Camera Calibration Considerations for UAV Photogrammetry

Prof. Clive Fraser
CRC for Spatial Information
Dept. of Infrastructure Engineering
University of Melbourne, Australia

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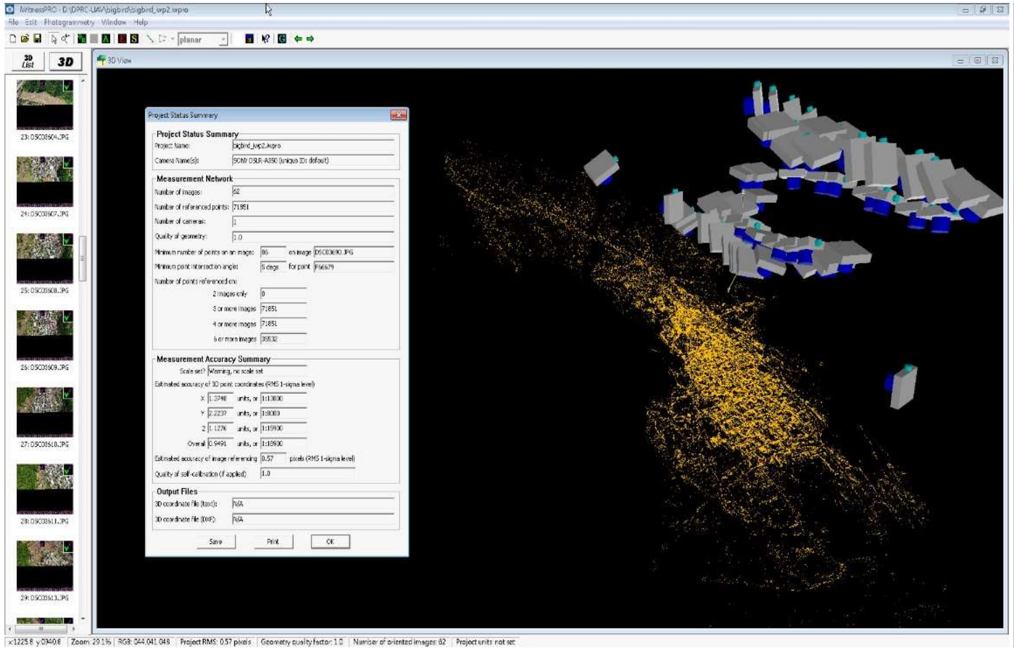
Cameras for Drones/UAS/UAVs

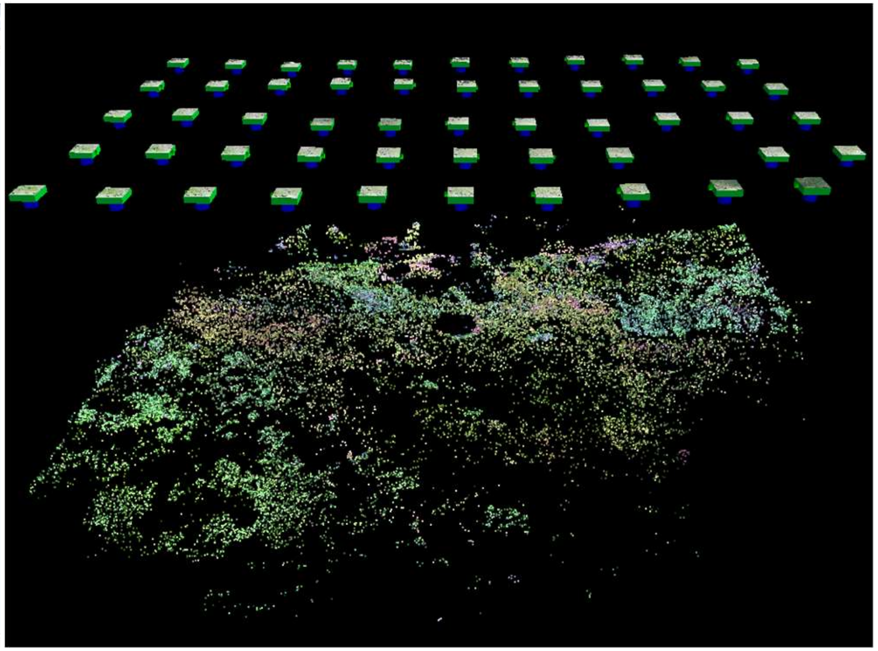
Vary from off-the-shelf point & shoot, to zoom compact, mirrorless, super-zoom, DSLRs and numerous specially designed cameras

Universal requirement for photogrammetric applications: cameras must be calibrated

UAVs for Spatial Information Generation

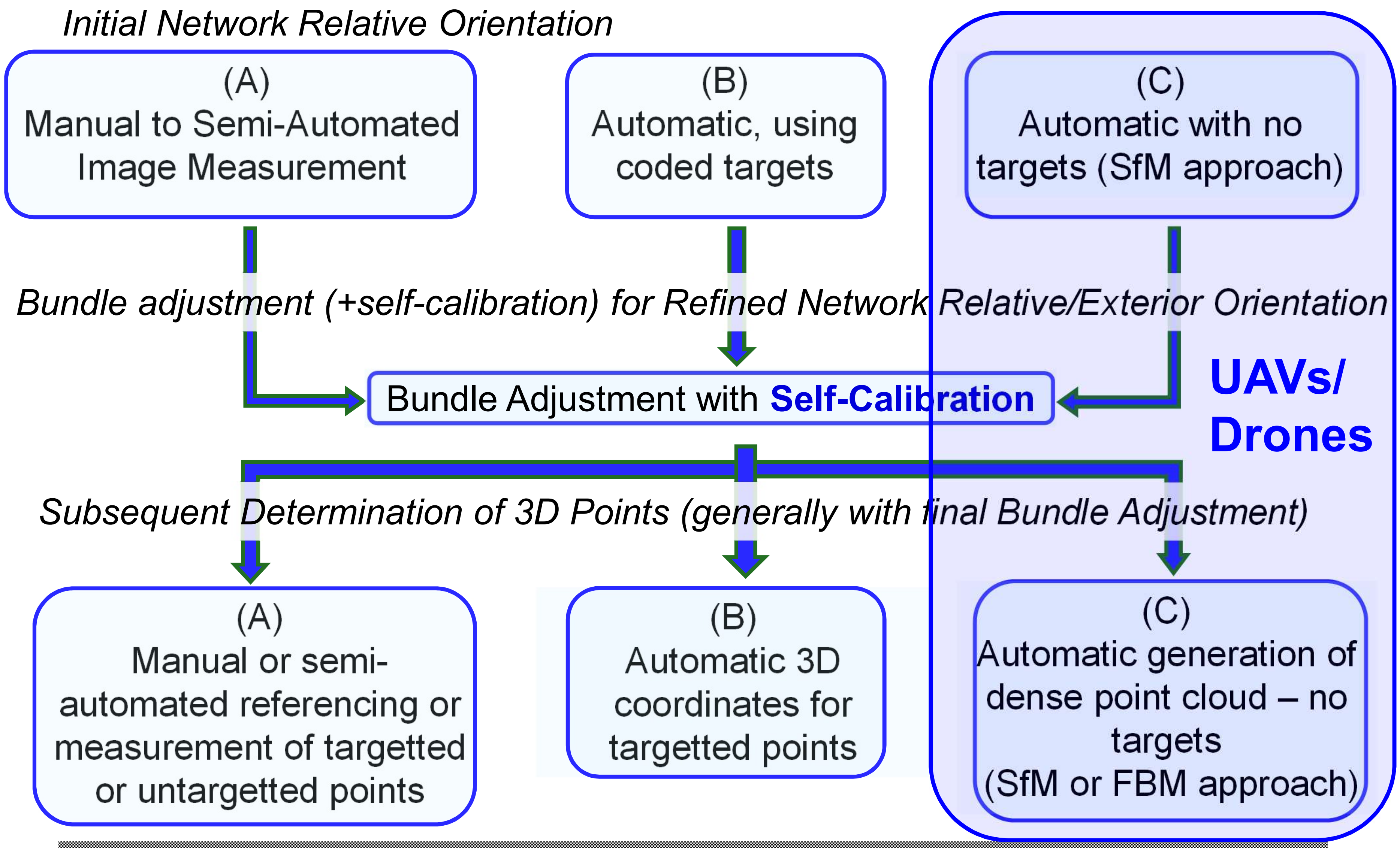
Networks can be regular or irregular





Photogrammetric processing must accommodate every configuration

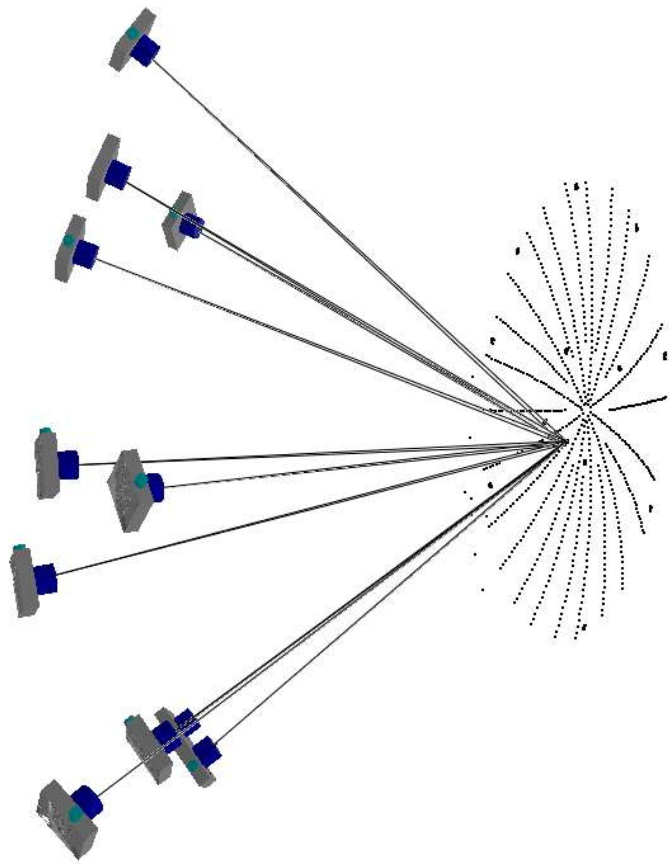
Sensor Calibration, Orientation & 3D Object reconstruction



Network Geometry for Self-Calibration

Attributes of successful self-calibration networks (No obj. space control):

- Multi-image, highly convergent network
- Orthogonal camera roll angles
- Depth in the object space (not mandatory, but very desirable)
- Highly redundant network (all pts >6 ray)
- High image measurement accuracy (targets: σ_{xy} to 0.03 pixel for monochrome CCD & generally 0.1 pixel for colour; targetless: σ_{xy} to 0.3 pixel for FBM/SfM)

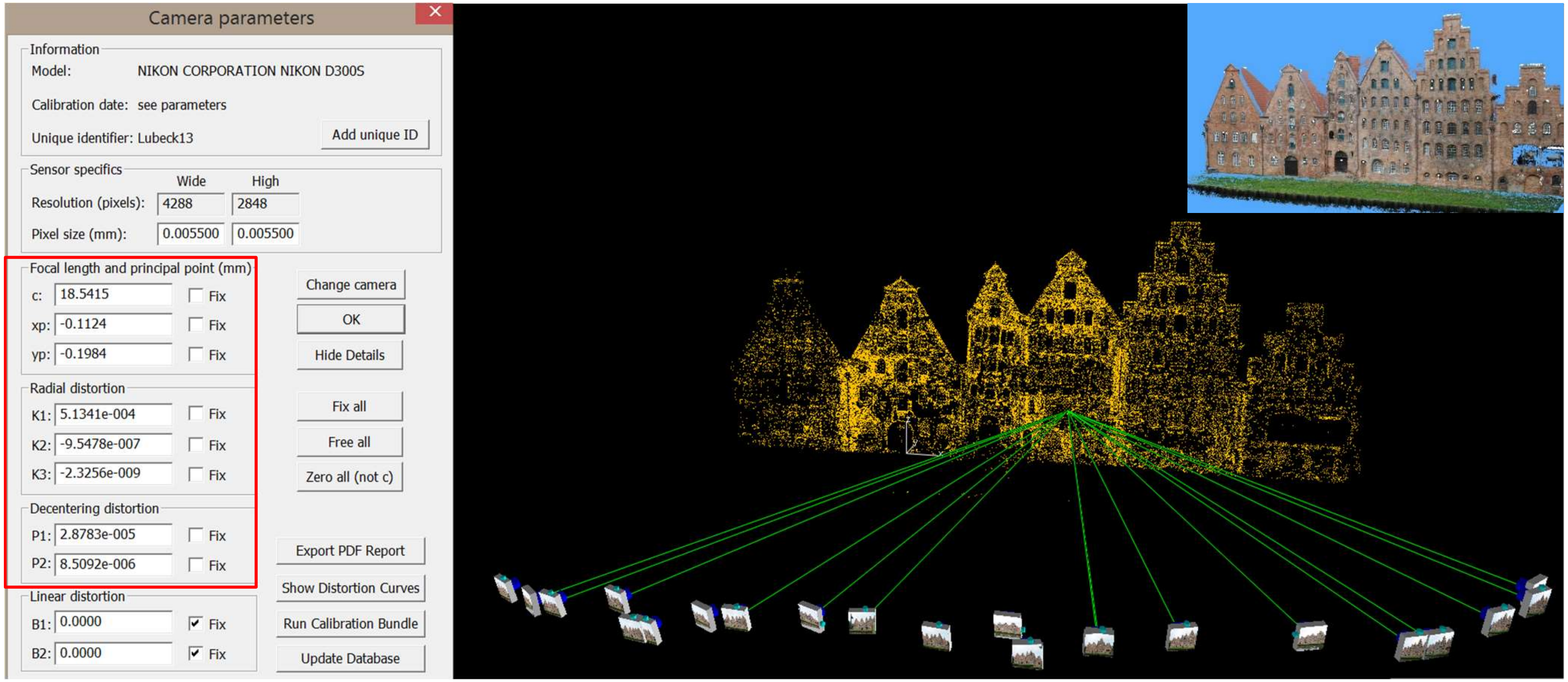


Plus

- Unifocal lens (desirable), fixed focus
- Stable interior orientation

FBM/SfM-based orientation with self-calibration

FBM-based approach affords massive redundancy to compensate for potential modest loss in geometric strength



