GEOS 639 – INSAR AND ITS APPLICATIONS

GEODETIC IMAGING AND ITS APPLICATIONS IN THE GEOSCIENCES

Lecturer:

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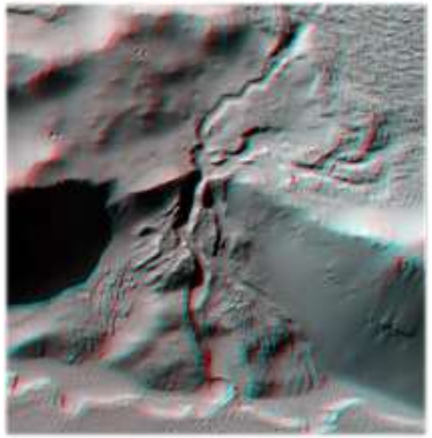
Lecture 6: Structure-from-Motion Processing and its Relationship to Stereo Photogrammetry

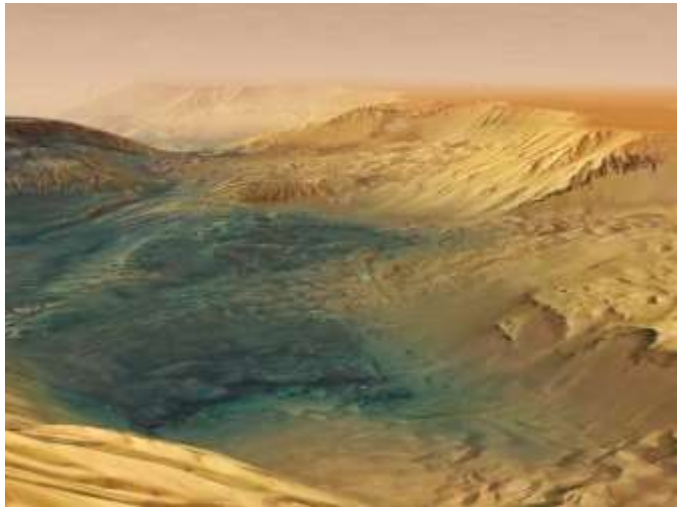
What we already know:



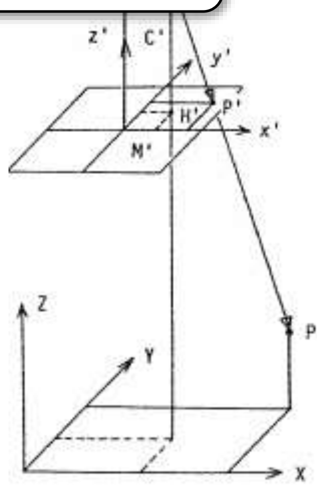
Stereo Image Pair

http://www.uahirise.org/anaglyph/

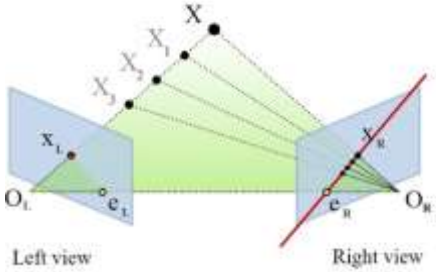
http://www.esa.int/Our_Activities/Space_Science/Fly_through_a_canyon_on_Mars



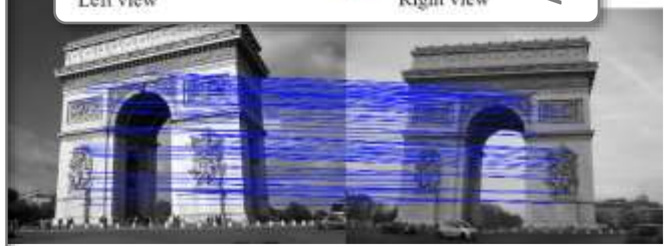
Ortho imagery & 3D Reconstruction



Collinearity condition



Epipolar Geometry



Robust Image Matching

Stereo-Photogrammetry Pipeline

Think – Pair – Share

Improving Upon Stereo Processing

Q1: One limitation of processing a stereo pair is that 3-D information can only be derived within the stereo-overlap area.

How would you go about 3-D mapping a very large area using stereo principles? What workflow would you envision?

Q2: A second limitation of stereo photogrammetry is the requirement for expensive (distortion-free) and fully calibrated cameras.

How could you go about allowing cameras of lesser quality to be used in 3-D mapping?

FROM IMAGE PAIRS TO IMAGE BLOCKS

From Image Pairs to Groups of Images

- **Motivation for (Jointly) Processing Groups of Images:**

(1) Image pairs are limited in spatial extent	→ **Limited areal coverage of stereo region**
(2) Image pairs are limited in "observation diversity"	→ **Ability to resolve for lens distortion parameters is limited (due to their correlation in "low diversity data")**
(3) Joint processing of groups of images has mathematical advantages over processing independent stereo pairs	→ **(i) Lower requirement for ground control; (ii) Multi-view points stabilize epipolar geometry; (iii) Multi-view points allow solving for lens distortions**

- **Mathematical Concept for Jointly Processing a Group of (Overlapping) Images:**

!! Bundle Block Adjustment !!

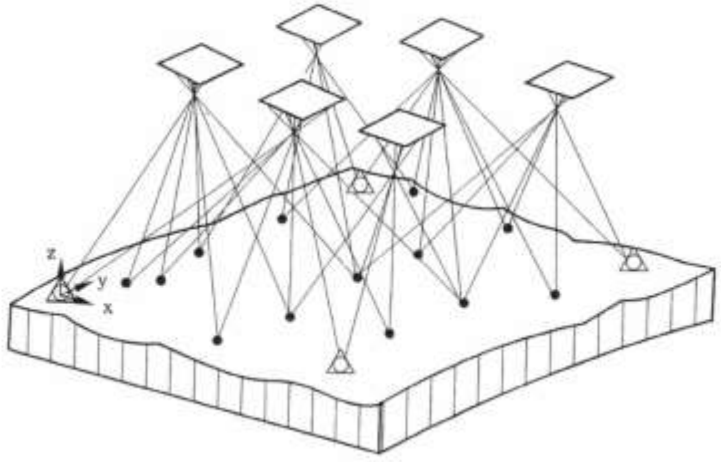
Bundle Block Adjustment

Some Basics

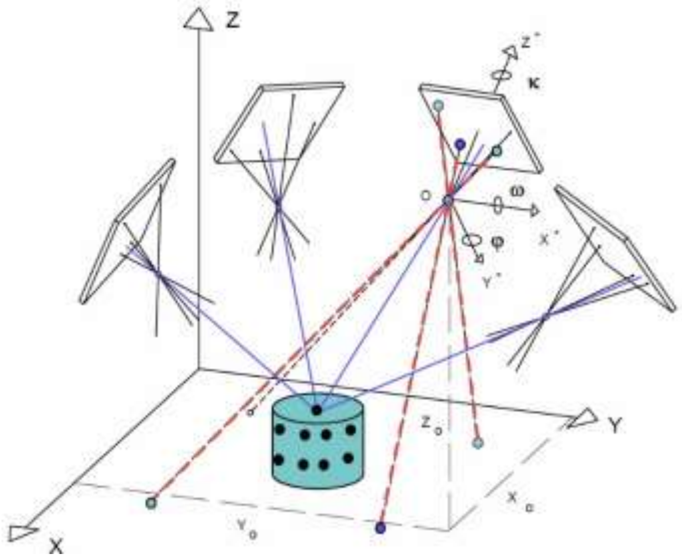
- Starting point is block-shaped image set with high image overlap ($> 60\%$ along track & $> 20\%$ across track)
- **Basic observations:** Image coordinates of interest points in individual images

- **Bundle block adjustment** jointly processes blocks of images from either spaceborne, airborne, or terrestrial sensors

Airborne configuration



Terrestrial configuration



Block of Images Math – General Case

Collinearity Equations – the Core Relationship of Bundle Adjustment

- **Collinearity Equations – The Bundle Block Case**:
  - If (measured) image point $P_{ij}\left(x_{ij}, y_{ij}\right)$ = projection of object space point P_i **into image *j***, then

$$
\begin{aligned}
x_{ij} &= x_{0j} - c_j \frac{r_{11,j}\left(X_i - X_{0j}\right) + r_{21,j}\left(Y_i - Y_{0j}\right) + r_{31,j}\left(Z_i - Z_{0j}\right)}{r_{13,j}\left(X_i - X_{0j}\right) + r_{23,j}\left(Y_i - Y_{0j}\right) - r_{33,j}\left(Z_i - Z_{0j}\right)} \\
y_{ij} &= y_{0j} - c_j \frac{r_{12,j}\left(X_i - X_{0j}\right) + r_{22,j}\left(Y_i - Y_{0j}\right) + r_{32,j}\left(Z_i - Z_{0j}\right)}{r_{13,j}\left(X_i - X_{0j}\right) + r_{23,j}\left(Y_i - Y_{0j}\right) - r_{33,j}\left(Z_i - Z_{0j}\right)}
\end{aligned}
$$

  is the collinearity condition connecting the images in an image block with each other and the ground! [$R_j\{\omega_j, \varphi_j, \kappa_j\}$ is rotation matrix of image j]

- **Observations and Unknowns of Bundle Block Adjustment**:
  - **Observations:** Image coordinates $P_{ij}\left(x_{ij}, y_{ij}\right)$
  - **Unknowns:**
    - **Exterior orientation parameters**: $X_{0j}, Y_{0j}, Z_{0j}, \omega_j, \varphi_j, \kappa_j$
    - **Object coordinates**: X_i, Y_i, Z_i
    - **Interior Orientation parameters**: x_{0j}, y_{0j}, c_j

Photogrammetry typically treats these as **known**
Structure from Motion treats these as **unknowns**

The Mathematics of Blocks of Images

Joint Estimation of Relative and Absolute Orientation

- **Solving the Bundle Block Adjustment Problem:**
  1. **At least 5 3D GCPs** with known coordinates are needed
  2. **Accurate measurement of coordinates** (x_{ij}, y_{ij}) associated with each GCP in all affected images
  3. **Then, solving of collinearity equation system using either**
     - **Joint Non-linear least-squares inversion in the Gauss-Newton model (previous slide)**
     - **Gradient Descent solution**
     - **Levenberg-Marquardt algorithm (solution between the first two algorithms)**

  – Note: Collinearity equation system is non-linear → approximate values for the unknown exterior orientation parameters are needed

References for Levenberg-Marquardt algorithm:

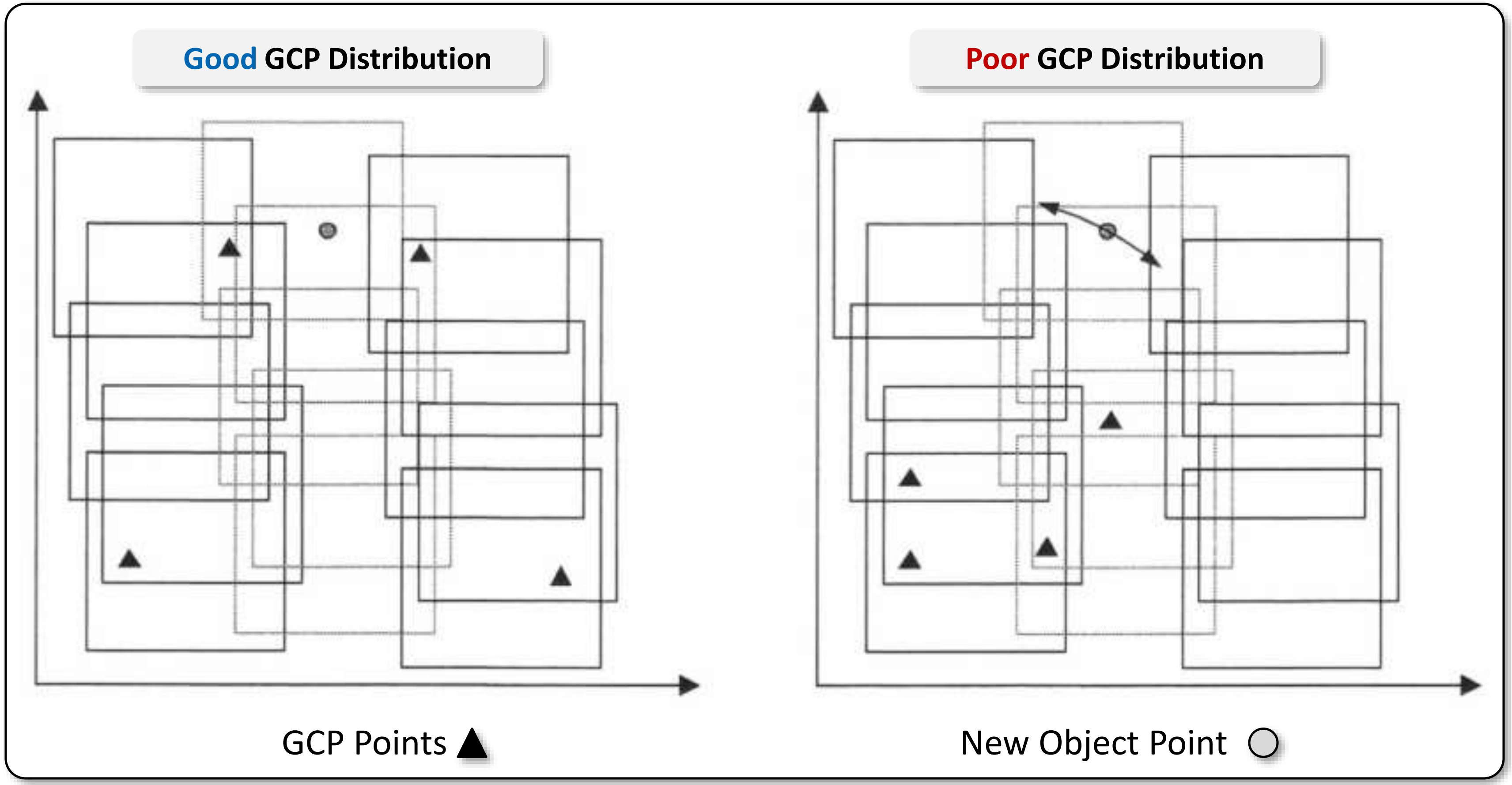
Kenneth Levenberg (1944). "A Method for the Solution of Certain Non-Linear Problems in Least Squares". Quarterly of Applied Mathematics 2: 164–168.

