Epipolar Resampling of Pushbroom Satellite Imagery

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Motivation

Advancing high-resolution commercial satellite technology

- Improving spatial resolution
- Shorter revisit time
- Advanced stereo capabilities
- Improving georeferencing performance

1. Feature extraction
   - Using standard stereo tools (airborne imagery)
2. Airborne image orientation
   - Inexpensive ground control for areas that lack a good geodetic infrastructure
   - Using stereo 3D or mono with DEM (2.5D) for ground control
3. Terrain-based/Image-referenced navigation
   - Alternative technology for GPS denied navigation
   - Reference system with potentially high update rate

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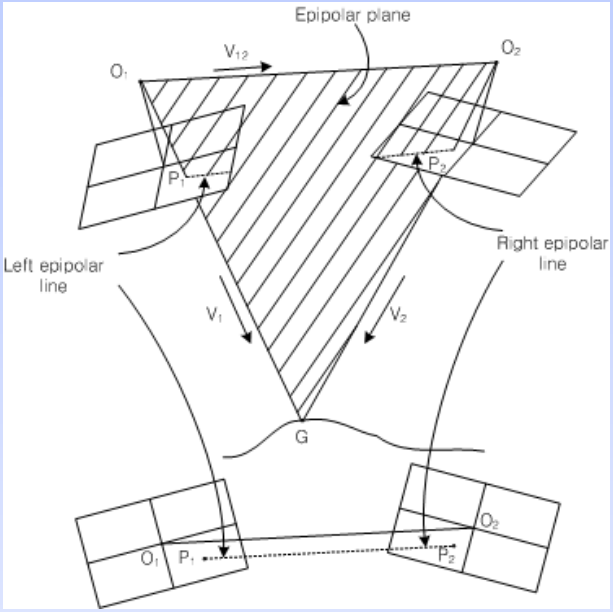
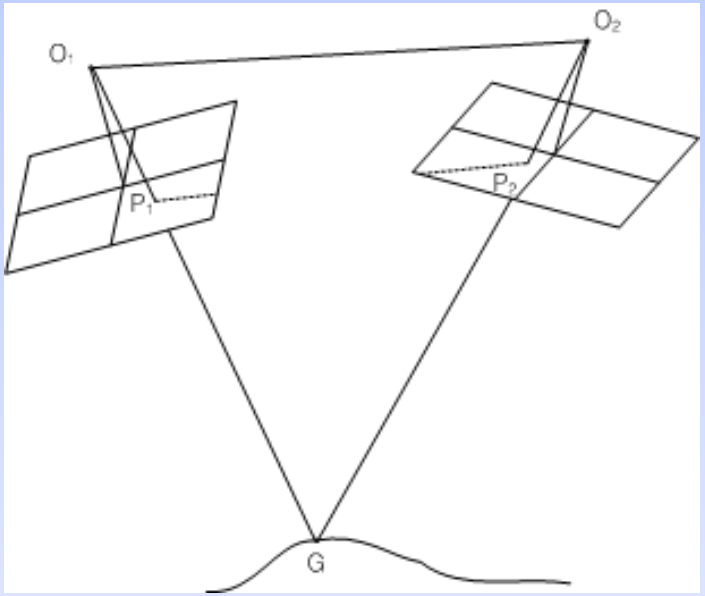
Epipolar Geometry

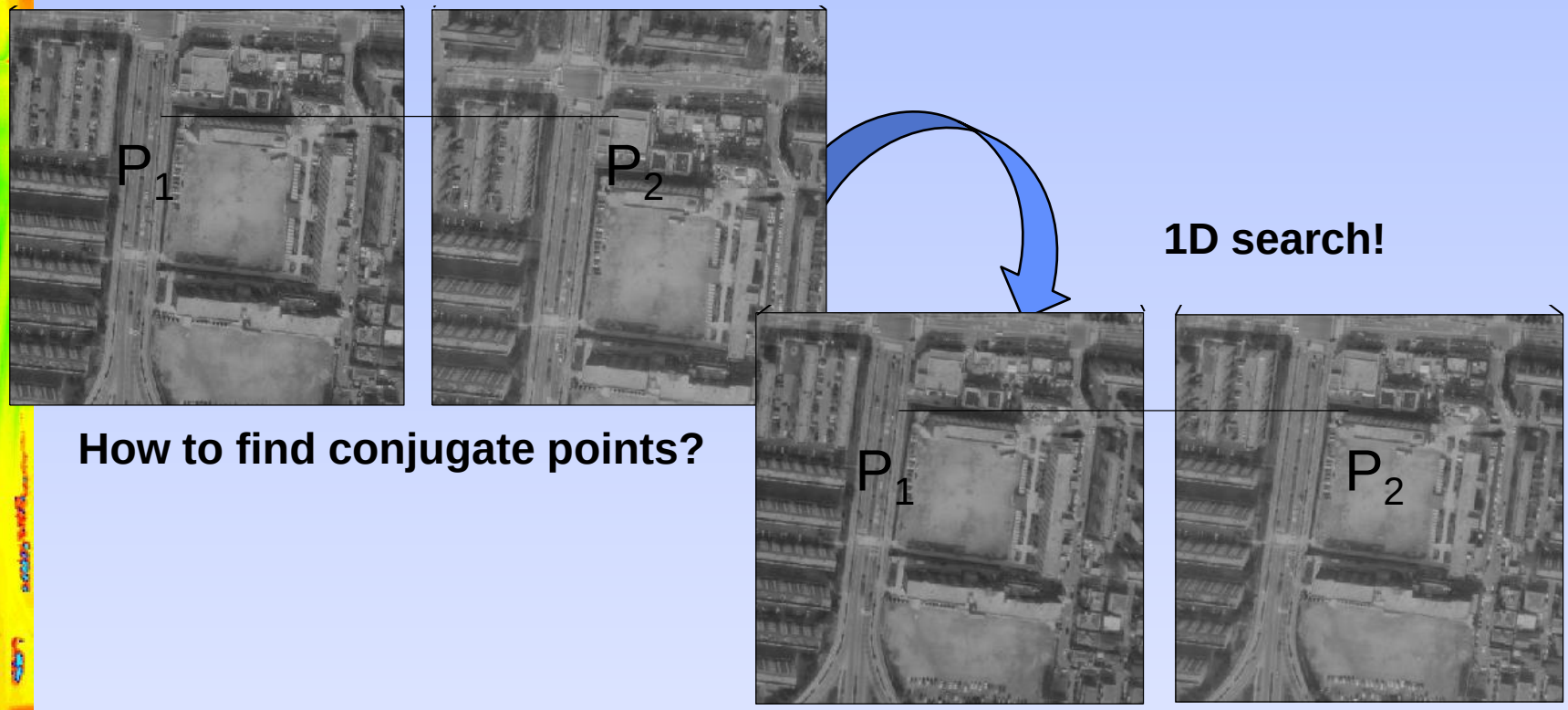
- ✓ Epipolar geometry enables searching regions for conjugate points to be constrained along a single line
- ✓ Epipolar plane: the left and right camera perspective centers, an object point, and the left and right images of the object point lie in a common plane
- ✓ Epipolar line: intersection of the epipolar plane with the left and right photo planes





Epipolar Resampling

- ✓ Epipolar resampling removes all y-parallax and leaves only x-parallax which is directly related to height or elevation.
- ✓ Epipolar lines are parallel to image rows



How to find conjugate points?