Salzspeicher network: 23 images, 46,000 points, RMS v_{xy} = 0.25 pixel

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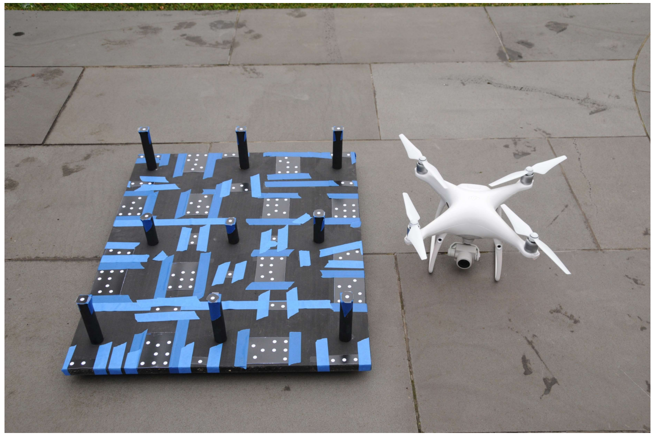
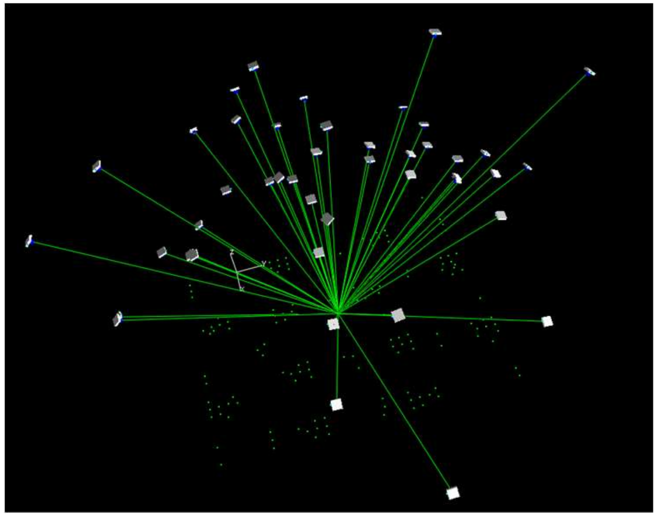
On-ground calibration via self-calibration

A very feasible approach for short focal length UAS cameras

Camera parameters: c, xp, yp, K1, K2, K3, P1, P2						
	1-moving	2-moving	3-moving	4-Static	5-Static	6-Static
Images	44	62	49	35	44	41
Points	149	151	144	129	141	139
RMS vxy (pl)	0.30	0.33	0.41	0.45	0.38	0.28
Max rays	42	54	47	31	43	33
Min rays	5	7	7	5	5	6
c (mm)	8.729	8.733	8.732	8.735	8.735	8.738
xp (mm)	0.000	-0.001	-0.006	0.000	0.001	0.002
yp (mm)	-0.026	-0.023	-0.025	-0.017	-0.022	-0.018
dr @ r	Micrometres					
4 mm	0.2	1.0	1.0	1.6	1.5	1.7
5 mm	4.1	4.3	4.5	4.2	4.5	4.8
6 mm	9.1	9.3	10.0	8.1	9.0	9.2
7mm	4.9	11.7	13.6	11.5	12.3	11.3
P(r) @ r	Micrometres					
6 mm	5.1	5.0	4.3	5.0	5.3	5.5
7mm	4.9	6.8	5.9	6.8	7.2	7.5



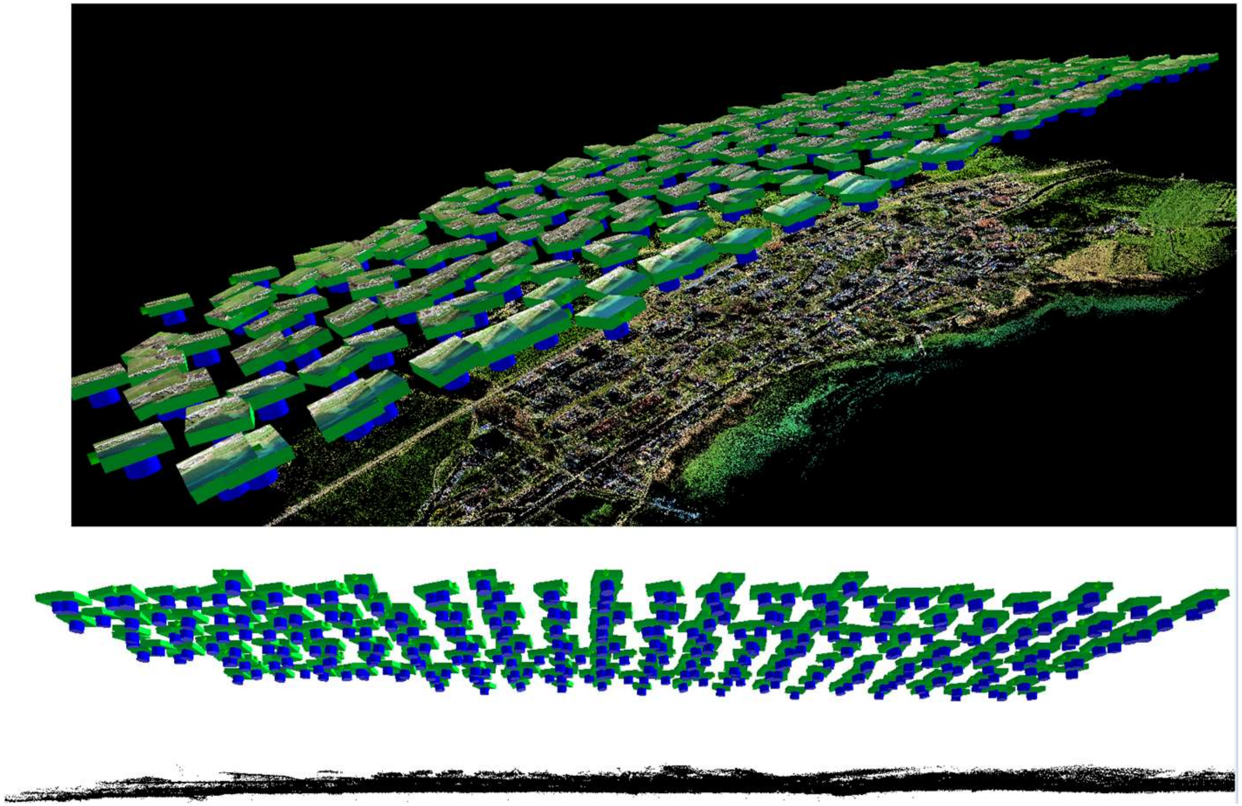


Results of 6 separate self-calibrations of a 20mpixel Phantom P4P camera

Note high level of calibration stability of the Phantom 4 PRO camera

Geometric Attributes of UAV Networks for Self-Calibration

Case 1: 'Standard' aerial block with limited terrain relief



Oriented UAV image block of 297 images & 480,000 points, 68K pts in >6 images; many in >10.

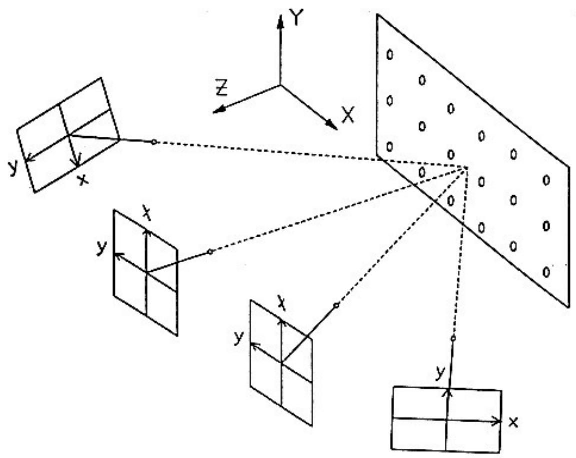
No convergence, no orthogonal roll, limited depth in obj. space, RMS vxy=0.8pl

Self-calibration of IO not feasible; lens distortion possibly OK, depending upon overlap & control

Geometric Attributes of UAV Networks for Self-Calibration

Brief revisit to mechanism of projective coupling/compensation

- Roll-angles orthogonally diverse (0°, 90°, 270°)
- A strongly convergent imaging configuration
- For comprehensive modelling of distortion, especially lens distortion, the image points should cover the full image format
- A 3D object point field is very useful, though not mandatory for self–calibration



Note: usually one of two aims being pursued through

i) provide systematic error compensation, not necessarily camera calibration

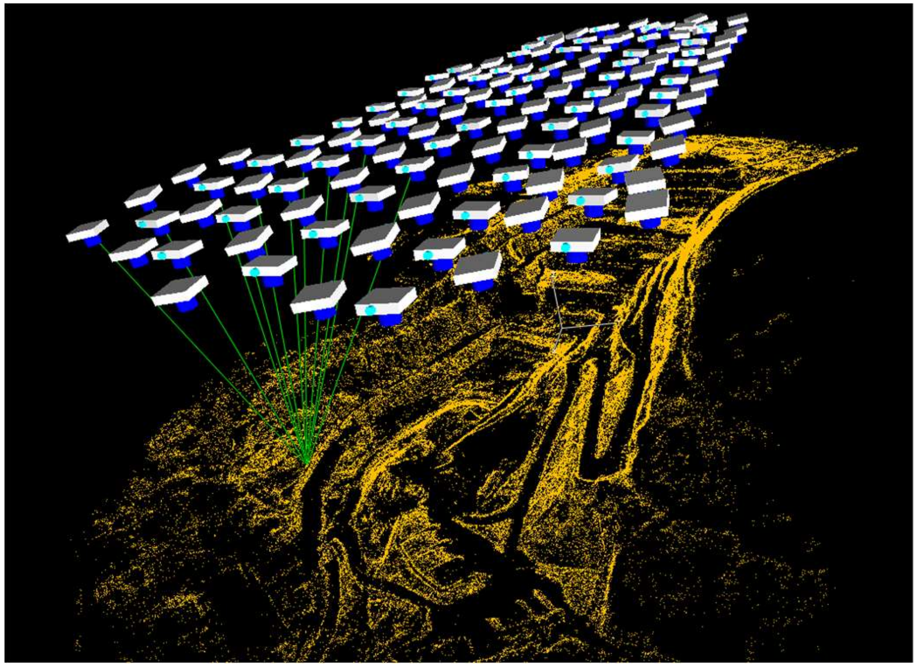
ii) to provide a scene-independent calibration of the camera(s)

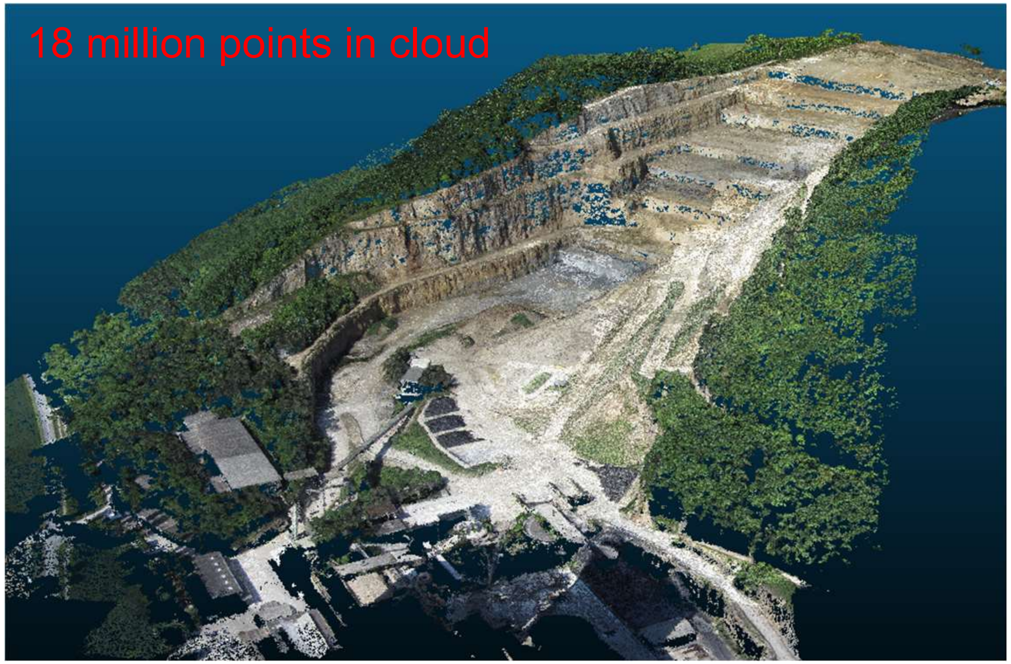
Under-Appreciated Requirement to Minimize Projective Coupling between Calibration Parameters:

Maximise Scale Variation within & between Images

Geometric Attributes of UAV Networks for Self-Calibration

Case 2: 'Standard' aerial block with large depth variation in object space





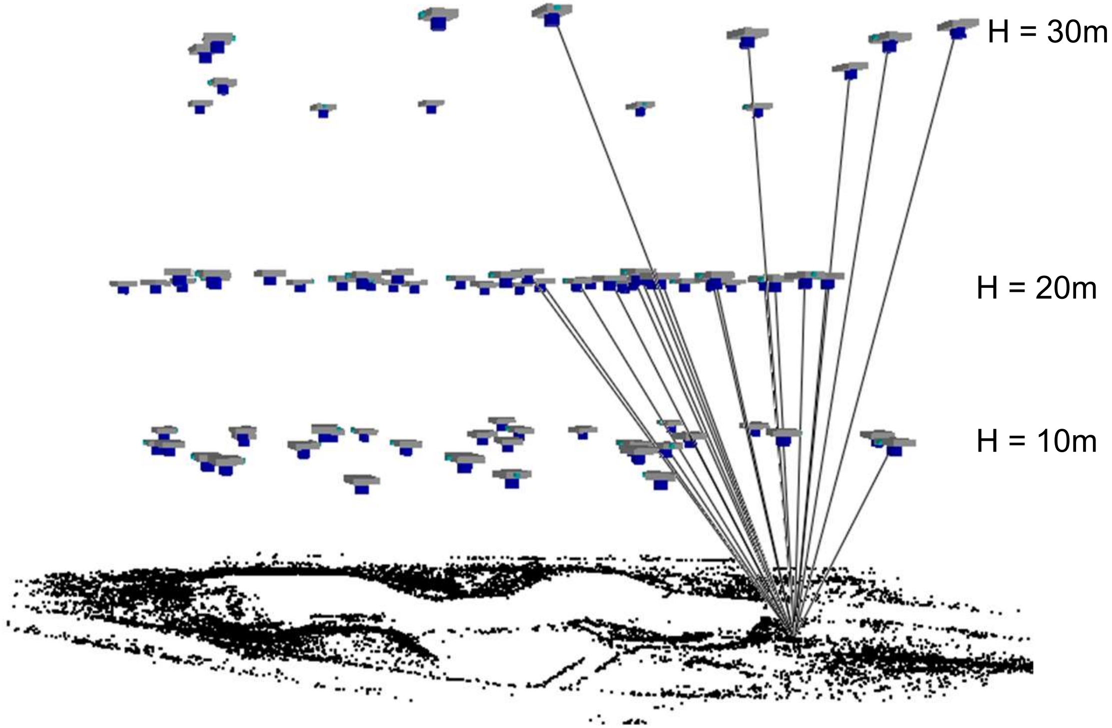
Oriented UAV image block of 127 images & 180,000 points, 31K pts in >6 images; many in >10.

No convergence, no orthogonal roll, but very significant depth in obj. space (H-h varies from 130m to 290m, so scale varies within some images by 50% from the mean), RMS vxy=0.45pl

Full self-calibration of IO & lens distortion feasible, good precision & low projective couplings (no need for object space control)

Geometric Attributes of UAV Networks for Self-Calibration

Case 3: Mixed range network (scale variation between images, not within)



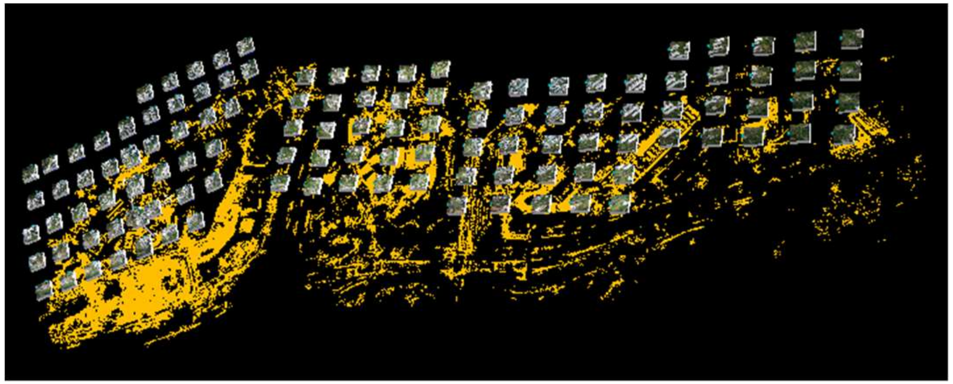
UAV image block of 84 images & 30,000 pts in >6 images; many in >10.

No convergence, no roll, but significant scale diff. between 3 flying heights, RMS vxy=0.8pl

Full self-calibration of IO & lens distortion feasible, but strong projective coupling between principal distance & camera stn Z coord. (ideal example of where in-air & on-ground GPS constraints should apply)

Geometric Attributes of UAV Networks for Self-Calibration

Case 4: Scale variation from presence of high buildings



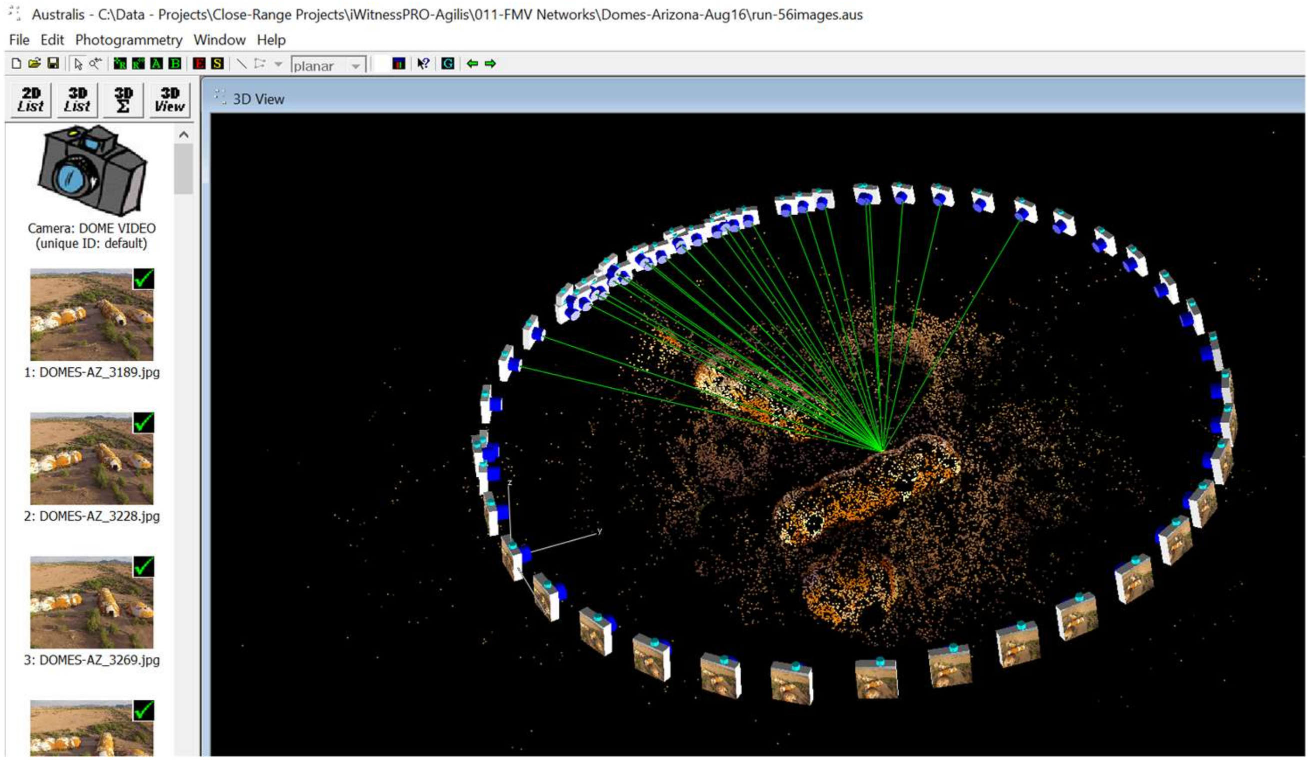
UAV image block of 122 images & >100K points, RMS vxy=0.4pl

No convergence, no roll, but significant scale diff. between the ground & tops of buildings
(Building height >50% of flying height)

Full self-calibration of IO & lens distortion feasible, good precision & low projective couplings
(no need for object space control)

Geometric Attributes of UAV Networks for Self-Calibration

Case 5: Highly overlapping oblique imagery of a 3D object scene (images from FMV)



UAV image block of 56 images & 28K points, 200 with >6 rays, RMS vxy=0.44pl

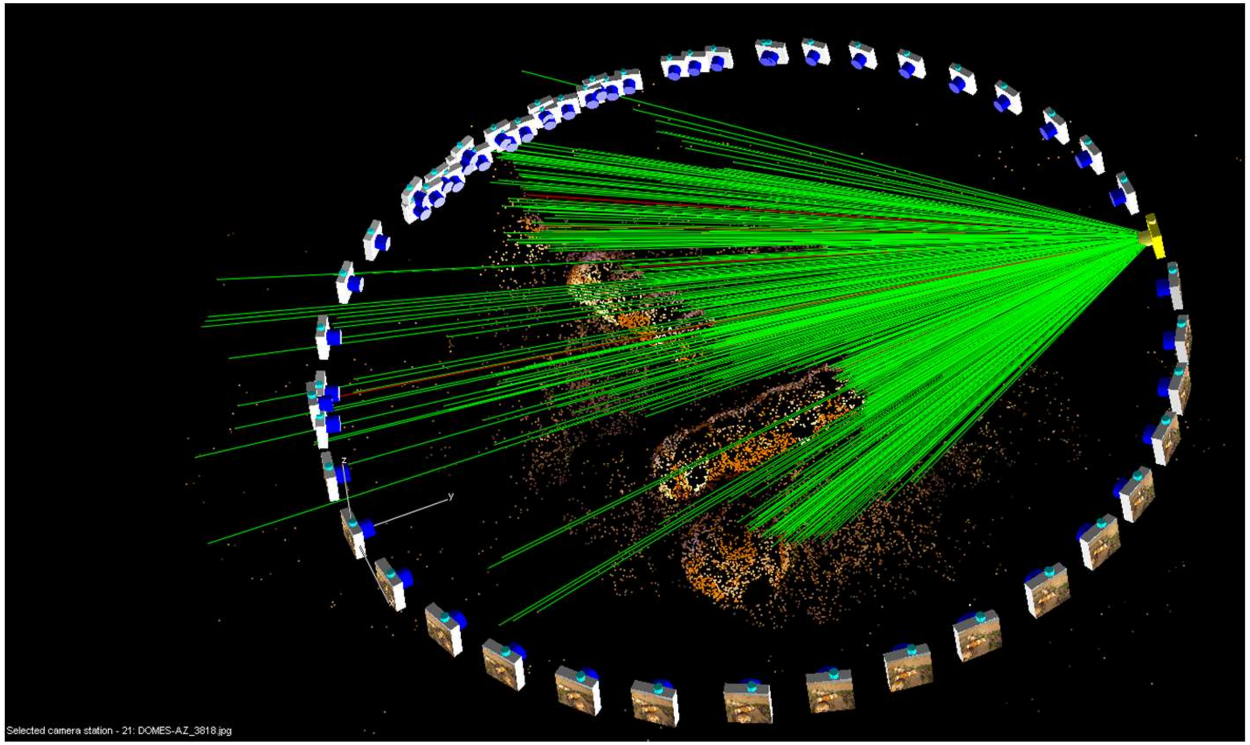
No convergence, no roll, but significant scale diff. within each image, and 3D

Full self-calibration of IO & lens distortion feasible, moderate precision with moderate projective couplings (espec. related to IO/EO and decentring distortion)

(no requirement for object space control)

Geometric Attributes of UAV Networks for Self-Calibration

Case 5: Highly overlapping oblique imagery of a 3D object scene (images from FMV)



