The Photogrammetric Process

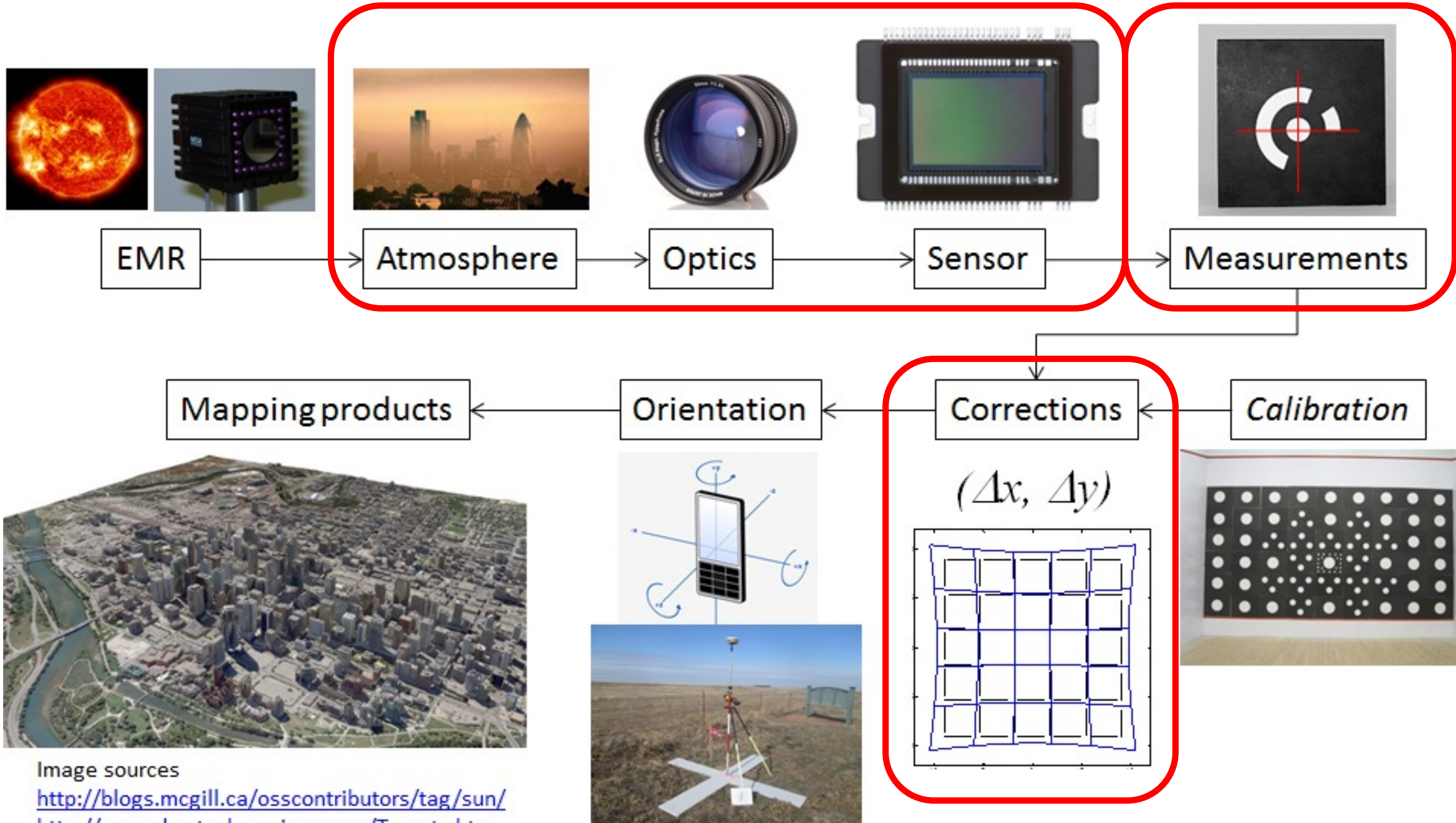
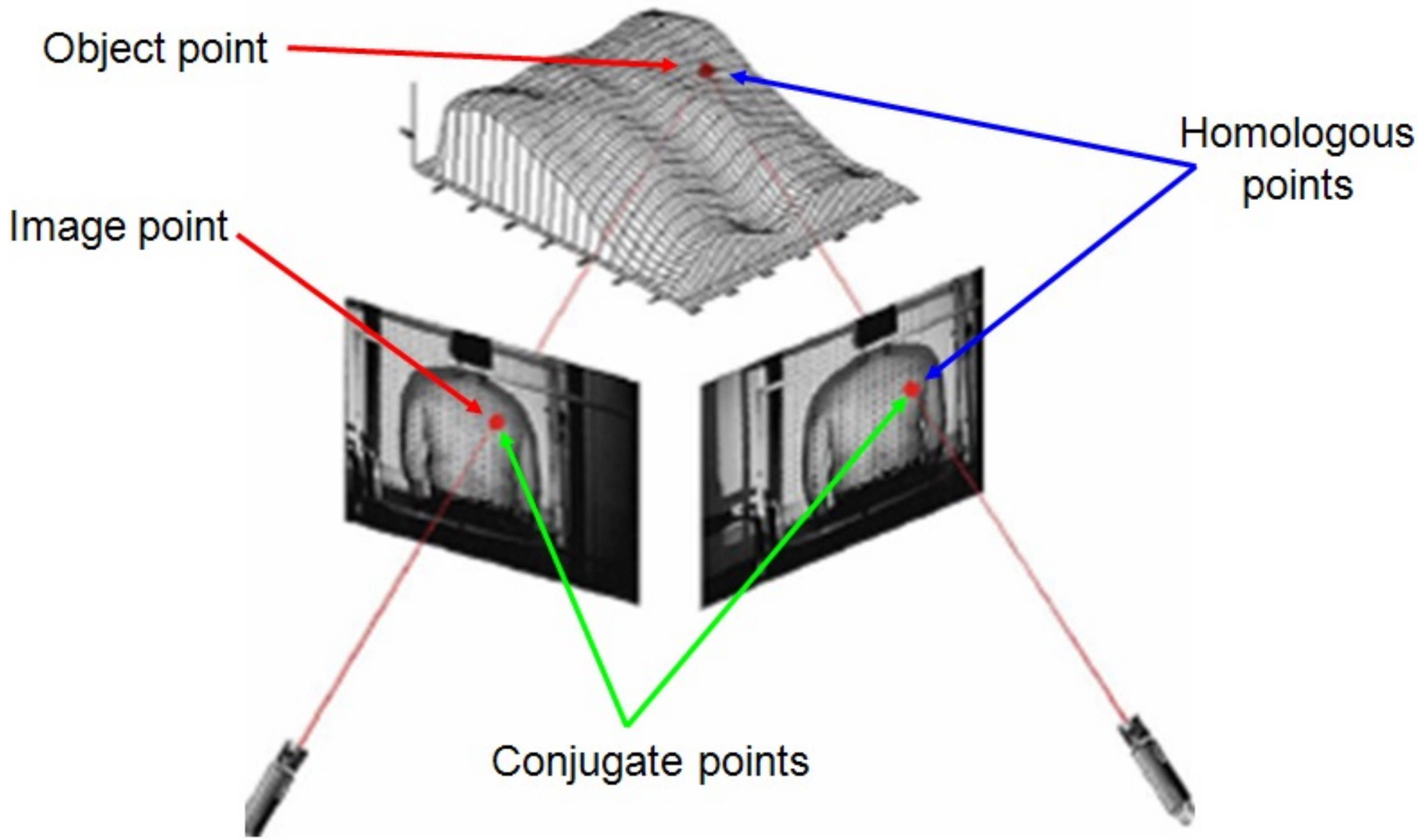


Image sources
http://blogs.mcgill.ca/osscontributors/tag/sun/
http://www.dcmtechservices.com/Targets.htm
http://www.theguardian.com/environment/2011/jan/28/europe-air-quality-pollution
https://www.ephotozine.com/article/slr-magic-50mm-f-0-95-hyperprime-lens-review-23001
http://oneslidephotography.com/ccd-vs-cmos-dslr-camera-wich-one-is-better/
http://www.rpsurveying.com/img/proj/ControlPoint.Full.png
http://www.3dcadbrowser.com/download.aspx?3dmodel=20756

All Slides Courtesy of:

Dr. Derek Lichti
University of Calgary

Point Terminology



Lazaros SECHIDIS, Vassilios TSIOUKAS, Petros PATIAS 2000. AN AUTOMATIC PROCESS FOR THE EXTRACTION OF THE 3D MODEL OF THE HUMAN BACK SURFACE FOR SCOLIOSIS TREATMENT International Archives of Photogrammetry and Remote Sensing. Vol. XXXIII, Supplement B5. Amsterdam

Types of Interest Points—Signalized Points




http://www.pobonline.com/articles/93907-aerial-targets
http://www.laser-engrave-it.com/Store/products/PhotoModeler-Complete-Target-Kit-(294-Pcs.).html
https://www.brainlab.com/en/surgery-products/overview-spinal-trauma-products/trauma-navigation/

Types of Interest Points—Others

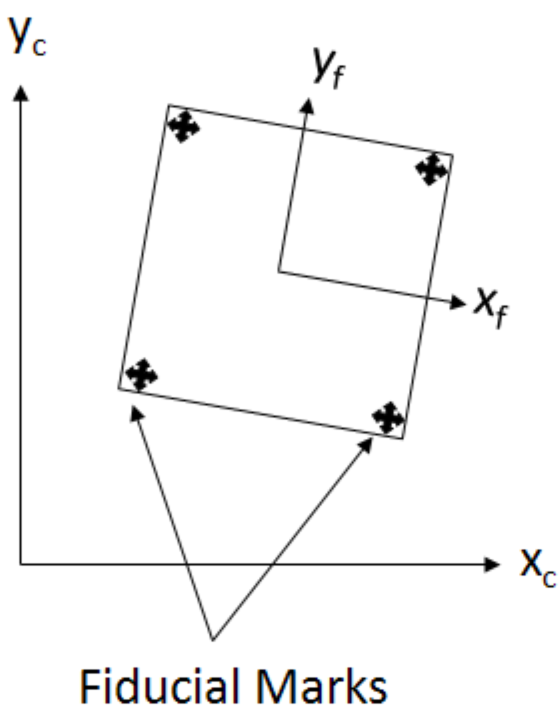
Natural feature

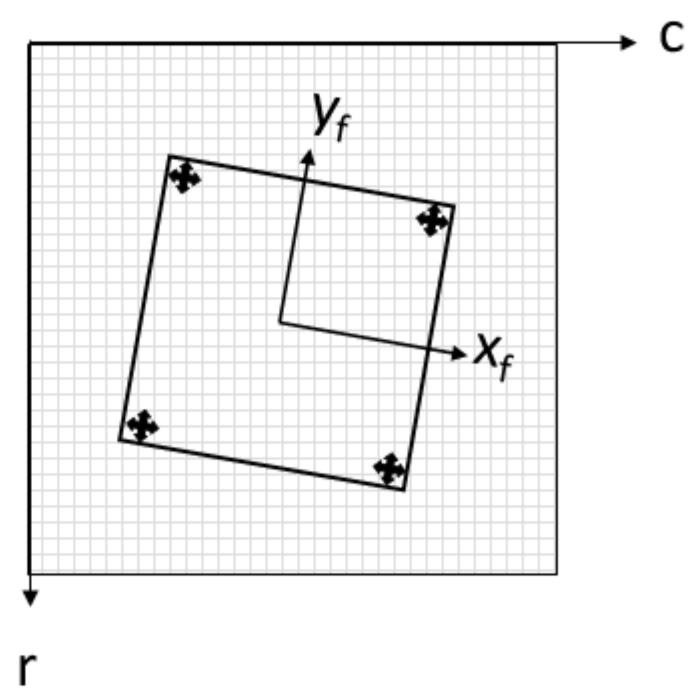
Projected pattern

https://www.3dhubs.com/talk/thread/matterthings-hosts-3d-hubs-sketchfab-3d-scanner-party

Relationships Between 2D Co-ordinate Systems

- Analogue image
  - Comparator (c) and fiducial (f) systems
- Scanned digital image
  - Pixel (r,c) and fiducial systems





Camera Calibration Certificate Example

USGS Report No. OSL/3431

United States Department of the Interior

U.S. GEOLOGICAL SURVEY
Reston, Virginia 20192

REPORT OF CALIBRATION
of Aerial Mapping Camera

November 20, 2008

Camera type: Wild RC30*
Lens type: Wild Universal Aviogon /4-S
Nominal focal Length: 153 mm

Camera serial no.: 5283
Lens serial no.: 13332
Maximum aperture: f/4
Test aperture: f/4

Submitted by: [redacted]

Reference:

These measurements were made on Agfa glass plates, 0.19 inch thick, with spectroscopic emulsion type APX Panchromatic, developed in D-19 at 68° F for 3 minutes with continuous agitation. These photographic plates were exposed on a multicollimator camera calibrator using a white light source rated at approximately 5200K.