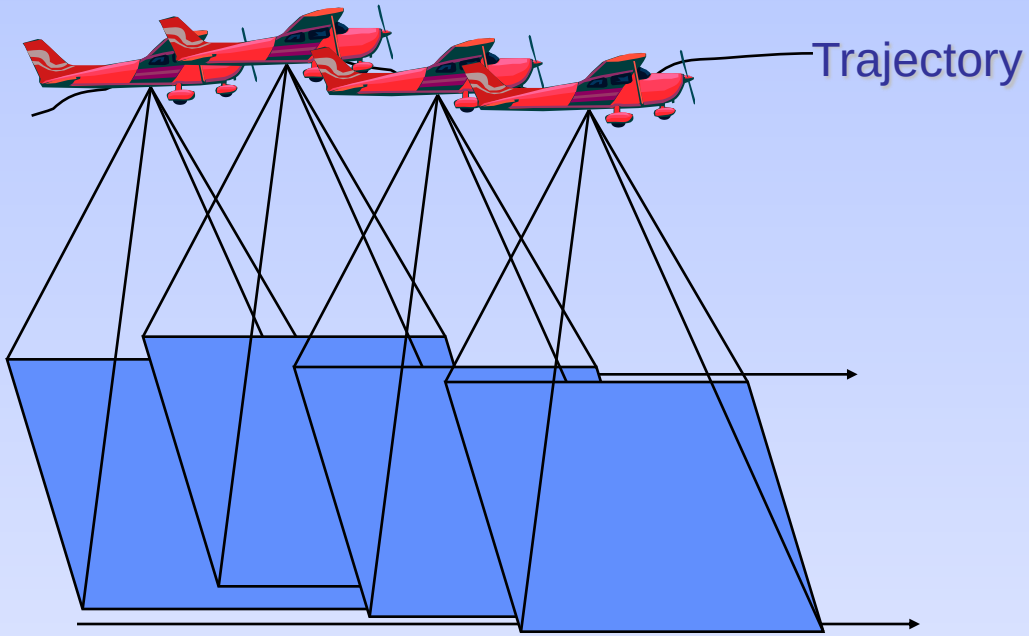
Epipolar Resampled Image

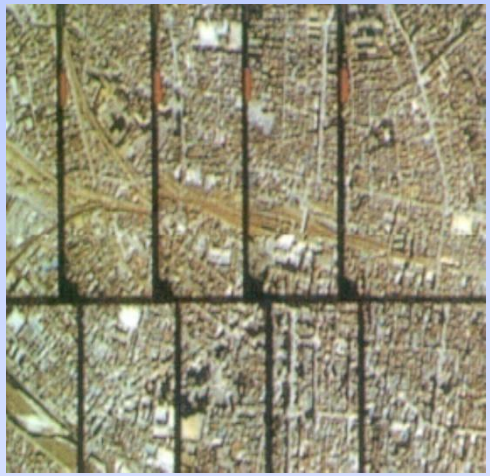
- ✓ Epipolar resampled imagery enables simple 3D displaying and efficient stereo image processing (feature extraction)

A dedicated 3D camera acquires images in epipolar geometry so no resampling is required

Frame Sensor Model

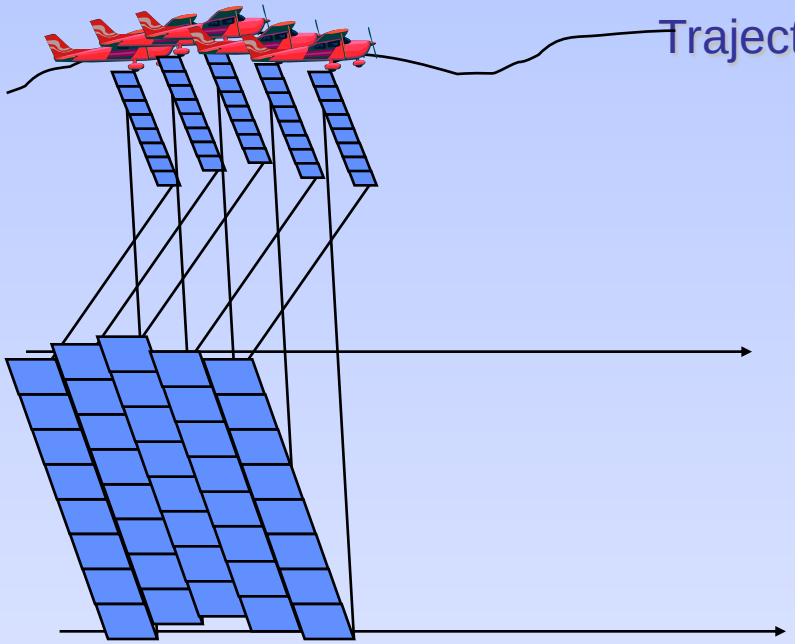
- ✓ Frame: each projection center (one image) has 6 EOPs (exterior orientation parameters)
- ✓ Produces a number of images with large footprint and strong geometry

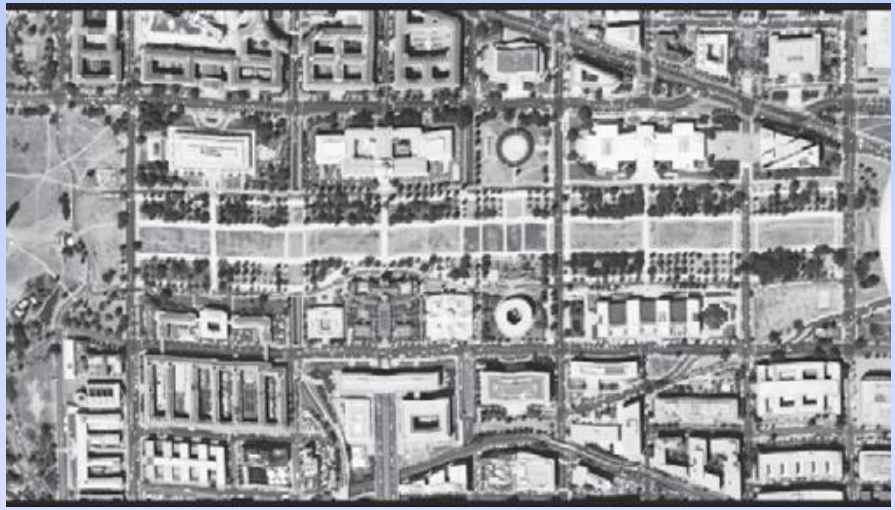




Pushbroom Sensor Model

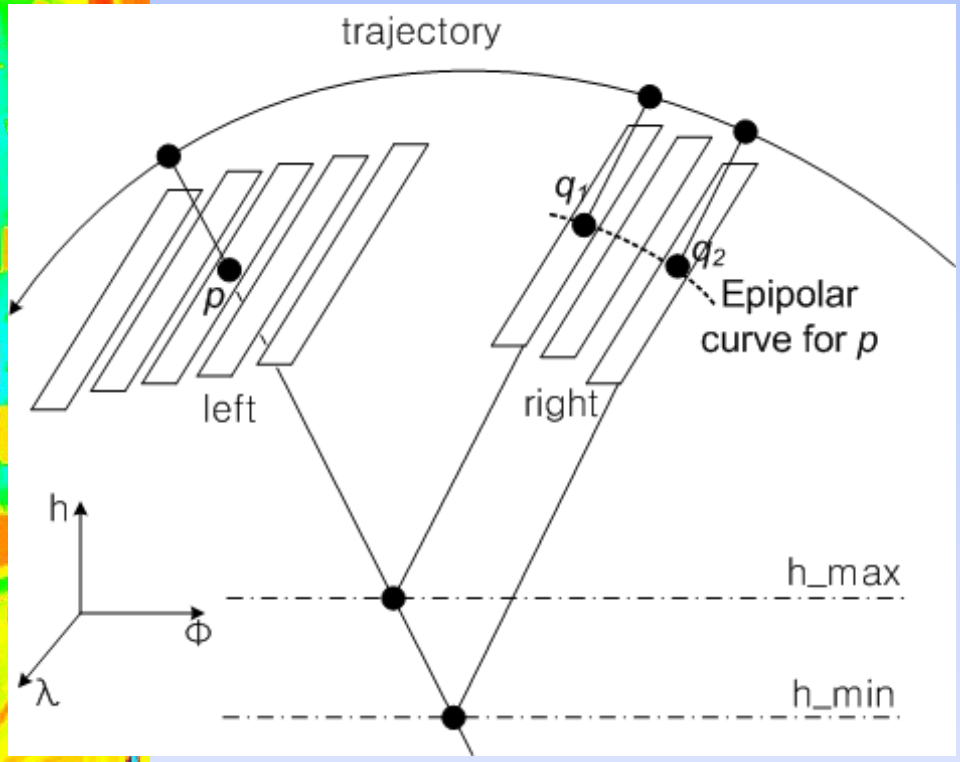
- ✓ Pushbroom: each image projection has 6 EOPs, i.e. one image has "6 x number of lines" unknown parameters
- ✓ Produce single image "carpet", weak geometry

