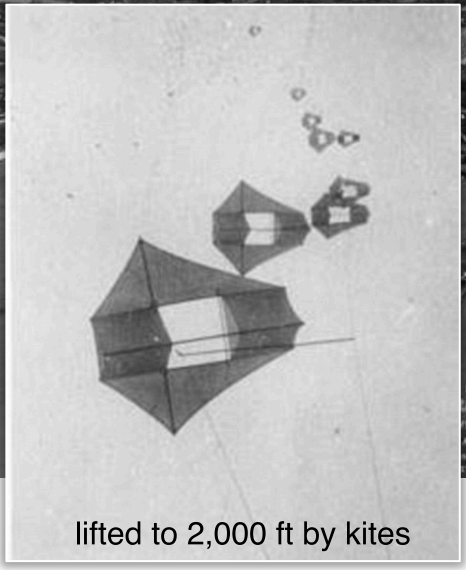
Panoramic Imaging

George R. Lawrence, San Francisco in ruins after earthquake of 1906

Panoramic Imaging

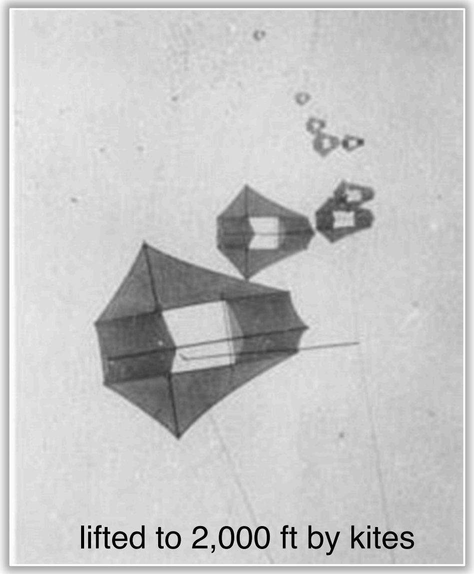
49 lbs camera


lifted to 2,000 ft by kites

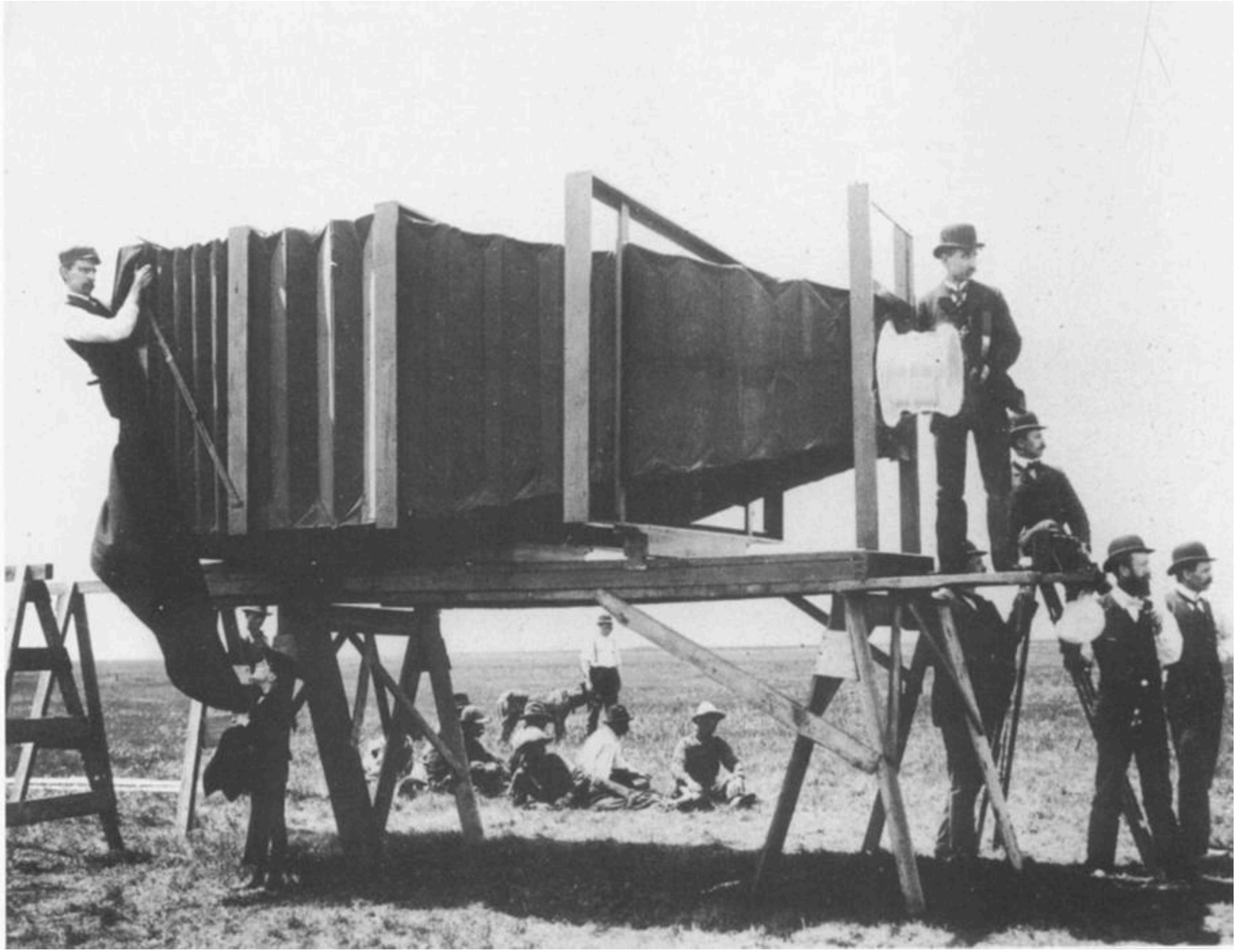
George R. Lawrence, San Francisco in ruins after earthquake of 1906

Panoramic Imaging

49 lbs camera



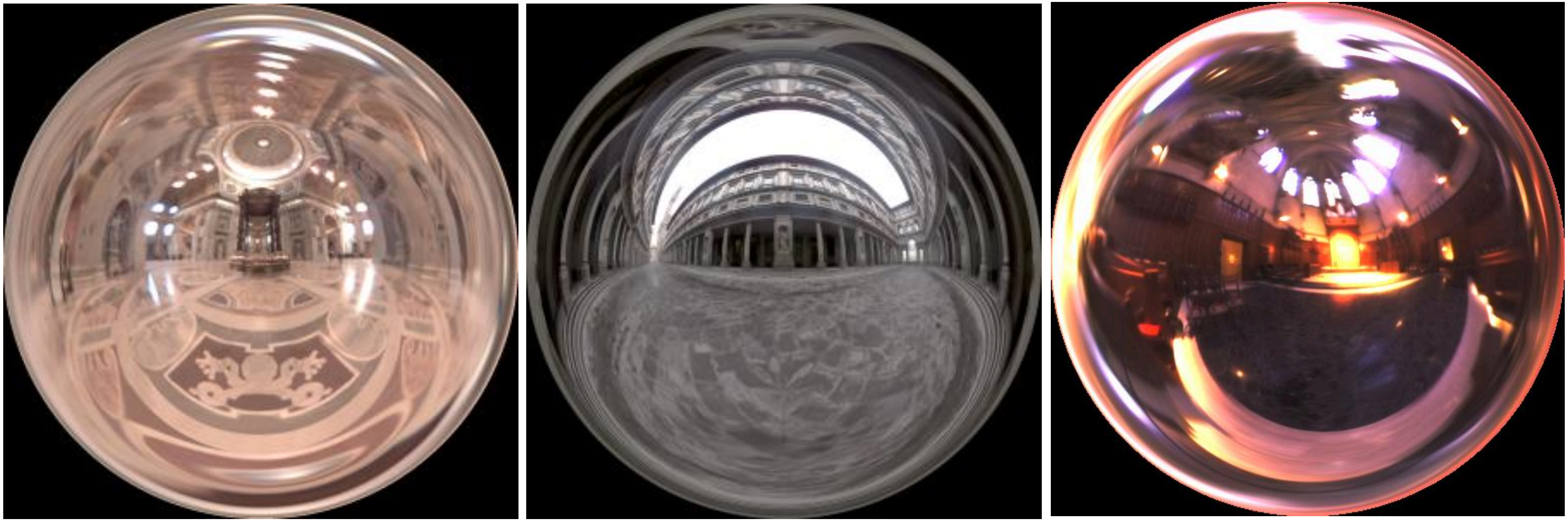
lifted to 2,000 ft by kites



George R. Lawrence

Panoramic Imaging

Paul Debevec, Light Probe Gallery, photographs of reflective spheres



Panoramic Imaging

Samsung Gear 360

Panoramic Imaging

Ricoh Theta

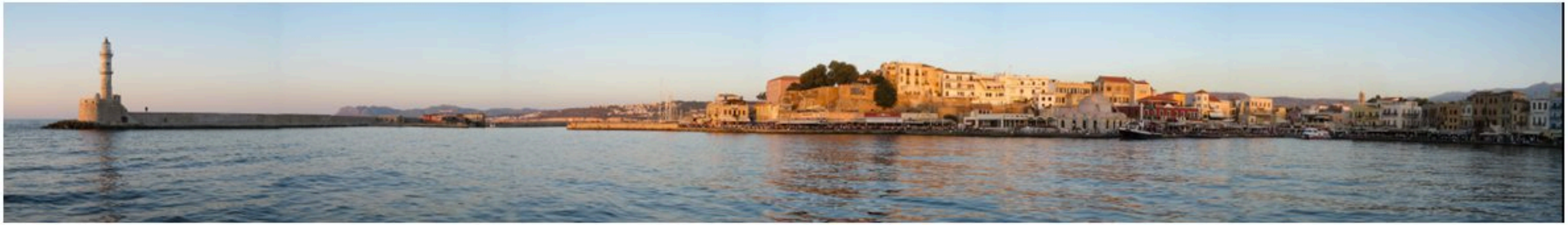
Kathy Schrock

Panoramic Imaging – Fisheye Lenses

photos from wikipedia

- large form factor
- heavy image distortion
- low resolution, i.e. spread pixel budget over large area

Panoramic Imaging – Stitching Photos



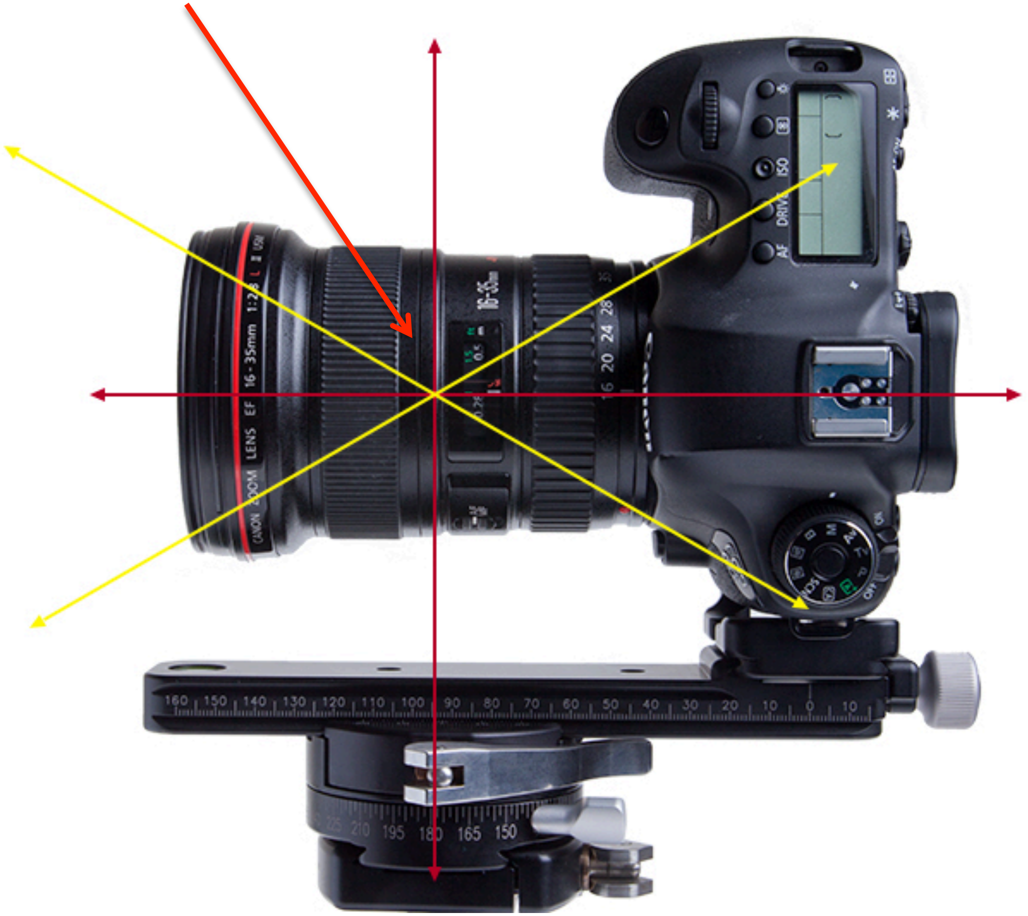
https://more4u2c.wordpress.com/2010/11/18/panorama-pictures/

Panoramic Imaging - Overview

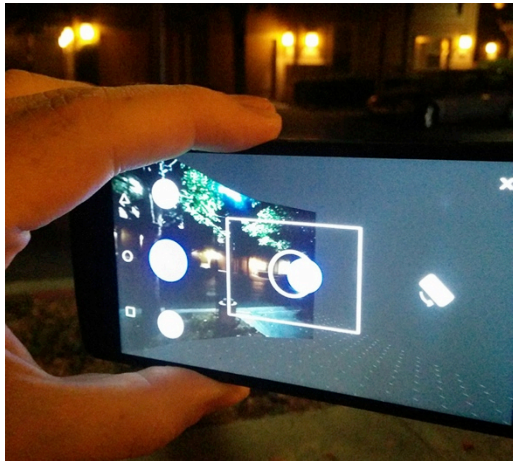
1. take photos
2. find features and matches, i.e. with SIFT
3. find transform between image pair, use RANSAC to remove outliers
4. blend overlapping parts
5. if >2 images, pick reference image first, do the above for one image, then use the resulting mosaic as reference image and pick a new image

Panoramic Imaging – 1. Take Photos

center of projection

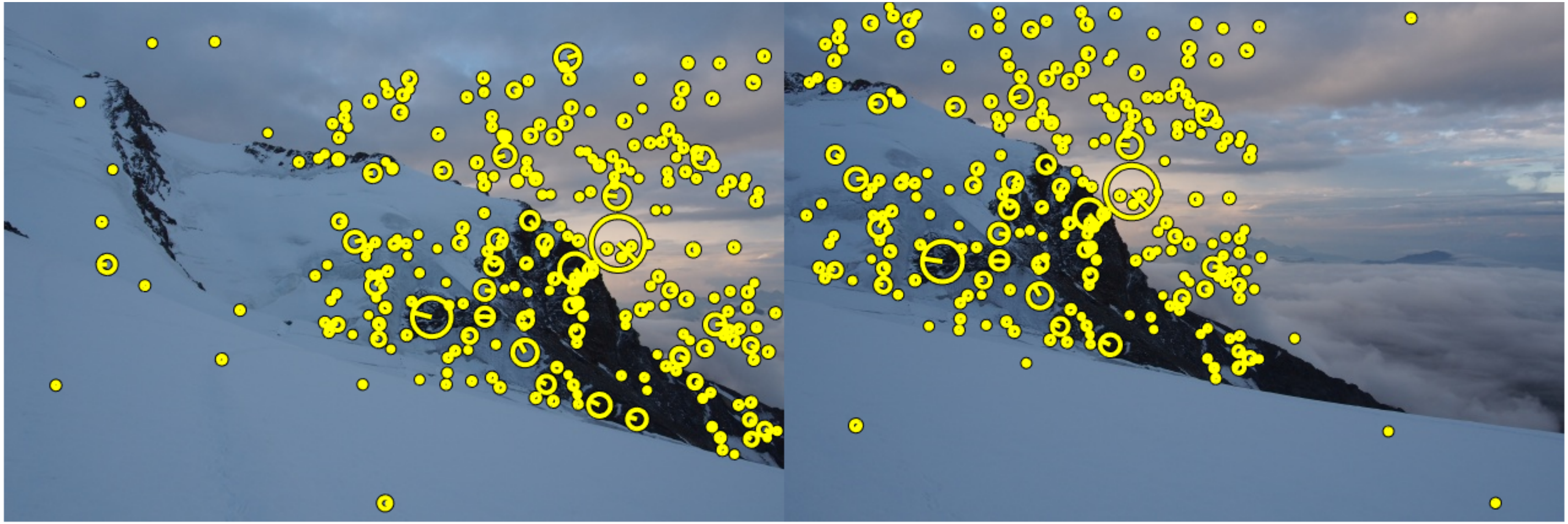


gigapan



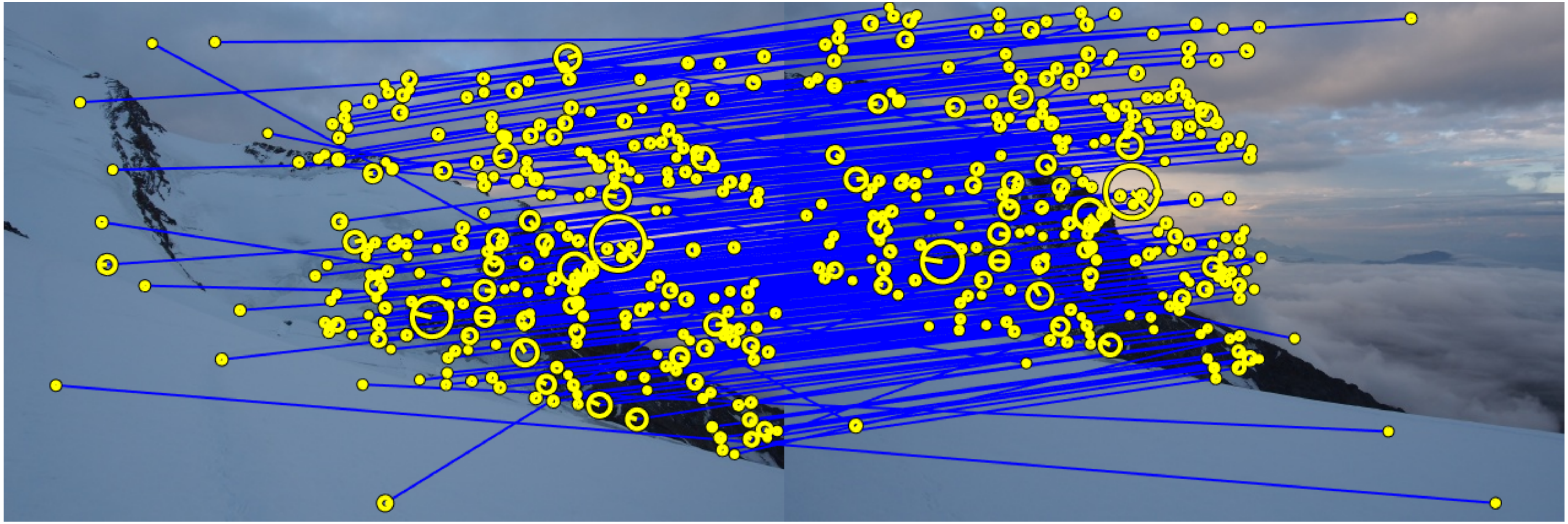
Panoramic Imaging – 2. Find Features and Matches