Camera Calibration Certificate (cont'd)

I. Calibrated Focal Length: 153.358 mm

II. Lens Distortion

Field angle:	7.5°	15°	22.7°	30°	35°	40°
Symmetric radial (μm)	-2	-3	-2	0	2	3
Decentering tangential (μm)	0	0	1	1	2	2

Symmetric radial distortion	Decentering distortion	Calibrated principal point
K_0 = 0.8878E-04	P_1 = 0.1346E-06	x_p = -0.006 mm
K_1 = -0.1528E-07	P_2 = 0.1224E-07	y_p = 0.006 mm
K_2 = 0.5256E-12	P_3 = 0.0000	
K_3 = 0.0000	P_4 = 0.0000	
K_4 = 0.0000		

The values and parameters for Calibrated Focal Length (CFL), Symmetric Radial Distortion (K_0,K_1,K_2,K_3,K_4), Decentering Distortion (P_1,P_2,P_3,P_4), and Calibrated Principal Point [point of symmetry] (x_p,y_p) were determined through a least-squares Simultaneous Multiframe Analytical Calibration (SMAC) adjustment. The x and y-coordinate measurements utilized in the adjustment of the above parameters have a standard deviation (σ) of ±3 microns.

Camera Calibration Certificate (cont'd)

USGS Report No. OSL/3431

III. Lens Resolving Power in cycles/mm

Area-weighted average resolution: 110

Field angle:	0°	7.5°	15°	22.7°	30°	35°	40°
Radial Lines	134	134	134	113	113	113	95
Tangential Lines	134	134	134	113	113	95	80

The resolving power is obtained by photographing a series of test bars and examining the resultant image with appropriate magnification to find the spatial frequency of the finest pattern in which the bars can be counted with reasonable confidence. The series of patterns has spatial frequencies from 5 to 268 cycles/mm in a geometric series having a ratio of the 4th root of 2. Radial lines are parallel to a radius from the center of the field, and tangential lines are perpendicular to a radius.

IV. Filter Parallelism

The two surfaces of the Wild 525 filter No. 7592 accompanying this camera are within 10 seconds of being parallel. This filter was used for the calibration.

Camera Calibration Certificate (cont'd)

V. Shutter Calibration

Indicated Time (sec)	Rise Time (µ sec)	Fall Time (µ sec)	½ Width Time (ms)	Nom. Speed (sec)	Efficiency (%)
1/125	1022	1007	8.68	1/120	93
1/250	531	520	4.52	1/240	93
1/500	266	263	2.33	1/460	93
1/1000	137	134	1.17	1/920	93

The effective exposure times were determined with the lens at aperature f/4. The method is considered accurate within 3 percent. The technique used is described in International Standard ISO 516:1999(E).

VI. Film Platen

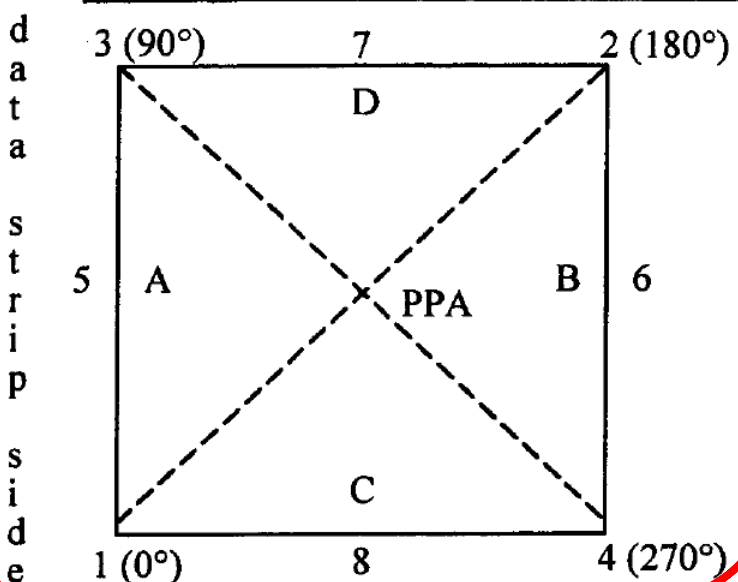
The platen mounted in Wild drive unit No. 5283 does not depart from a true plane by more than 13 µm (0.0005 in).

This camera is equipped with a platen identification marker that will register "655" in the data strip area for each exposure.

Camera Calibration Certificate (cont'd)

USGS Report No. OSL/3431

VII. Principal Point and Fiducial Mark Coordinates



Positions of all points are referenced to the principal point of autocollimation (PPA) as origin. The diagram indicates the orientation of the reference points when the camera is viewed from the back, or a contact positive with the emulsion up. The data strip is to the left.

	X coordinate (mm)	Y coordinate (mm)
Indicated principal point, corner fiducials	0.005	0.008
Indicated principal point, midside fiducials	0.003	0.007
Principal point of autocollimation (PPA)	0.000	0.000
Calibrated principal point (point of symmetry)	-0.006	0.006

Camera Calibration Certificate (cont'd)

Fiducial Marks

1	-105.997	-105.995
2	106.004	106.008
3	-106.000	106.009
4	106.012	-105.995
5	-112.000	0.007
6	112.006	0.007
7	0.005	112.007
8	0.002	-111.998

VIII. Distances Between Fiducial marks

Corner fiducials (diagonals)	1-2:	299.816 mm	3-4:	299.825 mm

Lines joining these markers intersect at an angle of 90° 00' 03"

Midside fiducials	5-6:	224.005 mm	7-8:	224.006 mm

Lines joining these markers intersect at an angle of 89° 59' 57"

Corner fiducials (perimeter)	1-3:	212.003 mm	2-3:	212.004 mm
	1-4:	212.009 mm	2-4:	212.003 mm

The Method of measuring these distances is considered accurate within 0.003 mm

Note: For GPS applications, the nominal entrance pupil distance from the focal plane is 277mm.

Camera Calibration Certificate (cont'd)

USGS Report No. OSL/3431

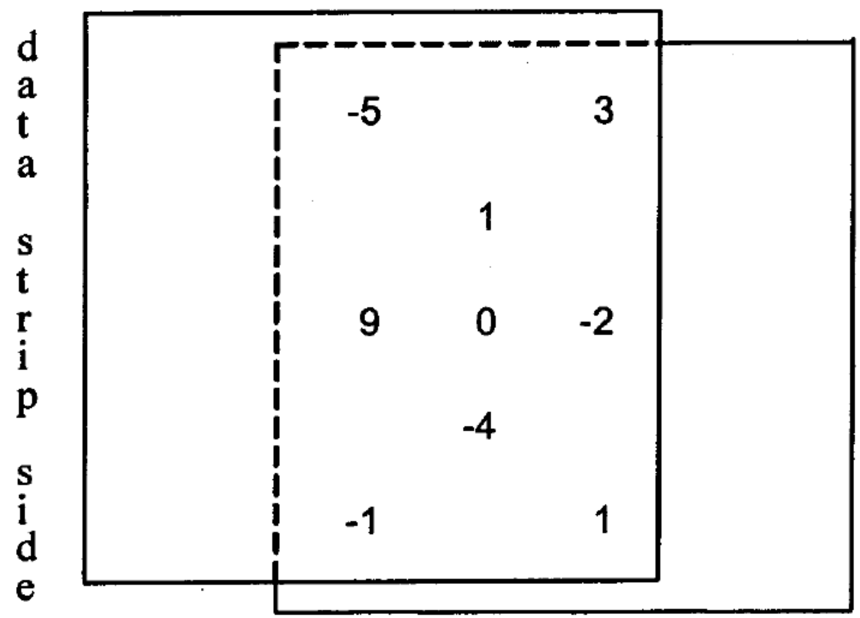
IX. Stereomodel Flatness

FMC Drive Unit No: 5283

Platen ID: 655

Base/Height ratio: 0.6

Maximum angle of field tested: 40°



Stereomodel Test Point Array
(values in micrometers)

Camera Calibration Certificate (cont'd)

The values shown on the diagram are the average departures from flatness (at negative scale) for two computer-simulated stereo models. The values are based on comparator measurements on Agfa Avitone P3P copy film made from Kodak 2405 film exposures. These measurements are considered accurate to within 5 µm.

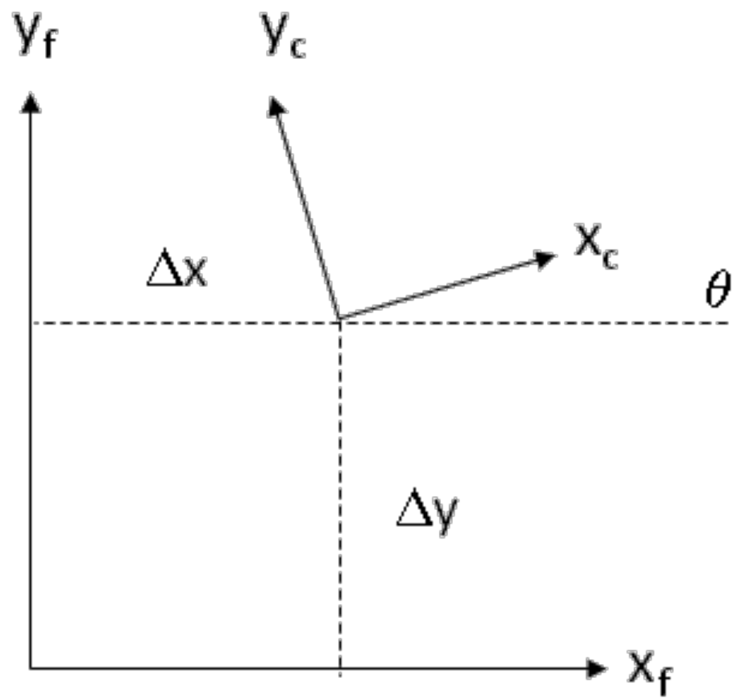
X. System Resolving Power on film in cycles/mm

Area-weighted average resolution: 52 **Film:** Type 2405

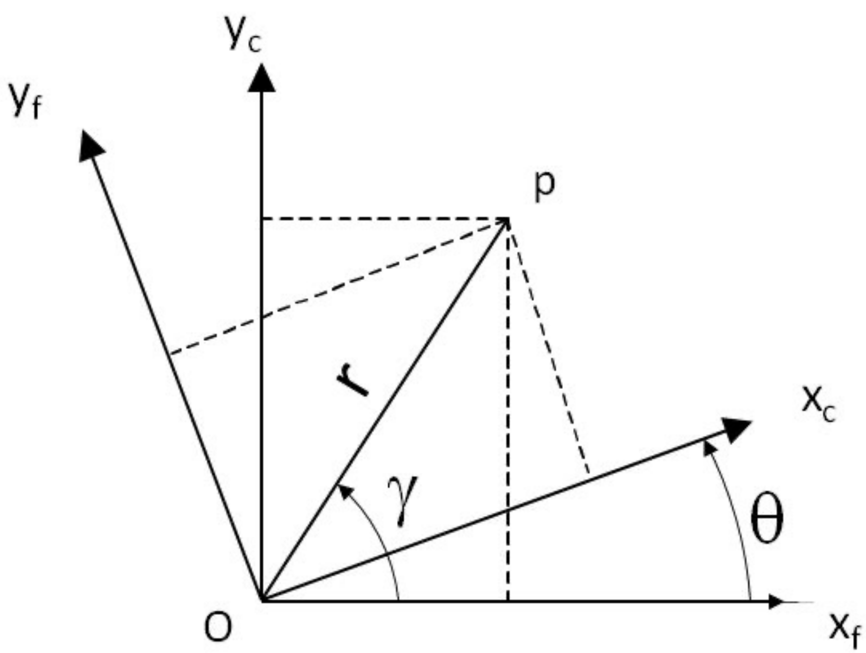
Field angle:	0°	7.5°	15°	22.7°	30°	35°	40°
Radial Lines	67	57	57	57	57	48	48
Tangential Lines	67	57	57	57	48	48	40

This aerial mapping camera calibration report supersedes the previously issued USGS Report No. OSL/2936, dated April 7, 2003.

