Y, Z)$.**
- **Sensor models depend on Sensor type**
  - Mathematical relations for frame cameras (left) differ from those of pushbroom cameras (right)



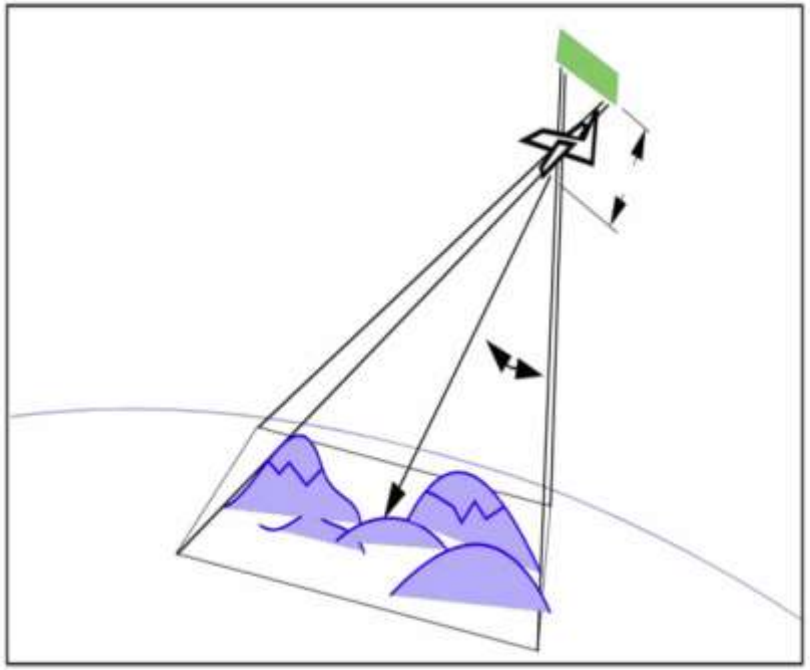
Frame Camera Sensor Models



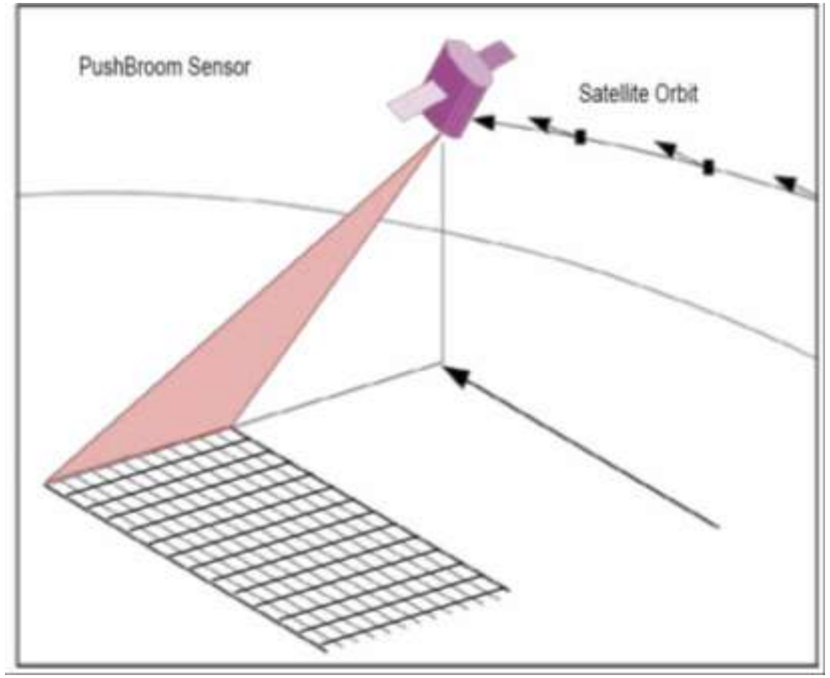
Pushbroom Sensor Models

Sensor Models and Collinearity Conditions

Frame Cameras		Pushbroom Sensors
Perspective projection		Perspective projection perpendicular to flight line Parallel projection parallel to flight line
Exterior orientation consistent per image		Every scan line as separate exerior orientation parameters