Panoramic Imaging – 2. Find Features and Matches



- e.g. SIFT features (with vlfeat: *vl_sift*)

Panoramic Imaging – 2. Find Features and Matches



- e.g. SIFT features (here with vlfeat library)
- nearest neighbor search between SIFT descriptors (with vlfeat: *vl_ubcmatch*)

Panoramic Imaging – 3. Find Transform

homogeneous 2D point

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

⇨

translation

$$\begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix}$$

rotation

$$\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

scale

$$\begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

perspective

$$\begin{bmatrix} \alpha f & 0 & c_x \\ 0 & f & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

general homography

$$H = \begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & h_{22} \end{bmatrix}$$

Panoramic Imaging – 3. Find Transform

1. transformation with homography

$$\begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

2. perspective divide

$$x' = \frac{x''}{z''} = \frac{h_{10}x + h_{11}y + h_{12}}{h_{20}x + h_{21}y + h_{22}}$$

$$y' = \frac{y''}{z''} = \frac{h_{00}x + h_{01}y + h_{02}}{h_{20}x + h_{21}y + h_{22}}$$

↑ transformed coordinates

Panoramic Imaging – 3. Find Transform

homography matrix: 9 elements, but only 8 degrees of freedom (scale ambiguity)

$$H = \begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & h_{22} \end{bmatrix}$$

rotation, scale, shear

translation

$$\begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ 0 & 0 & 1 \end{bmatrix}$$

perspective, etc.

$$\begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & 1 \end{bmatrix}$$

<u>affine homography</u> (no perspective)

- 6 elements (easier)
- estimate from 3 point correspondences

<u>homography</u> (without ambiguity)

- 8 elements
- estimate from 4 point correspondences

Panoramic Imaging – 3. Find Transform

affine homography estimation

given 3 point correspondences (SIFT matches)

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix}, \begin{bmatrix} \bar{x}_1 \\ \bar{y}_1 \end{bmatrix}$$

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix}, \begin{bmatrix} \bar{x}_2 \\ \bar{y}_2 \end{bmatrix}$$

$$\begin{bmatrix} x_3 \\ y_3 \end{bmatrix}, \begin{bmatrix} \bar{x}_3 \\ \bar{y}_3 \end{bmatrix}$$

each one must obey affine homography

$$0 = x_i - \bar{x}'_i = x_i - \left(h_{00}\bar{x}_i + h_{01}\bar{y}_i + h_{02} \right)$$

$$0 = y_i - \bar{y}'_i = y_i - \left(h_{10}\bar{x}_i + h_{11}\bar{y}_i + h_{12} \right)$$

→ 6 equations, 6 unknowns

Panoramic Imaging – 3. Find Transform

affine homography estimation

rewrite as matrix-vector multiplication

$$\begin{bmatrix} -x_1 \\ -y_1 \\ -x_2 \\ -y_2 \\ -x_3 \\ -y_3 \end{bmatrix} = \begin{bmatrix} -\bar{x}_1 & -\bar{y}_1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\bar{x}_1 & -\bar{y}_1 & -1 \\ -\bar{x}_2 & -\bar{y}_2 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\bar{x}_2 & -\bar{y}_2 & -1 \\ -\bar{x}_3 & -\bar{y}_3 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\bar{x}_3 & -\bar{y}_3 & -1 \end{bmatrix} \begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \end{bmatrix}$$

b A h

each one must obey affine homography

$$0 = x_i - \bar{x}'_i = x_i - \left(h_{00}\bar{x}_i + h_{01}\bar{y}_i + h_{02} \right)$$

$$0 = y_i - \bar{y}'_i = y_i - \left(h_{10}\bar{x}_i + h_{11}\bar{y}_i + h_{12} \right)$$

→ 6 equations, 6 unknowns

→ use Matlab to solve $h = A \backslash b$

Panoramic Imaging – 3. RANSAC

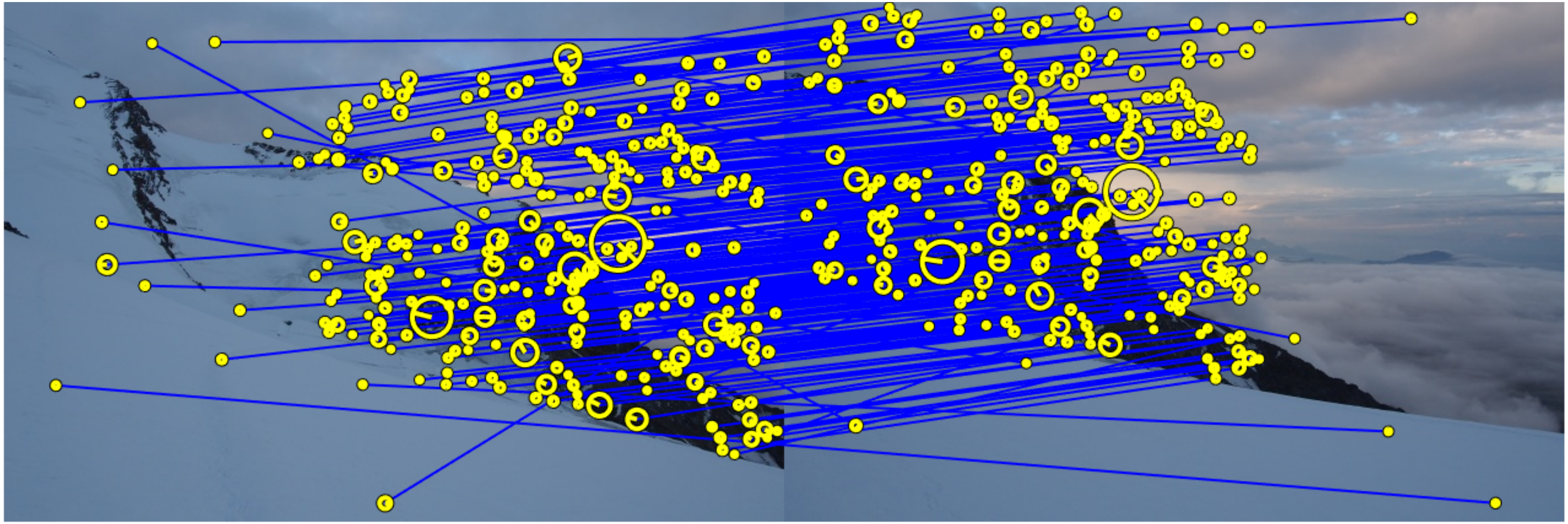
affine or not, need to get robust transform – use RANdom SAmple Consensus

for i=1:S

- pick k random (but different) matches, k = 3 (affine) or 4 (general)
- assemble coordinates into b and A (see last slides)
- solve for homography: h=A\b
- transform ALL matched feature coords from 2nd image to 1st image
- count number of inliers (i.e. those that are within a radius of r=3 from corresponding feature of 1st image
- if current num inliers > max num inliers: save h as best homography

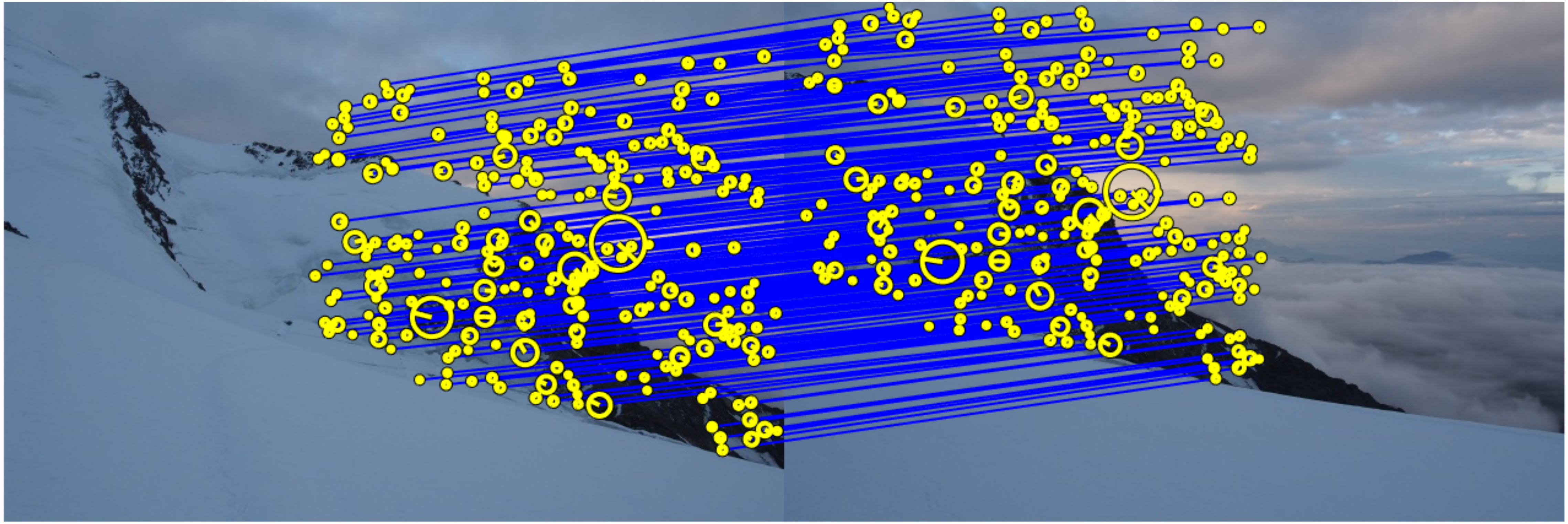
end

Panoramic Imaging – 2. Find Features and Matches



before RANSAC

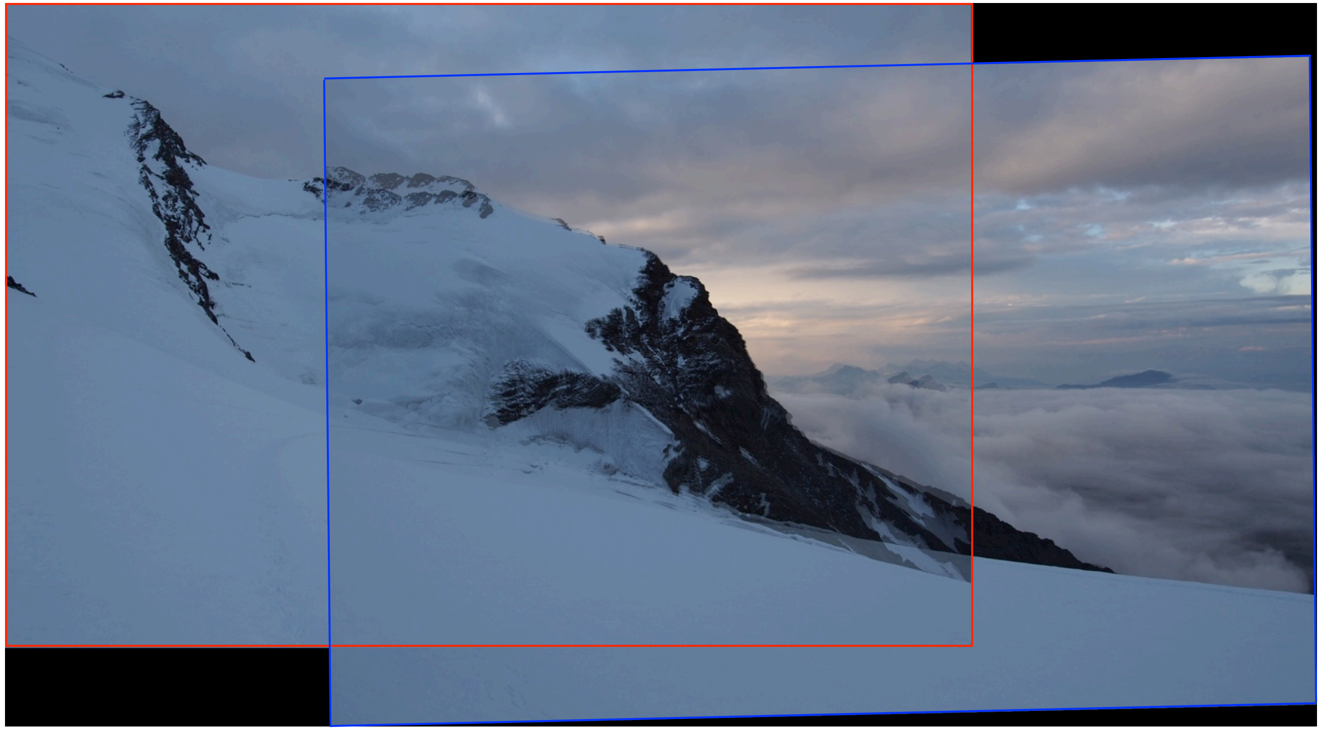
Panoramic Imaging – 3. Find Transform



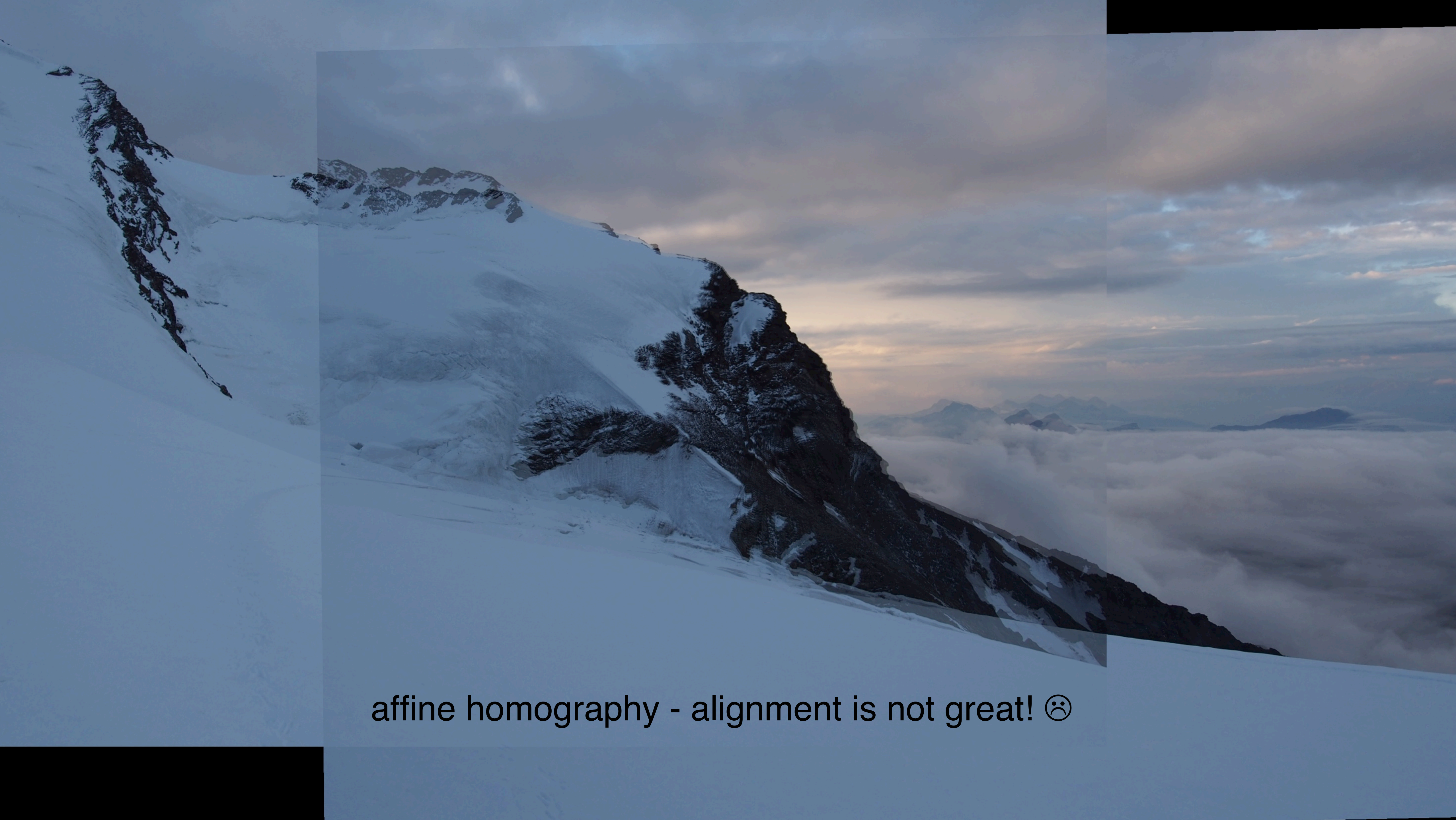
after RANSAC (and have corresponding homography H)

Panoramic Imaging – 3. Find Transform

<u>**affine** homography estimation</u>



- now warp both images to common plane; for image 2 apply H to coordinates
- need to resample images to common plane → use Matlab function *griddata()*
- linearly interpolate between both images in overlapping region


affine homography - alignment is not great! ☹

Panoramic Imaging – 3. Find Transform

general homography estimation

given 4 point correspondences (SIFT matches)

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix}, \begin{bmatrix} \bar{x}_1 \\ \bar{y}_1 \end{bmatrix}$$

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix}, \begin{bmatrix} \bar{x}_2 \\ \bar{y}_2 \end{bmatrix}$$

$$\begin{bmatrix} x_3 \\ y_3 \end{bmatrix}, \begin{bmatrix} \bar{x}_3 \\ \bar{y}_3 \end{bmatrix}$$

$$\begin{bmatrix} x_4 \\ y_4 \end{bmatrix}, \begin{bmatrix} \bar{x}_4 \\ \bar{y}_4 \end{bmatrix}$$

each one must obey affine homography

$$0 = x_i - \bar{x}'_i = x_i - \left(\frac{h_{00}\bar{x}_i + h_{01}\bar{y}_i + h_{02}}{h_{20}\bar{x}_i + h_{21}\bar{y}_i + 1} \right)$$

$$0 = y_i - \bar{y}'_i = y_i - \left(\frac{h_{10}\bar{x}_i + h_{11}\bar{y}_i + h_{12}}{h_{20}\bar{x}_i + h_{21}\bar{y}_i + 1} \right)$$

→ 8 equations, 8 unknowns

Panoramic Imaging – 3. Find Transform

general homography estimation

given 4 point correspondences (SIFT matches)

