Pre-analysis of Camera Calibration Effectiveness

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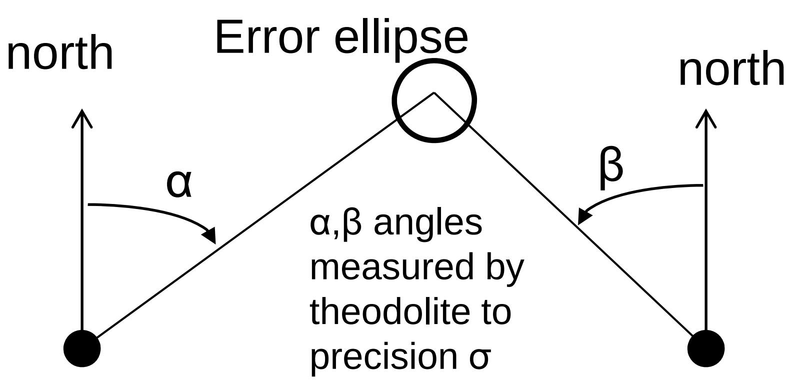
Outline

- Background and Purpose
- Experiment Layout
- Procedure
- Quality Metric
- Parameter Plots
- Sensitivities
- Correlation Consideration
- Conclusions and Future Work

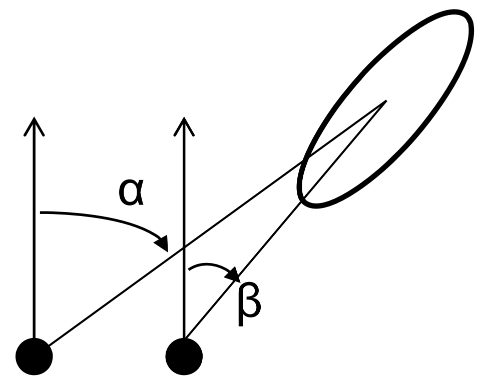
Background

- Pre-analysis, or network design, is the concept of analytically predicting the uncertainty of parameters of an adjustment as a function of:
  - Geometric configuration (setup)
  - Measurement uncertainty

Good configuration



Bad configuration



Purpose (1/2)

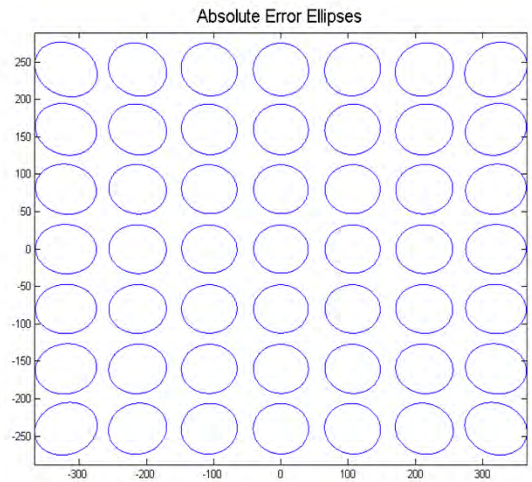
- Motivation is to demonstrate a camera calibration pre-analysis tool
  - Not to study or improve the estimation technique
- Typical calibration output: one-sigma precision for each parameter in its native units
- This briefing provides image space summary statistics and error ellipse plots

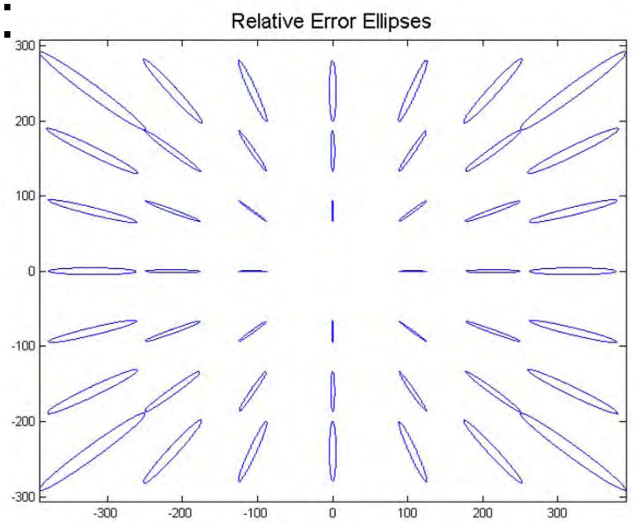
Purpose (2/2)

Typical output is 1-sigma precisions:

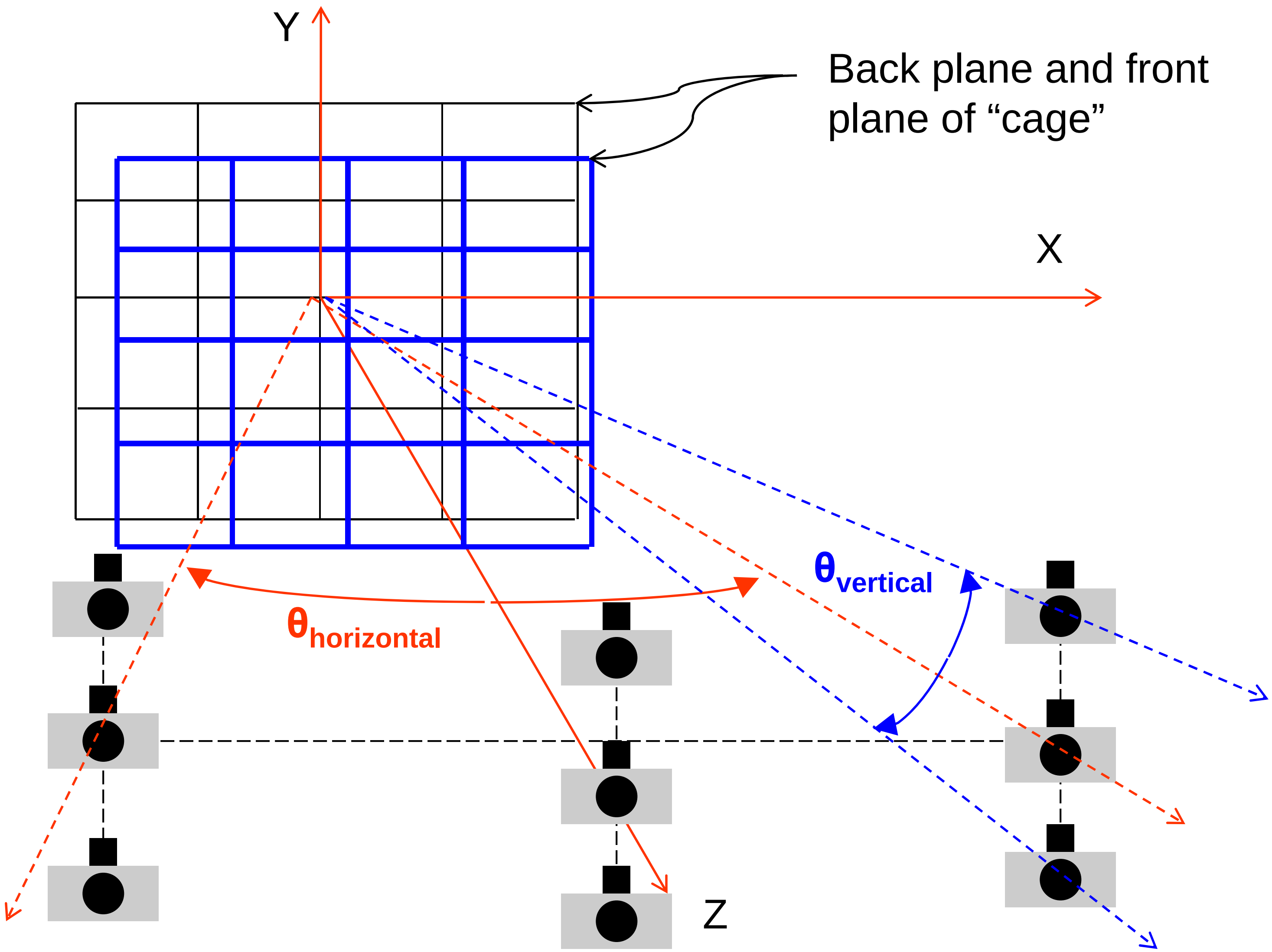
xo:	4.8701e-002	K1:	5.2864e-004	P1:	8.9838e-005
yo:	3.8587e-002	K2:	5.0805e-005	P2:	7.3206e-005
f:	5.2553e-002	K3:	1.4896e-006	b1:	2.8531e-004
				b2:	2.6187e-004

This briefing provides projection of total parameter uncertainty into image space at different locations:



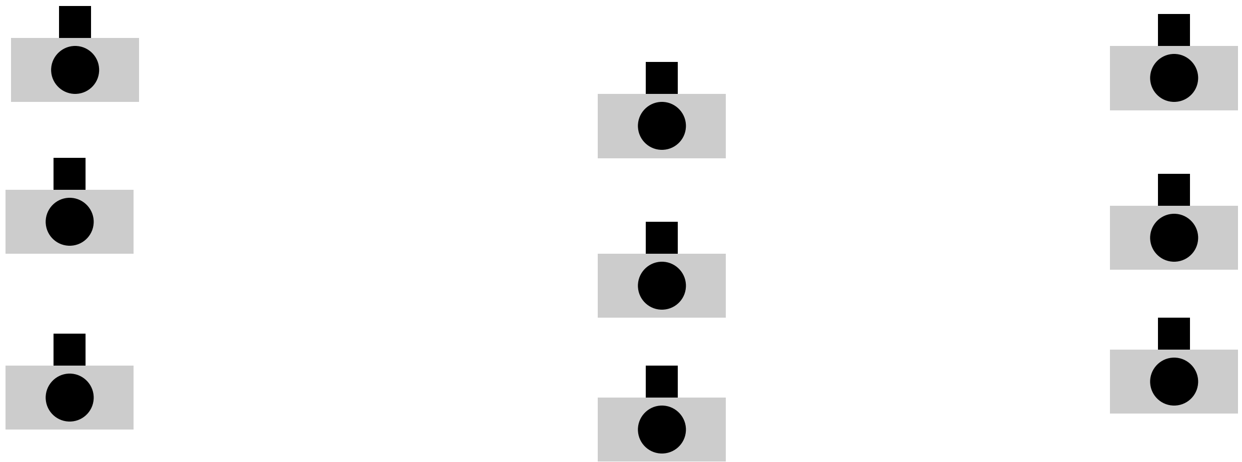


Experiment Layout (1/3)

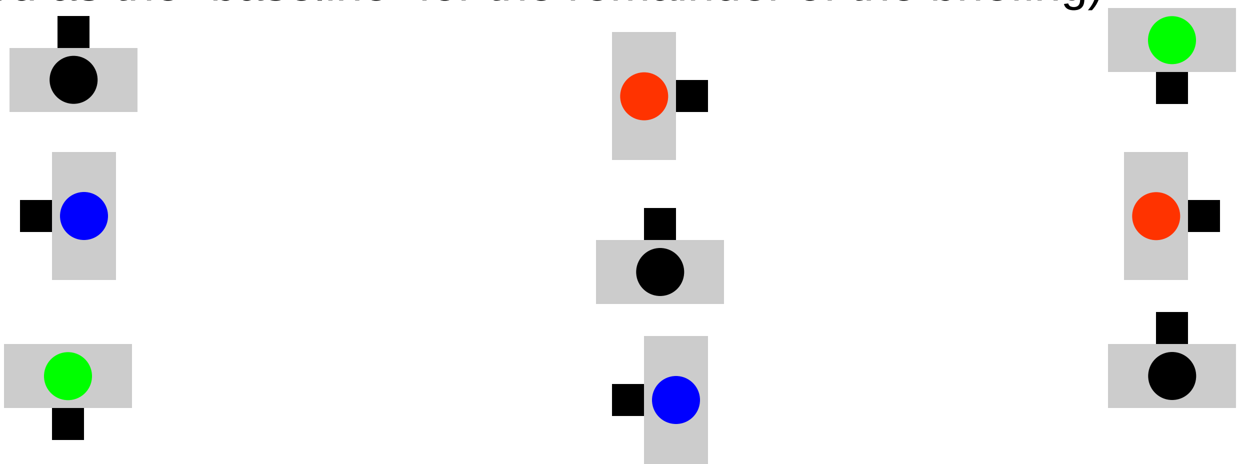


Experiment Layout (2/3)

Unrotated (as shown on the previous slide)



Rotated (used as the “baseline” for the remainder of the briefing)



Experiment Layout (3/3)

- Camera characteristics
  - 640 (horizontal) by 480 (vertical) pixels
  - FOV: 30 (horizontal) by 23 (vertical)
  - Pixel pitch: 12 microns
  - Focal length: 14.24 mm
  - Format: 7.68 mm (hz) by 5.76 mm (vl)

Procedure (1/2)

	vectors of values	*A priori* weight
Image coordinate measurements	M,	$W_M = \Sigma_{MM}^{-1}$
Camera calibration parameters	C,	$W_C = \Sigma_{CC}^{-1} = 0$
Exterior Orientation parameters	E,	$W_E = \Sigma_{EE}^{-1} = 0$
Tie point ground coordinates	G,	$W_G = \Sigma_{GG}^{-1} = 0$

→ Bundle Adjustment →

Full *a posteriori* covariance matrix

$$\begin{bmatrix} \Sigma_{MM} & \Sigma_{MC} & \Sigma_{ME} & \Sigma_{MG} \\ & \Sigma_{CC} & \Sigma_{CE} & \Sigma_{CG} \\ & & \Sigma_{EE} & \Sigma_{EG} \\ sym & & & \Sigma_{GG} \end{bmatrix}$$

Cross covariance blocks discarded since intent is to use the camera in a new "session"

$$\Delta = \begin{bmatrix} \delta x \\ \delta y \end{bmatrix} = F(x, y, \overbrace{x_o, y_o, f, K_1, K_2, K_3, P_1, P_2, b_1, b_2}^{C})$$

$$\underset{2n,2n}{\Sigma} = \underset{2n,10}{J_{FC}} \; \underset{10,10}{\Sigma_{CC}} \; \underset{10,2n}{J_{FC}^{T}}$$, for a grid of *n* points in any image.

Equation Reference: Fraser, C. S., 1997: "Digital camera self-calibration", Invited Review Paper, ISPRS Journal of Photogrammetry & Remote Sensing, Vol. 52, pp. 149-159.