Donald Marquardt (1963). "An Algorithm for Least-Squares Estimation of Nonlinear Parameters". SIAM Journal on Applied Mathematics 11 (2): 431–441.

Bundle Block Adjustment

Selecting Ground Control Points

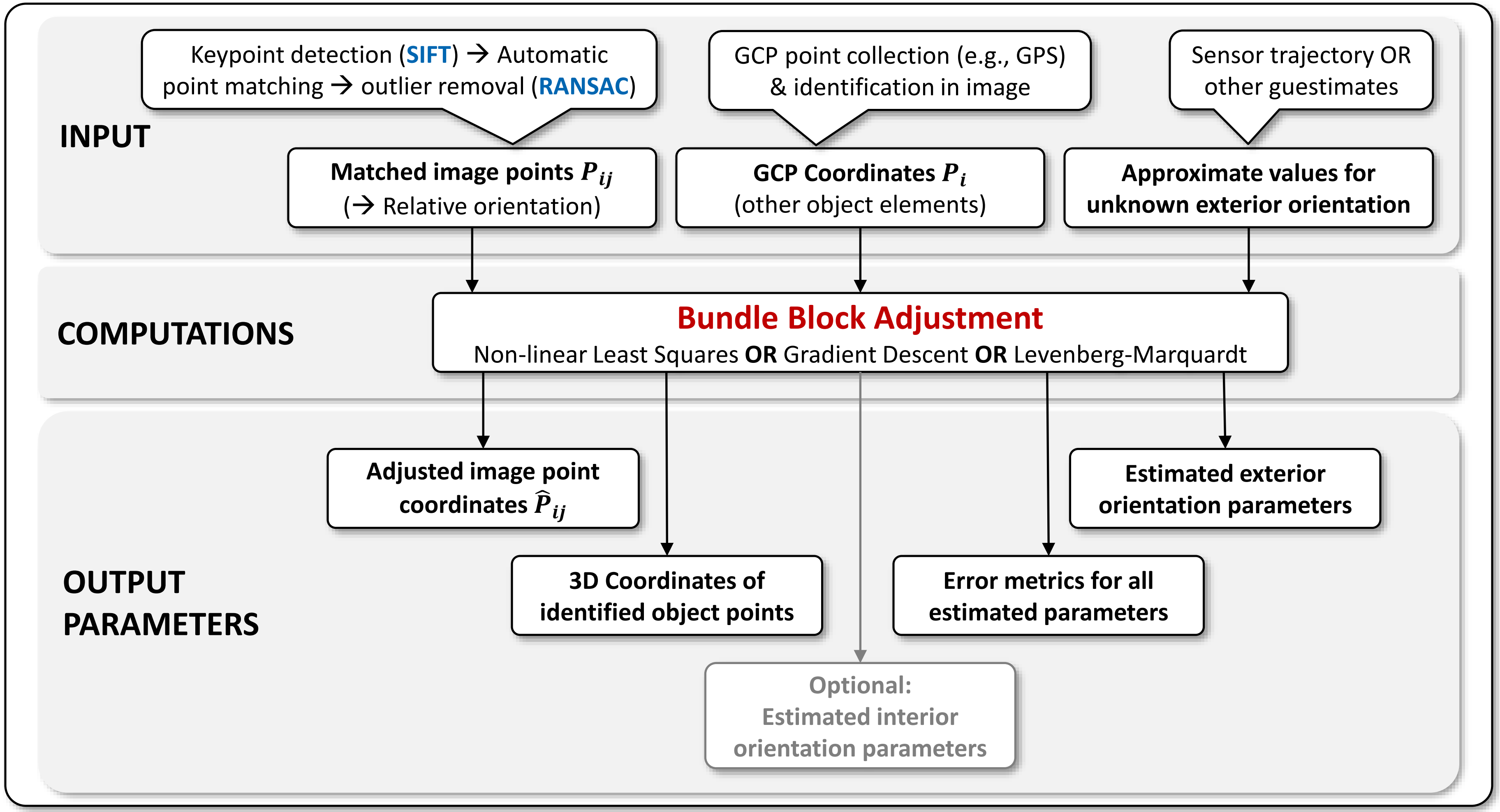
- **When selecting GCPs, ensure sufficient spatial distribution**



Stereo-Photogrammetry from Blocks of Images

Workflow

- **Typical Workflow of image block processing using bundle block adjustment**



The Mathematics of Bundle Block Adjustment

Integration of Camera Self Calibration

- **Integration Camera Self Calibration:**
  - **Estimation of interior orientation parameters** incl. lens distortions **within** bundle block adjustment.

- **Simultaneous camera self calibration** is possible **if** sufficiently diverse observation angles, strongly overlappling images, and sufficient density of matched object points are available.

From Traditional Photogrammetry to Structure from Motion

- **Structure from Motion is a photogrammetric method that**
  - Analyzes dense groups of highly overlapping images ...
  - ... acquired with **potentially uncalibrated cameras** ...
  - ... to extract dense 3D object space coordinates of an observed scene.

- **Structure from Motion is ...**
  - **very similar** to photogrammetric bundle block adjustment in method, **but** ...
  - **differs in execution** through (1) the **full integration of camera self calibration** and (2) the **useage of modern high-performance image processing techniques** (SIFT, RANSAC, optical flow),

Integrating Lens Distortion

Think – Pair – Share

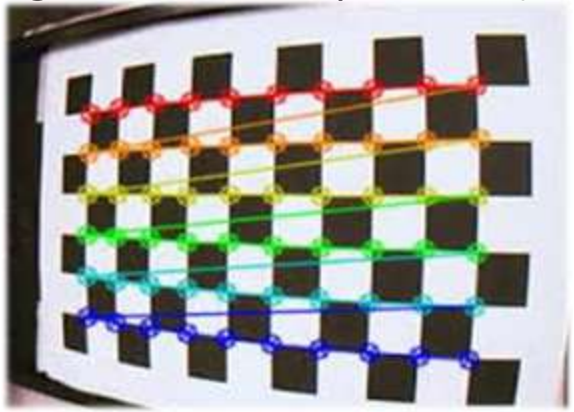
Lens Distortions

Q1: Lens distortions like the ones shown below are typical for low-grade cameras.

Why are these distortions so detrimental for the traditional stereo photogrammetry process?

Q2: Lens distortions can be removed using cameral calibration (e.g., using chess board patterns).

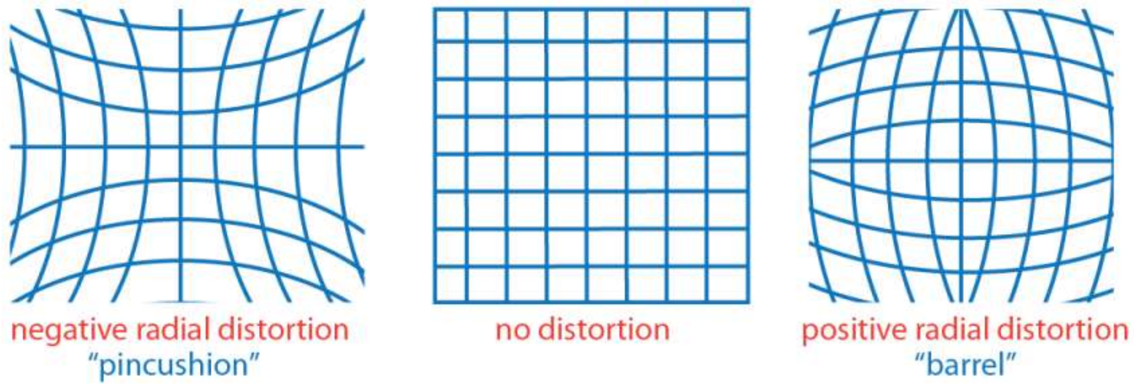
Why camera calibration is a robust approach for high-grade photogrammetric cameras, it often fails for off the shelf cameras (zoom and autofocus) cameras. Why do you think that is?



Integrating Lens Distortions into Math. Model

Modeling Radial and Tangential Distortions

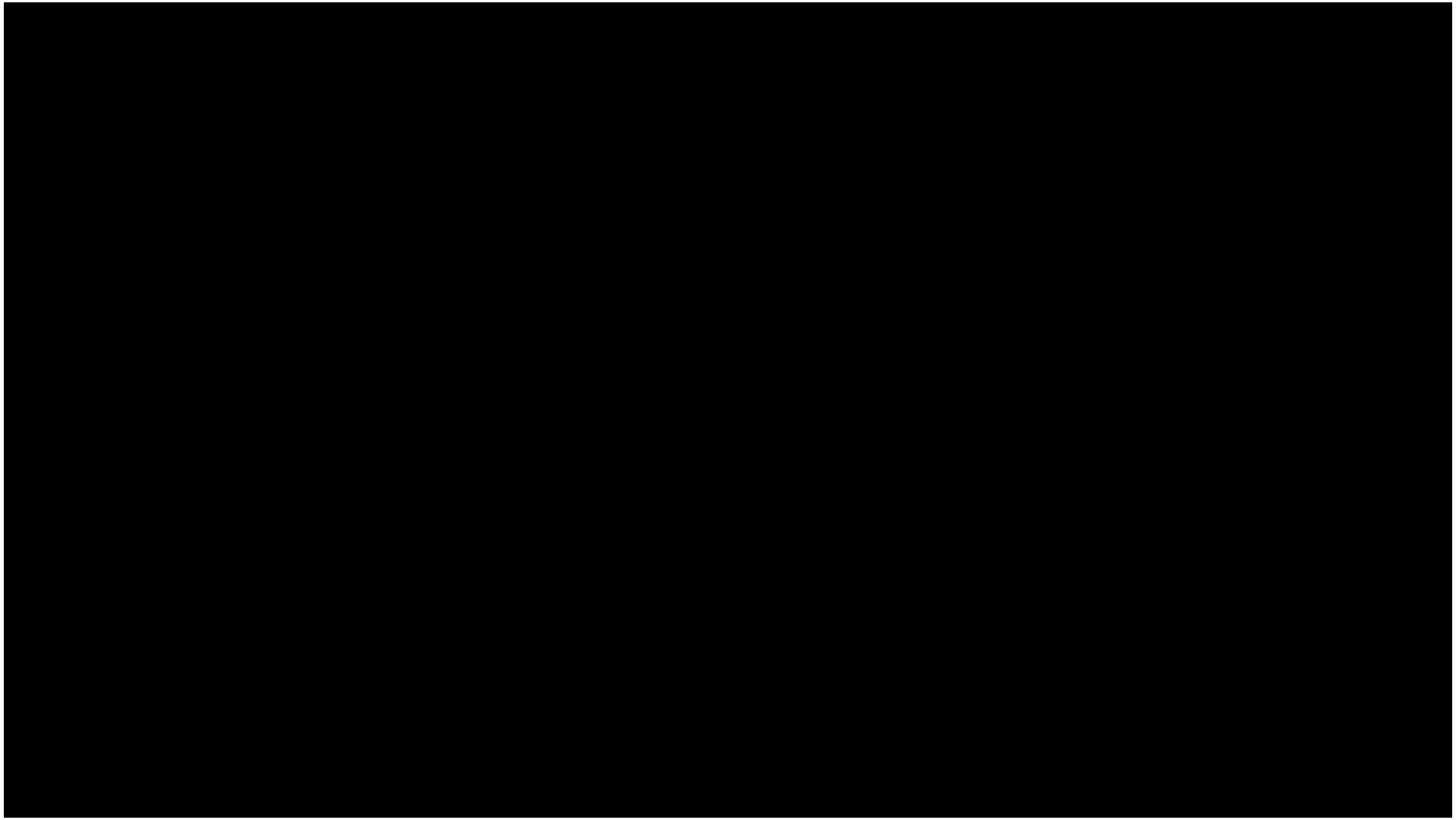
- **Typically, lens distortions are grouped into two parts:**
  1. **Radial Distortions**