Similarity Transformation



Similarity Transformation (cont'd)



IO Example

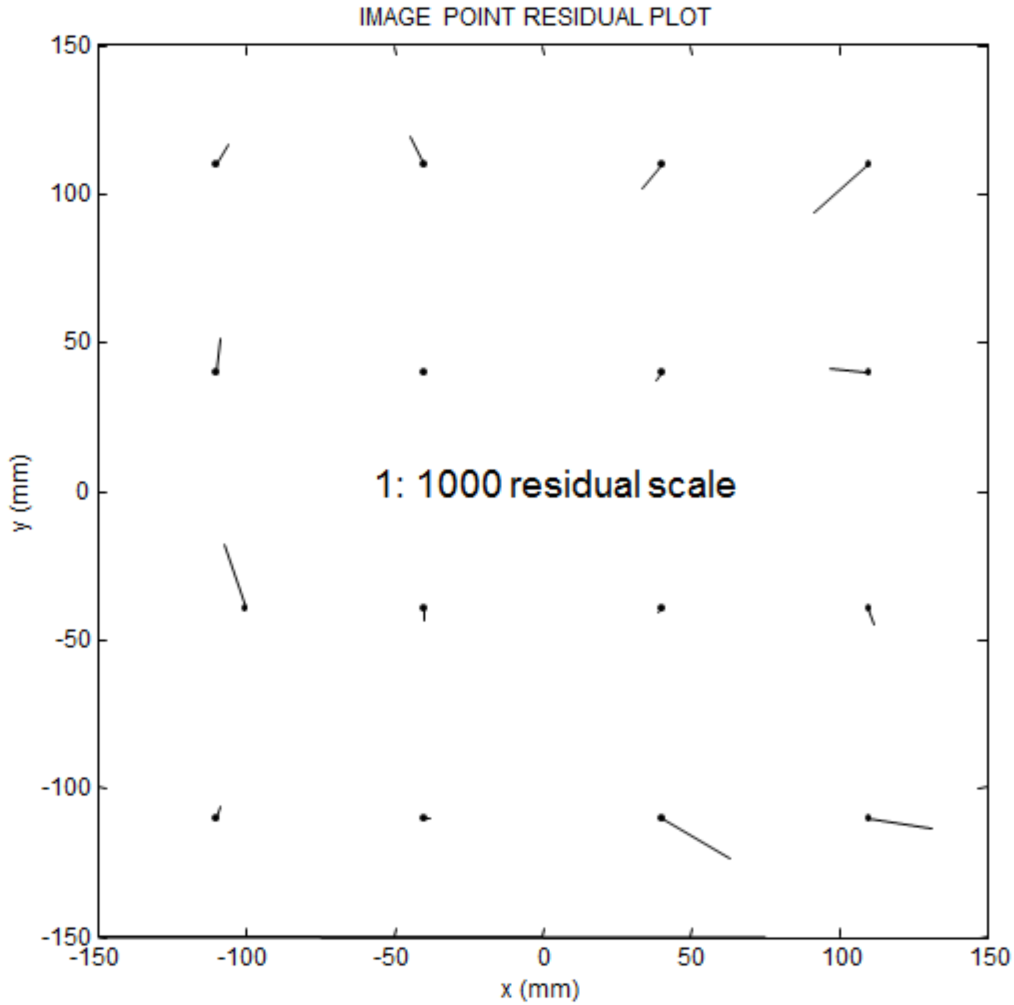
- RC8
  - c = 152.15 mm
  - Fitted with réseau plate
  - 16 réseau crosses measured to determine the IO
  - Observed and calibrated réseaux co-ordinates given at right

	comparator		reseau	
ID	x (mm)	y (mm)	x (mm)	y (mm)
1	-113.767	-107.400	-110	-110
2	-43.717	-108.204	-40	-110
3	36.361	-109.132	40	-110
4	106.408	-109.923	110	-110
5	107.189	-39.874	110	-40
6	37.137	-39.070	40	-40
7	-42.919	-38.158	-40	-40
8	-102.968	-37.446	-100	-40
9	-112.052	42.714	-110	40
10	-42.005	41.903	-40	40
11	38.051	40.985	40	40
12	108.089	40.189	110	40
13	108.884	110.221	110	110
14	38.846	111.029	40	110
15	-41.208	111.961	-40	110
16	-111.249	112.759	-110	110

Similarity Transformation Results

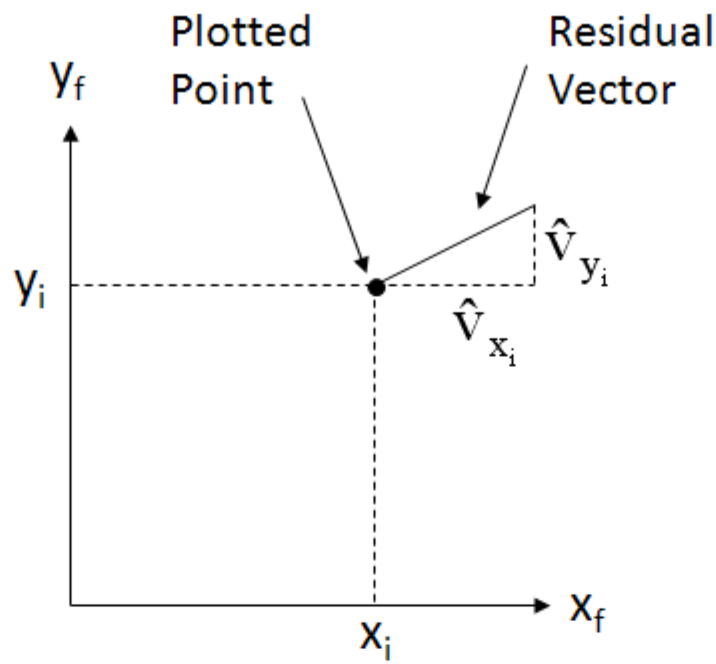
Transformation	parameters
A=	0.999162
B=	0.011416
Dx=	2.4471
Dy=	-1.3878

id	rx (mm)	ry (mm)
1	0.0015	0.0035
2	0.0020	-0.0001
3	0.0234	-0.0132
4	0.0207	-0.0039
5	0.0014	-0.0047
6	-0.0010	-0.0011
7	-0.0003	-0.0038
8	-0.0071	0.0221
9	0.0014	0.0112
10	-0.0011	0.0005
11	-0.0017	-0.0028
12	-0.0133	0.0014
13	-0.0185	-0.0162
14	-0.0070	-0.0084
15	-0.0045	0.0089
16	0.0041	0.0067
RMS	0.0101	0.0091