Procedure (2/2)

$$\underset{2n,2n}{\Sigma} \equiv \begin{bmatrix} \Sigma_{00} & \cdots & \Sigma_{0i} & \cdots & \Sigma_{0n} \\ & \ddots & & & \\ & & \Sigma_{ii} & & \\ & & & \ddots & \\ sym & & & & \Sigma_{nn} \end{bmatrix}$$

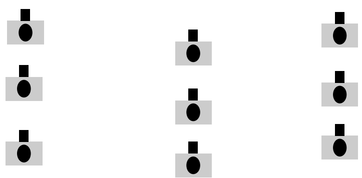
Absolute 2 by 2 error covariance matrix for the i[th] point:

$$\Sigma_{ii}$$

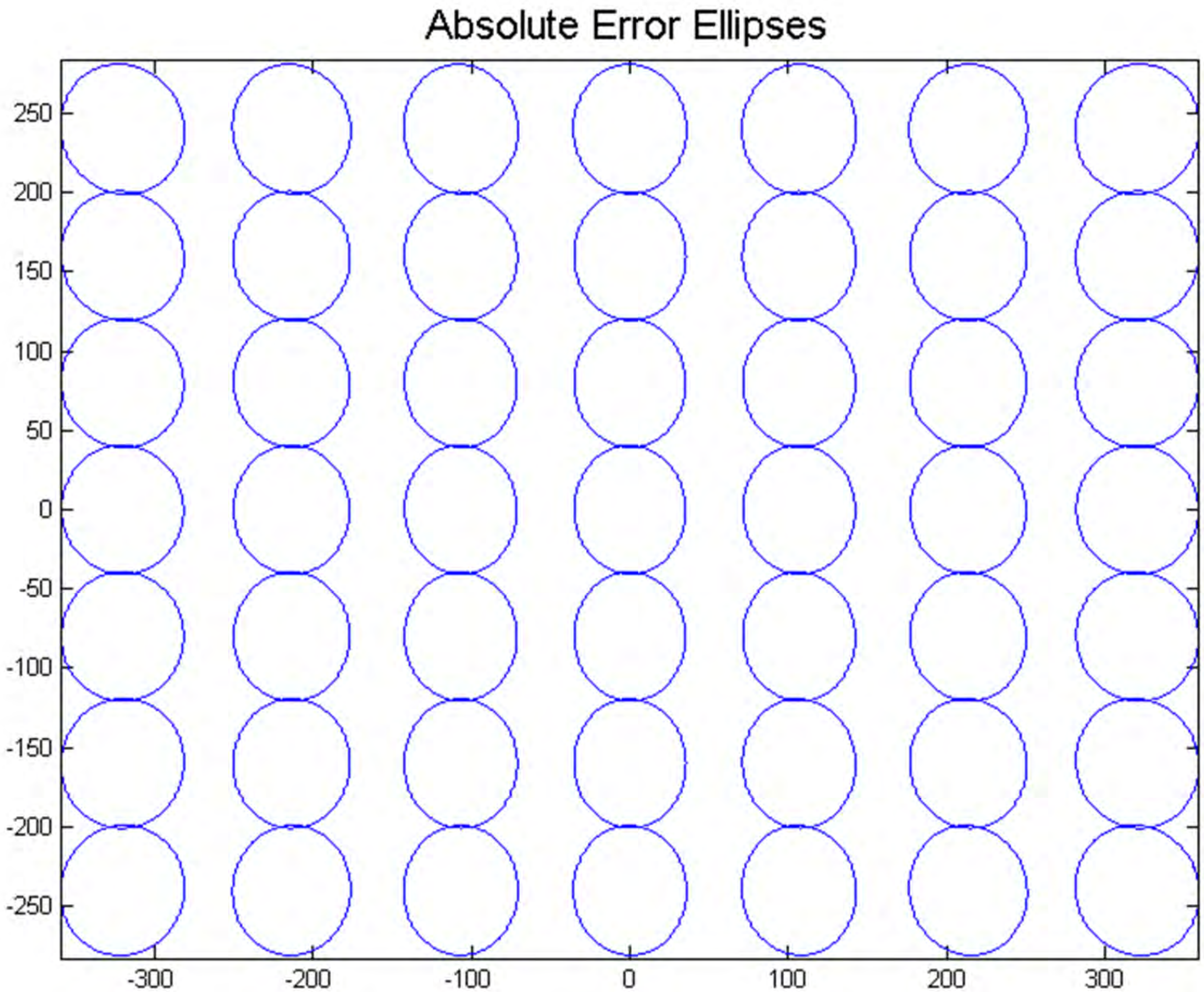
Relative 2 by 2 error covariance matrix for the i[th] point with respect to the 0[th] point (image's origin):

$$R_{ii} = \Sigma_{ii} + \Sigma_{00} - \Sigma_{0i} - \Sigma_{0i}^{T}$$

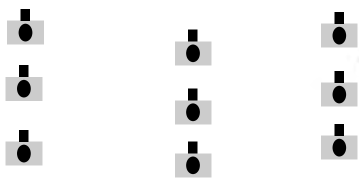
All Cameras unrotated

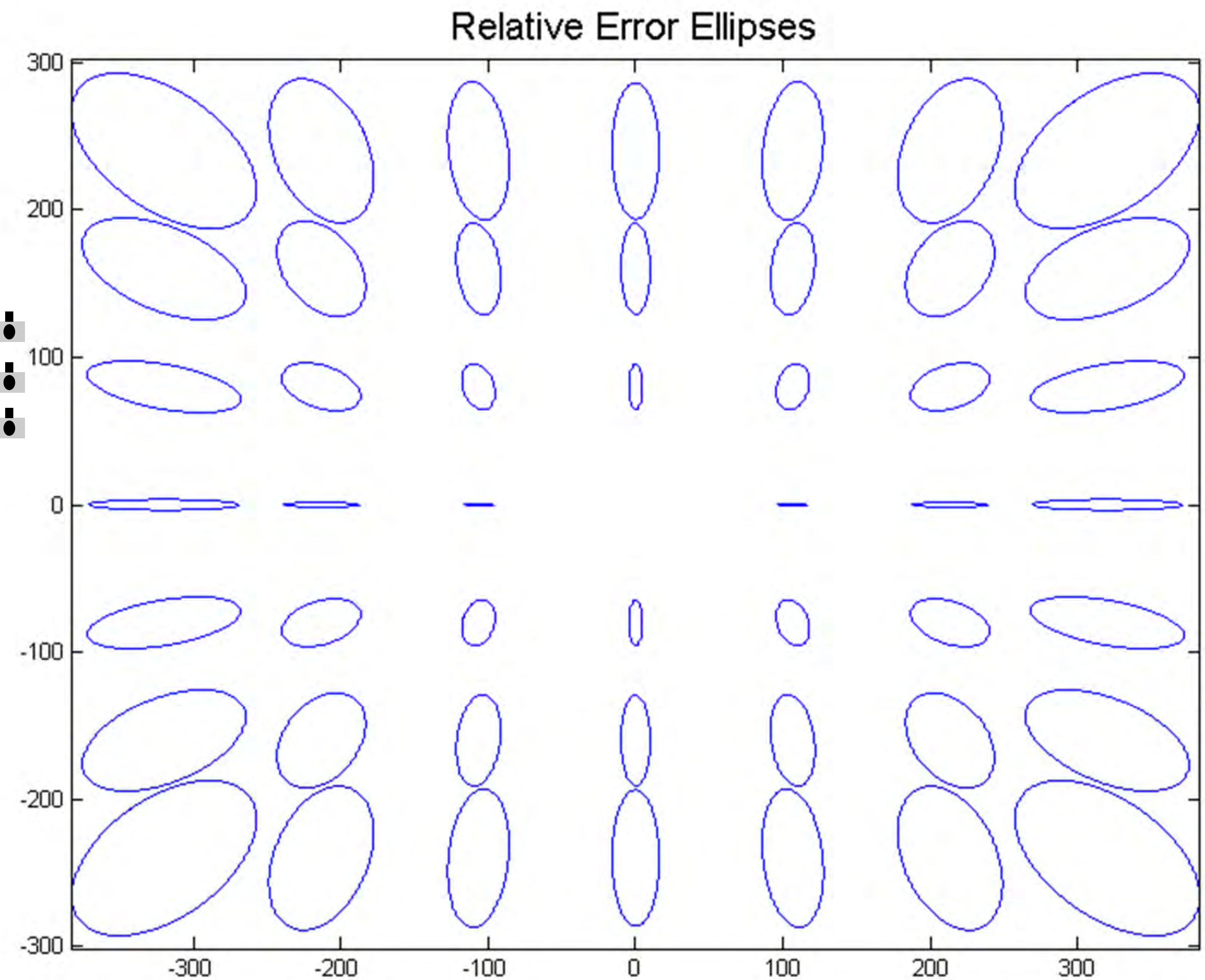


21 pixels



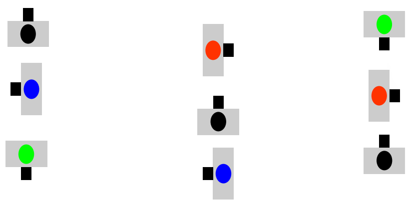
All Cameras unrotated

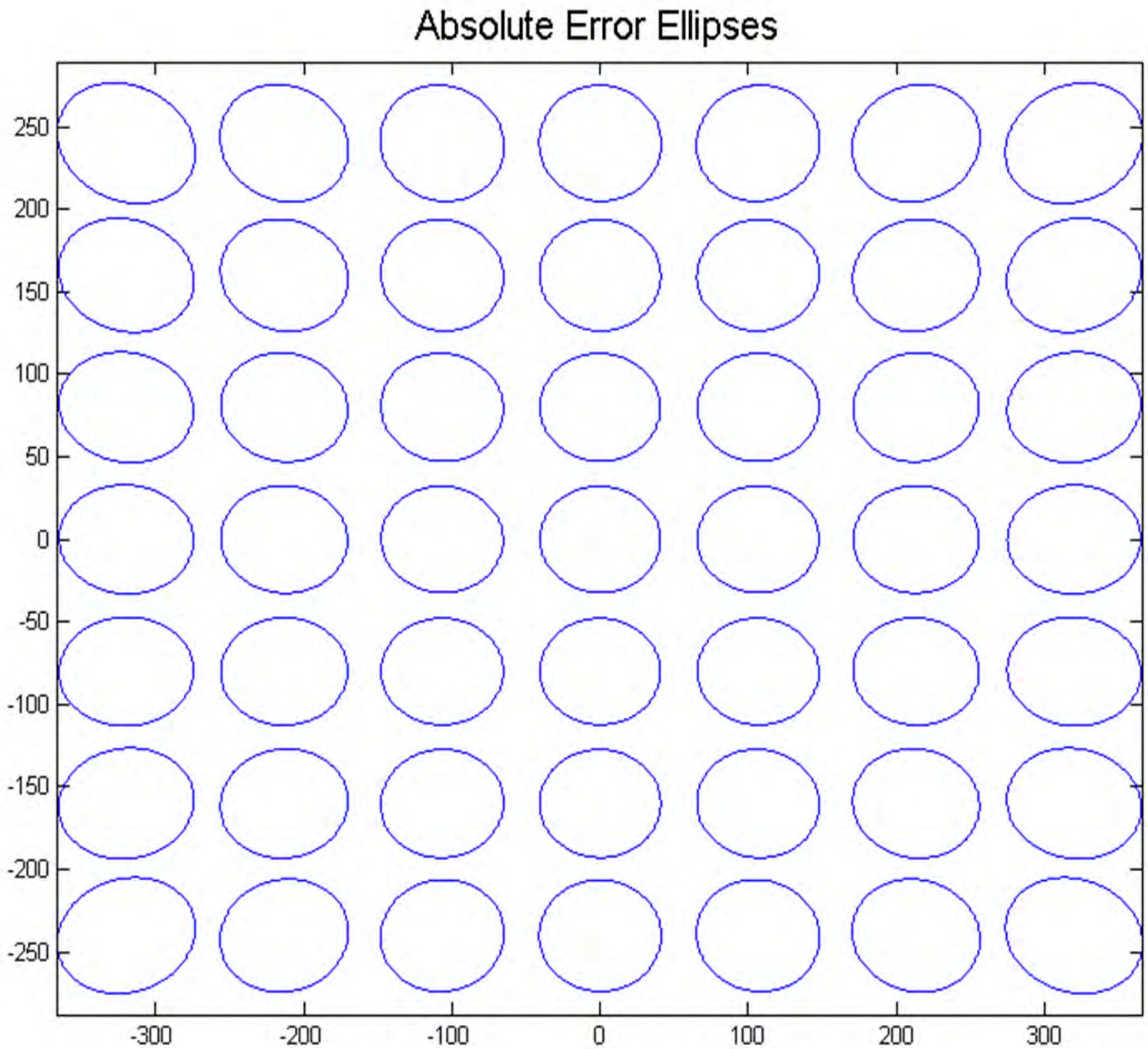




2.9 pixels

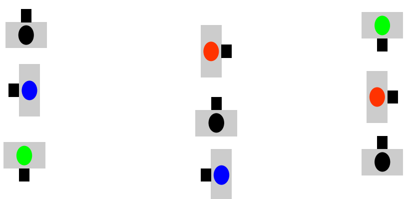
Cameras at
different orientations

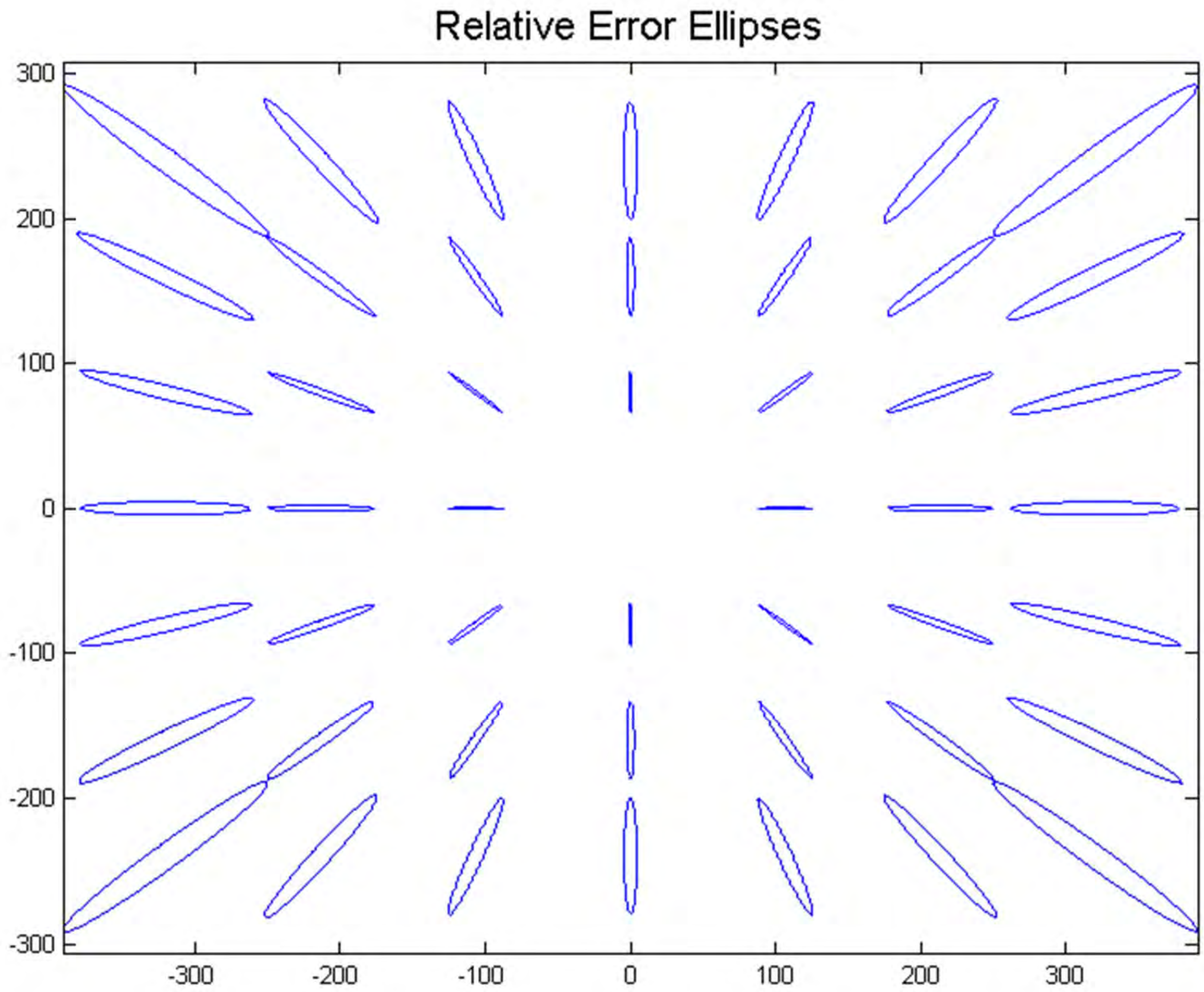




4.7 pixels

Cameras at
different orientations

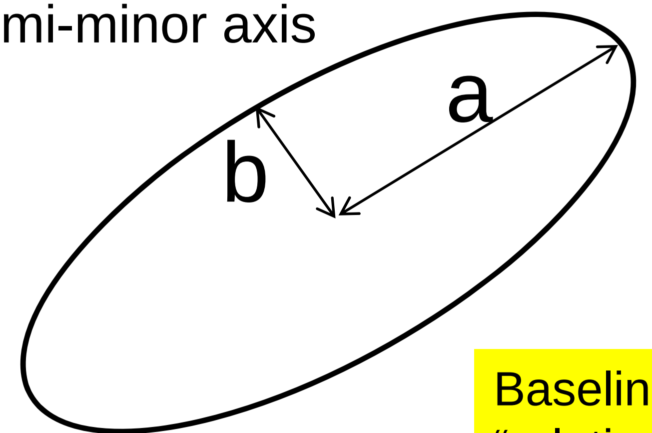




1.8 pixels

Quality Metric

a = semi-major axis
b = semi-minor axis



Baseline case is "relative, rotated"