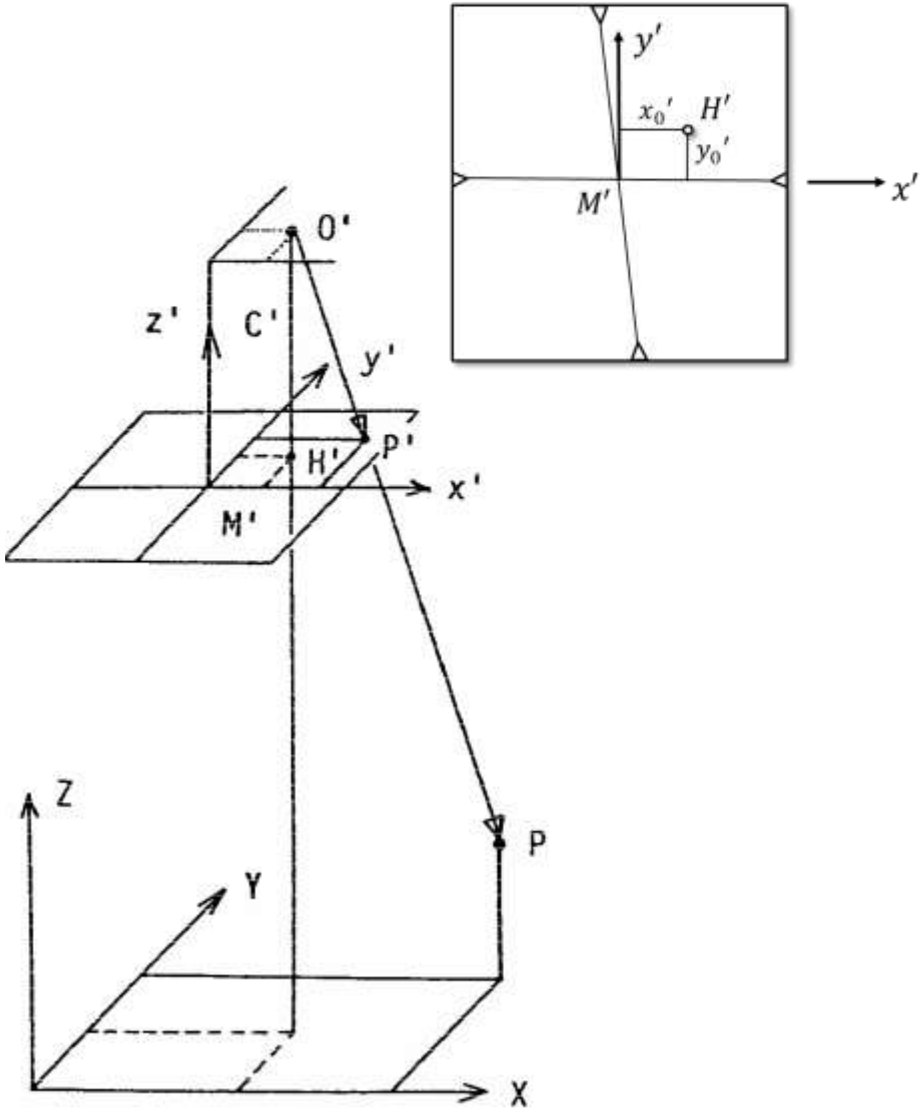
Frame Camera Sensor Models



Pushbroom Sensor Models

Single Image Math – Nadir View; Perspective Case

Coordinate Systems and Collinearity Equations



- **Image Coordinate System**:
  - $x'\ y'$: Coordinates measured relative to M'
  - $x'_0\ y'_0$: Coordinates of principal point H'
  - $x'\ y'\ z'$: spatial image coordinates
  - $P'(x'\ y'\ 0)$: Point in image
  - $O'(x'_0\ y'_0\ c')$: Projection center (focal length c')
- **Object Coordinate System**:
  - $X\ Y\ Z$: Ground (real world) object coordinates
  - $P(X\ Y\ Z)$: Object point
  - $O'(X'_0\ Y'_0\ Z'_0)$: Projection center in object coords
- **Collinearity Equations – Nadir View**:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} X'_0 \\ Y'_0 \\ Z'_0 \end{bmatrix} = m' \left(\begin{bmatrix} x' \\ y' \\ 0 \end{bmatrix} - \begin{bmatrix} x'_0 \\ y'_0 \\ c' \end{bmatrix} \right)$$

  - $m' = {}^{(z'_0 - z)}/_{c'}$: scale factor for point P

Using Collinearity Equations to Calculate Object Coordinates

- **From previous slide**:

$$\left.\begin{aligned} X - X_0' &= m'(x' - x_0') \\ Y - Y_0' &= m'(y' - y_0') \\ Z - Z_0' &= -m'c' \end{aligned}\right\} \Rightarrow \begin{aligned} \frac{X - X_0'}{Z - Z_0'} &= \frac{x' - x_0'}{c'} \\ \frac{Y - Y_0'}{Z - Z_0'} &= \frac{y' - y_0'}{c'} \end{aligned}$$

→ **From single image**: Two independent collinearity equations

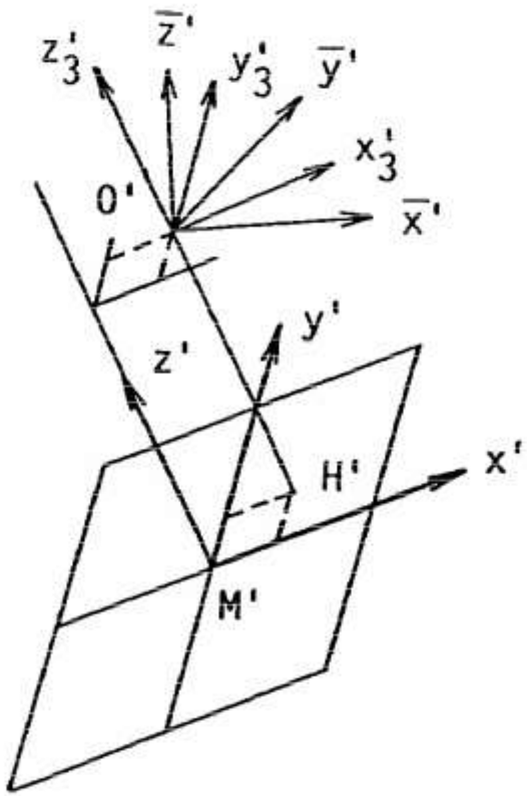
- **Calculate object coordinates from collinearity equations**:

$$\begin{aligned} X &= X_0' - (Z - Z_0')\frac{x' - x_0'}{c'} \quad , \quad x' = x_0' - c'\frac{X - X_0'}{Z - Z_0'} \\ Y &= Y_0' - (Z - Z_0')\frac{y' - y_0'}{c'} \quad , \quad y' = y_0' - c'\frac{Y - Y_0'}{Z - Z_0'} \end{aligned}$$

→ **From single image**: **Only two object coordinates can be resolved**

Single Image Math – General Case

Coordinate Systems and Collinearity Equations



- **Image Coordinate System $x'\ y'\ z'$ rotated relative to $X\ Y\ Z$:**
  - New coordinate system $\bar{x}'\ \bar{y}'\ \bar{z}'$ defined parallel to $X\ Y\ Z$ with origin in O'
  - **Relationship of $\boldsymbol{x'\ y'\ z'}$ and $\boldsymbol{\bar{x}'\ \bar{y}'\ \bar{z}'}$**
    - 3D rotation from $\bar{x}'\ \bar{y}'\ \bar{z}' \rightarrow x_3'\ y_3'\ z_3'$ usually described as the combination of three 3D rotation matrices.
    - Spatial shift from $x_3'\ y_3'\ z_3' \rightarrow x'\ y'\ z'$

- **Collinearity Equations – General Case:**

$$\begin{bmatrix} X - X_0' \\ Y - Y_0' \\ Z - Z_0' \end{bmatrix} = m' \underbrace{\begin{bmatrix} r_{11}' & r_{12}' & r_{13}' \\ r_{21}' & r_{22}' & r_{23}' \\ r_{31}' & r_{32}' & r_{33}' \end{bmatrix}}_{\boxed{\text{Rotation matrix } R\{\omega', \varphi', \kappa'\}}} \begin{bmatrix} x' - x_0' \\ y' - y_0' \\ -c' \end{bmatrix} = m' \begin{bmatrix} \bar{x}' \\ \bar{y}' \\ \bar{z}' \end{bmatrix}$$

- **Solving Collinearity Equations – General Case:**

$$\begin{aligned} X &= X_0' + (Z - Z_0') \frac{r_{11}'(x' - x_0') + r_{12}'(y' - y_0') - r_{13}'c'}{r_{31}'(x' - x_0') + r_{32}'(y' - y_0') - r_{33}'c'} \\ Y &= Y_0' + (Z - Z_0') \frac{r_{21}'(x' - x_0') + r_{22}'(y' - y_0') - r_{23}'c'}{r_{31}'(x' - x_0') + r_{32}'(y' - y_0') - r_{33}'c'} \end{aligned}$$

Single Image Math – General Case

Parameters of Interior and Exterior Orientation

- **Solving Collinearity Equations – General Case:**

$$
\begin{aligned}
X &= X_0' + (Z - Z_0')\frac{r_{11}'(x' - x_0') + r_{12}'(y' - y_0') - r_{13}'c'}{r_{31}'(x' - x_0') + r_{32}'(y' - y_0') - r_{33}'c'} \\
Y &= Y_0' + (Z - Z_0')\frac{r_{21}'(x' - x_0') + r_{22}'(y' - y_0') - r_{23}'c'}{r_{31}'(x' - x_0') + r_{32}'(y' - y_0') - r_{33}'c'}
\end{aligned}
$$

- **Unknown Orientation Parameters of Photogrammetry:**
  - **3 Parameters of interior orientation**: x_0', y_0', c' } Position of Projection Center
  - **6 Parameters of exterior orientation**: $\underbrace{X_0', Y_0', Z_0'}_{\text{Sensor Position}}$, and rotation parameters in $R\ \underbrace{(\omega', \varphi', \kappa')}_{\text{Sensor Attitude}}$

Think – Pair – Share

You are planning a flight campaign to create a DEM of your area of interest. To do so, you are flying on a Cesna 172 aircraft equipped with a Nikon D600 Camera and a Nikon 50mm f/1.8d lense

- We've learned that we need the **3 parameters of the interior orientation** and the **6 parameters of the exterior orientation** to measure coordinates from the acquired images.
  - **Q1**: How would you determine the interior orientation parameters? What would you expect their approximate values would be (in units of millimeters).
  - **Q2**: How would you measure the 6 exterior orientation parameters? Which devices would you use to determine these variables?