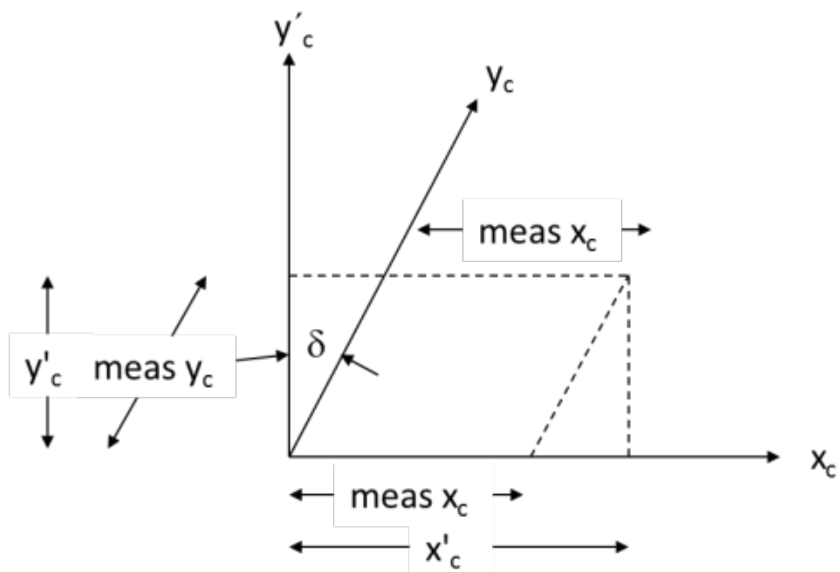


Plotting Residual Vectors

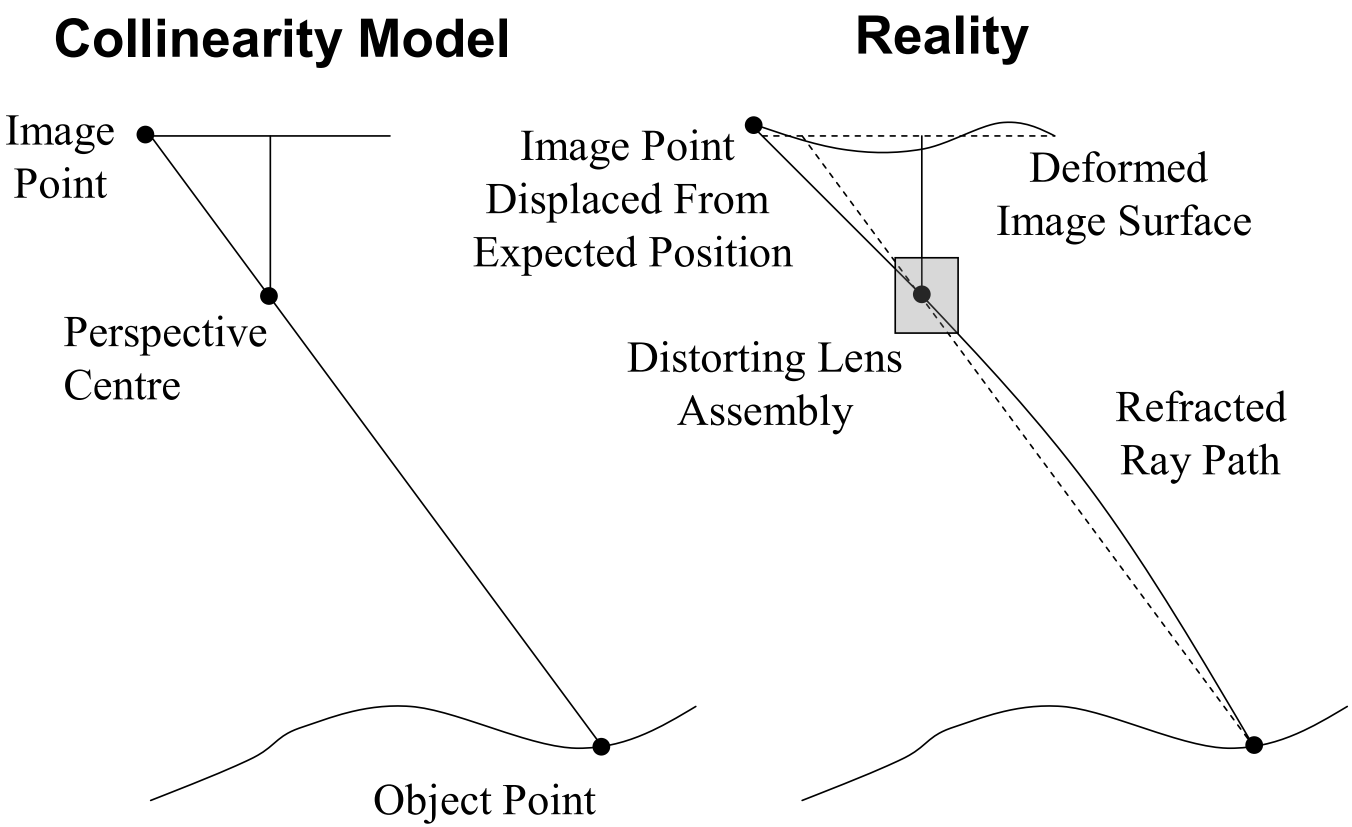
- MATLAB function: quiver



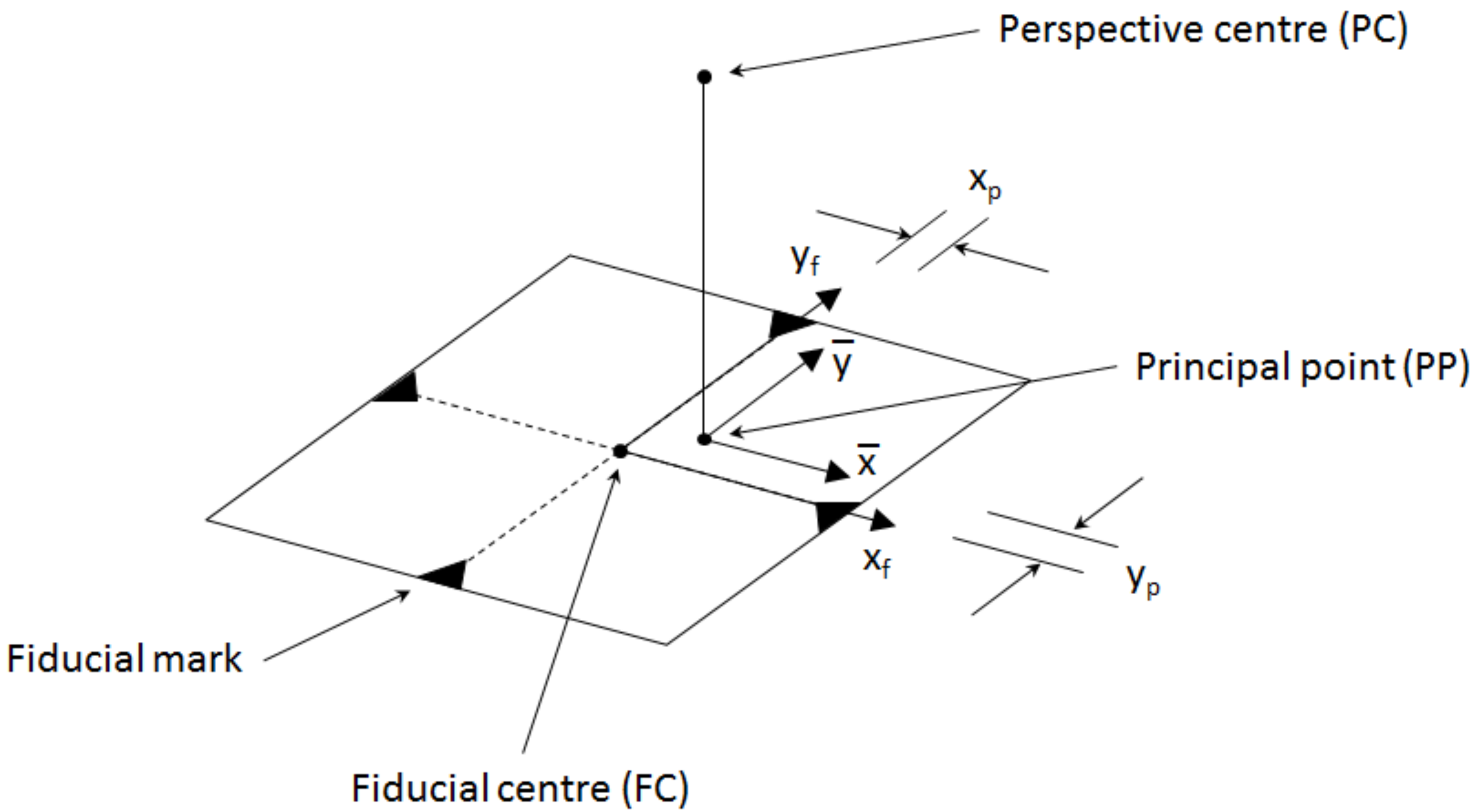
Affine Transformation



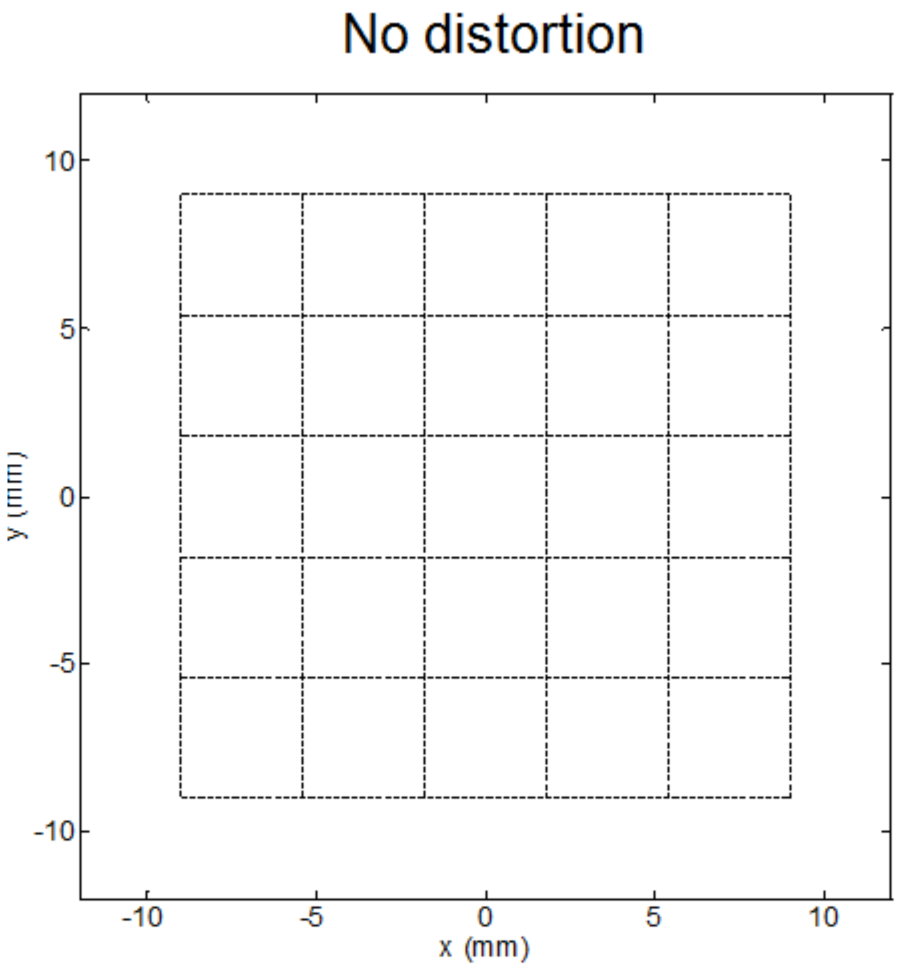
Collinearity and Distortions

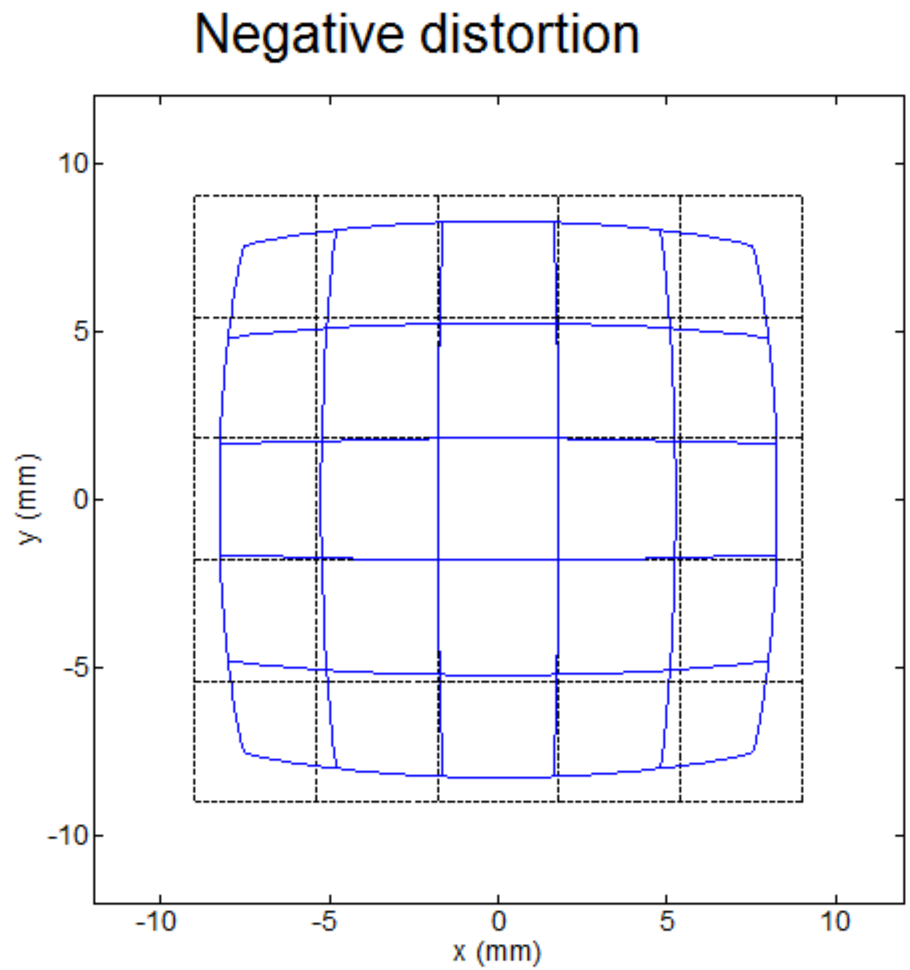


Principal Point Offset

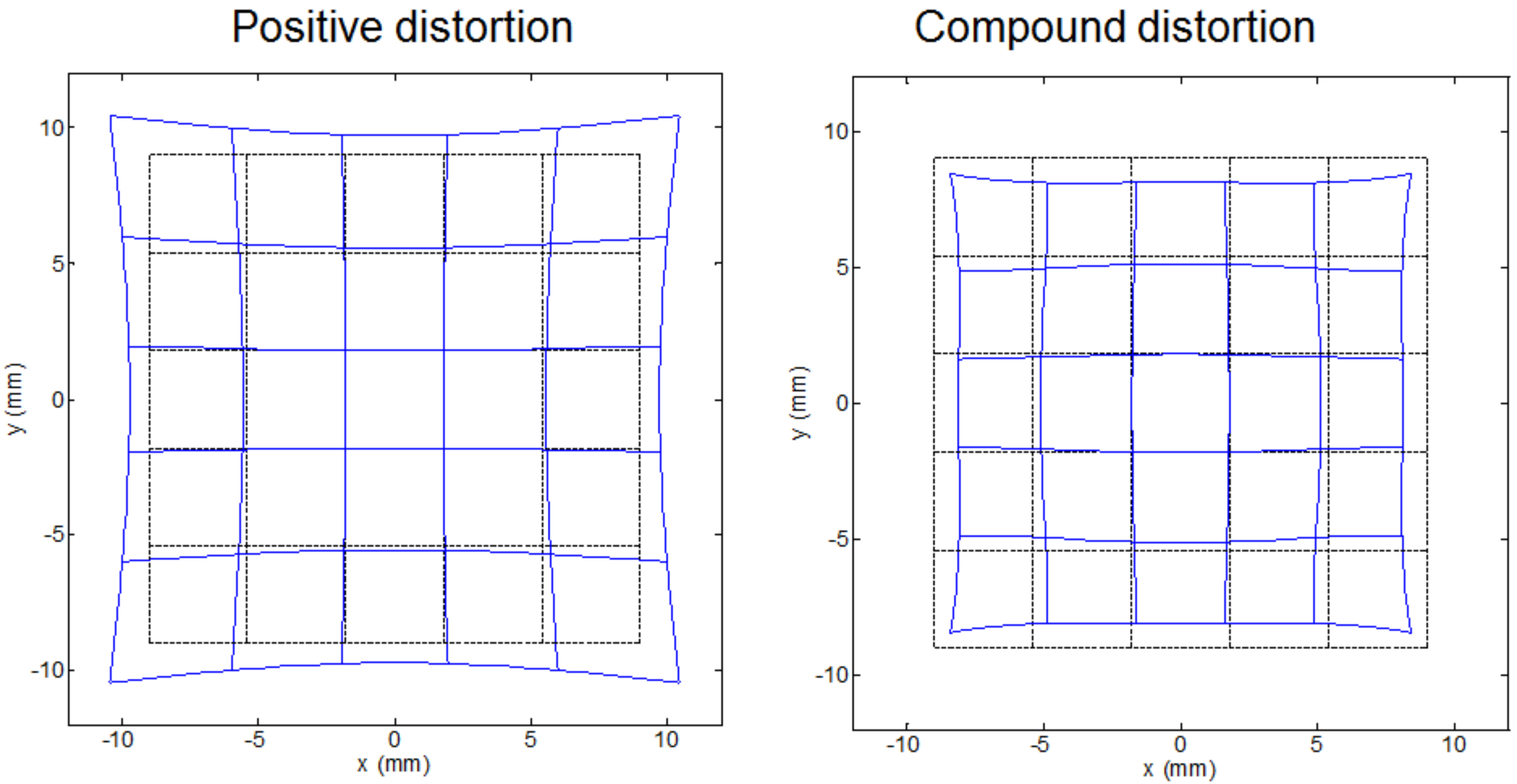


Radial Lens Distortion

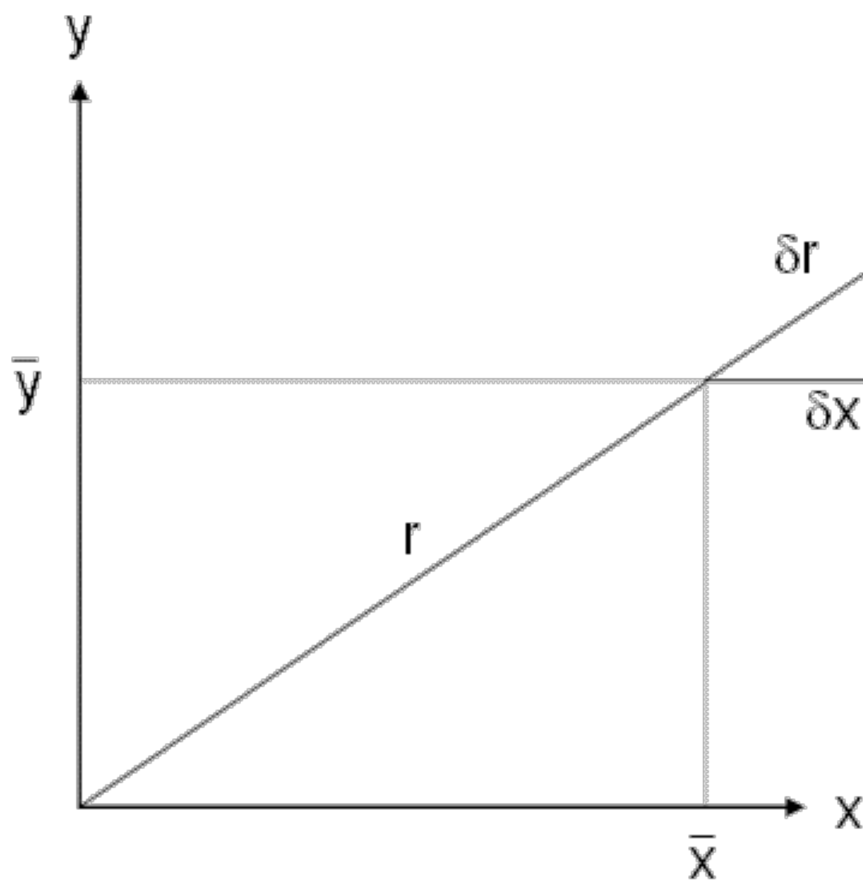




Radial Lens Distortion (cont'd)

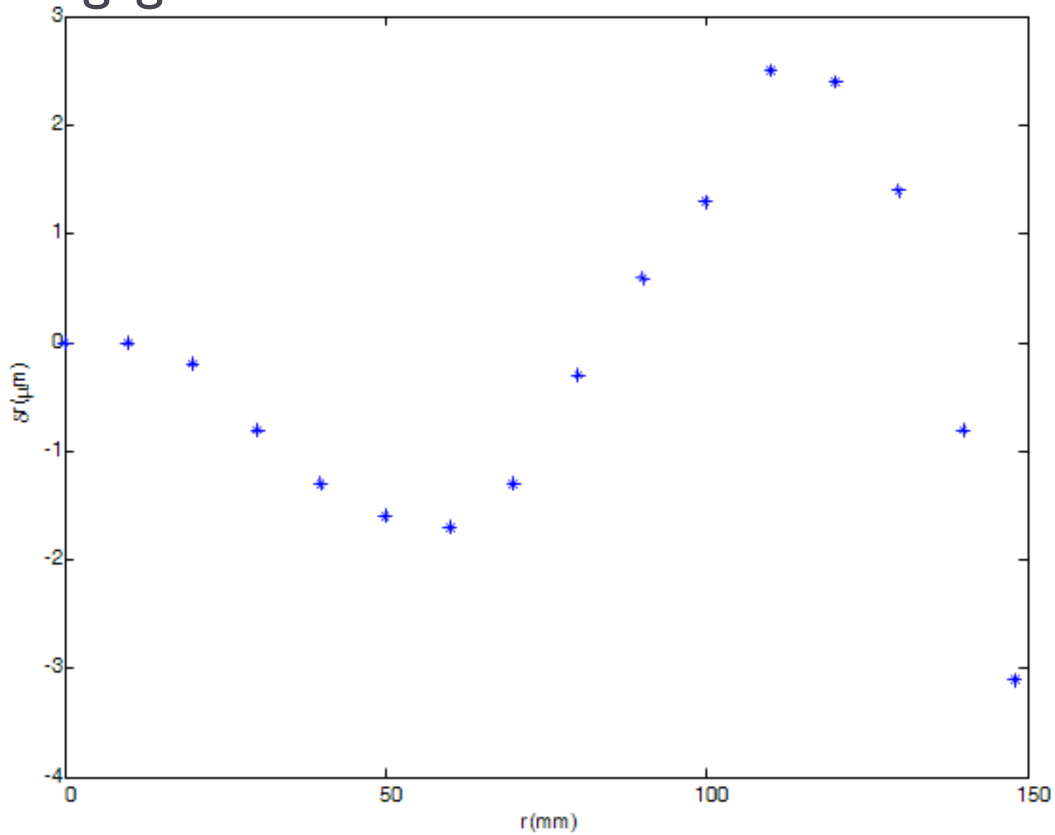


Radial Lens Distortion (cont'd)



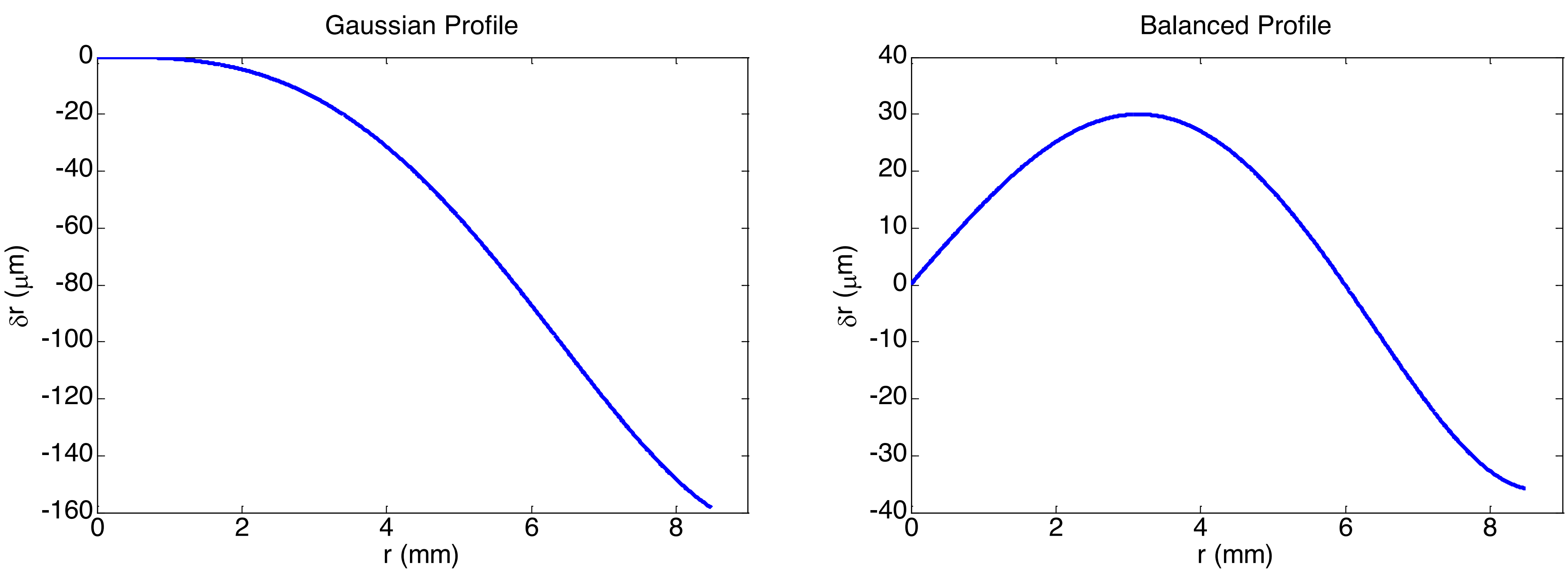
Radial Lens Distortion (cont'd)

- Aerial camera example: RC 30 (c = 152.87 mm)
  - Tabular distortion values as a function of r
  - Almost negligible distortion



Radial Lens Distortion (cont'd)