Typical Radial Distortion Types

Radial Distortion Example

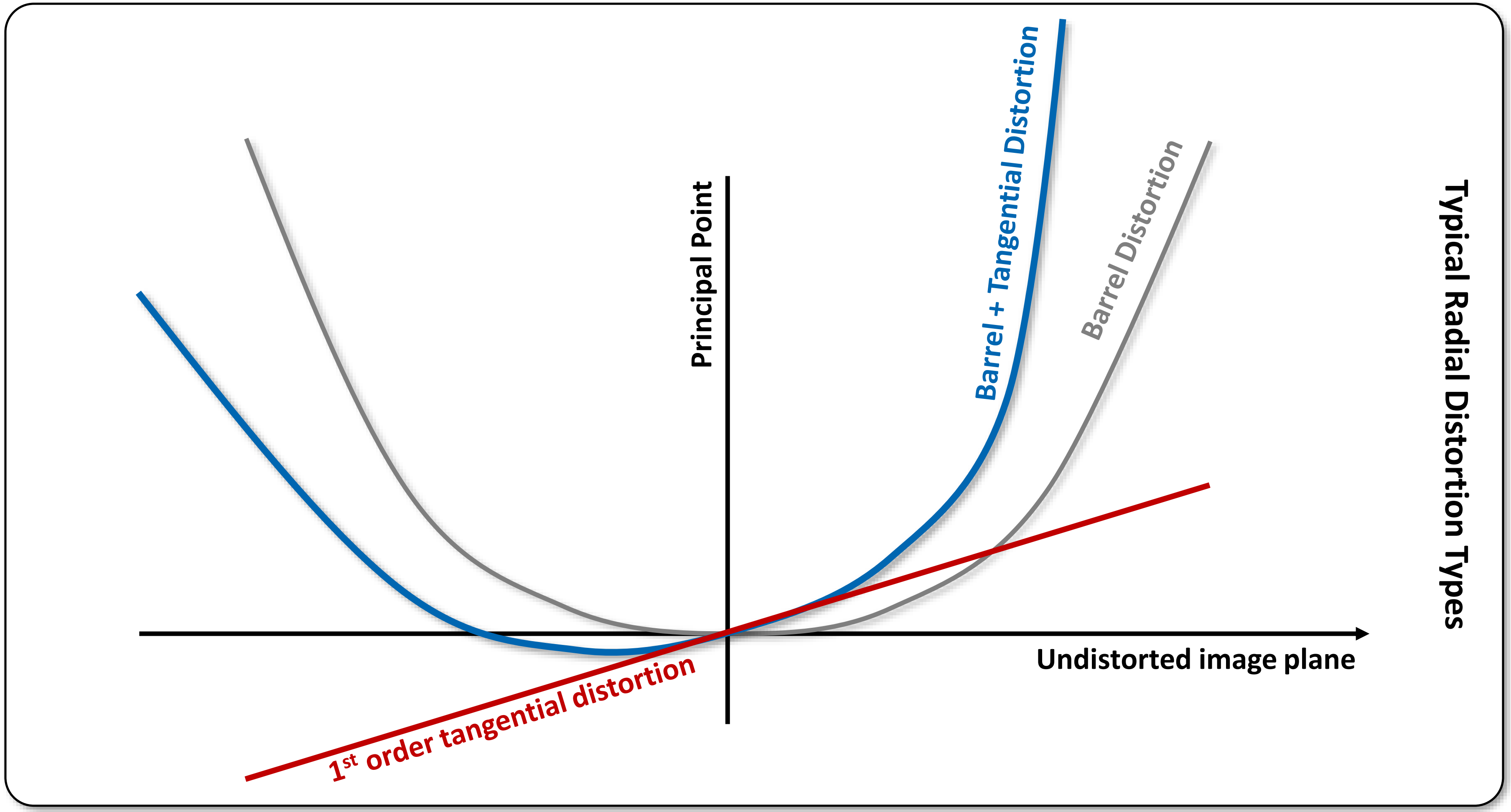
Example of Fish Eye Lens Distortions [extreme radial distortions]



Integrating Lens Distortions into Math. Model

Modeling Radial and Tangential Distortions

- **Typically, lens distortions are grouped into two parts:**
  2. **Tangential or "Decentering" Distortions**



Integrating Lens Distortions into Math. Model

Modeling Radial and Tangential Distortions

- **Mathematical Model:**

$$\begin{aligned} x_{ij}^d &= x_{ij}(1 + k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6) + \left(p_2\left(r^2 + 2x_{ij}^2\right) + 2p_1 x_{ij} y_{ij}\right) \cdot (1 + p_3 r^2 + p_4 r^4) \\ y_{ij}^d &= y_{ij}(1 + k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6) + \left(p_1\left(r^2 + 2y_{ij}^2\right) + 2p_2 x_{ij} y_{ij}\right) \cdot (1 + p_3 r^2 + p_4 r^4) \end{aligned}$$

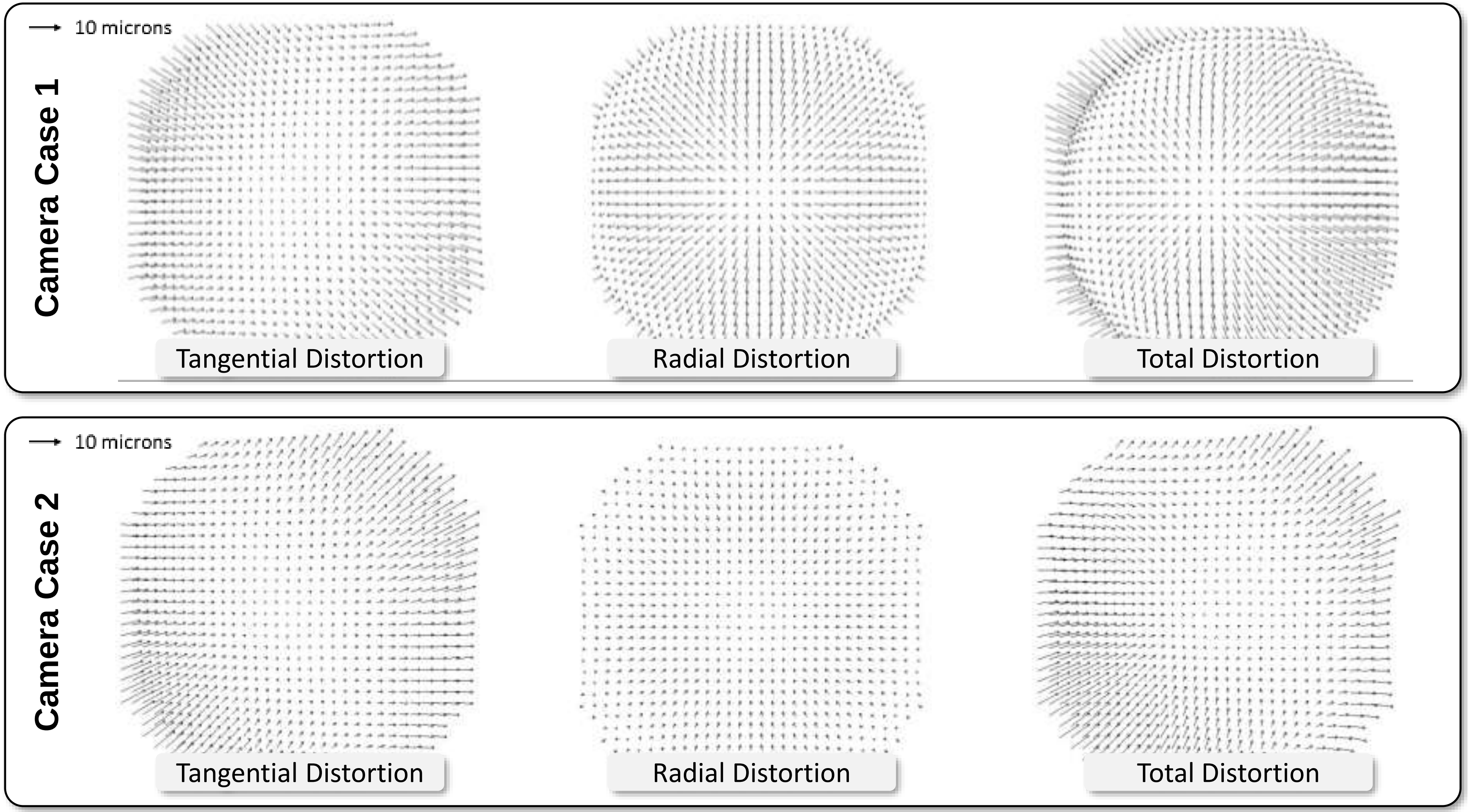
  – where:
    - $\left(x_{ij}^d, y_{ij}^d\right) =$ distorted image point coordinates
    - $\left(x_{ij}, y_{ij}\right) =$ **un**distorted image point coordinates
    - $k_n =$ **radial** distortion parameters
    - $p_n =$ **tangential** distortion parameters
    - $r = \sqrt{\left(x_{ij} - x_{0j}\right)^2 + \left(y_{ij} - y_{0j}\right)^2}$

- Provided sufficient image overlap, sufficient geometric diversity, and sufficient object point density, **parameters k_n and p_n can be added to the mathematical model**

Integrating Lens Distortions into Math. Model

Modeling Radial and Tangential Distortions

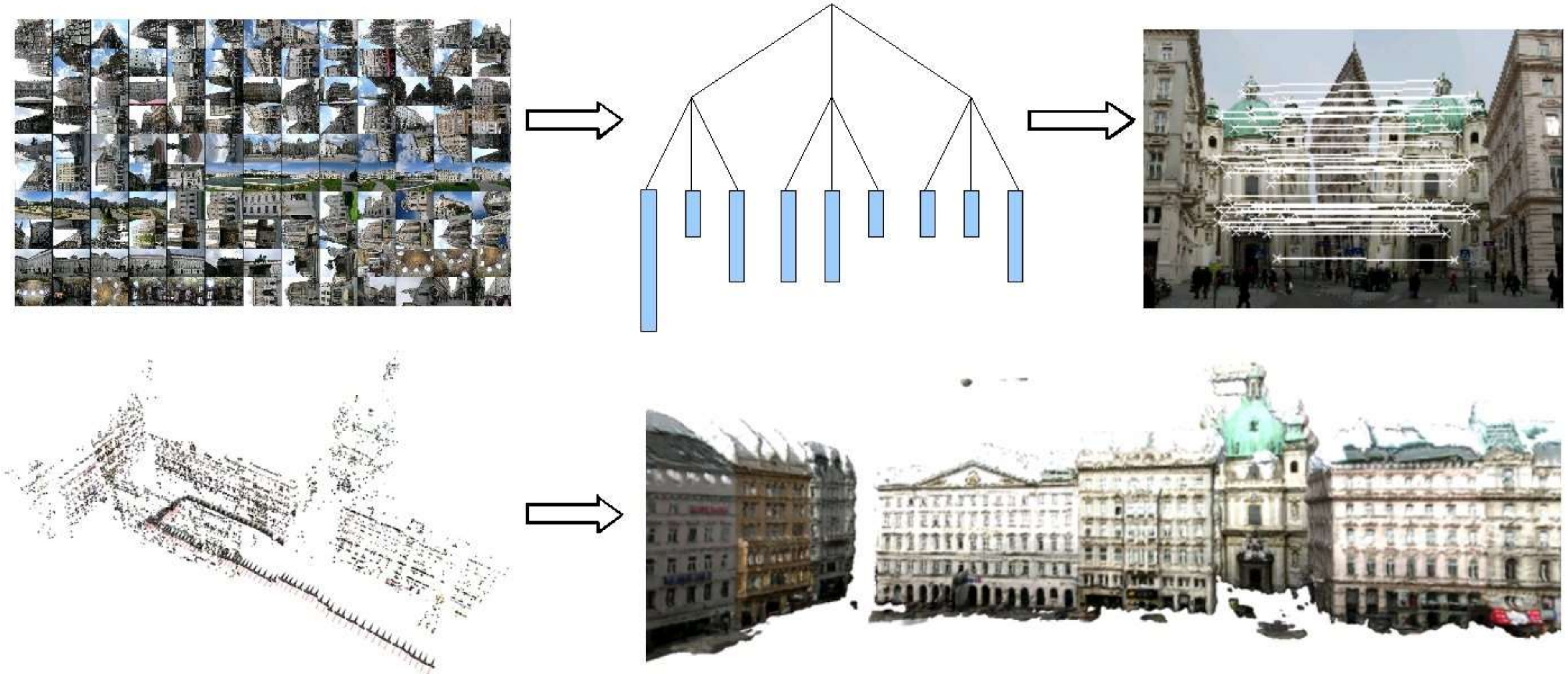
- **Examples of radial and tangential distortions:**



The Structure-From-Motion Concept

Structure from Motion (SfM)

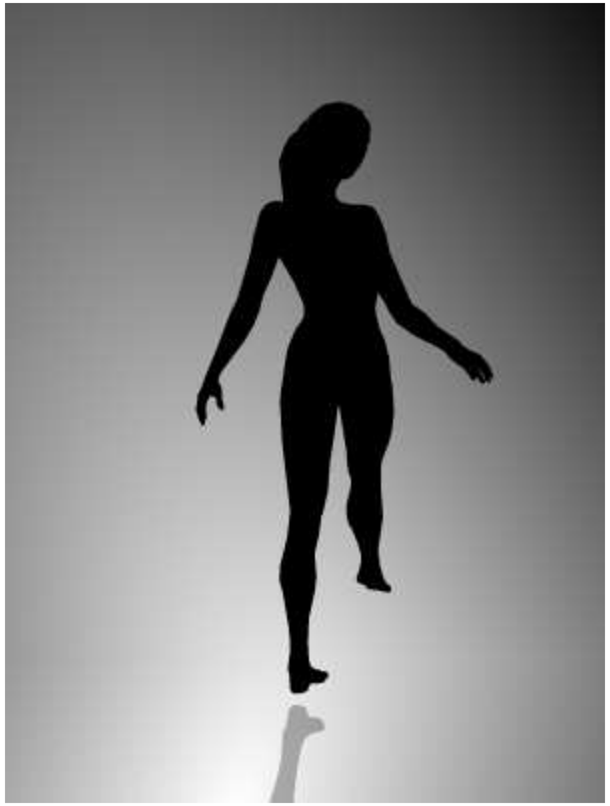
- **An evolution of traditional photogrammetric methods**
  - Allows for the use of off-the-shelf camera systems for 3D object reconstruction
  - Integrates modern image processing techniques into processing flow
  - Allows for simultaneous camera-self-calibration