THE MATHEMATICS OF IMAGES

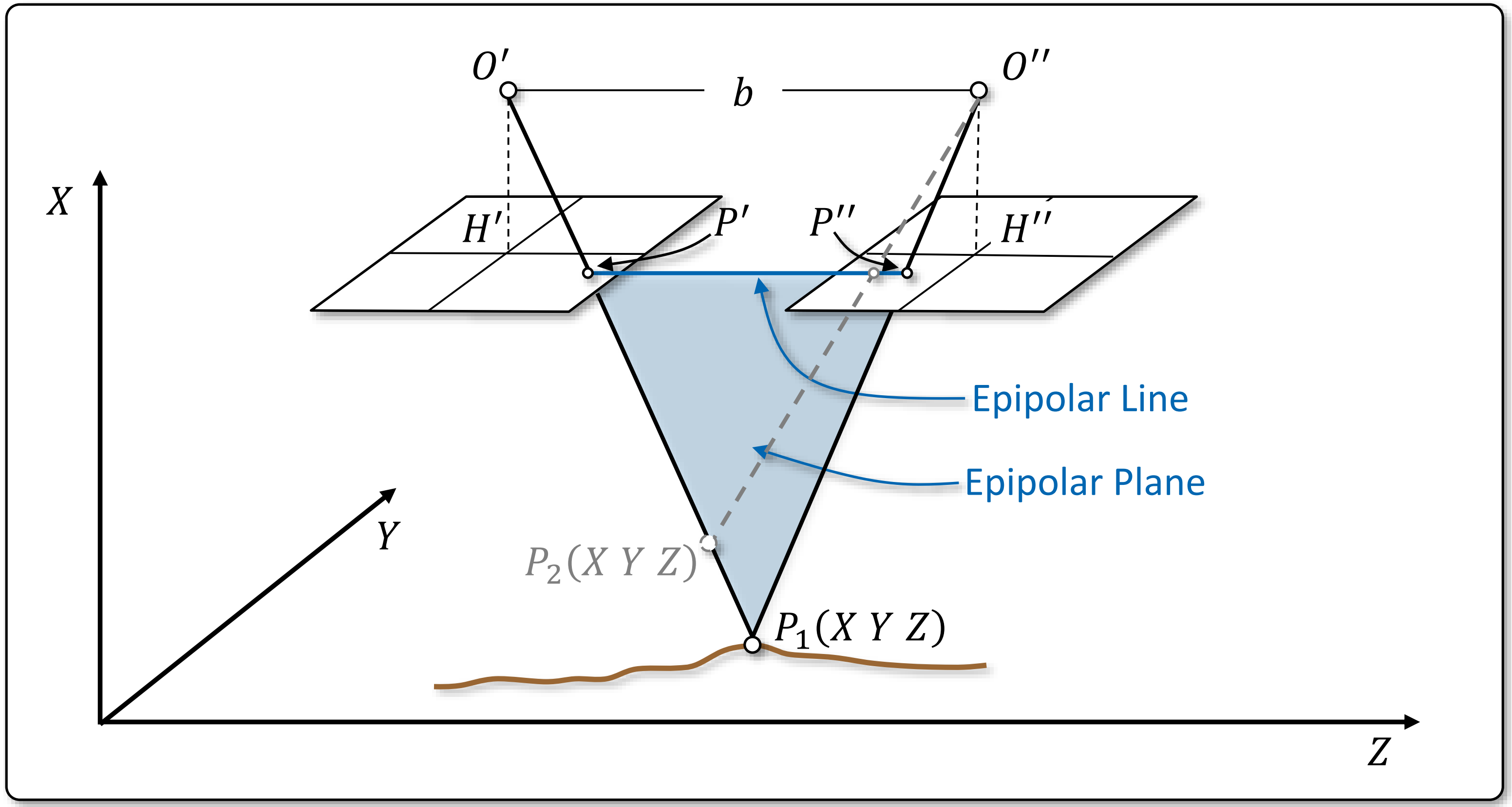
STEREO PAIRS

EXPECTED QUALITY OF EXTRACTED OBJECT COORDINATES

Geometry of Stereo Imaging

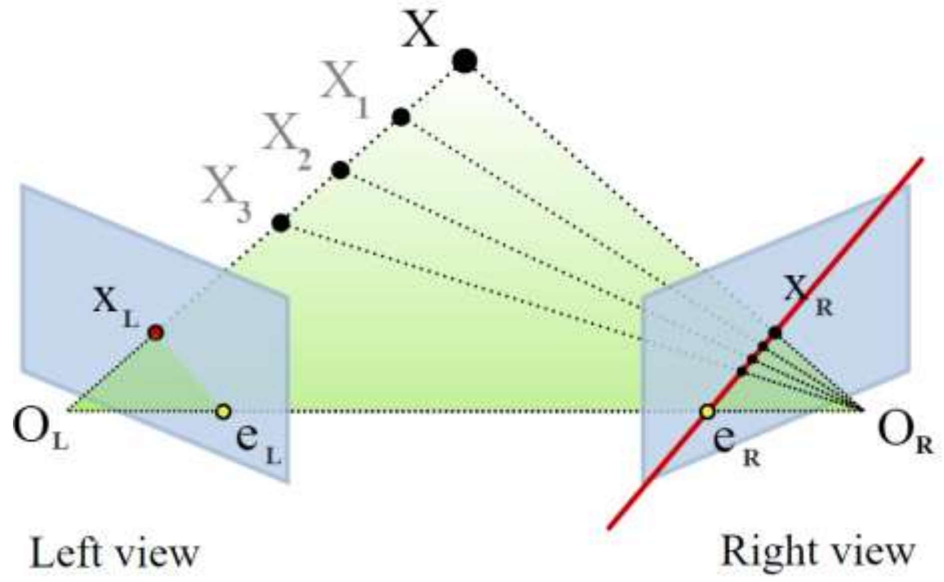
- **Reconstructing 3D object space coordinates:** Intersect two lines passing through the perspective centers and the point located in both images.
- We usually rotate images such that the intersecting lines, the perspective centers, and the object point form a plane → **epipolar geometry**.