	absolute		relative	
	Un-rotated	rotated	Un-rotated	**rotated**
mean b	18.4	3.3	0.7	**0.1**
mean a	20.4	4.3	1.6	**0.9**
max a	20.7	4.7	2.9	**1.8**

All in units of pixels

One-sigma absolute uncertainties (with respect to IO in mm)

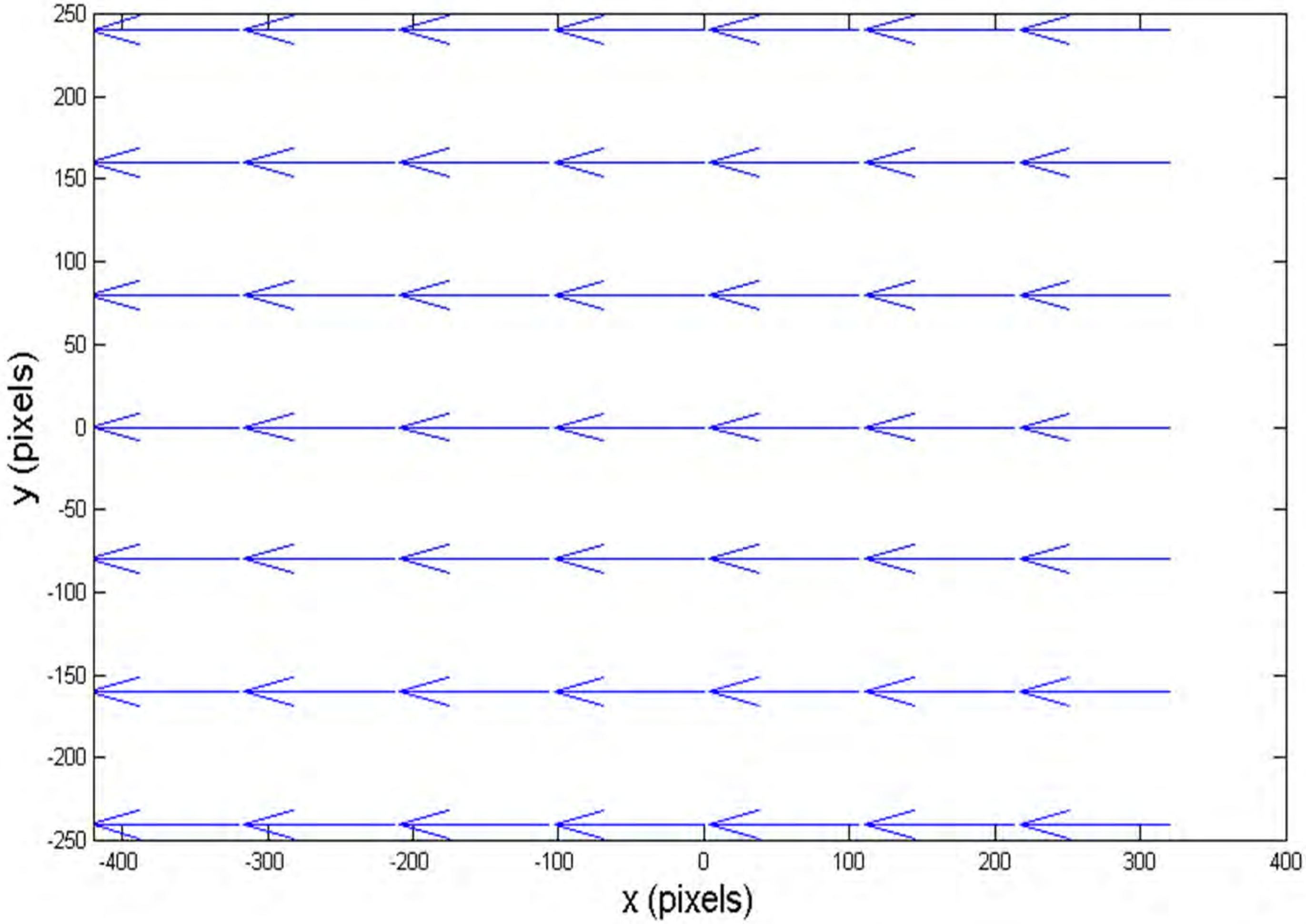
	Un-rotated	rotated
xo:	25.40e-2	4.87e-2
yo:	28.31e-2	3.86e-2
f:	13.28e-2	5.26e-2
K1:	7.71e-4	5.29e-4
K2:	9.43e-5	5.08e-5
K3:	3.55e-6	1.49e-6
P1:	56.79e-5	8.98e-5
P2:	14.61e-5	7.32e-5
b1:	89.56e-4	2.85e-4
b2:	25.73e-4	2.62e-4

Parameter Plots

- The previous slide states that the baseline case for this briefing is “relative”, i.e. the scenario of all sensitivity plots
- In so doing, we are assuming that the primary use of these images in downstream applications will involve image registration or relative mensuration (where adjustable parameters essentially remove offsets), vice direct geopositioning (where every offset must be accounted)
- The next 10 slides plot the effect of each of the camera calibration parameters in an absolute sense, however, to give the audience an understanding of their full effect

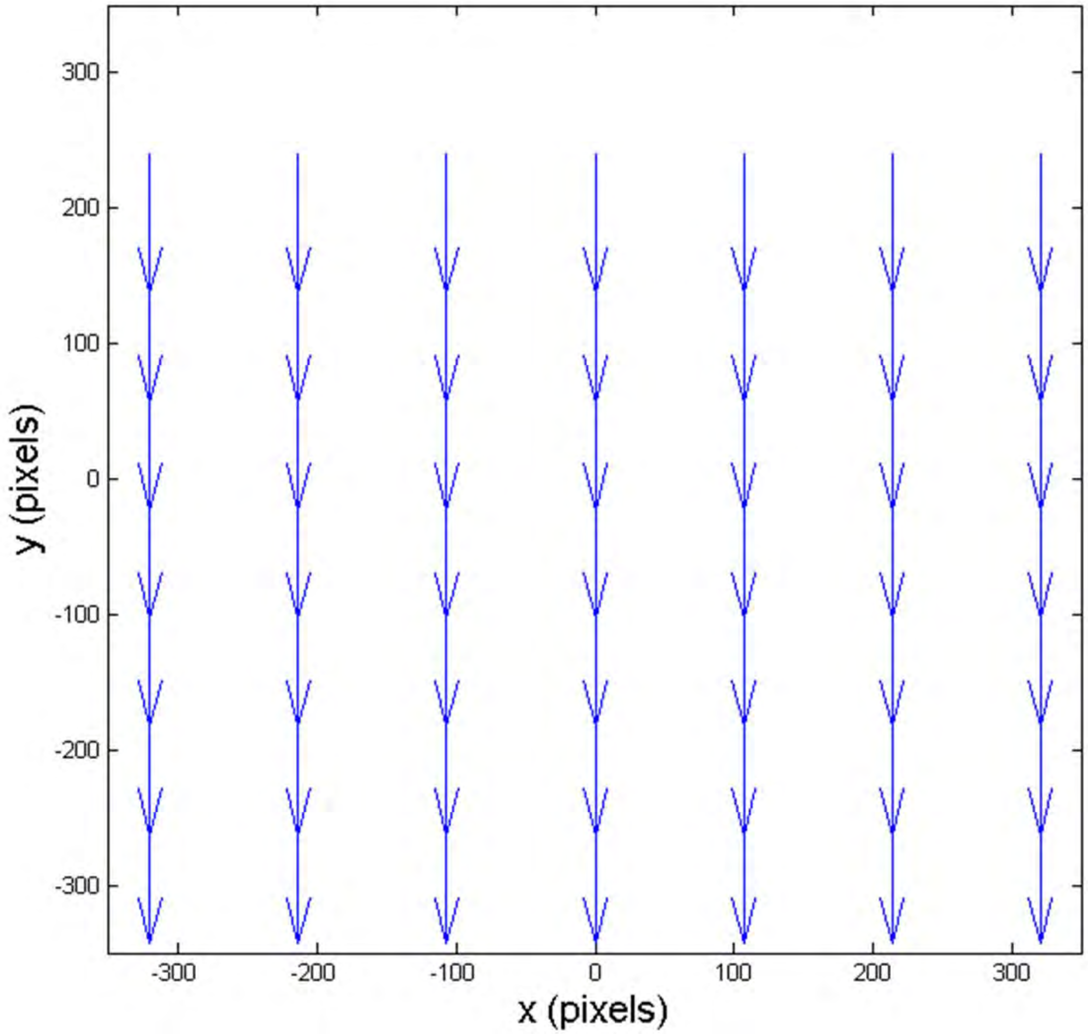
x_o (Principal Point Offset)

- Plot shows effect of a $+x_o$ value set equal to the one-sigma uncertainty of the “baseline” case



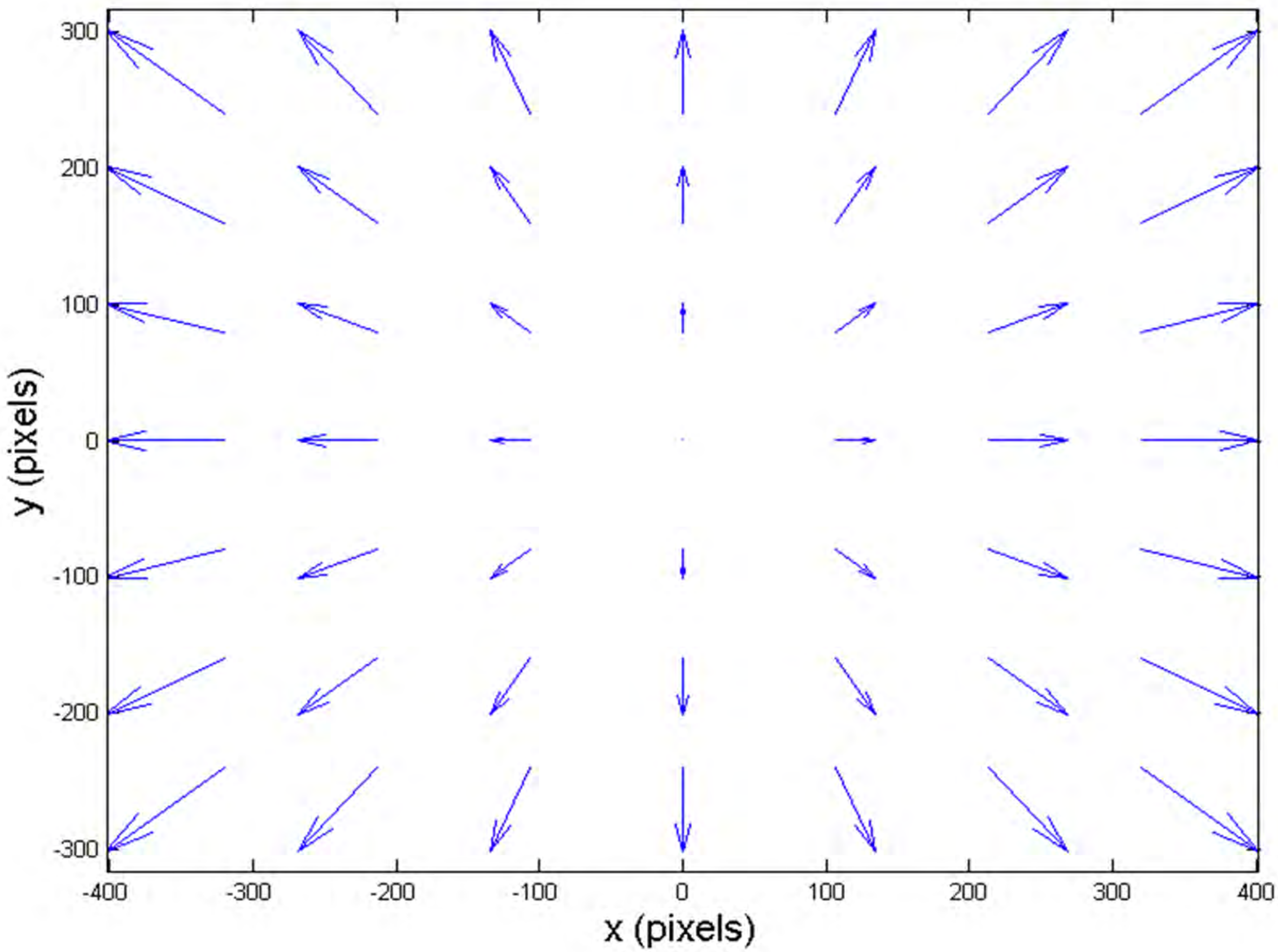
4.1 pixels

y_o (Principal Point Offset)



