Image Stitching

Computational Photography

Derek Hoiem, University of Illinois

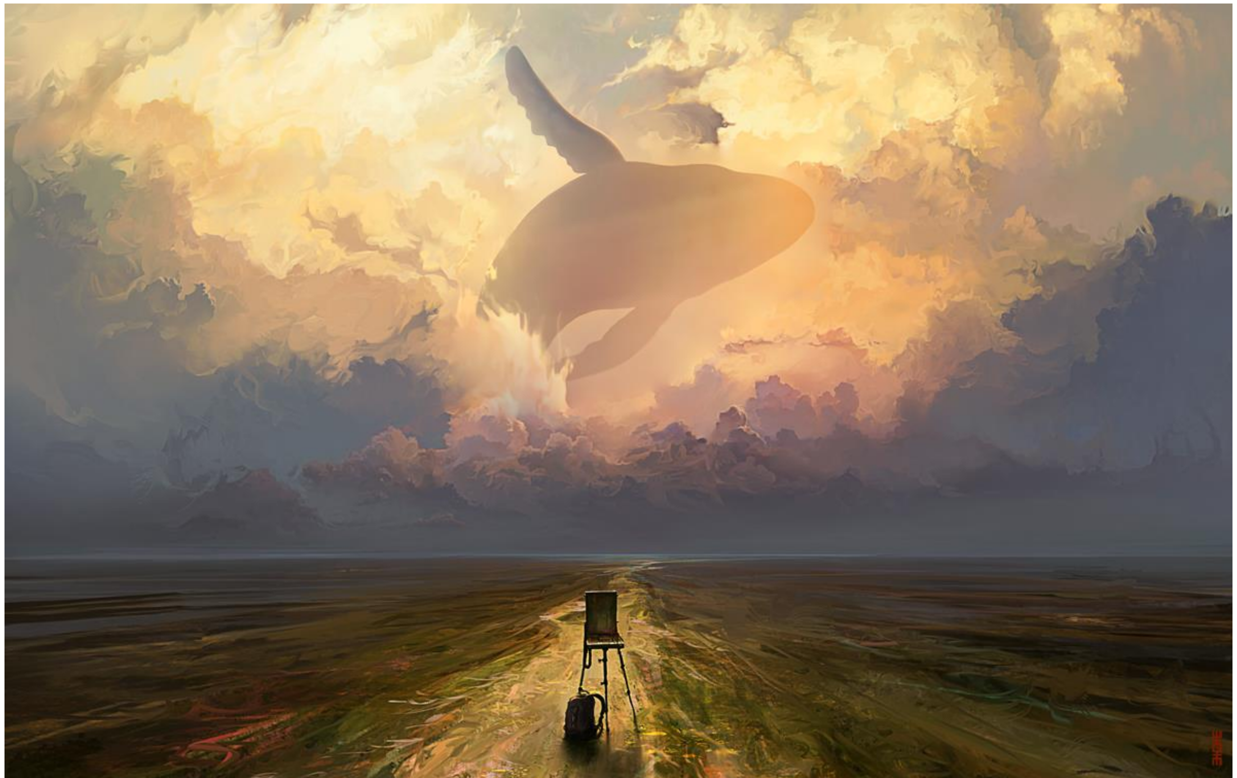
Photos by Russ Hewett

Project 3 Highlights

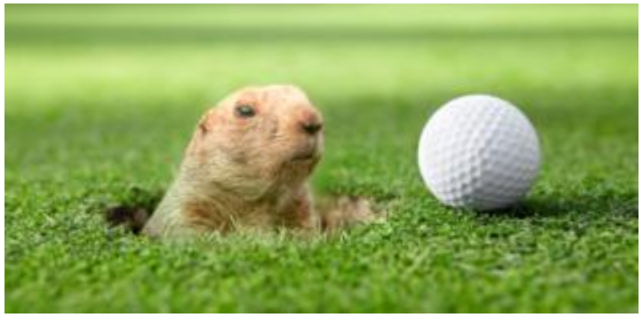
- http://kagrawa3.web.engr.illinois.edu/cs445/proj3/ very good main result (most likes)
- http://vjdixit2.web.engr.illinois.edu/cs445/proj3/ overall very blends.
- http://zhung2.web.engr.illinois.edu/cs445/proj3/ overall good results, and nice texture flattening
- http://tliang7.web.engr.illinois.edu/cs445/proj3/ nice texture flattening results and all ec
- http://jdrynld2.web.engr.illinois.edu/cs445/proj3/ very believable poisson results and ec

Honorable mentions:

- http://brthomp2.web.engr.illinois.edu/cs445/proj3/ nice main result
- http://xjin12.web.engr.illinois.edu/cs445/proj3/ nice mixed gradients results
- http://akvijay2.web.engr.illinois.edu/cs445/proj3/ nice mixed gradient results
- http://roush2.web.engr.illinois.edu/cs445/proj3/ nice main result
- http://mscraft2.web.engr.illinois.edu/cs445/proj3/ nice ec results
- http://lavisha2.web.engr.illinois.edu/cs445/proj3/ overall good results and all ec
- http://rgupta31.web.engr.illinois.edu/cs445/proj3/ all good results and nice main result
- http://hhuang81.web.engr.illinois.edu/cs445/proj3/ nice results
- http://jjwu2.web.engr.illinois.edu/cs445/proj3/
- http://agou2.web.engr.illinois.edu/cs445/proj3/
- http://tcai4.web.engr.illinois.edu/cs445/proj3/



http://kagrawa3.web.engr.illinois.edu/cs445/proj3/



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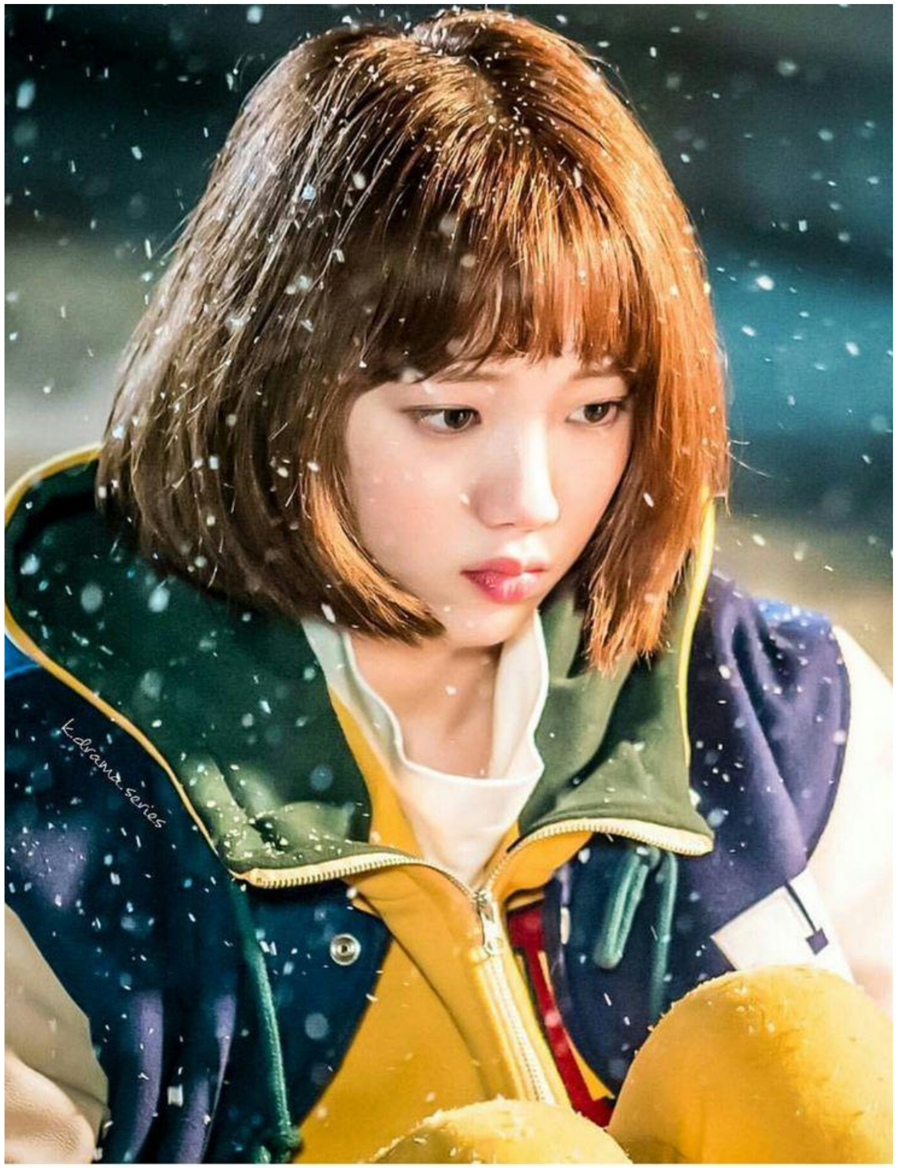
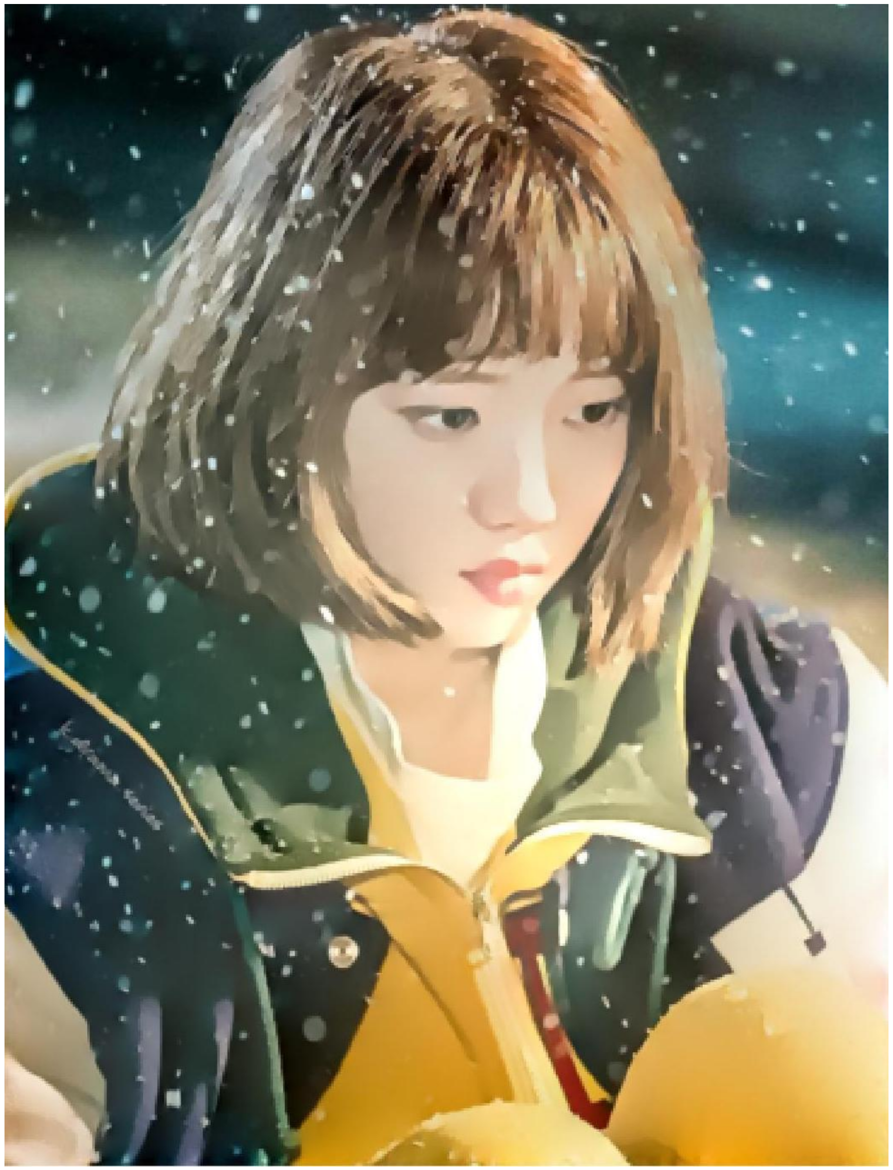




http://tliang7.web.engr.illinois.edu/cs445/proj3/

http://jdrynld2.web.engr.illinois.edu/cs445/proj3/

Project 5

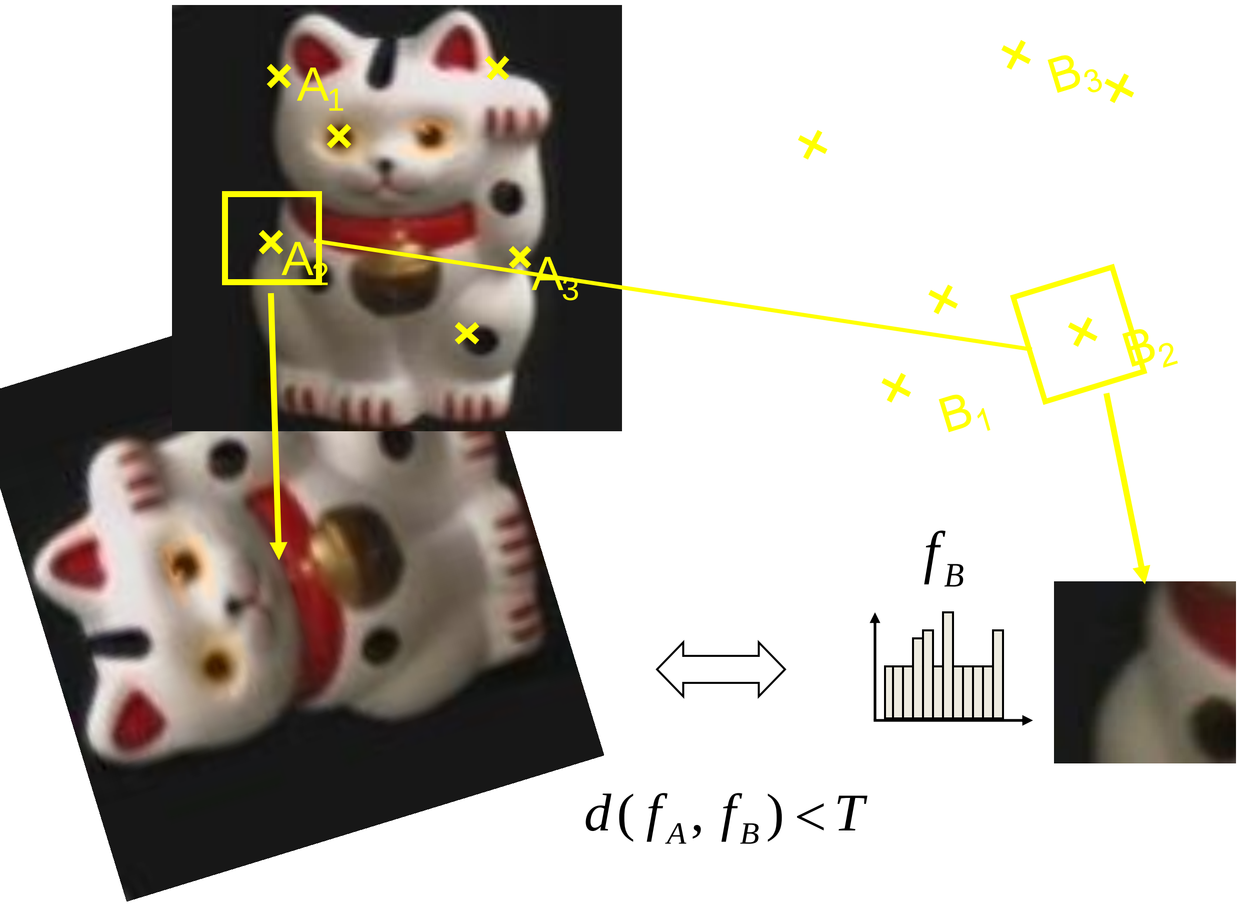
Input video:
https://www.youtube.com/watch?v=agI5za_gHHU

Aligned frames:
https://www.youtube.com/watch?v=Uahy6kPotaE

Background:
https://www.youtube.com/watch?v=Vt9vv1zCnLA

Foreground:
https://www.youtube.com/watch?v=OICkKNndEt4

Last Class: Keypoint Matching

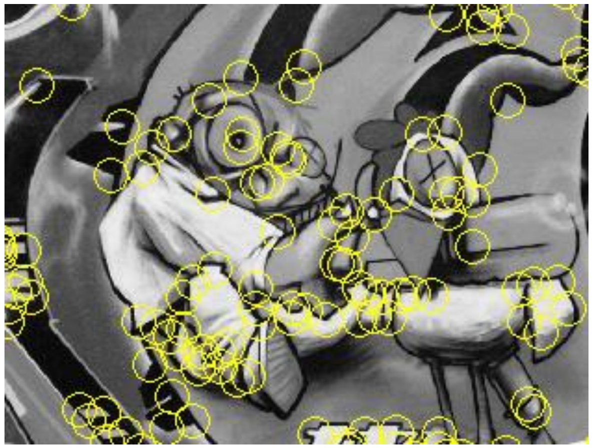


1. **Find a set of distinctive key-points**
2. **Define a region around each keypoint**
3. **Extract and normalize the region content**
4. **Compute a local descriptor from the normalized region**
5. **Match local descriptors**

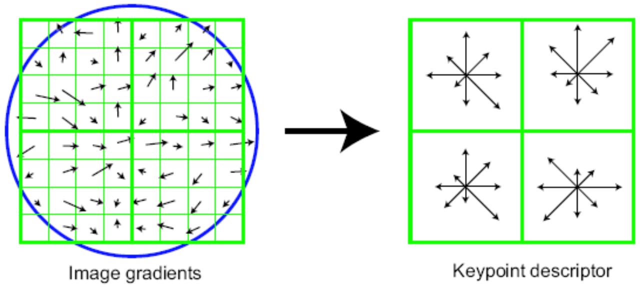
K. Grauman, B. Leibe

Last Class: Summary

- Keypoint detection: repeatable and distinctive
  - Corners, blobs
  - Harris, DoG

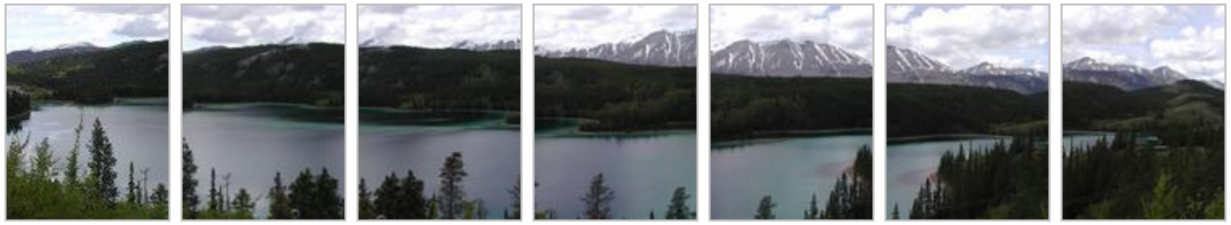


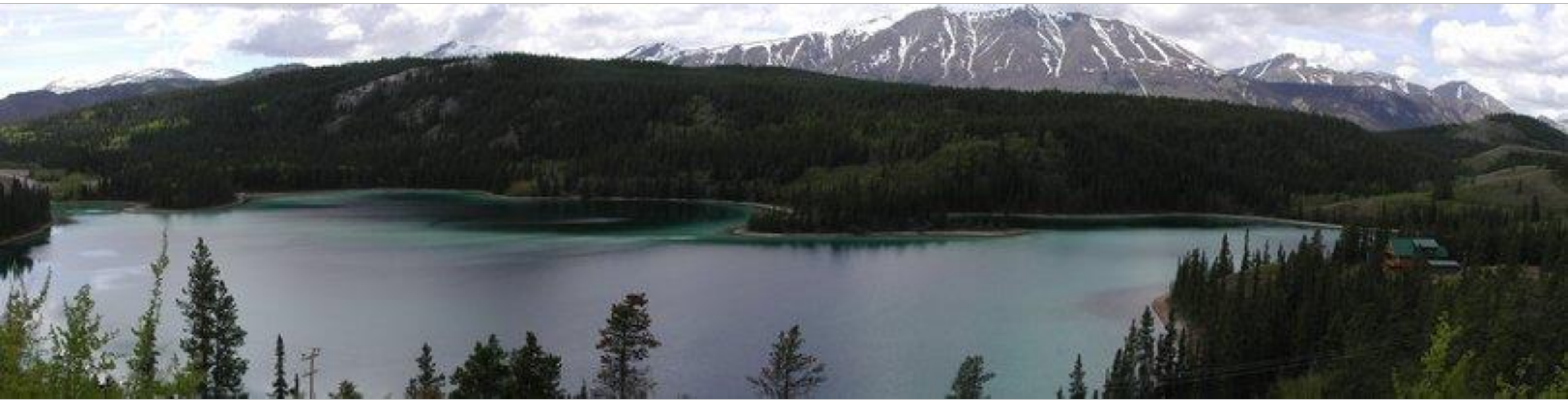
- Descriptors: robust and selective
  - SIFT: spatial histograms of gradient orientation