UAV image block of 56 images & 28K points, 200 with >6 rays, RMS vxy=0.44pl

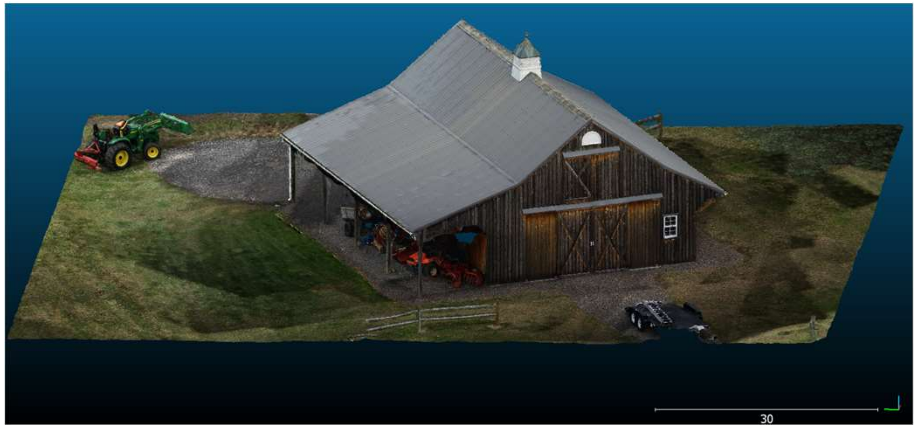
No convergence, no roll, but significant scale diff. within each image, and 3D

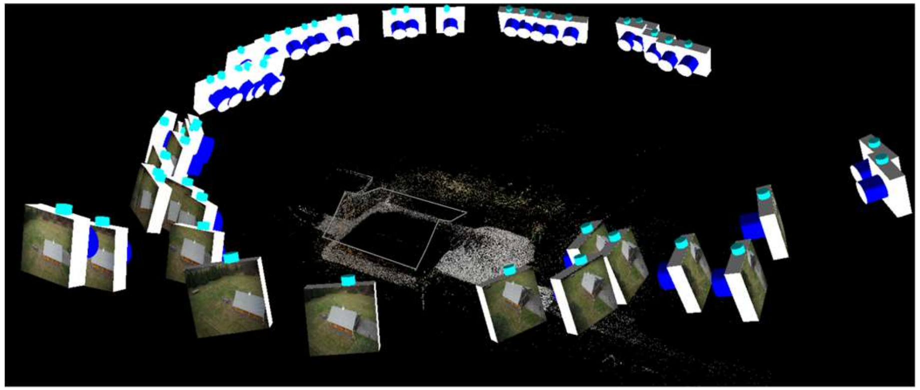
Full self-calibration of IO & lens distortion feasible, moderate precision with moderate projective couplings (espec. related to IO/EO and decentring distortion)

(no requirement for object space control)

Geometric Attributes of UAV Networks for Self-Calibration

Case 7: Network for 3D reconstruction of a historic barn





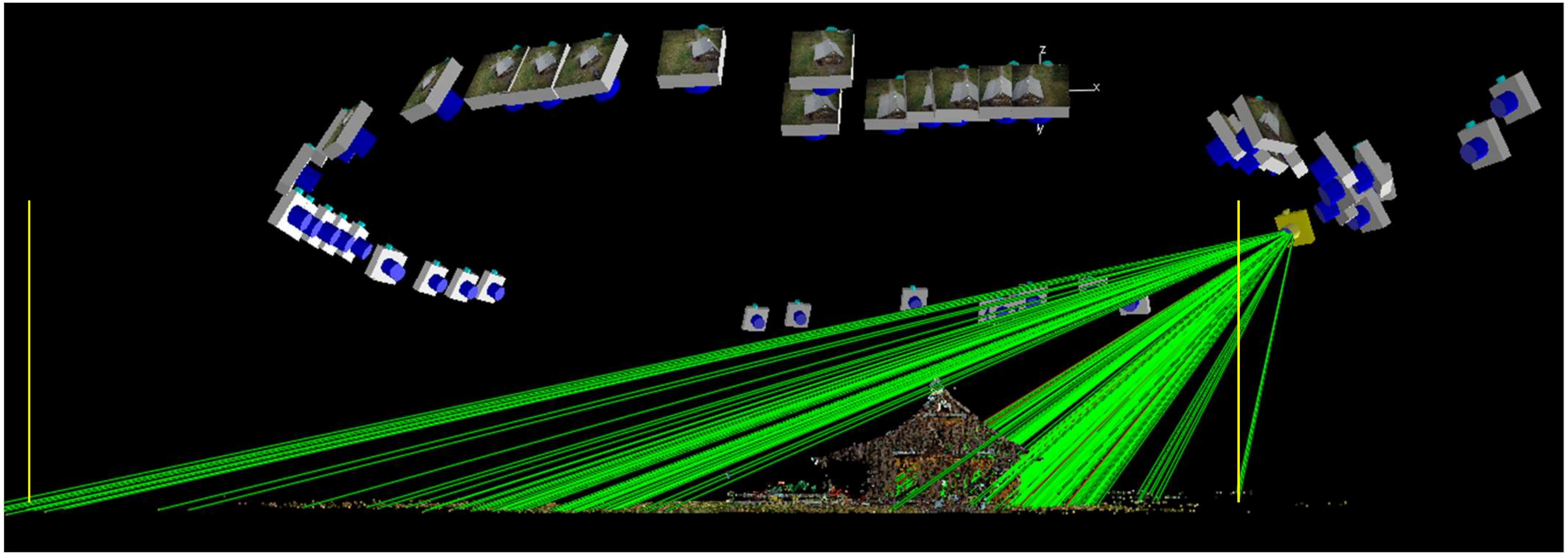
UAV image network of 49 images & 50K points, 6000 with >6 rays, RMS vxy=0.3pl

No convergence, no roll, but significant scale diff. within each image

Full self-calibration of IO & lens distortion feasible, moderate precision with moderate projective couplings (no necessity for object space control)

Geometric Attributes of UAV Networks for Self-Calibration

Case 7: Network for 3D reconstruction of a historic barn

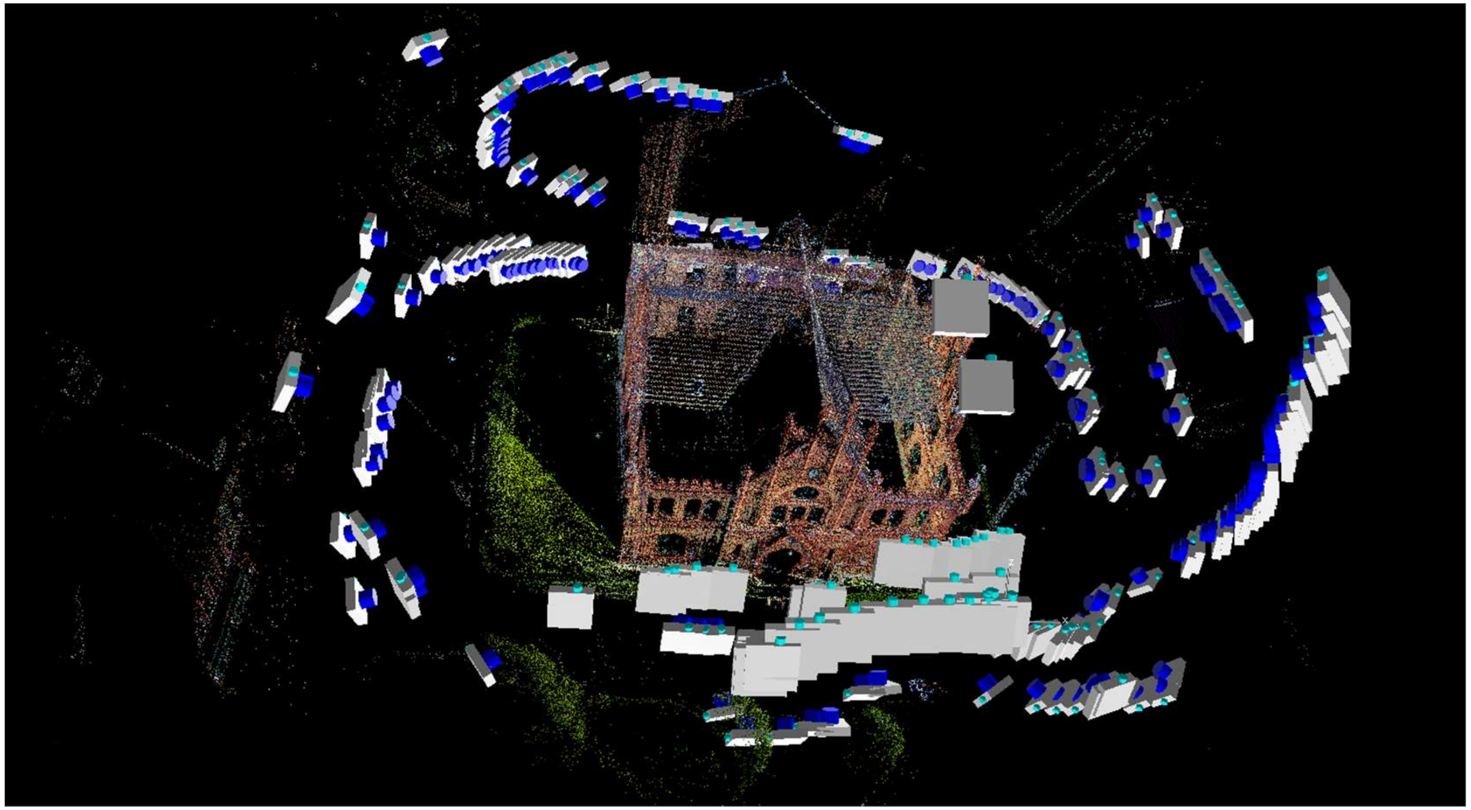


Self-calibration OK due substantial variation in image scale within each image, but note projective linkage between principal point & elevation angle/Z

Recovery of IO is moderately strong (sigmas of a few micrometers)

Geometric Attributes of UAV Networks for Self-Calibration

Case 8: 2-camera ISPRS benchmark network



UAV image block of 224 images & >150K points, RMS vxy=0.4pl

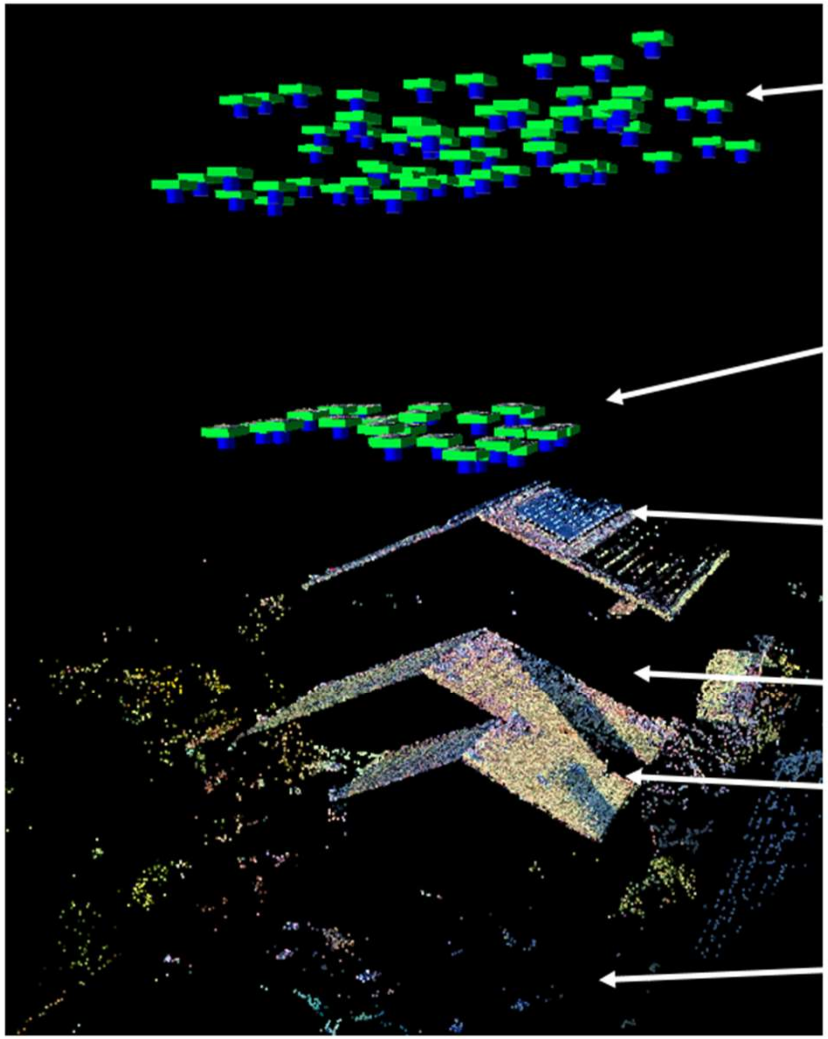
'Accidental' convergence, no roll & limited scale variation within the images

Full self-calibration feasible but not strong, high projective coupling espec. between IO & EO

(Camera roll would dramatically improve accurate IO recovery)

In-air versus on-ground calibration via self-calibration of P4P

Camera parameters: c, xp, yp, K1, K2, K3, P1, P2			
	On-ground	In-Air SfM	In-Air Tgts
Images	62	91	91
Points	151	61,000	200
RMS vxy (pl)	0.33	0.45	0.29
Max rays	54	84	90
Min rays	7	5	25
c (mm)	8.733	8.766	8.758
xp (mm)	-0.001	-0.001	0.000
yp (mm)	-0.023	-0.016	-0.018
dr @ r			
4 mm	1.0	2.2	2.6
5 mm	4.3	5.7	6.6
6 mm	9.3	11.2	13.2
7mm	11.7	16.8	20.7
P(r) @ r			
6 mm	5.0	5.3	5.2
7mm	6.8	7.2	7.1



Recall importance of image scale variation

Obj XYZ discrepancies: <1mm in XY, 3mm in Z for tgts, 5mm for FBM

Affine distortion in object space – a problem?