NOTE: Epipolar geometry is a second important concept to remember



A Word on the Epipolar Geometry

- The epipolar geometry is rather important as it is used to limit the search for corresponding (conjugate) points in the left and right images into one dimension.
- **As shown in the image to the right, the search for conjugate points is limited to the epipolar lines**



- **In Stereo Photogrammetry, we usually use a simplified epipolar geometry:**
  - We usually **rotate images such that the image planes of the two cameras coincide**
    - → Epipolar lines parallel with one image direction
    - → **one dimensional search suffices for finding corresponding points**

The Mathematics of Stereo Pairs

- **Parameters:**

Left Image		Right Image
$x' \; y'$	Image coordinates	$x'' \; y''$
x'_0, y'_0, c'	Interior Orientation parameters	x''_0, y''_0, c''
$X'_0, Y'_0, Z'_0, \omega', \varphi', \kappa'$	Exterior Orientation Parameters	$X''_0, Y''_0, Z''_0, \omega'', \varphi'', \kappa''$
X, Y, Z	Object coordinates	X, Y, Z

- **In stereo-photogrammetry we usually use calibrated survey-grade cameras**

  → **Interior orientation parameters x'_0, y'_0, c' and x''_0, y''_0, c'' usually known and assumed free of error.**

- **Stereo processing approach:**
  1. Determine the 12 exterior orientation parameters ($X'_0, Y'_0, Z'_0, \omega', \varphi', \kappa'$ and $X''_0, Y''_0, Z''_0, \omega'', \varphi'', \kappa''$)
  2. Once exterior orientation parameters were determined → **identify points in both images and calculate their 3-D coordinates using the stereo collinearity equations (see next pages)**

The Mathematics of Stereo Pairs

Components of Exterior Orientation: Relative and Absolute Orientation

- **Exterior orientation can be split into two components**
  1. **Relative Orientation**: Orientation of images relative to each other
     → **5 parameters** → **deriving of a relative stereo model**
  2. **Absolute Orientation**: Orientation of relative stereo model in object coordinate system
     → **7 parameters** → **scaling of model, rotation, and shift**

- **The 5 Parameters of Relative Orientation:**
  - **Method 1 "Orientation along Baseline b":**
    - **Assume:** $bx =$ from orbit information; $by = bz = 0$; $\omega_r' = 0$
    - **5 Unknown parameters**: $\varphi_r',\ \kappa_r', \omega_r'', \varphi_r'', \kappa_r''$ (suffix "r" indicates "relative")
    - In other words: *"We assume we know the images' relative location and determine their relative rotations".*
  - **Method 2 "Image Bridging":**
    - **Assume:** $bx =$ from orbit information; $\omega_r' = \varphi_r' = \kappa_r' = 0$
    - **5 Unknown parameters**: $by,\ bz, \omega_r'', \varphi_r'', \kappa_r''$ $(R_r' = I, R_r'')$ (suffix "r" indicates "relative")
    - In other words: *"We assume we know the attitude of image 1 and distance between images and estimate distance vector and relative rotation of image 2".*

  - **Output of relative orientation:** Coordinates of **relative stereo model** $(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$

The Mathematics of Stereo Pairs

Components of Exterior Orientation: Relative and Absolute Orientation

- **The 7 Parameters of Absolute Orientation:**
  - **7 unknown parameters:** m_a (model scaling); $R_a(\omega_a, \varphi_a, \kappa_a)$ (model rotation); $O'(X_0', Y_0', Z_0')$ (model location)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = m_a R_a \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} X_0' \\ Y_0' \\ Z_0' \end{bmatrix}$$

Scaling and rotating model coordinates (x, y, z)

Shifting to correct model location

- **Joint Estimation of exterior orientation using ground control points (X_i, Y_i, Z_i)**
  - **Per ground control point, solve the following simultaneous observation equations:**

$$
\begin{aligned}
x_i' + \hat{\varepsilon}_{x_i'} &= \hat{x}_i'(\hat{X}_i, \hat{Y}_i, \hat{Z}_i, x_0', y_0', c', \hat{X}_0', \hat{Y}_0', \hat{Z}_0', \hat{\omega}', \hat{\varphi}', \hat{\kappa}') \\
y_i' + \hat{\varepsilon}_{y_i'} &= \hat{y}_i'(\hat{X}_i, \hat{Y}_i, \hat{Z}_i, x_0', y_0', c', \hat{X}_0', \hat{Y}_0', \hat{Z}_0', \hat{\omega}', \hat{\varphi}', \hat{\kappa}')
\end{aligned}
$$

Relations for Image 1

$$
\begin{aligned}
x_i'' + \hat{\varepsilon}_{x_i''} &= \hat{x}_i''(\hat{X}_i, \hat{Y}_i, \hat{Z}_i, x_0'', y_0'', c'', \hat{X}_0'', \hat{Y}_0'', \hat{Z}_0'', \hat{\omega}'', \hat{\varphi}'', \hat{\kappa}'') \\
y_i'' + \hat{\varepsilon}_{y_i''} &= \hat{y}_i''(\hat{X}_i, \hat{Y}_i, \hat{Z}_i, x_0'', y_0'', c'', \hat{X}_0'', \hat{Y}_0'', \hat{Z}_0'', \hat{\omega}'', \hat{\varphi}'', \hat{\kappa}'')
\end{aligned}
$$

Relations for Image 2

$$
\begin{aligned}
X_i + \hat{\varepsilon}_{X_i} &= \hat{X}_i \\
Y_i + \hat{\varepsilon}_{Y_i} &= \hat{Y}_i \\
Z_i + \hat{\varepsilon}_{Z_i} &= \hat{Z}_i
\end{aligned}
$$

Allowing for errors ε in ground control points

In **blue**: exterior orientation parameters; $\hat{\blacksquare}$ ← the "hat" indicates estimated parameters

- **How many GCPs do we need?**
  - **At least 3 GCPs** if GCPs are known in three-dimensions (X_i, Y_i and Z_i measured)
  - **At least 5 GCPs** if two GCPs are known in three-dimensions (X_i, Y_i and Z_i measured) and one only in height (Z_i measured)
  - ⋮

The Mathematics of Stereo Pairs

Estimating Exterior Orientation – Approach 2: Estimating Relative & Absolute Orientation Separately

- **For relative orientation, identify and measure corresponding points in the overlap area of the two images (often referred to as "Tie Points")**
  - Per corresponding point pair**, 7 simultaneous observation equations** (similar to previous slide)

- **If n_P is number of tie points then**
  - Number of independent observations: $n = 4 \cdot n_P$
  - Number of unknowns: $\mathrm{u} = 3 \cdot n_P + 5$
  - System redundancy: $\mathrm{r} = n - u = n_P - 5$