Today: Image Stitching

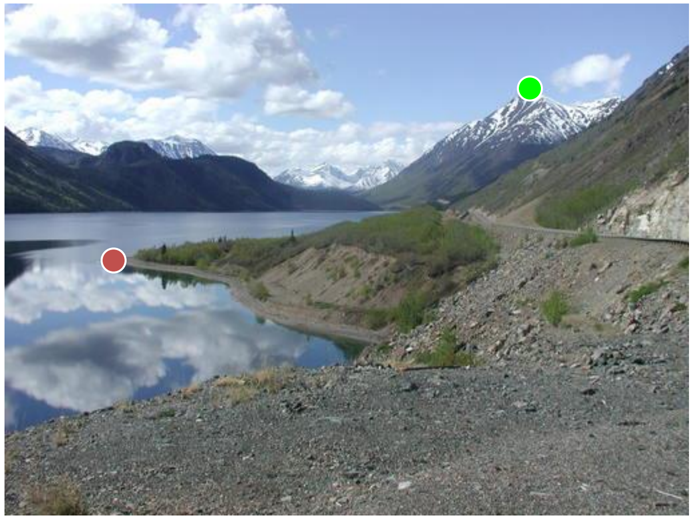
- Combine two or more overlapping images to make one larger image

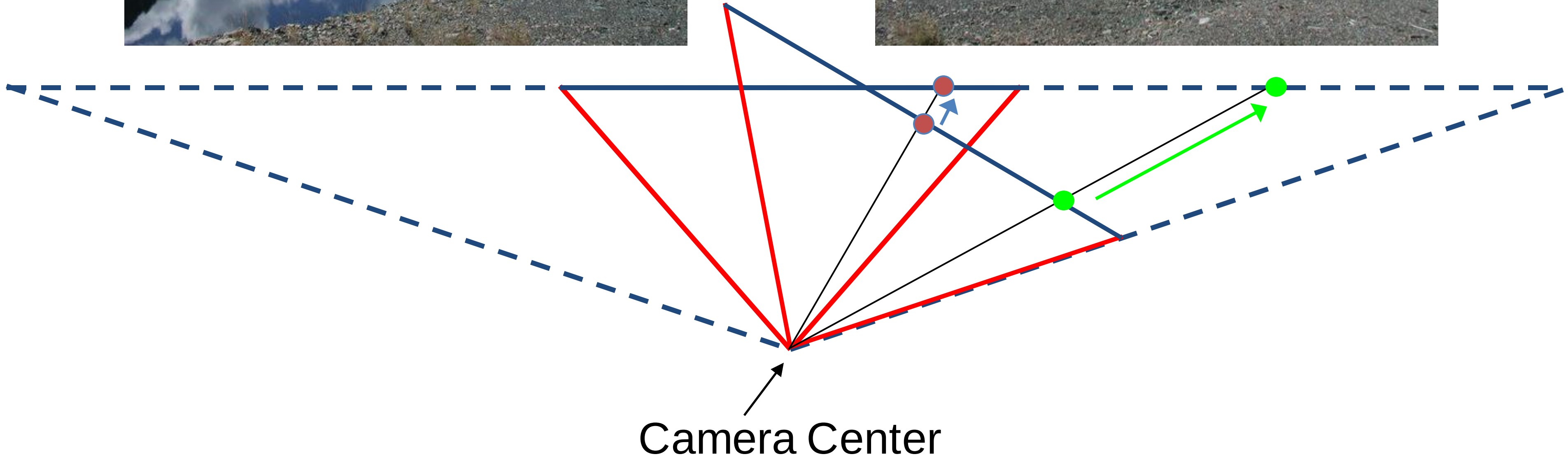




Slide credit: Vaibhav Vaish

Views from rotating camera



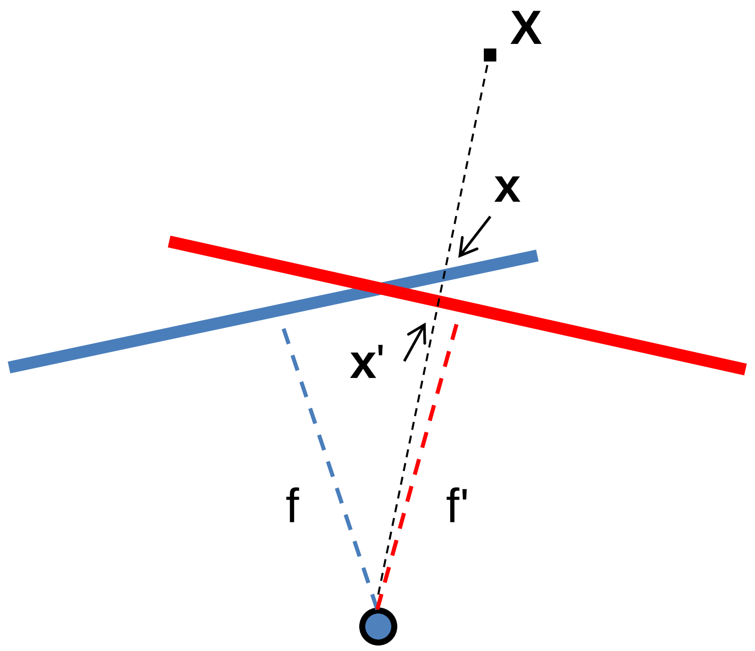


Problem basics

- Do on board

Basic problem

- $x = K\ [R\ t]\ X$
- $x' = K'\ [R'\ t']\ X'$
- $t = t' = 0$



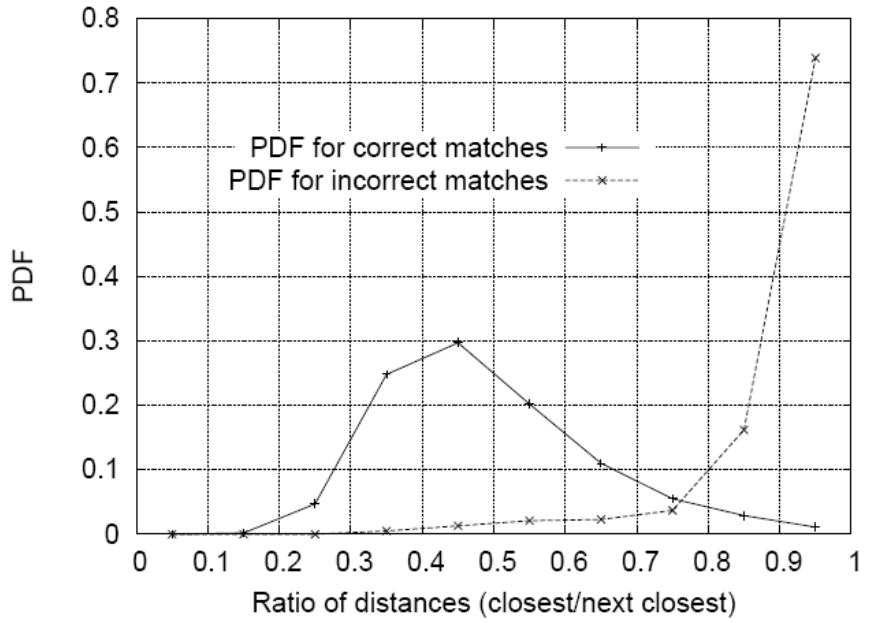
- $x' = Hx$ where $H = K'\ R'\ R^{-1}\ K^{-1}$
- Typically only R and f will change (4 parameters), but, in general, H has 8 parameters

Image Stitching Algorithm Overview

1. Detect keypoints
2. Match keypoints
3. Estimate homography with four matched keypoints (using RANSAC)
4. Project onto a surface and blend

Image Stitching Algorithm Overview

1. Detect/extract keypoints (e.g., DoG/SIFT)
2. Match keypoints (most similar features, compared to 2nd most similar)



Computing homography

Assume we have four matched points: How do we compute homography **H**?

Direct Linear Transformation (DLT)

$$\mathbf{x}' = \mathbf{H}\mathbf{x} \qquad \mathbf{x}' = \begin{bmatrix} w'u' \\ w'v' \\ w' \end{bmatrix} \qquad \mathbf{H} = \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix}$$

$$\begin{bmatrix} -u & -v & -1 & 0 & 0 & 0 & uu' & vu' & u' \\ 0 & 0 & 0 & -u & -v & -1 & uv' & vv' & v' \end{bmatrix} \mathbf{h} = \mathbf{0} \qquad \mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \\ h_9 \end{bmatrix}$$

Computing homography

Direct Linear Transform

$$\begin{bmatrix} -u_1 & -v_1 & -1 & 0 & 0 & 0 & u_1 u_1' & v_1 u_1' & u_1' \\ 0 & 0 & 0 & -u_1 & -v_1 & -1 & u_1 v_1' & v_1 v_1' & v_1' \\ & & & & \vdots & & & & \\ 0 & 0 & 0 & -u_n & -v_n & -1 & u_n v_n' & v_n v_n' & v_n' \end{bmatrix} \mathbf{h} = \mathbf{0} \Rightarrow \mathbf{A}\mathbf{h} = \mathbf{0}$$

- Apply SVD: $\boldsymbol{UDV}^T = \boldsymbol{A}$
- $\boldsymbol{h} = \boldsymbol{V}_{\text{smallest}}$ (column of ***V*** corr. to smallest singular value)

$$\mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_9 \end{bmatrix} \quad \mathbf{H} = \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix}$$

Matlab

```
[U, S, V] = svd(A);
h = V(:, end);
```

Computing homography

Assume we have four matched points: How do we compute homography **H**?

Normalized DLT

1. Normalize coordinates for each image
   a) Translate for zero mean
   b) Scale so that u and v are ~=1 on average

$$\tilde{\mathbf{x}} = \mathbf{T}\mathbf{x} \qquad \tilde{\mathbf{x}}' = \mathbf{T}'\mathbf{x}'$$

   – This makes problem better behaved numerically (see Hartley and Zisserman p. 107-108)

2. Compute $\tilde{\mathbf{H}}$ using DLT in normalized coordinates
3. Unnormalize: $\mathbf{H} = \mathbf{T}'^{-1}\tilde{\mathbf{H}}\mathbf{T}$

$$\mathbf{x}_i' = \mathbf{H}\mathbf{x}_i$$

Computing homography

- Assume we have matched points with outliers: How do we compute homography **H**?

Automatic Homography Estimation with RANSAC

RANSAC: RANdom SAmple Consensus

Scenario: We’ve got way more matched points than needed to fit the parameters, but we’re not sure which are correct

RANSAC Algorithm

- Repeat N times
  1. Randomly select a sample
     - Select just enough points to recover the parameters
  2. Fit the model with random sample
  3. See how many other points agree
- Best estimate is one with most agreement
  - can use agreeing points to refine estimate

Computing homography

- Assume we have matched points with outliers: How do we compute homography **H**?

Automatic Homography Estimation with RANSAC

1. Choose number of samples *N*
2. Choose 4 random potential matches
3. Compute **H** using normalized DLT
4. Project points from **x** to **x**' for each potentially matching pair: $\mathbf{x}'_i = \mathbf{H}\mathbf{x}_i$
5. Count points with projected distance < t
   - E.g., t = 3 pixels
6. Repeat steps 2-5 *N* times
   - Choose **H** with most inliers

HZ Tutorial '99

Automatic Image Stitching

1. Compute interest points on each image

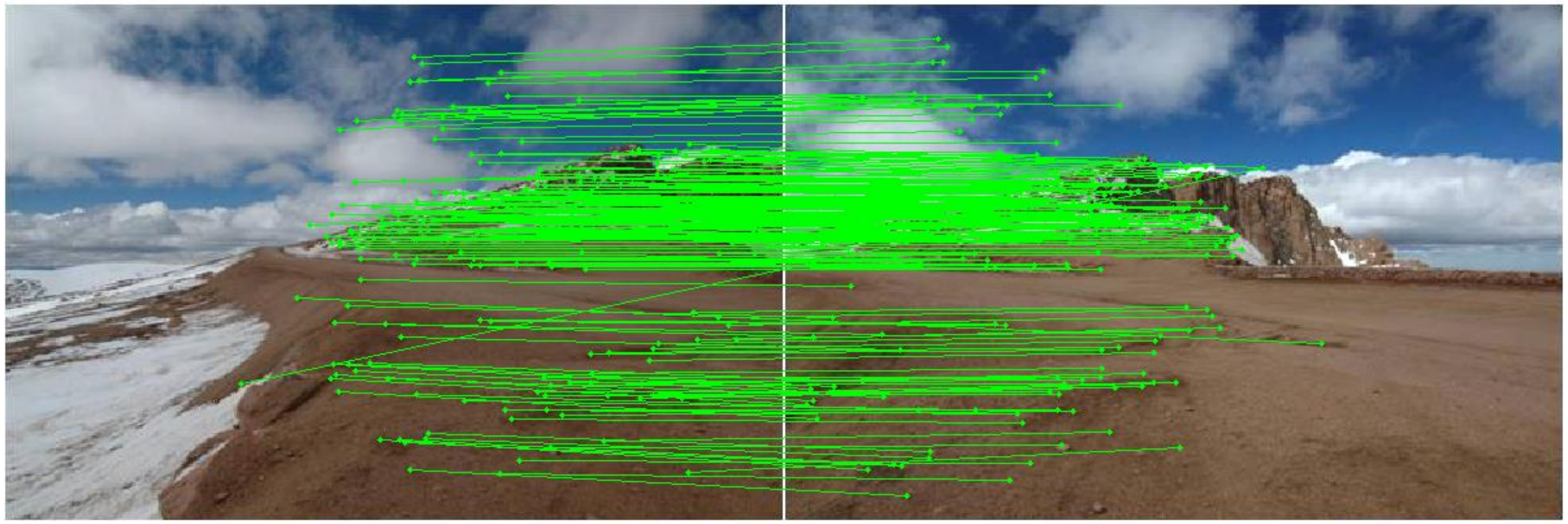
2. Find candidate matches

3. Estimate homography **H** using matched points and RANSAC with normalized DLT

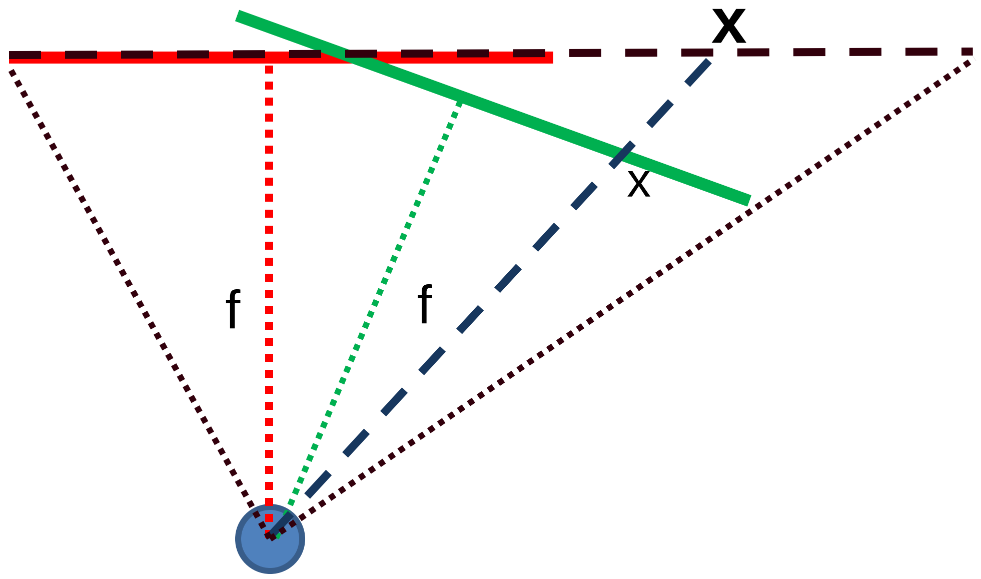
4. Project each image onto the same surface and blend

Choosing a Projection Surface

Many to choose: planar, cylindrical, spherical, cubic, etc.

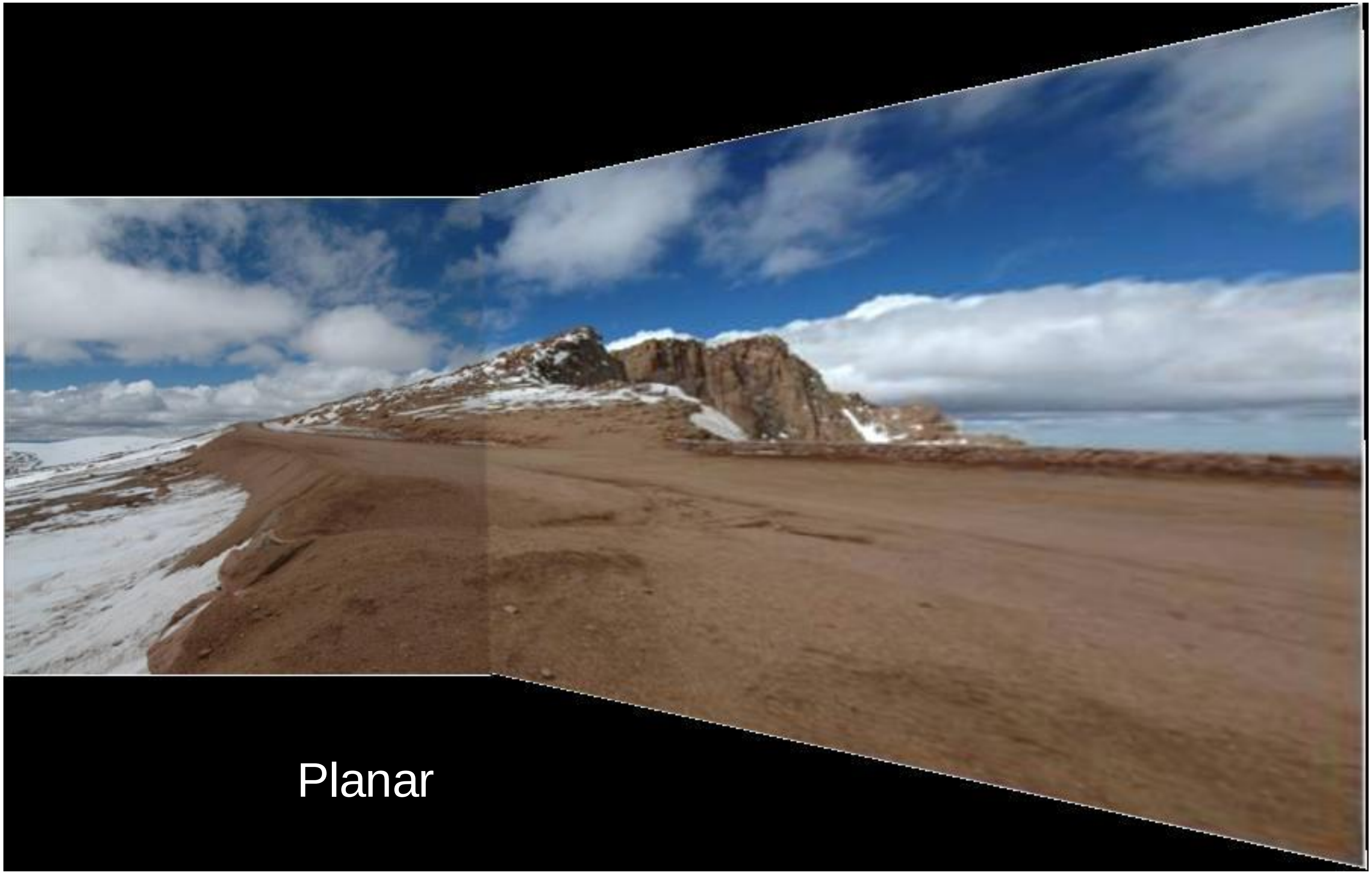


Planar Mapping



1) For red image: pixels are already on the planar surface
2) For green image: map to first image plane