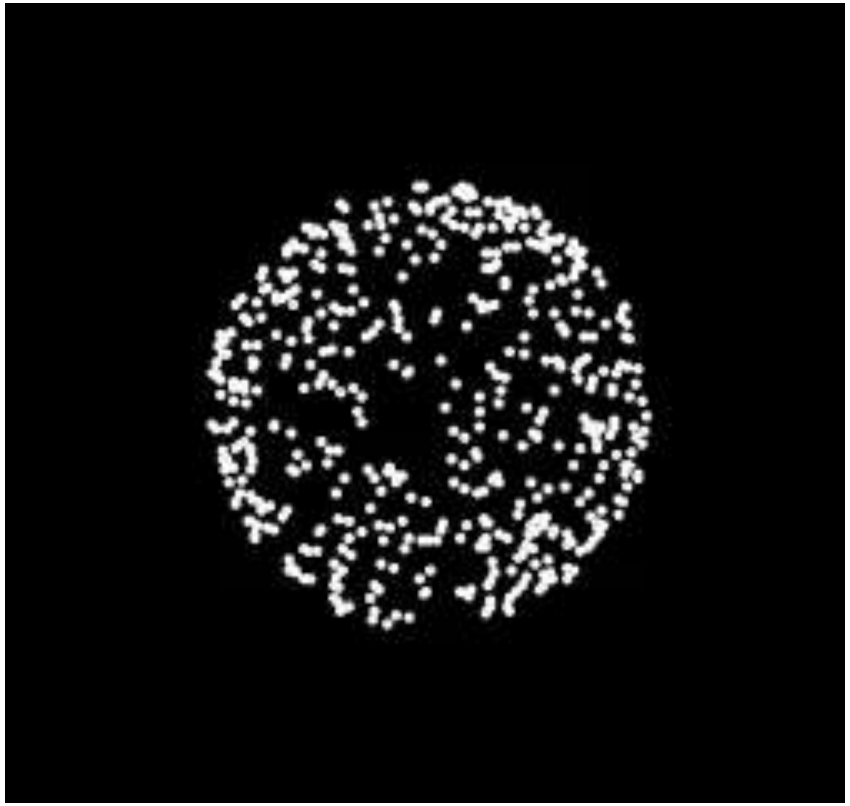
Structure from Motion (SfM)

- **SfM is attempting to emulate the human vision by utilizing kinetic depth theory** (theory of 3D reconstruction from dense samples of object motion)

Kinetic Depth Example "Spinning Dancer"



Kinetic Depth Example "Rotating Sphere"



Structure From Motion (SfM)

General Workflow

- **Workflow:**
  1. **Acquire highly overlapping image sequences** of your object of interest **from a diversity of views** **[see slides on processing of groups of images]**
  2. **Define your sensor model** (parameterization of interior orientation) **[see lectures on stereo photogrammetry]**
  3. **Solve the Correspondence problem** (identify identical points in two or more image views) **[SIFT** for interest point detection and matching; **RANSAC** for robust identification of outliers; optional integrating exterior orientation prior to speed up correspondence search**]**
  4. **Perform relative orientation [see lectures on stereo photogrammetry]**
  5. **Identify GCP information in images [see lectures on stereo photogrammetry]**
  6. **Solve Bundle Block Adjustment problem for absolute orientation [math a bit different than before]**
  7. **Generate dense cloud of 3D-reconstructed object points [SIFT, RANSAC** (again)**]**
  8. **Generate DEM and Orthophoto mosaic [see lectures on stereo photogrammetry]**
  9. **Report Error metrics for all estimated parameters**

Structure From Motion (SfM)

These are the Items I want to discuss with you today

- **Workflow:**
  1. **Acquire highly overlapping image sequences** of your object of interest **from a diversity of views**
     [see slides on processing of groups of images]
  2. **Define your sensor model** (parameterization of interior orientation)
     [see lectures on stereo photogrammetry]
  3. **Solve the Correspondence problem** (identify identical points in two or more image views)
     [**SIFT** for interest point detection and matching; **RANSAC** for robust identification of outliers; optional integrating exterior orientation prior to speed up correspondence search]
  4. **Perform relative orientation [see lectures on stereo photogrammetry]**
  5. **Identify GCP information in images [see lectures on stereo photogrammetry]**
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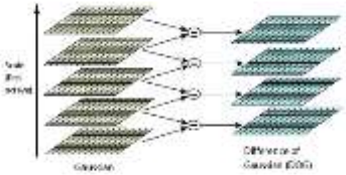
  8. **Generate DEM and Orthophoto mosaic [see lectures on stereo photogrammetry]**
  9. **Report Error metrics for all estimated parameters**

Structure From Motion (SfM)

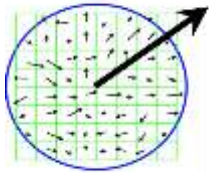
Solving the Correspondence Problem – Feature Matching using SIFT

- **Useful Properties of SIFT for interest point selection and matching:**

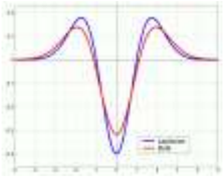
Scale invariance [due to: Gaussian scale space & DoG]



Rotation invariance [alignment with largest gradient]



Illumination invariance [gradient-based method]



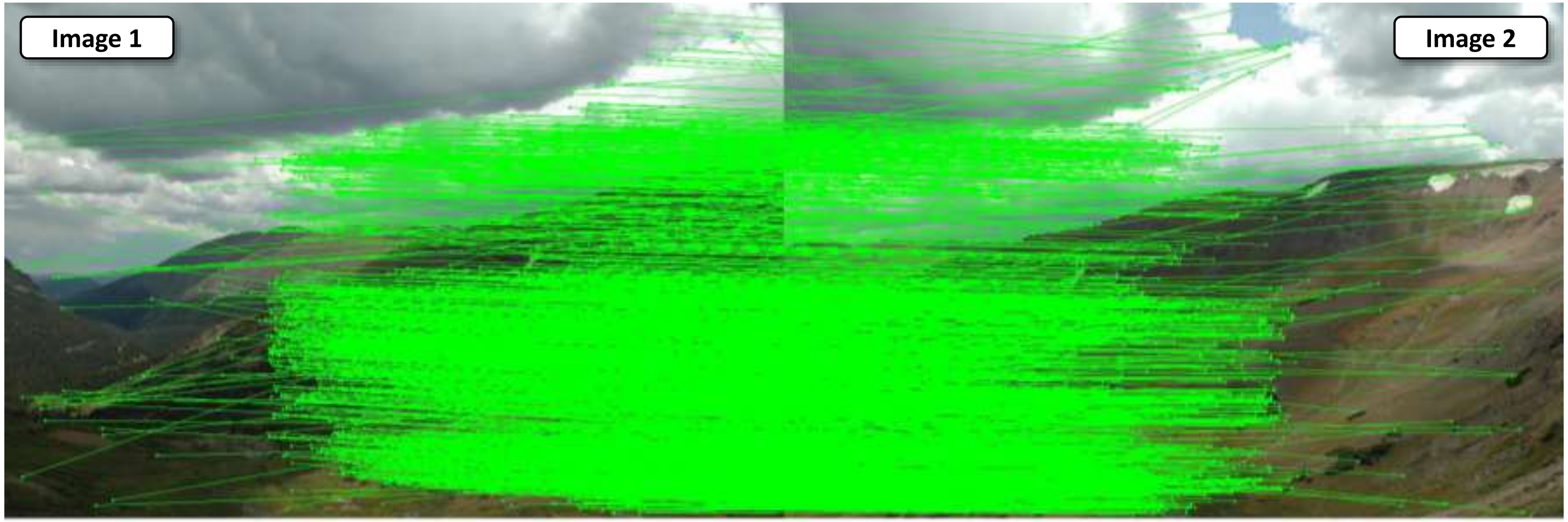
Some pose invariance [less focused on gray value structure]

Robust at finding matching points [due to rich keypoint descriptors]

Structure From Motion (SfM)

Solving the Correspondence Problem – Outlier Detection with RANSAC

- **RANSAC**: **RAN**dom **SA**mple **C**onsensus
  - Estimate parameters of a mathematical model (**here**: relative orientation parameters) from observed data that contains outliers.



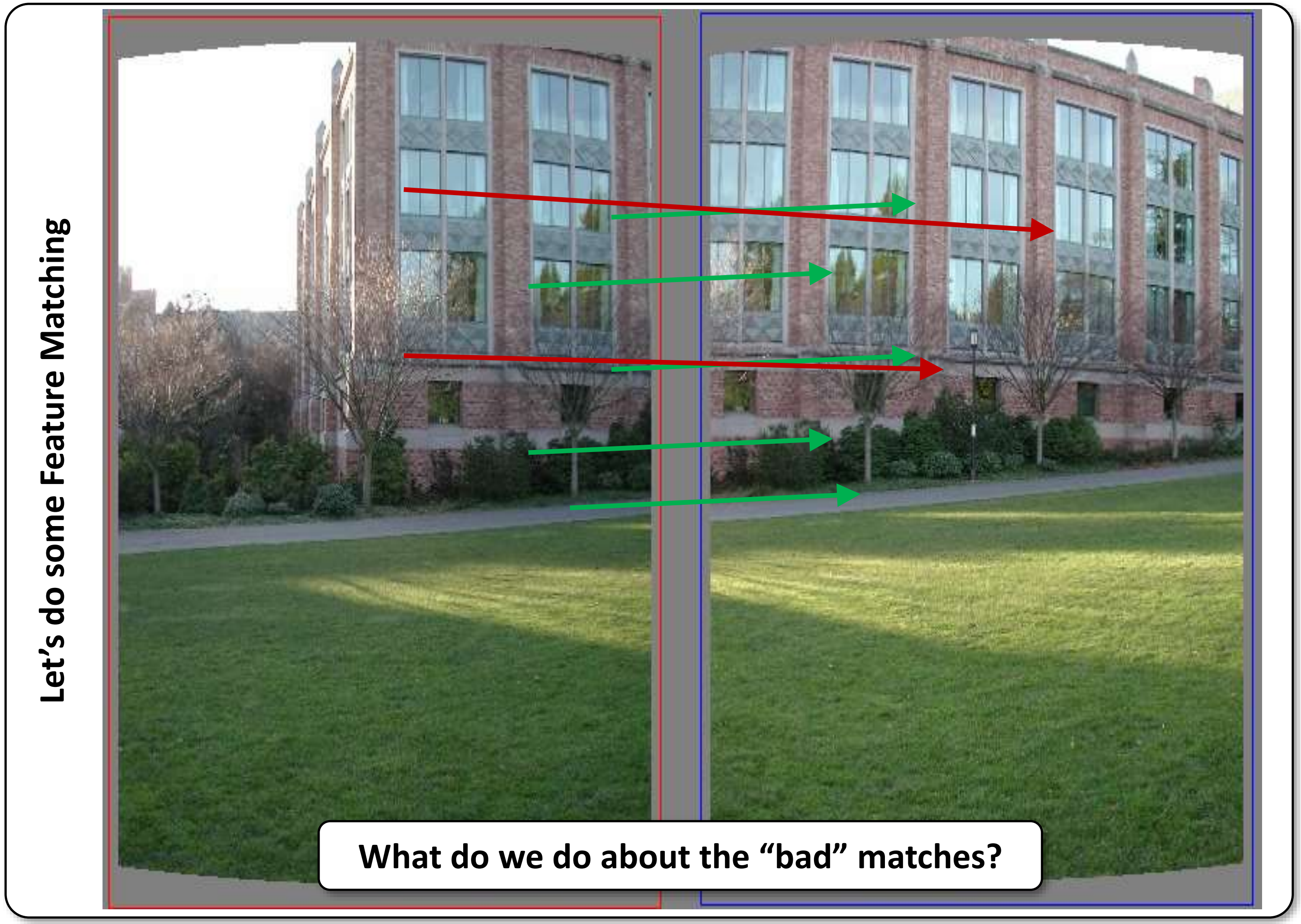
Example of the Correspondence Problem
SIFT-generated point correspondences with outliers (see varying directions of point connections)

  - The example shows data with outliers (some green lines have different orientation than most others) → **GOAL**: disregard bad matches using RANSAC

Structure From Motion (SfM)