  - Hence: **At least 5 tie points are needed to solve for relative orientation**

The Mathematics of Stereo Pairs

Estimating Relative and Absolute Orientation Separately

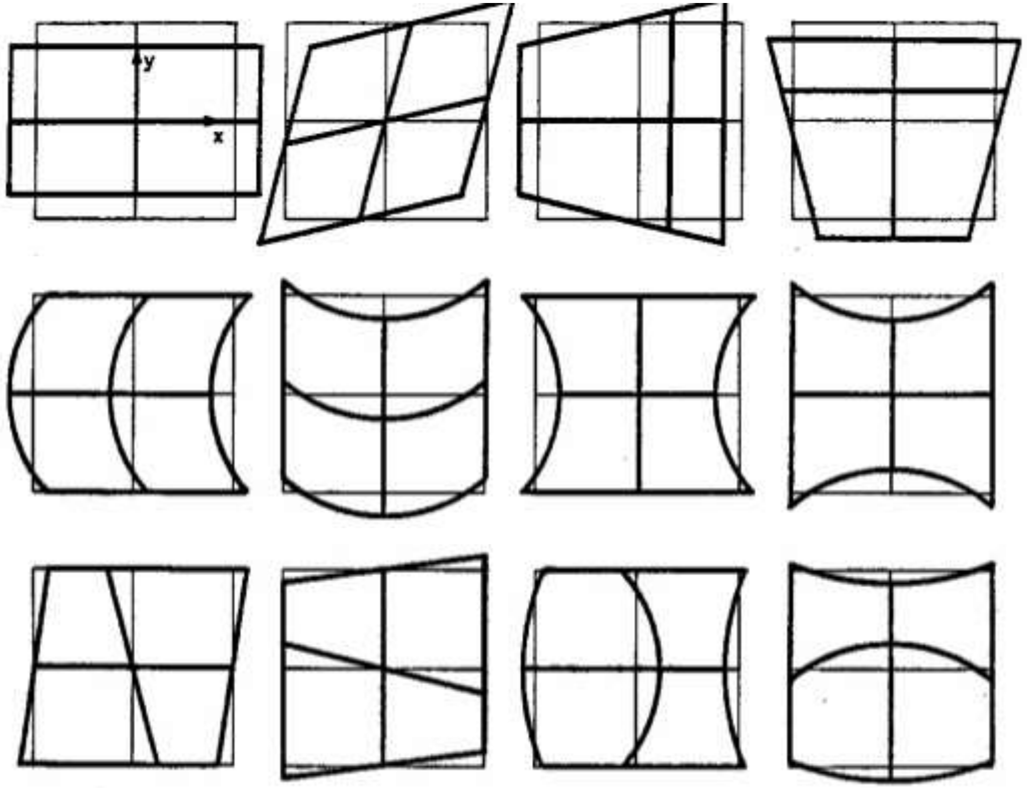
- **For <u>absolute orientation</u>, identify and measure GCPs** (X_i, Y_i, Z_i)
  - Per GCP, **6 simultaneous observation equations**

- **If $\boldsymbol{n_P}$ is number of total GCPs, $\boldsymbol{n_{3D}}$ is number of 3D GCPs, $\boldsymbol{n_{2D}}$ is number of points measured only in $(\boldsymbol{X}, \boldsymbol{Y})$ and $\boldsymbol{n_{1D}}$ are points measured only in $(\boldsymbol{Z})$:**
  - Number of independent observations: $n = 3 \cdot n_P + 3 \cdot n_{3D} + 2 \cdot n_{2D} + n_{1D}$
  - Number of unknowns: $\mathrm{u} = 3 \cdot n_P + 7$
  - System redundancy: $\mathrm{r} = n - u = 3 \cdot n_{3D} + 2 \cdot n_{2D} + n_{1D} - 7$

  - Hence: **At least two 3D points and one 1D point are needed to solve for <u>absolute</u> orientation**

The Steps of Stereo Data Acquisition and Processing

1. **Calibration of Camera:**
   - For 3D mapping from image pairs we need to assume that (1) interior orientation parameters (x_0', y_0', c') are known and that lens distortions are either small or were calibrated and corrected

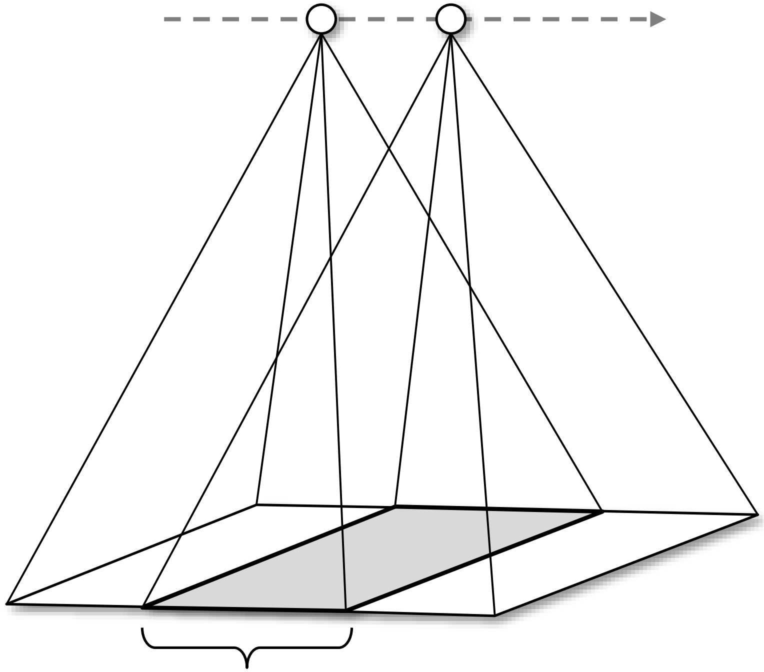


- **Summary of lens distortion effects in frame cameras:**
  - Due to their spatial correlation, difficult to determine within stereo processing flow
  - More than two images (views) needed to robustly estimate and correct for lens distortions
  - **Hence**: Separate camera calibration is preferred

The Steps of Stereo Data Acquisition and Processing

2. Image Acquisition:

- Acquire image pair with sufficient overlap → **stereo mapping only possible in overlap region**



Standard: 60% stereo overlap

3. Digitize Images (if analog):

- Modern stereo stations are digital stations

4. Load into Digital Photogrammetric Workstation:

- Several workstations for stereo-processing
- Main products:
  - SOCET SET (owned by BAE Systems; available at UAF)
  - Leica Photogrammetric Suite (owned by ERDAS)
  - INPHO (owned by Trimble)
  - Intergraph ImageStation2015

The Steps of Stereo Data Acquisition and Processing

5. **Setup Stereo Model:**
   - Series of steps to determine processing approach and parameters (e.g., type of relative orientation; interior orientation parameters; acceptable accuracy for automatic matching techniques, …)

6. **Perform automatic relative orientation:**
   - **Within overlap area**, automatic **identification** of **interest points** (edges; points) in both partner images (*using an interest point operator* → digital image processing)
   - **Automatic matching** of points in image 1 to points in image 2 *using a similarity measure* (e.g., cross-correlation; see Wednesday lecture) → tie points

→**Derive 5 relative orientation parameters**

→**Calculate relative stereo model (relative model coordinates (x_i, y_i, y_i))**

7. **Absolute Orientation:**
   - Identify and measure GCPs in image and solve for 7 absolute orientation parameters

The Steps of Stereo Data Acquisition and Processing

8. **Rectify images for simplified epipolar geometry (coinciding image planes):**
   - Improves stereo vision and simplifies search for corresponding points to 1D search

9. **Automatic identification and matching of dense point pairs for DEM generation:**
   - Similar as before, use interest point detectors and similarity measures to identify and match corresponding points.
   - To create dense point clouds and reduce outliers, matching is typically done through cascading pyramids (start with lower resolution → first points; next higher resolution level → more points; …)

10. **Interpolate DEM from measured points using TIN Interpolation:**
    - Identify and measure GCPs in image and solve for 7 absolute orientation parameters

11. **Verification; Quality Control; Editing:**
    - Superimpose estimated DEM points on stereo model and compare → edit points where estimated height and stereo model don't match