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix}, \begin{bmatrix} \bar{x}_1 \\ \bar{y}_1 \end{bmatrix}$$

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix}, \begin{bmatrix} \bar{x}_2 \\ \bar{y}_2 \end{bmatrix}$$

$$\begin{bmatrix} x_3 \\ y_3 \end{bmatrix}, \begin{bmatrix} \bar{x}_3 \\ \bar{y}_3 \end{bmatrix}$$

$$\begin{bmatrix} x_4 \\ y_4 \end{bmatrix}, \begin{bmatrix} \bar{x}_4 \\ \bar{y}_4 \end{bmatrix}$$

each one must obey affine homography

$$0 = x_i \left(h_{20} \bar{x}_i + h_{21} \bar{y}_i + 1 \right) - \left(h_{00} \bar{x}_i + h_{01} \bar{y}_i + h_{02} \right)$$

$$0 = y_i \left(h_{20} \bar{x}_i + h_{21} \bar{y}_i + 1 \right) - \left(h_{10} \bar{x}_i + h_{11} \bar{y}_i + h_{12} \right)$$

→ 8 equations, 8 unknowns

Panoramic Imaging – 3. Find Transform

general homography estimation

rewrite as matrix-vector multiplication

$$\underbrace{\begin{bmatrix} -x_1 \\ -y_1 \\ -x_2 \\ -y_2 \\ -x_3 \\ -y_3 \\ -x_4 \\ -y_4 \end{bmatrix}}_{b} = \underbrace{\begin{bmatrix} -\bar{x}_1 & -\bar{y}_1 & -1 & 0 & 0 & 0 & x_1\bar{x}_1 & x_1\bar{y}_1 \\ 0 & 0 & 0 & -\bar{x}_1 & -\bar{y}_1 & -1 & y_1\bar{x}_1 & y_1\bar{y}_1 \\ -\bar{x}_2 & -\bar{y}_2 & -1 & 0 & 0 & 0 & x_2\bar{x}_2 & x_2\bar{y}_2 \\ 0 & 0 & 0 & -\bar{x}_2 & -\bar{y}_2 & -1 & y_2\bar{x}_2 & y_2\bar{y}_2 \\ -\bar{x}_3 & -\bar{y}_3 & -1 & 0 & 0 & 0 & x_3\bar{x}_3 & x_3\bar{y}_3 \\ 0 & 0 & 0 & -\bar{x}_3 & -\bar{y}_3 & -1 & y_3\bar{x}_3 & y_3\bar{y}_3 \\ -\bar{x}_4 & -\bar{y}_4 & -1 & 0 & 0 & 0 & x_4\bar{x}_4 & x_4\bar{y}_4 \\ 0 & 0 & 0 & -\bar{x}_4 & -\bar{y}_4 & -1 & y_4\bar{x}_4 & y_4\bar{y}_4 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \end{bmatrix}}_{h}$$

each one must obey affine homography

$$0 = x_i\left(h_{20}\bar{x}_i + h_{21}\bar{y}_i + 1\right) - \left(h_{00}\bar{x}_i + h_{01}\bar{y}_i + h_{02}\right)$$

$$0 = y_i\left(h_{20}\bar{x}_i + h_{21}\bar{y}_i + 1\right) - \left(h_{10}\bar{x}_i + h_{11}\bar{y}_i + h_{12}\right)$$

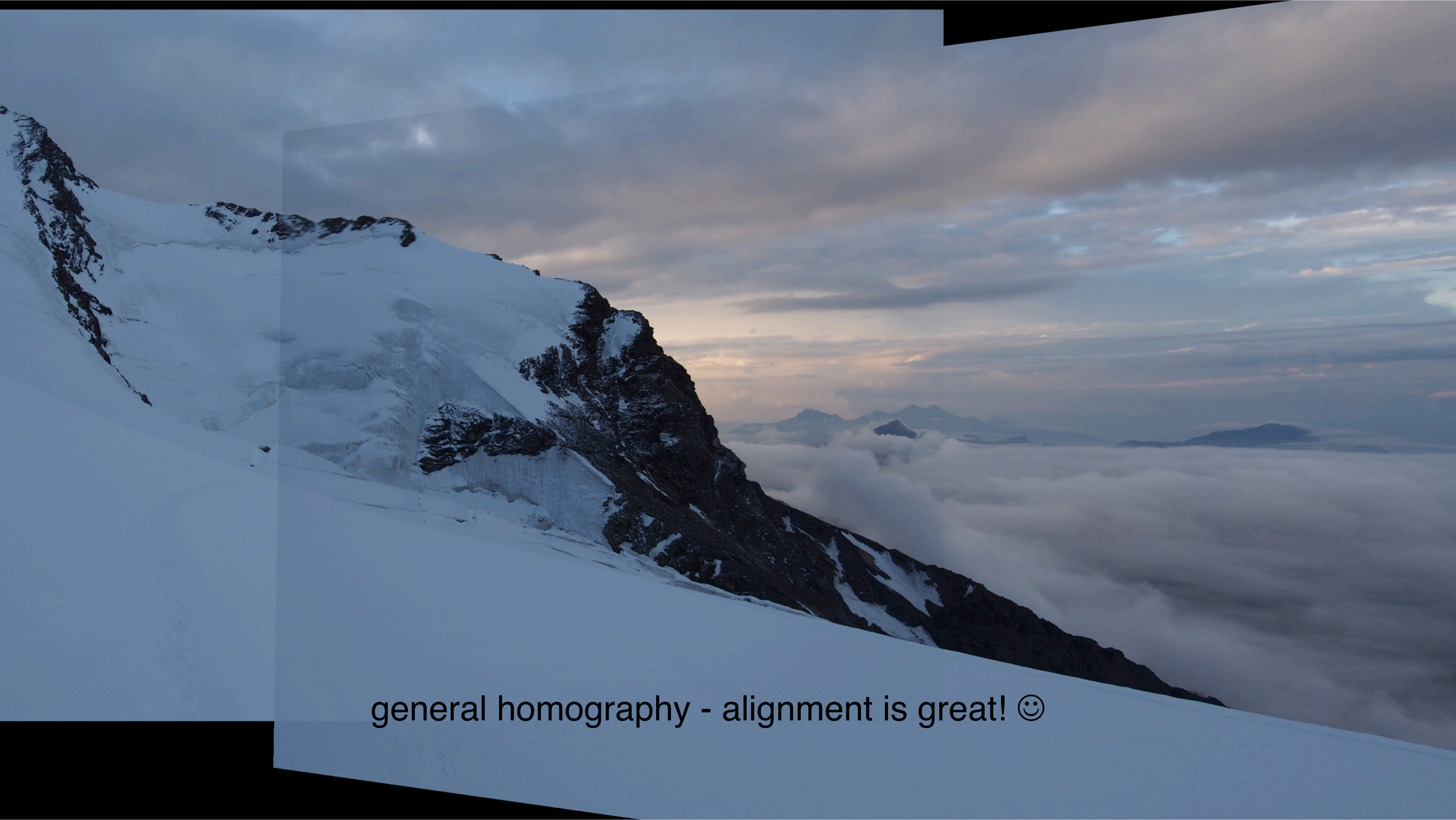
→ 8 equations, 8 unknowns

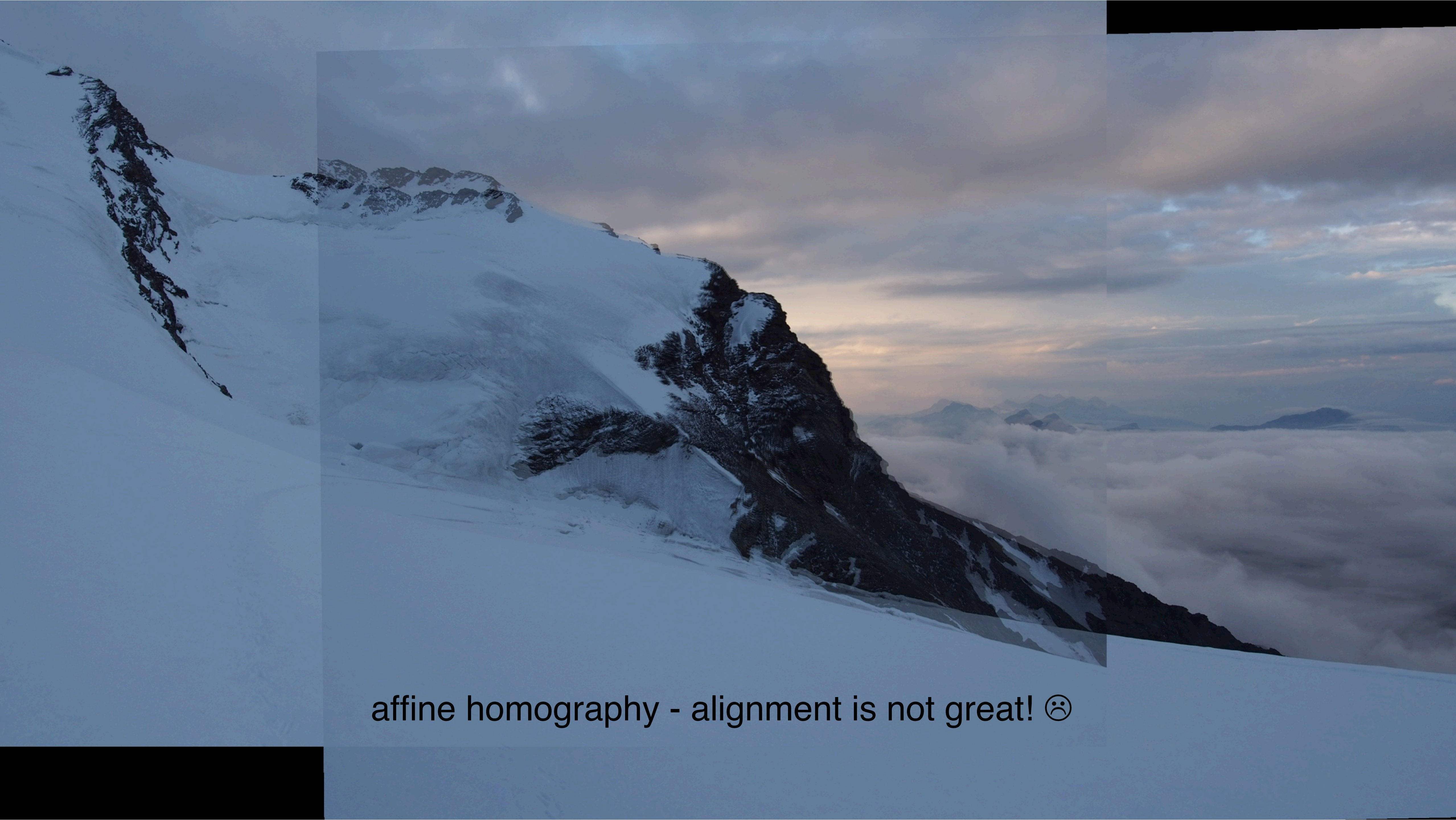
→ use Matlab to solve $h = A \backslash b$

Panoramic Imaging – 3. Find Transform

general homography estimation

- again, need to use RANSAC
- then warp both images to common plane; for image 2 apply H to coordinates
- need to resample images to common plane → use Matlab function *griddata()*


general homography - alignment is great! ☺


affine homography - alignment is not great! ☹

Panoramic Imaging – 4. Blending

- transformation may still not be perfect (e.g., lens distortion)
- definitely vignetting, camera parameters may have slightly changed

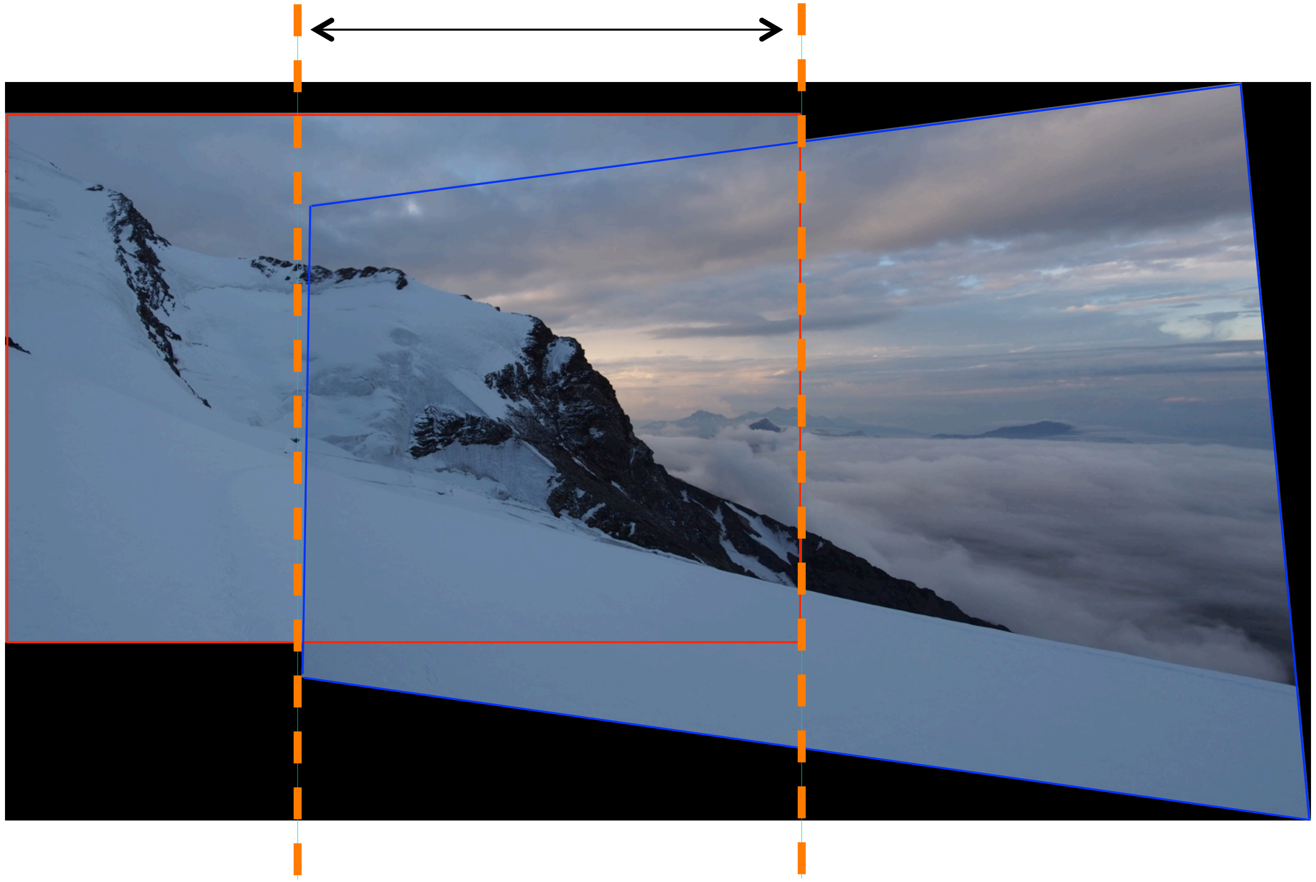
→ use (better) blending to hide seams between images

- so far: no blending or linear interpolation
- a bit better: weighted linear blending
- much better: Poisson blending, 2-scale or pyramid blending …

Panoramic Imaging – 4. Linear Blending

moderately effective but simple way:

- warp white images instead of image 1 & 2
- identify region of horizontal overlap and weight linearly according to distance



Panoramic Imaging – 4. Linear Blending

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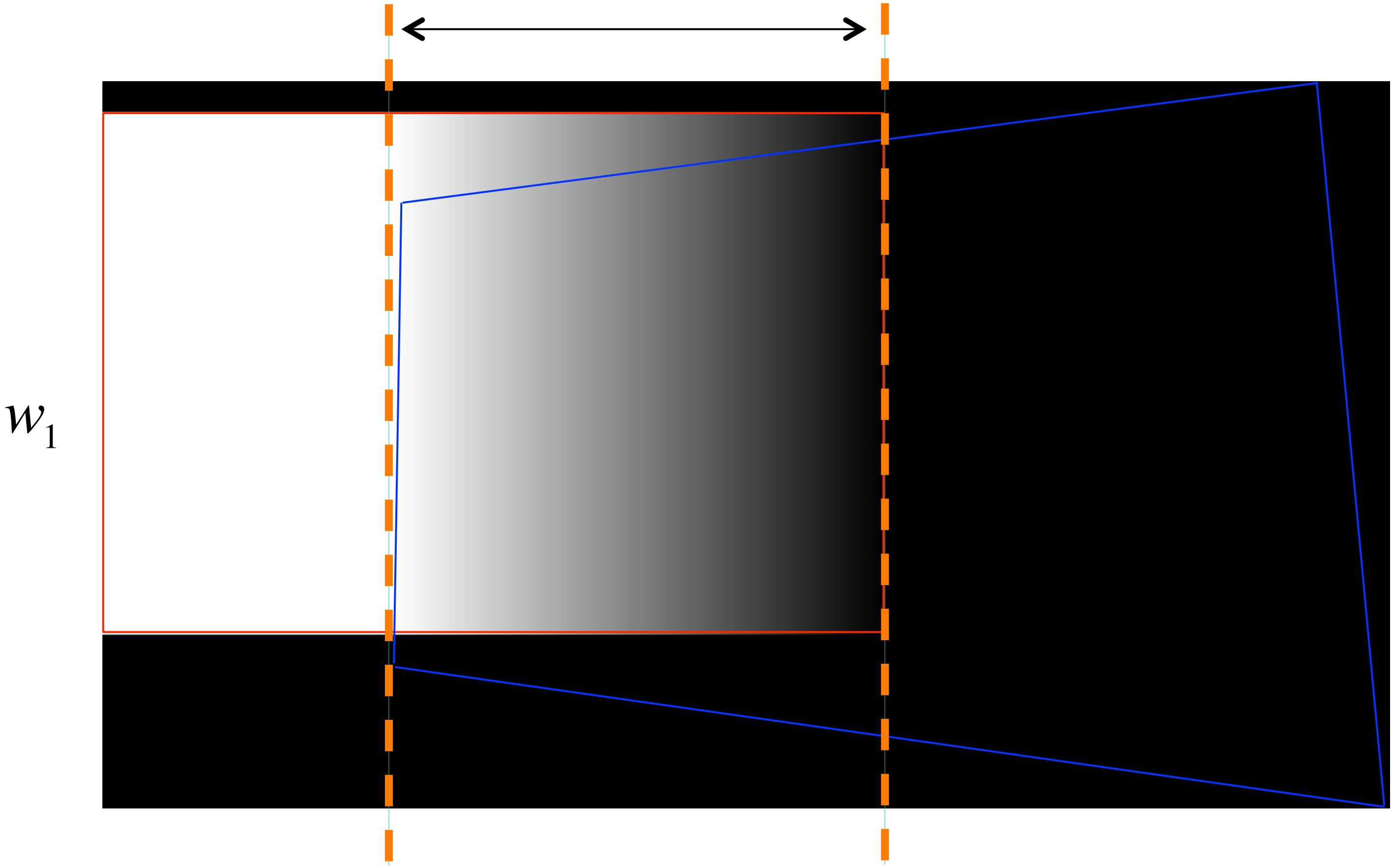