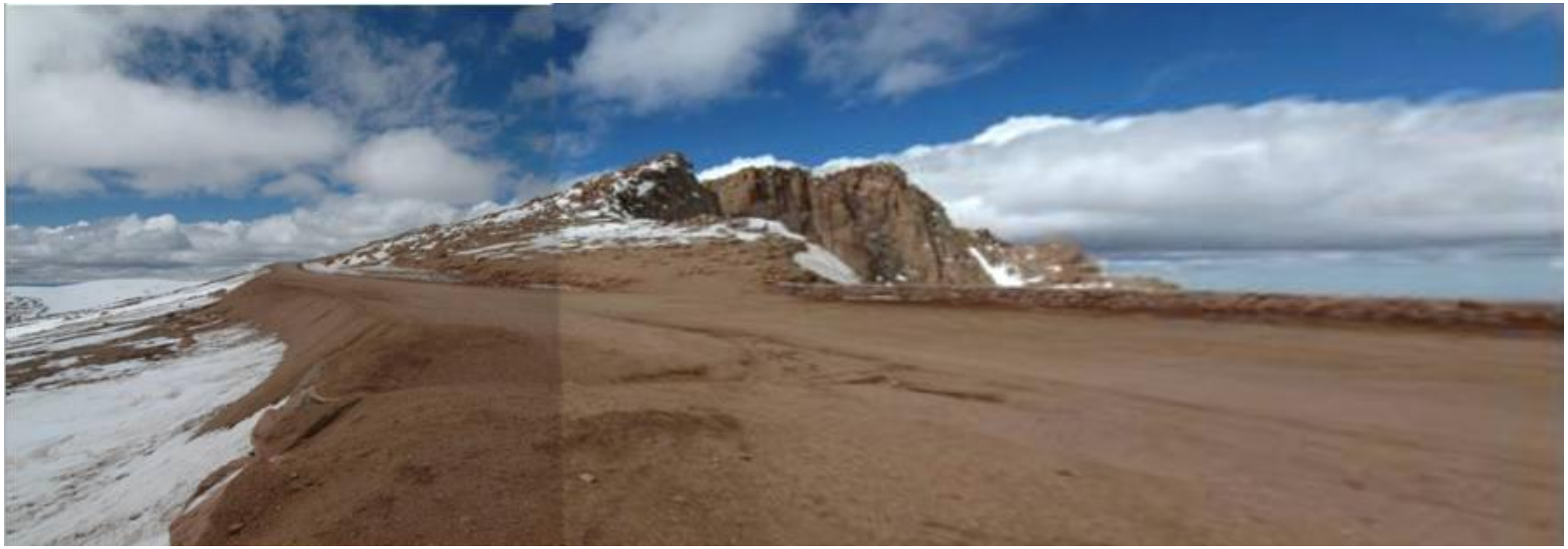
Planar vs. Cylindrical Projection



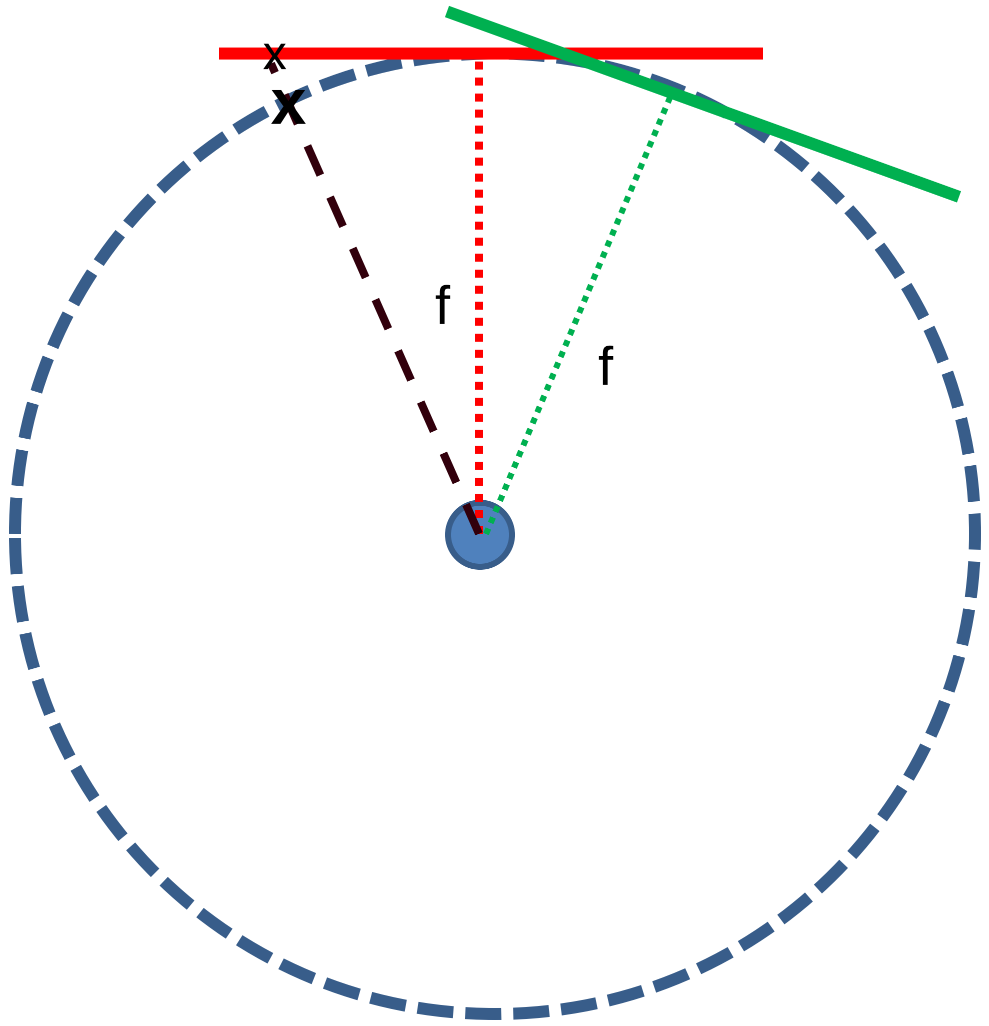
Photos by Russ Hewett

Planar vs. Cylindrical Projection

Planar



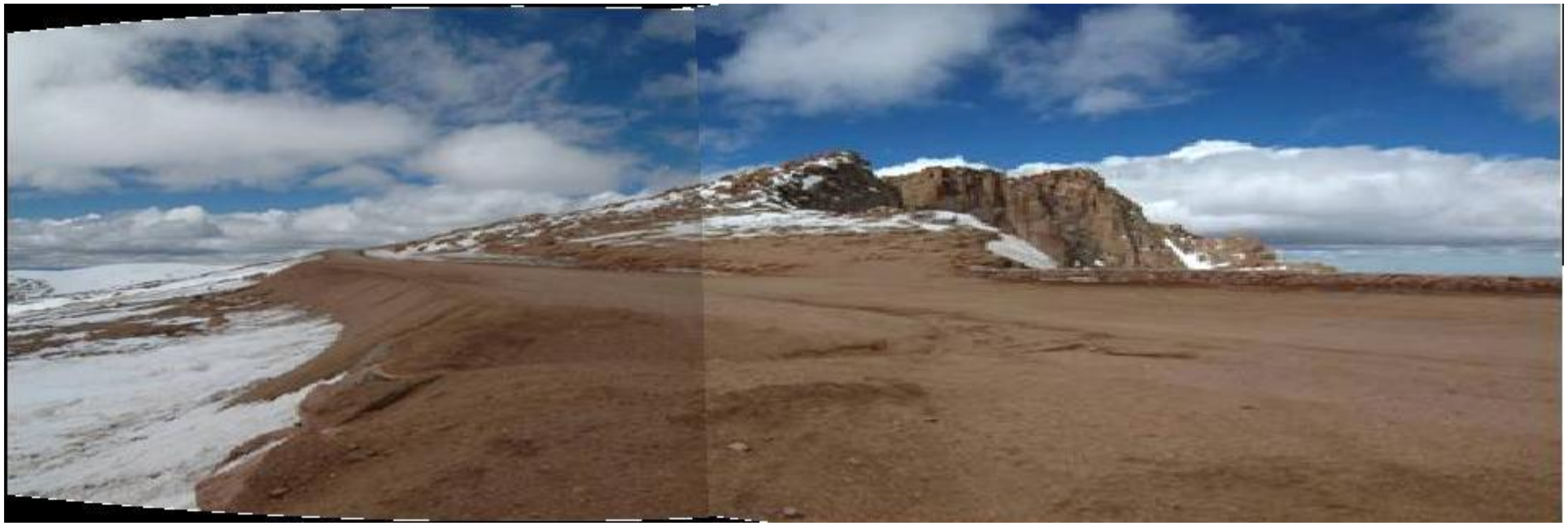
Cylindrical Mapping



1) For red image: compute h, theta on cylindrical surface from (u, v)
2) For green image: map to first image plane, than map to cylindrical surface