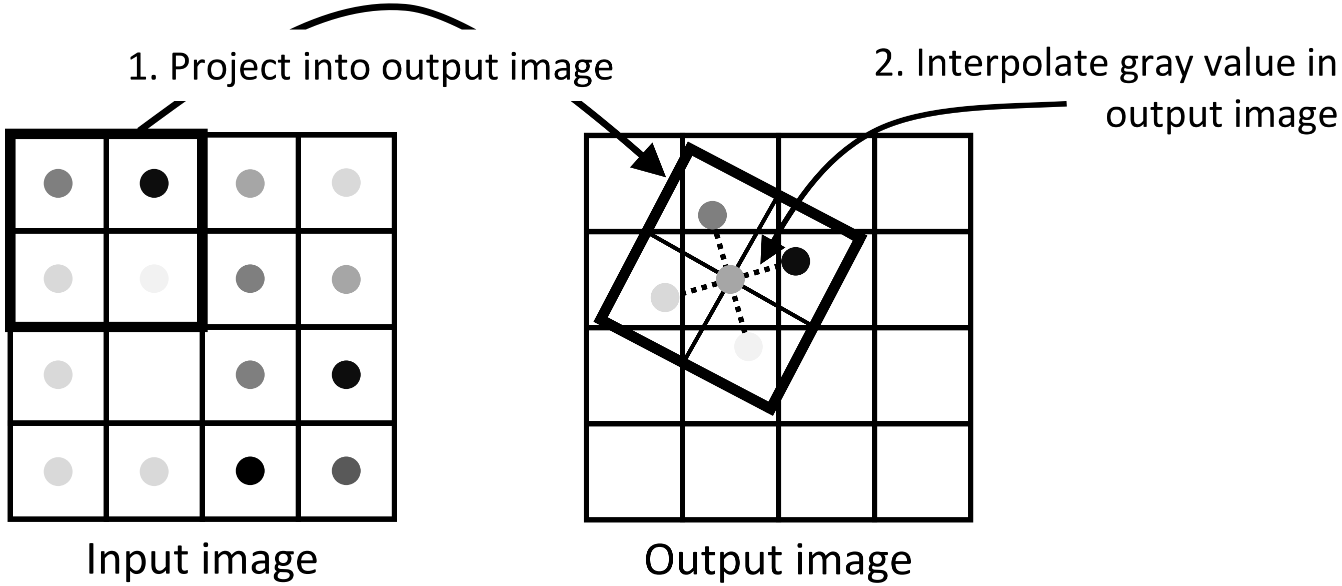
The Steps of Stereo Data Acquisition and Processing

12. Create Orthorectified Images:

– Using estimated DEM, project every image point into object coordinate system using either **forward mapping** or **inverse mapping**.

Forward mapping:

- **Step 1:** Project pixels (x_i, y_i) into output image g_o
- **Step 2:** Determine gray values in output image by interpolation between projected pixels



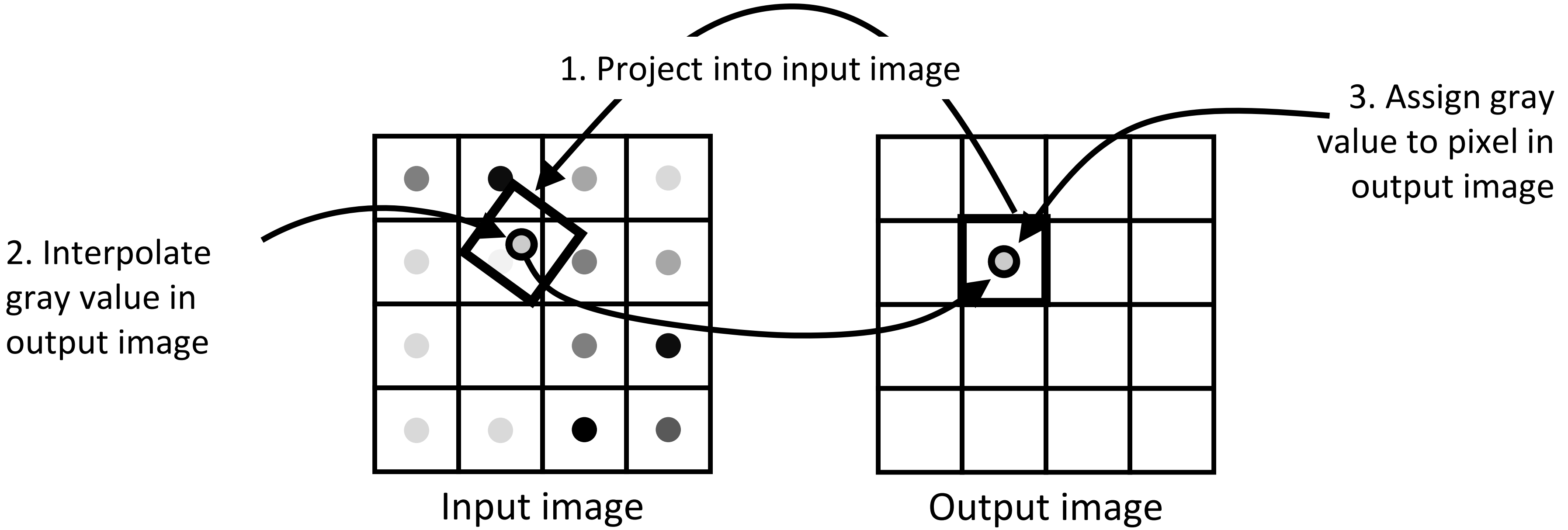
The Steps of Stereo Data Acquisition and Processing

12. Create Orthorectified Images:

– Using estimated DEM, project every image point into object coordinate system using either **forward mapping** or **inverse mapping**.

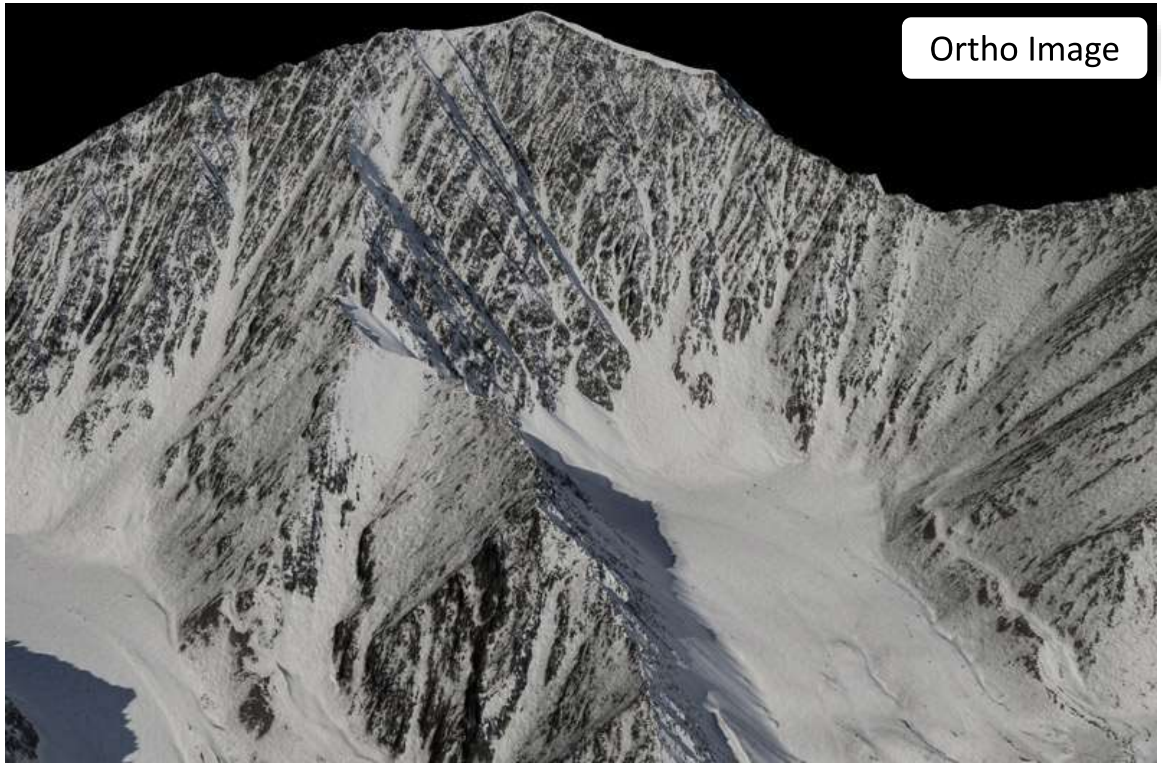
Inverse mapping:

- **Step 1:** Project output image pixels (x_o,y_o) into input image g_i
- **Step 2:** calculated gray value of projected pixel and assign to pixel in output image



Stereo Photogrammetry
Products

- DEM information
- Ortho Imagery
- Accurate information about sensor trajectory
- GIS-ready vector information



http://fairbanksfodar.com/understanding-fodar

STEREO PAIRS

EXPECTED QUALITY OF EXTRACTED OBJECT COORDINATES

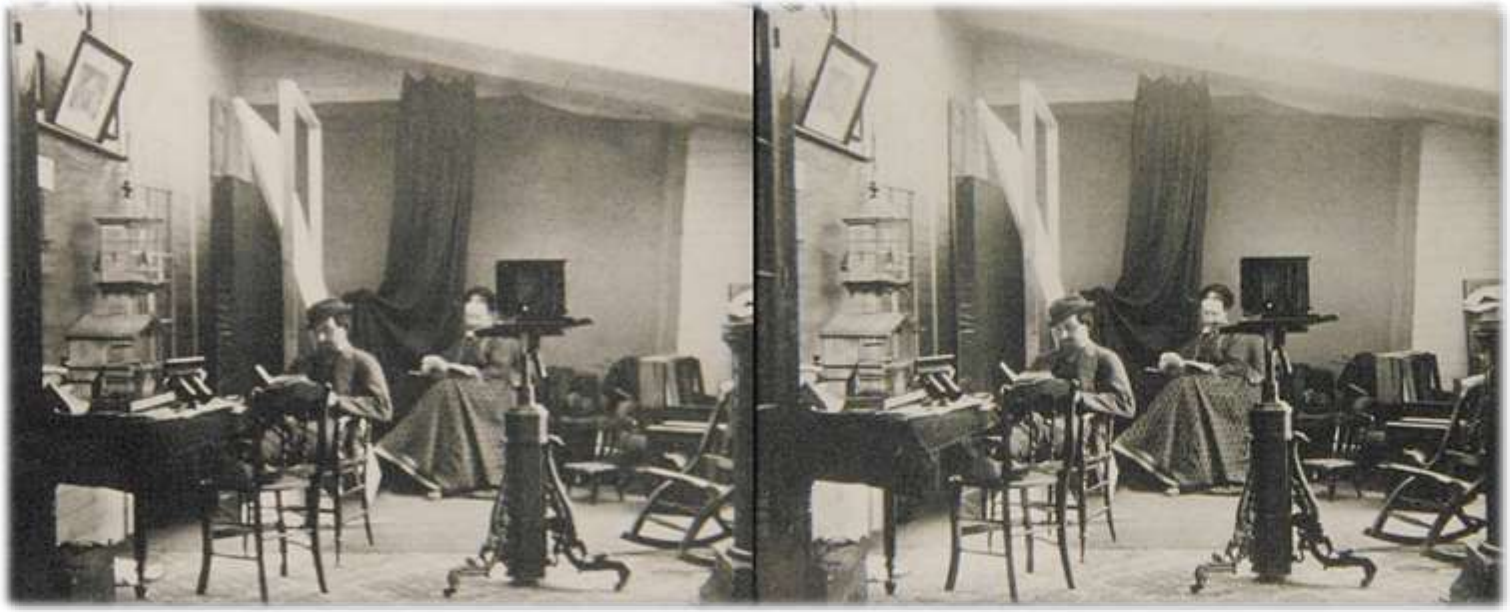
Think – Pair – Share

Q1: A fundamental conditions of photogrammetry is the **Collinearity Condition**.

What is the collinearity condition and how does it relate camera position, image point, surface point to each other.

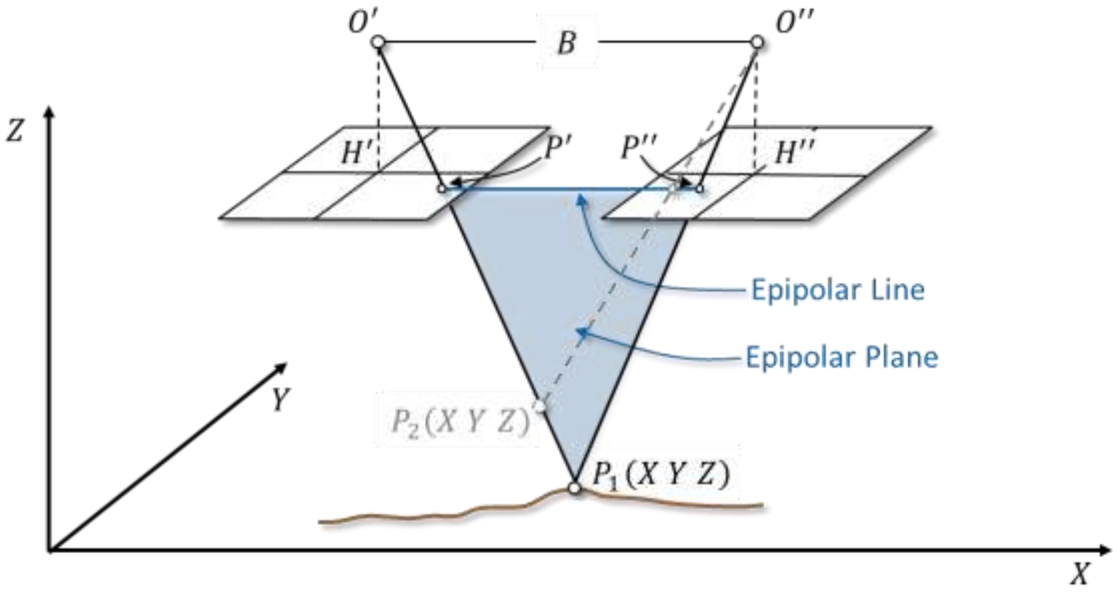
Q2: In stereo photogrammetry we take advantage of the **Epipolar Geometry**.

Please explain this term and discuss why it is useful in stereo processing.