Panoramic Imaging – 4. Linear Blending

moderately effective but simple way:

- warp white images instead of image 1 & 2
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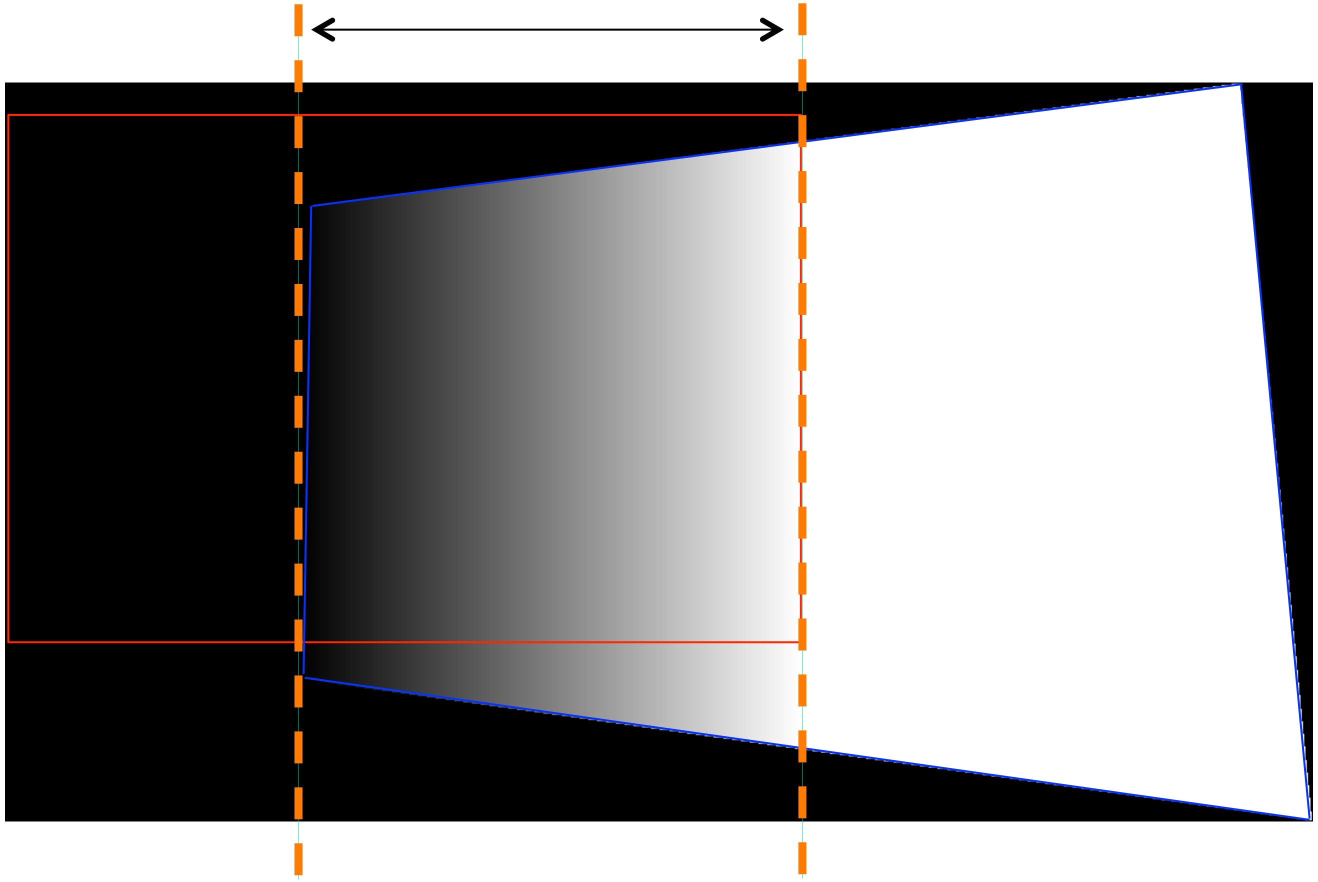


w_2

Panoramic Imaging – 4. Linear Blending

moderately effective but simple way:

- warp white images instead of image 1 & 2
- identify region of horizontal overlap and weight linearly according to distance

$$\frac{w_1 I_1 + w_2 I_2}{w_1 + w_2}$$

without linear blending

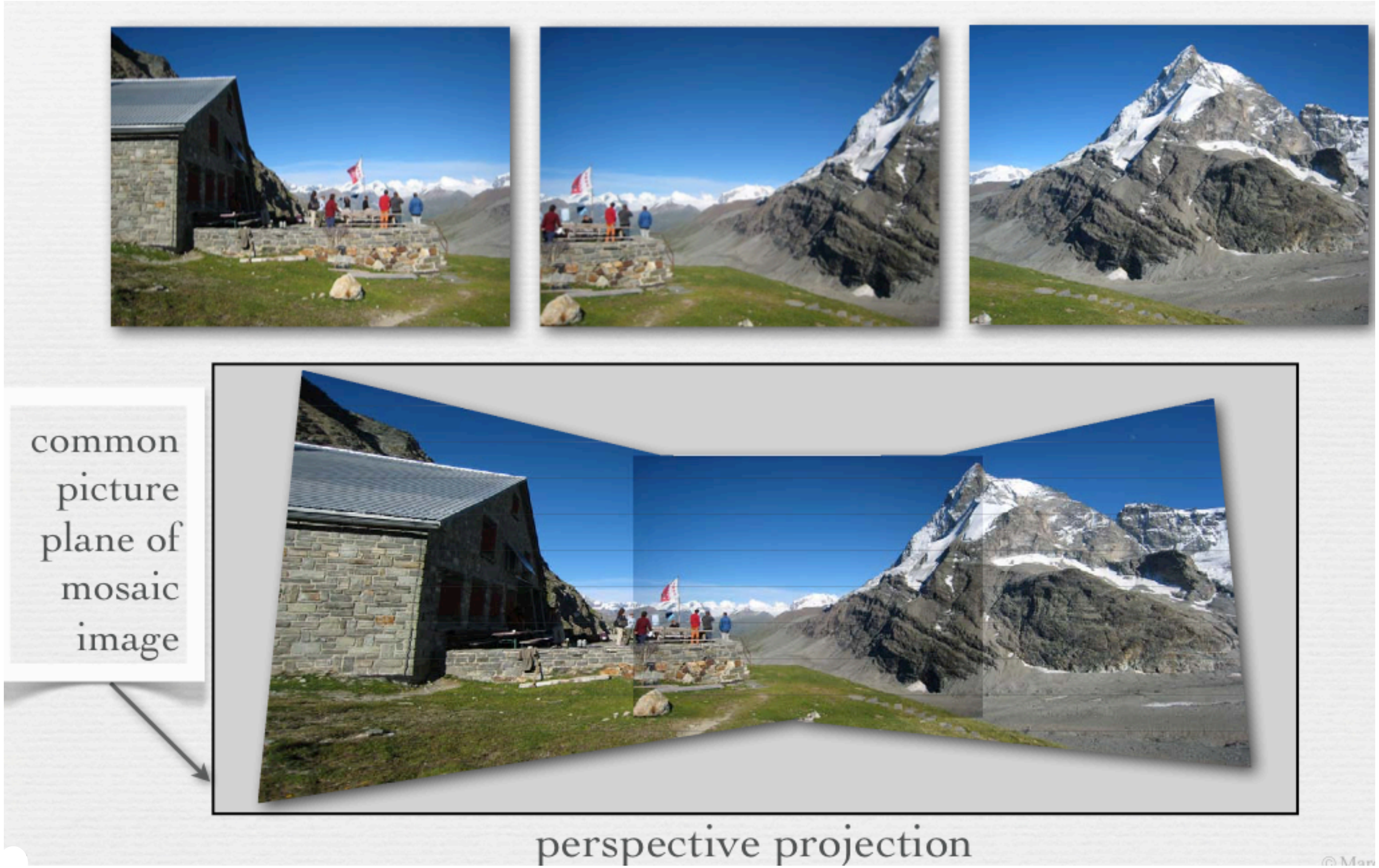
with linear blending

Panoramic Imaging – 4. Blending

- again, linear horizontal blending is simple and only works horizontally
- much better: Poisson blending, 2-scale or pyramid blending …

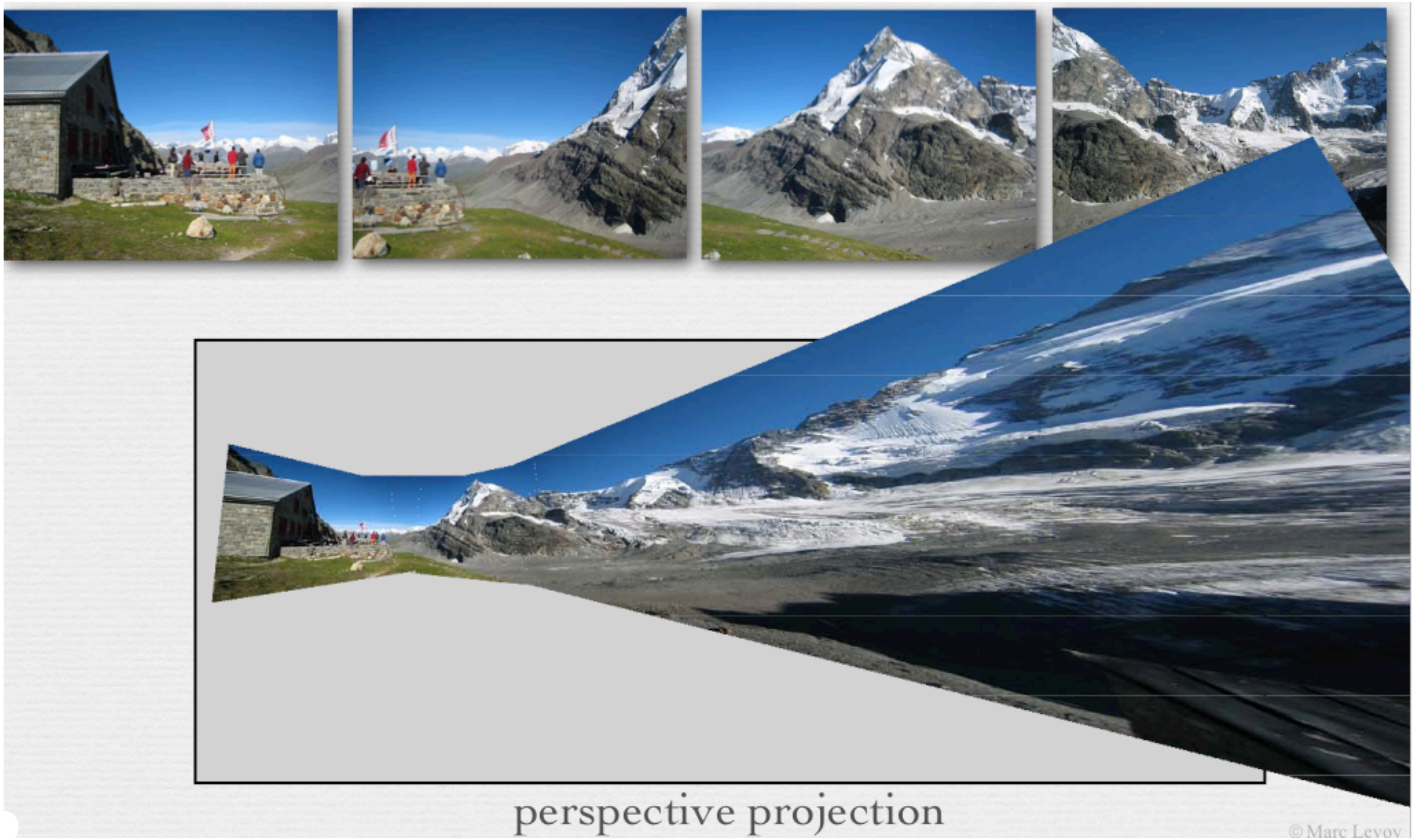
3 images instead of 2 – lots of perspective distortion
don’t project on a common **plane**, but a different surface! (can’t use homography)

Example: Stitching 3 Images



Slide: Marc Levoy

Example: Stitching 4 Images



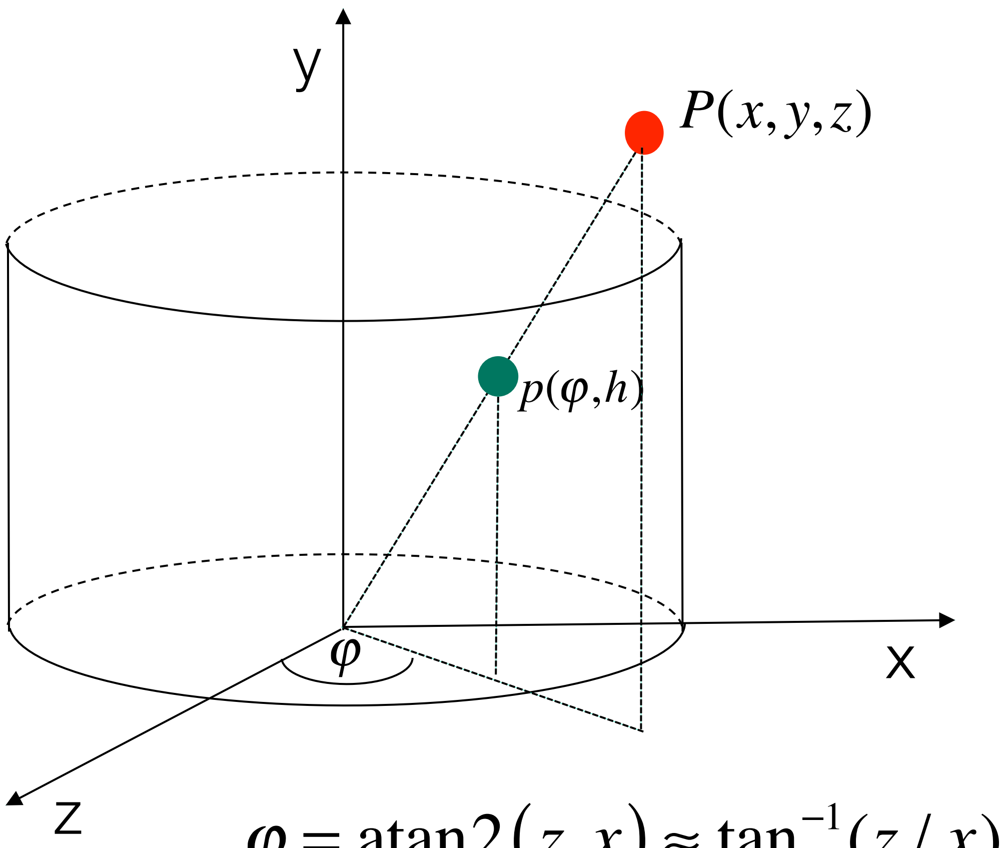
How to avoid this stretching?

Don't restrict image surface to a plane

Slide: Marc Levoy

Cylindrical Panorama

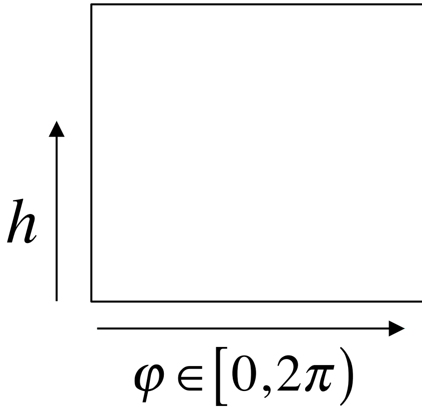
Assume cylinder of unit radius



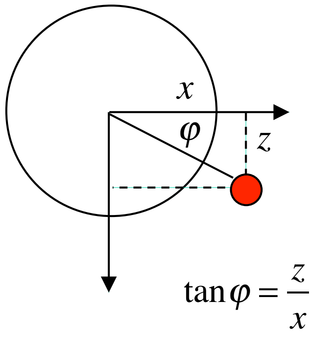
$$\varphi = \text{atan2}(z,x) \approx \tan^{-1}(z/x)$$

$$h = y/\sqrt{x^2+z^2}$$

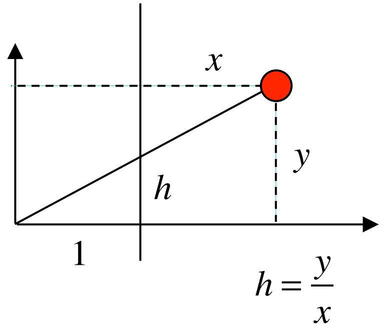
Unwrapped Cylinder



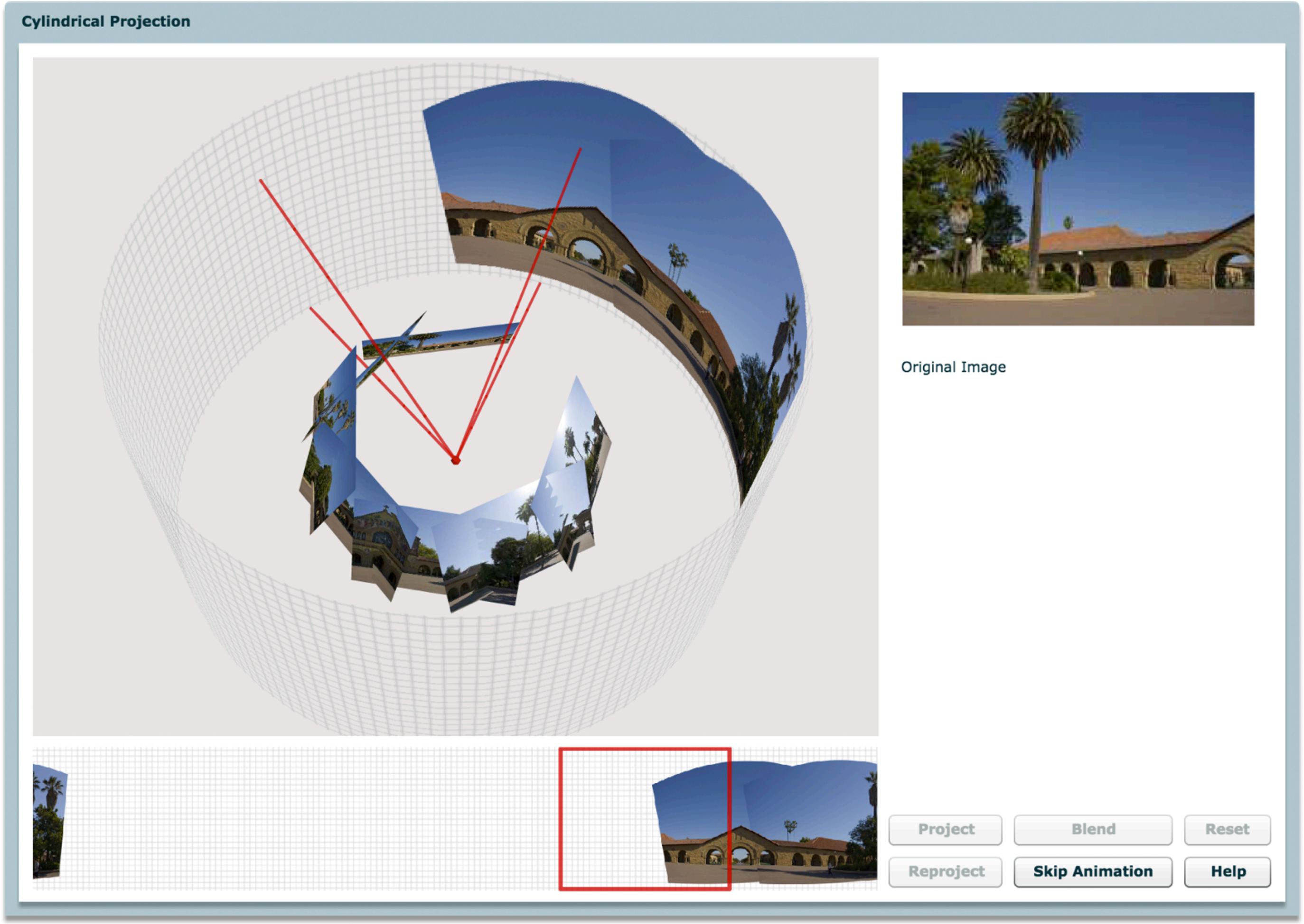
top view



side view (1D)