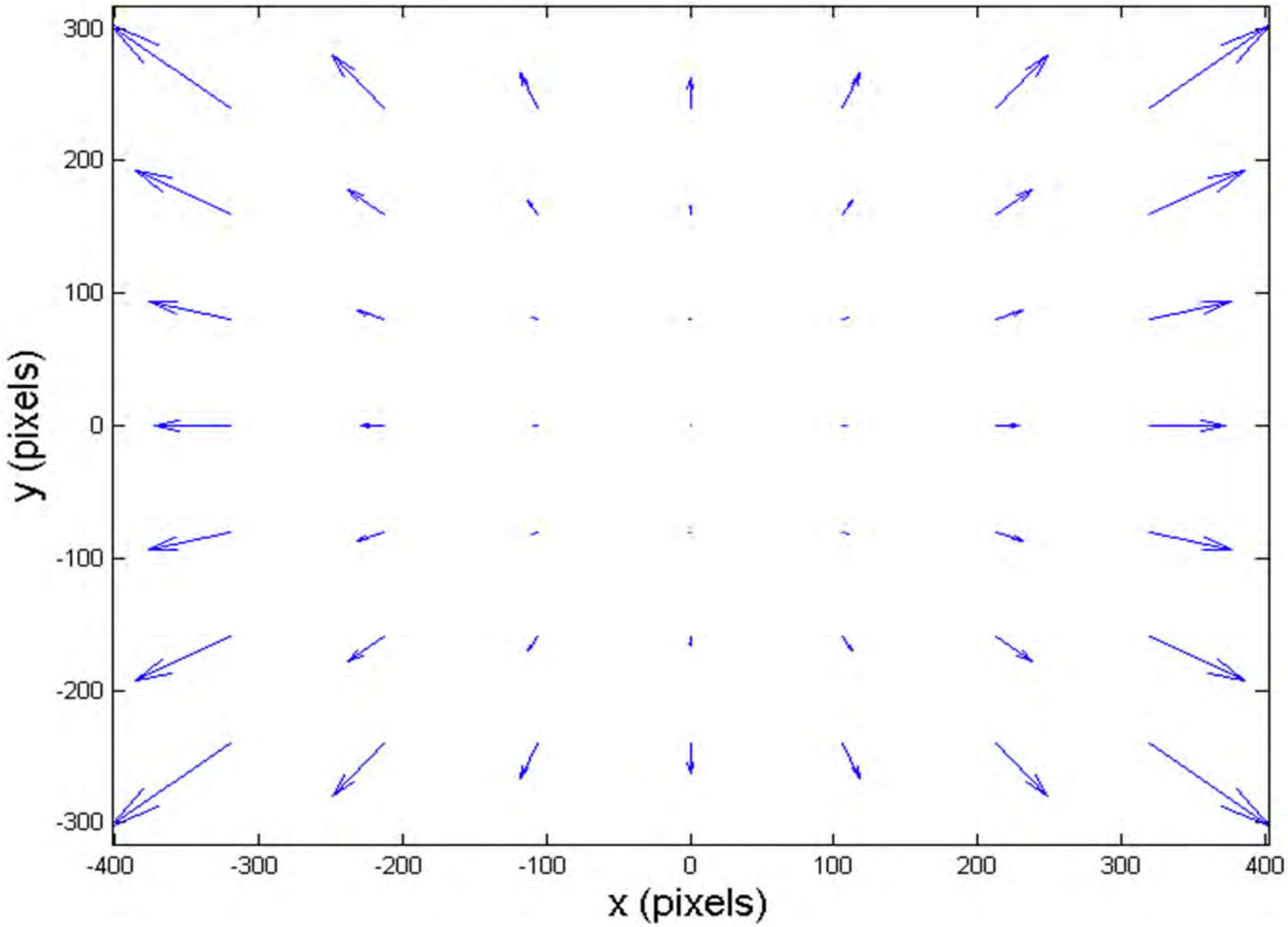
3.2 pixels

f (focal length)



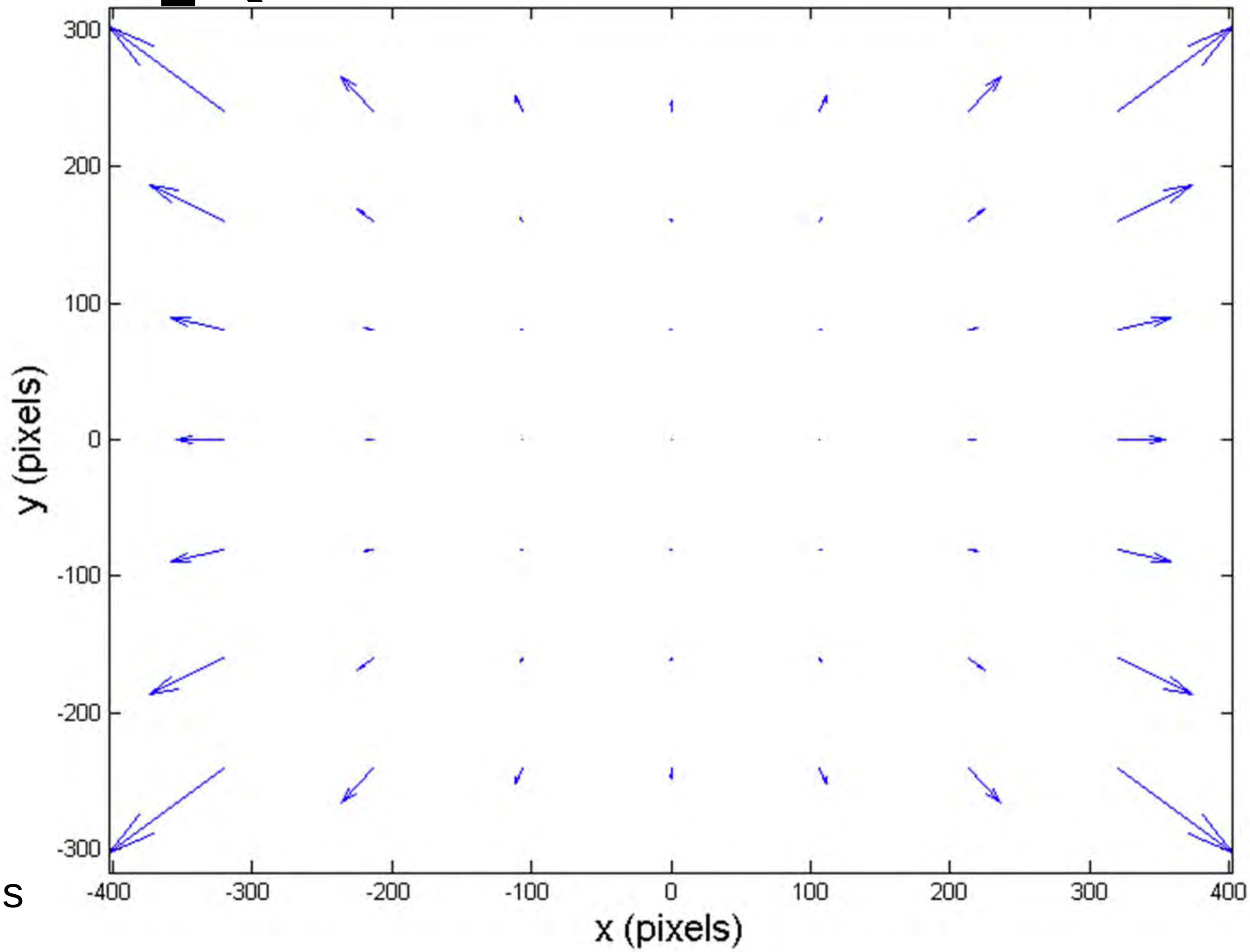
1.5 pixels

K_1 (Radial Lens Distortion)



4.9 pixels

K_2 (Radial Lens Distortion)



10.8 pixels

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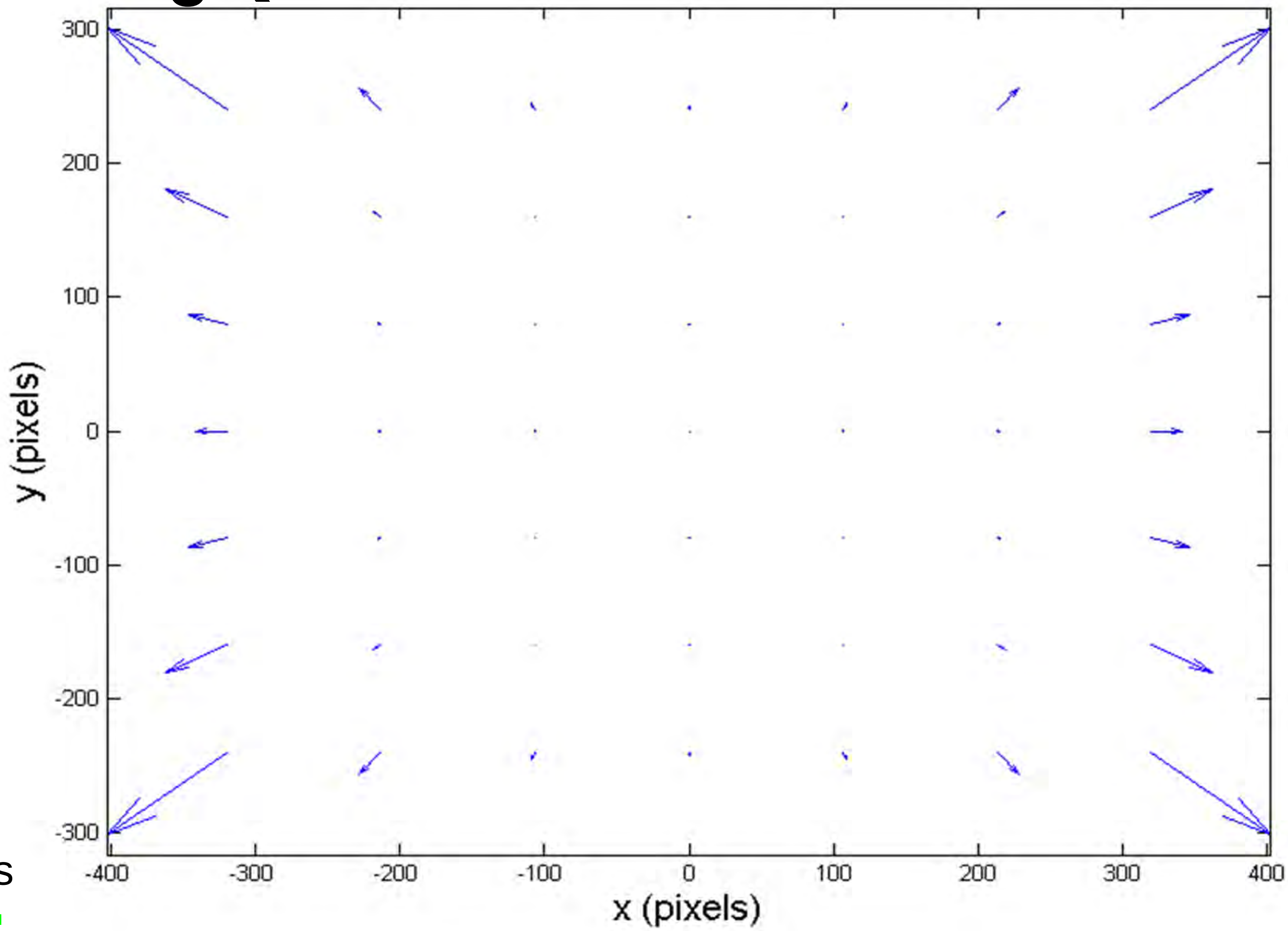
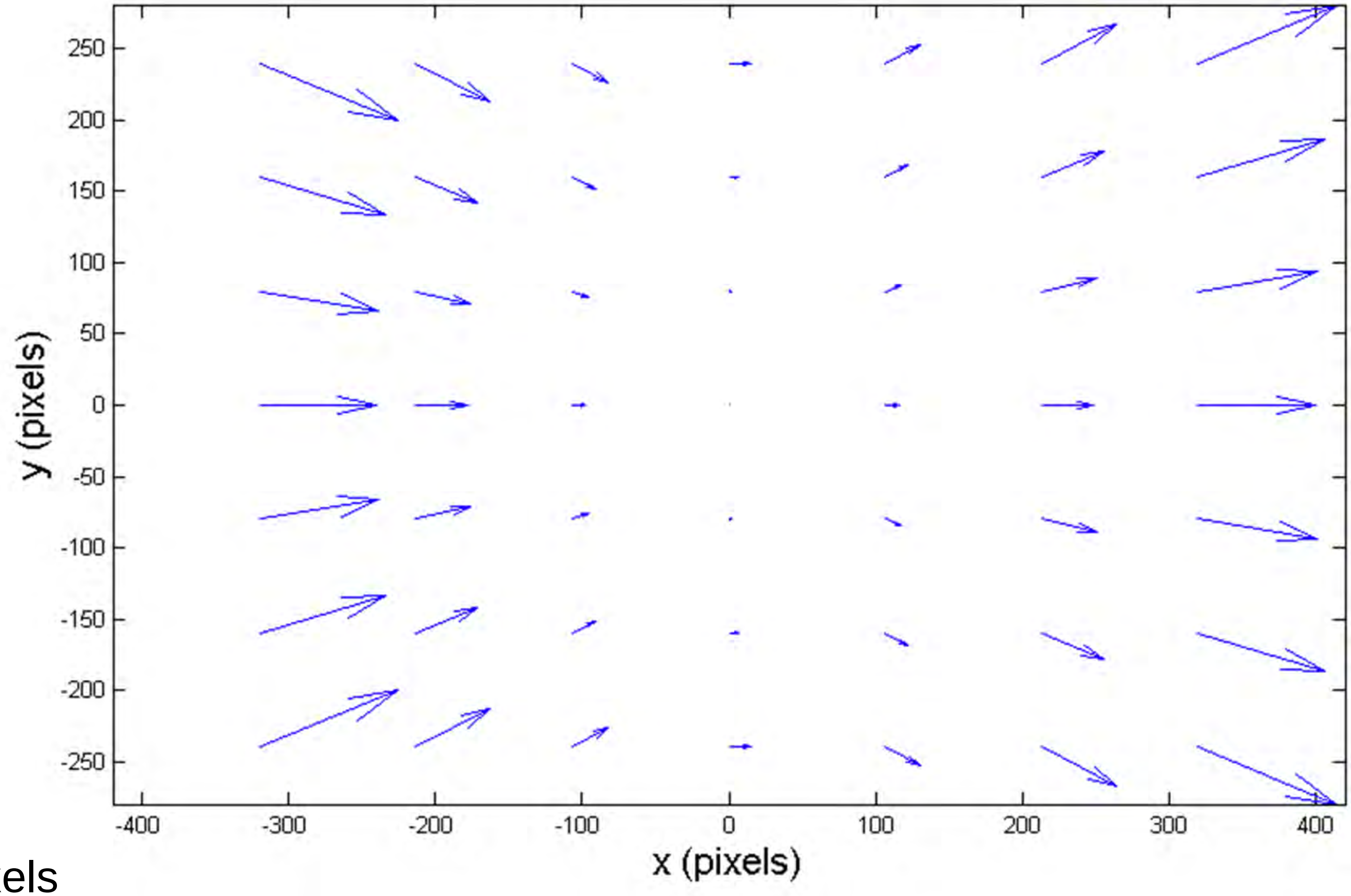
K_3 (Radial Lens Distortion)