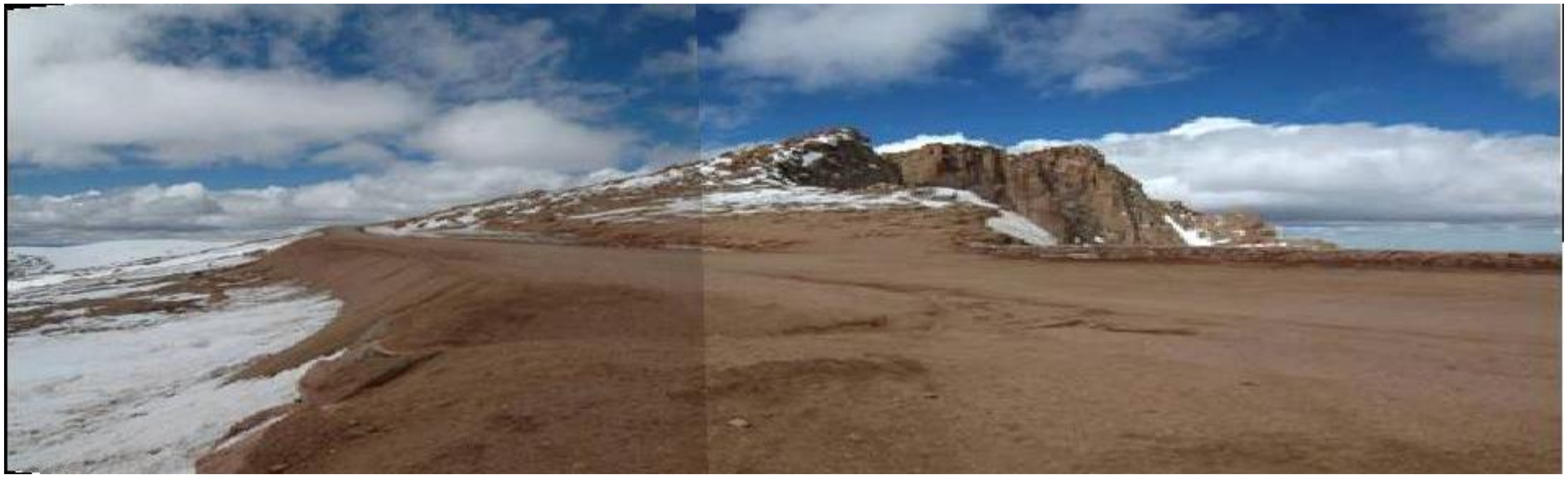
Planar vs. Cylindrical Projection

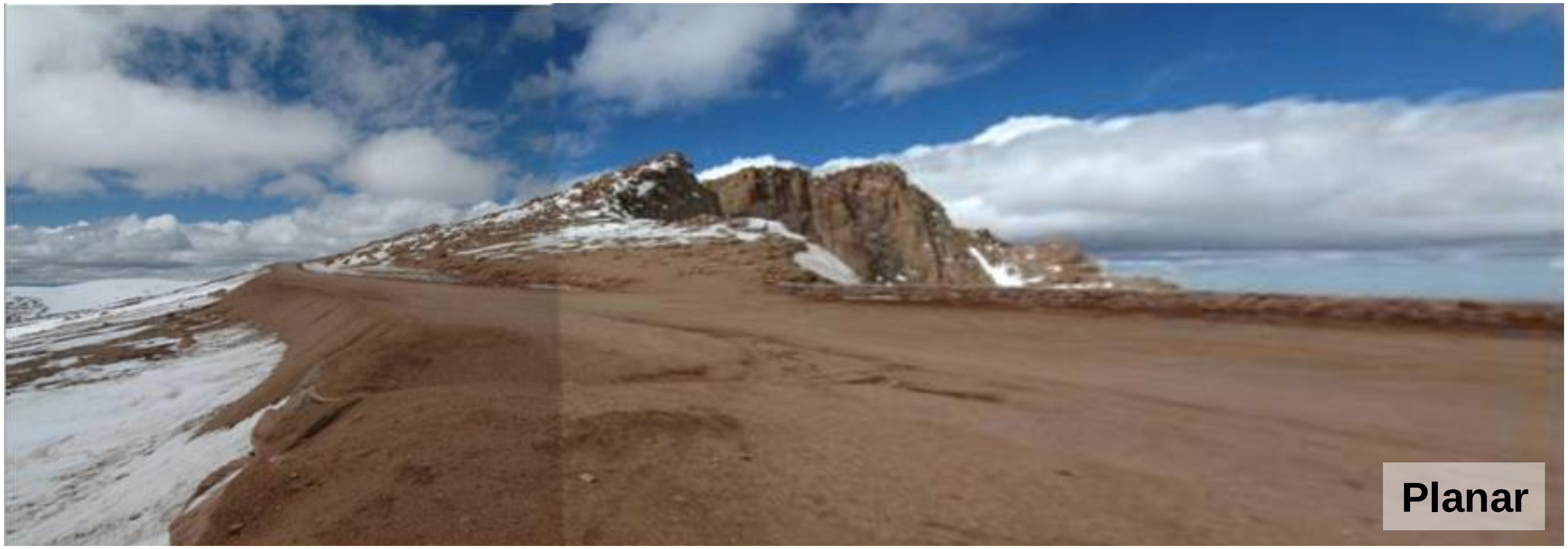
Cylindrical

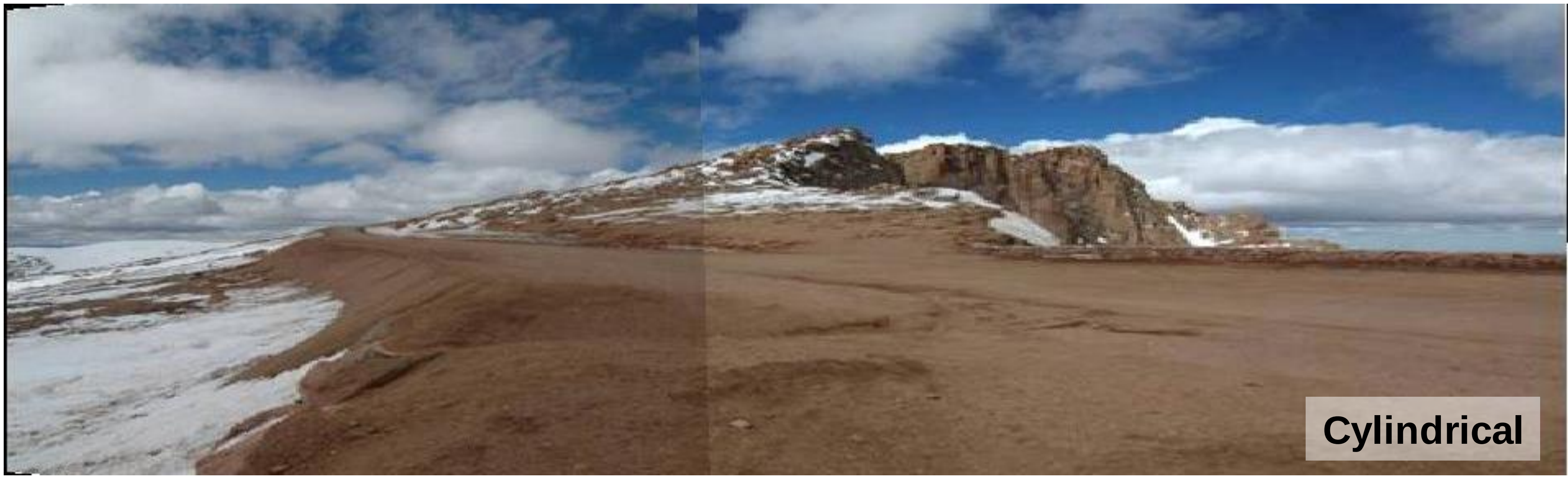


Planar vs. Cylindrical Projection

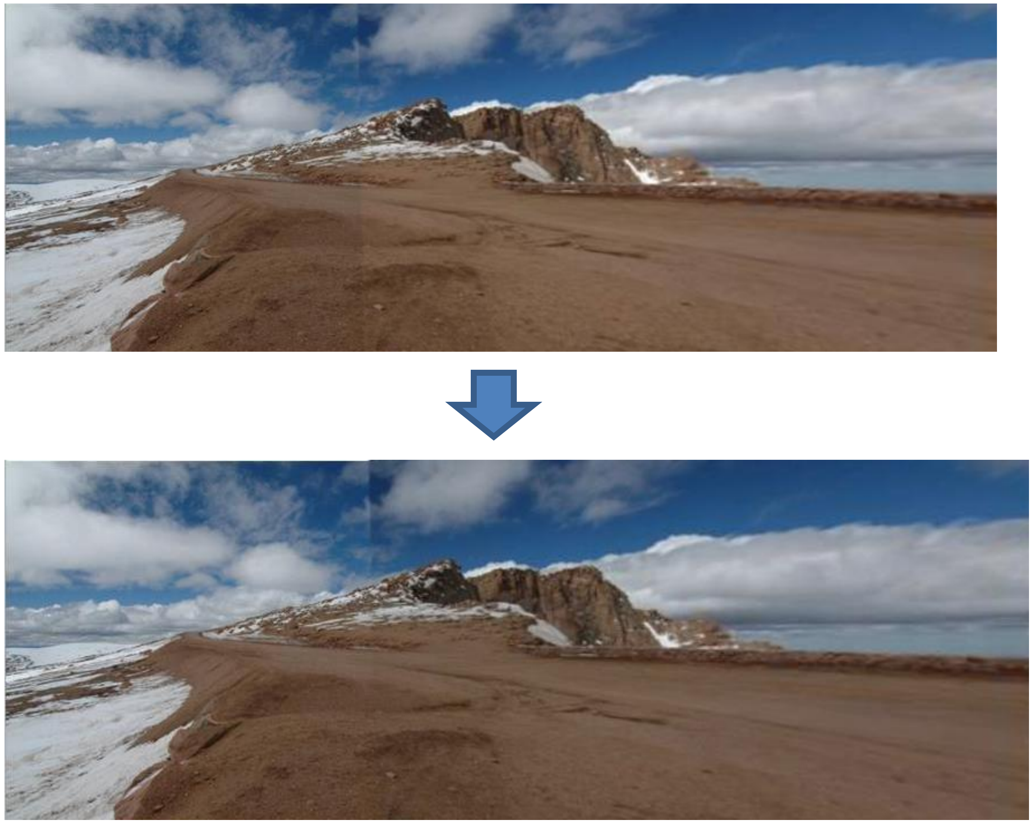
Cylindrical

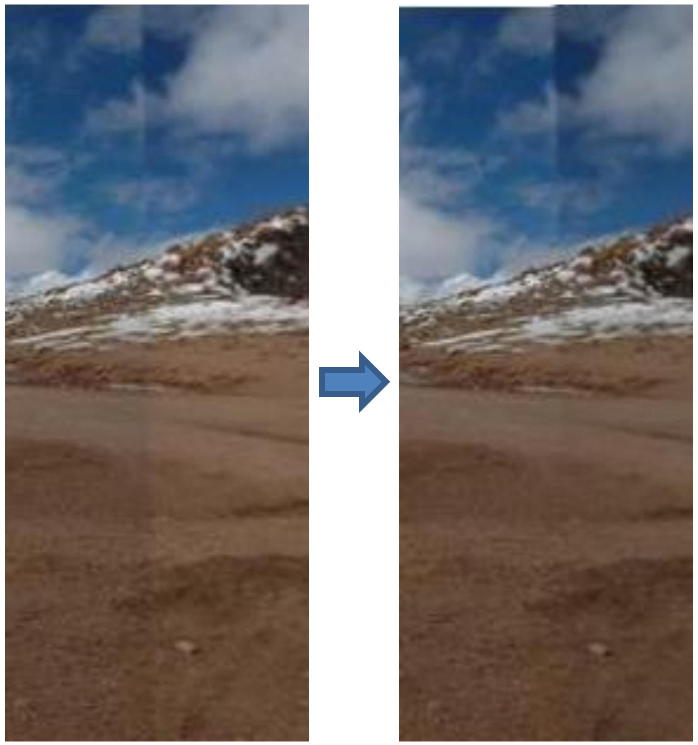



Planar


Cylindrical

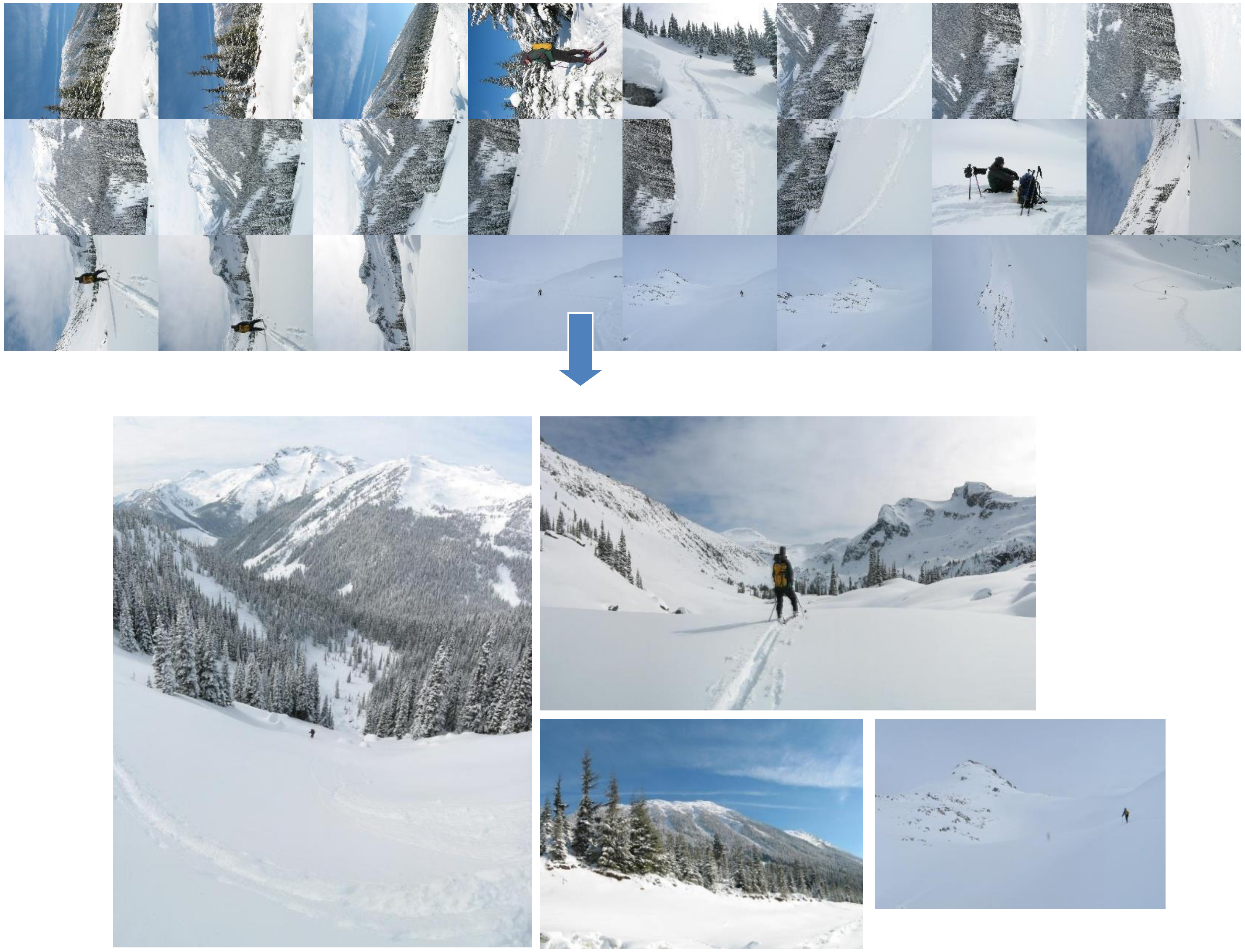
Simple gain adjustment





Automatically choosing images to stitch

Recognizing Panoramas



Some of following material from Brown and Lowe 2003 talk

Brown and Lowe 2003, 2007

Recognizing Panoramas

Input: N images

1. Extract SIFT points, descriptors from all images
2. Find K-nearest neighbors for each point (K=4)
3. For each image
    a) Select M candidate matching images by counting matched keypoints (M=6)
    b) Solve homography $\mathbf{H}_{ij}$ for each matched image

Recognizing Panoramas

Input: N images

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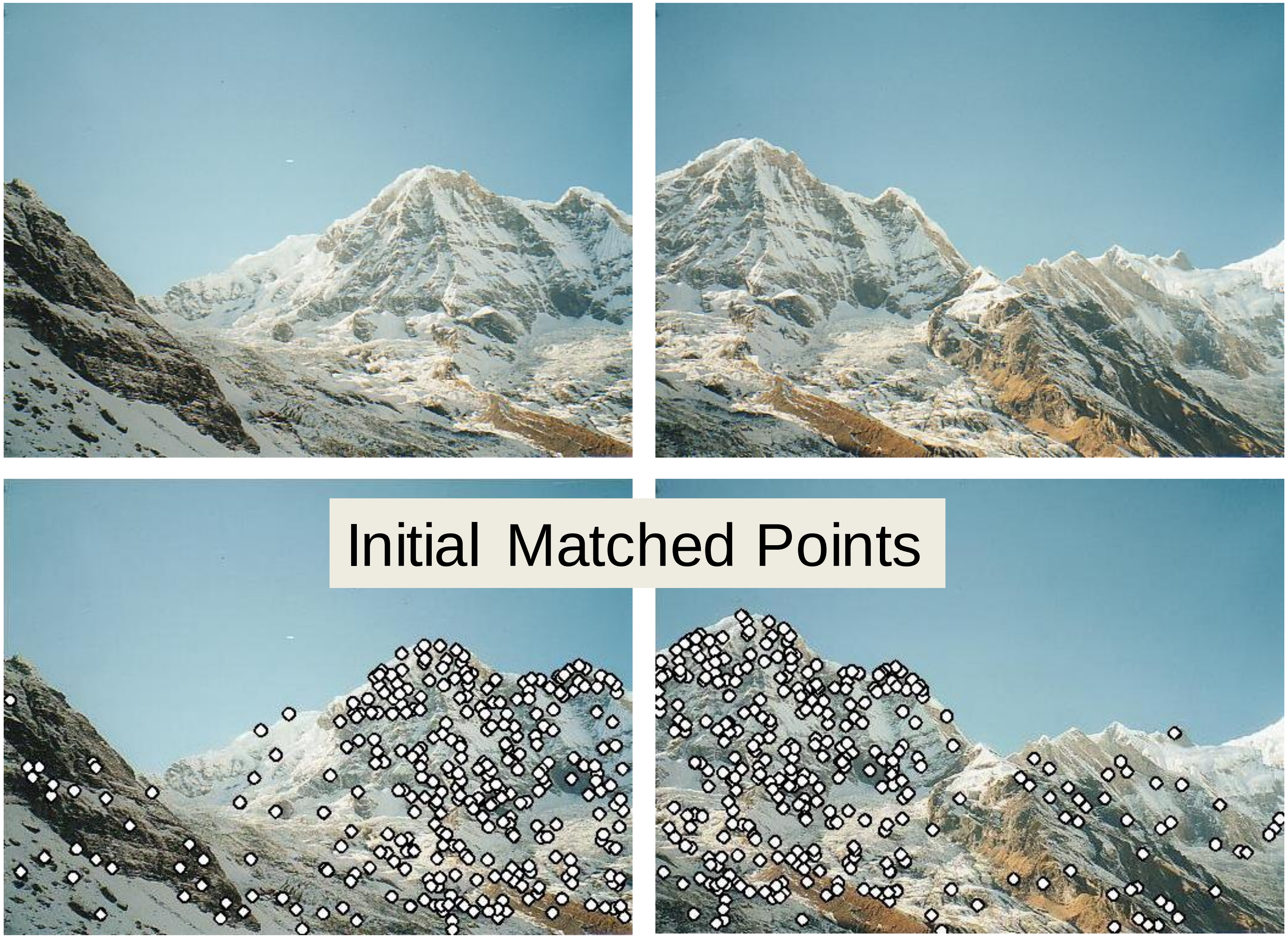
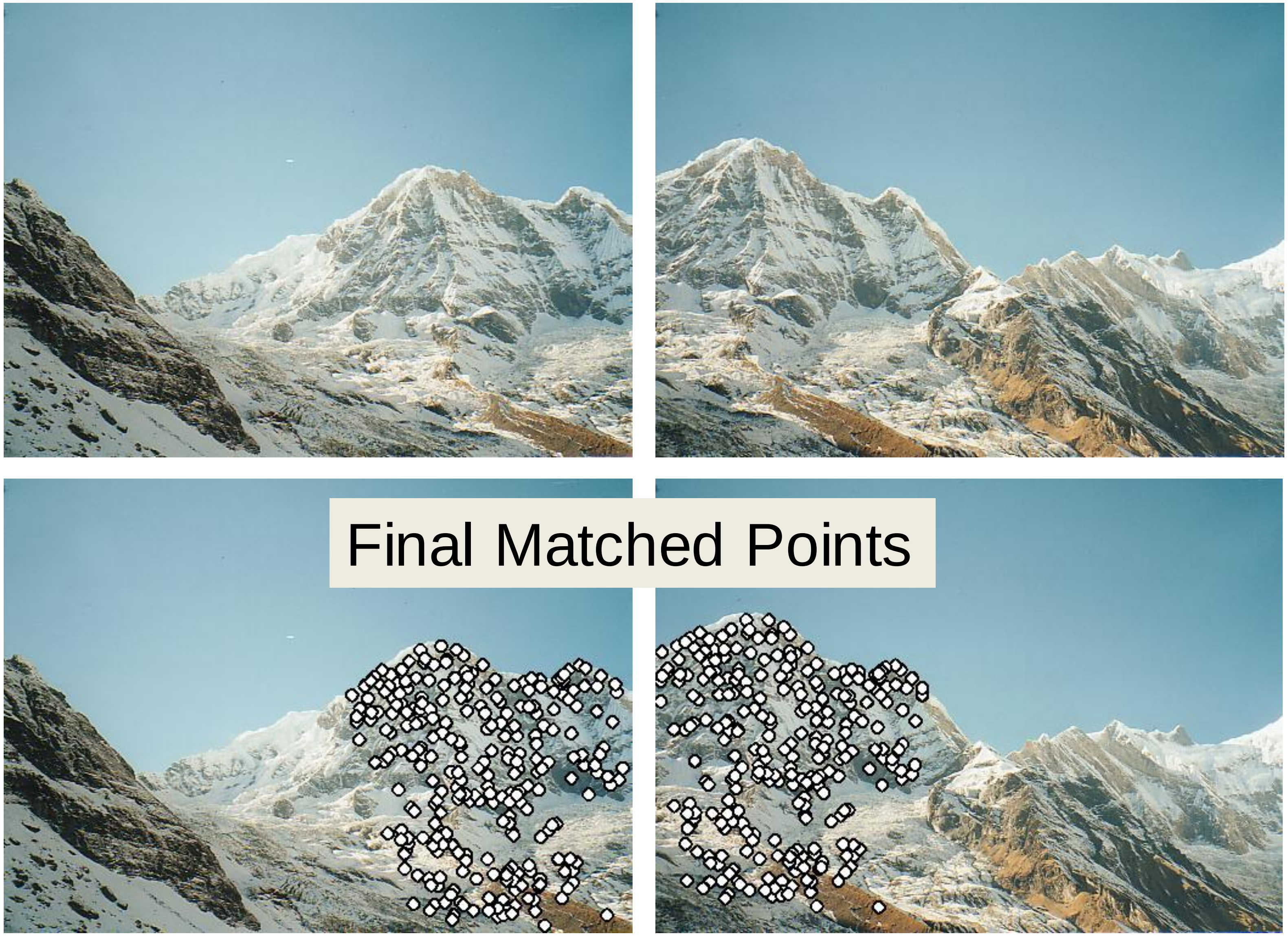
   a) Select M candidate matching images by counting matched keypoints (M=6)
   b) Solve homography $\mathbf{H}_{ij}$ for each matched image
   c) Decide if match is valid $(\underbrace{n_i}_{\text{\# inliers}} > 8 + 0.3\ \underbrace{n_f}_{\text{\# keypoints in overlapping area}})$

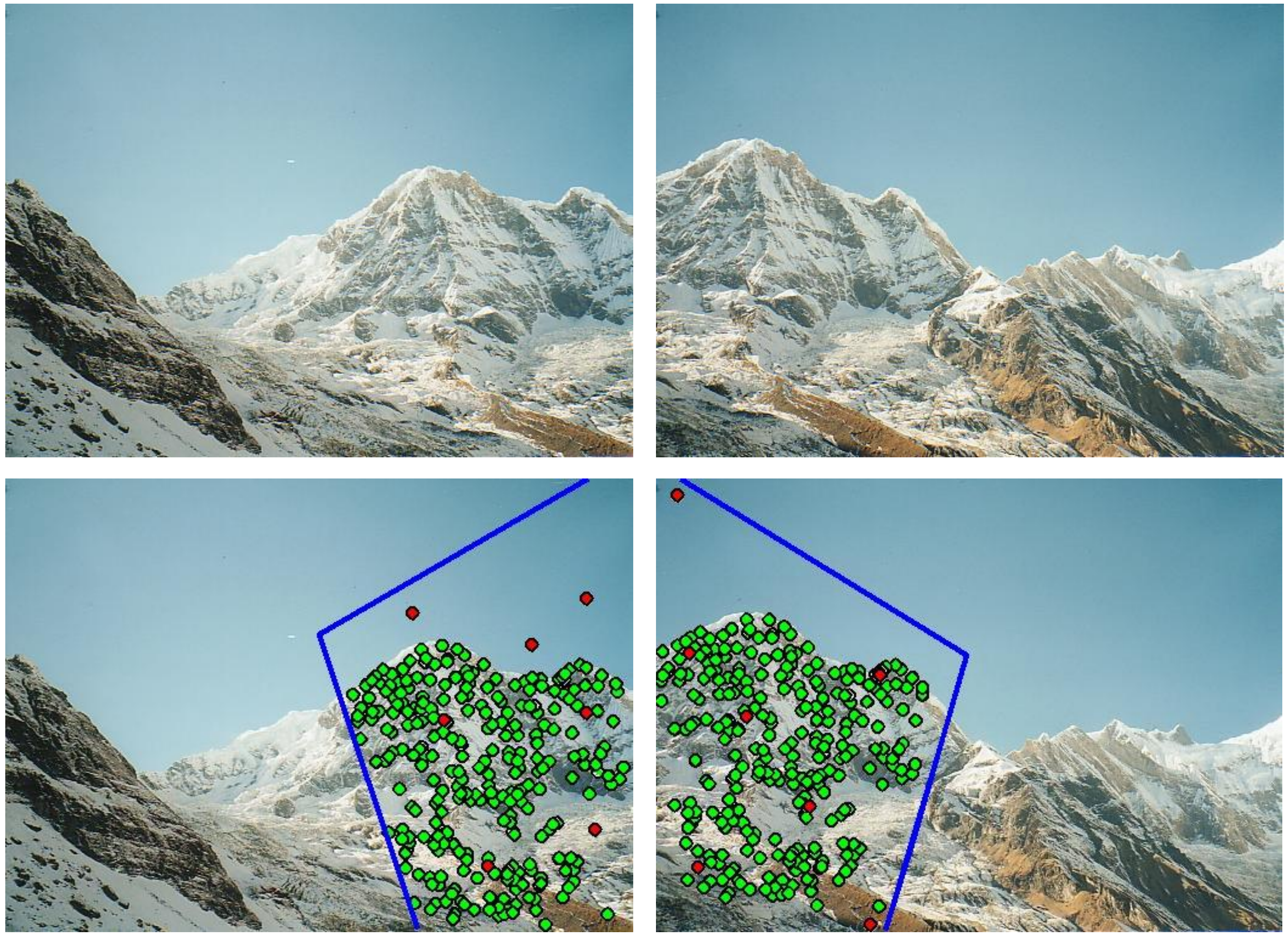
RANSAC for Homography



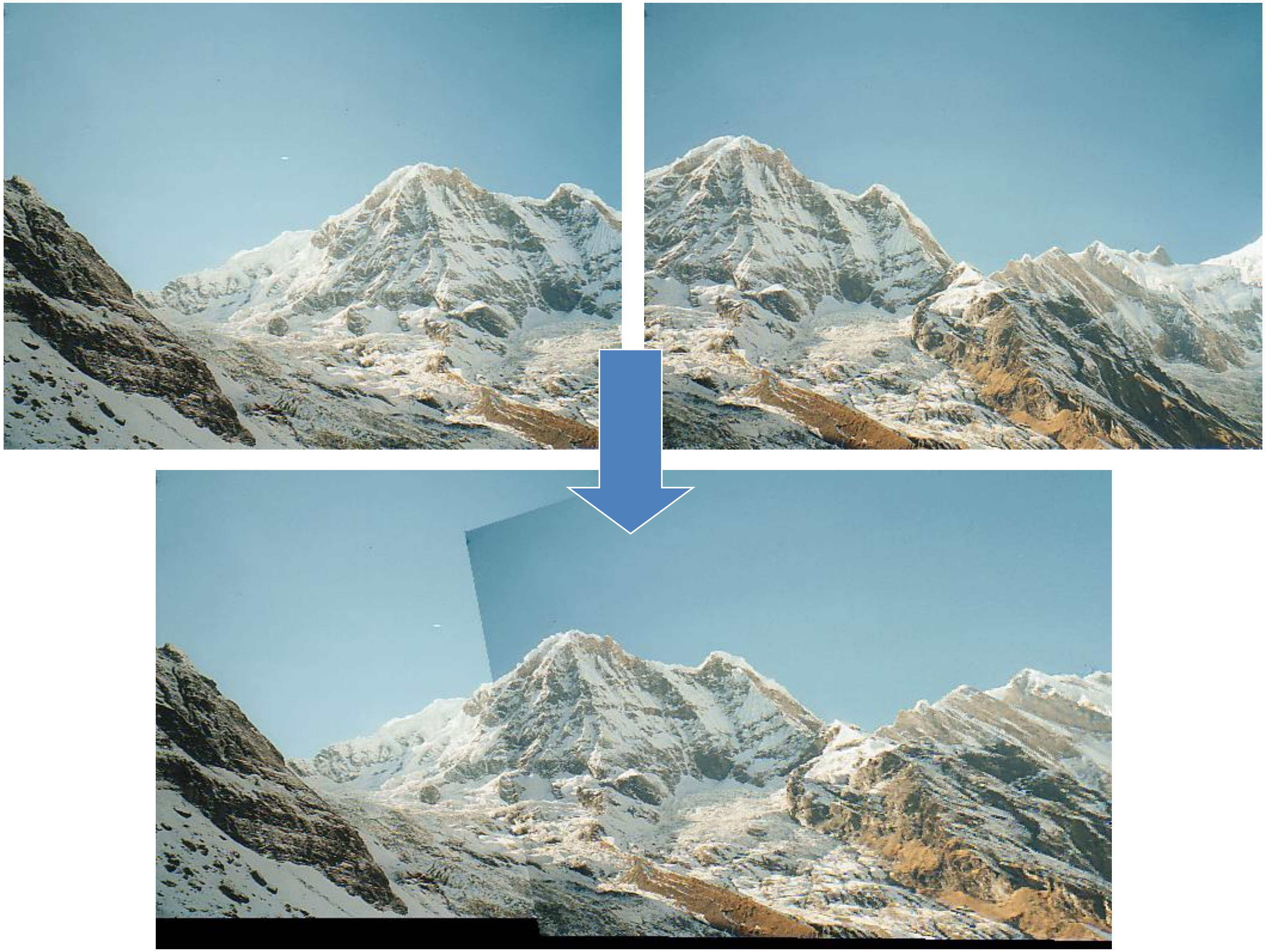
RANSAC for Homography



Verification



RANSAC for Homography

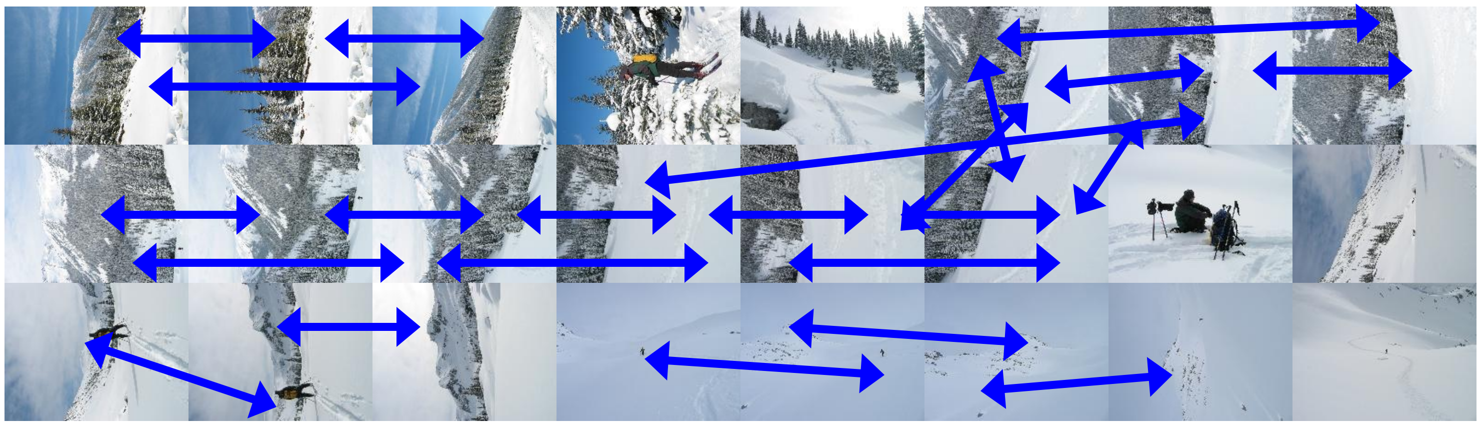


Recognizing Panoramas (cont.)