- Example: Kodak DC 260 digital camera
  - Gaussian profile at left (c = 15.3051 mm)
  - Balanced profile at right (r_0= 6 mm, Δc = 0.2251 mm)



Radial Lens Distortion (cont'd)

- Question: which lens distortion profile is given in the camera calibration certificate?

II. Lens Distortion

Field angle:	7.5°	15°	22.7°	30°	35°	40°
Symmetric radial (μm)	-2	-3	-2	0	2	3
Decentering tangential (μm)	0	0	1	1	2	2

Symmetric radial distortion

K_0 = 0.8878E-04
K_1 = -0.1528E-07
K_2 = 0.5256E-12
K_3 = 0.0000
K_4 = 0.0000

Decentering distortion

P_1 = 0.1346E-06
P_2 = 0.1224E-07
P_3 = 0.0000
P_4 = 0.0000

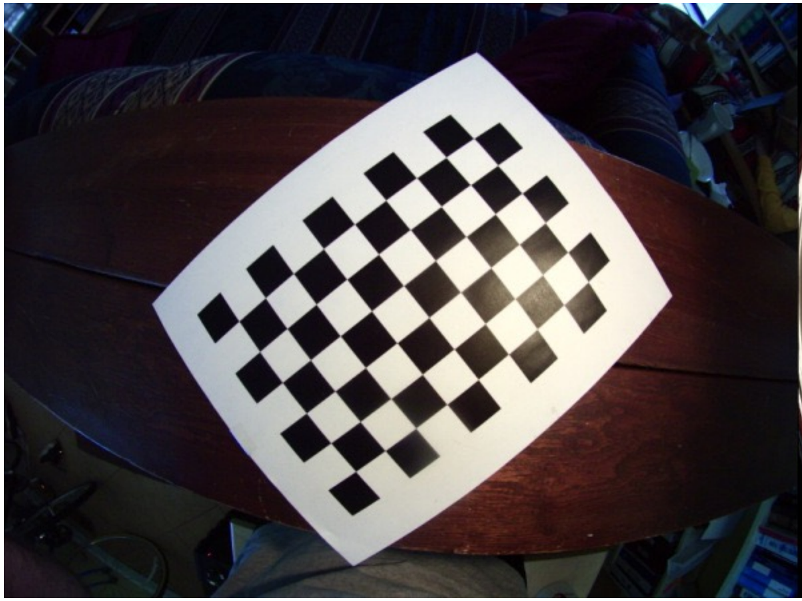
Calibrated principal point

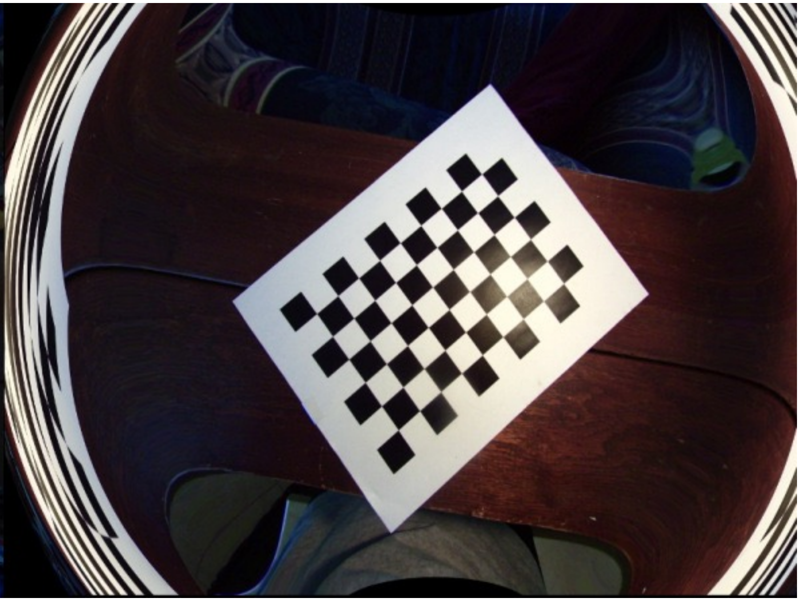
x_p = -0.006 mm
y_p = 0.006 mm

- Question: does it matter which lens distortion profile is used?