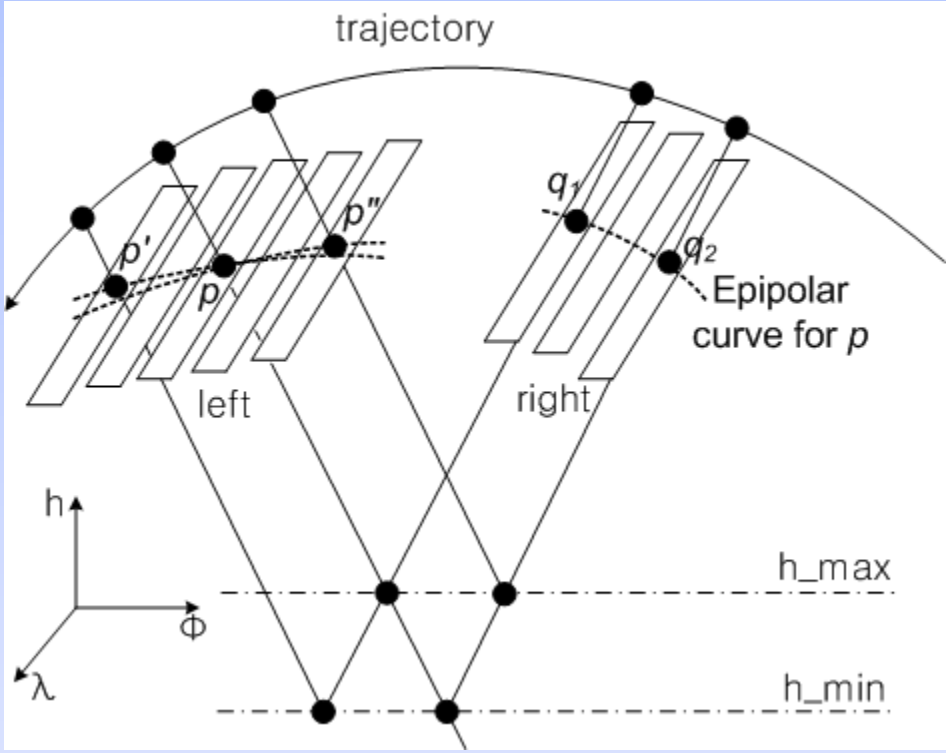




Epipolar Geometry of Pushbroom Sensor

- ✓ 1. The pushbroom sensor does not produce straight epipolar lines, but hyperbolic-like shape
- ✓ 2. No epipolar pair does exist for the entire scene

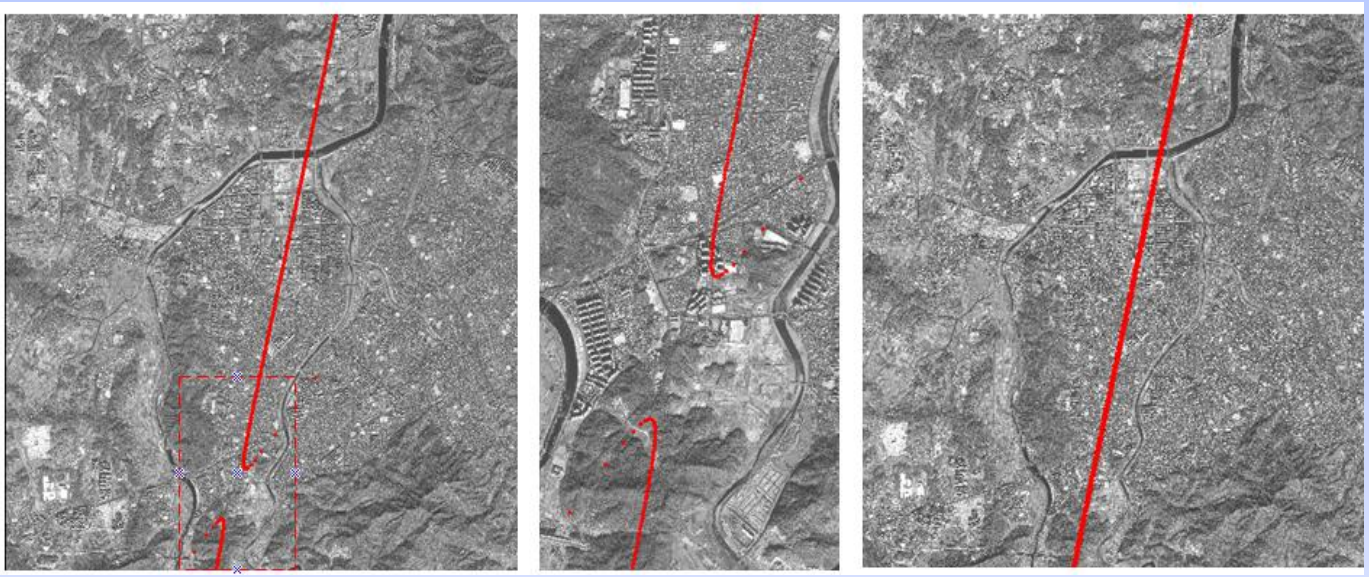




Epipolar Geometry of Pushbroom Sensor

- ✓ The epipolar curve on the right image from the left image center point is computed based on RPC by incrementing the ground height by 50m from -10,000 m to +10,000 m

  (RPC: Rational Polynomial Coefficient, replacement sensor model most widely used for high-resolution satellite imagery)



(a) (b) (c)

Epipolar curve shape from RPC; (a) hyperbolic shaped curve, (b) magnified curve, and (c) shape changed after RPC accuracy increased

Epipolar Curve Straightness Test

- ✓ A straight line fitting to epipolar curve points is performed to characterize the straightness of the curve depending on the ground height range
- ✓ The epipolar curve could be approximated with straight lines at sub-pixel accuracy for a local image scene