Solving the Correspondence Problem – Outlier Detection with RANSAC

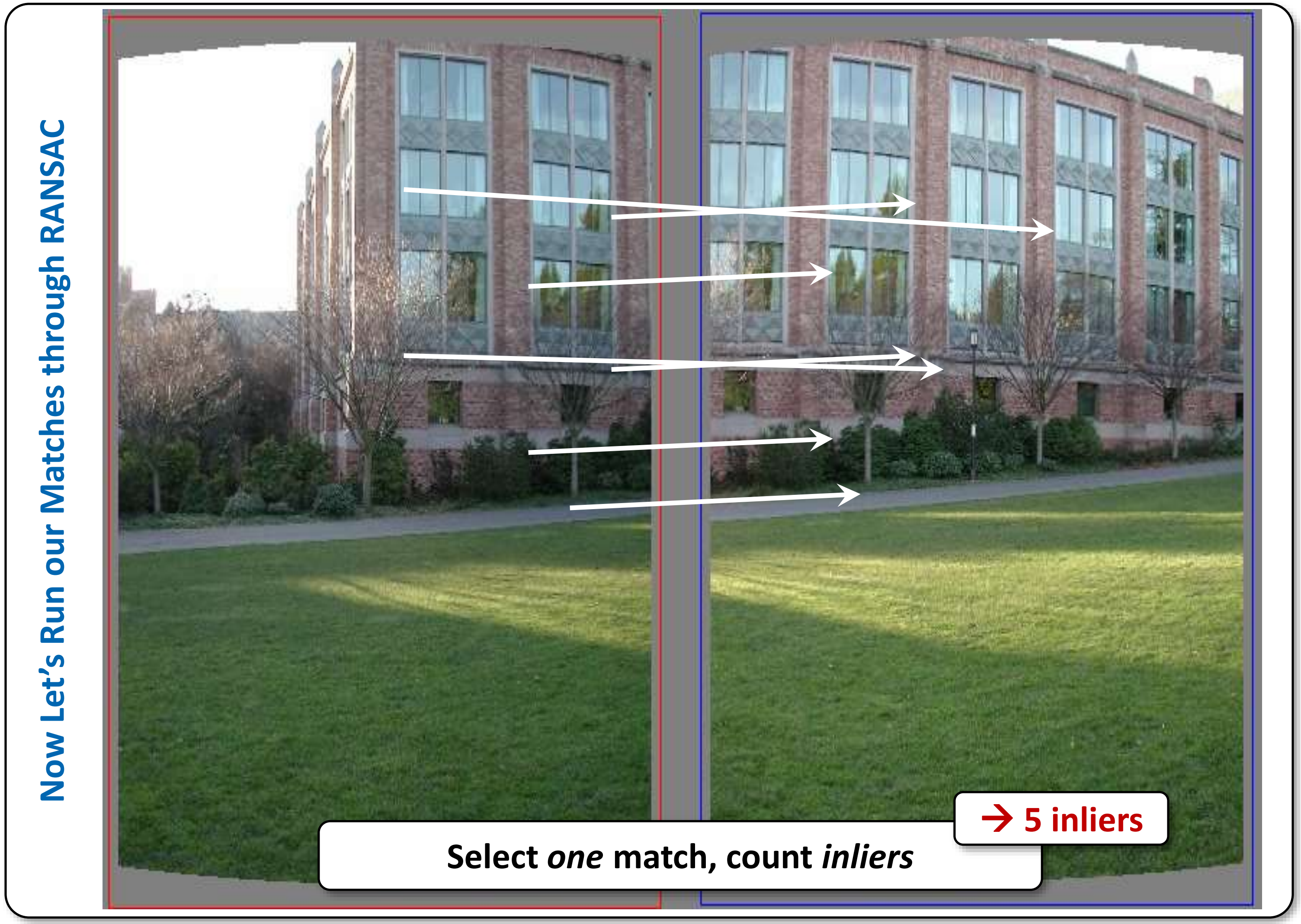
- **A visual explanation of the RANSAC process**



Structure From Motion (SfM)

Solving the Correspondence Problem – Outlier Detection with RANSAC

- **A visual explanation of the RANSAC process**

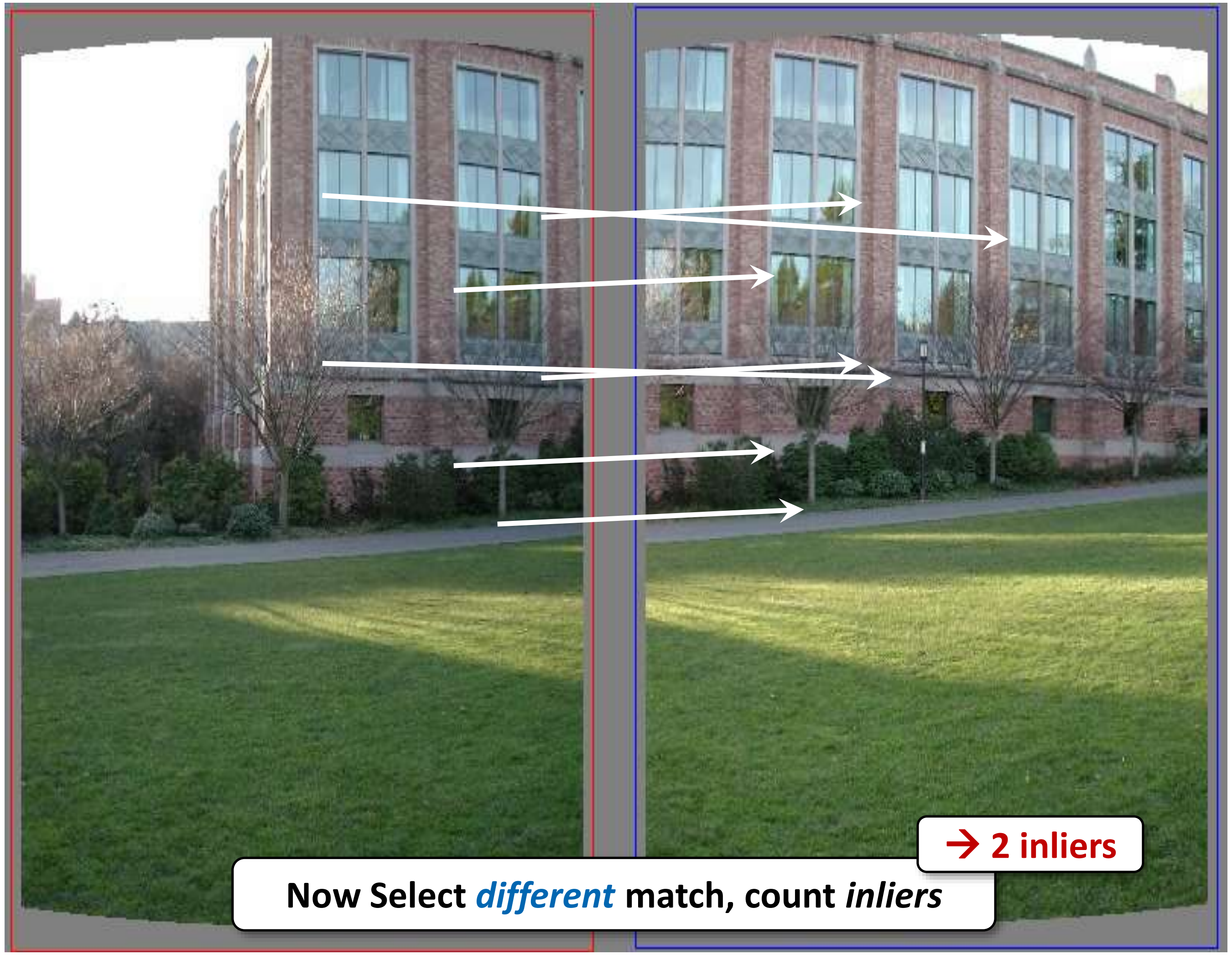


Structure From Motion (SfM)

Solving the Correspondence Problem – Outlier Detection with RANSAC

- **A visual explanation of the RANSAC process**

Now Let's Run our Matches through RANSAC



→ 2 inliers

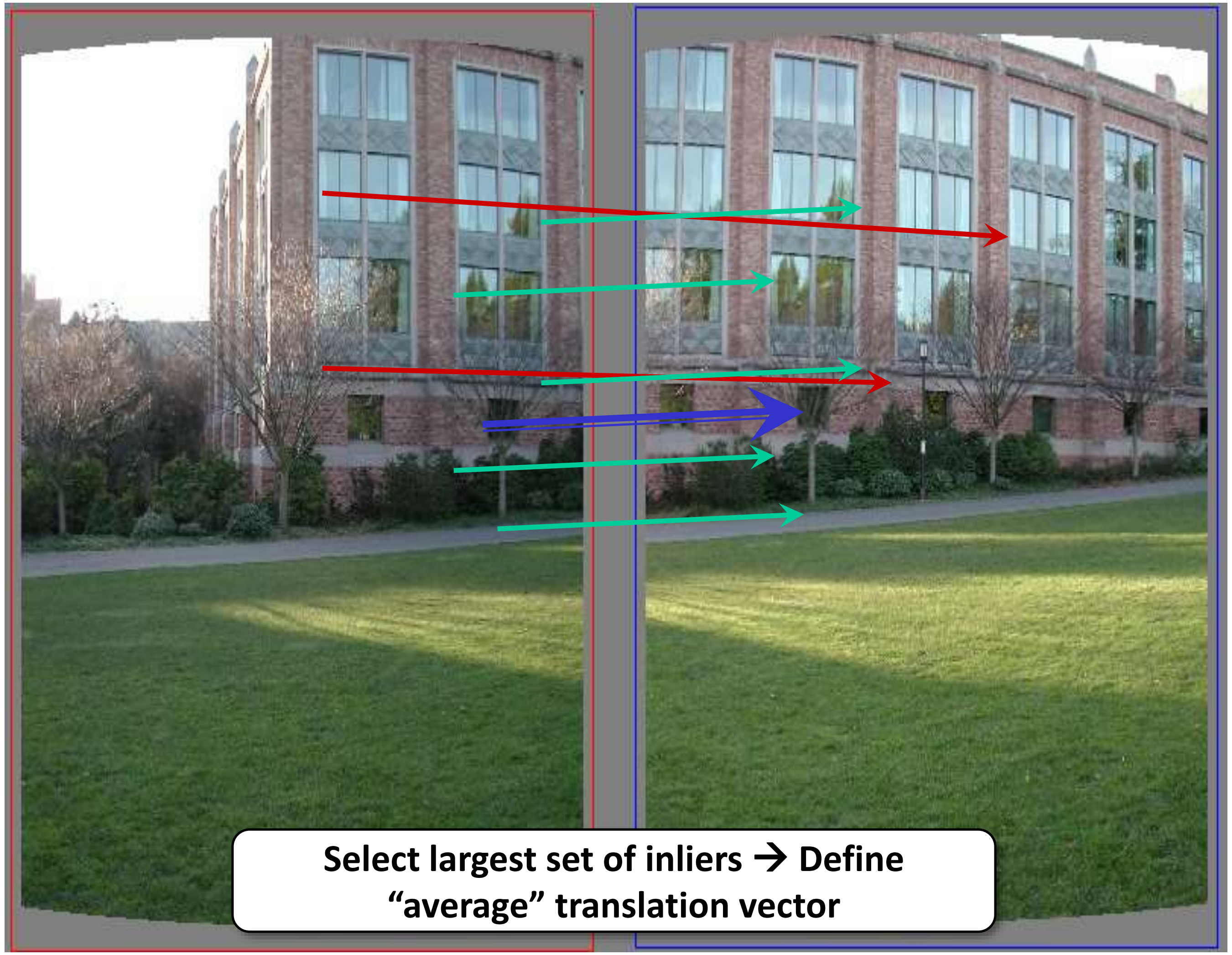
Now Select *different* match, count *inliers*

Structure From Motion (SfM)

Solving the Correspondence Problem – Outlier Detection with RANSAC

- **A visual explanation of the RANSAC process**

Now Let's Run our Matches through RANSAC



Select largest set of inliers → Define "average" translation vector

Structure From Motion (SfM)

Solving the Correspondence Problem – Outlier Detection with RANSAC

- **RANSAC**: Summary of Processing Steps

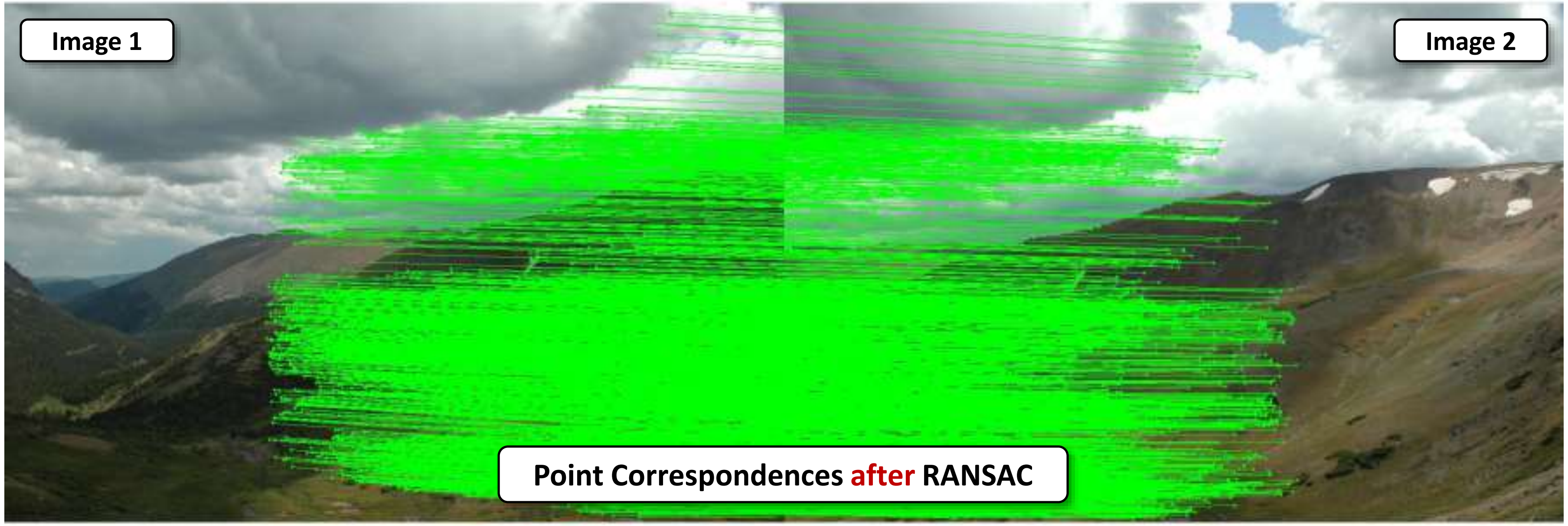
1. Select four (or similar number of) feature pairs p_i (at random)
2. Compute projection geometry H between images from random set (exact)
3. Compute number of *inliers* where sum of squared differences $SSD(p_i, H) < \varepsilon$

4. **Identify largest set of inliers**
5. Re-compute least-squares H for solution with largest set of inliers
6. **DONE**

Structure From Motion (SfM)

Solving the Correspondence Problem – Outlier Detection with RANSAC

- **RANSAC**: **RAN**dom **SA**mple **C**onsensus
  - Back to the example we started with:



Example of the Correspondence Problem
SIFT-generated point correspondences with outliers (see varying directions of point connections)

Structure From Motion (SfM)

Modeling SfM Geometry – The Essential Matrix E

- As in photogrammetry, in SfM, **relationship** between object point $X = [X, Y, Z]^T$ and its projections $P'(x'\ y'\ 0)$ and $P''(x''\ y''\ 0)$ into image I' and I'' are **defined by collinearity and epipolar** geometries.