Radial Lens Distortion (cont'd)

- Before
- After correction

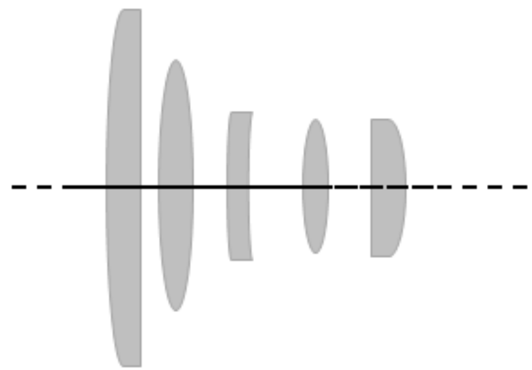




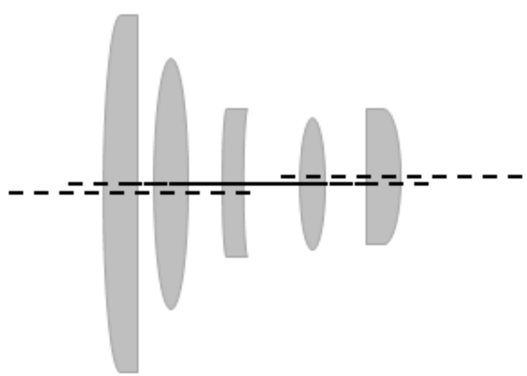
https://bovineaerospace.wordpress.com/tag/gopro/

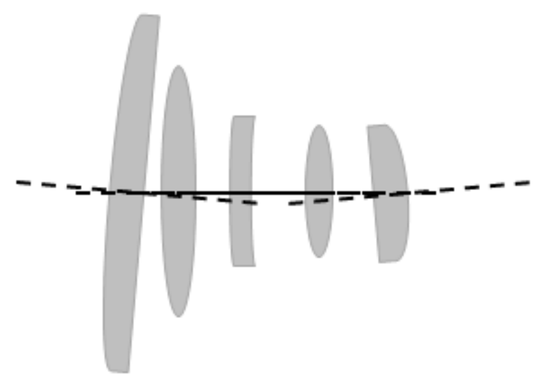
Decentring Lens Distortion

- An ideal compound lens

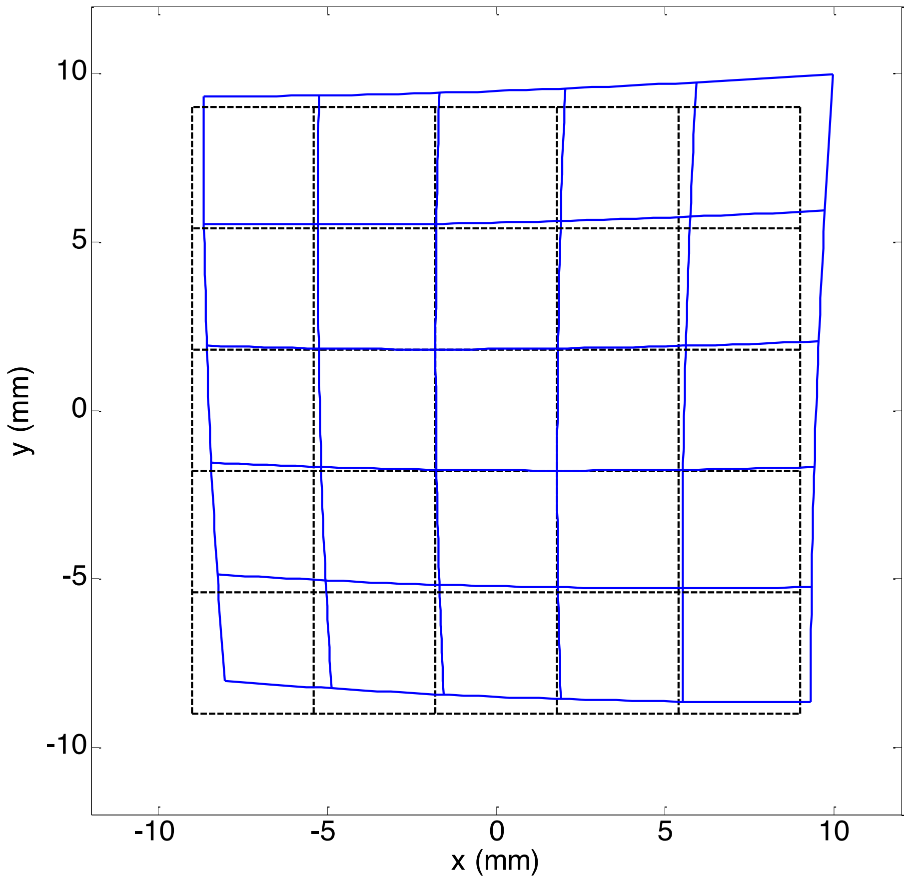


- A decentred lens

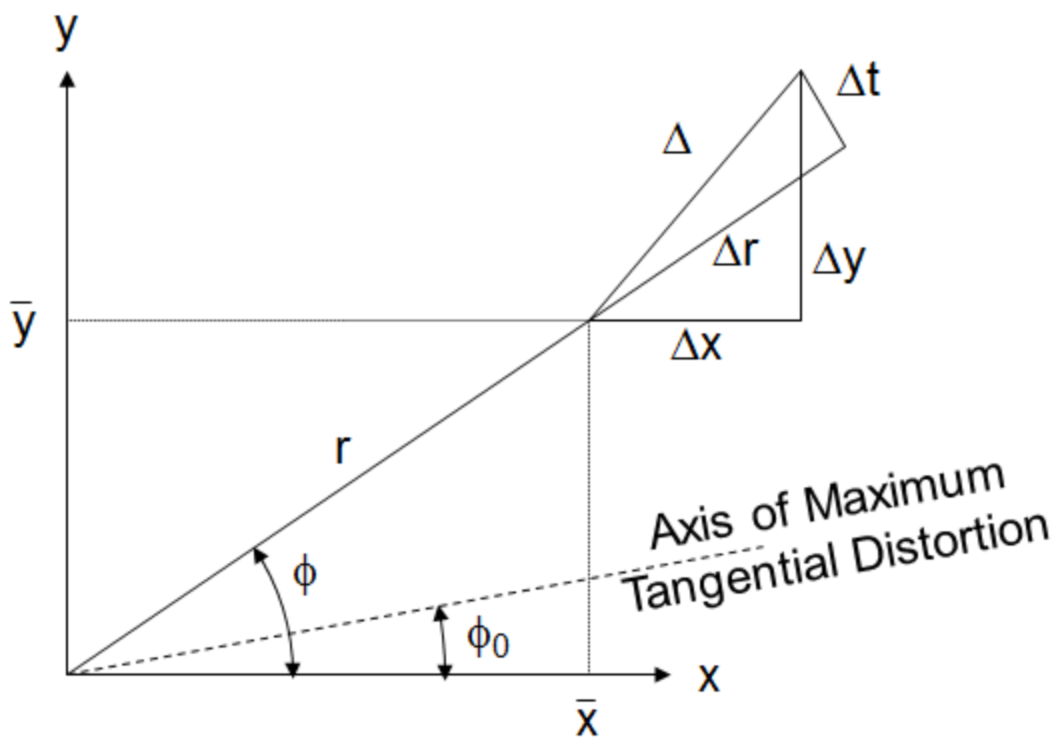




Decentring Lens Distortion (cont'd)

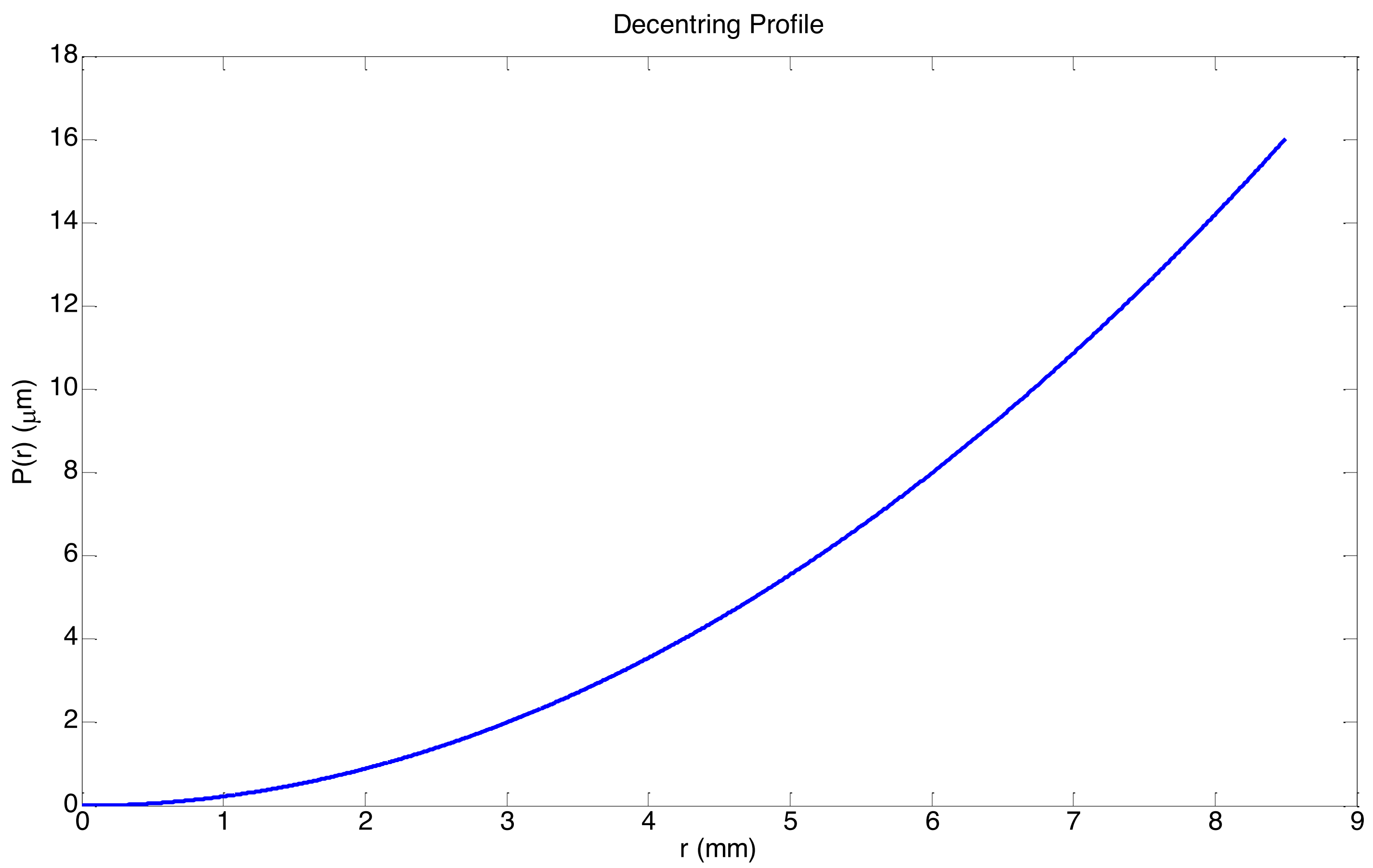


Decentring Lens Distortion (cont'd)