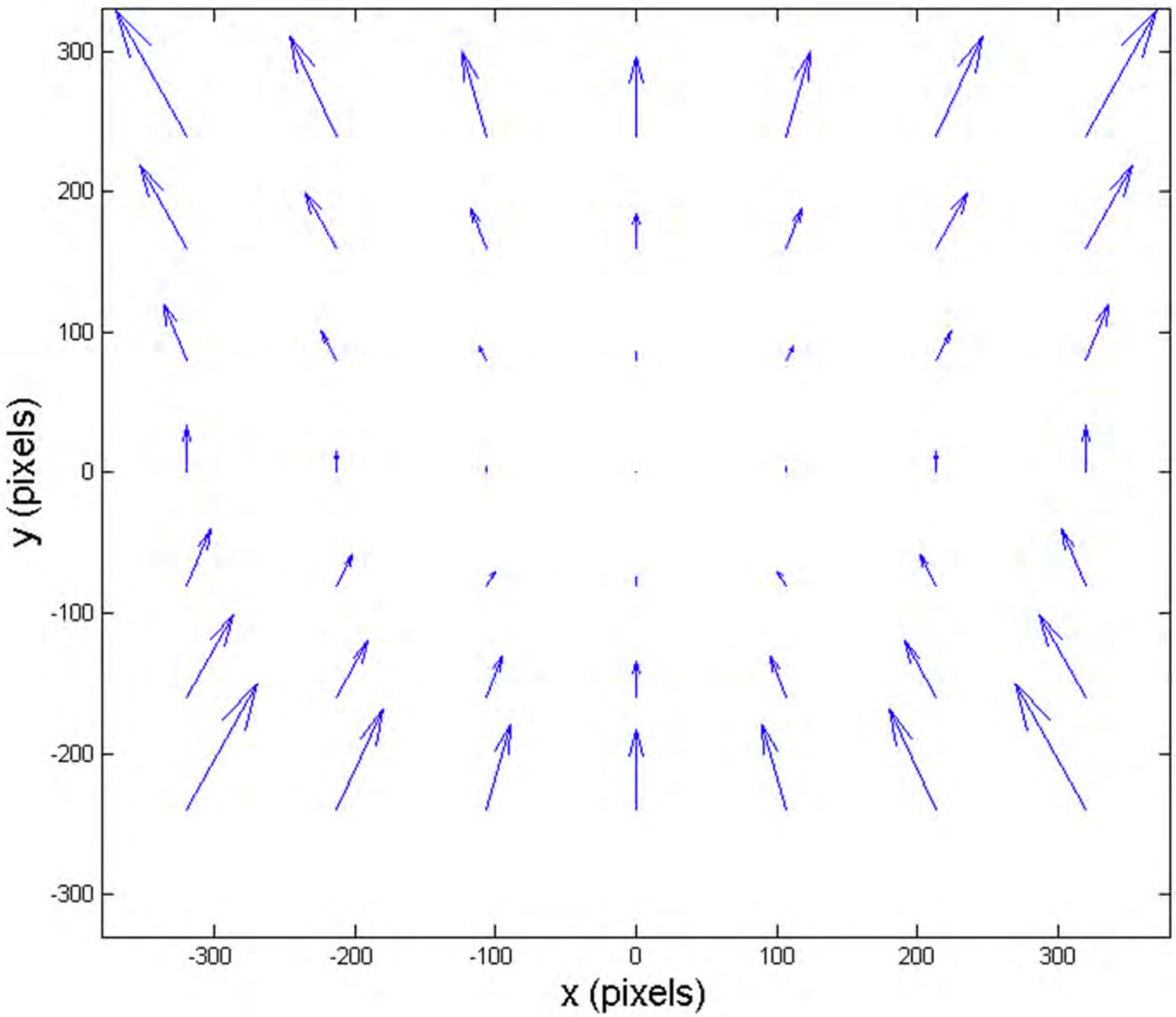
7.3 pixels

P_1 (Decentering Lens Distortion)



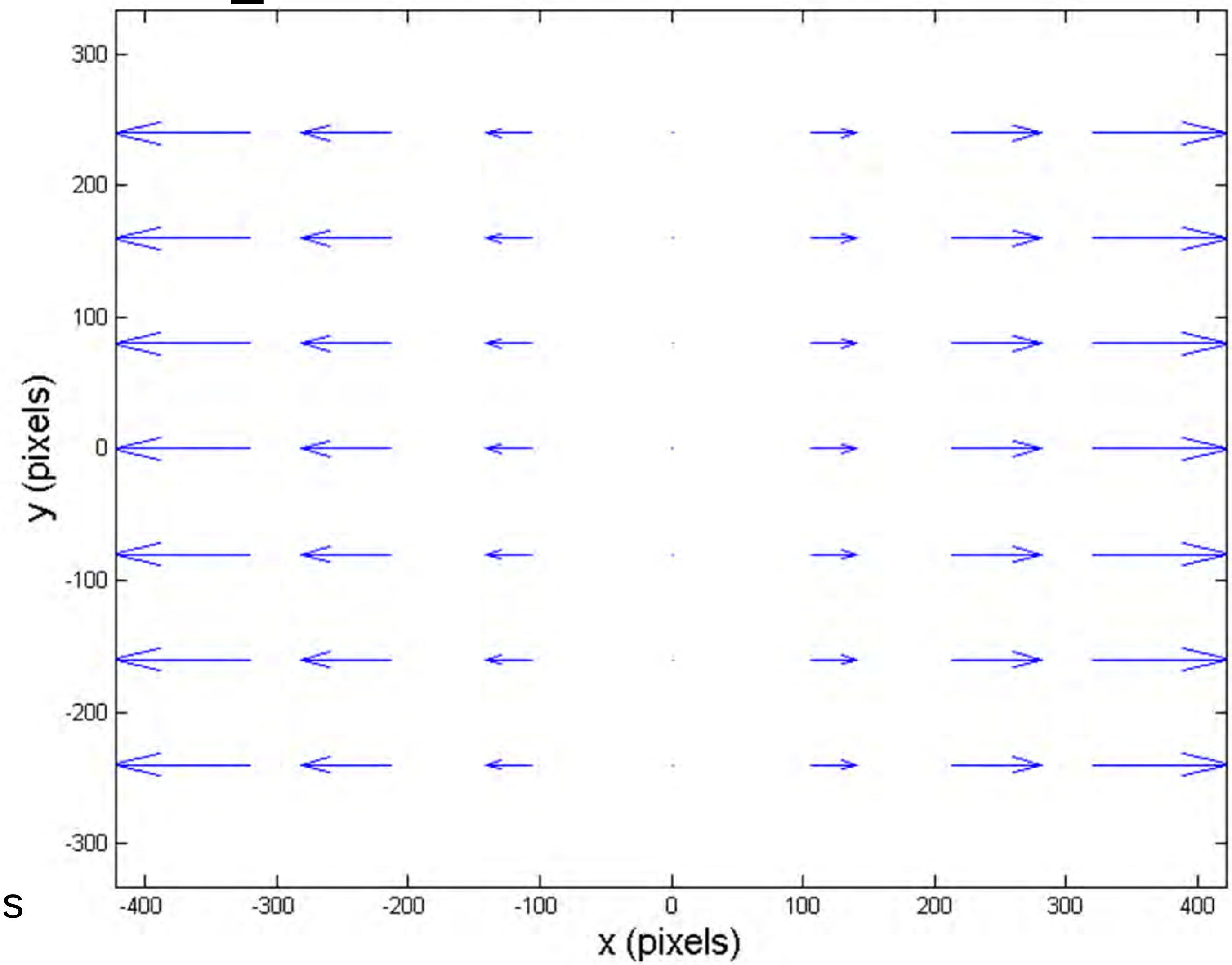
0.4 pixels

P_2 (Decentering Lens Distortion)



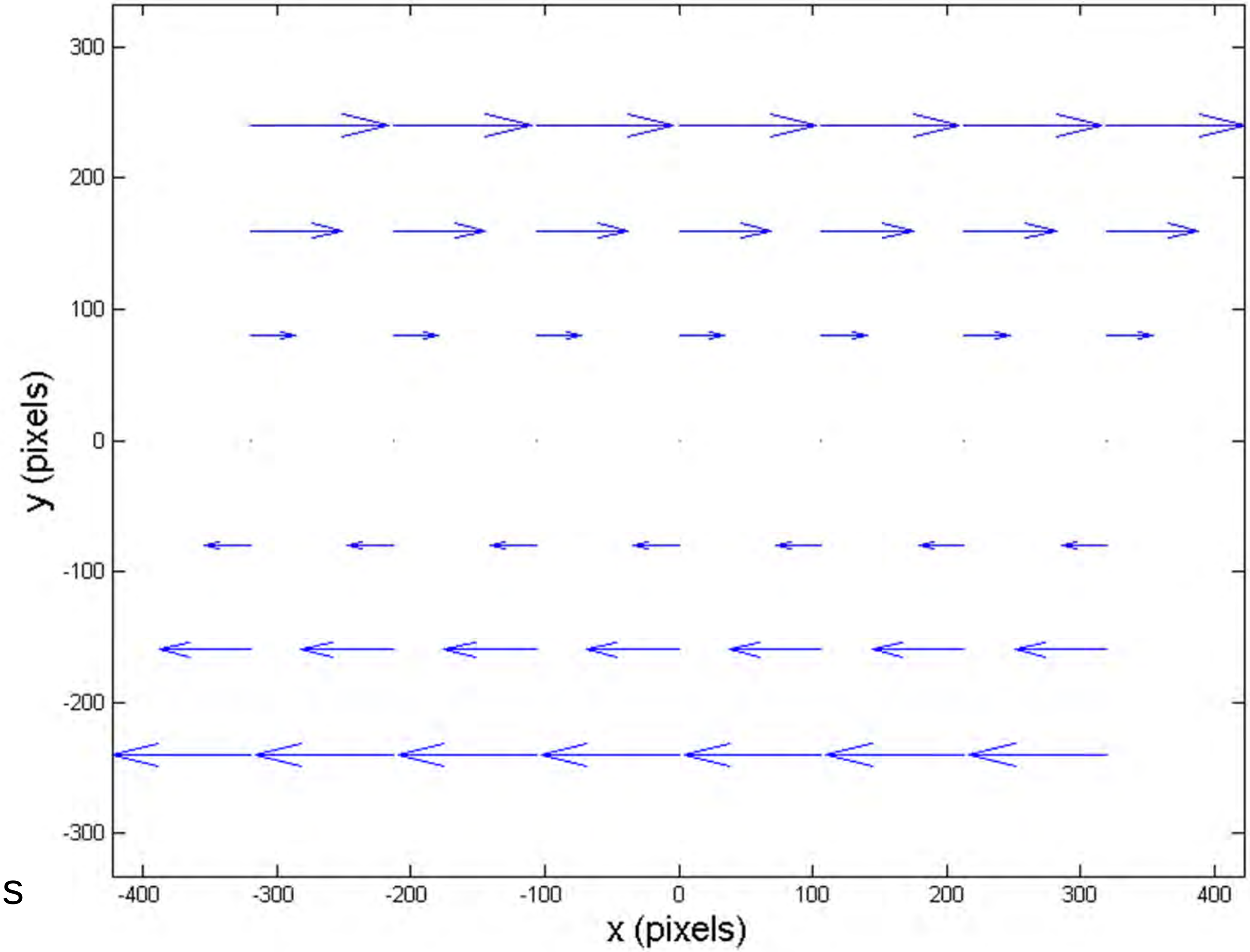
0.3 pixels

b_1 (Differential Scale)



0.09 pixels

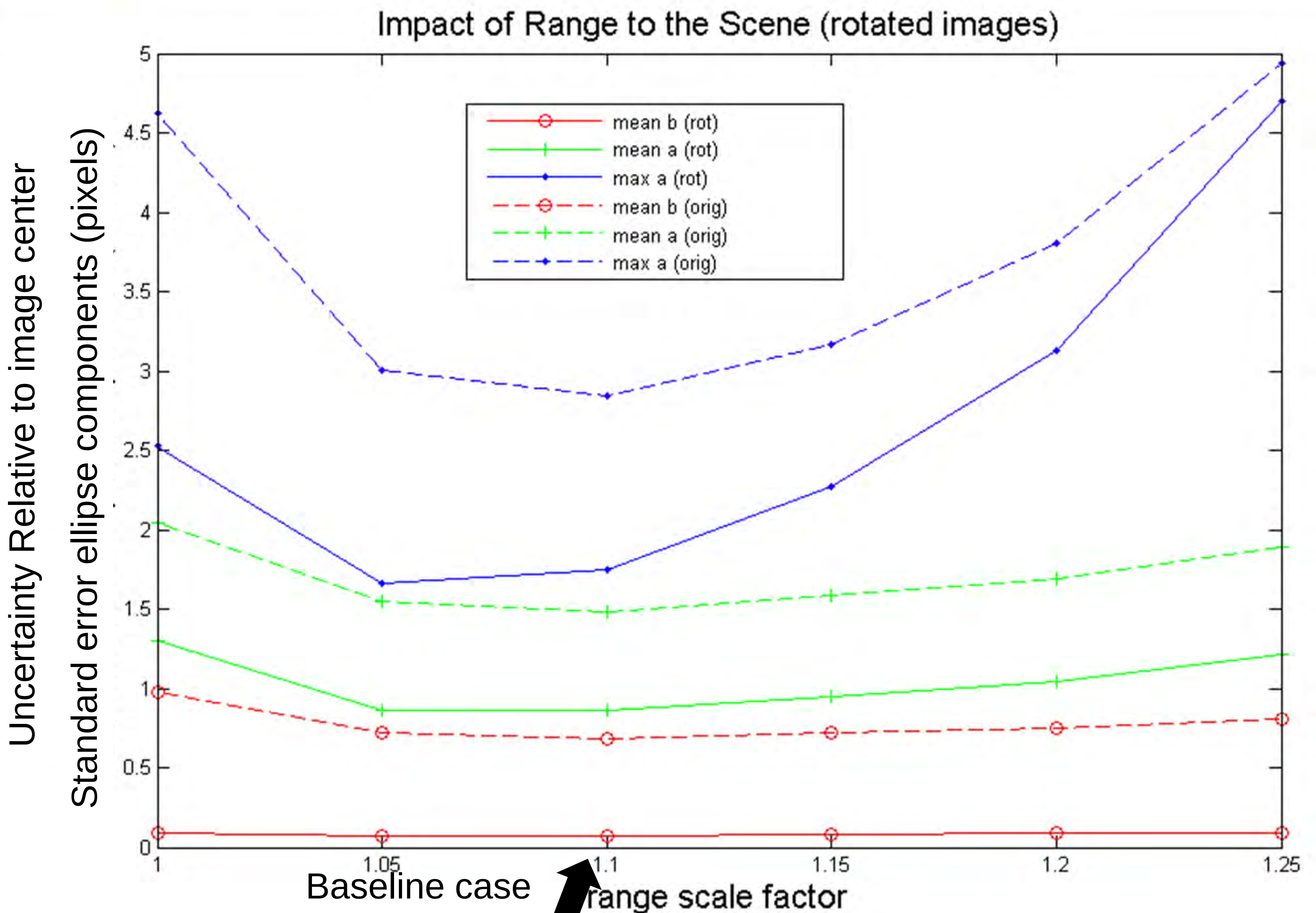
b_2 (Skew)