- **Based on collinearity and epipolar geometry we can write**:

$$\begin{bmatrix} x' \\ y' \\ 0 \end{bmatrix} = m' \begin{bmatrix} r'_{11} & r'_{12} & r'_{13} \\ r'_{21} & r'_{22} & r'_{23} \\ r'_{31} & r'_{32} & r'_{33} \end{bmatrix} \begin{bmatrix} x'' \\ y'' \\ 0 \end{bmatrix} + \begin{bmatrix} \Delta X_0 \\ \Delta Y_0 \\ \Delta Z_0 \end{bmatrix}$$

Which describes the geometric relationship between image coordinates in image I' and I''.

- **Ignoring scale factor m', we can rewrite in matrix-form:**

$$P' = RP'' + T$$

Relative Rotation between images $R\{\Delta\omega, \Delta\varphi, \Delta\kappa\}$

Relative translation between images

Structure From Motion (SfM)

Modeling SfM Geometry – The Essential Matrix $\boldsymbol{E}$

- **In SfM nomenclature, equation system $(\boldsymbol{P}' = \boldsymbol{R}\boldsymbol{P}'' + \boldsymbol{T})$ is typically restructured** by pre-multiplying both sides by $X^T[O]_\times$:

$$P'^T[O]_\times RP'' = P'^T\boldsymbol{E}P'' = 0$$

- Resulting projection matrix $\boldsymbol{E} = [O]_\times R$ is then called the Essential Matrix
  - $[O]_\times$ is the cross product matrix of O

- **Note that $\boldsymbol{E}$ in SfM literature *is identical to*** the **relative orientation** of images I' and I'' **in traditional photogrammetry**.
  - Hence, E contains five parameters, which are the five parameters of relative orientation

- Also, note that **Essential Matrix-based SfM** does **NOT consider lens distortions** → calibrated camera's are expected → **SfM based on $\boldsymbol{E}$** is **mathematically equivalent to traditional photogrammetry**
  - But usage of better image processing routines

Structure From Motion (SfM)

Modeling SfM Geometry – The Fundamental Matrix F

- **Now, let's include camera distortions** by considering a camera distortion matrix K, which includes the radial and tangential distortion parameters (k_n and p_n)
- **If un-calibrated cameras are used,** image point P' may differ from pixel location U' by the inversion of the camera distortion matrix K^{-1}

$$P' = K'^{-1} U'$$

- To include K, we need to **rewrite epipolar geometry in terms of pixel position**

$$\begin{aligned} \left(K'^{-1} U'\right)^T \boldsymbol{E} \left(K''^{-1} U''\right) &= 0 \\ U'^T \left(K'^{-1^T} \boldsymbol{E} \; K''^{-1}\right) U'' &= 0 \\ U'^T \boldsymbol{F} \; U'' &= 0 \end{aligned}$$

- The emerging matrix $\boldsymbol{F} = \left(K'^{-1^T} E \; K''^{-1}\right)$ is called the **Fundamental Matrix**

Structure From Motion (SfM)

Solving for E or F using Bundle Block Adjustment

- **As in photogrammetry**, we solve for E (or F) using **bundle block adjustment**
- **If E is utilized**, then bundle block adjustment is identical to photogrammetry
- **If F is used** → bundle block adjustment equation system technically underdetermined (more unknowns than observations)
  - **Solution is found using Singular value decomposition**

- **Two typical solution concepts for SfM Bundle Block Adjustment**:
  1. **Sequential methods**
     - Incorporate successive views one at a time, starting with first image pair
     - **See Slide 33**
  2. **Factorization method**
     - Calculate camera poses and scene geometry using all images simultaneously
     - **See Slide 34**

Structure From Motion (SfM)

Two Final Words of Caution

1. **Some Literature (very incorrectly) claims that SfM is fundamentally different from traditional photogrammetry as it would not require ground control**

   This statement is (boldly) WRONG in two ways:
   (1) SfM is NOT fundamentally different from photogrammetry (it follows similar processing flow). Rather than that, it is an evolution of photogrammetry
   (2) SfM **ABSOLUTELY DOES require external information** either in the form of GCPs, in the form of scaling measurements, or in the form of GPS/INS-tracked camera position data.

2. **Structure from Motion Solution is sub-optimal!**

   The fact that SfM performs camera calibration and 3D object reconstruction in one step is often claimed as a virtue of the technique. In contrast to popular belief, this approach is sub-optimal as camera calibration and object reconstruction have different requirements on acquisition geometry (e.g., calibration is best if camera only rotates but doesn't translate).
   Solution will improve if calibration & object reconstruction are broken up into two steps!

Selected (& Incomplete) Recent SfM Literature

- Snavely, N., Seitz, S.M. and Szeliski, R., 2006, July. Photo tourism: exploring photo collections in 3D. In ACM transactions on graphics (TOG) (Vol. 25, No. 3, pp. 835-846). ACM.
- Häming, Klaus, and Gabriele Peters. "The structure-from-motion reconstruction pipeline–a survey with focus on short image sequences." Kybernetika 46, no. 5 (2010): 926-937.
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A STRUCTURE-FROM-MOTION EXAMPLE

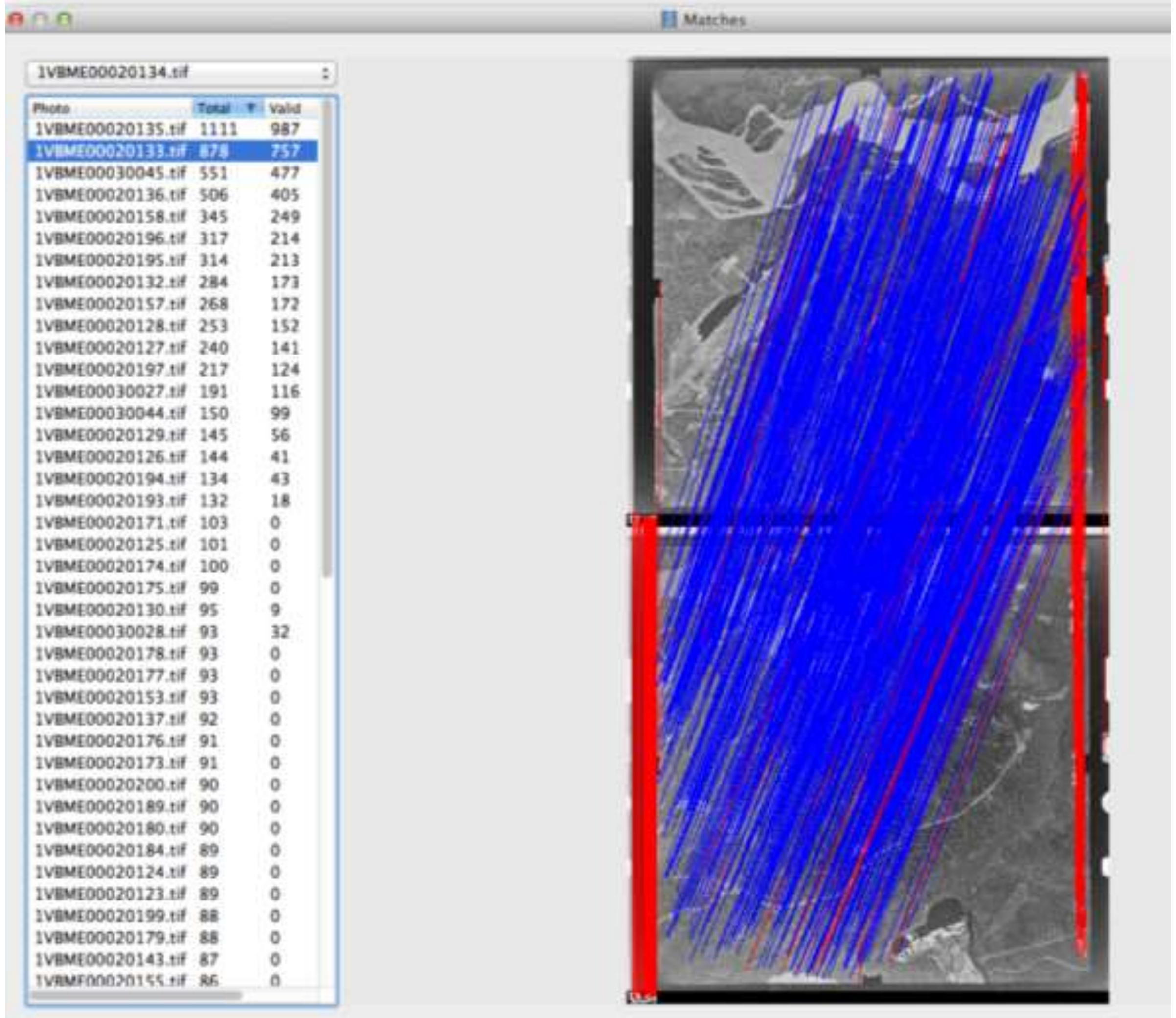
Structure From Motion (SfM)

Example 1: Processing AHAP Data in Agisoft PhotoScan Pro

- **Workflow:**
  1. **Load and Mask Data**
     (Historic data often require some measure of pre-processing)
  2. **Define your sensor model**

Structure From Motion (SfM)

Example 1: Processing AHAP Data in Agisoft PhotoScan Pro

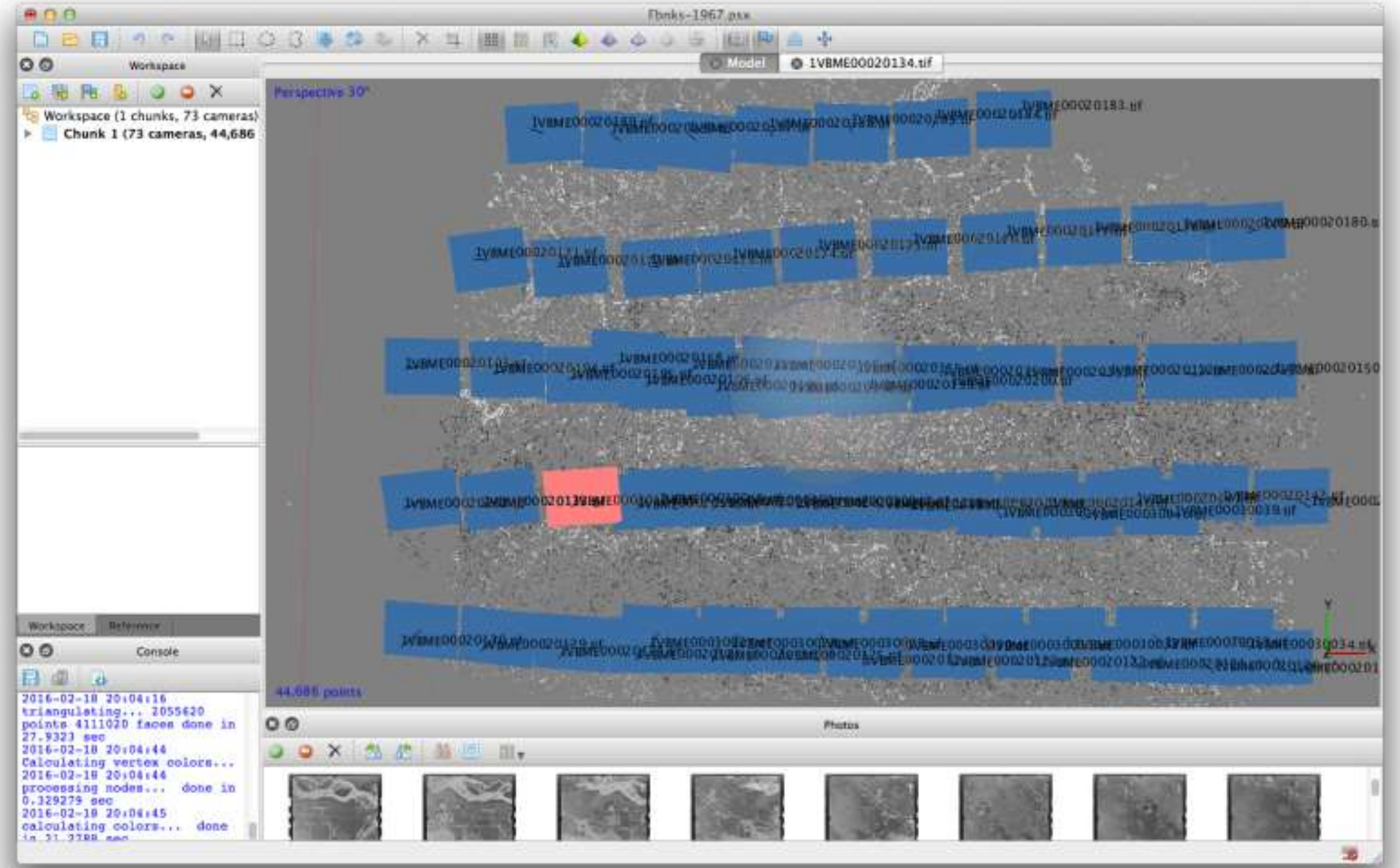


- **Workflow:**
  3. **Solve the Correspondence problem** (identify identical points in two or more image views)
     [SIFT for interest point detection and matching; RANSAC for robust identification of outliers; optional integrating exterior orientation prior to speed up correspondence search**]**