Accuracy of Estimated Object Coordinates

- **Assumptions:**
  - Exterior Orientation was estimated without error
  - Images are separated by baseline $b = [b_X, 0, 0]^T$ with $|b| = B$
  - The accuracy with which matching points are estimated in the images is constant



- **Deriving Accuracy Equations:**
  - Based on assumptions, accuracy equations for $\hat{P} = [\hat{X}, \hat{Y}, \hat{Z}]^T$ can be derived based on the collinearity equations and using least-square inverse modeling methods

Accuracy of Estimated Object Coordinates

- **Accuracy Estimates and their Dependencies:**

$$\sigma_{\hat{X}} = \sqrt{\sigma_0^2 m^2 \frac{X^2 + (X-B)^2}{B^2}}$$

$$\sigma_{\hat{Y}} = \sqrt{\sigma_0^2 m^2 \left(\frac{1}{2} + \frac{2Y^2}{B^2}\right)}$$

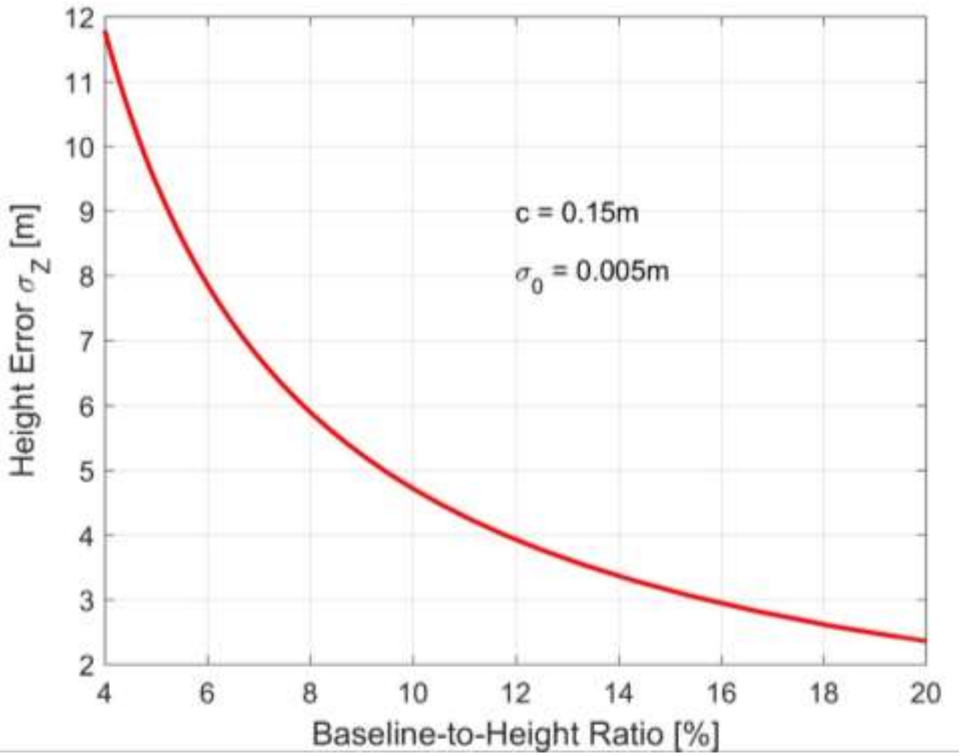
$$\sigma_{\hat{Z}} = \sqrt{\sigma_0^2 m^2 \frac{2Z^2}{B^2}}$$

$\sigma_0 =$ Accuracy of measured image coordinates [m]

- **Interpretation of error equations:**
  - **Standard deviations of all coordinate directions directly proportional to scale factor $\boldsymbol{m}$** (for constant focal length, error increases with flying height)
  - **Standard deviations of $\boldsymbol{X}$ and $\boldsymbol{Y}$** coordinates are independent of Z
    - Min. error for X is achieved at $X = B/2$: $\sigma_{\hat{X}} = \sigma_0 m\left(\sqrt{2}/2\right)$
    - Min. error for Y is achieved at $Y = 0$: $\sigma_{\hat{Y}} = \sigma_0 m\left(\sqrt{2}/2\right)$
  - **Standard deviation of $\boldsymbol{Z}$**: (1) independent of X and Y, (2) inverse proportional to the baseline-flying height ratio B/H (with $H = Z_0 - Z$), and (3) proportional to flying height H (through relationship with m)

Accuracy of Estimated Object Coordinates

- **Dependence of height accuracy ($\sigma_{\hat{Z}}$) on baseline-to-flying height ratio (B/H)**
  - **Parameters used in the plot:**
    - **Flying height:** $H = [1000, 5000]\ m$
    - **Focal Length:** $c = 0.15\ m$ (e.g., Leica RC30 Aerial Camera System)
    - **Image coordinate accuracy:** $\sigma_0 = 0.005\ m$

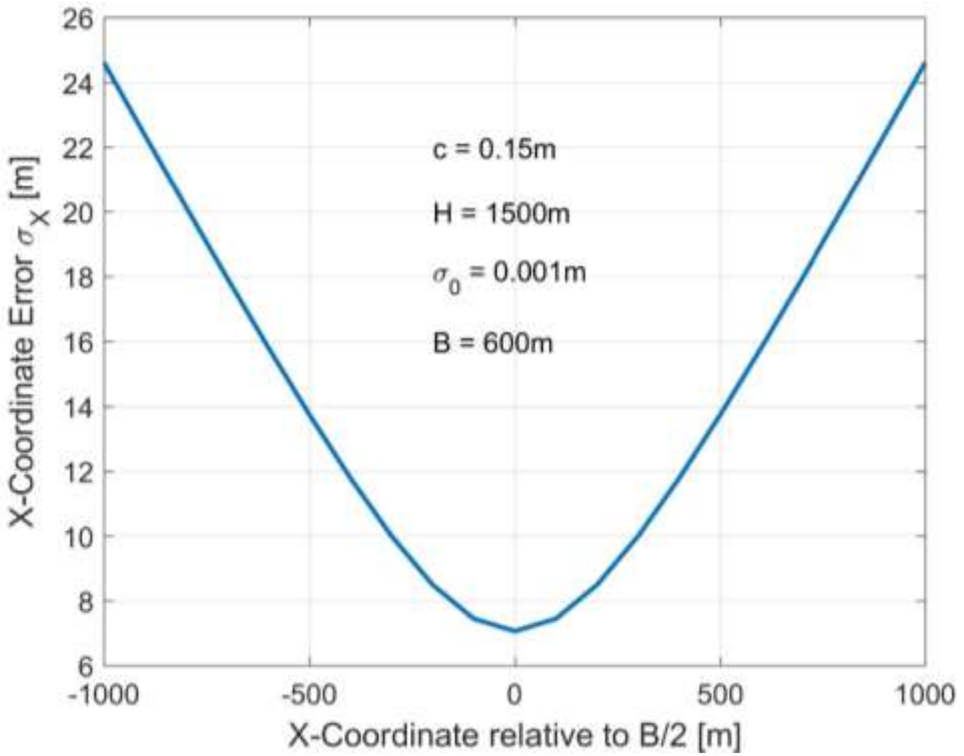


For a given camera system with predefined focal length:

→ Optimize flying height and baseline to meet customer needs

Accuracy of Estimated Object Coordinates

- **Dependence of X-coordinate accuracy ($\sigma_{\hat{X}}$) on position in the image**
  - **Flying height:** $H = 1500\ m$
  - **Focal Length:** $\mathrm{c} = 0.15\ m$ (e.g., Leica RC30 Aerial Camera System)
  - **Image coordinate accuracy:** $\sigma_0 = 0.001\ m$
  - **Stereo baseline:** $B = 600\ m$



Y-coordinate behavior is equivalent

What’s Next

- **Next Lecture:**
  - **Lecture:** A bit more details about Stereo-Photogrammetry processing

- **After that:**
  - **Lecture:** Structure-from-Motion Processing to generate Digital Elevation Models