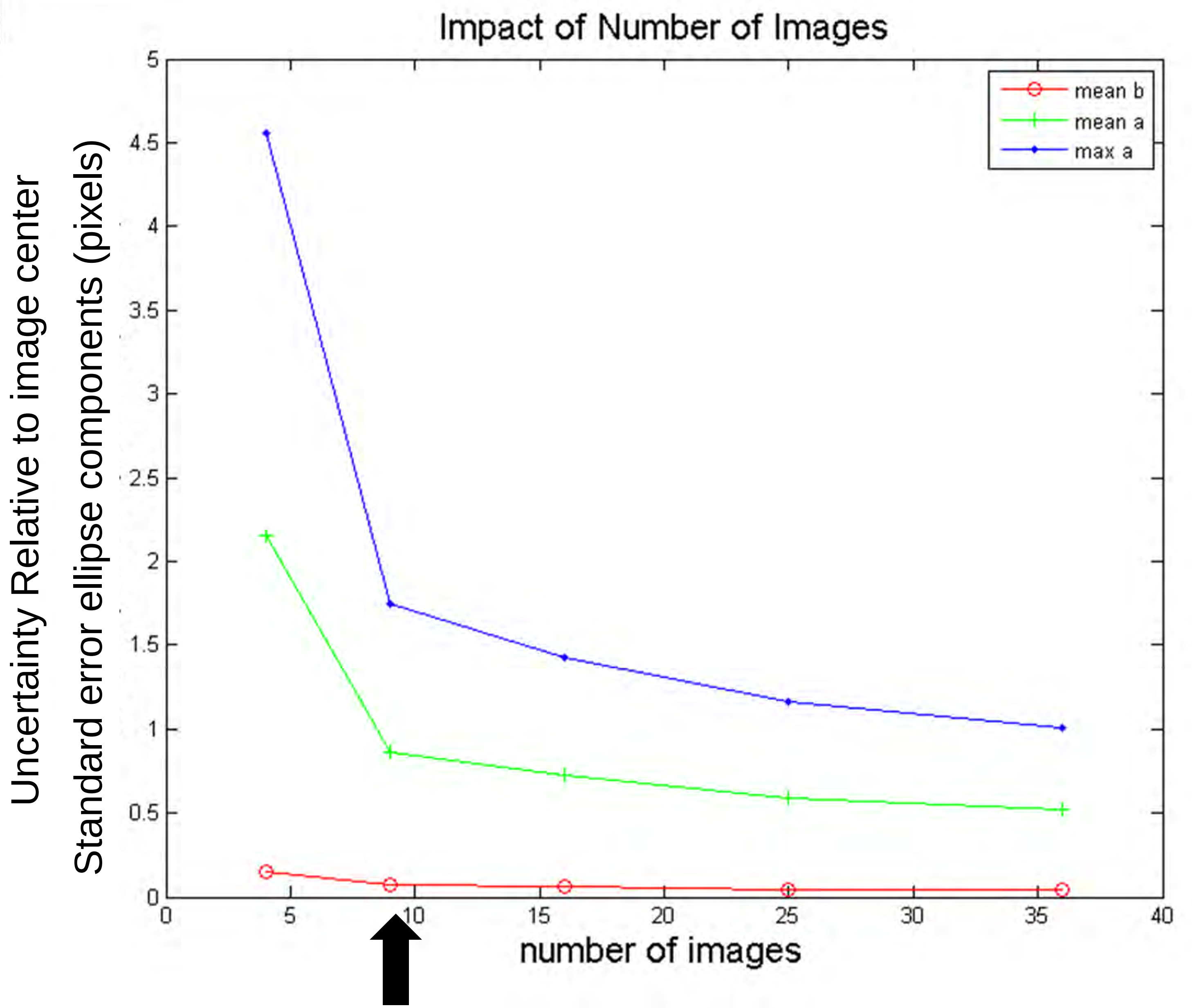
0.06 pixels

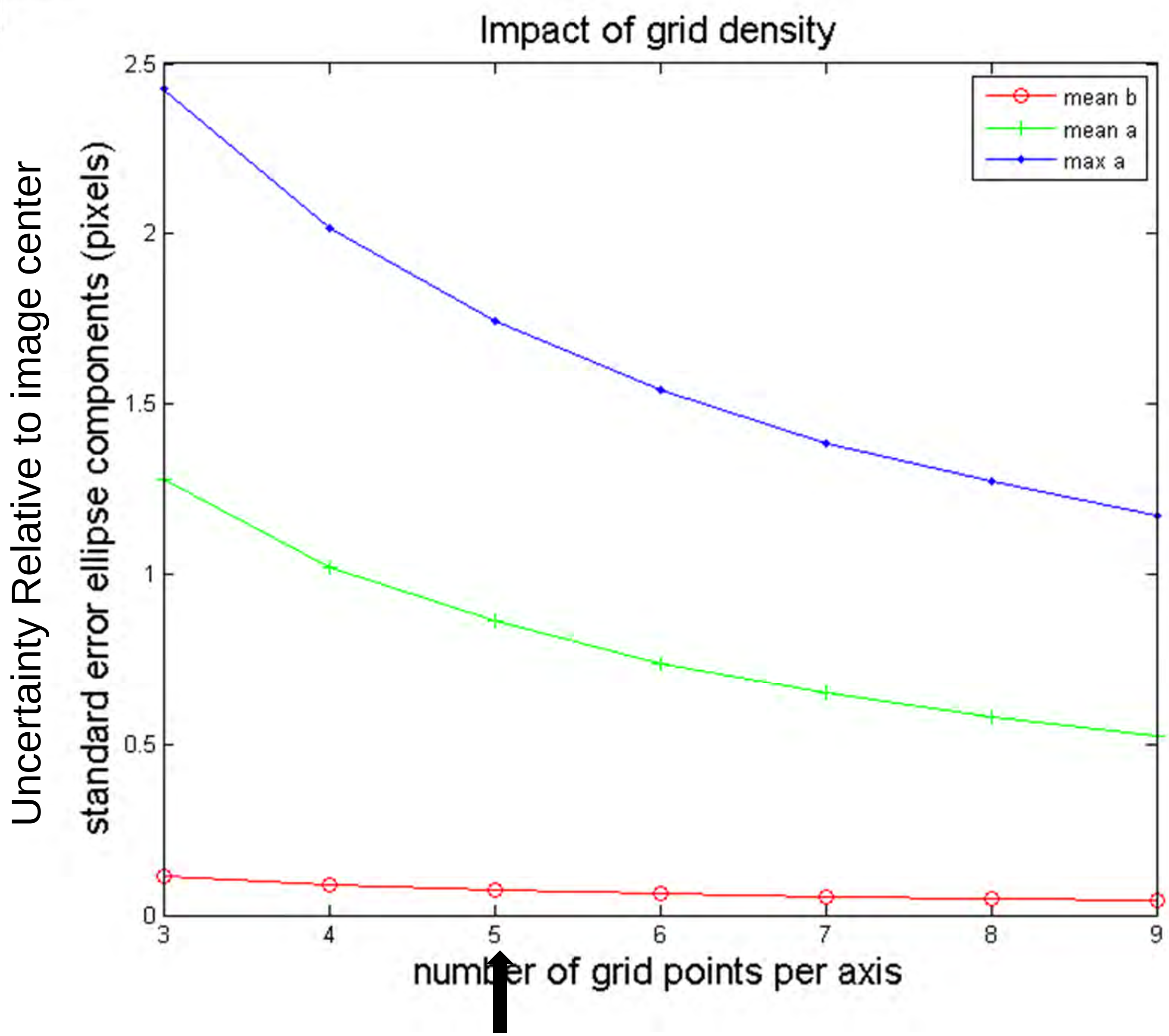
Sensitivities

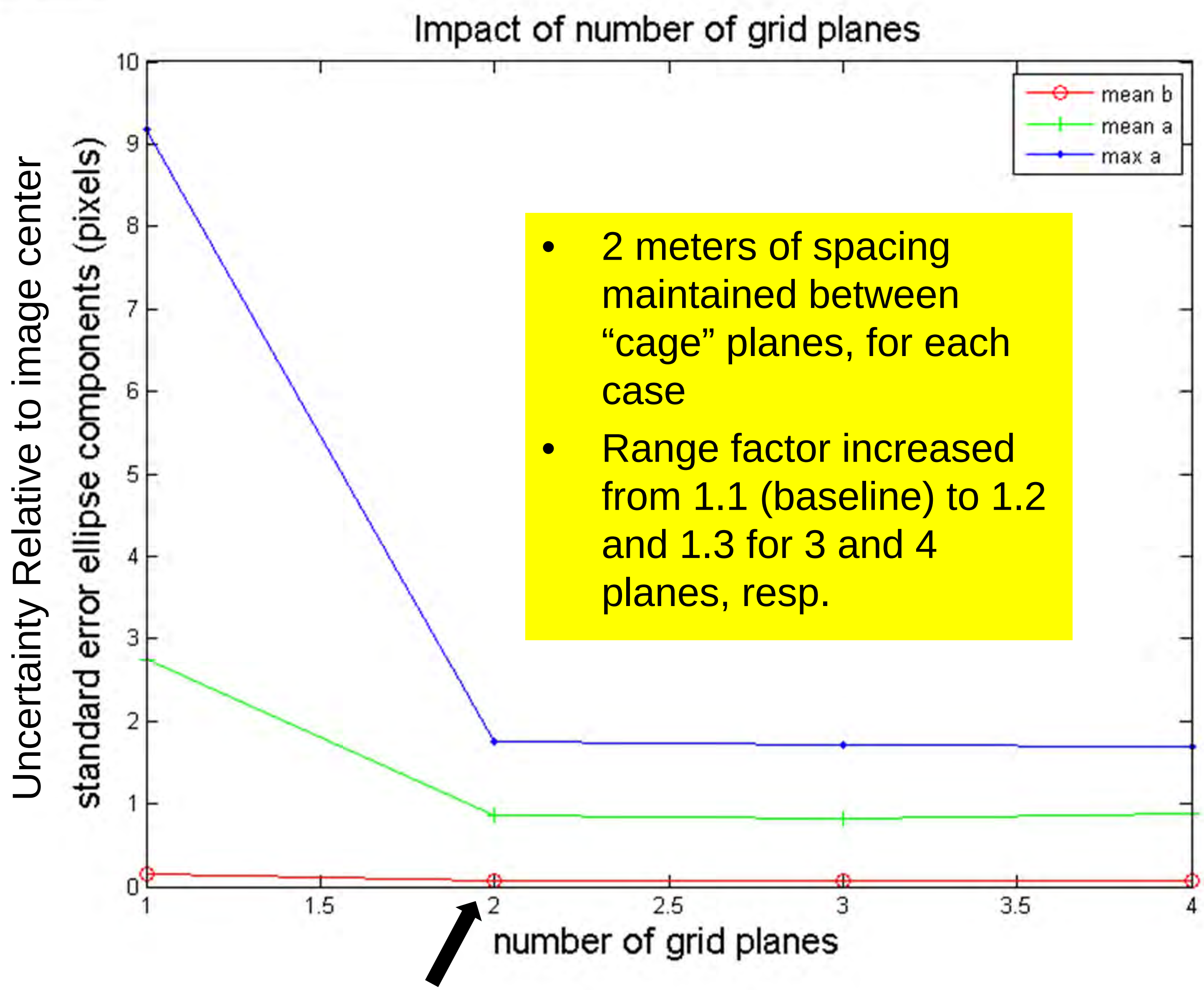
- Range to the Scene
- Number of Images
- Grid Density
- Number of “Cage” Planes
- Plane Spacing
- Image Coordinate Measurement Precision
- Horizontal Convergence Angle
- Vertical Convergence Angle
- Focal Length
- Fewer Calibration Parameters
- Ground Control Points