Structure From Motion (SfM)

Example 1: Processing AHAP Data in Agisoft PhotoScan Pro

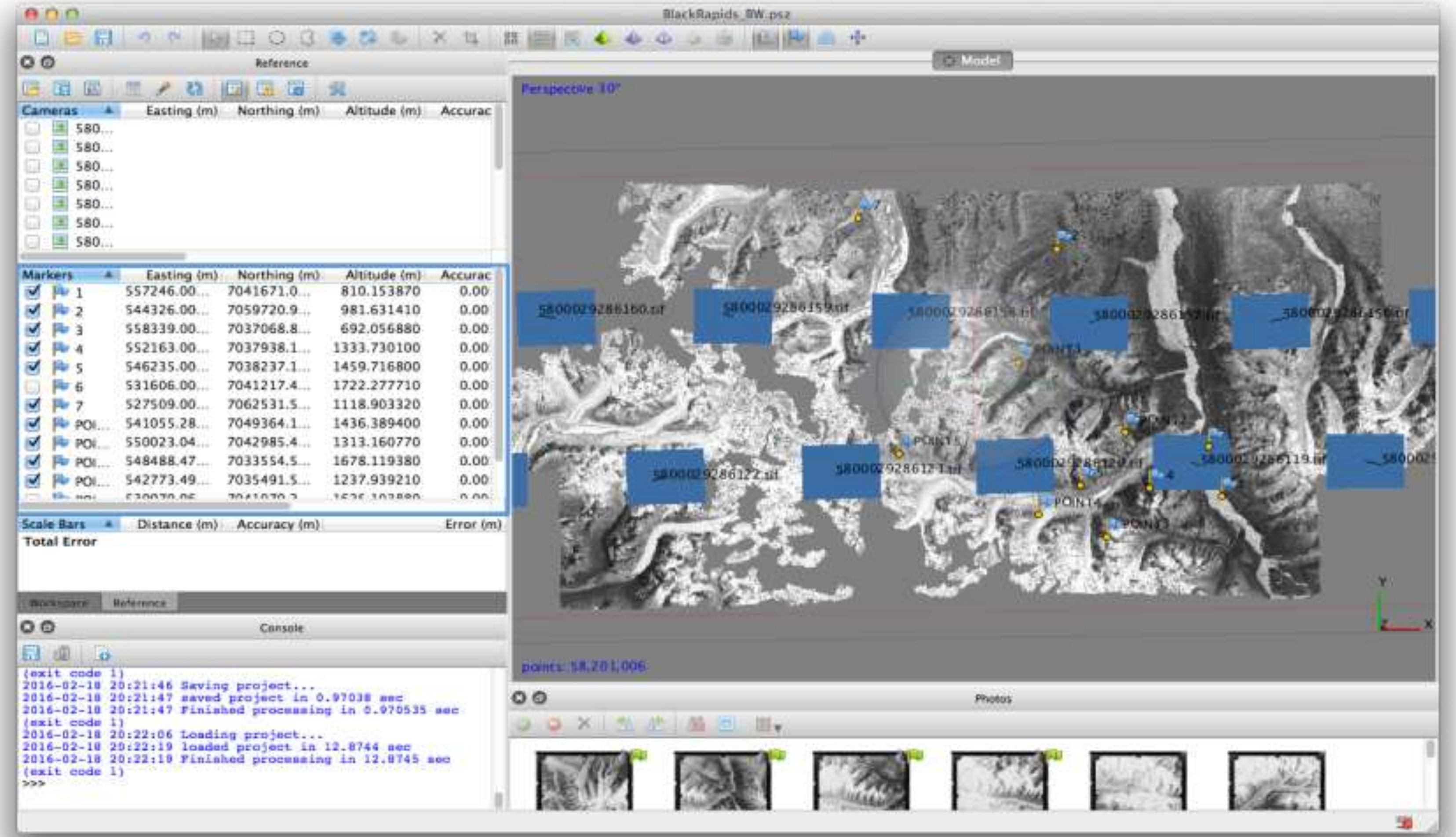
- **Workflow:**
  4. **Perform relative orientation** [see lectures on stereo photogrammetry]



Structure From Motion (SfM)

Example 1: Processing AHAP Data in Agisoft PhotoScan Pro

- **Workflow:**
  5. Identify GCP information in images [see lectures on stereo photogrammetry]

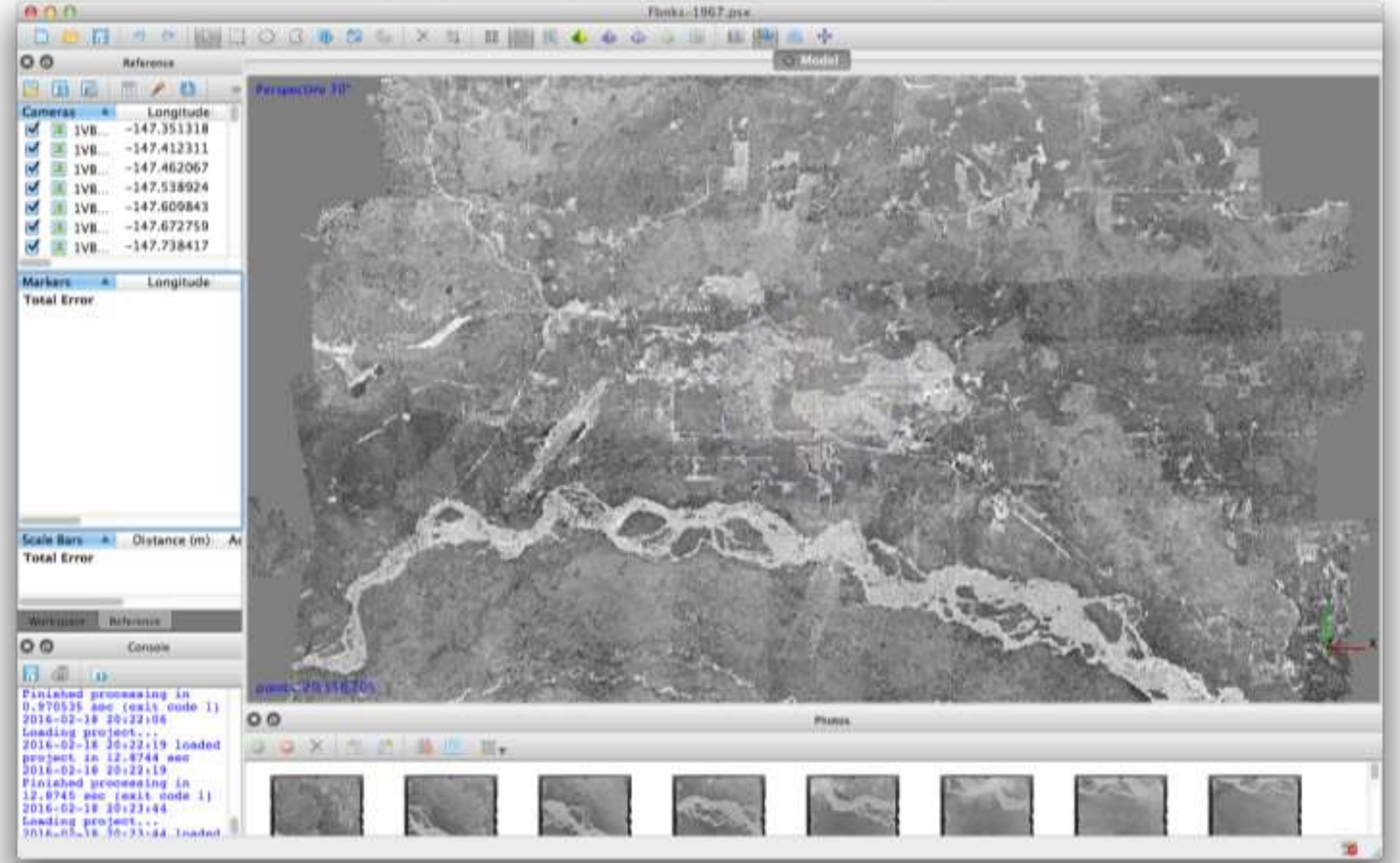


Structure From Motion (SfM)

Example 1: Processing AHAP Data in Agisoft PhotoScan Pro

- **Workflow:**
  6. **Solve Bundle Block Adjustment problem for absolute orientation**
  7. **Generate DEM through interpolation of point cloud**

Dense Point Cloud

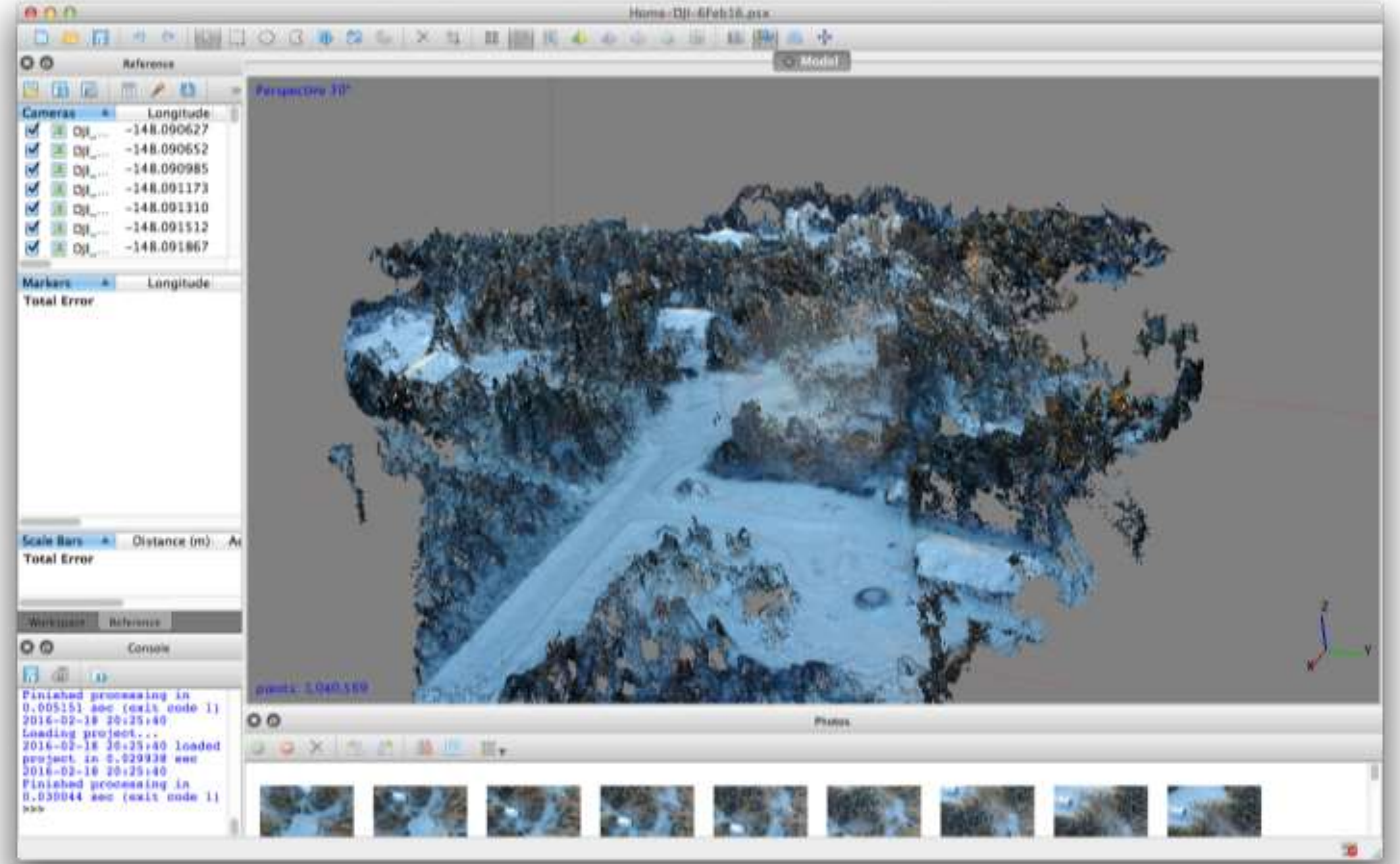


Structure From Motion (SfM)