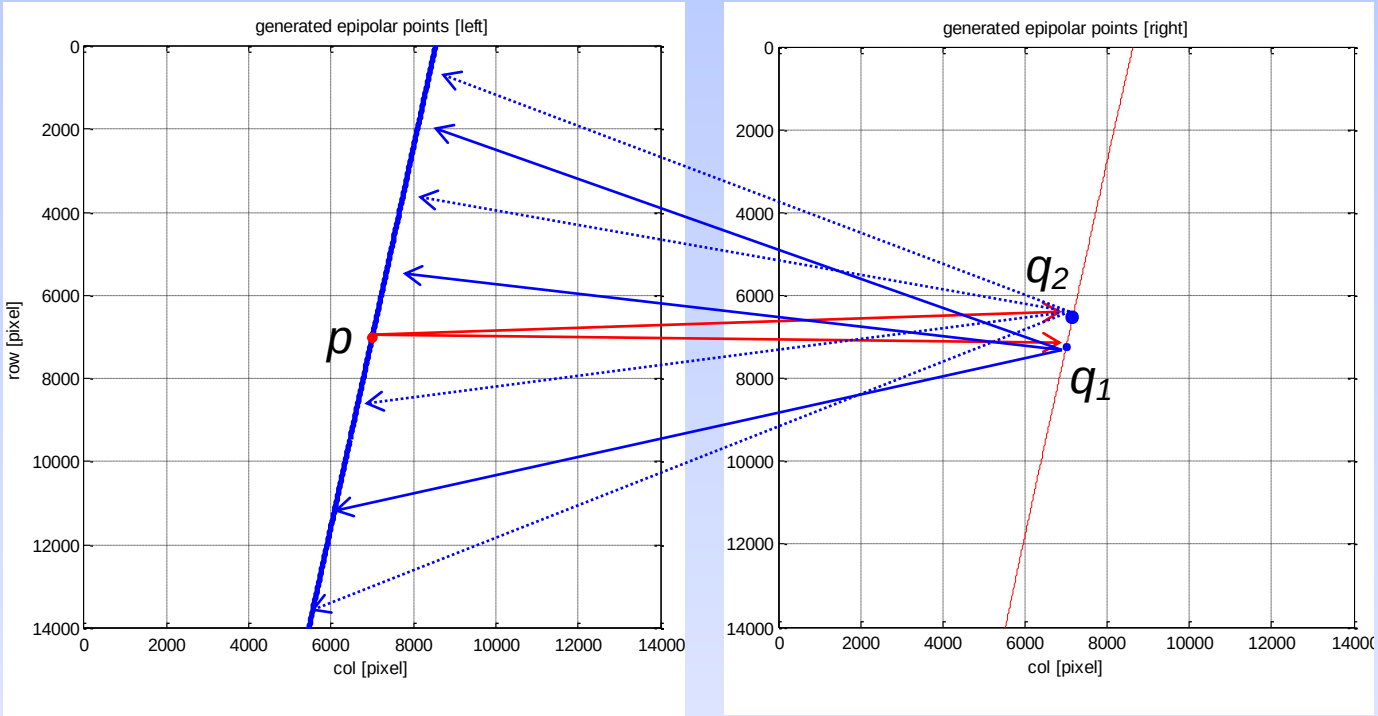
Straight line fitting, residuals of local epipolar curves in orthogonal direction

Height range [m]	**0 – 1,000**	**0 – 2,000**	**0 – 3,000**	**0 – 5,000**	0 – 10,000
Mean [pixel]	**0.00**	**0.02**	**0.05**	**0.22**	1.76
Max [pixel]	**0.01**	**0.05**	**0.15**	**0.66**	5.56

Height range is large enough considering general terrain height range

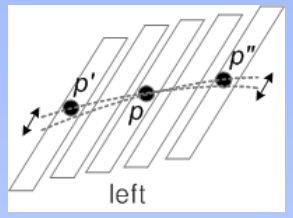
Epipolar Curve Pair Test

- ✓ Two image points, q_1 and q_2, on the right image, which correspond to the left image point *p,* with ground height of 0m and 1000m, respectively, are selected along the epipolar curve
- ✓ Epipolar curves for q_1 and q_2 are generated using ground height range of -15,000m – +15,000m

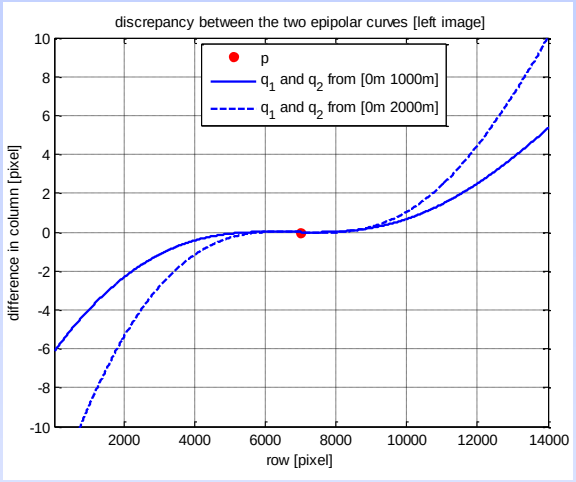


Epipolar Curve Pair Test

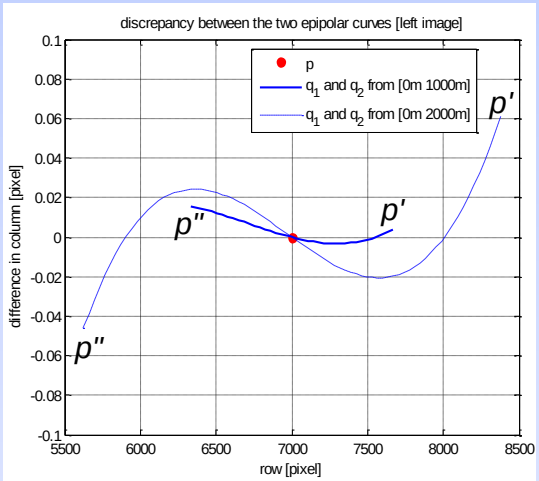
- ✓ The discrepancy between the two curves in the column direction is computed



- ✓ The nonexistence of the global epipolar curve pair can be identified
- ✓ For a given local height range, two epipolar curves can be approximated as a single epipolar curve