Camera parameters: c, xp, yp, K1, K2, K3, P1, P2			
	On-ground	In-Air SfM	In-Air Tgts
Images	62	91	91
Points	151	61,000	200
RMS vxy (pl)	0.33	0.45	0.29
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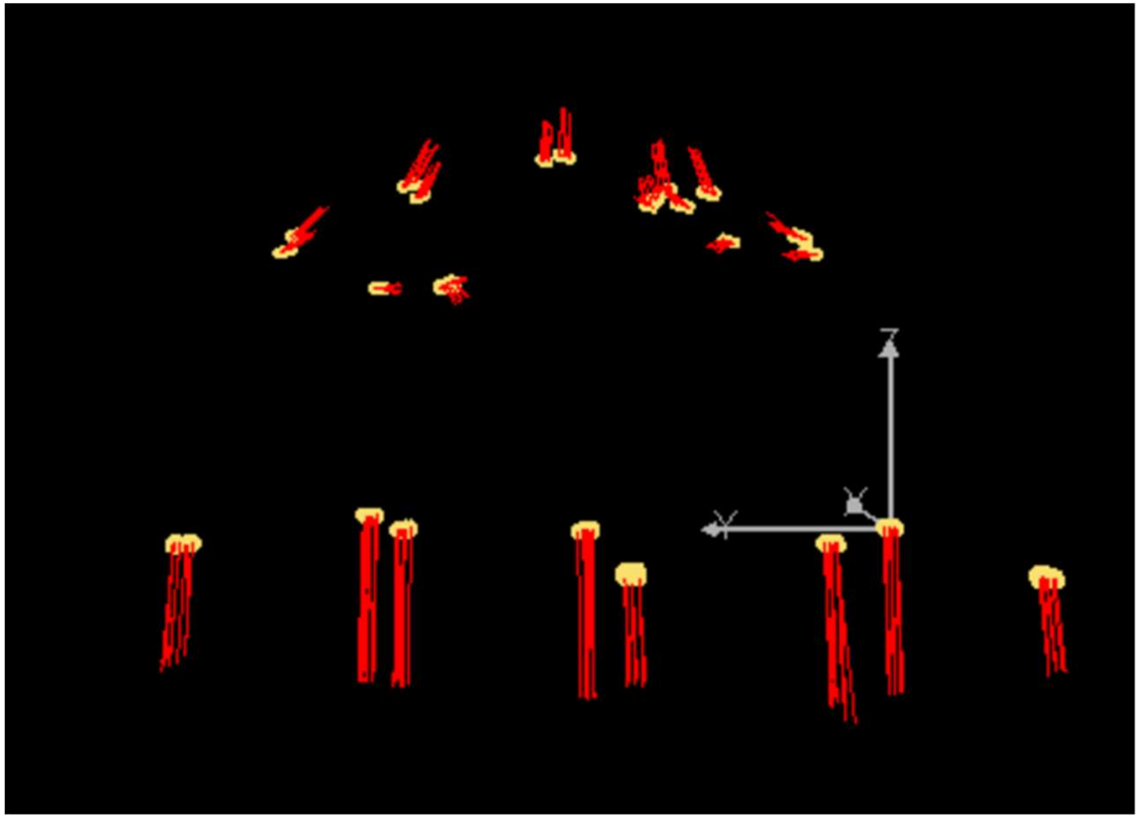
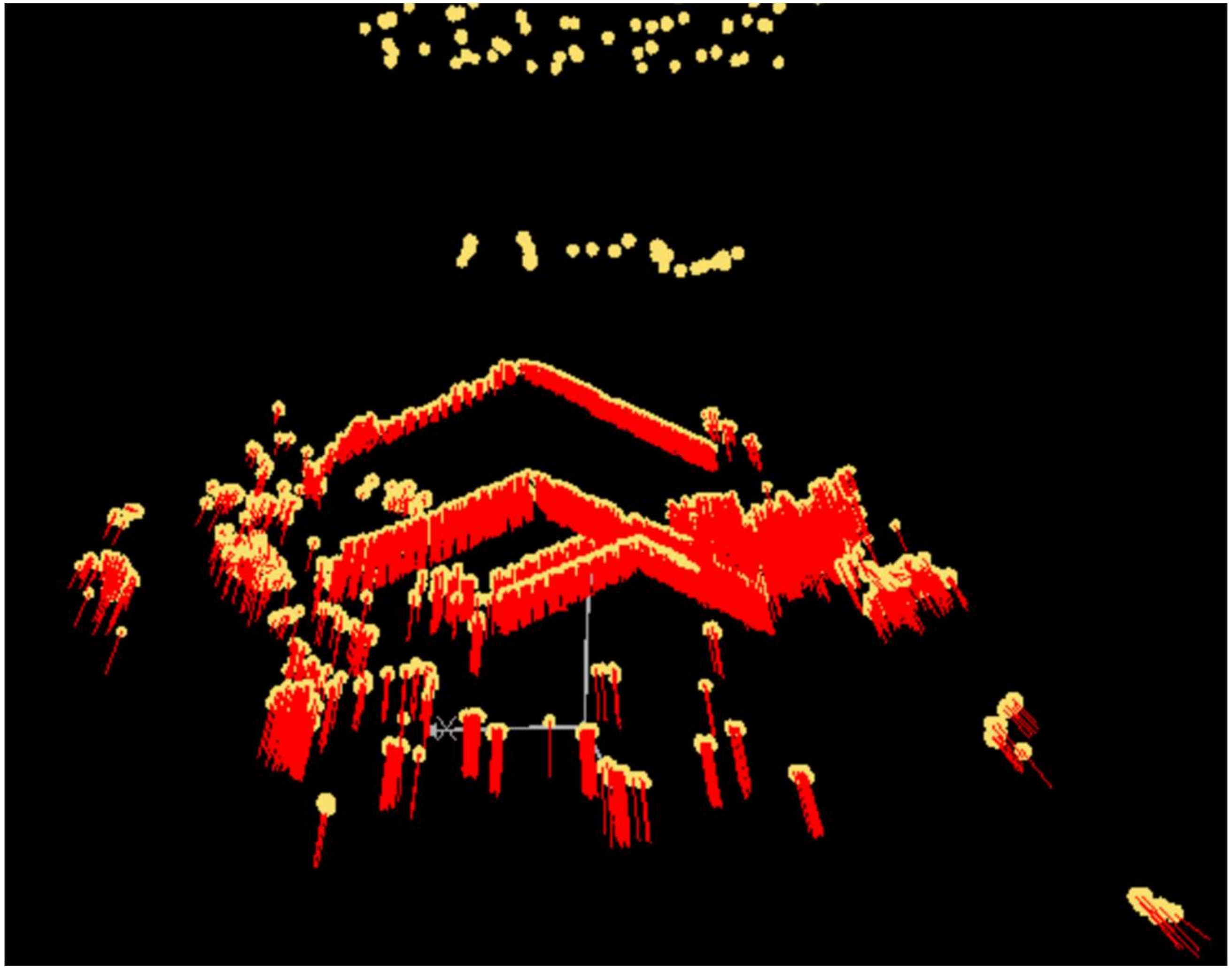
7mm	11.7	16.8	20.7
P(r) @ r			
6 mm	5.0	5.3	5.2
7mm	6.8	7.2	7.1



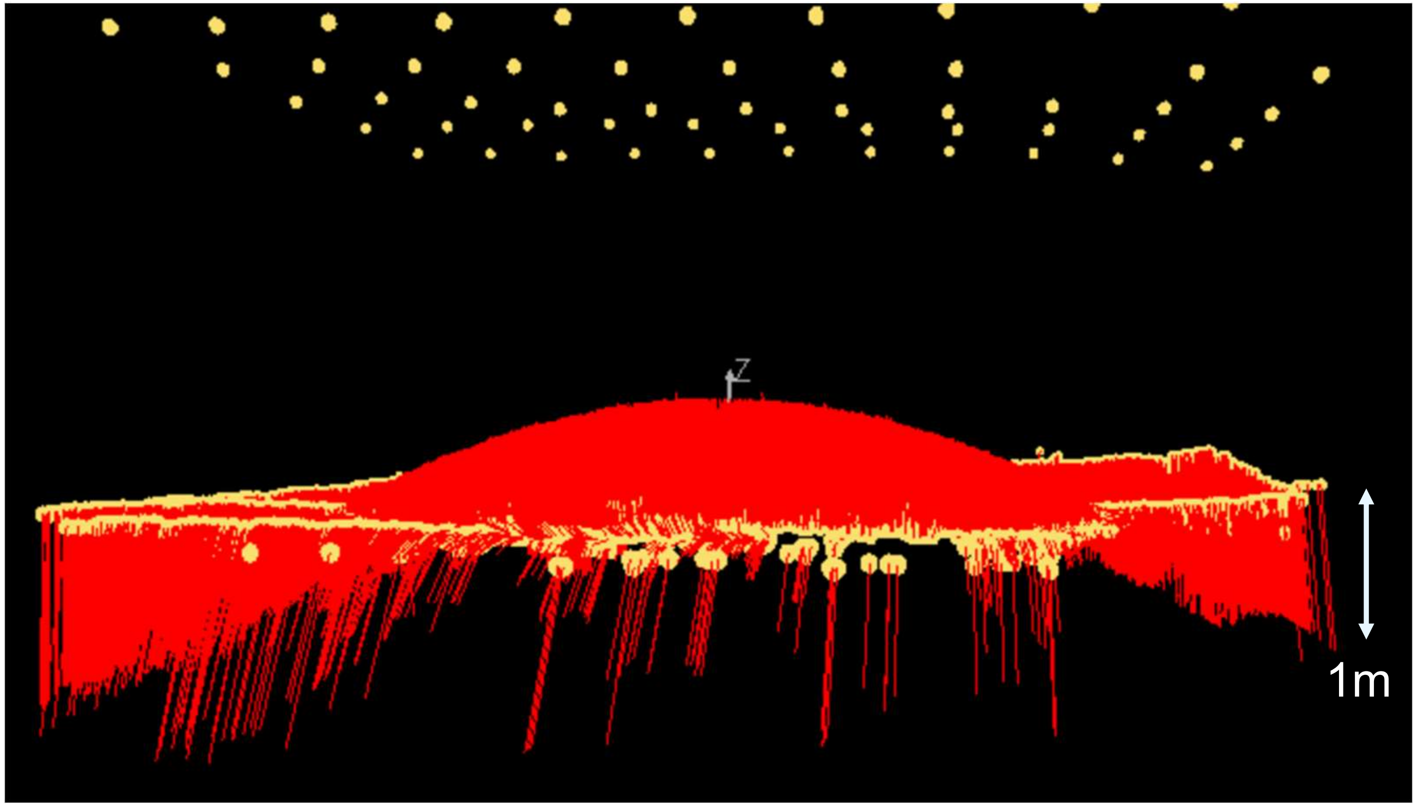
Differential scale difference between XY and Z
length of vectors at ground level is 6 – 9mm

Bias introduced through different focal length



Δc of 0.033mm at scale of 1:1200 → ΔZ of 40mm; actual RMS is 37mm

Self-calibration in a one-level high-overlap near-nadir aerial P4P network with small height variation – definitely <u>not</u> recommended!