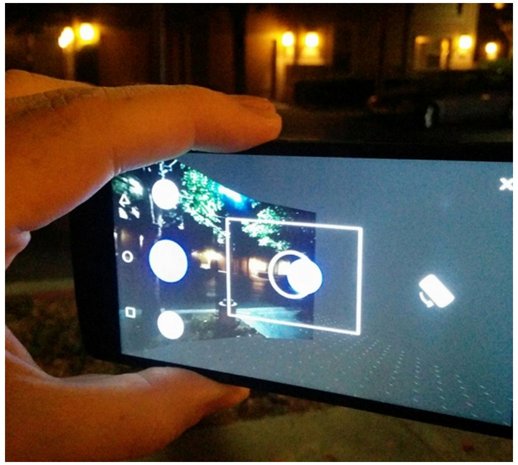
Cylindrical Panorama



https://graphics.stanford.edu/courses/cs178/applets/projection.html

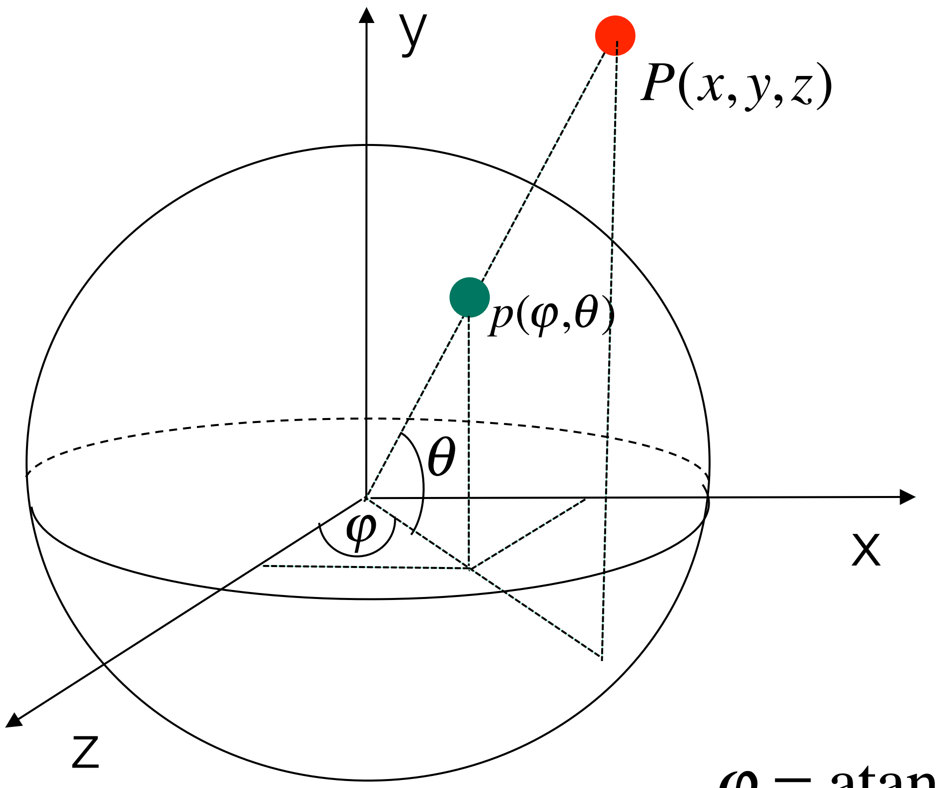
Cylindrical Panorama

- works well when all images are captured with limited vertical field of view and without tilting camera!
    - either use tripod
    - or manual help, e.g. Android panorama mode →

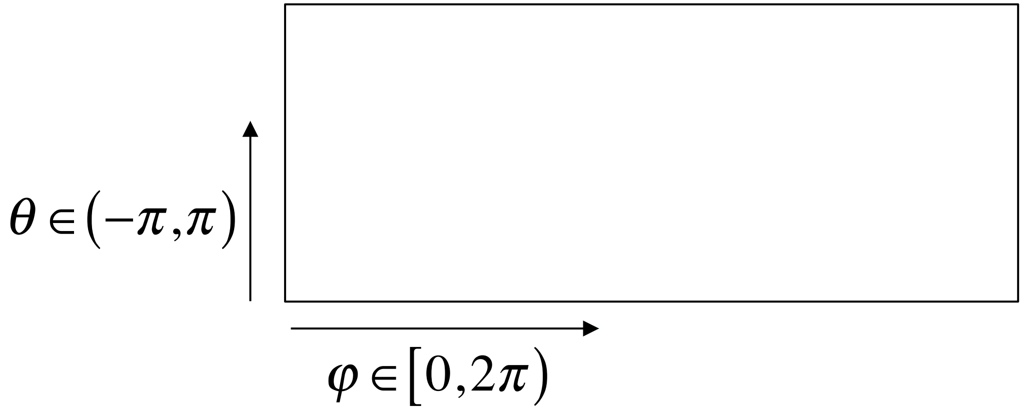


Spherical Panorama

Assume sphere of unit radius



Unwrapped Sphere



$$\varphi = \text{atan2}(z,x)$$

$$\theta = \text{atan2}(y,x)$$

Example of Spherical Panorama

Constructed from 54 photographs
[Image Alignment and Stitching: A Tutorial, by Szeliski, 2006]

Cinematic VR

e.g. Jaunt VR


JAUNT

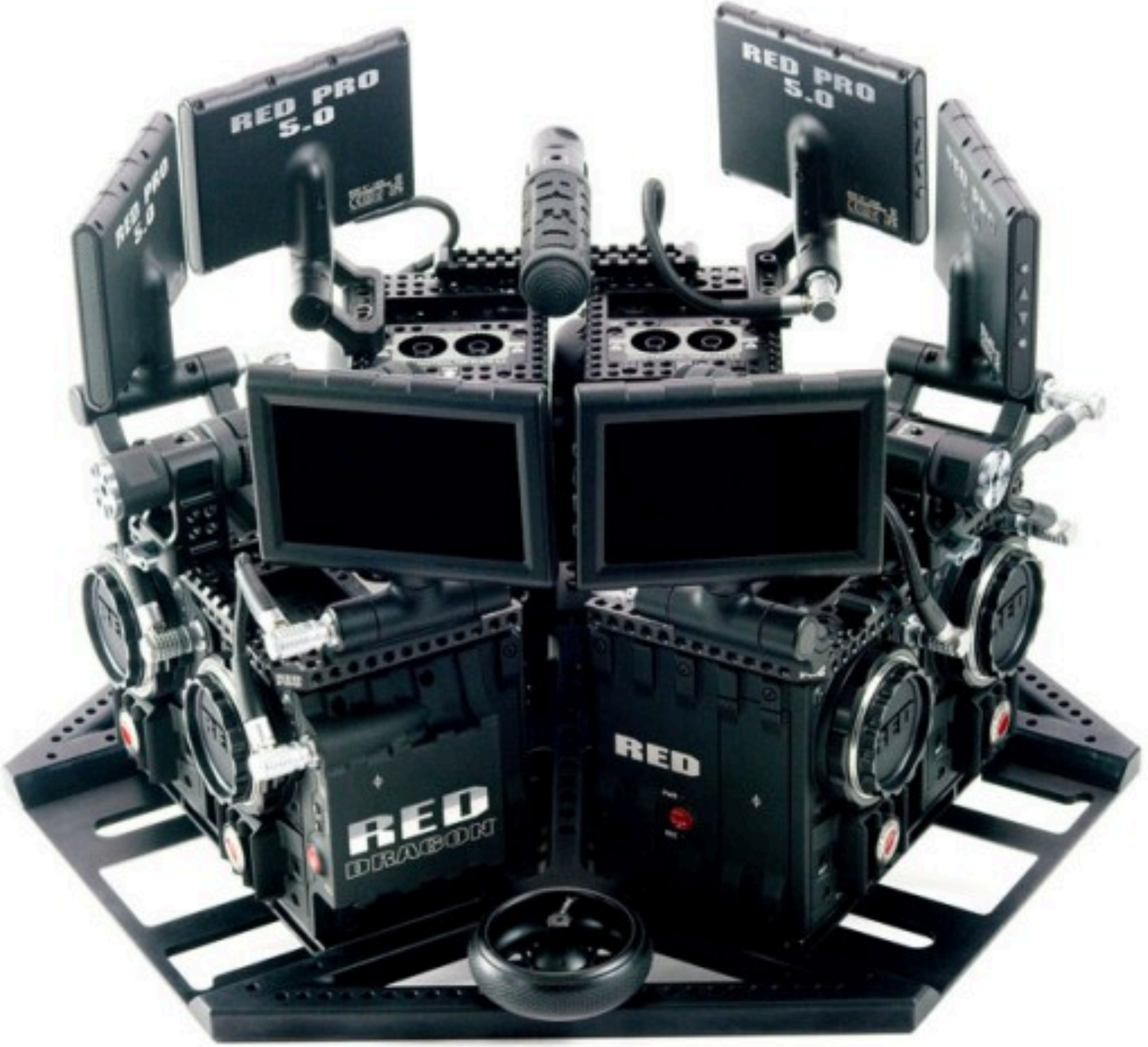
Lytro

Google

Nokia

Facebook Surround 360

Red

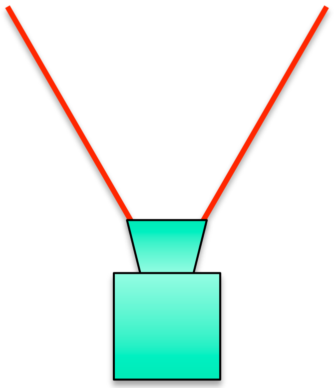


Samsung

Panorama v Stereo Movie v Stereo Panorama

Panorama

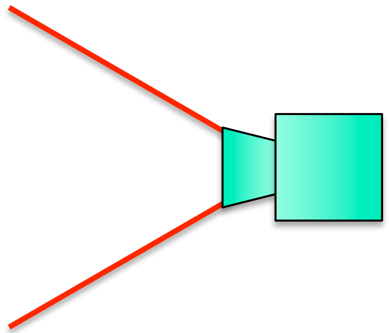
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

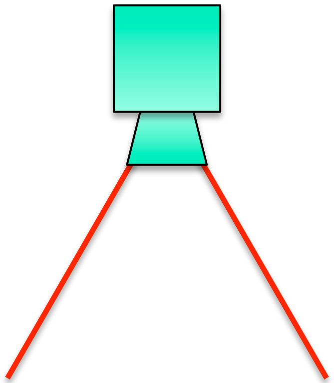
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

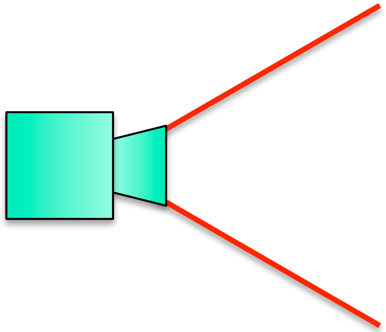
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

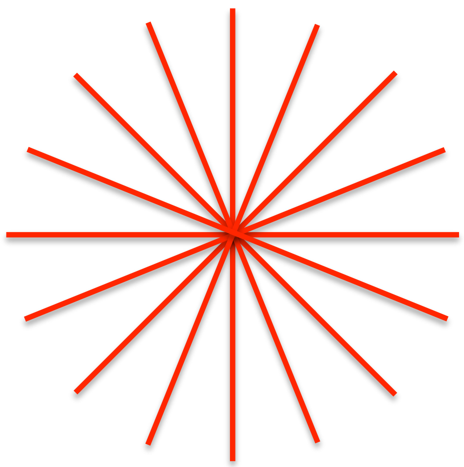
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation

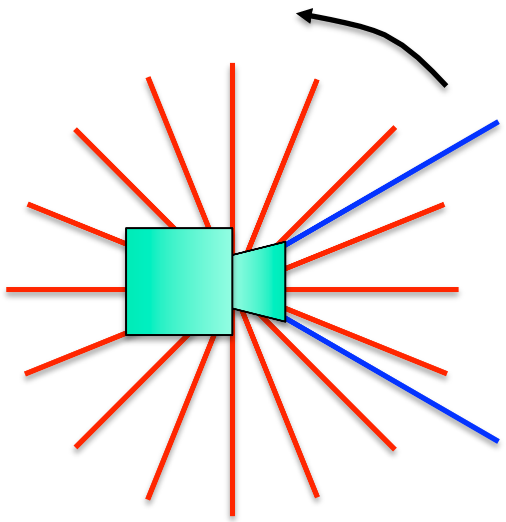


1 center of projection!

Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation

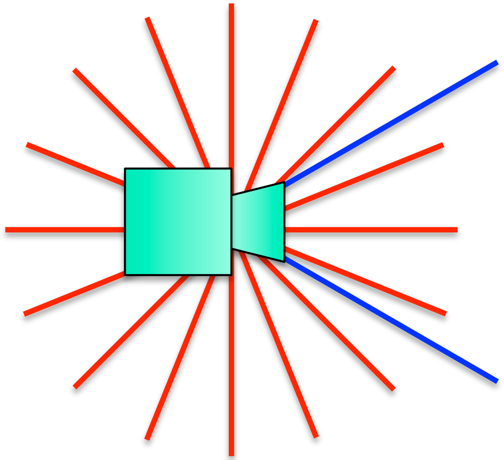


1 center of projection!

Panorama v Stereo Movie v Stereo Panorama

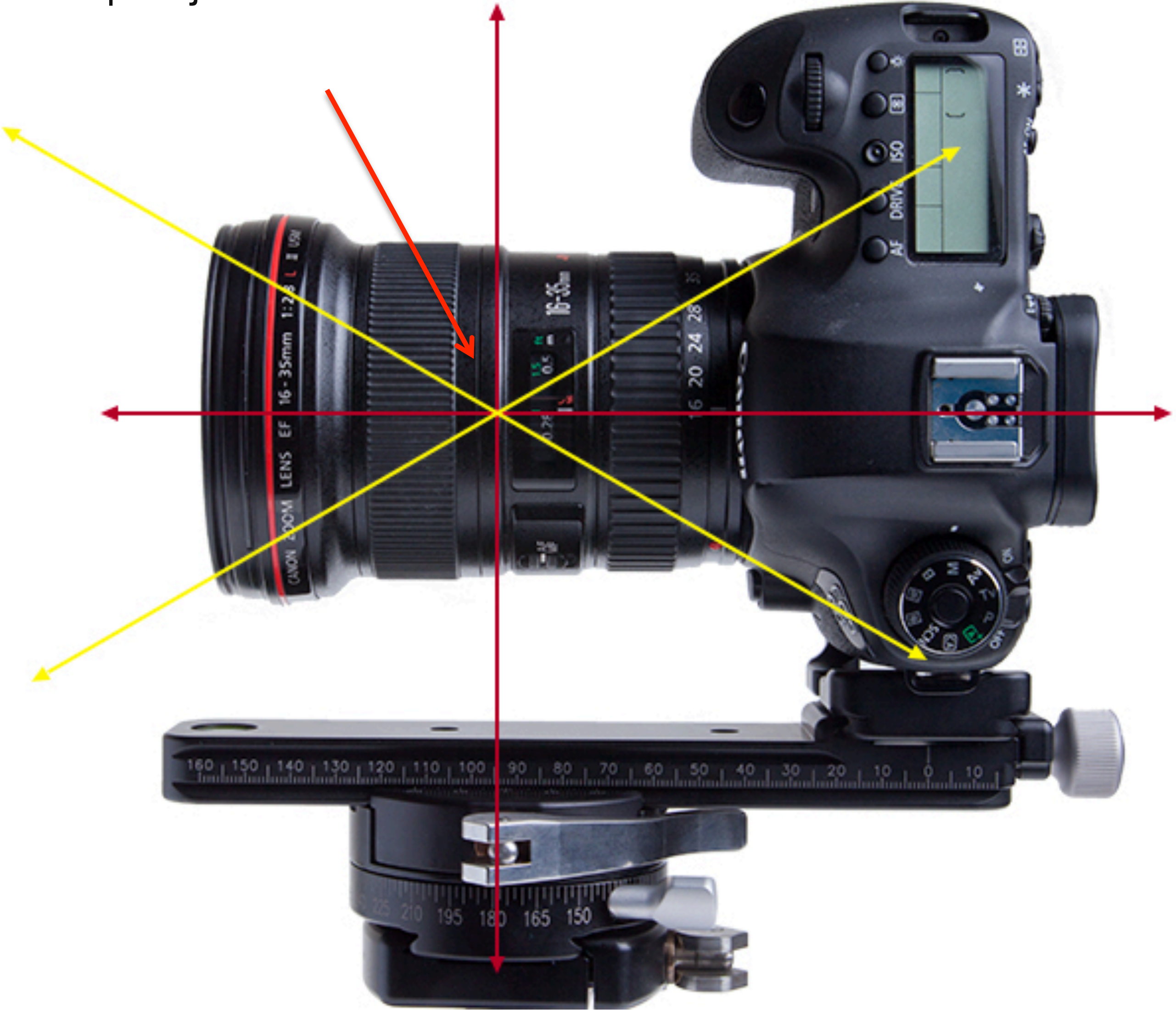
Panorama

mono & head rotation



1 center of projection!

center of projection



Panorama v Stereo Movie v Stereo Panorama

Panorama

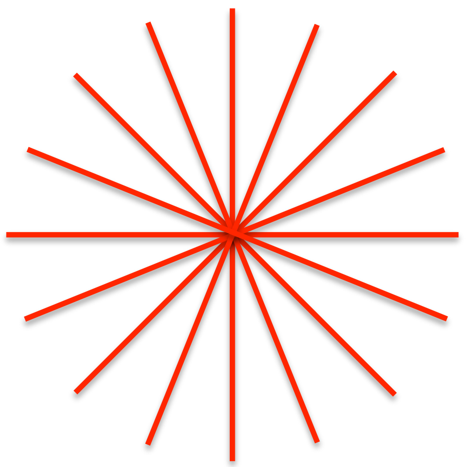
mono & head rotation

Stereo

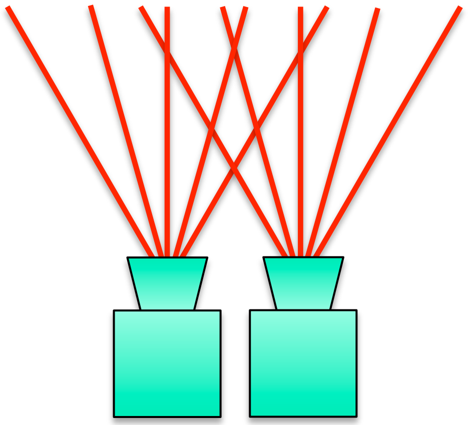
stereo & no head rotation

Stereo Panorama

stereo & head rotation



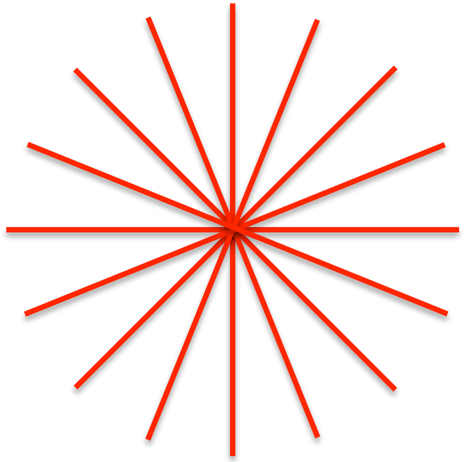
1 center of projection!