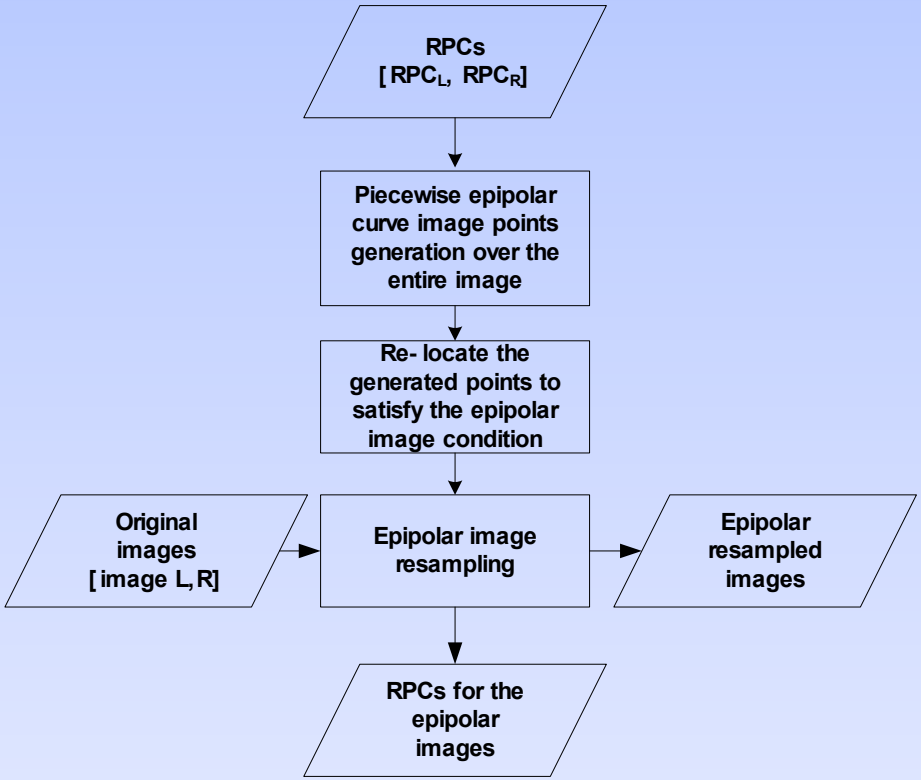
Discrepancy for the global scene



For the local area determined by the ground height range

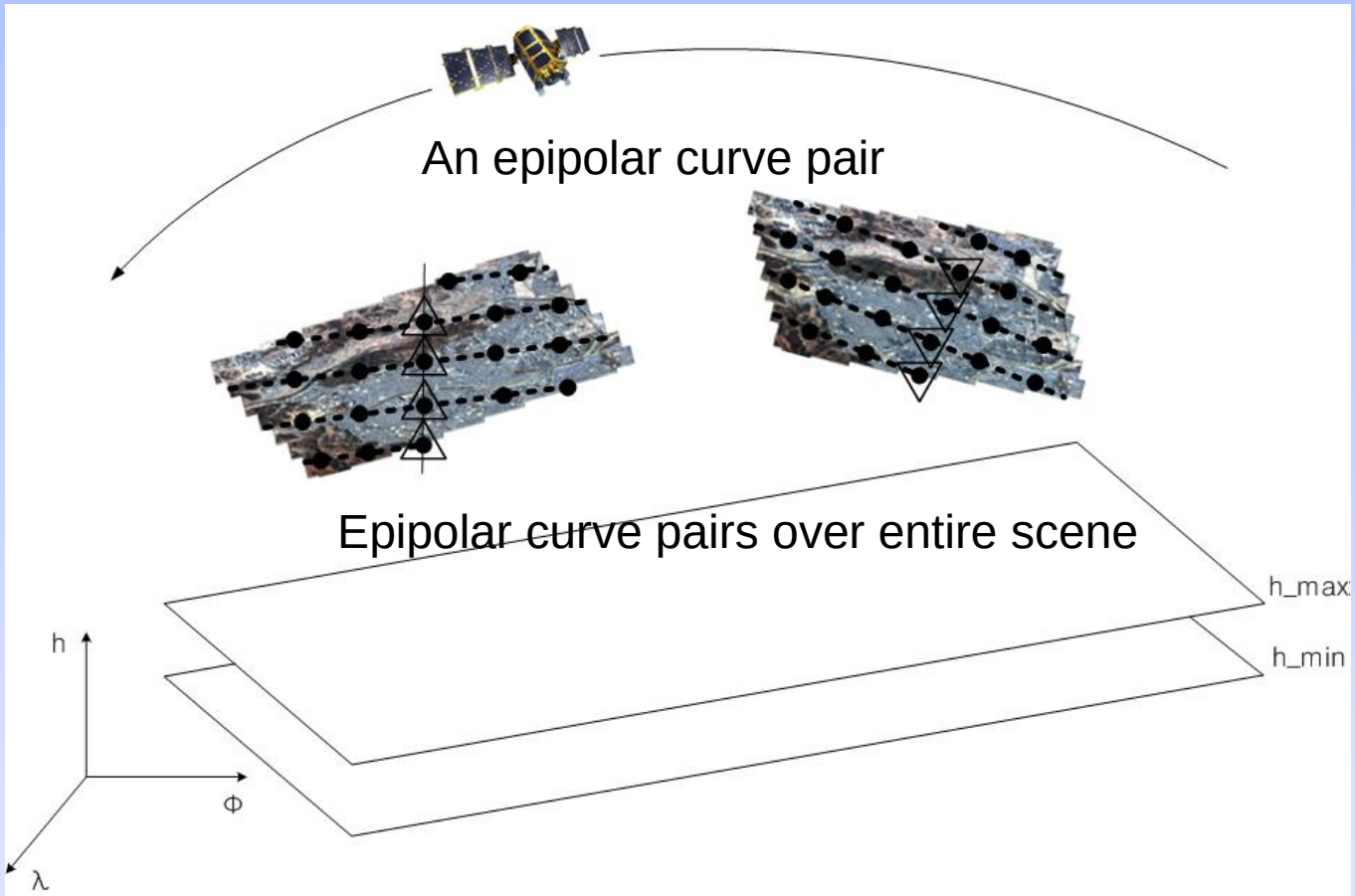
Proposed Epipolar Resampling

- ✓ The epipolar resampling consists of three steps:
  1. Generation of the epipolar curve points
  2. Reassignment of the points to satisfy the epipolar image conditions
  3. The image transformation (image resampling)



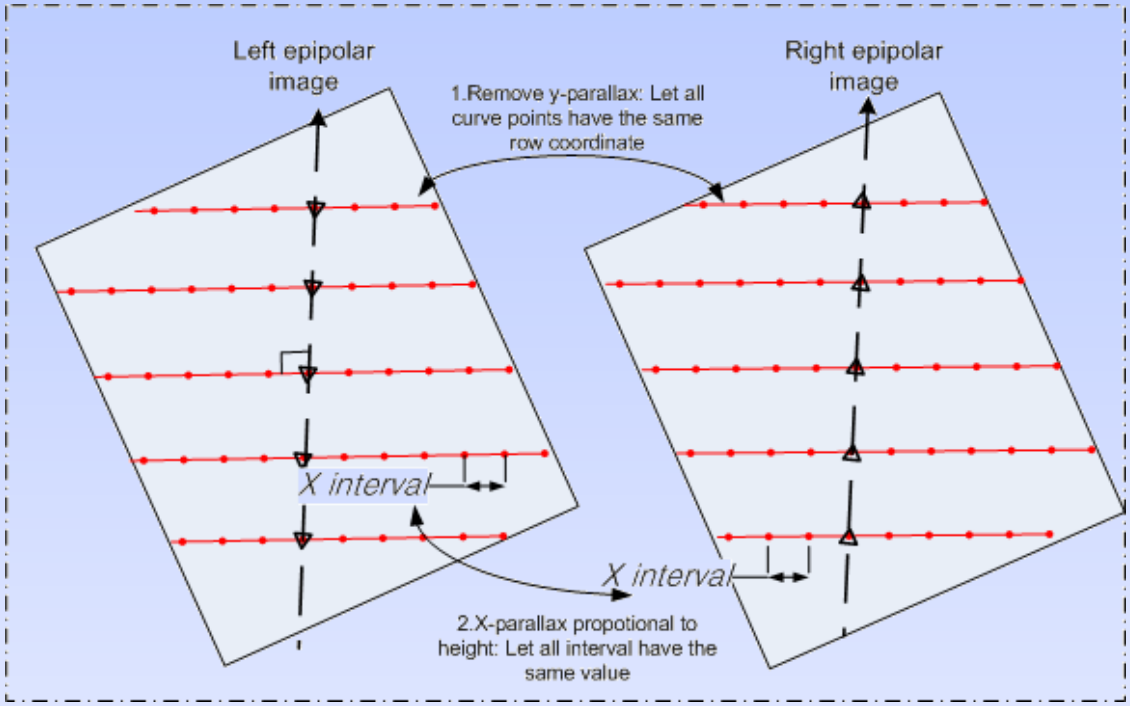
(1) Piecewise Epipolar Curve Generation

- ✓ Based on the finding that epipolar curve pairs exist for local areas defined by the ground height range, a piecewise epipolar curve generation is proposed



(2) Curve Point Reassignment

- ✓ Starting points ($\triangle, \bigtriangledown$) are aligned along y-direction in the epipolar resampling domain because the y-axis should be orthogonal to the trajectory
- ✓ Identical y-coordinates are assigned to each curve pair to remove y-parallax
- ✓ Fixed x-interval is introduced that the x-parallax is linearly proportional to the ground height