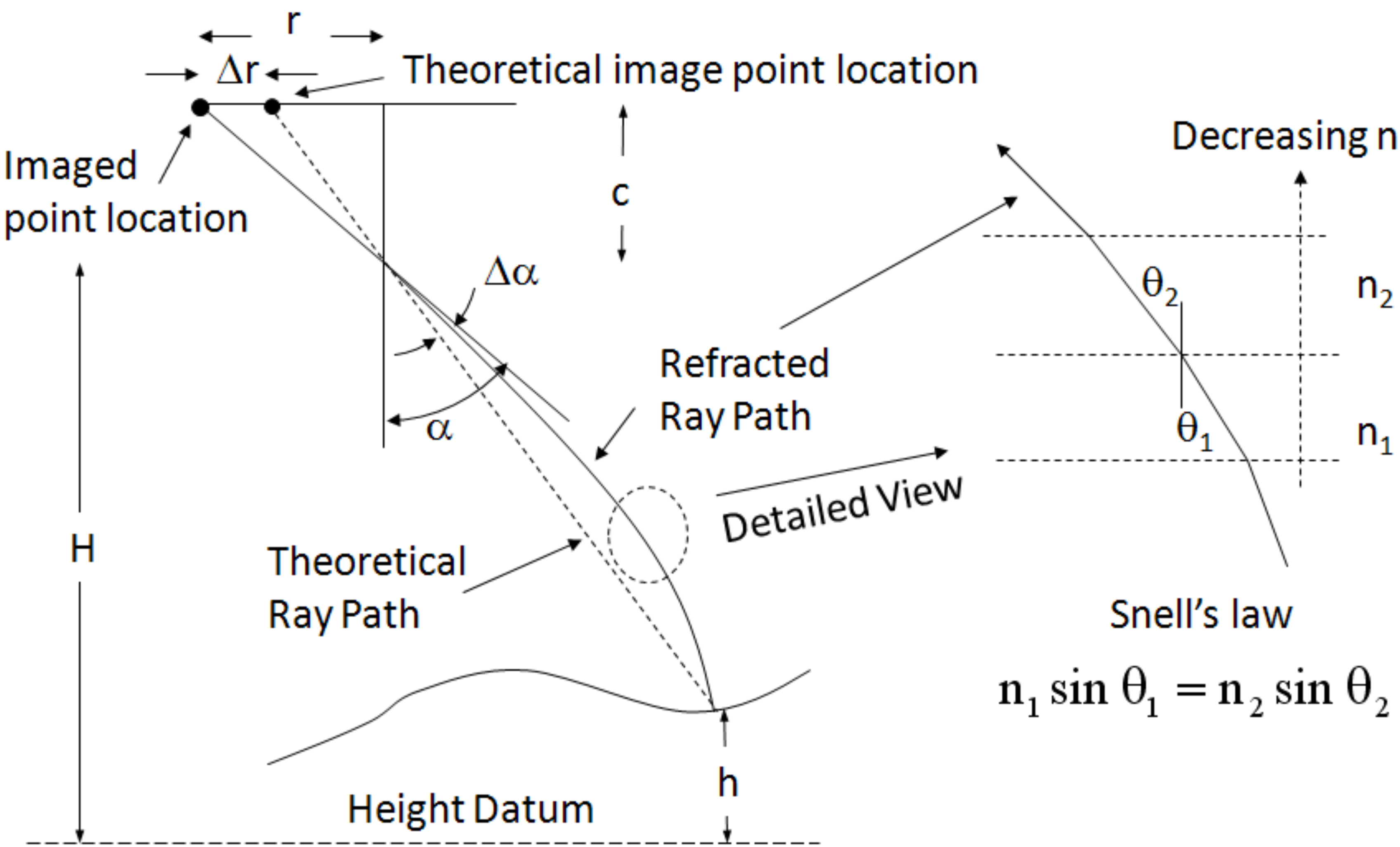


Decentring Lens Distortion (cont'd)

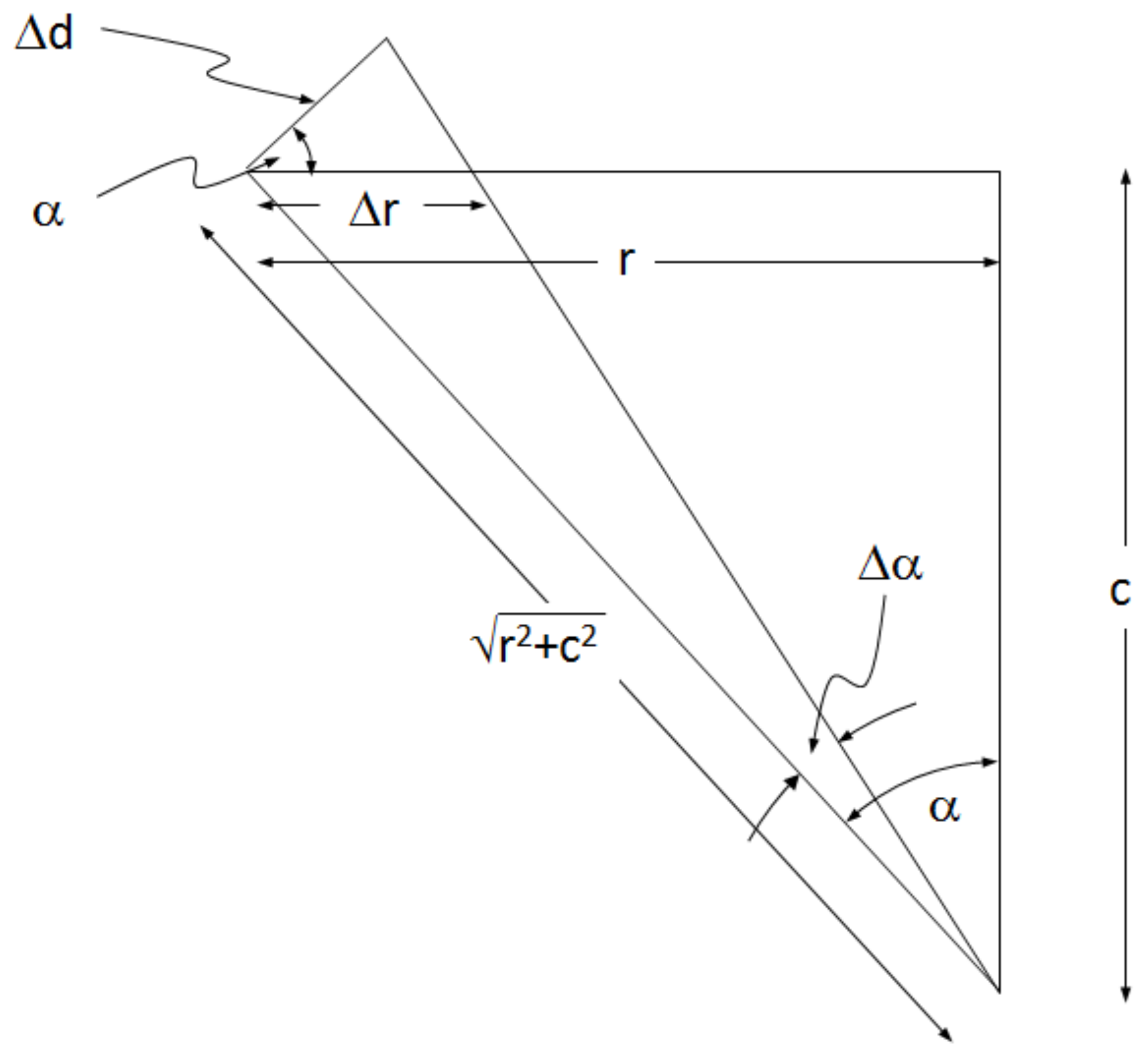
- Example: Kodak DC 260 digital camera



Atmospheric Refraction



Atmospheric Refraction (cont'd)

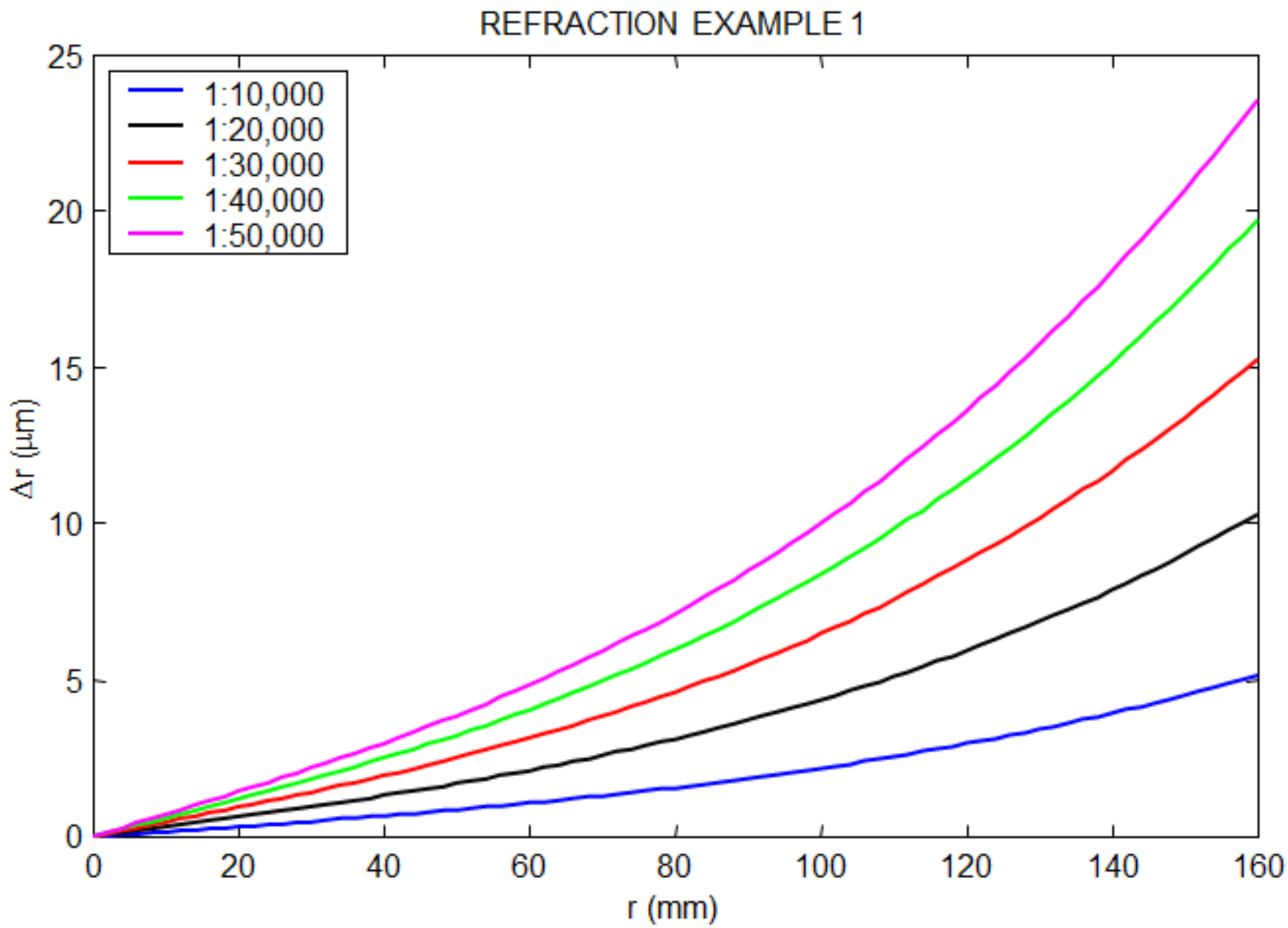


Atmospheric Refraction (cont'd)

- Example 1
  - Five cases for different scales (flying heights) for constant focal length
  - Refraction increases with flying height

c (mm)	h (m)	H (m)	S	K (μrad)
152	50	1520	10,000	15.0
152	50	3040	20,000	30.4
152	50	4560	30,000	45.1
152	50	6080	40,000	58.5
152	50	7600	50,000	69.9