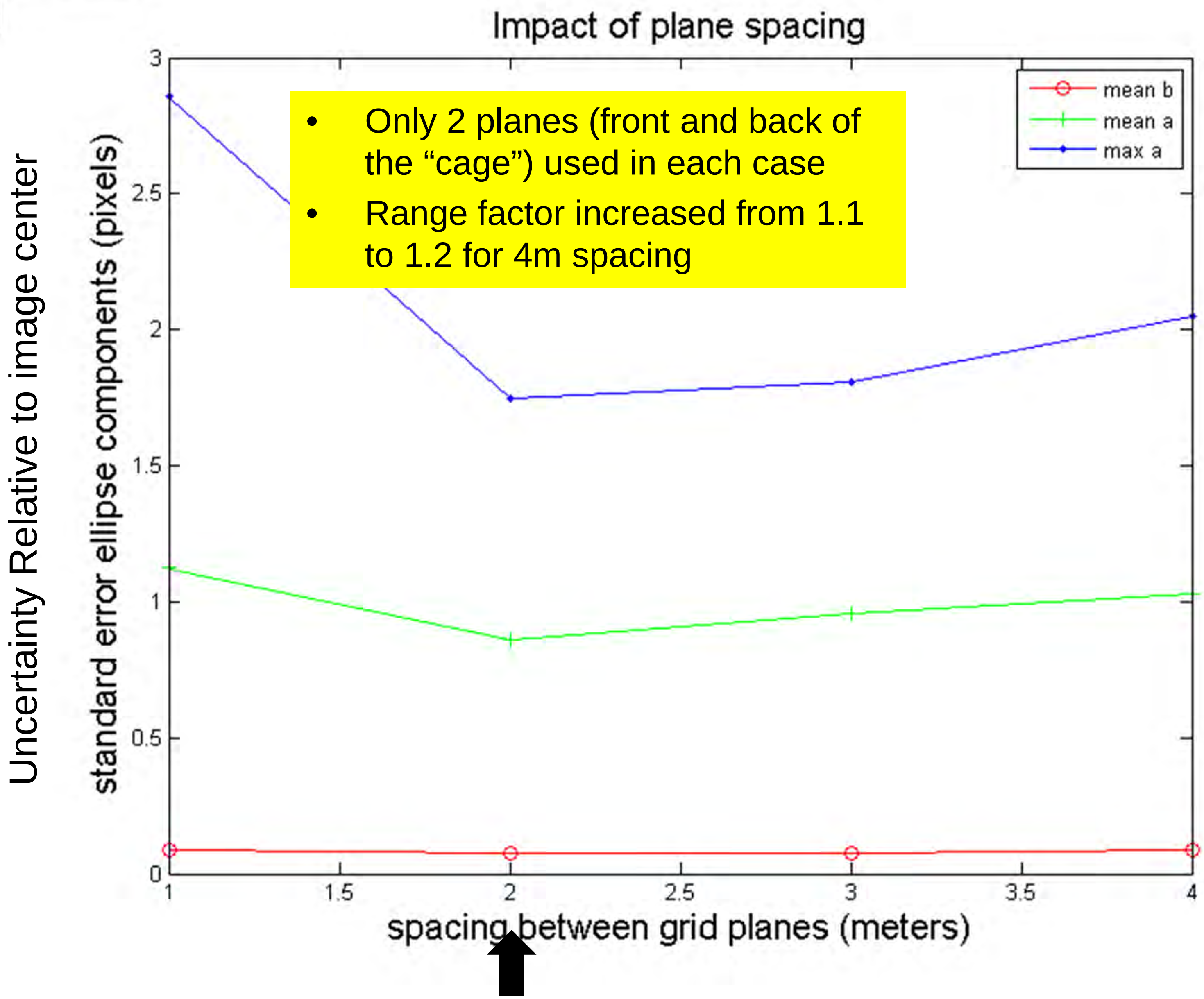


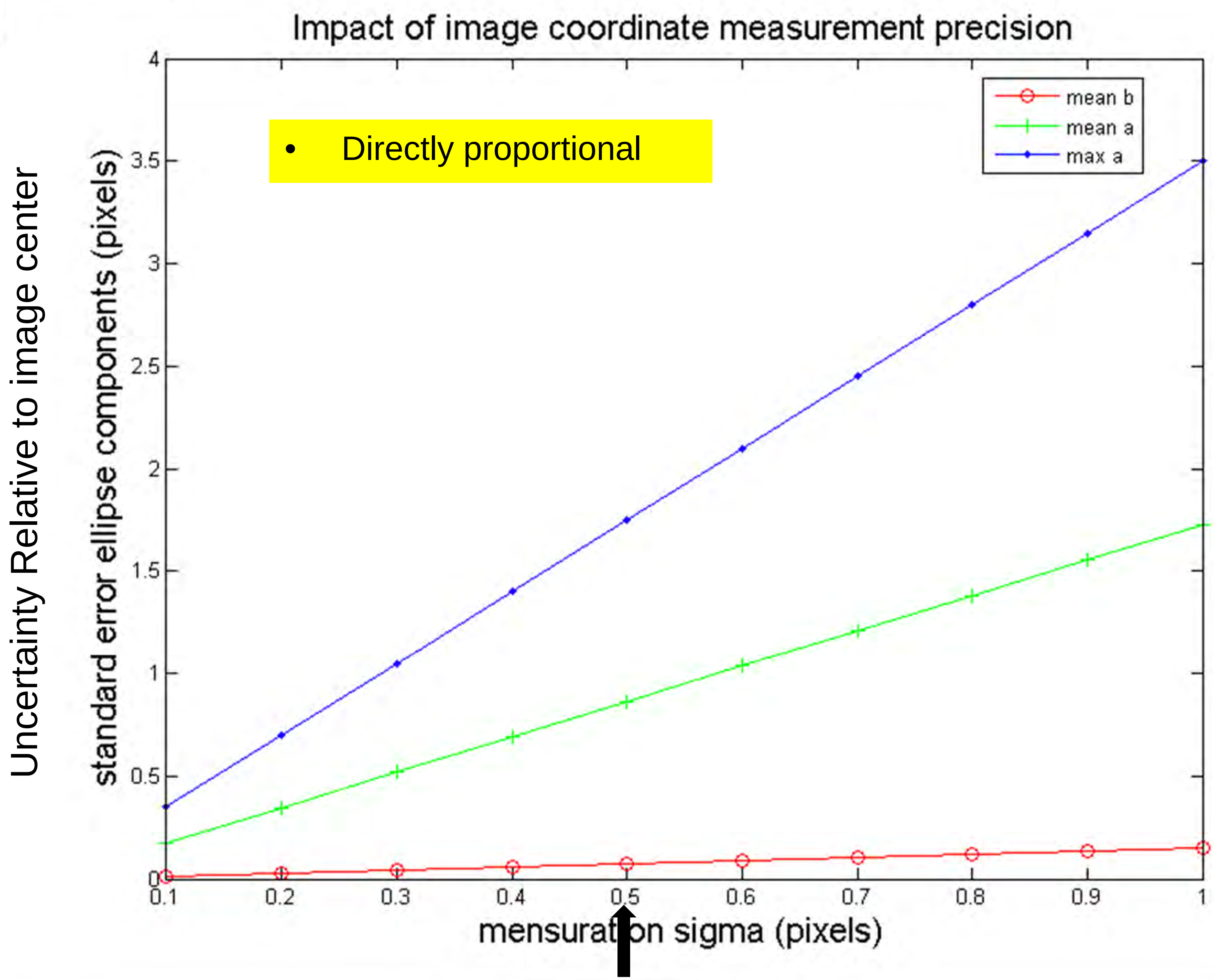
Baseline case
(Range = 9m)

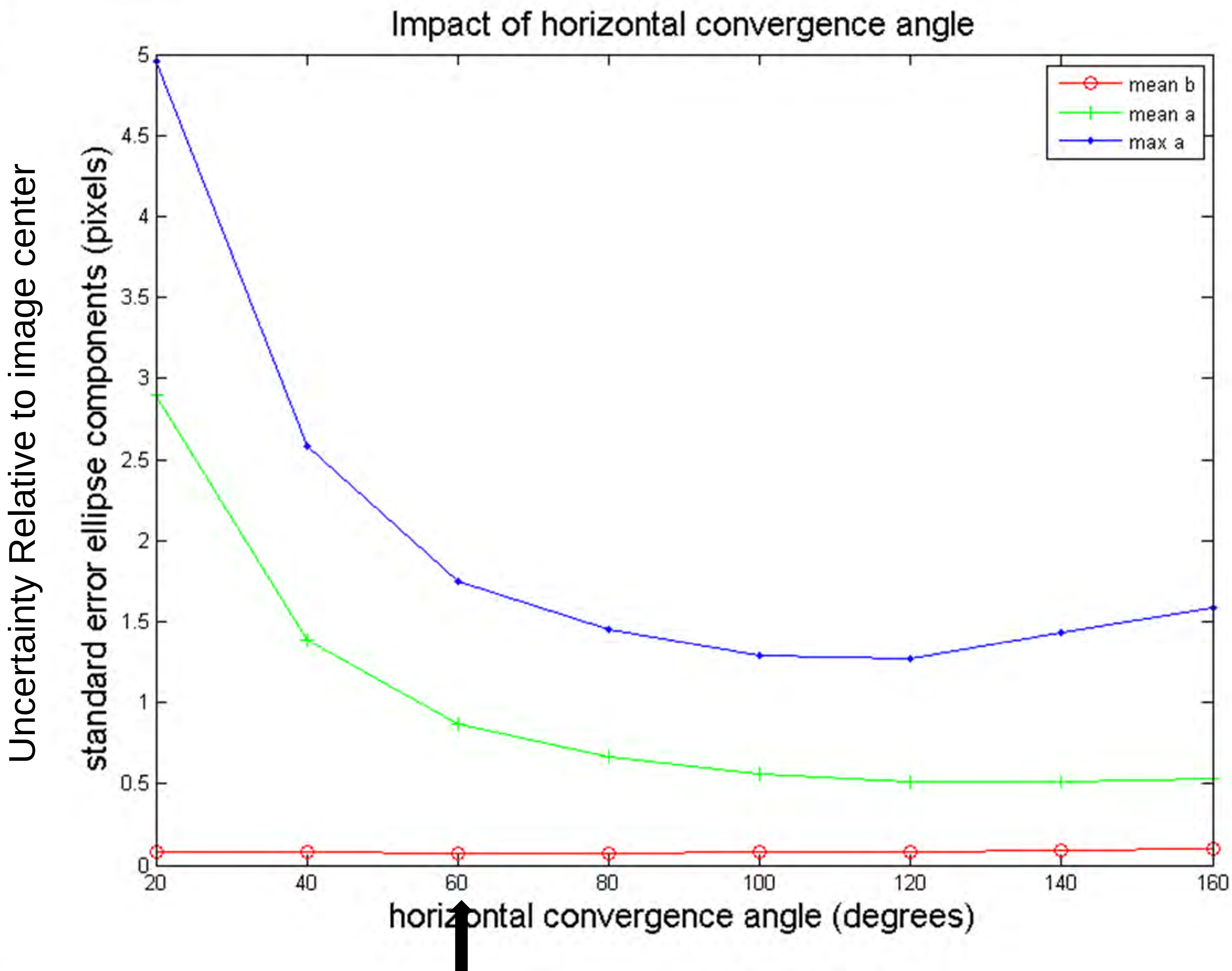

Impact of Number of Images
Uncertainty Relative to image center
Standard error ellipse components (pixels)
number of images
mean b
mean a
max a
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
5
10
15
20
25
30
35
40

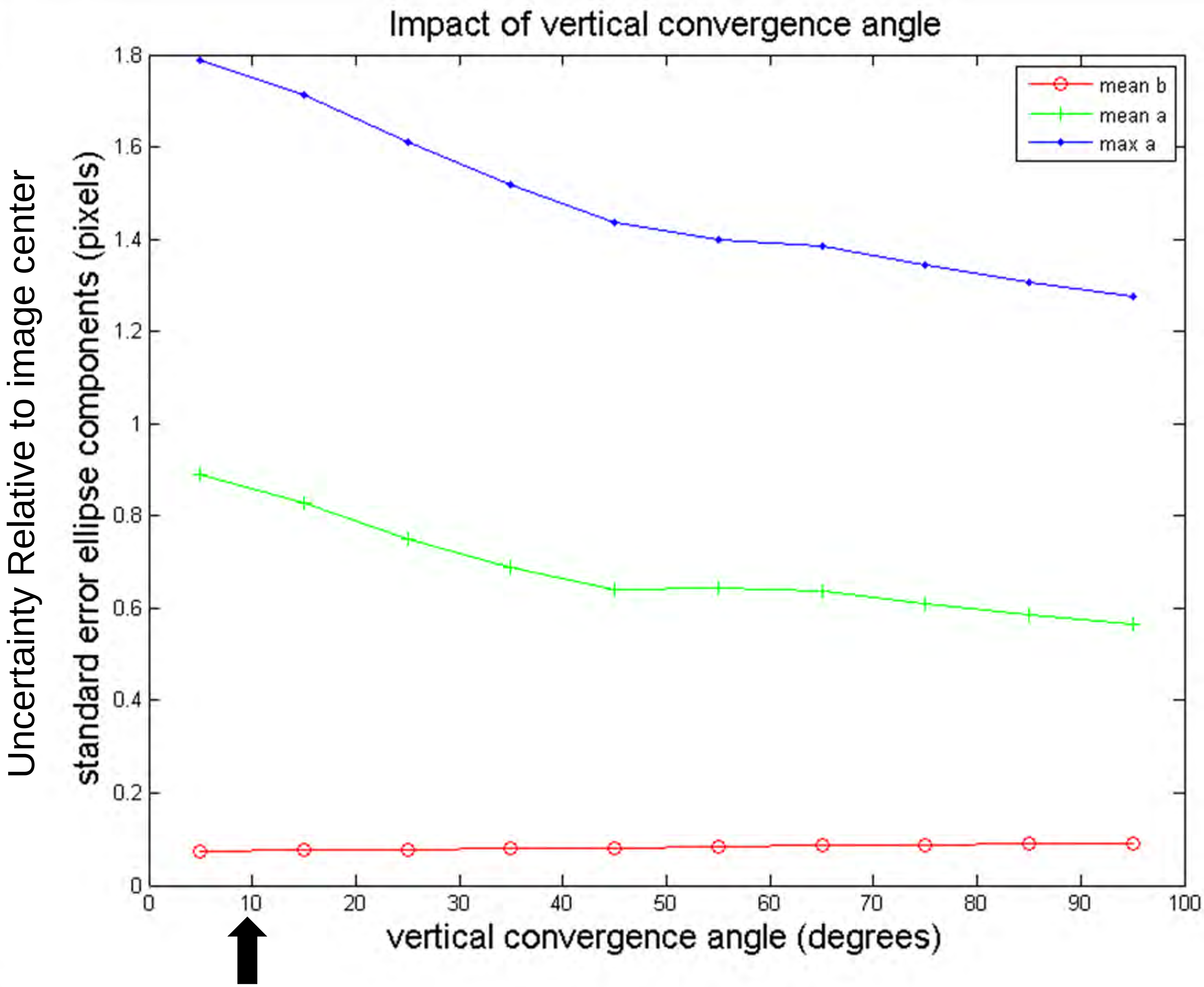

Impact of grid density
Uncertainty Relative to image center
standard error ellipse components (pixels)
number of grid points per axis
mean b
mean a
max a
0
0.5
1
1.5
2
2.5
3
4
5
6
7
8
9


Impact of number of grid planes
Uncertainty Relative to image center
standard error ellipse components (pixels)
number of grid planes
mean b
mean a
max a
0
1
2
3
4
5
6
7
8
9
10
1
1.5
2
2.5
3
3.5
4
2 meters of spacing maintained between "cage" planes, for each case
Range factor increased from 1.1 (baseline) to 1.2 and 1.3 for 3 and 4 planes, resp.

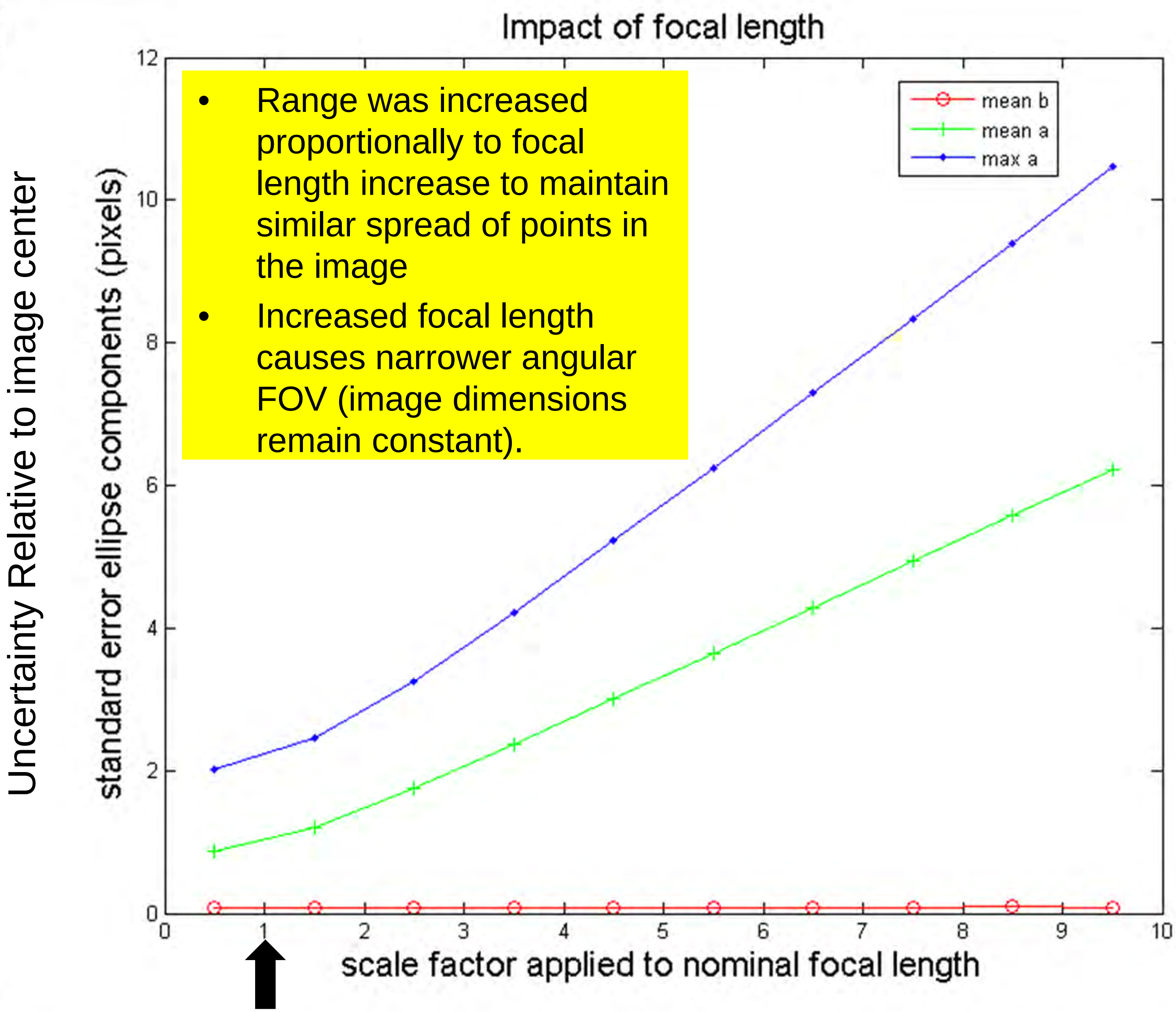

Impact of plane spacing
Uncertainty Relative to image center
standard error ellipse components (pixels)
spacing between grid planes (meters)
mean b
mean a
max a
0
0.5
1
1.5
2
2.5
3
1
1.5
2
2.5
3
3.5
4
• Only 2 planes (front and back of the "cage") used in each case
• Range factor increased from 1.1 to 1.2 for 4m spacing