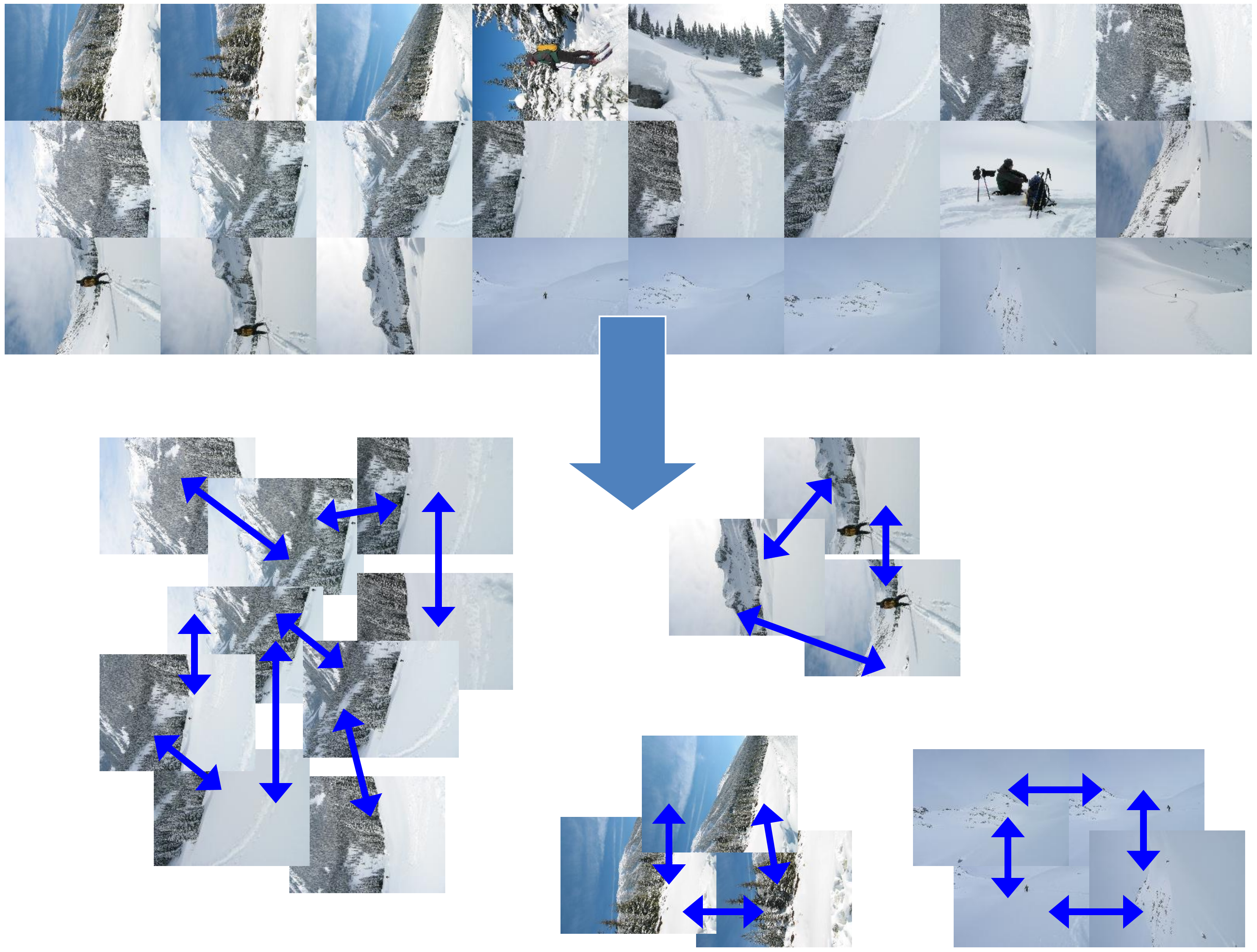
(now we have matched pairs of images)

4. Find connected components

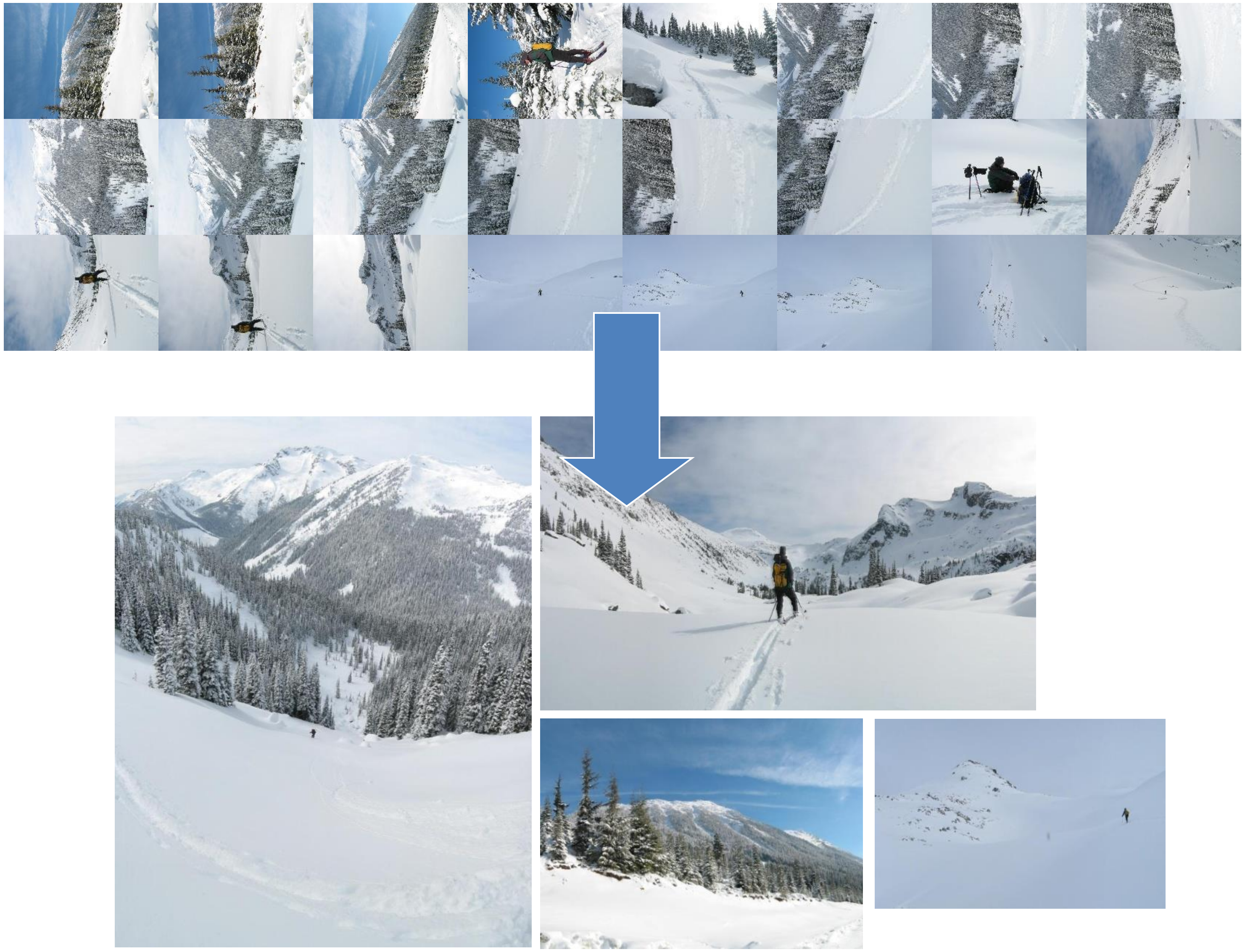
Finding the panoramas



Finding the panoramas



Finding the panoramas



Recognizing Panoramas (cont.)

(now we have matched pairs of images)

4. Find connected components
5. For each connected component
   a) Perform bundle adjustment to solve for rotation (θ_1, θ_2, θ_3) and focal length f of all cameras
   b) Project to a surface (plane, cylinder, or sphere)
   c) Render with multiband blending

Bundle adjustment for stitching

- Non-linear minimization of re-projection error

$$\mathbf{R}_i = e^{[\boldsymbol{\theta}_i]_\times}, \ [\boldsymbol{\theta}_i]_\times = \begin{bmatrix} 0 & -\theta_{i3} & \theta_{i2} \\ \theta_{i3} & 0 & -\theta_{i1} \\ -\theta_{i2} & \theta_{i1} & 0 \end{bmatrix}$$

- $\hat{\mathbf{x}}' = \mathbf{H}\mathbf{x}$ where **H = K' R' R^{-1} K^{-1}**

$$\mathbf{K}_i = \begin{bmatrix} f_i & 0 & 0 \\ 0 & f_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$error = \sum_{1}^{N} \sum_{j}^{M_i} \sum_{k} dist(\mathbf{x}', \hat{\mathbf{x}}')$$

- Solve non-linear least squares (Levenberg-Marquardt algorithm)
  - See paper for details

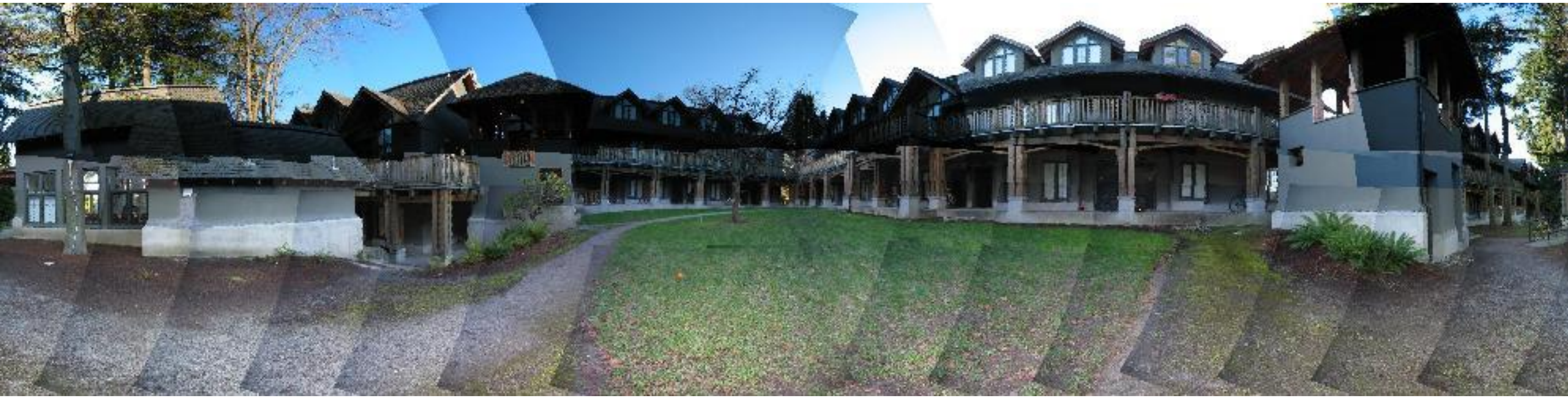
Bundle Adjustment

New images initialized with rotation, focal length of the best matching image

Bundle Adjustment

New images initialized with rotation, focal length of the best matching image

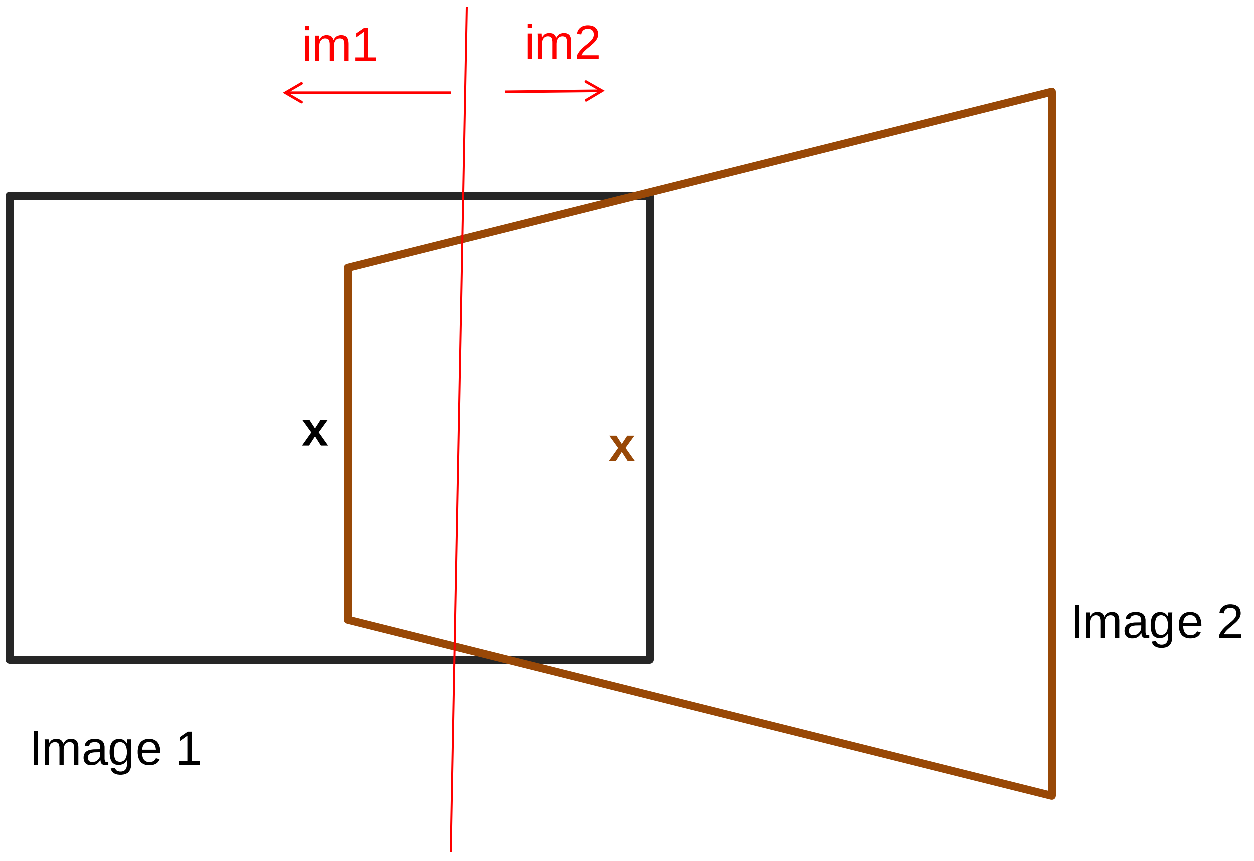
Details to make it look good



- Choosing seams
- Blending

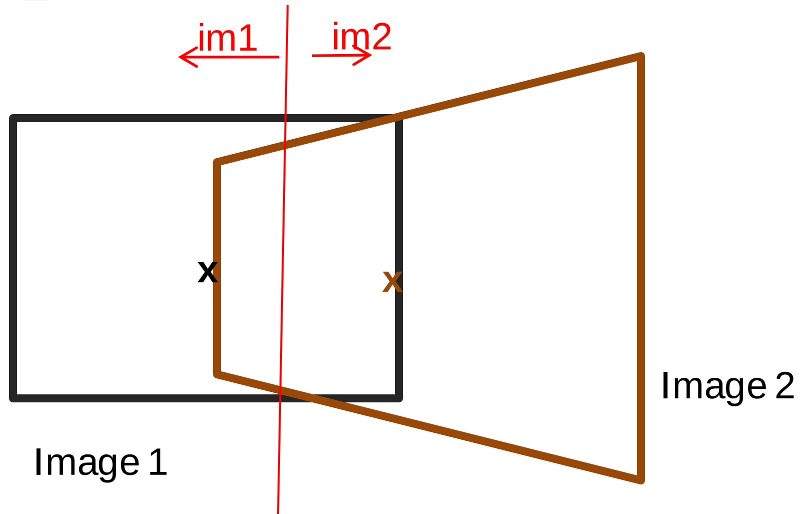
Choosing seams

- Easy method
  - Assign each pixel to image with nearest center



Choosing seams

- Easy method
  - Assign each pixel to image with nearest center
  - Create a mask:
    - `mask(y, x) = 1` iff pixel should come from im1
  - Smooth boundaries (called "feathering"):
    - `mask_sm = imfilter(mask, gausfil);`
  - Composite
    - `imblend = im1_c.*mask + im2_c.*(1-mask);`