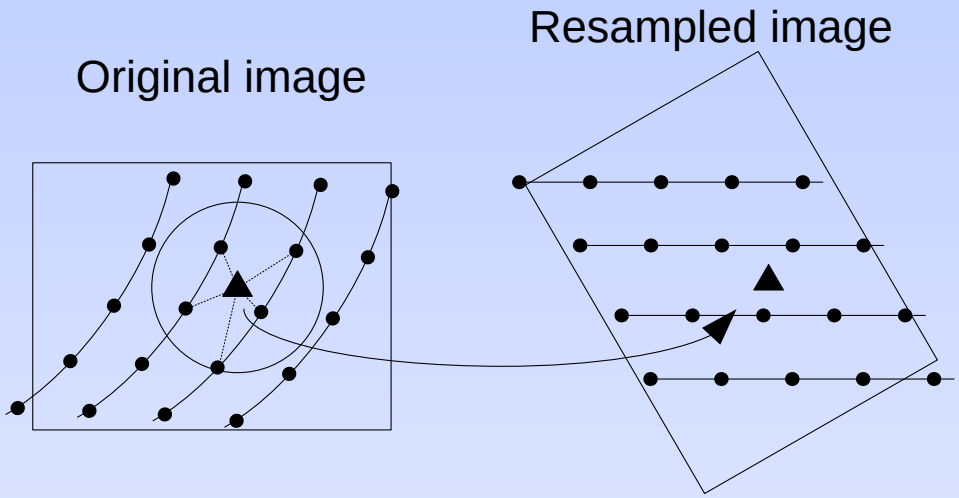
(3) Transformation

- Transformation should account for curve-to-straight-line transform (obviously, affine model cannot be used)
- Polynomial transformation or interpolation can be used
  - Polynomial transformation

$$x' = a_1 + a_2 x + a_3 y + a_4 x^2 + a_5 xy + a_6 y^2 + \ldots$$

$$y' = b_1 + b_2 x + b_3 y + b_4 x^2 + b_5 xy + b_6 y^2 + \ldots$$

  - Interpolation

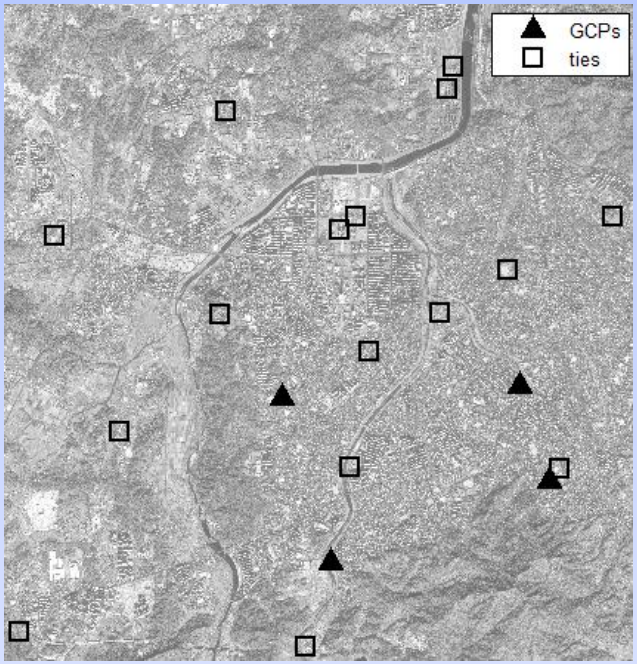


Interpolation for the epipolar resampling

Experiment

- ✓ IKONOS stereo images, acquired Nov 11, 2001
- ✓ The product level of each image is Level 2 Geo, which has a 50m horizontal positional accuracy at a 90% confidence level
- ✓ Four GCPs and 16 image tie points were measured

Site Satellite	Daejeon, Korea	
Image	IKONOS Level 2 Stereo Geo	
	Left Image	Right Image
Acquisition date	2001-11-19 02:19 GMT	2001-11-19 02:18 GMT
Image size	14336×13816	13824× 13816



Distribution of GCPs and tie points

RPC Accuracy Improvement

- IKONOS RPCs are refined by estimating only shift terms, i.e. A_0 and B_0, from four GCPs

$$l + A_0 + A_1 l + A_2 s = \frac{Num_L(U,V,W)}{Den_L(U,V,W)} L_s + L_0$$

$$s + B_0 + B_1 l + B_2 s = \frac{Num_s(U,V,W)}{Den_s(U,V,W)} S_s + S_0$$

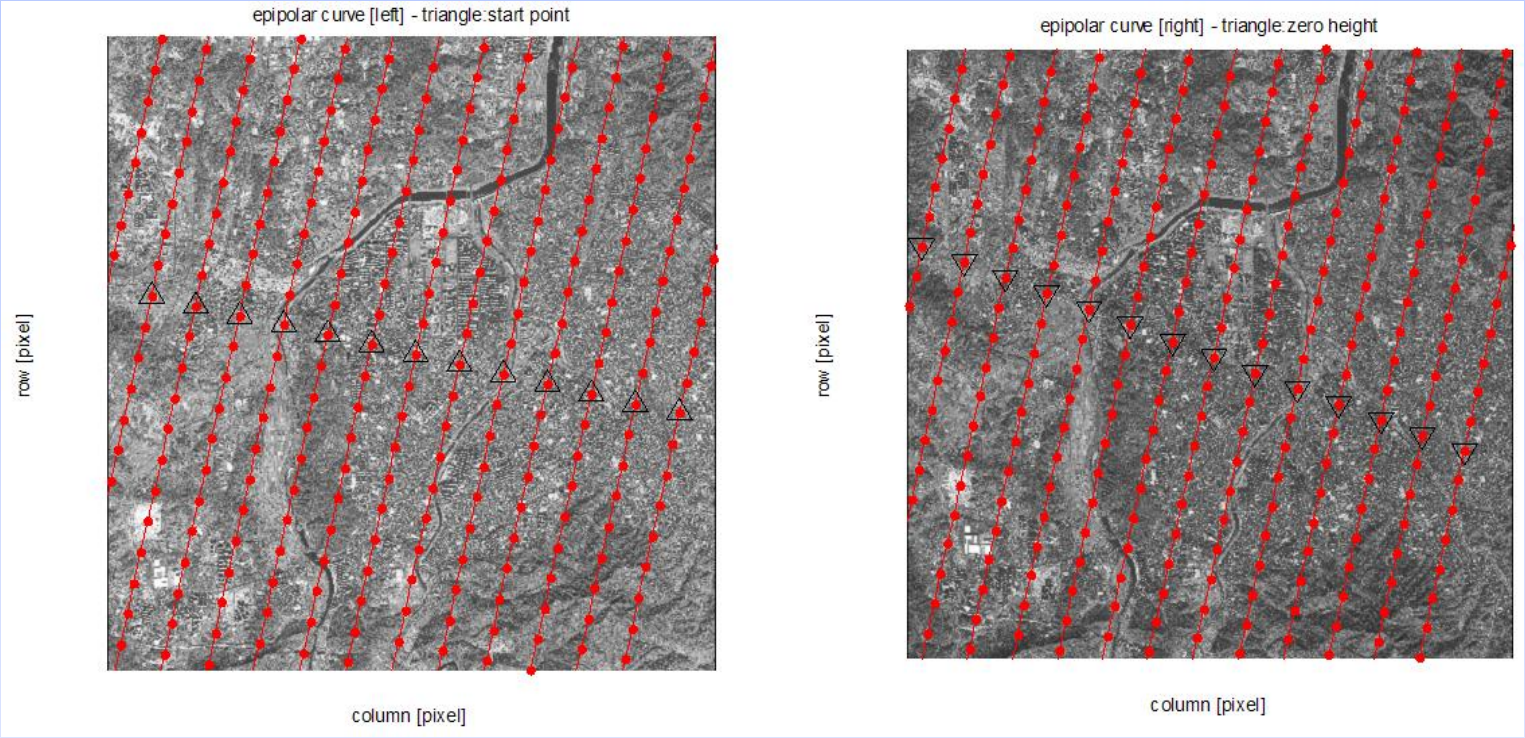
where, $A_0, A_1, \ldots, B_2$ are the image adjustment parameters