Panorama v Stereo Movie v Stereo Panorama

Panorama

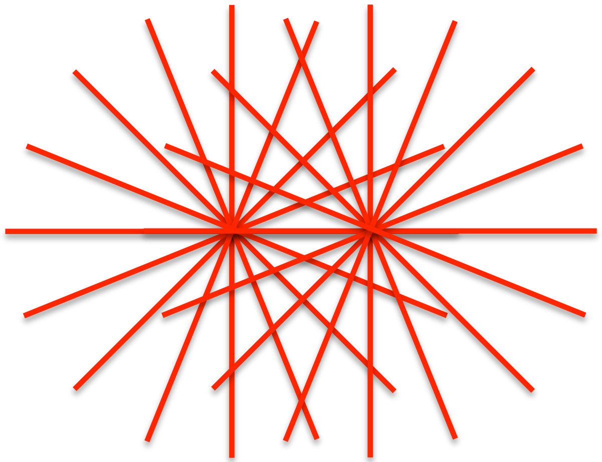
mono & head rotation



1 center of projection!

Stereo

stereo & no head rotation



2 centers of projection!

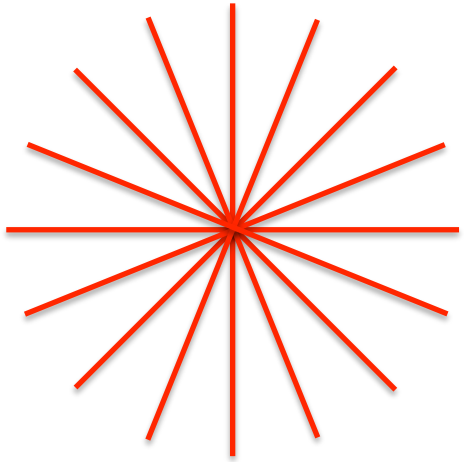
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

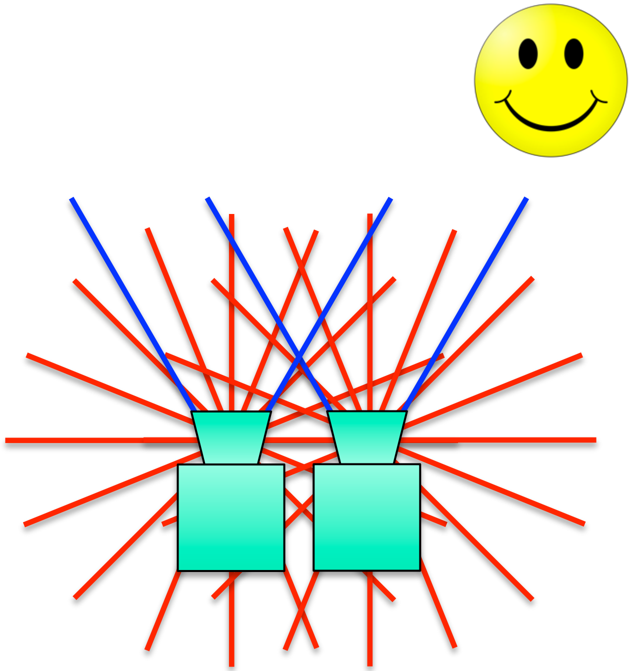
mono & head rotation



1 center of projection!

Stereo

stereo & no head rotation



2 centers of projection!

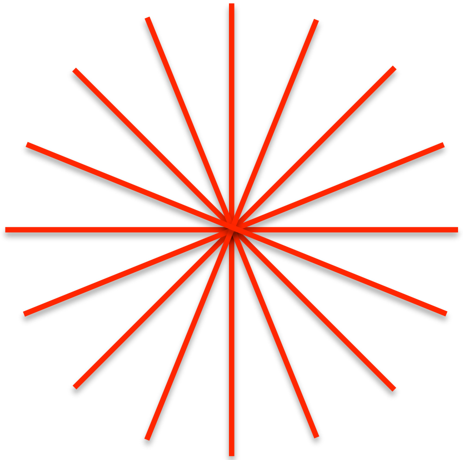
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

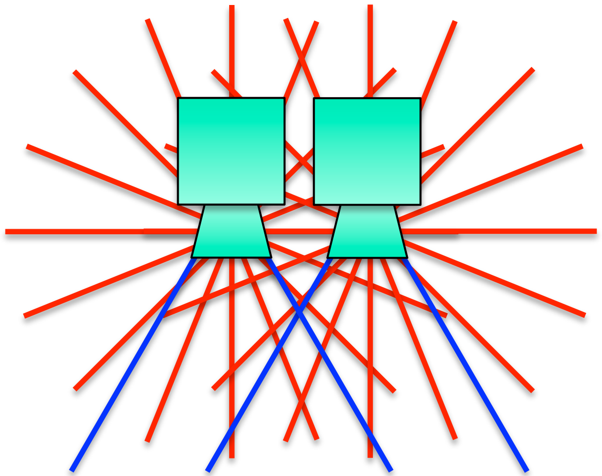
mono & head rotation



1 center of projection!

Stereo

stereo & no head rotation



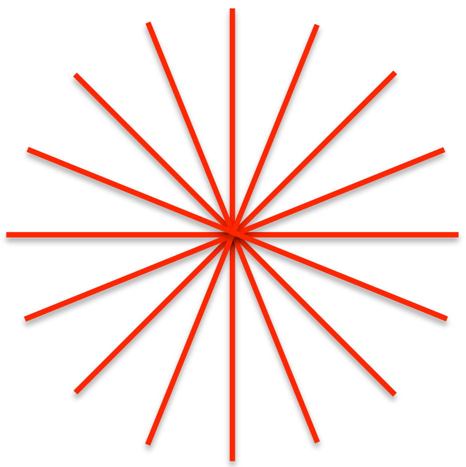
2 centers of projection!

Stereo Panorama

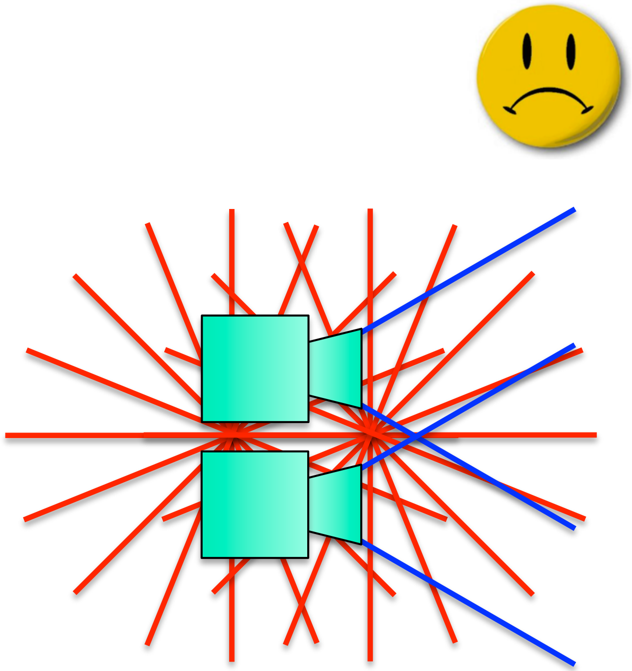
stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama	Stereo	Stereo Panorama
mono & head rotation	stereo & no head rotation	stereo & head rotation



1 center of projection!

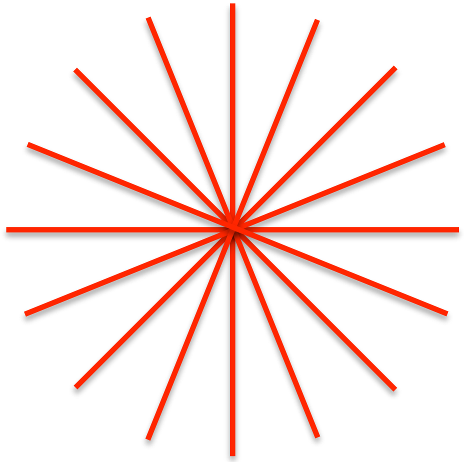


2 centers of projection!

Panorama v Stereo Movie v Stereo Panorama

Panorama

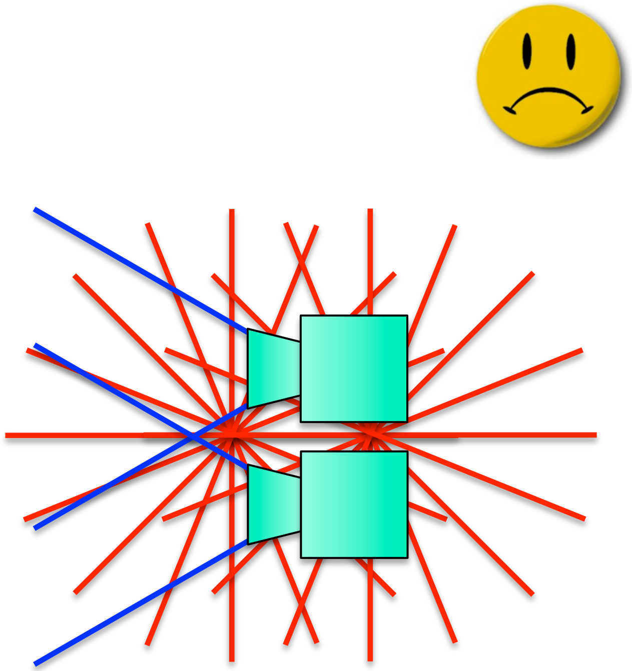
mono & head rotation



1 center of projection!

Stereo

stereo & no head rotation



2 centers of projection!

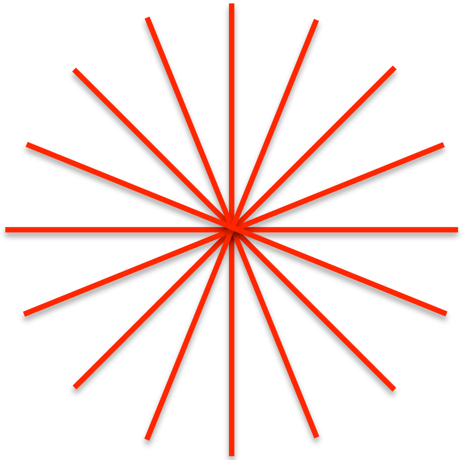
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

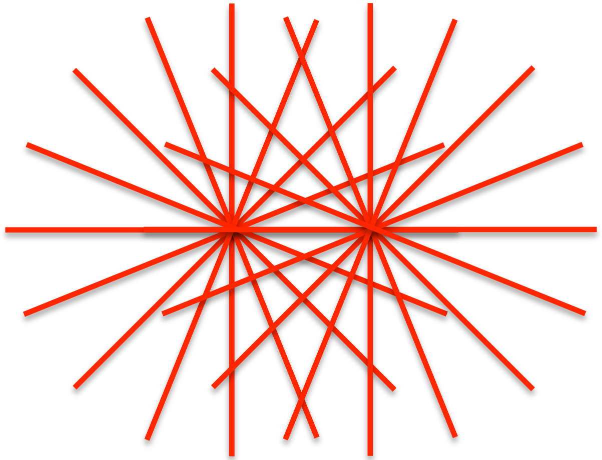
mono & head rotation



1 center of projection!

Stereo

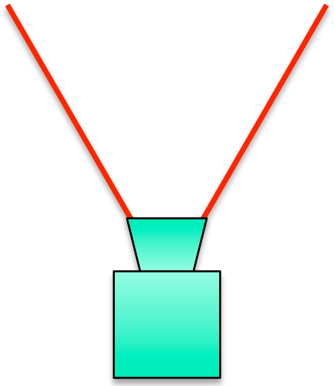
stereo & no head rotation



2 centers of projection!

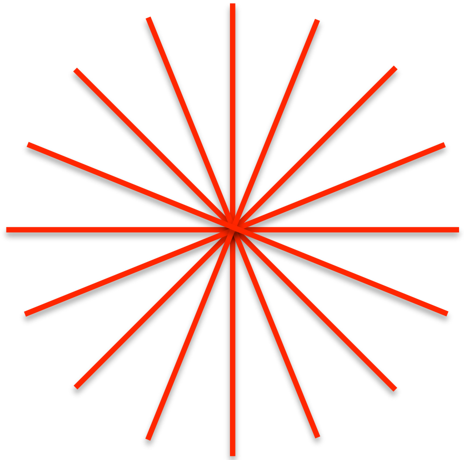
Stereo Panorama

stereo & head rotation

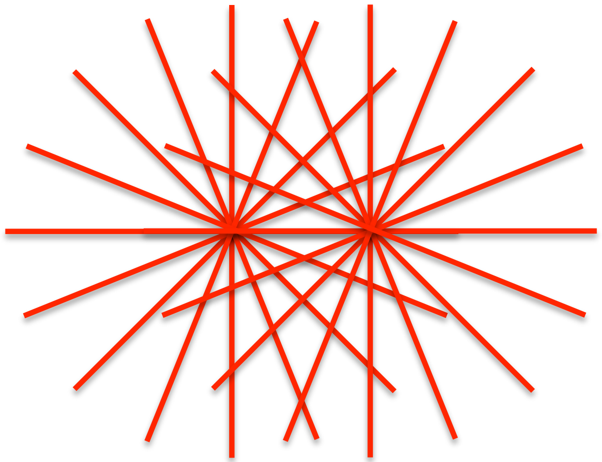


Panorama v Stereo Movie v Stereo Panorama

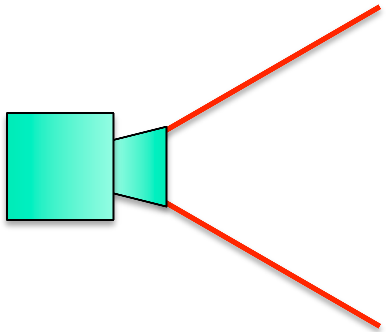
Panorama	Stereo	Stereo Panorama
mono & head rotation	stereo & no head rotation	stereo & head rotation



1 center of projection!



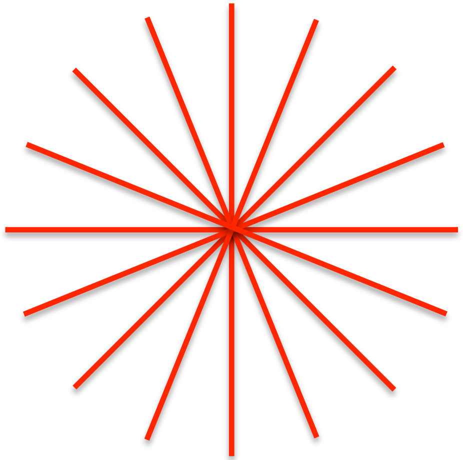
2 centers of projection!



Panorama v Stereo Movie v Stereo Panorama

Panorama

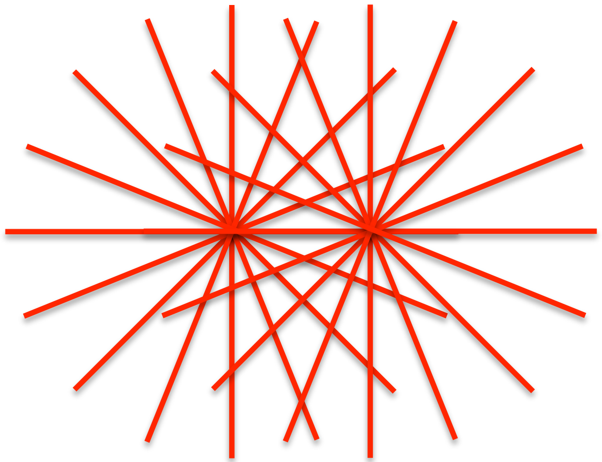
mono & head rotation



1 center of
projection!