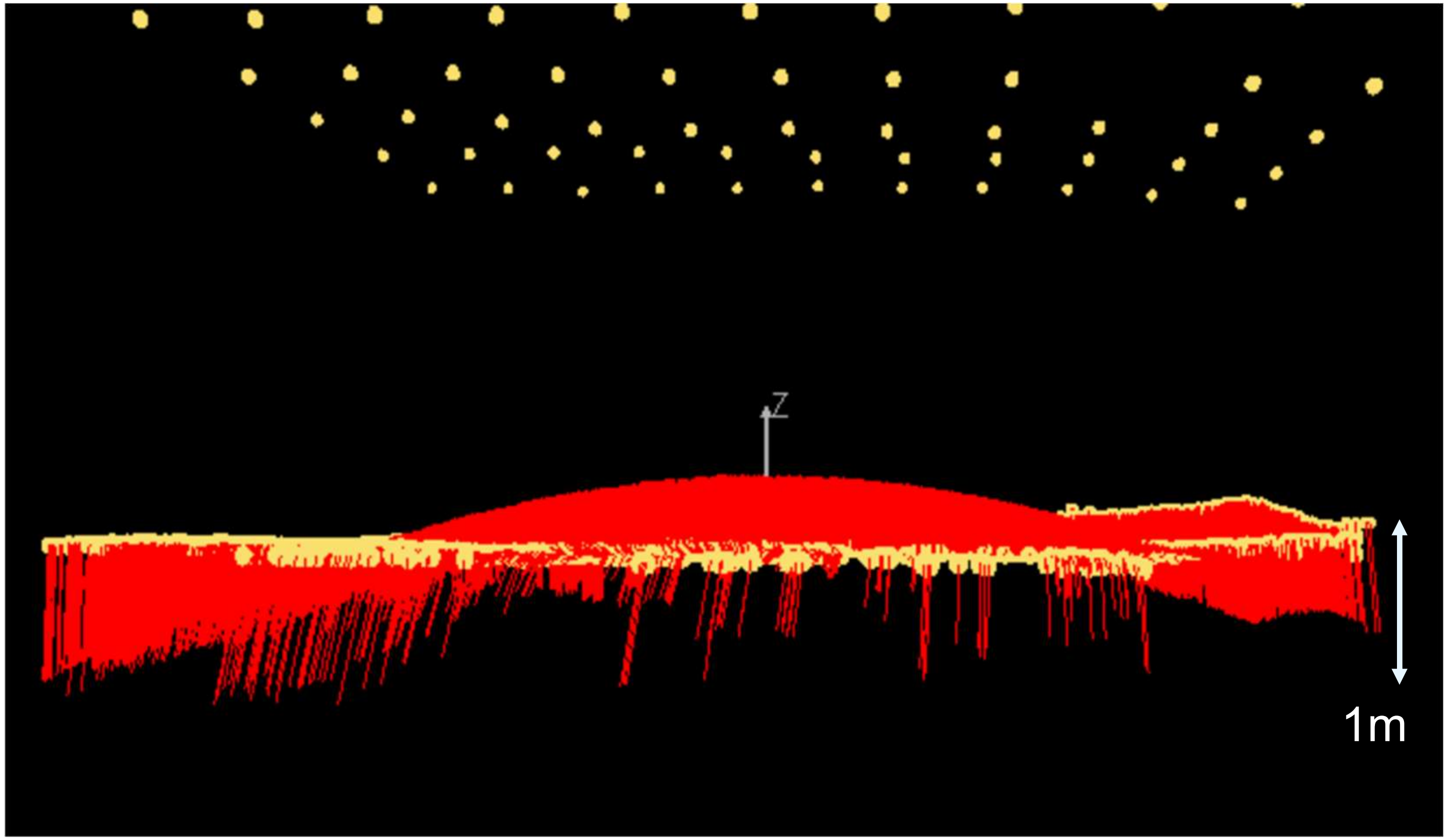
Flying Ht= 35m
53 images
32,000 pts
RMSvxy = 0.51 pl

σXY= 5mm
σZ= 10mm

Should not constrain GPS cam. stn coords since accuracy too low (0.5m RMS)

Result: classical doming of terrain plus mean bias of 0.6m in XY & 0.9m in Z

Fixed IO (pre-calibrated) & self-calibration of radial distortion only – also <u>not</u> recommended!



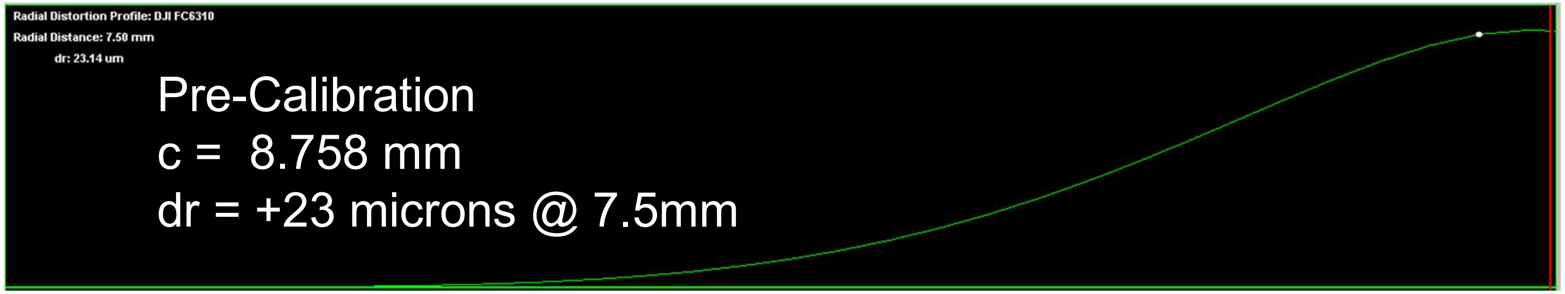
Flying Ht= 35m
53 images
32,000 pts
RMSvxy = 0.51 pl

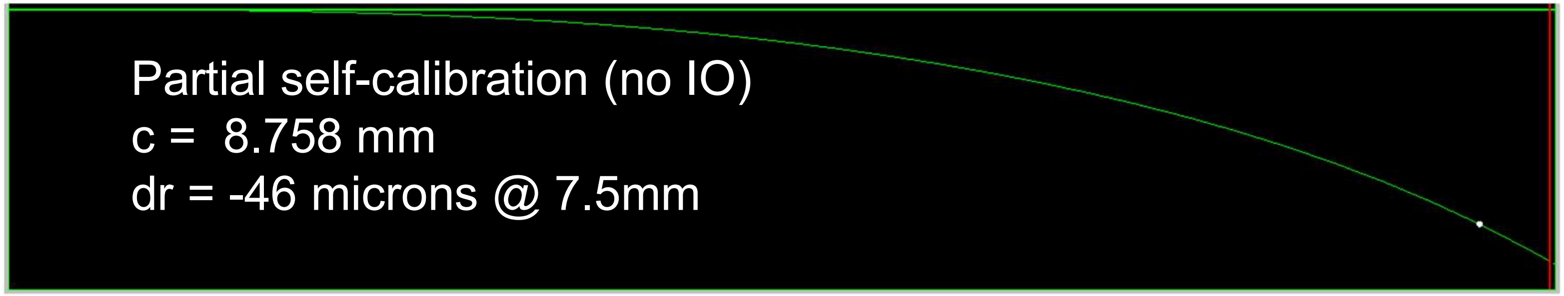
σXY= 4mm
σZ= 10mm

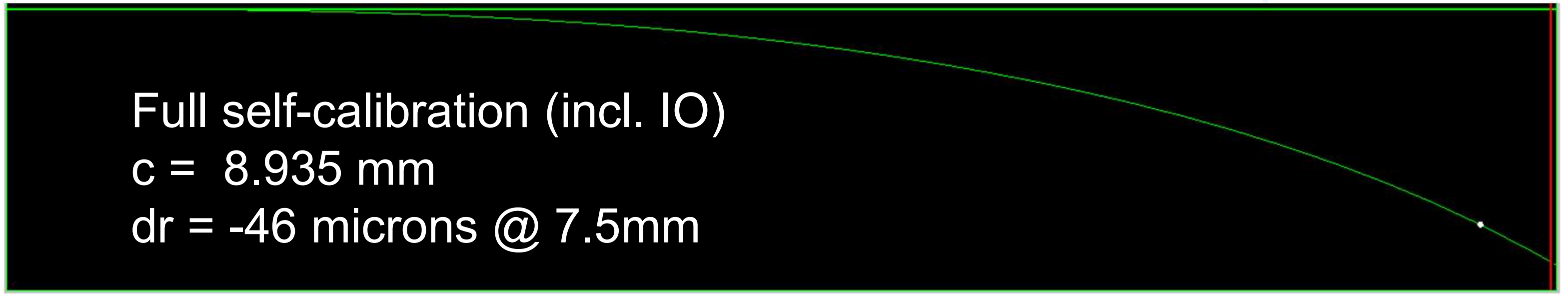
Should not constrain GPS cam. stn coords since accuracy too low (0.5m RMS)

Result: classical doming of terrain, Z-discrepancy range of -0.9m to +0.51m

Three radial distortion profiles for 53-image P4P network







All three solutions have same internal closure, RMS vxy = 0.50 pixel

In the absence of accurate cam. stn control, opt for pre-calibration

Constraints in Bundle Adjustment of UAV Image Blocks

PURPOSE: To remove both datum & configuration defects

		Precision	→ Weights
i)	Image coord. obs.	σ_{xy}	→ P
ii)	GCPs	σ_{XYZ}	→ $P2$
iii)	GPS camera stns.	$\sigma_{X^cY^cZ^c}$	→ $P1$

Bundle Adjustment

$$\begin{pmatrix} A_1^T P A_1 + P_1 & A_1^T P A_2 & A_1^T P A_3 \\ A_2^T P A_1 & A_2^T P A_2 + P_2 & A_2^T P A_3 \\ A_3^T P A_1 & A_3^T P A_2 & A_3^T P A_3 \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{pmatrix} + \begin{pmatrix} A_1^T P w + P_1 w_1 \\ A_2^T P w + P_2 w_2 \\ A_3^T P w \end{pmatrix} = 0$$

Consider the case where $\sigma_{xy}^* \approx \sigma_{XYZ} \approx \sigma_{X^cY^cZ^c}$ & where $\sigma_{xy}^* = \textit{Scale No.}^* \, \sigma_{xy}$

Now consider number of constraints in FBM orientation by self-calib. bundle adj.

σ_{xy}	σ_{XYZ}	$\sigma_{X^cY^cZ^c}$
10,000s -100,000s	10s	100s

The relative magnitudes of σ_{XYZ} & $\sigma_{X^cY^cZ^c}$ against σ_{xy}^* are critically important in self-calibration within UAV image networks

Constraints in Bundle Adjustment of UAV Image Blocks

Removal of the datum defect

i) Delete 7 rows/columns from the normal equations (usually related to δ_2)

ii) Assign 7 σ_{XYZ} or $\sigma_{X^c Y^c Z^c}$ values to 'zero' (eg 2 GCPs fixed in XYZ & 3rd in Z)

iii) Free-Network adjustment (via Helmert bordering or less useful pseudo inverse)

iv) Assign appropriately 'tight' values to σ_{XYZ} & $\sigma_{X^c Y^c Z^c}$

Optimal precision of XYZ ground point coordinates will only be attained when computational base is assigned zero variance, ie (i) – (iii) with δ_2 parameters only

Important to remember that for non-minimal constraint

$$\left(A^T PA + k^2 I\right)\delta = \left(A^T Pw + k^2 I w^*\right) \qquad k^2 I = \begin{pmatrix} P_1 \\ P_2 \\ 0 \end{pmatrix}$$

Note that for a moderate range of k

$$\delta = (A^T PA)^+ (A^T Pw) \approx (A^T PA + k^2 I)^{-1} (A^T Pw + k^2 I w^*)$$

but

$$C_\delta = (A^T PA)^+ \neq (A^T PA + k^2 I)^{-1}$$

can result in seriously inflated variances & covariances of the parameters δ

Constraints in Bundle Adjustment of UAV Image Blocks

Removal of the configuration defect

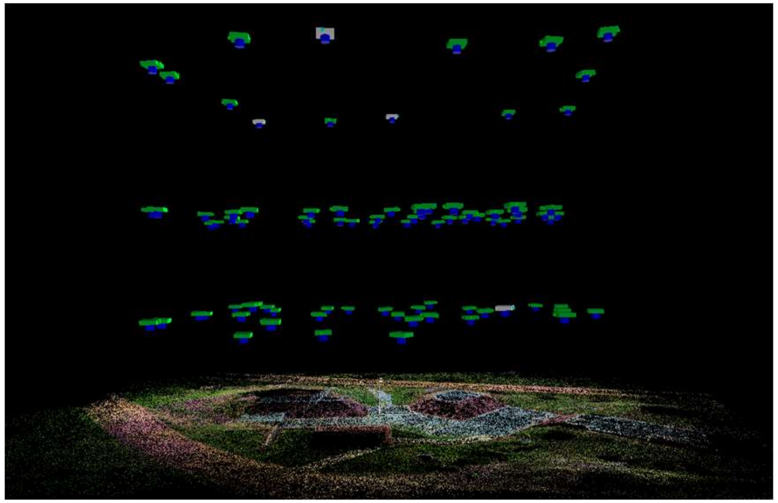
i) Utilise a network geometry that supports self-calibration (especially of IO parameters of c, x_p,y_p)

And/or

ii) Impose constraints σ_{XYZ} & $\sigma_{X^cY^cZ^c} \ll \sigma_{xy}^*$ such that projective coupling of IO & EO parameters is sufficiently suppressed, while at the same time the imposed constraints lead to a normal equation matrix of full rank.

Options for (i) centre upon introduction of significant scale variation within and/or between images.