Choosing seams

- Better method: dynamic program to find seam along well-matched regions

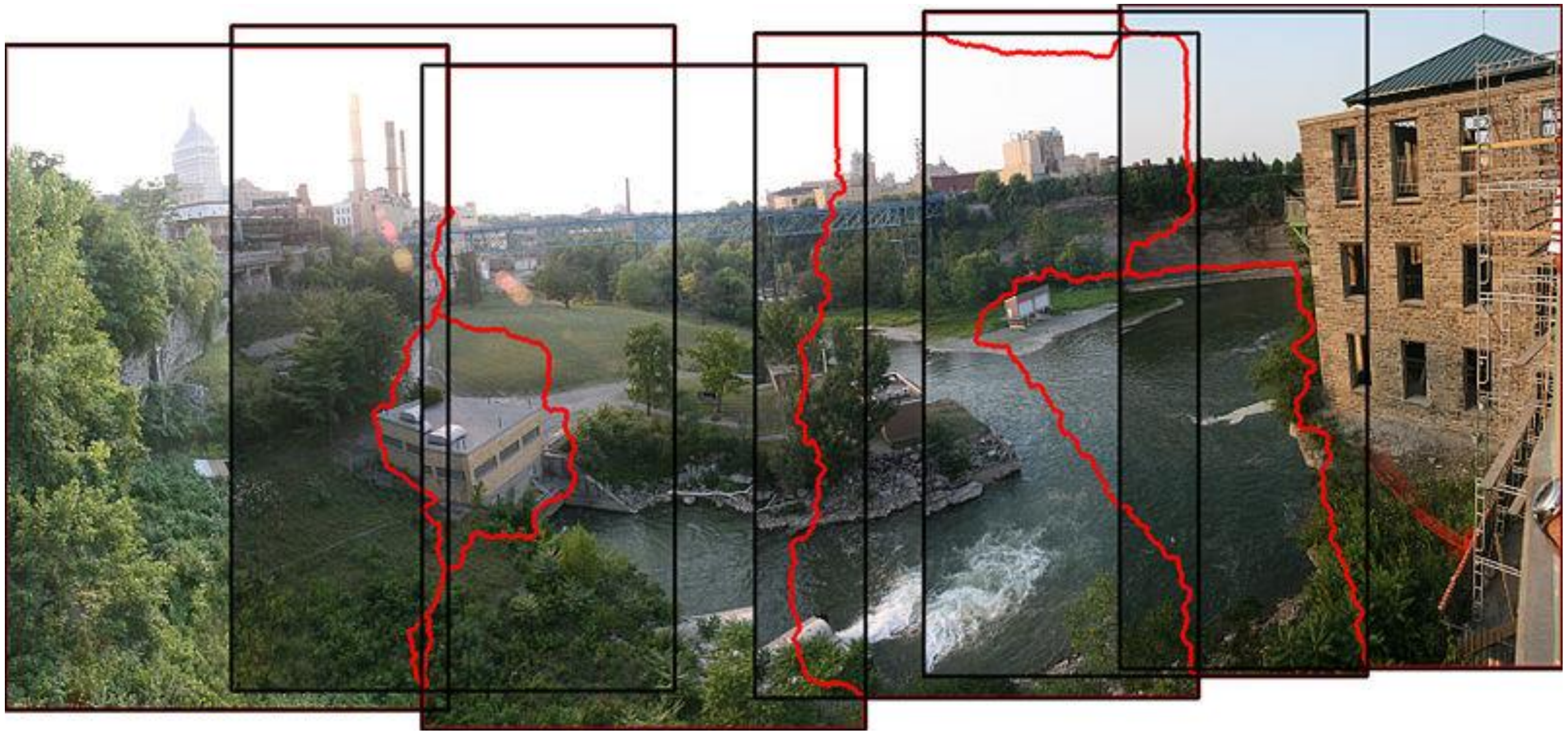
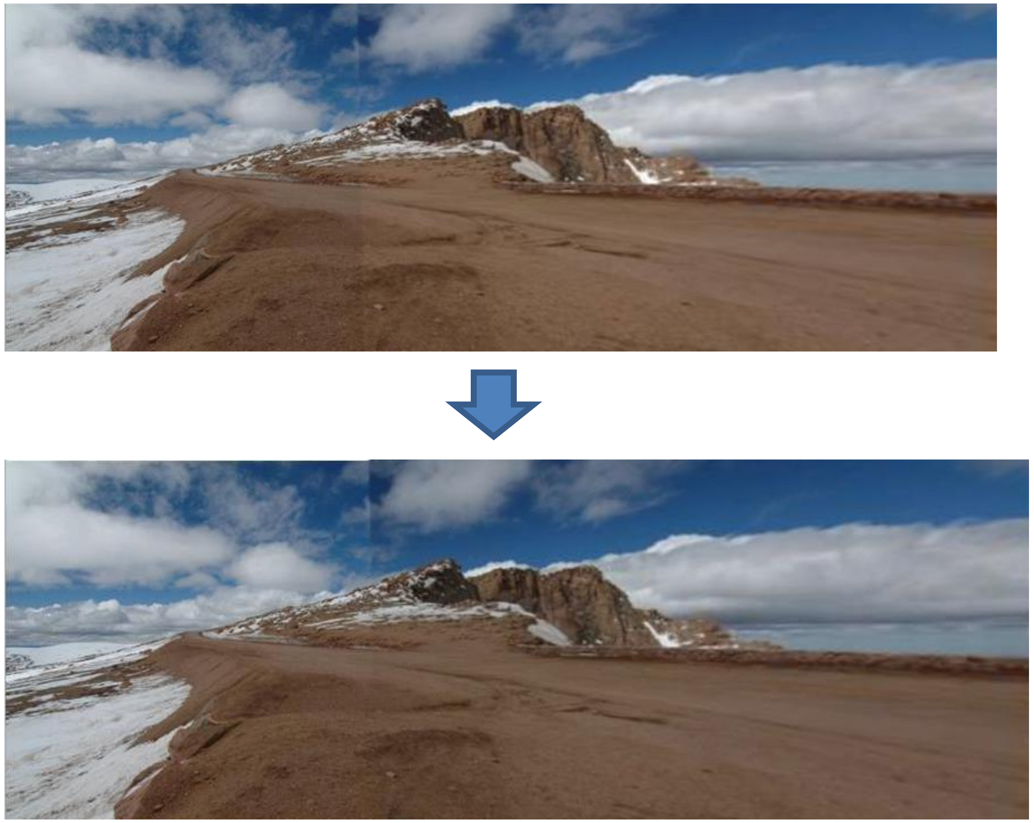
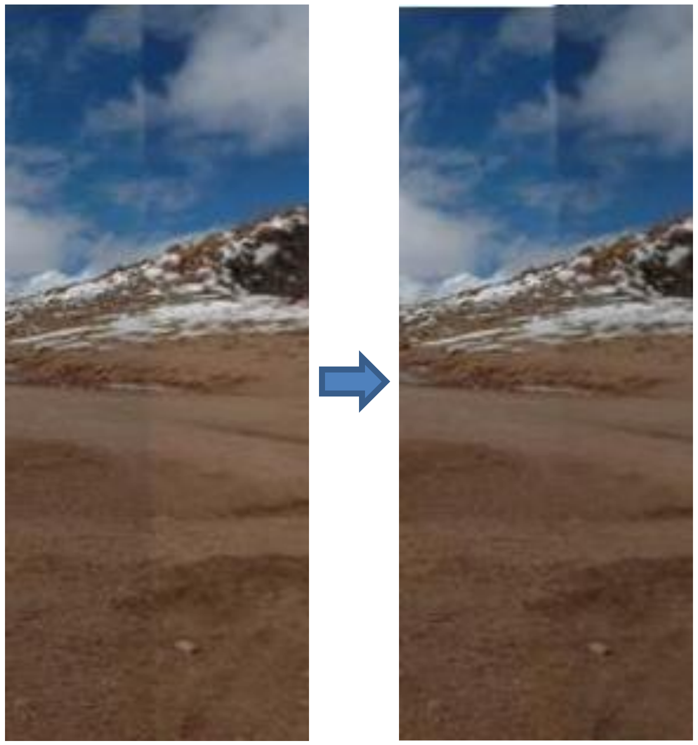


Illustration: http://en.wikipedia.org/wiki/File:Rochester_NY.jpg

Gain compensation

- Simple gain adjustment
  - Compute average RGB intensity of each image in overlapping region
  - Normalize intensities by ratio of averages



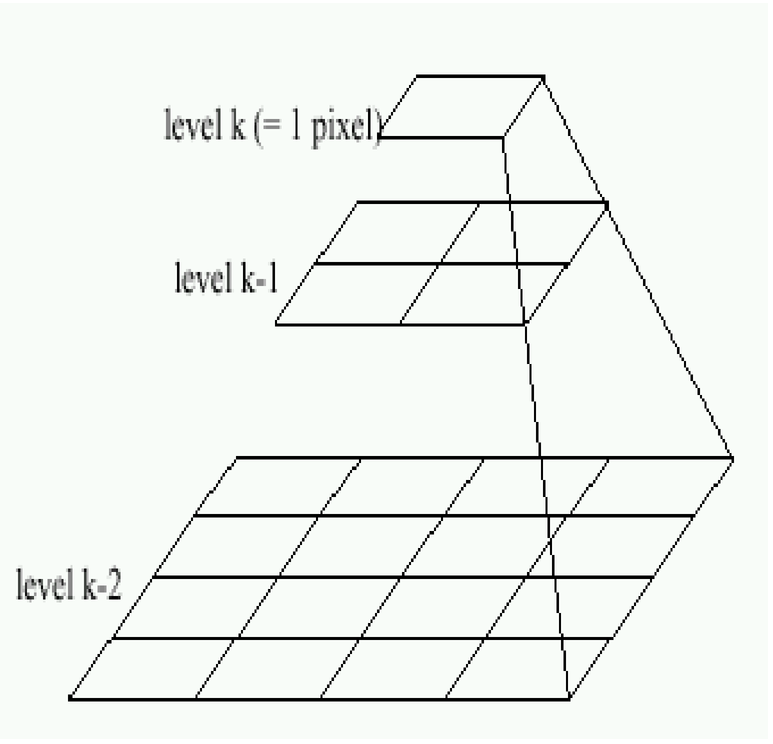


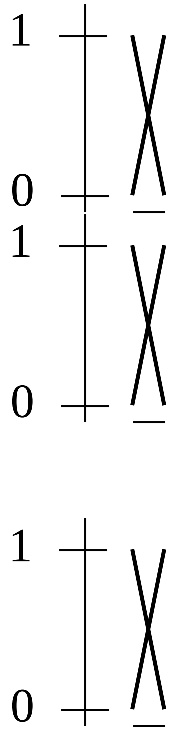
Multi-band Blending

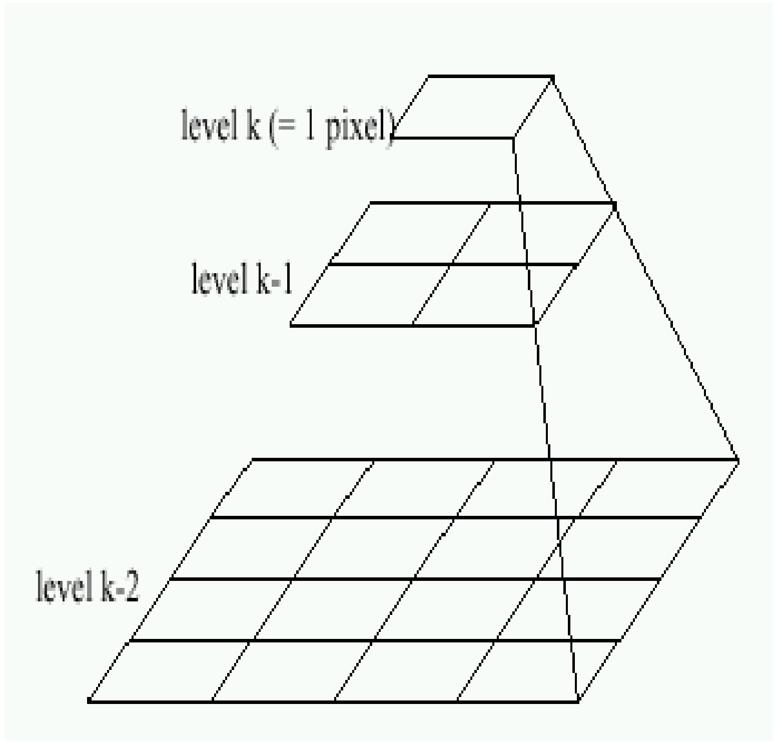
- Burt & Adelson 1983
  - Blend frequency bands over range $\propto \lambda$

Multiband Blending with Laplacian Pyramid

- At low frequencies, blend slowly
- At high frequencies, blend quickly







Left pyramid

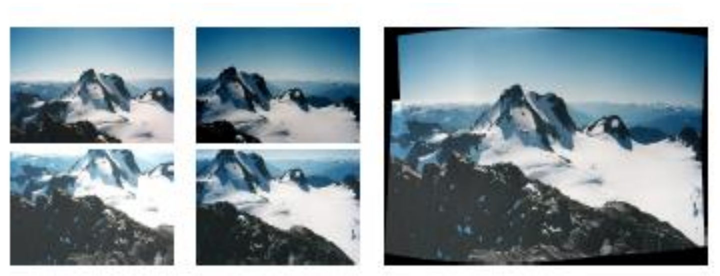
blend

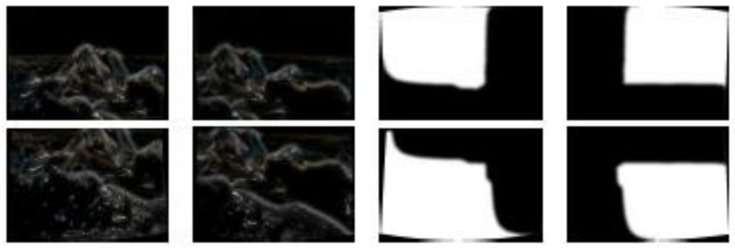
Right pyramid

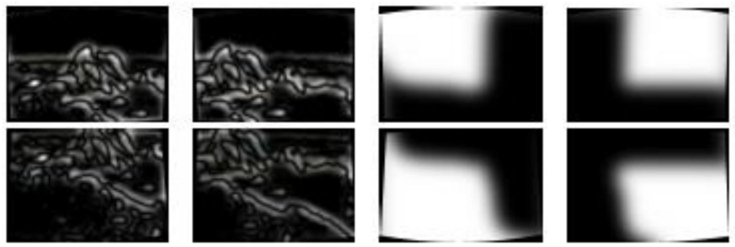
Multiband blending

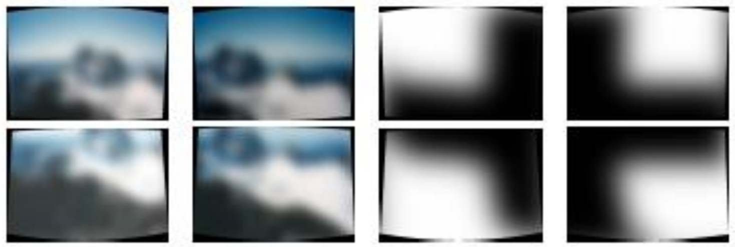
1. Compute Laplacian pyramid of images and mask
2. Create blended image at each level of pyramid
3. Reconstruct complete image

Laplacian pyramids

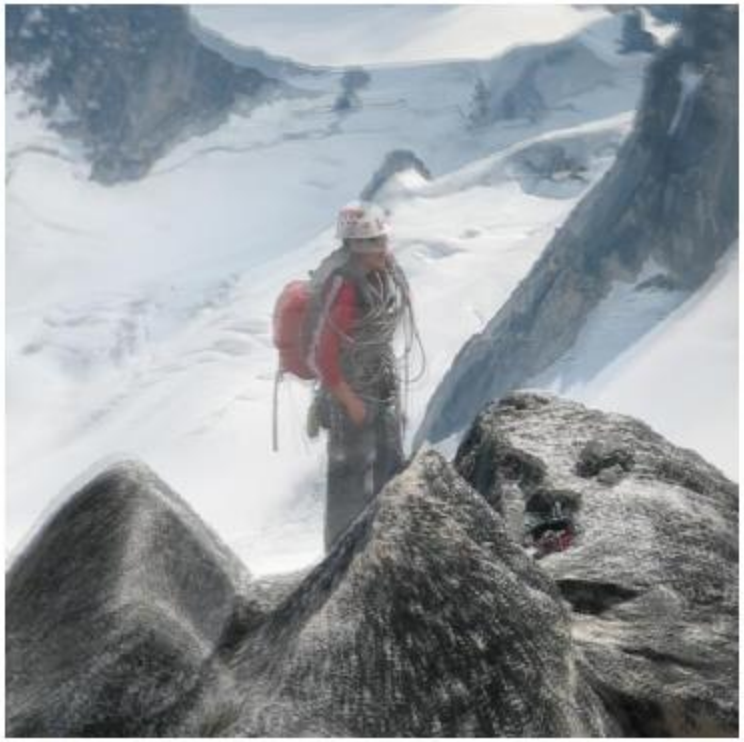

(a) Original images and blended result

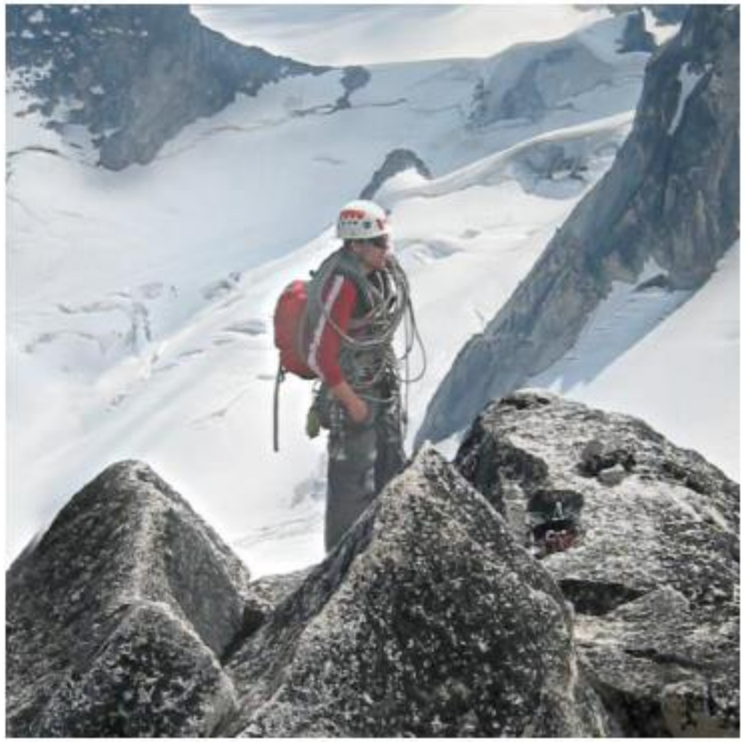

(b) Band 1 (scale 0 to σ)


(c) Band 2 (scale σ to 2σ)

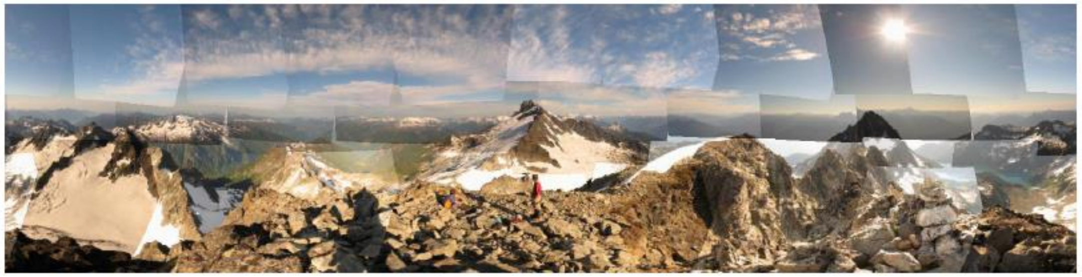

(d) Band 3 (scale lower than 2σ)

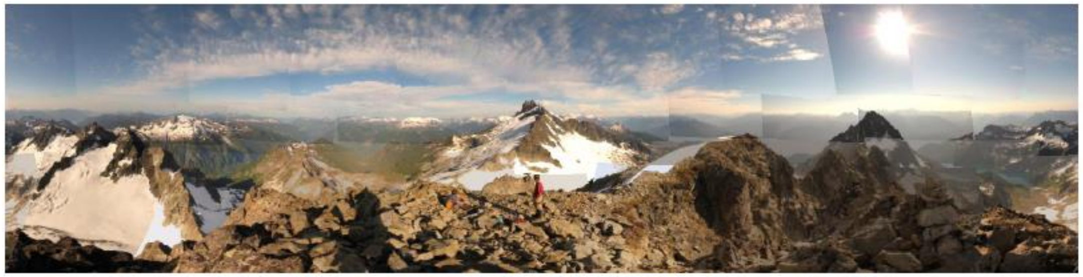
Blending comparison (IJCV 2007)