Stereo

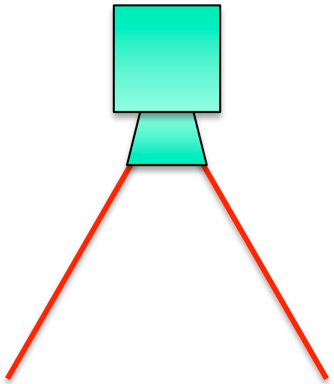
stereo & no head rotation



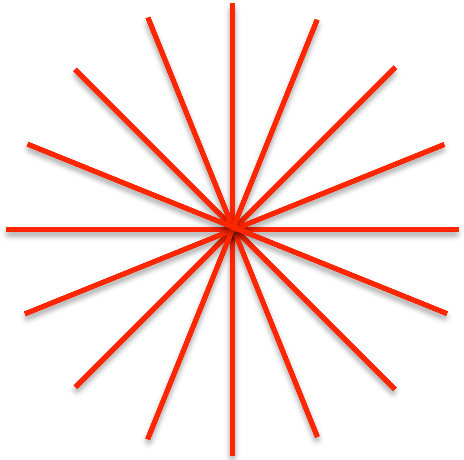
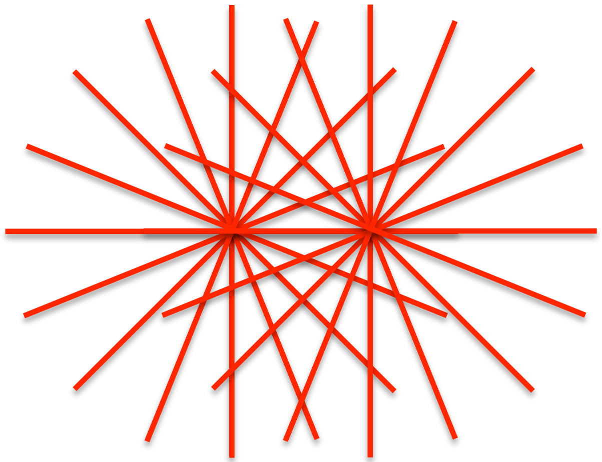
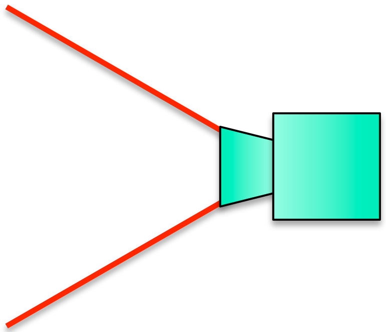
2 centers of
projection!

Stereo Panorama

stereo & head rotation



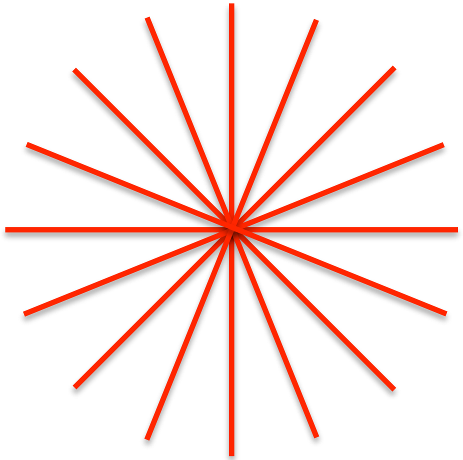
Panorama v Stereo Movie v Stereo Panorama

Panorama	Stereo	Stereo Panorama
mono & head rotation	stereo & no head rotation	stereo & head rotation
		
1 center of projection!	2 centers of projection!	

Panorama v Stereo Movie v Stereo Panorama

Panorama

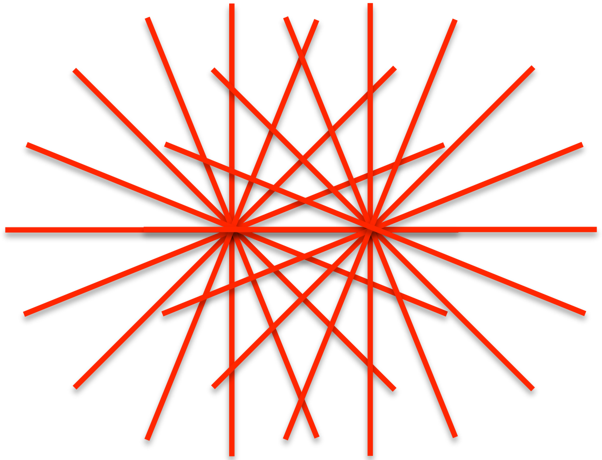
mono & head rotation



1 center of projection!

Stereo

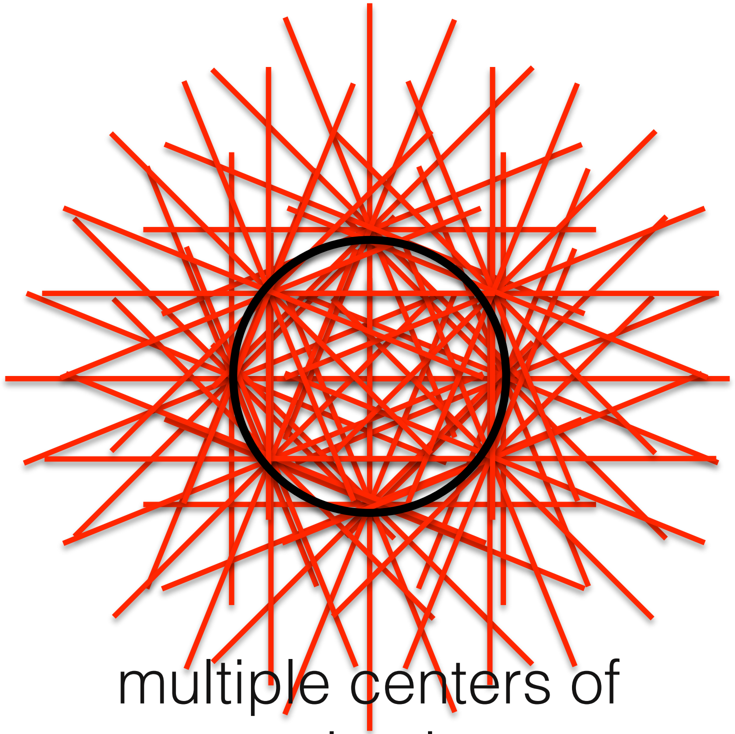
stereo & no head rotation



2 centers of projection!

Stereo Panorama

stereo & head rotation

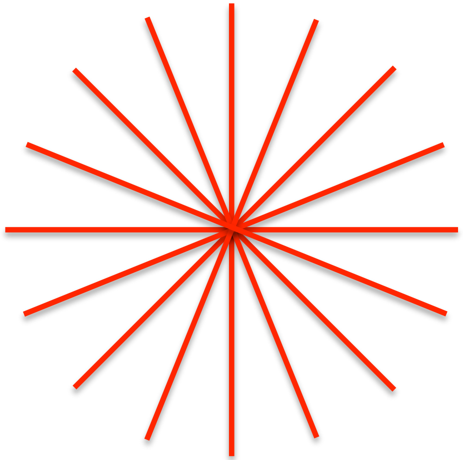


multiple centers of projection

Panorama v Stereo Movie v Stereo Panorama

Panorama

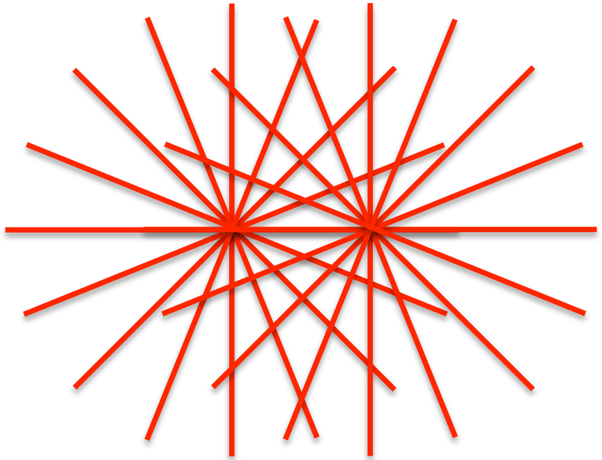
mono & head rotation



1 center of projection!

Stereo

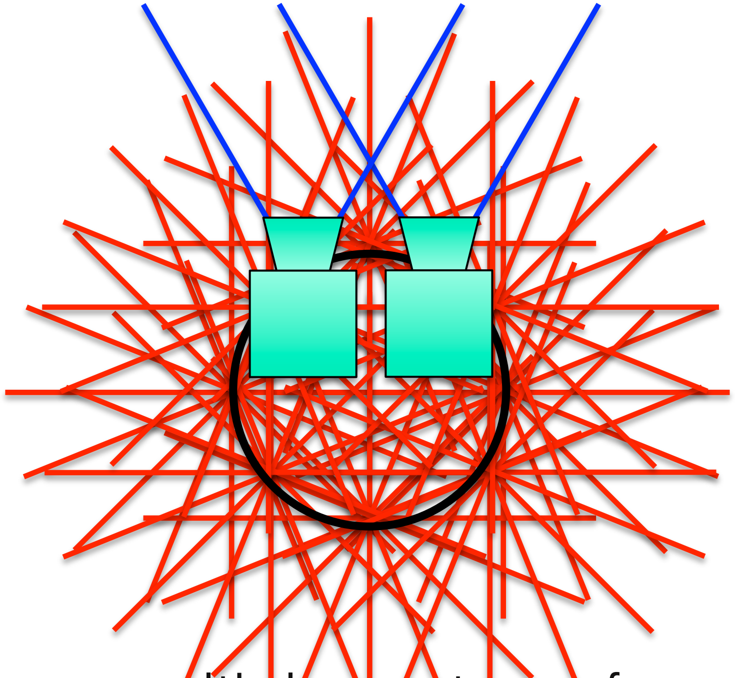
stereo & no head rotation



2 centers of projection!

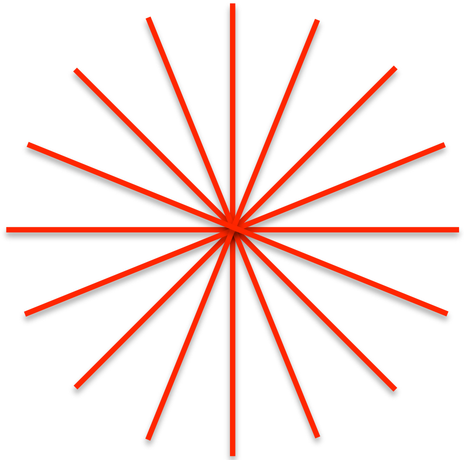
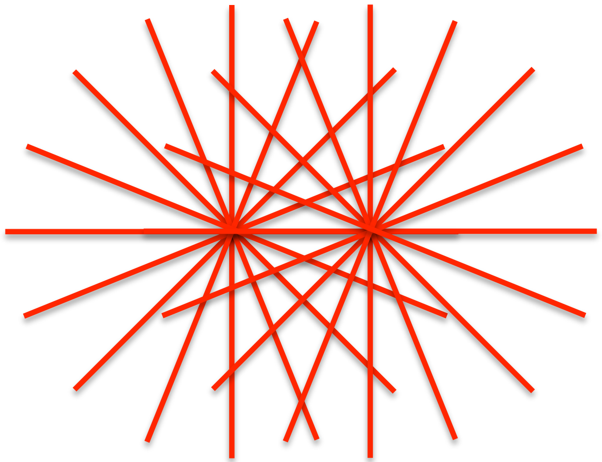
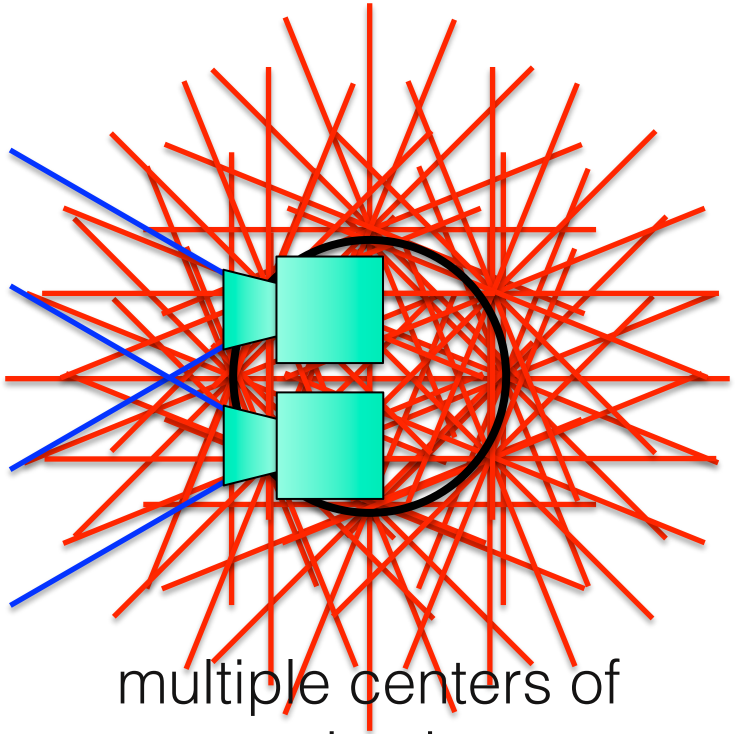
Stereo Panorama

stereo & head rotation



multiple centers of projection

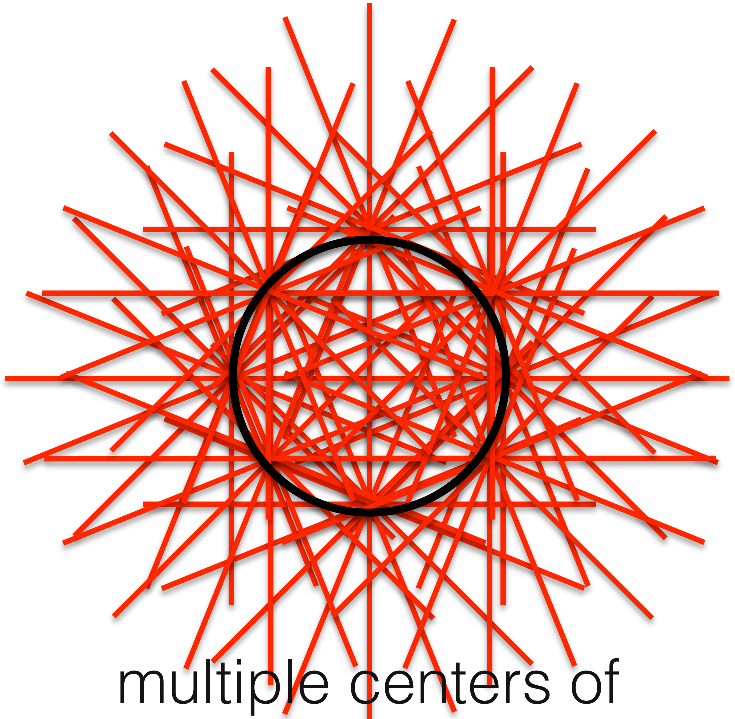
Panorama v Stereo Movie v Stereo Panorama

Panorama	Stereo	Stereo Panorama
mono & head rotation	stereo & no head rotation	stereo & head rotation
		
1 center of projection!	2 centers of projection!	multiple centers of projection

Panorama v Stereo Movie v Stereo Panorama

Stereo Panorama

stereo & head rotation



Light Field!

multiple centers of projection

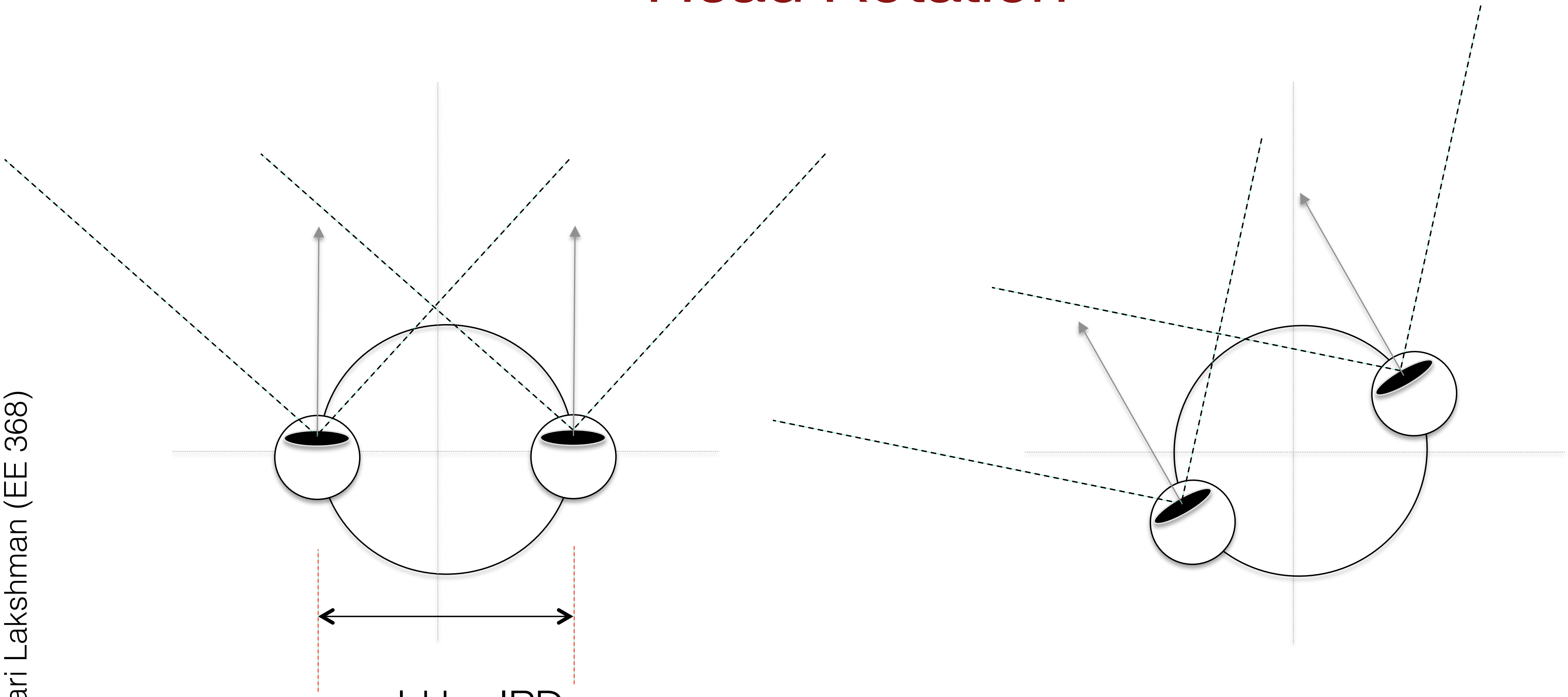
Panorama v Stereo Movie v Stereo Panorama

Panorama	Stereo	Stereo Panorama
mono & head rotation	stereo & no head rotation	stereo & head rotation