Atmospheric Refraction (cont'd)

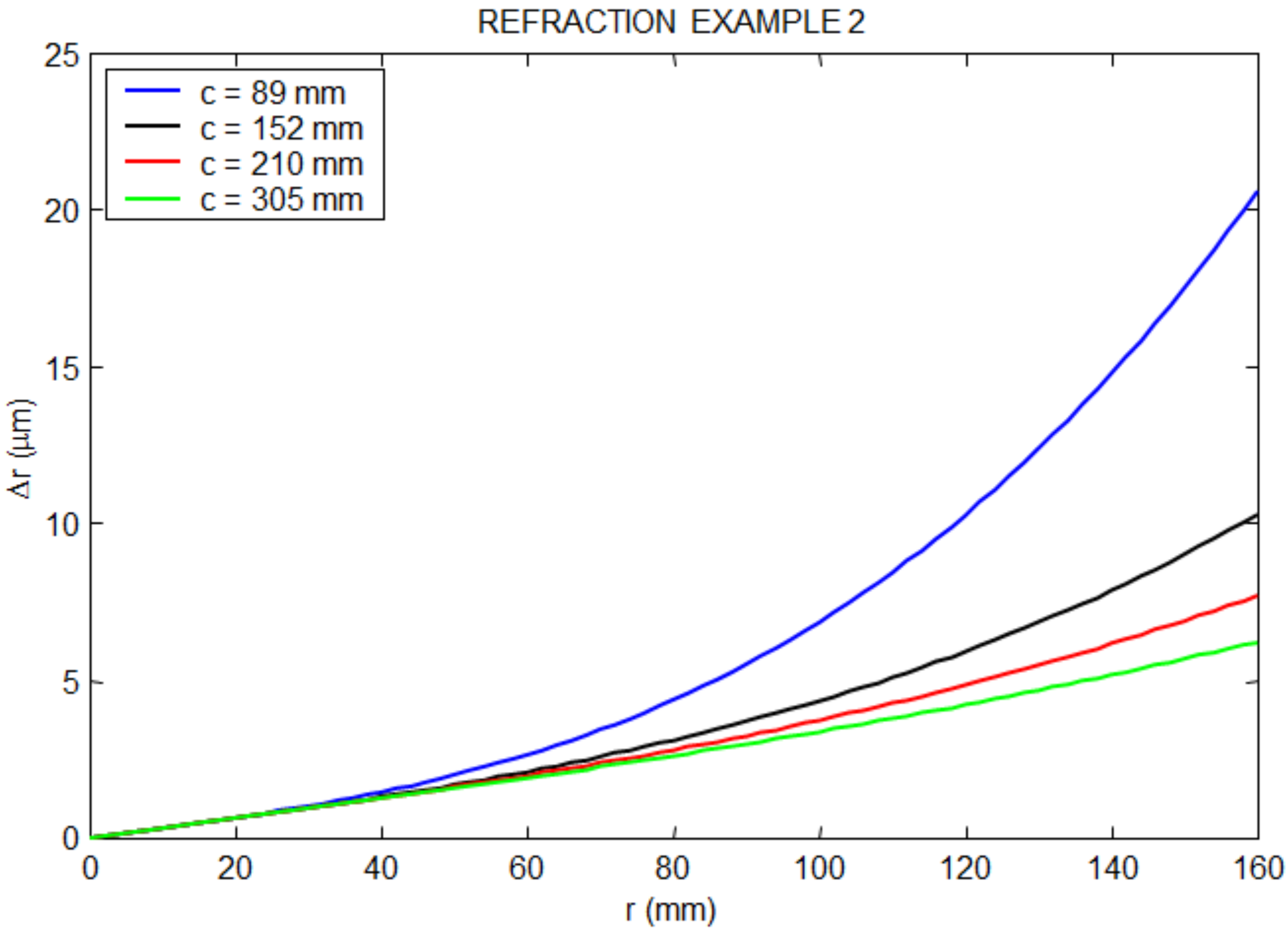


Atmospheric Refraction (cont'd)

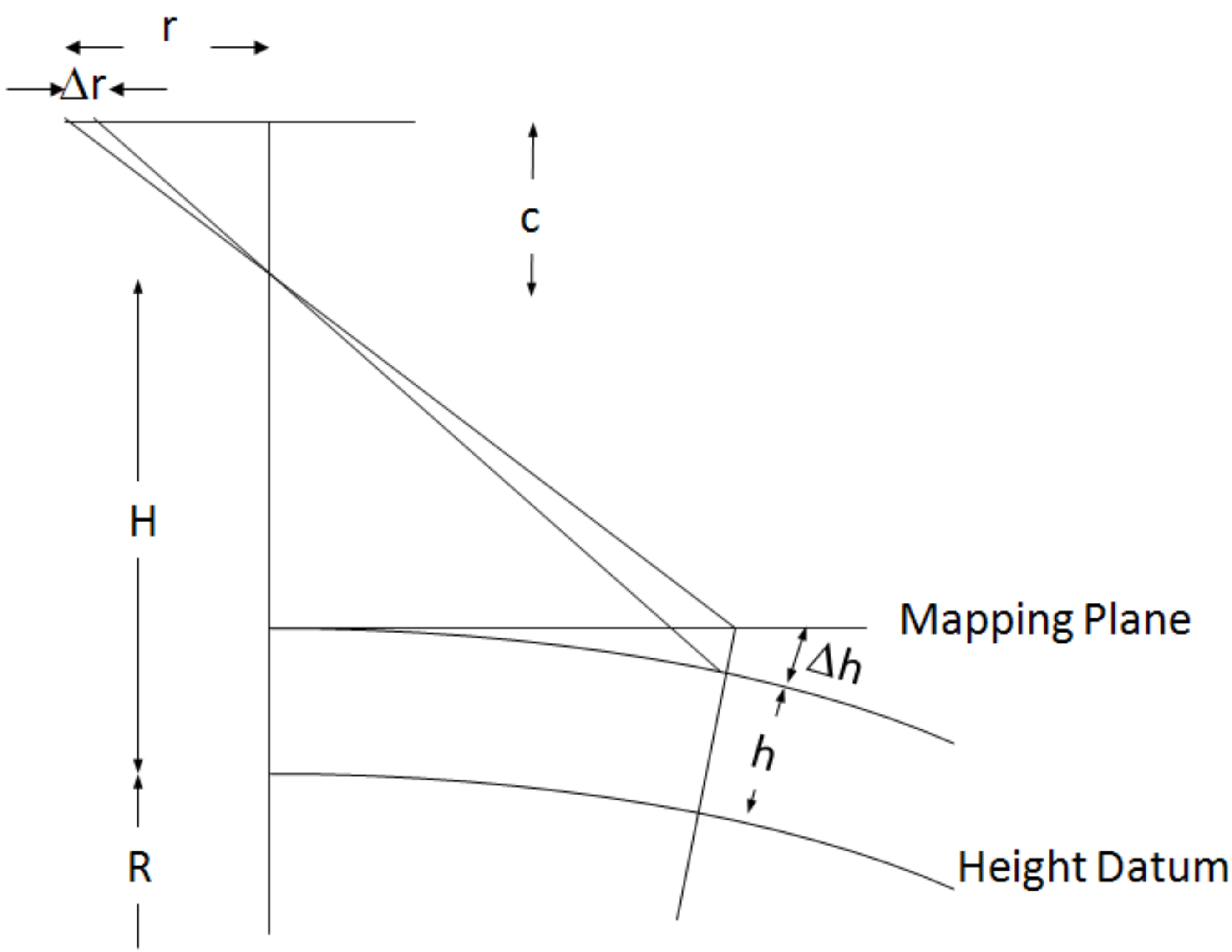
- Example 2
  - Four cases for different focal lengths at constant flying height
  - Refraction decreases as focal length increases (decreasing α) and the effect becomes nearly linear

c (mm)	h (m)	H (m)	S	K (μrad)
89	50	3040	34,200	30.4
152	50	3040	20,000	30.4
210	50	3040	14,500	30.4
305	50	3040	10,000	30.4

Atmospheric Refraction (cont'd)



Earth Curvature



Example

- How significant are the lens distortions?
- What is the impact of ignoring the corrections?
- $k_1 = 1.5 \times 10^{-6}$
- $x_p = y_p = 0$ mm
- $c = 152.4$ mm
- $g = 228$ mm
- $S = 20\,000$

Summary of Equations

- Pixel to comparator coordinates $\begin{pmatrix} x_c \\ y_c \end{pmatrix} = \begin{pmatrix} \text{col} \\ -\text{row} \end{pmatrix}$
- 2D similarity transformation

$$\begin{pmatrix} x \\ y \end{pmatrix}_f = \lambda \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}_c + \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} \qquad \begin{pmatrix} x \\ y \end{pmatrix}_f = \begin{pmatrix} a & -b \\ b & a \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}_c + \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix}$$

$$\theta = \arctan\left(\frac{b}{a}\right) \qquad \lambda = \sqrt{a^2 + b^2}$$

- 2D affine transformation

$$\begin{pmatrix} x_f \\ y_f \end{pmatrix} = \begin{pmatrix} s_x \cos\theta & s_y \sin\delta\cos\theta - s_y \cos\delta\sin\theta \\ s_x \sin\theta & s_y \sin\delta\sin\theta + s_y \cos\delta\cos\theta \end{pmatrix} \begin{pmatrix} x_c \\ y_c \end{pmatrix}_i + \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} \qquad \begin{pmatrix} x \\ y \end{pmatrix}_f = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}_c + \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix}$$

$$\theta = \arctan\left(\frac{c}{a}\right) \qquad s_x = \sqrt{a^2 + c^2} \qquad s_y = \sqrt{b^2 + d^2} \qquad \delta = \arctan\left(\frac{ab + cd}{ad - bc}\right)$$

- 2D projective transformation

$$x_f = \frac{a_1 x_c + a_2 y_c + a_3}{c_1 x_c + c_2 y_c + 1} \qquad y_f = \frac{b_1 x_c + b_2 y_c + b_3}{c_1 x_c + c_2 y_c + 1}$$

Summary of Corrections—Note the Signs!

$$x' = \bar{x} + \Delta x_{rad} + \Delta x_{dec} + \Delta x_{atm} + \Delta x_{curv} \qquad y' = \bar{y} + \Delta y_{rad} + \Delta y_{dec} + \Delta y_{atm} + \Delta y_{curv}$$

- Principal point offset correction

$$\bar{x} = x - x_p \qquad \bar{y} = y - y_p \qquad r = \sqrt{\bar{x}^2 + \bar{y}^2}$$

- Radial lens distortion correction

$$\Delta x_{rad} = -\bar{x}\left(k_1 r^2 + k_2 r^4 + k_3 r^6\right)$$
$$\Delta y_{rad} = -\bar{y}\left(k_1 r^2 + k_2 r^4 + k_3 r^6\right)$$

or

$$\Delta x_{rad} = -\bar{x}\left(k'_0 + k'_1 r^2 + k'_2 r^4 + k'_3 r^6\right)$$
$$\Delta y_{rad} = -\bar{y}\left(k'_0 + k'_1 r^2 + k'_2 r^4 + k'_3 r^6\right)$$

- Decentring lens distortion correction

$$\Delta x_{dec} = -\left(p_1\left(r^2 + 2\bar{x}^2\right) + 2p_2\overline{xy}\right) \qquad \Delta y_{dec} = -\left(p_2\left(r^2 + 2\bar{y}^2\right) + 2p_1\overline{xy}\right)$$

- Atmospheric refraction correction

$$\Delta x_{atm} = -\bar{x}K\left(1 + \frac{r^2}{c^2}\right) \qquad \Delta y_{atm} = -\bar{y}K\left(1 + \frac{r^2}{c^2}\right) \qquad K = \frac{2410H}{H^2 - 6H + 250} - \frac{2410h}{h^2 - 6h + 250}\left(\frac{h}{H}\right)$$

- Earth curvature “correction”

$$\Delta x_{curv} = \frac{r^2(H-h)}{2Rc^2}\bar{x} \qquad \Delta y_{curv} = \frac{r^2(H-h)}{2Rc^2}\bar{y}$$