Hence the method of 'mixed range' or multi-scale calibration in aerial block adjustment

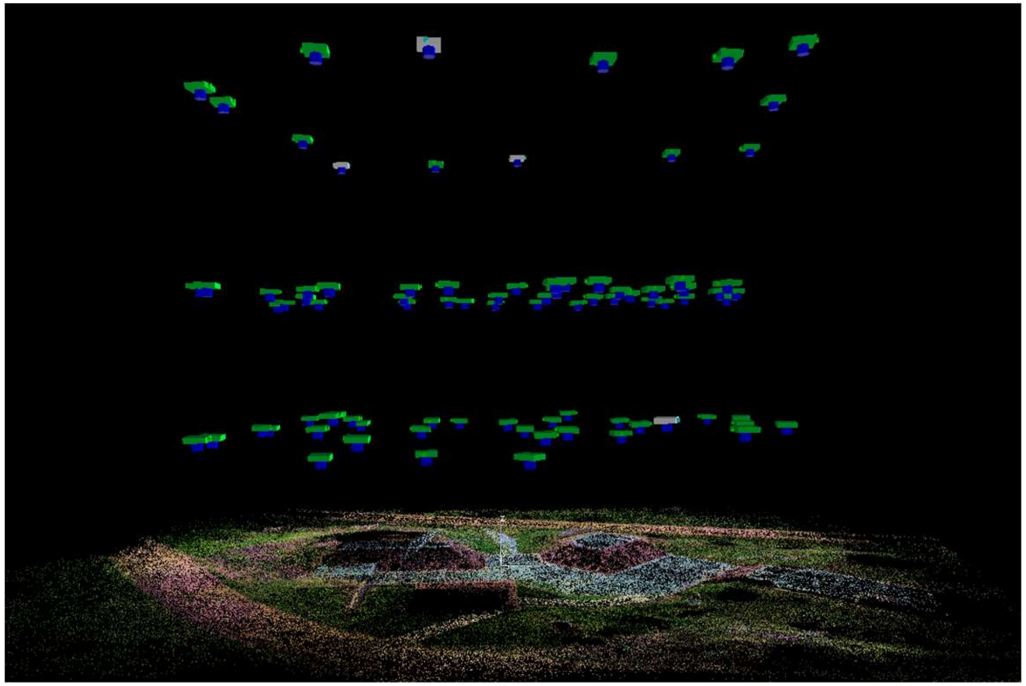


Example of mixed range calibration for a UAV camera

- UAV: DJI Phantom 3 with 12 mpixel camera of 3.8mm focal length
- 84-images & 30,000 FBM ground points (all with 6 or more rays)
- 3 Flying Heights: 10m, 20m & 30m; 31, 39 & 14 images, respectively
- 7 GCPs, 'true' standard error of σ_{XYZ} = 0.015m

Results of free-network self-calibration

- RMS v_{xy} = 0.89 pixel
- RMS $v_{X^cY^c}$ = 0.48m v_{Z^c} =0.54m
- RMS v_{XY} =0.011m v_Z =0.013m
- $\bar{\sigma}_{XY}$= 0.004m $\bar{\sigma}_Z$= 0.009m

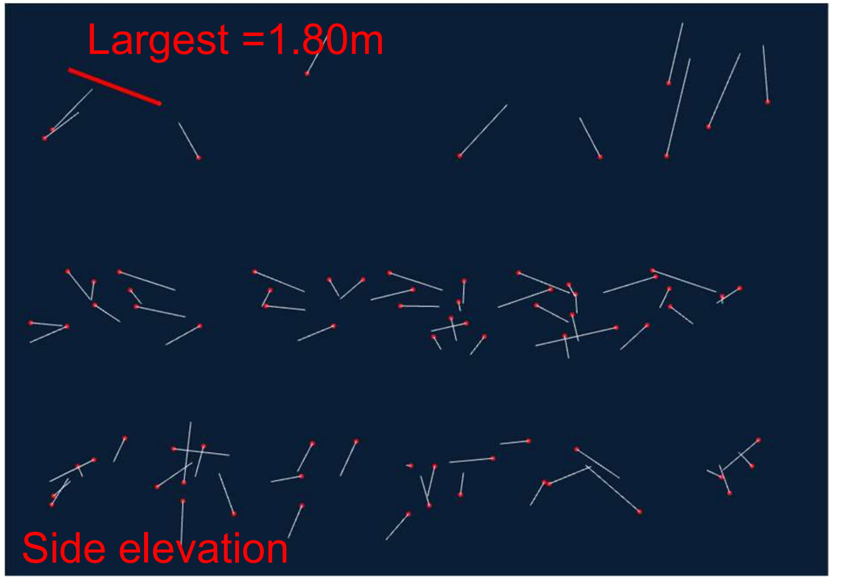


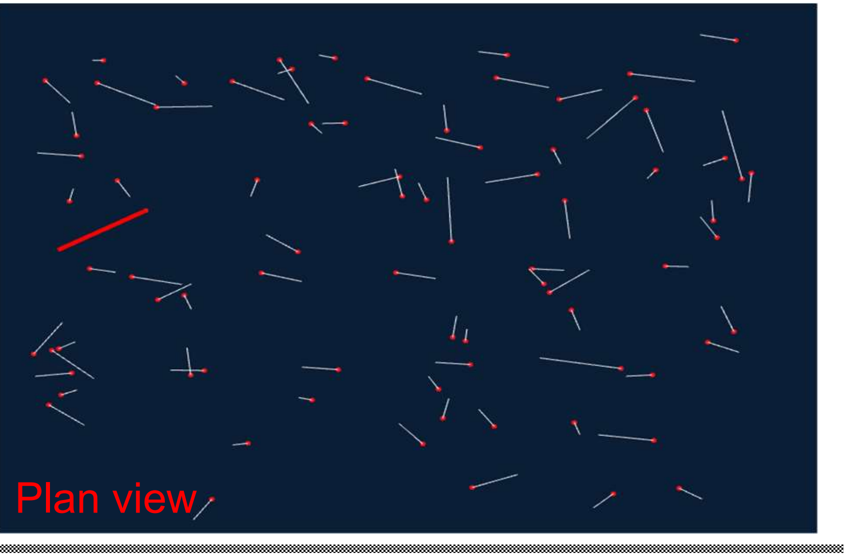
Quality of GPS UAV camera station coordinates

- 84-images & 30,000 FBM points
- 3 Flying Heights: 10m, 20m & 30m; 31, 39 & 14 images, respectively

Results of free-network self-calibration

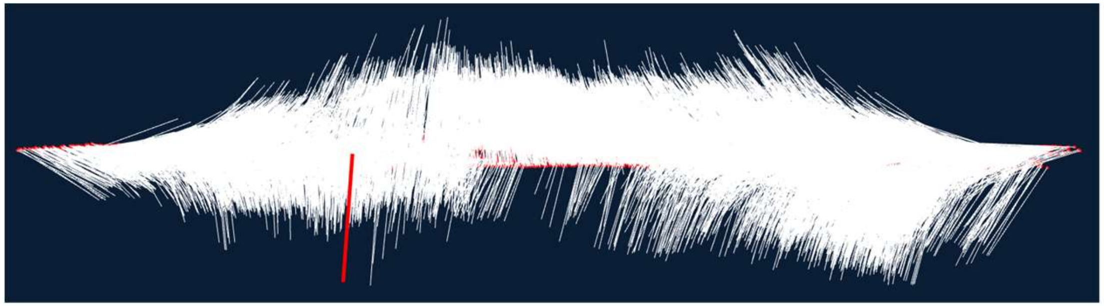
- RMS v_{xy} = 0.89 pixel
- RMS $v_{X^c Y^c}$ = 0.48m v_{Z^c} =0.51m
- RMS v_{XY} =0.011m v_Z =0.013m
- $\bar{\sigma}_{XY}$= 0.004m $\bar{\sigma}_Z$= 0.009m
- $\bar{\Delta}_{X^c Y^c}$ = 0.001m $\bar{\Delta}_{Z^c}$ = 0.028m



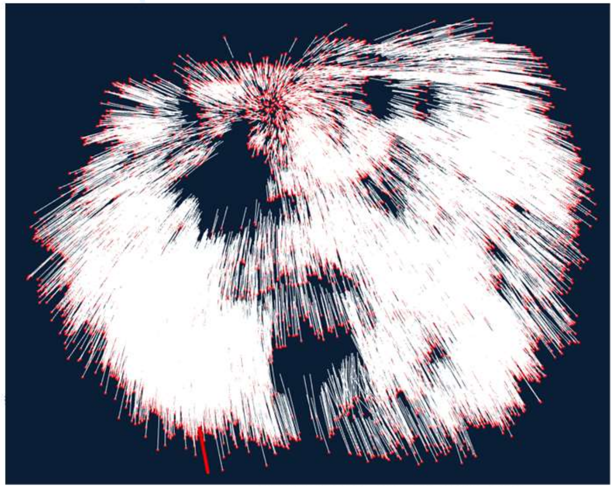


Results of Multi-Scale Self-Calibration: varying $\sigma_{X^c Y^c Z^c}$ & No GCPs

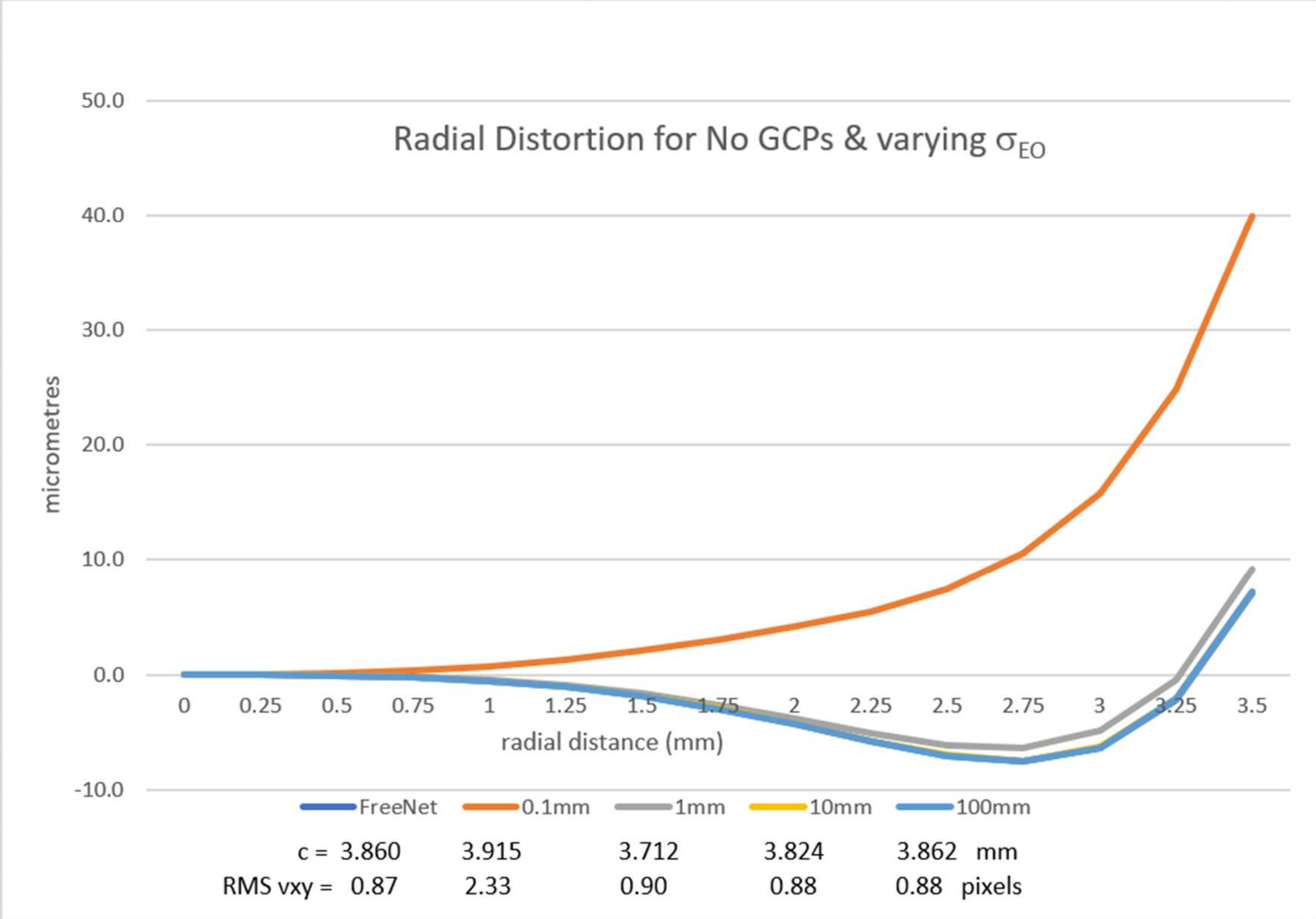
a priori constraint	RMS v_{xy} (pixel)	$\bar{\sigma}_{XY}$	$\bar{\sigma}_Z$	RMS $v_{X^c Y^c}$	RMS v_{Z^c}	RMS Δ_{XY}	RMS Δ_Z
Free-net	0.88	0.004m	0.009m	0.48m	0.51m		
Min CTRL 51,46,70	0.88	0.011	0.030	0.60	0.59		
$\sigma_{X^c Y^c Z^c}$ **0.1m**	0.89	0.47	0.48	0.48	0.51	0.003m	0.15m
$\sigma_{X^c Y^c Z^c}$ **.01m**	0.89	0.035	0.040	0.47	0.48	0.02	0.16
$\sigma_{X^c Y^c Z^c}$ **.001m**	0.90	0.005	0.010	0.39	0.43	0.06	0.62
$\sigma_{X^c Y^c Z^c}$ **.0001m**	2.33	0.008	0.020	0.20	0.23	0.13	0.17



Distortion in object space for $\sigma_{X^c Y^c Z^c}$ = .0001m
Largest error vector (red) = 0.59m