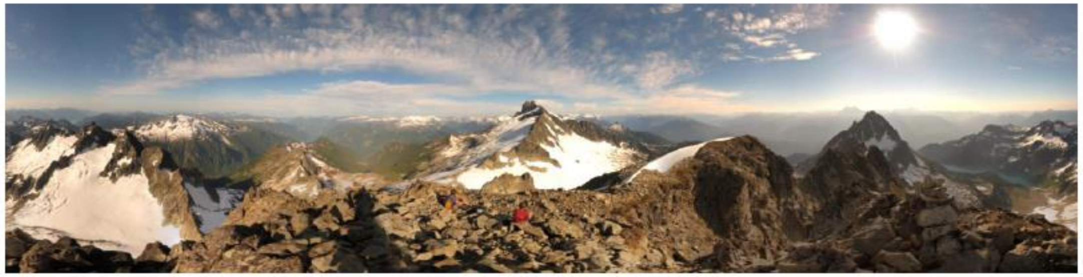

(a) Linear blending


(b) Multi-band blending

Blending Comparison

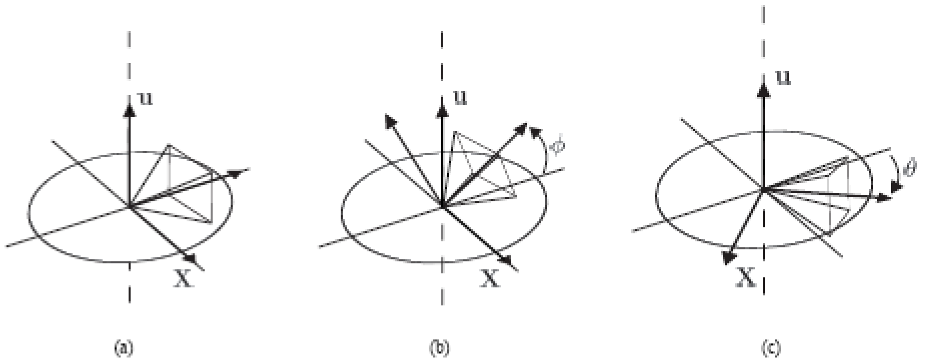

(b) Without gain compensation

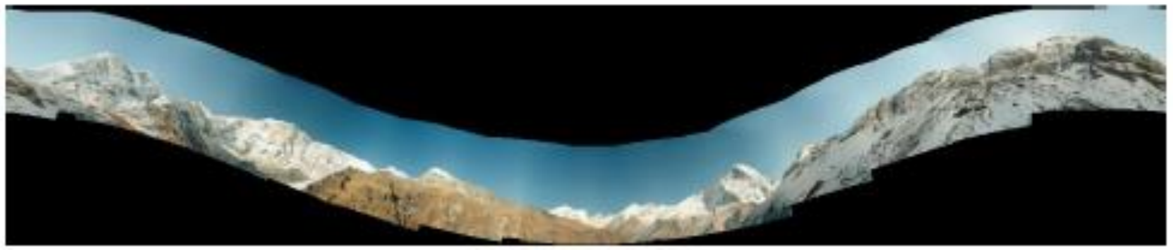

(c) With gain compensation

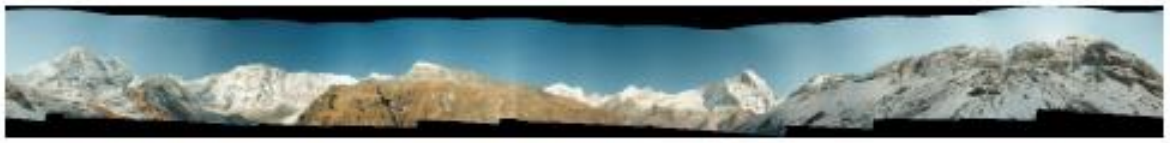

(d) With gain compensation and multi-band blending

Straightening

Rectify images so that "up" is vertical




(a) Without automatic straightening


(b) With automatic straightening

Further reading

Harley and Zisserman: Multi-view Geometry book

- DLT algorithm: HZ p. 91 (alg 4.2), p. 585
- Normalization: HZ p. 107-109 (alg 4.2)
- RANSAC: HZ Sec 4.7, p. 123, alg 4.6
- Tutorial: http://users.cecs.anu.edu.au/~hartley/Papers/CVPR99-tutorial/tut_4up.pdf

- Recognising Panoramas: Brown and Lowe, IJCV 2007 (also bundle adjustment)

How does iphone panoramic stitching work?

- Capture images at 30 fps
- Stitch the central 1/8 of a selection of images
  - Select which images to stitch using the accelerometer and frame-to-frame matching
  - Faster and avoids radial distortion that often occurs towards corners of images
- Alignment
  - Initially, perform cross-correlation of small patches aided by accelerometer to find good regions for matching
  - Register by matching points (KLT tracking or RANSAC with FAST (similar to SIFT) points) or correlational matching
- Blending
  - Linear (or similar) blending, using a face detector to avoid blurring face regions and choose good face shots (not blinking, etc)

http://www.patentlyapple.com/patently-apple/2012/11/apples-cool-iphone-5-panorama-app-revealed-in-5-patents.html

Tips and Photos from Russ Hewett

Capturing Panoramic Images

- Tripod vs Handheld
  - Help from modern cameras
  - Leveling tripod
  - Gigapan
  - Or wing it
- Image Sequence
  - Requires a reasonable amount of overlap (at least 15-30%)
  - Enough to overcome lens distortion
- Exposure
  - Consistent exposure between frames
  - Gives smooth transitions
  - Manual exposure
  - Makes consistent exposure of dynamic scenes easier
  - But scenes don’t have constant intensity everywhere
- Caution
  - Distortion in lens (Pin Cushion, Barrel, and Fisheye)
  - Polarizing filters
  - Sharpness in image edge / overlap region

Pike’s Peak Highway, CO

Photo: Russell J. Hewett

Nikon D70s, Tokina 12-24mm @ 16mm, f/22, 1/40s

Pike’s Peak Highway, CO

Photo: Russell J. Hewett

(See Photo On Web)

360 Degrees, Tripod Leveled

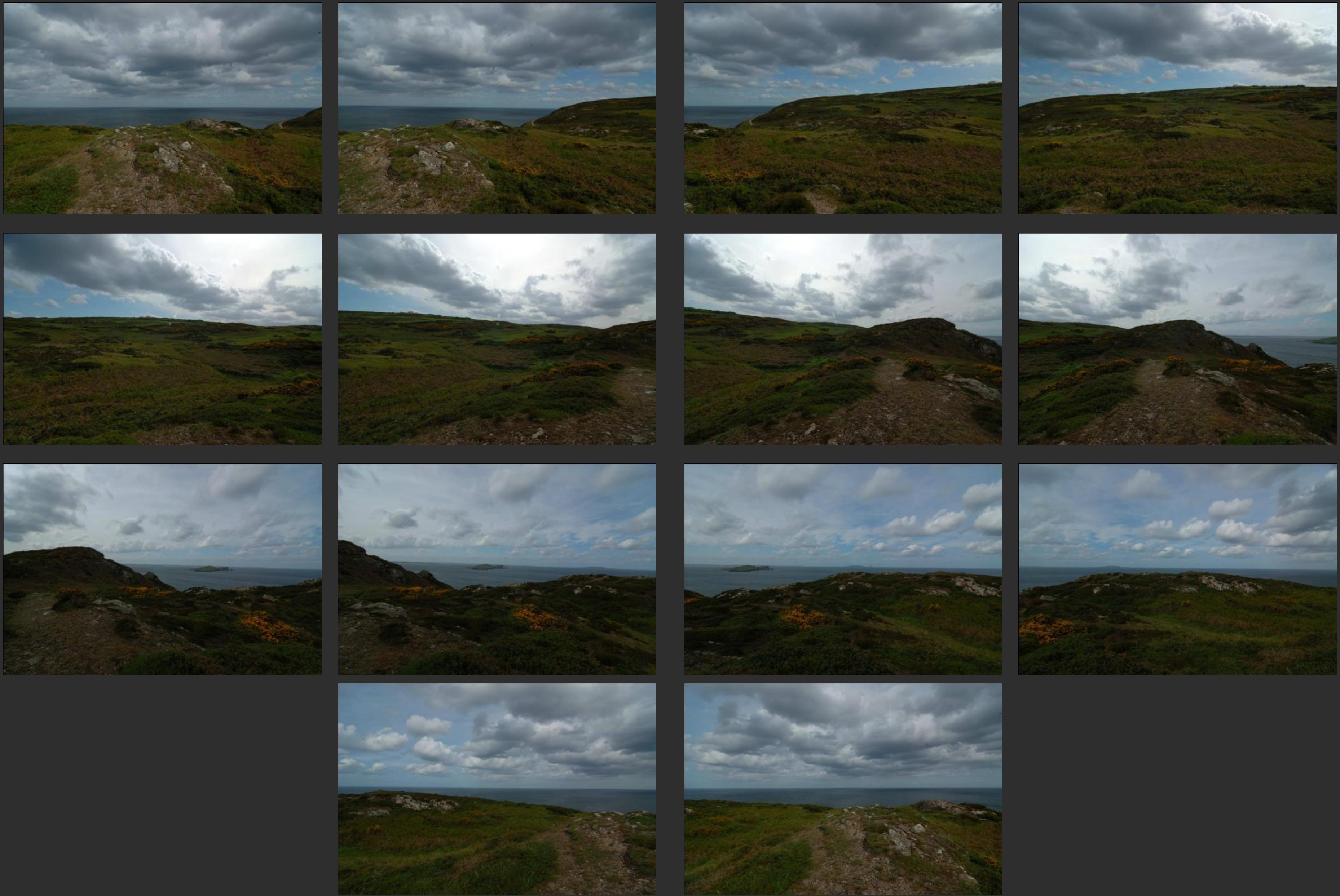


Photo: Russell J. Hewett

Nikon D70, Tokina 12-24mm @ 12mm, f/8, 1/125s

Howth, Ireland

Photo: Russell J. Hewett

(See Photo On Web)

Handheld Camera

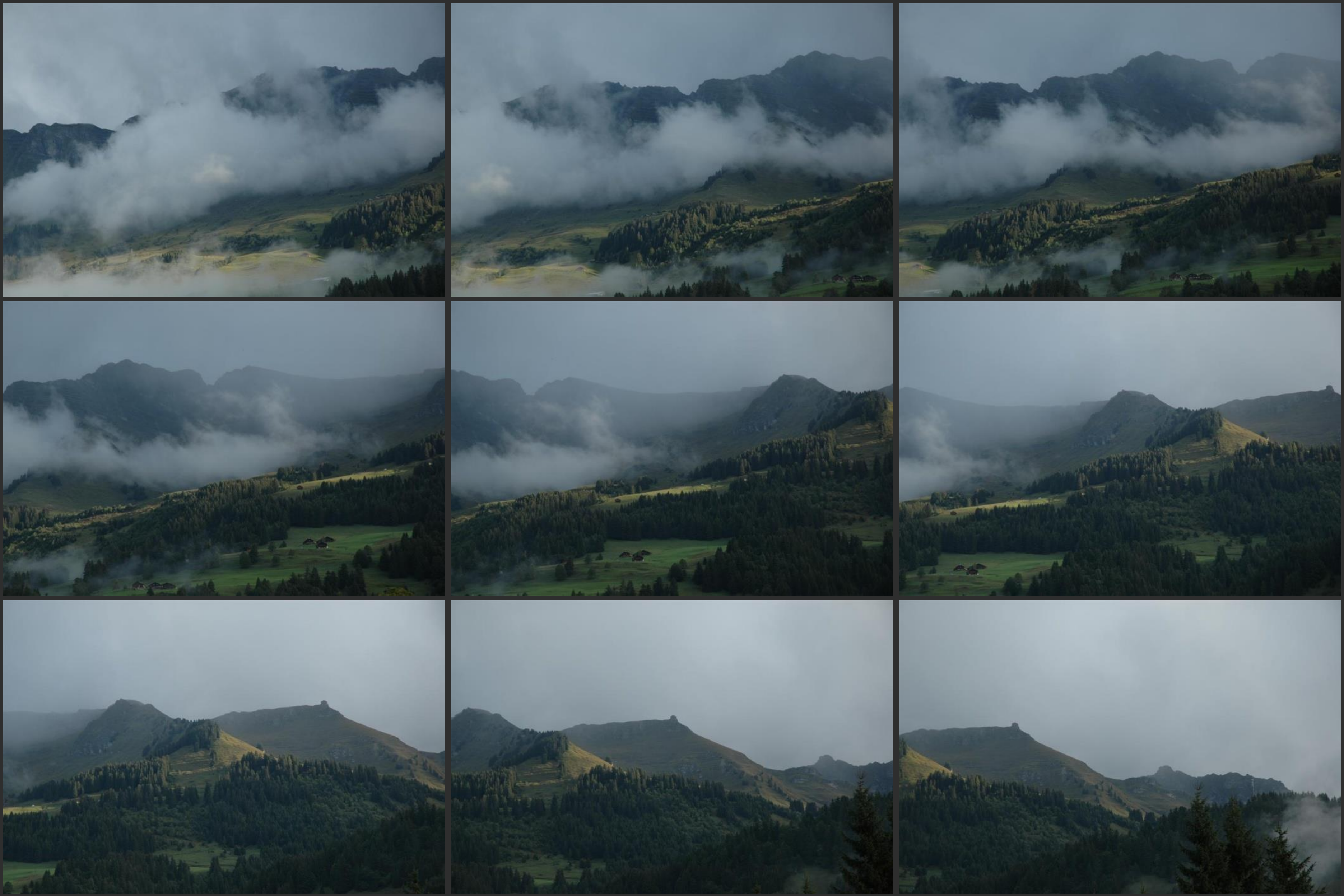


Photo: Russell J. Hewett

Nikon D70s, Nikon 18-70mm @ 70mm, f/6.3, 1/200s

Handheld Camera

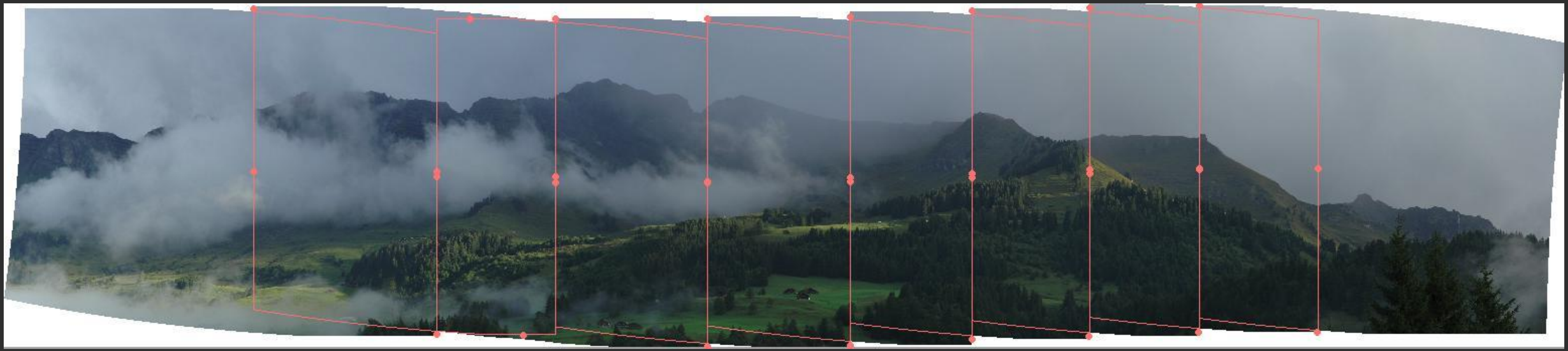


Photo: Russell J. Hewett

Les Diablerets, Switzerland

Photo: Russell J. Hewett

(See Photo On Web)

Macro

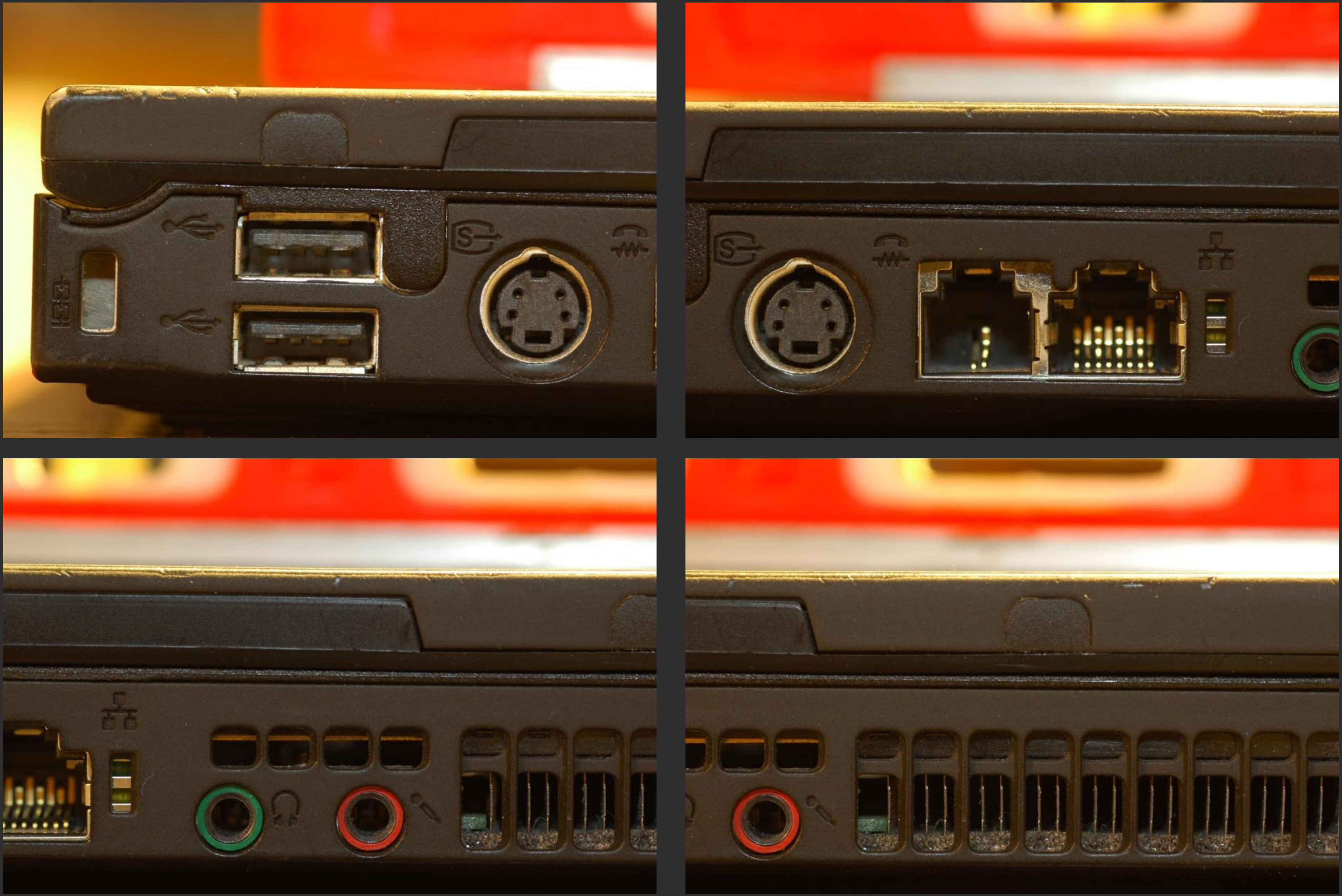


Photo: Russell J. Hewett & Bowen Lee

Nikon D70s, Tamron 90mm Micro @ 90mm, f/10, 15s

Side of Laptop

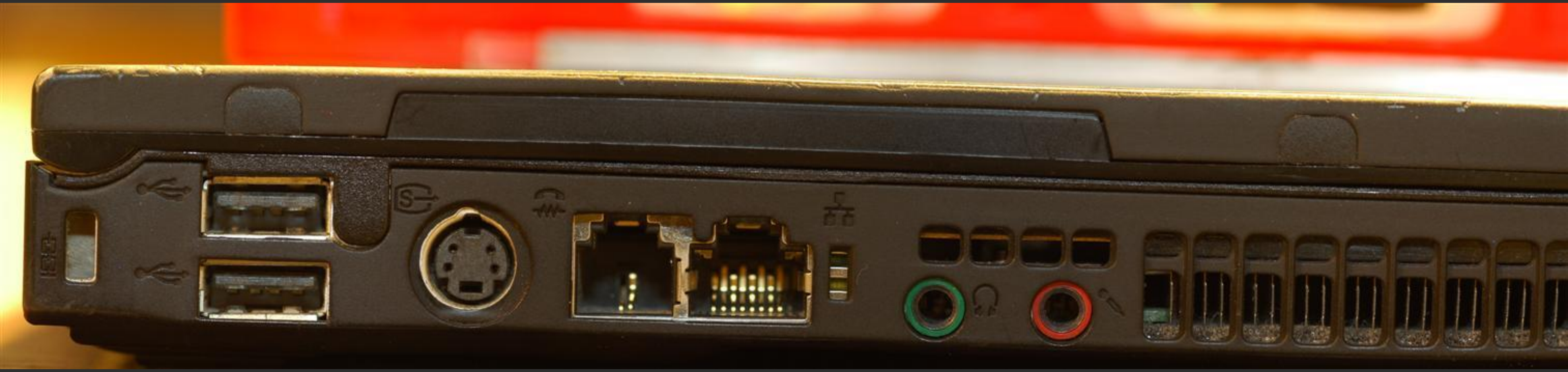


Photo: Russell J. Hewett & Bowen Lee

Considerations For Stitching

- Variable intensity across the total scene
- Variable intensity and contrast between frames
- Lens distortion
    - Pin Cushion, Barrel, and Fisheye
    - Profile your lens at the chosen focal length (read from EXIF)
    - Or get a profile from LensFun
- Dynamics/Motion in the scene
    - Causes ghosting
    - Once images are aligned, simply choose from one or the other
- Misalignment
    - Also causes ghosting
    - Pick better control points
- Visually pleasing result
    - Super wide panoramas are not always ‘pleasant’ to look at
    - Crop to golden ratio, 10:3, or something else visually pleasing