Example 1: Processing AHAP Data in Agisoft PhotoScan Pro

- **Workflow:**
  6. Solve Bundle Block Adjustment problem for absolute orientation
  7. Generate DEM through interpolation of point cloud

Dense Point Cloud

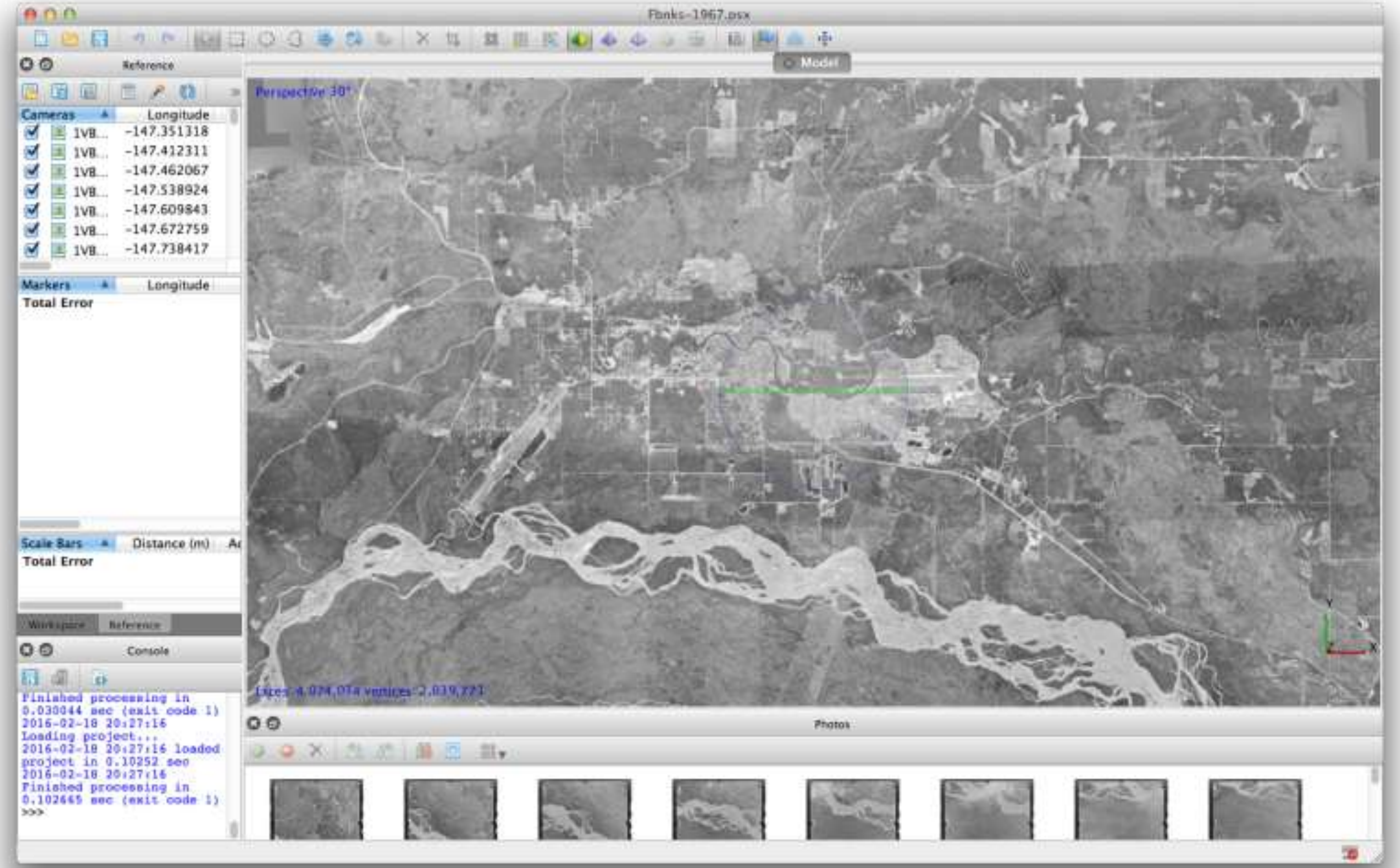


Structure From Motion (SfM)

Example 1: Processing AHAP Data in Agisoft PhotoScan Pro

- **Workflow:**
  8. Generate DEM & Orthophoto mosaic

Digital Surface Model & Orthoimagery



Structure From Motion (SfM)

Example 2: Multi-Temporal DSM Comparison over Ester, Alaska

- **Background:**
  - 1949 airborne imagery over western Fairbanks
  - Active gold mining occurring
  - Water being pumped from the Chena River over Chena Ridge and into Cripple Creek
  - Return waste being dumped into the Chena River

Structure From Motion (SfM)

Example 2: Multi-Temporal DSM Comparison over Ester, Alaska

Images from vilda.alaska.edu

Structure From Motion (SfM)

Example 2: Multi-Temporal DSM Comparison over Ester, Alaska

Ester Village in 1949

Structure From Motion (SfM)

Example 2: Multi-Temporal DSM Comparison over Ester, Alaska

Ester Village “now” (SDMI Data)

Structure From Motion (SfM)

Example 2: Multi-Temporal DSM Comparison over Ester, Alaska

Gold Hill in 1949

Structure From Motion (SfM)

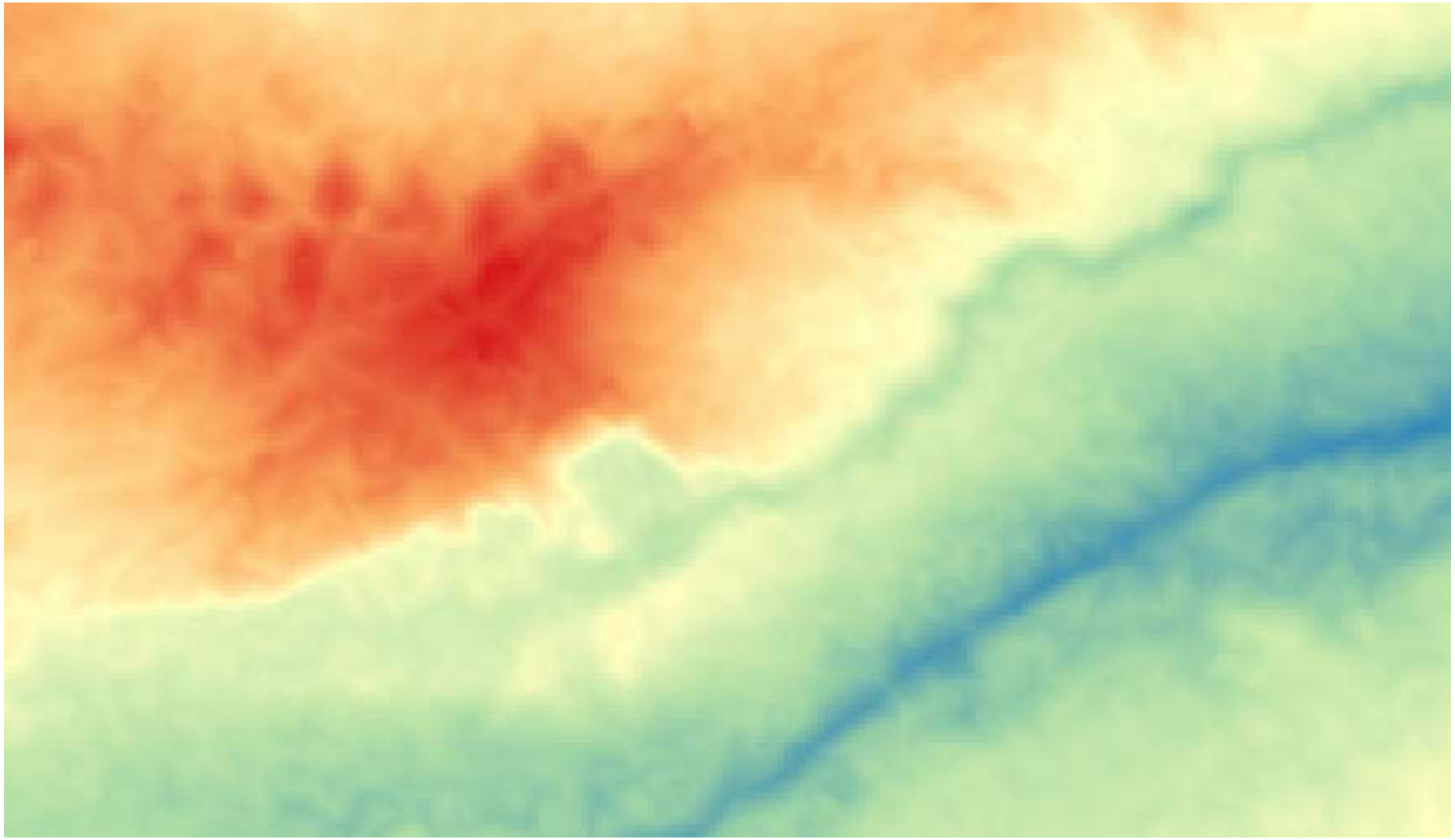
Example 2: Multi-Temporal DSM Comparison over Ester, Alaska

Gold Hill “now”

Structure From Motion (SfM)

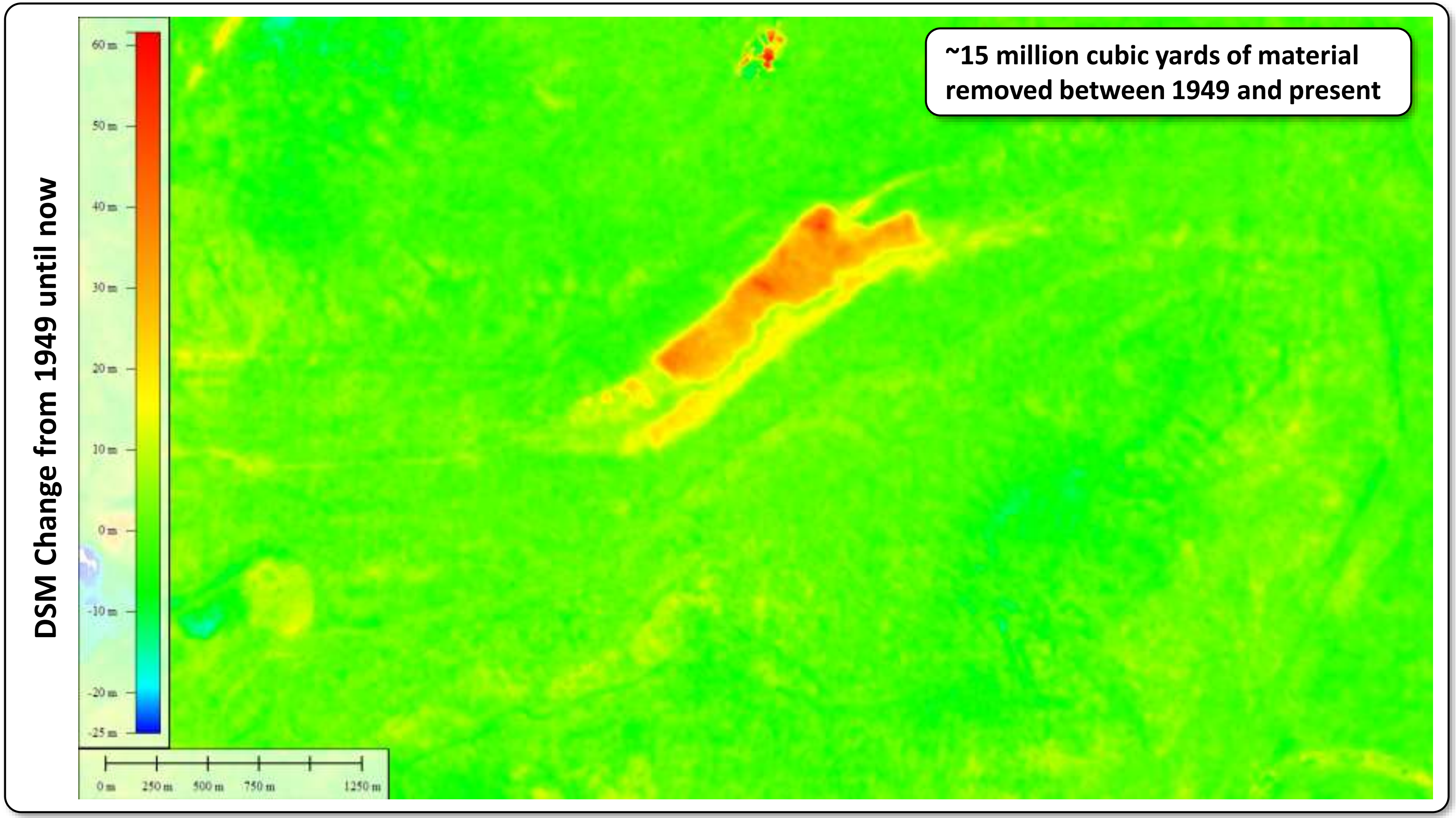
Example 2: Multi-Temporal DSM Comparison over Ester, Alaska

Gold Hill 1949 DSM from SfM



Structure From Motion (SfM)

Example 2: Multi-Temporal DSM Comparison over Ester, Alaska



What's Next

- **Next Week:**
  - Lab on Structure-from-Motion
  - Then back to InSAR (YAY)