- RPC refinement improved accuracy to sub-pixel level for 4 GCPs

RPC RMS [pixels]		Before the update	After the update
Left	Row	25.6	0.8
	Column	8.3	0.8
Right	Row	1.7	0.8
	Column	5.5	0.5

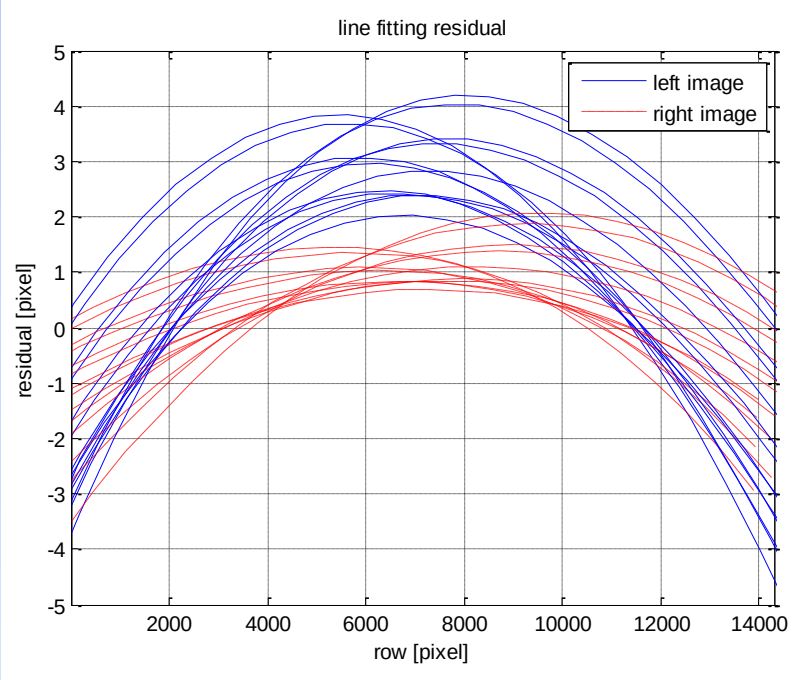
Piecewise Epipolar Curve Point Generation

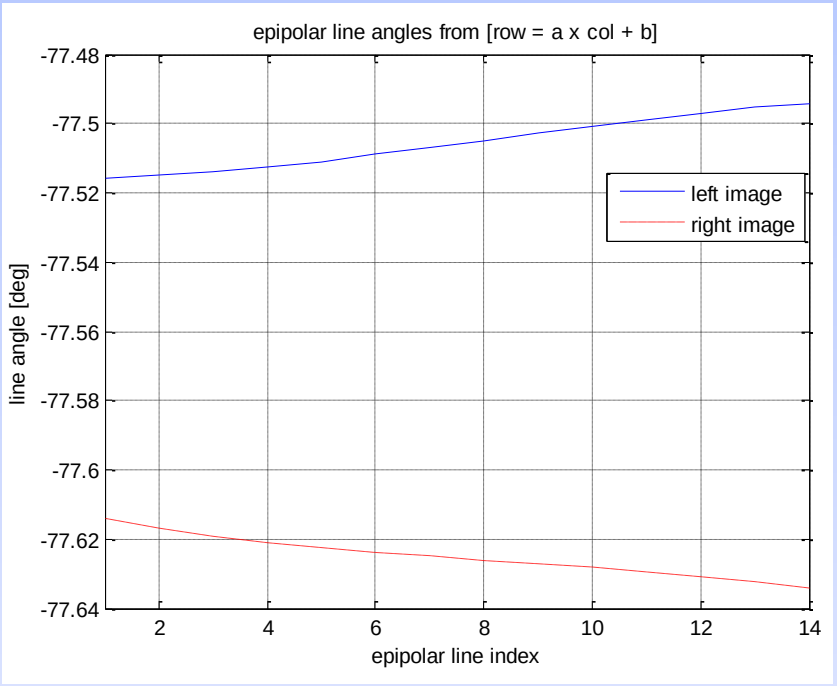
- ✓ Epipolar curve points are generated using the height interval of 0m and 1000m (large enough to account for the ground height variations)
- ✓ The triangles on the image indicate the starting point locations and the dots are the piecewise generated epipolar curve points



Property of Generated Epipolar Curves

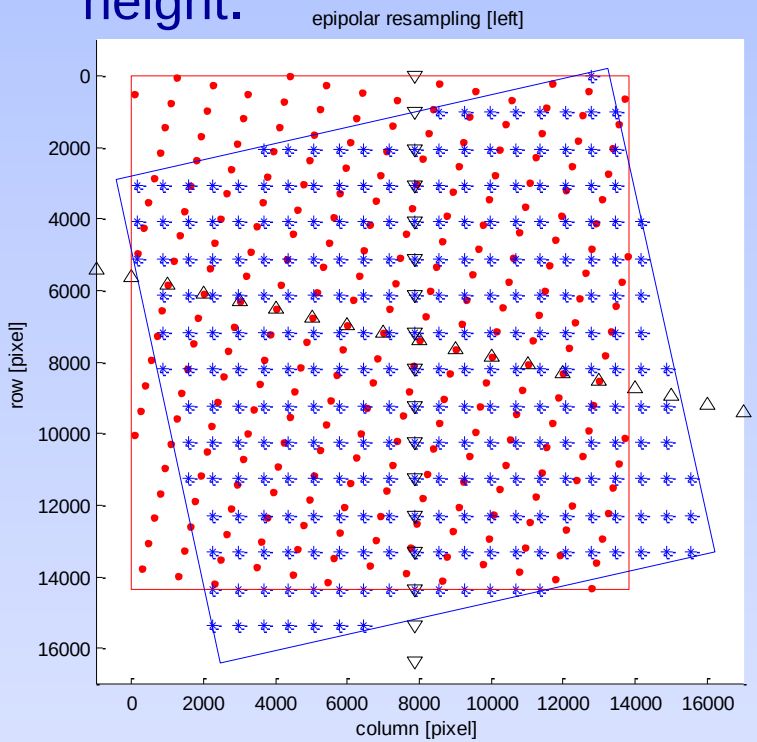
- ✓ Straight line fitting for each curve shows that the curves cannot be approximated by a straight line for the entire image
- ✓ Line fitting slope shows that each curve has slightly different slope