Ghosting and Variable Intensity

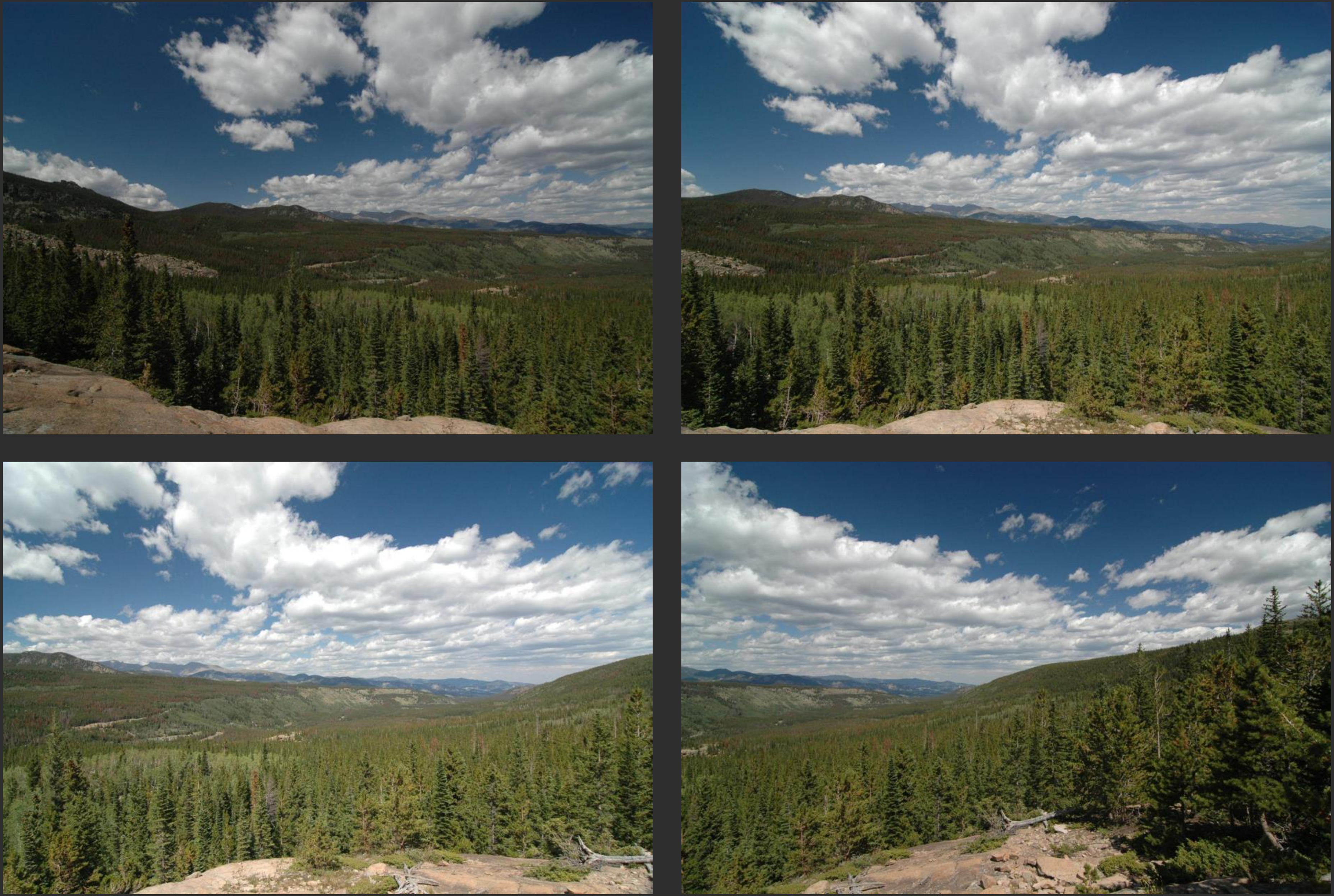


Photo: Russell J. Hewett

Nikon D70s, Tokina 12-24mm @ 12mm, f/8, 1/400s

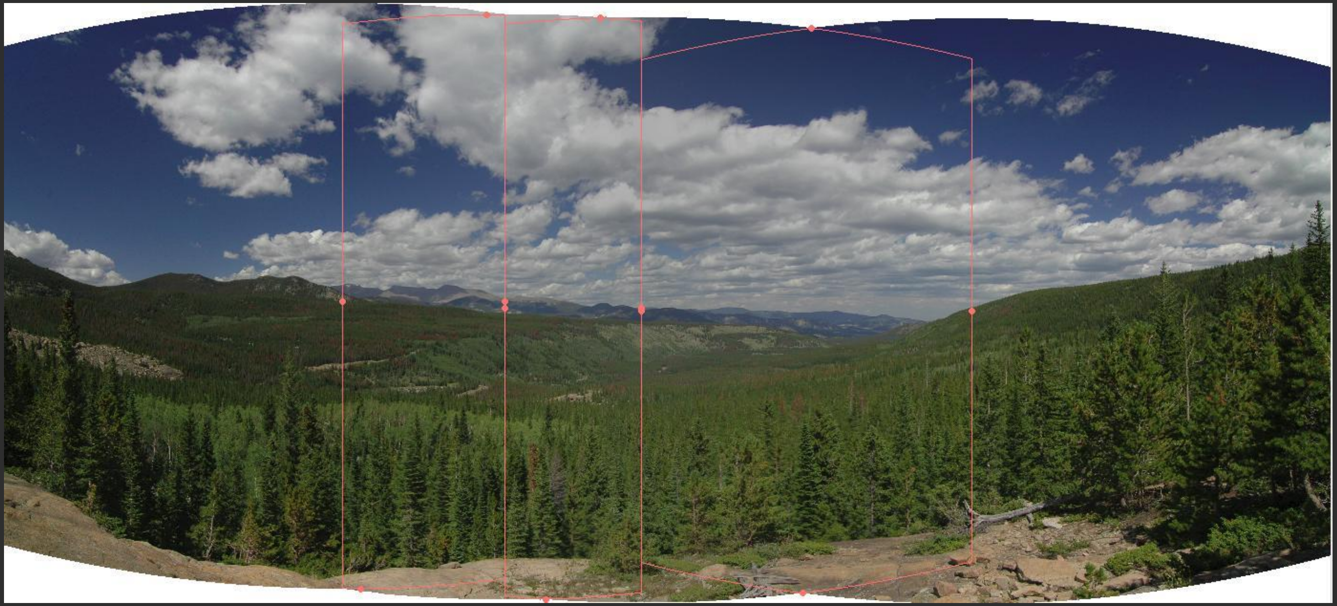
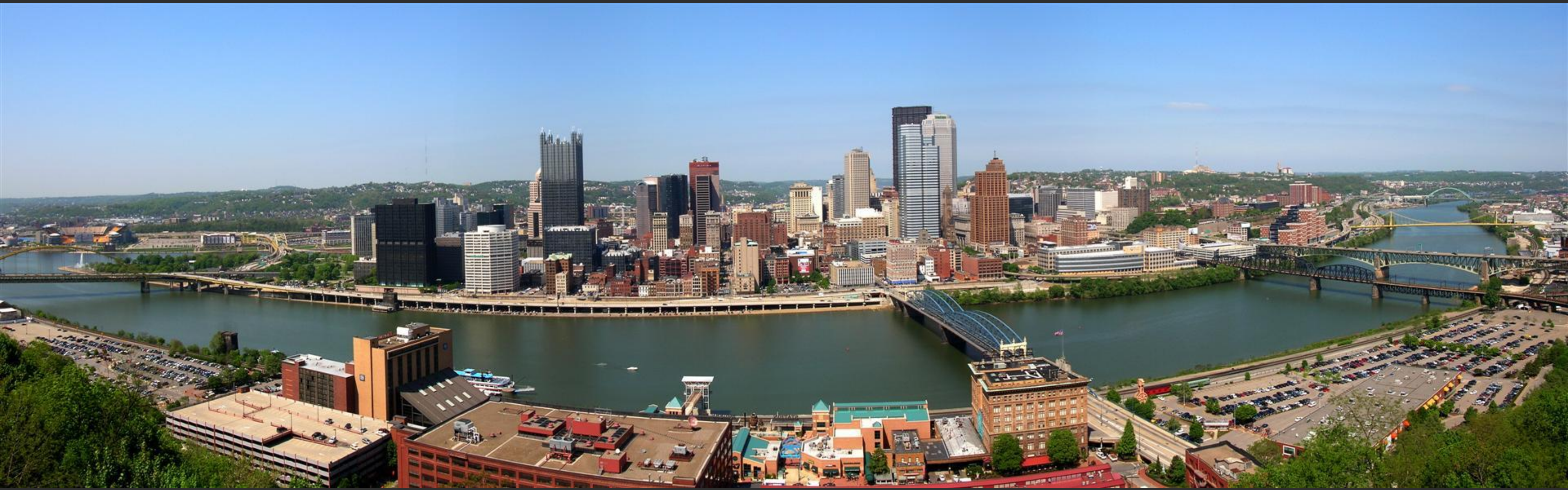


Photo: Russell J. Hewett

Ghosting From Motion



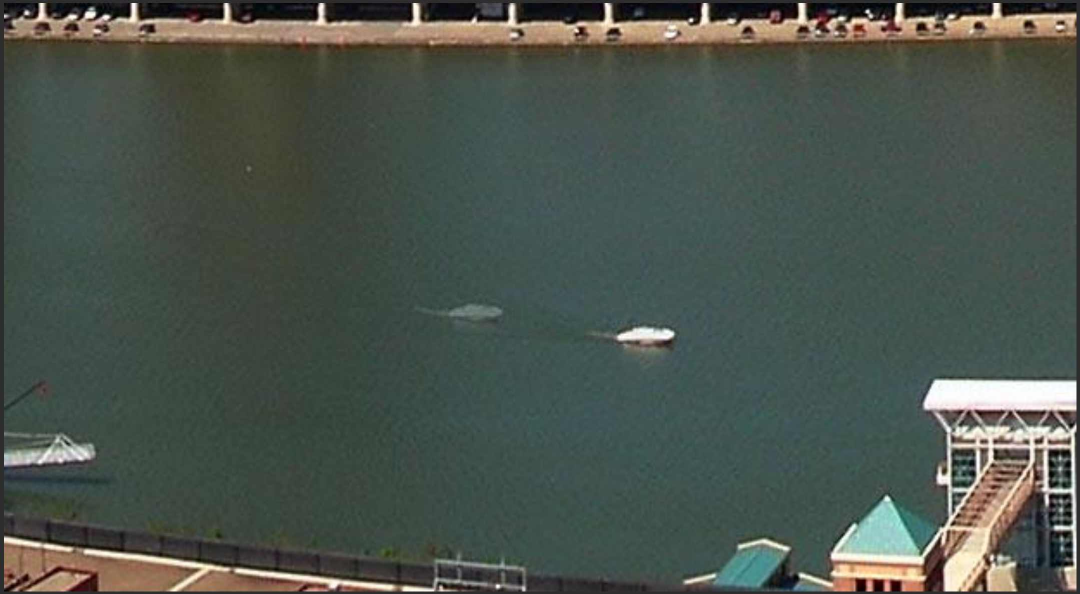
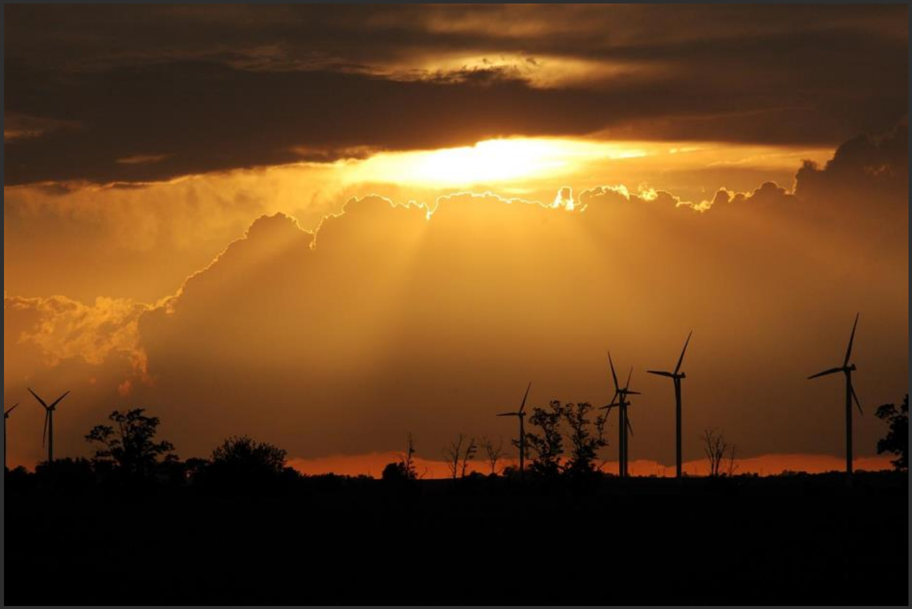


Photo: Bowen Lee

Nikon e4100 P&S

Motion Between Frames



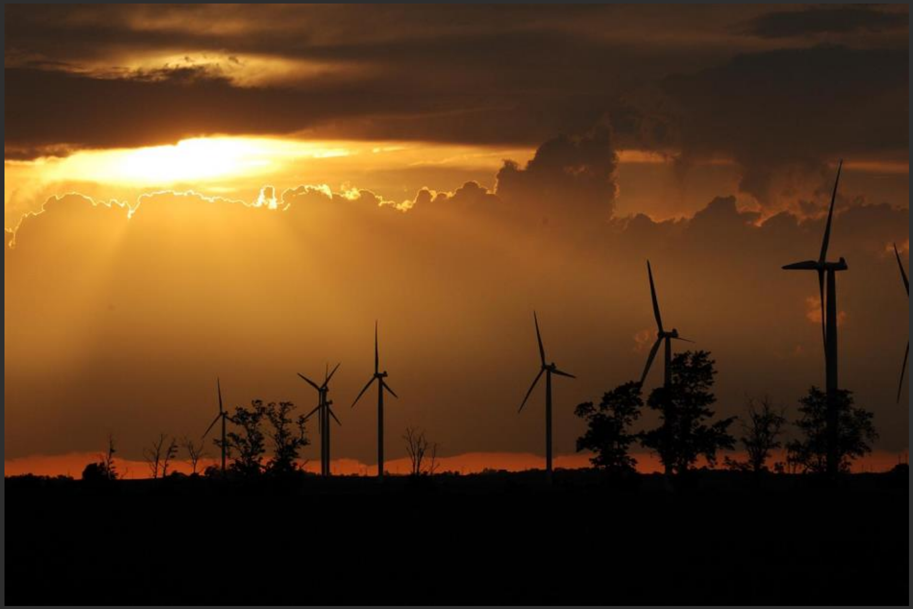


Photo: Russell J. Hewett

Nikon D70, Nikon 70-210mm @ 135mm, f/11, 1/320s

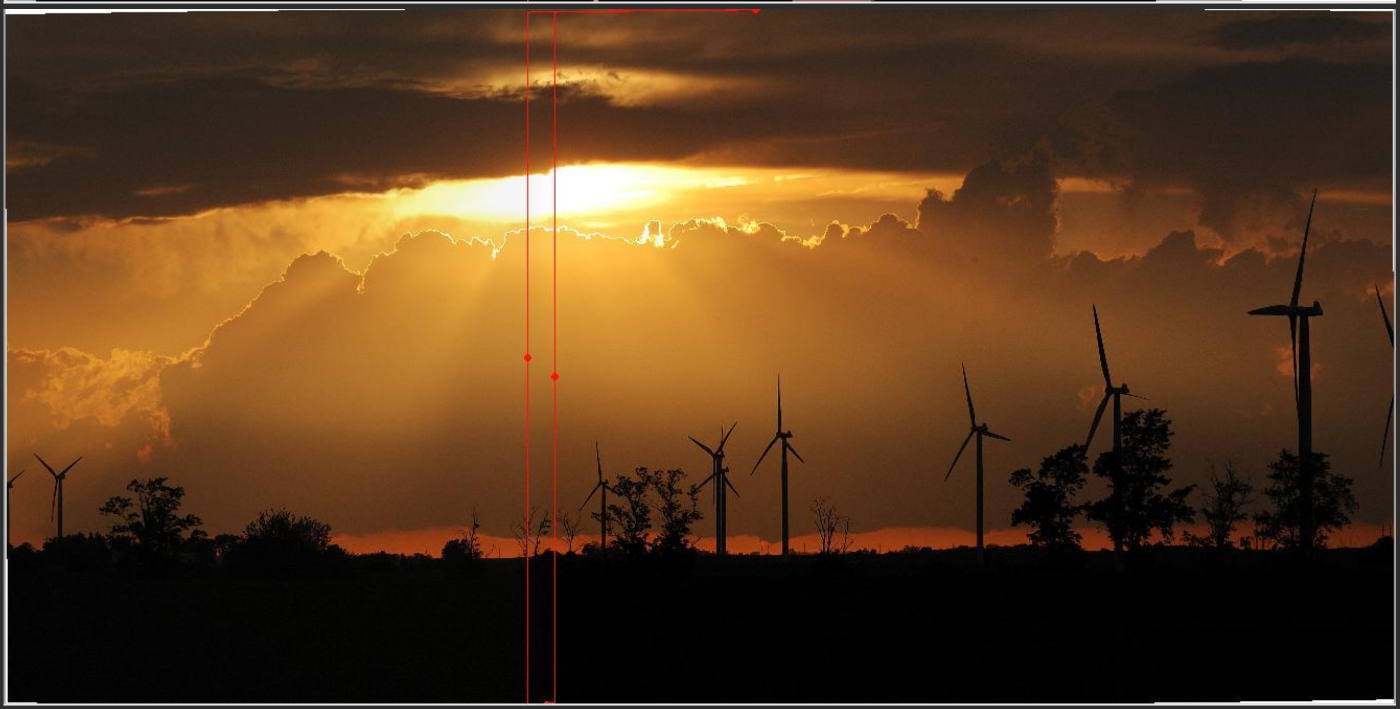


Photo: Russell J. Hewett

Gibson City, IL

Photo: Russell J. Hewett

(See Photo On Web)

Mount Blanca, CO

Photo: Russell J. Hewett

Nikon D70s, Tokina 12-24mm @ 12mm, f/22, 1/50s

Mount Blanca, CO

Photo: Russell J. Hewett

(See Photo On Web)

Things to remember

- Homography relates rotating cameras
  - Homography is plane to plane mapping

- Recover homography using RANSAC and normalized DLT

- Can choose surface of projection: cylinder, plane, and sphere are most common

- Refinement methods (blending, straightening, etc.)

Next class

- Object recognition and retrieval