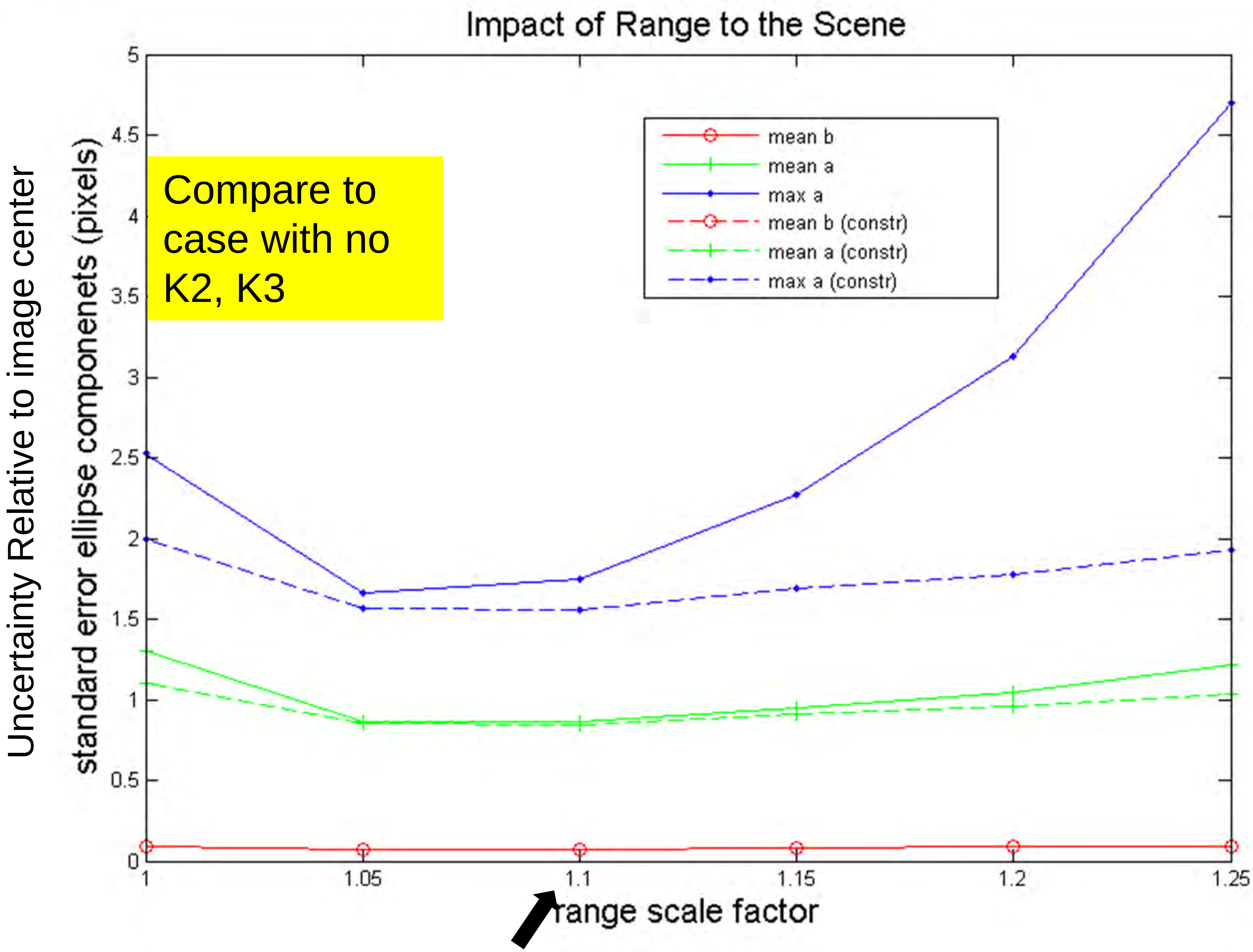

Impact of image coordinate measurement precision
Directly proportional
mean b
mean a
max a
Uncertainty Relative to image center
standard error ellipse components (pixels)
0
0.5
1
1.5
2
2.5
3
3.5
4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
mensuration sigma (pixels)

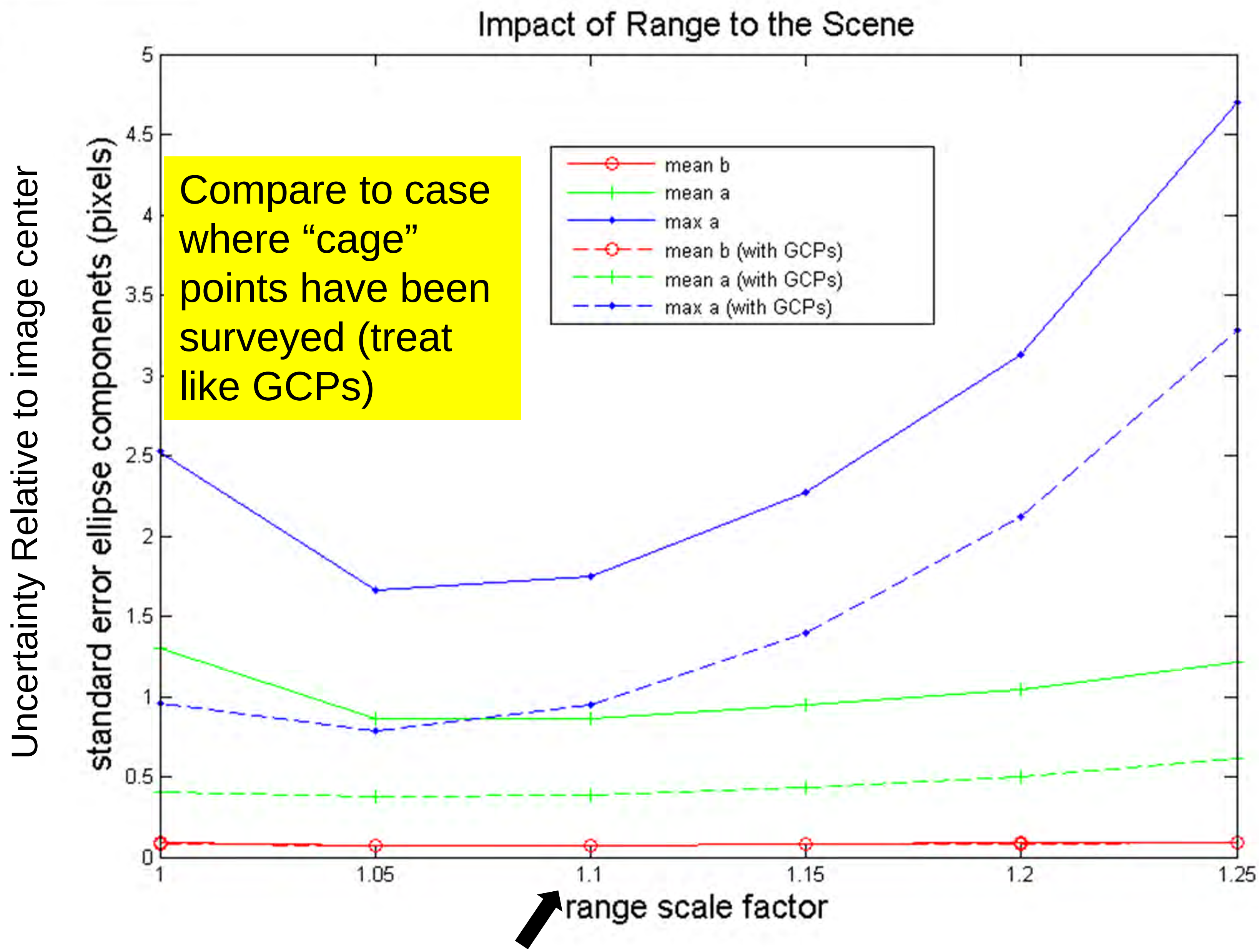

Impact of horizontal convergence angle
Uncertainty Relative to image center
standard error ellipse components (pixels)
horizontal convergence angle (degrees)
mean b
mean a
max a
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
20
40
60
80
100
120
140
160


Impact of vertical convergence angle
Uncertainty Relative to image center
standard error ellipse components (pixels)
vertical convergence angle (degrees)
mean b
mean a
max a
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
10
20
30
40
50
60
70
80
90
100

- Range was increased proportionally to focal length increase to maintain similar spread of points in the image
- Increased focal length causes narrower angular FOV (image dimensions remain constant).




Impact of Range to the Scene
Uncertainty Relative to image center
standard error ellipse componenets (pixels)
range scale factor
mean b
mean a
max a
mean b (constr)
mean a (constr)
max a (constr)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
1
1.05
1.1
1.15
1.2
1.25
Compare to case with no K2, K3



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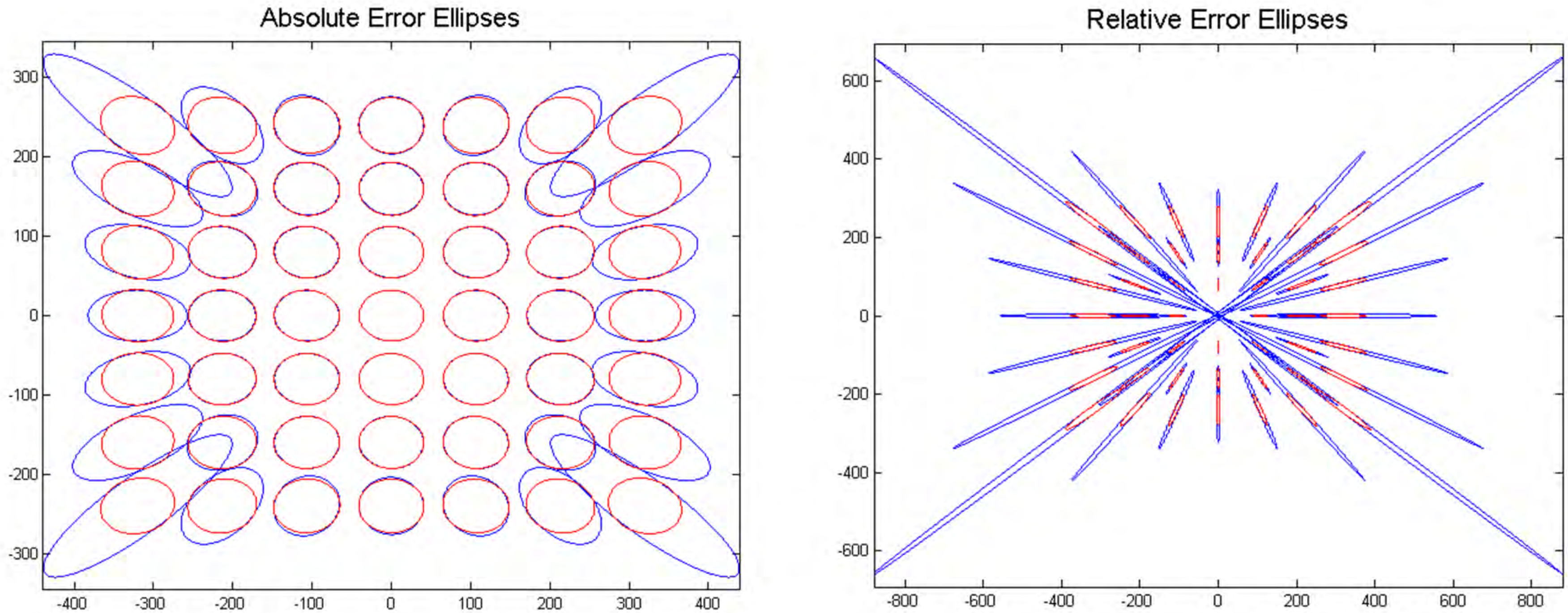
Correlation Consideration (1/3)

“Correlation Coefficient Matrix”

	xo	yo	f	K1	K2	K3	P1	P2	b1	b2
xo	1.00	0.00	0.02	-0.00	-0.00	0.00	**-0.96**	-0.01	0.01	-0.00
yo	0.00	1.00	-0.08	0.02	-0.02	0.01	-0.01	**-0.91**	0.00	-0.00
f	0.02	-0.08	1.00	-0.46	0.42	-0.36	-0.02	0.04	0.16	0.00
K1	-0.00	0.02	-0.46	1.00	**-0.97**	**0.92**	0.01	-0.02	0.05	0.00
K2	-0.00	-0.02	0.42	-0.97	1.00	**-0.98**	-0.00	0.02	-0.04	-0.00
K3	0.00	0.01	-0.36	0.92	-0.98	1.00	-0.00	-0.02	0.05	0.00
P1	-0.96	-0.01	-0.02	0.01	-0.00	-0.00	1.00	0.01	-0.01	0.01
P2	-0.01	-0.91	0.04	-0.02	0.02	-0.02	0.01	1.00	-0.01	-0.00
b1	0.01	0.00	0.16	0.05	-0.04	0.05	-0.01	-0.01	1.00	0.00
b2	-0.00	-0.00	0.00	0.00	-0.00	0.00	0.01	-0.00	0.00	1.00

Correlation Consideration (2/3)



Blue: uses only diagonal elements of 10 by 10 error covariance matrix
Red: uses full 10 by 10 error covariance matrix

	Maximum "a" in pixels	
	Absolute	Relative
Full covariance	4.7	1.8
Diag covariance	14.5	14.0

Correlation Consideration (3/3)

- Previous two slides illustrate why it is desirable for a camera calibration tool to output the full 10 by 10 error covariance matrix for use in downstream processes
- If that full matrix had not been provided, then this pre-analysis tool could be used to create one, as long as the entire setup is known

Conclusions

- Big changes in camera calibration effectiveness have been shown, due to the camera and object setup
- The prototype demonstrates the ease of evaluating different setups
- Varying rotation of the camera about the optical axis has the most significant impact
- Care must be taken to maintain and use all cross-covariance components

Future Work

- Extend the terrestrial scenario to airborne and spaceborne platforms
- Extend interior orientation parameters to include mounting, lever-arm, and bore-sight offset calibration parameters
- Build a GUI to facilitate evaluation of various scenarios

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