Ricoh Theta

horizontal-only parallax

Head Rotation

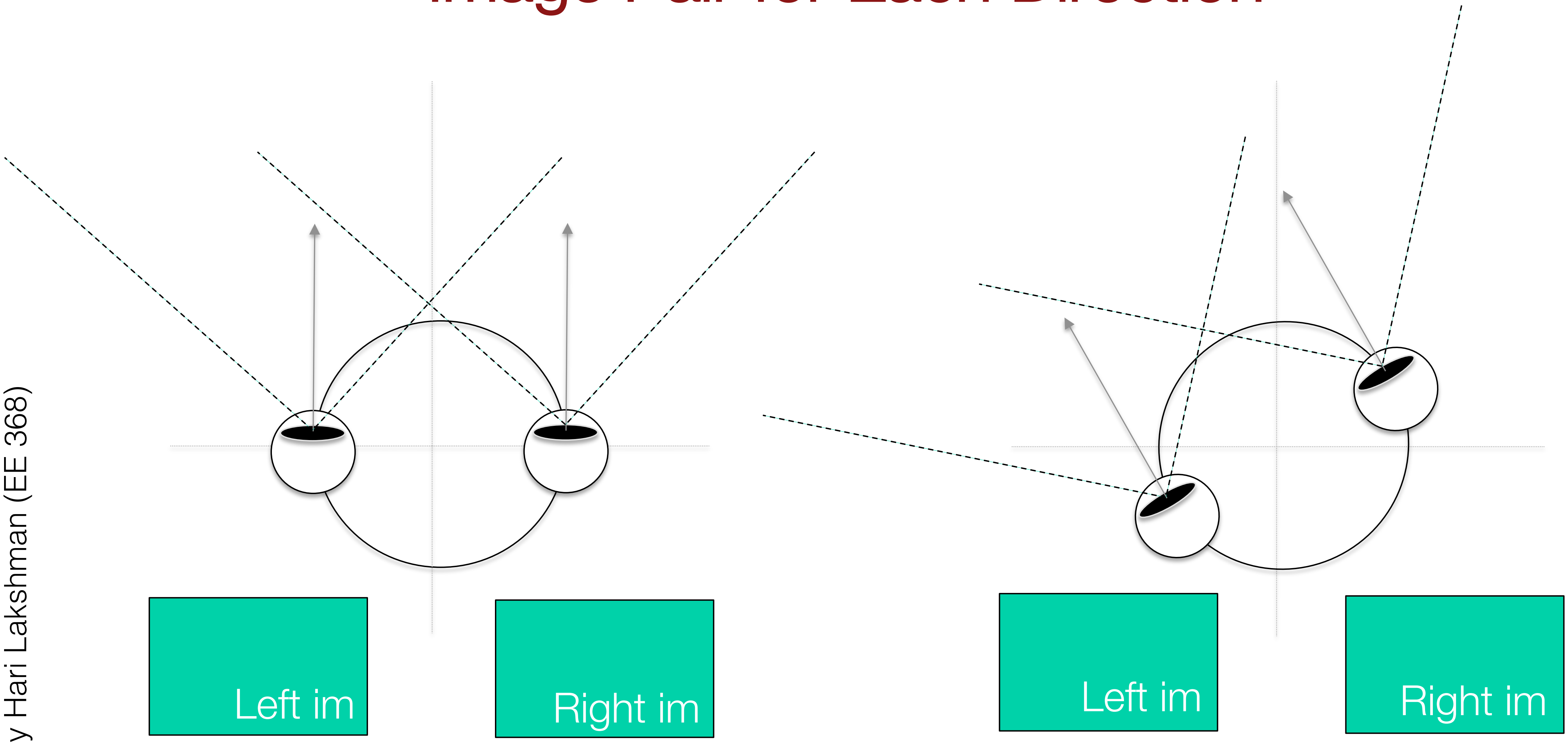


could be IPD
Inter Pupillary Distance

side by Hari Lakshman (EE 368)

Image Pair for Each Direction

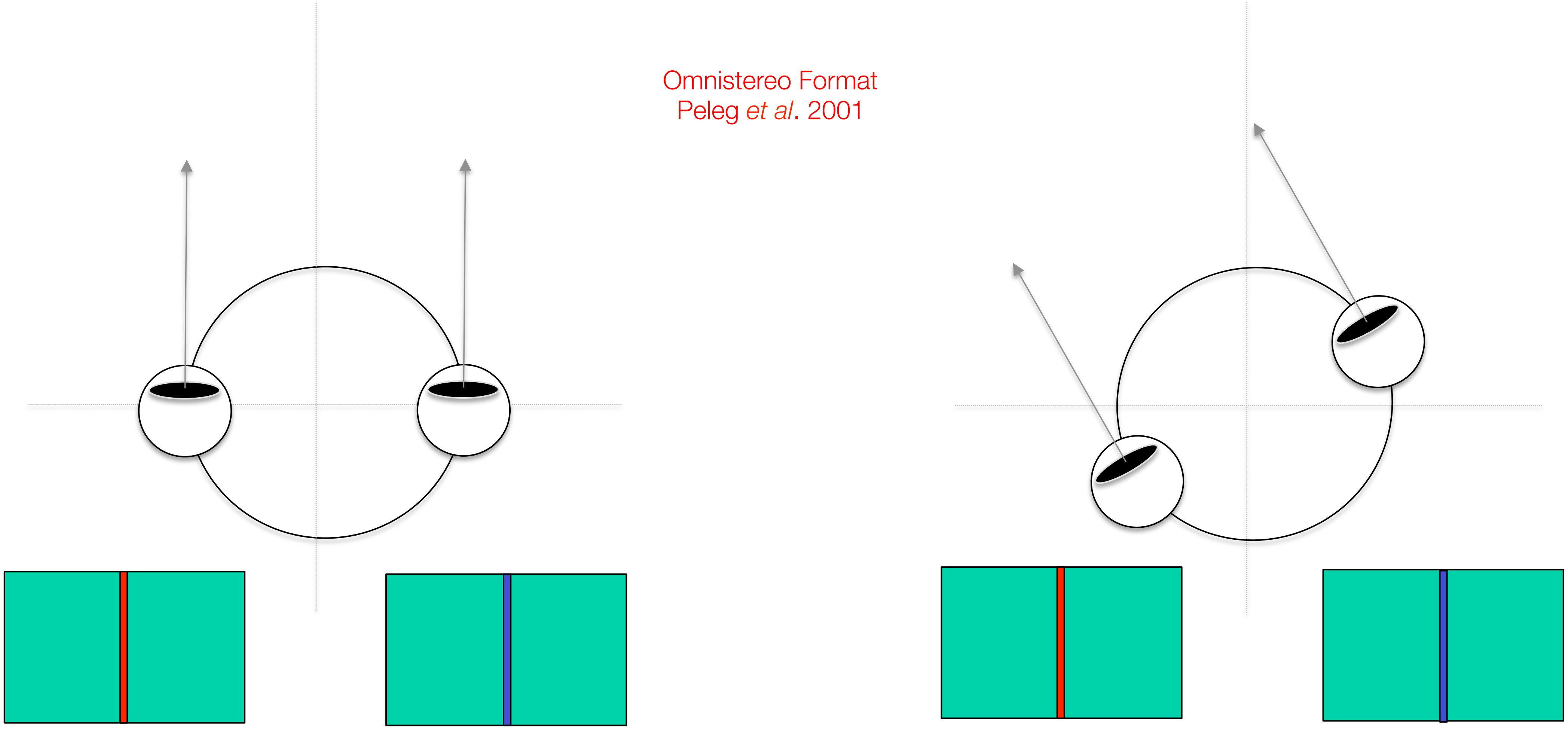
side by Hari Lakshman (EE 368)



Store image pair for each direction → Problem: Too much data

Approximation: Store only Middle Ray

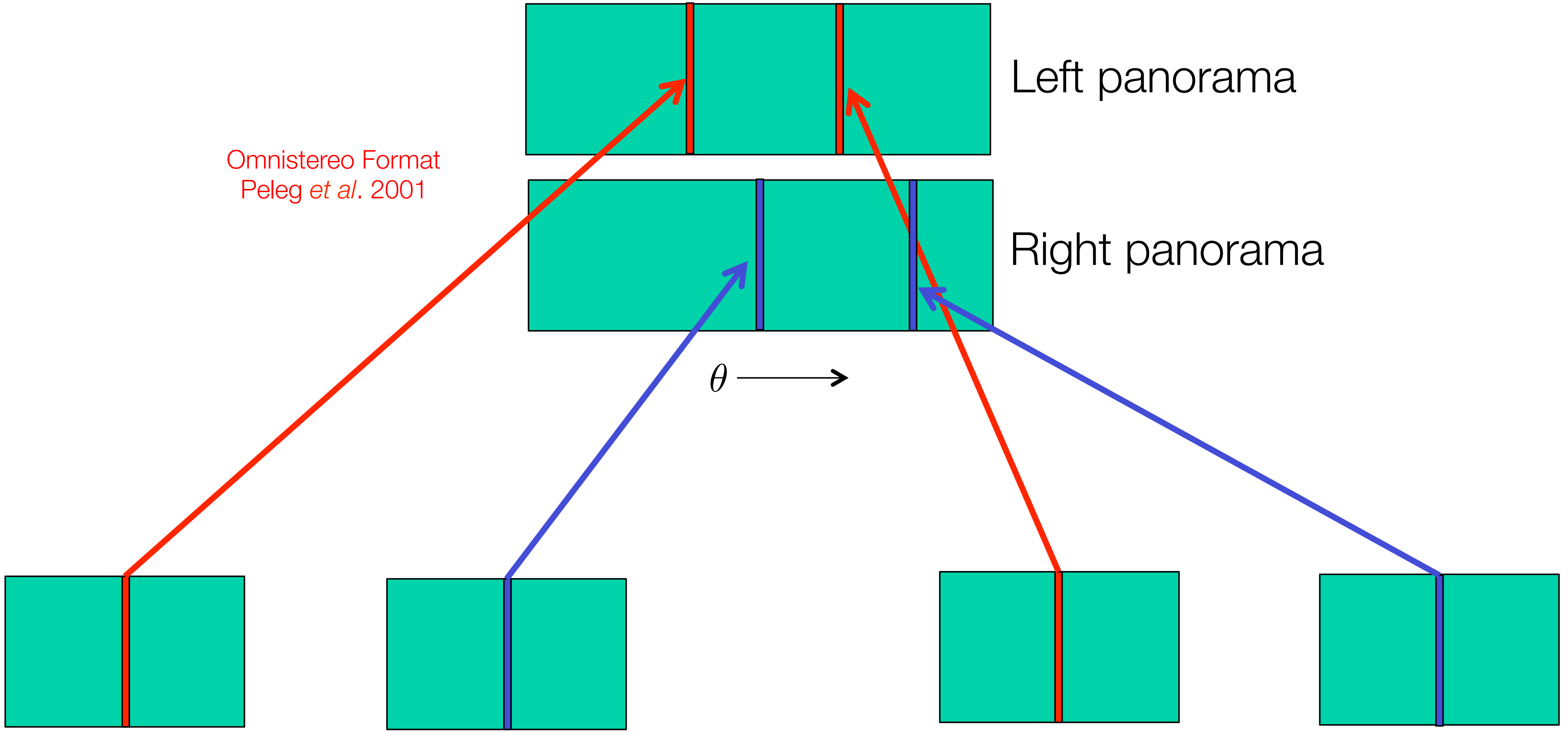
Omnistereo Format
Peleg *et al*. 2001



Approximation: store only middle ray for L and R eyes for each direction

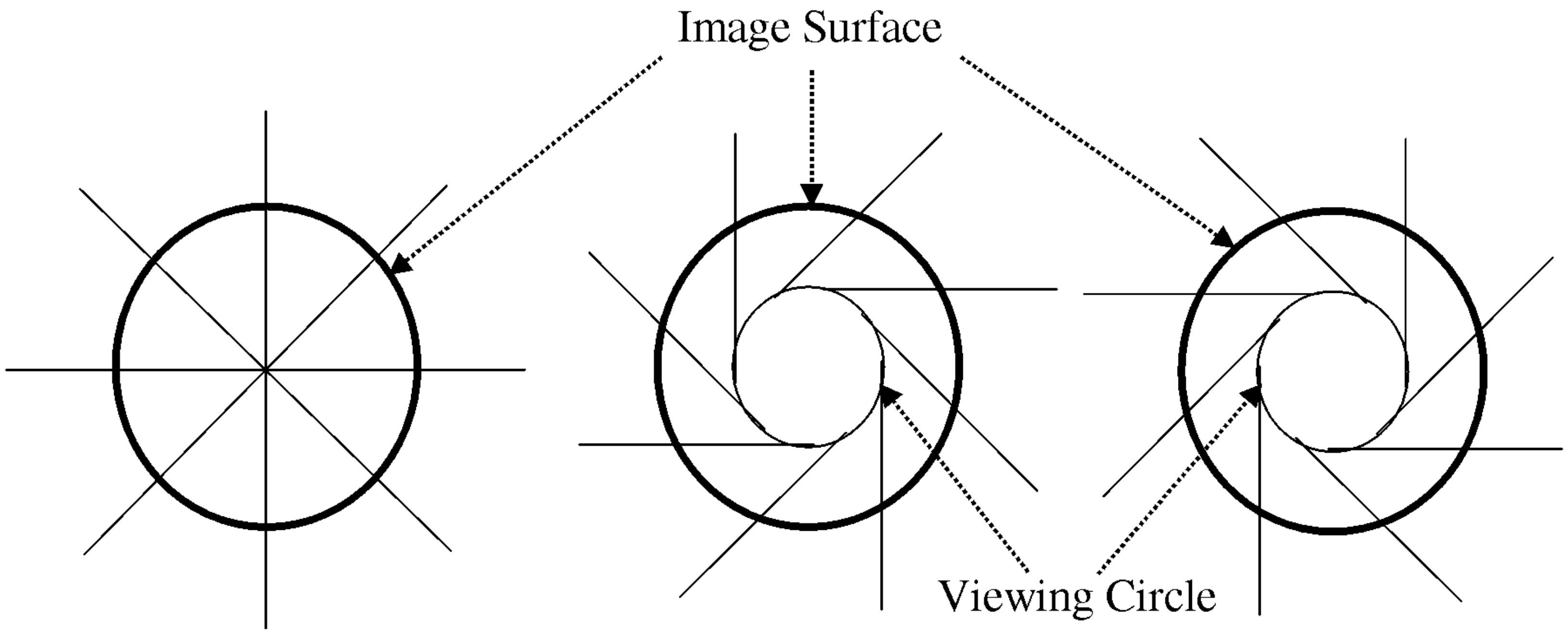
side by Hari Lakshman (EE 368)

Omnistereo Panoramas



side by Hari Lakshman (EE 368)

Comparison: Mono and Stereo Panoramas



Central,
a.k.a. Mono

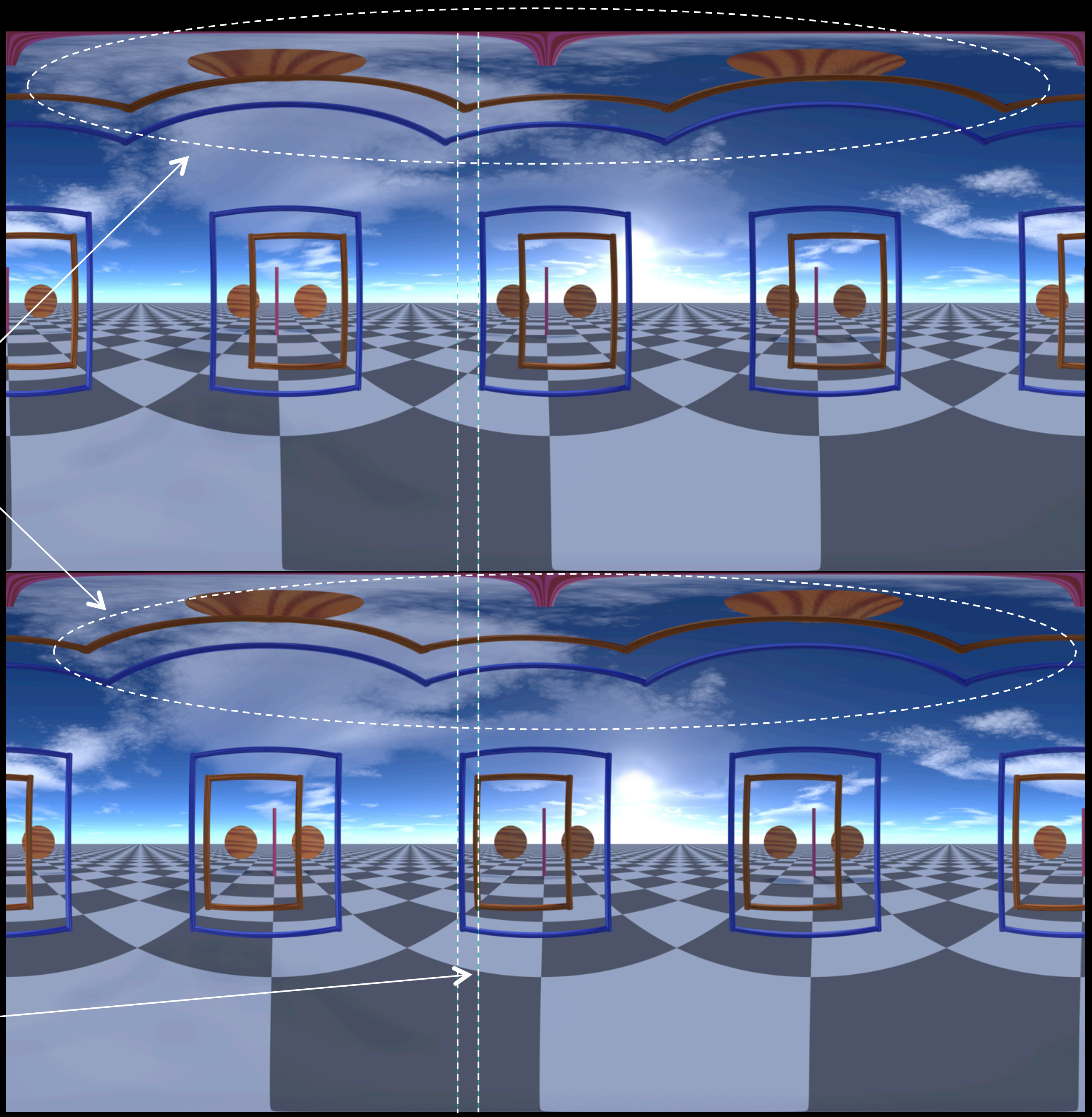
Omnistereo,
Multiperspective

side by Hari Lakshman (EE 368)

Peleg et al. 2001

Omnistereo example

Sphere-to-plane distortions



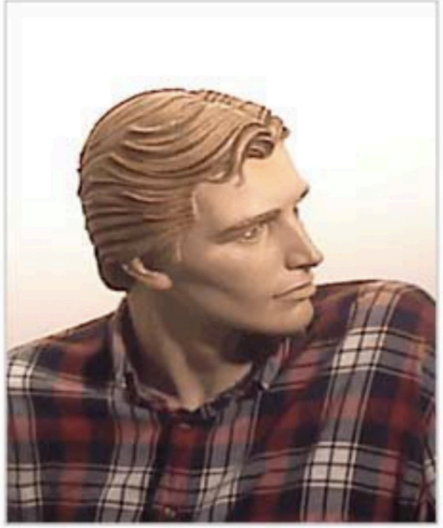
Left panorama

Right panorama

Disparity

side by Hari Lakshman (EE 368)

Multiperspective Projection



Jingyi Yu

Prototype Omnistereo Camera