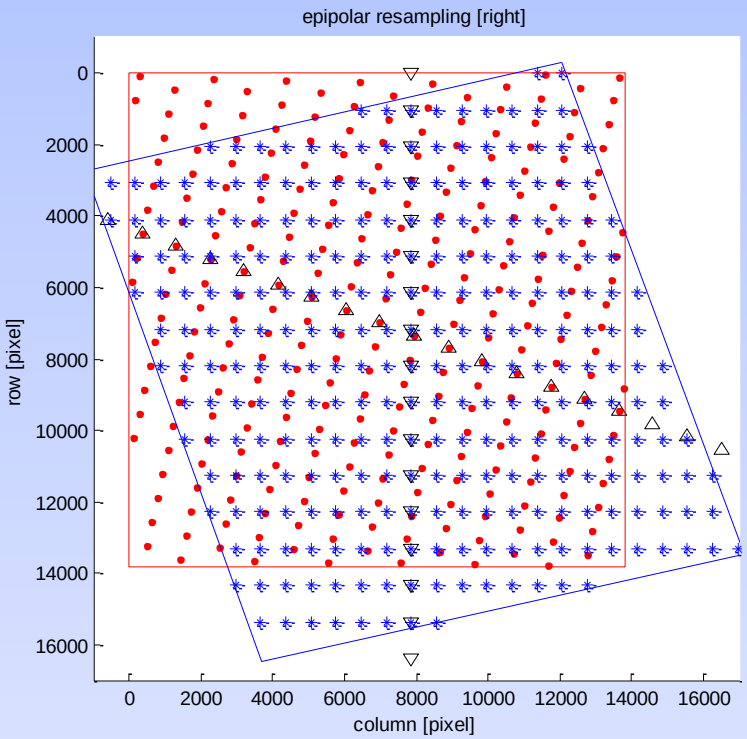




Reassignment of Epipolar Curve Points

- ✓ The starting points are aligned in the y-direction.
- ✓ The y-coordinates of each curve pair are assigned the same value→ remove y-parallax
- ✓ The x-interval is fixed → x-parallax proportional to the ground height.





Dots are piecewise generated epipolar curve points, upward pointing triangles are the starting points, the asterisks and downward pointing triangles are relocated points, satisfying the epipolar image condition

Y-parallax by Proposed Method

- ✓ Y-parallaxes are computed for the 16 manually measured tie points and 328 generated tie points
- ✓ Y-parallax of the measured tie points is approximately one pixel while the generated tie points show almost zero y-parallax, which means that nearly zero y-parallax can be obtained if there is no error in the image measurement and RPC

|y-parallax| [pixels]		**16 measured tie points**		**328 RPC-generated tie points**	
		Mean	**Max**	**Mean**	**Max**
Polynomial	**2nd order**	**0.40**	**1.26**	**0.02**	**0.08**
	3rd order	**0.40**	**1.25**	**0.00**	**0.04**
Linear interpolation		**0.41**	**1.26**	**0.03**	**0.09**

Y-parallax Comparison by Parallel Projection Method

- ✓ When parallel projection model is estimated from the four GCPs, y-parallax had a maximum of 19 pixels

  → because four GCPs are located at the lower right corner

- ✓ When the model is estimated from virtually generated GCPs, which are evenly distributed over the entire scene, from RPC, the maximum y-parallax was 4.6 pixels

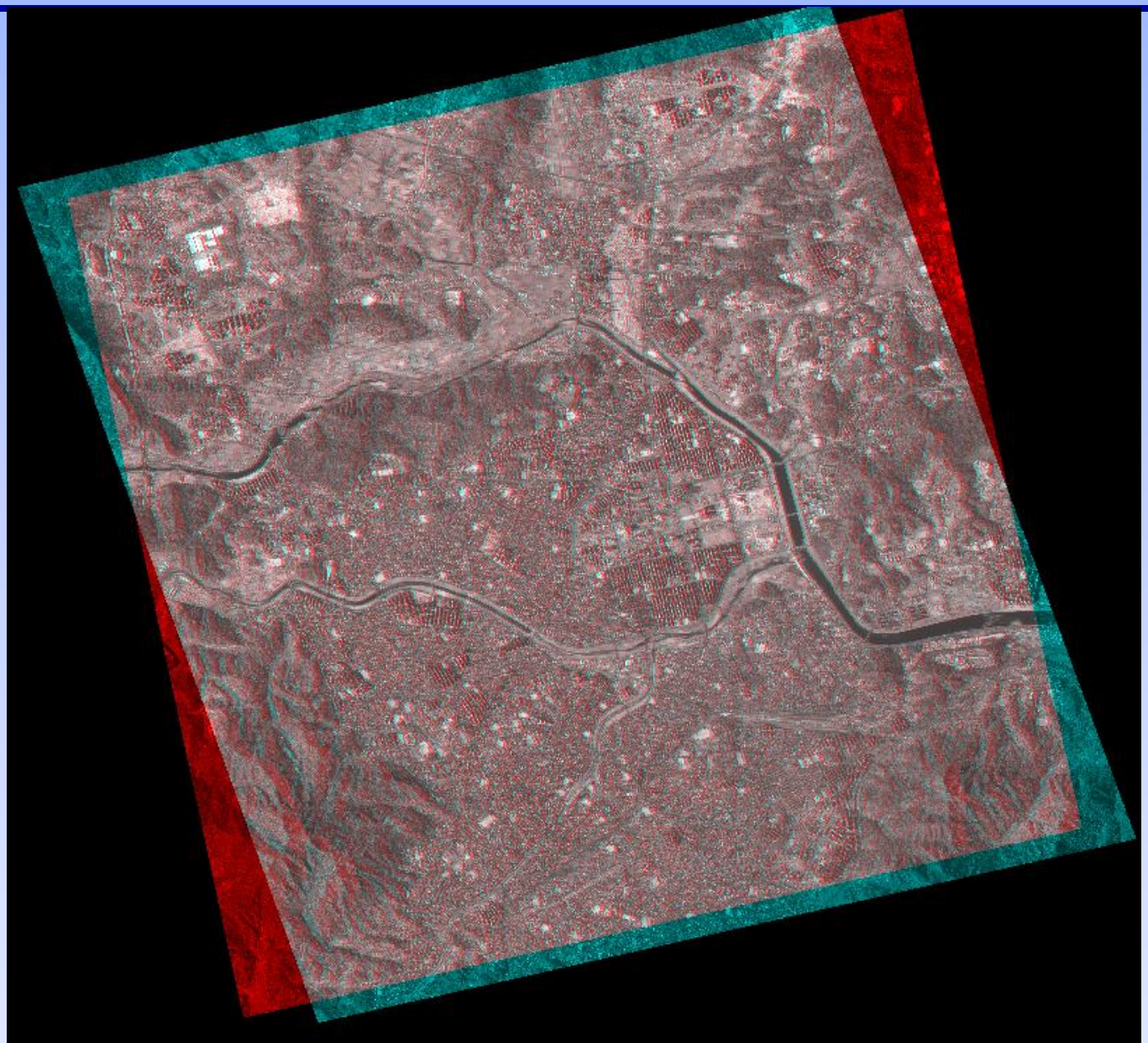
|y-parallax| [pixels]	**16 measured tie points**	
	Mean	**Max**
Four GCPs for parameter estimation	**4.75**	**18.98**
328 RPC-generated GCPs for parameter estimation	**1.10**	**4.59**

Ground Restitution Accuracy of the Proposed Method

- ✓ After the resampling, new RPCs are generated
- ✓ The new RPC showed accuracy of 1 meter and 0.5 meter RMS for horizontal and vertical components, respectively

Restitution RMS [m]		XY [m]	Z [m]
Polynomial	2nd order	1.03	0.51
	3rd order	1.03	0.51
Linear interpolation		1.03	0.47

Generated Anaglyph Image



Conclusions

- ✓ Pushbroom camera does not produce straight epipolar lines and the epipolar pair does not exist for the entire scene.
- ✓ Epipolar curves can be ocally approximated by a straight line and the epipolar pairs locally exist
- ✓ Global epipolar curve pairs can be approximately generated by the proposed piecewise approach
- ✓ Epipolar resampling procedure is proposed based on the generated global epipolar pairs
- ✓ From our test, the epipolar images could be successfully generated following the RPC refinement with four GCPs
- ✓ Results showed a maximum y-parallax of 1.25 pixels for manually measured tie points, while the resampling method by the parallel projection model showed a maximum of 4.6 pixels.

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Thank you