Results of Multi-Scale Self-Calibration varying $\sigma_{X^c Y^c Z^c}$ & No GCPs



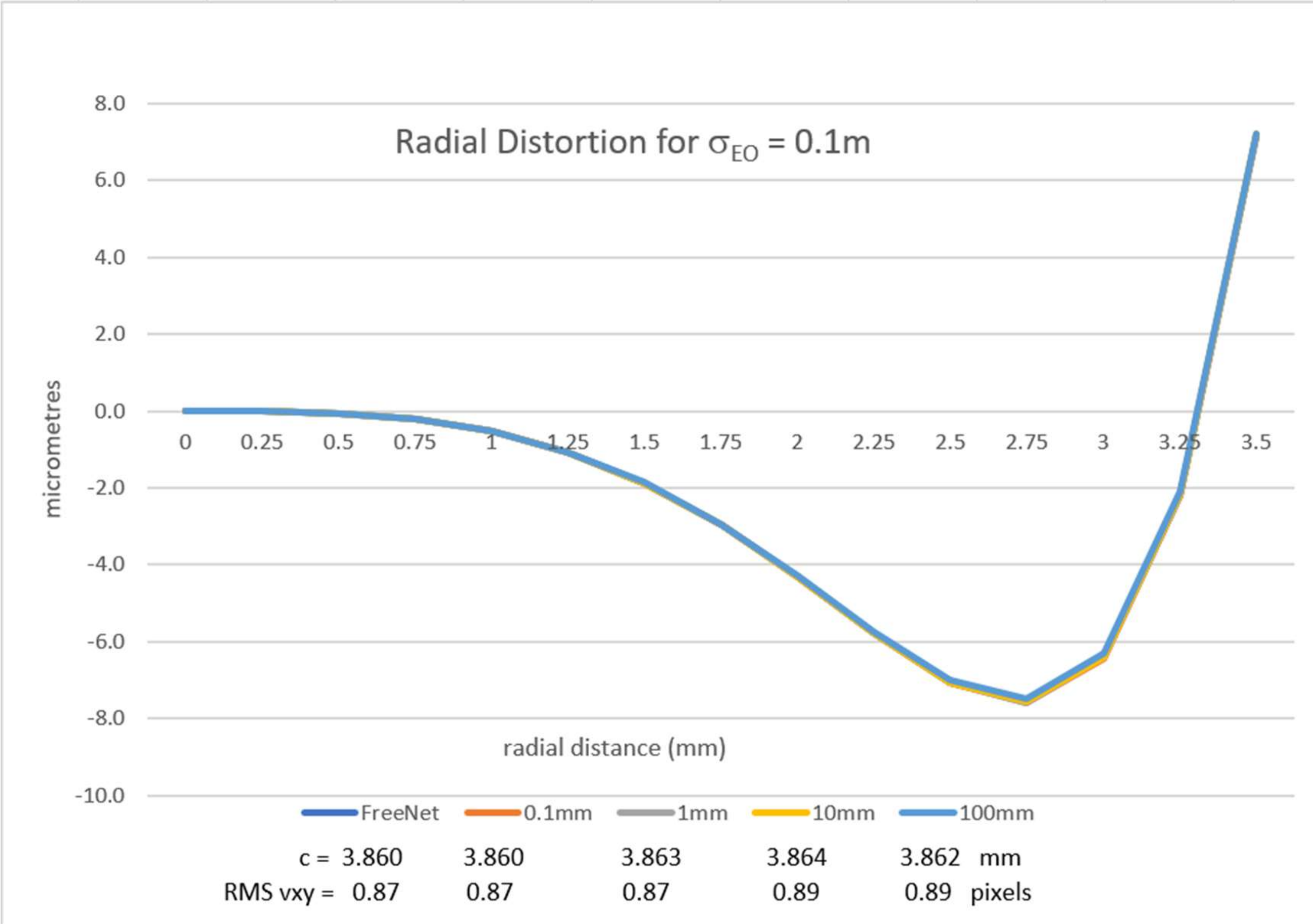
Calibration results not projectively equivalent, affine distortion introduced through changing c resulting from varying $\sigma_{X^c Y^c Z^c}$

Multi-Scale Self-Calibration results: varying σ_{XYZ} & $\sigma_{X^cY^cZ^c} = 0.1m$

a priori constraint	RMS v_{xy} (pixel)	$\bar{\sigma}_{XY}$	$\bar{\sigma}_Z$	RMS $v_{X^cY^c}$	RMS v_{Z^c}	RMS Δ_{XY} (v. 7 GCPs)	RMS Δ_Z (v. 7 GCPs)
Free-net	0.88	0.004m	0.009m	0.48m	0.51m	(0.011)	(0.009)
Min CTRL 2pts in XYZ, 1 in Z	0.88	0.004	0.011	0.48	0.54	(0.018)	(0.131)
σ_{XYZ} **0.1m**	0.89	0.313	0.306	0.48	0.51	0.009m (0.018)	0.006m (0.132)
σ_{XYZ} **.01m**	0.88	0.079	0.092	0.48	0.53	0.01 (0.017)	0.12 (0.019)
σ_{XYZ} **.001m**	0.87	0.009	0.014	0.48	0.53	0.02 (0.012)	0.13 (0.009)
σ_{XYZ} **.0001m**	0.87	0.004	0.009	0.49	0.54	0.02 (0.005)	0.14 (0.001)

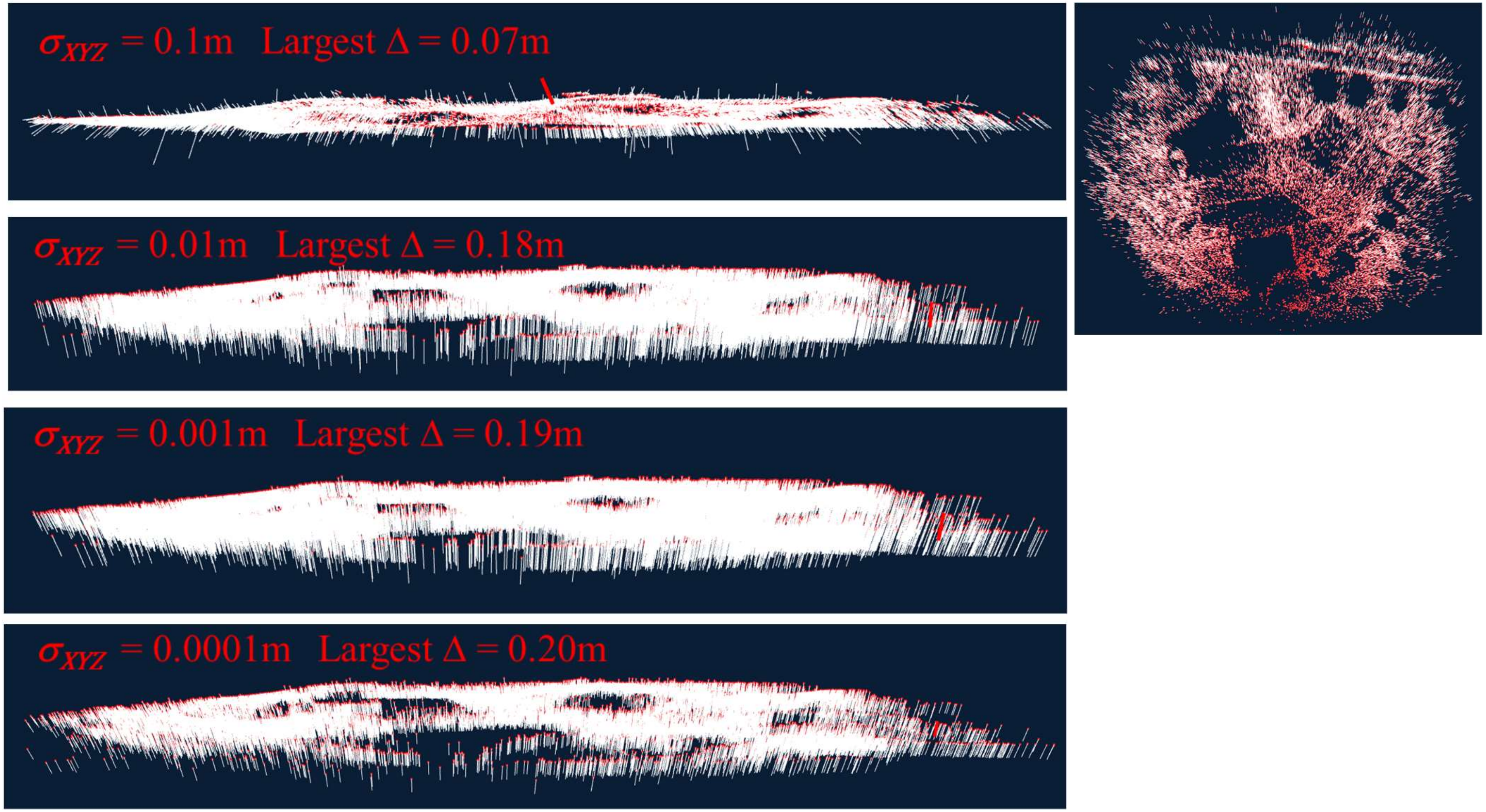
- RMS v_{xy} basically invariant with changing σ_{XYZ}
- Large inflation in $\bar{\sigma}_{XY}$ & $\bar{\sigma}_Z$ with decreasing weight of GCP constraints
- RMS fit to camera stations largely invariant with changing GCP weights
- RMS Δ_Z increasing with increasing GCP weight due to bias in calibration params.

Multi-Scale Self-Calibration results: varying σ_{XYZ} & $\sigma_{X^c Y^c Z^c}$ = 0.1m



Calibration results are quite consistent

Multi-Scale Self-Calibration results: varying σ_{XYZ} & $\sigma_{X^c Y^c Z^c} = 0.1$m



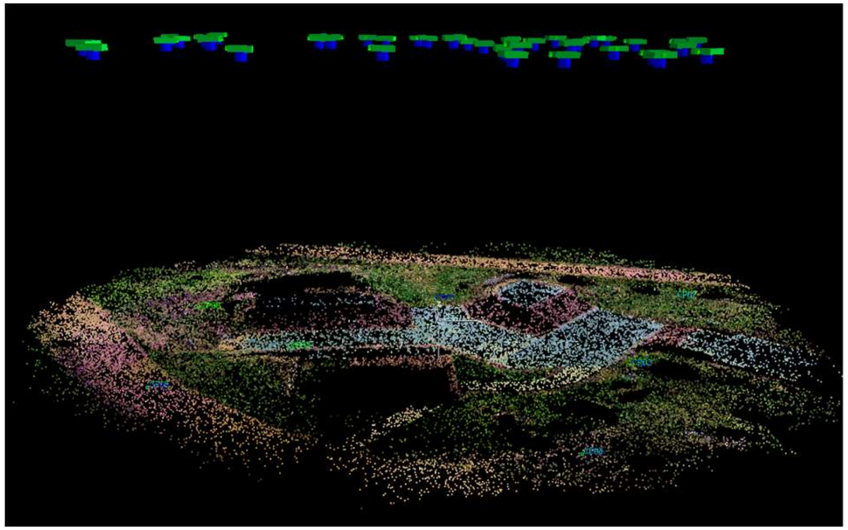
Plots of distortion in object space for different GCP weights

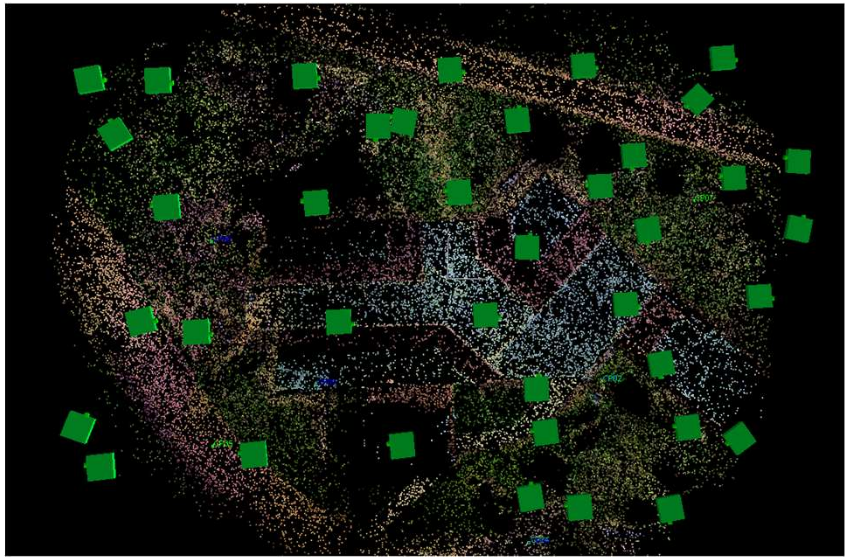
Self-Calibration from Constrained Single-Scale UAV Image Network

- 39-images & 33,000 FBM points
- Flying Height of 20m
- All points in 4 or more images
- Same GCP & Camera Stn data as 3-level 84-stn network

Free-network BA with fixed calibration (from 84-stn self-cal)

- RMS v_{xy} = 0.85 pixel
- RMS $v_{X^c Y^c}$ = 0.50m v_{Z^c} =0.43m
- RMS v_{XY} =0.011m v_Z =0.013m
- $\bar{\sigma}_{XY} = 0.006$m $\bar{\sigma}_Z = 0.015$m





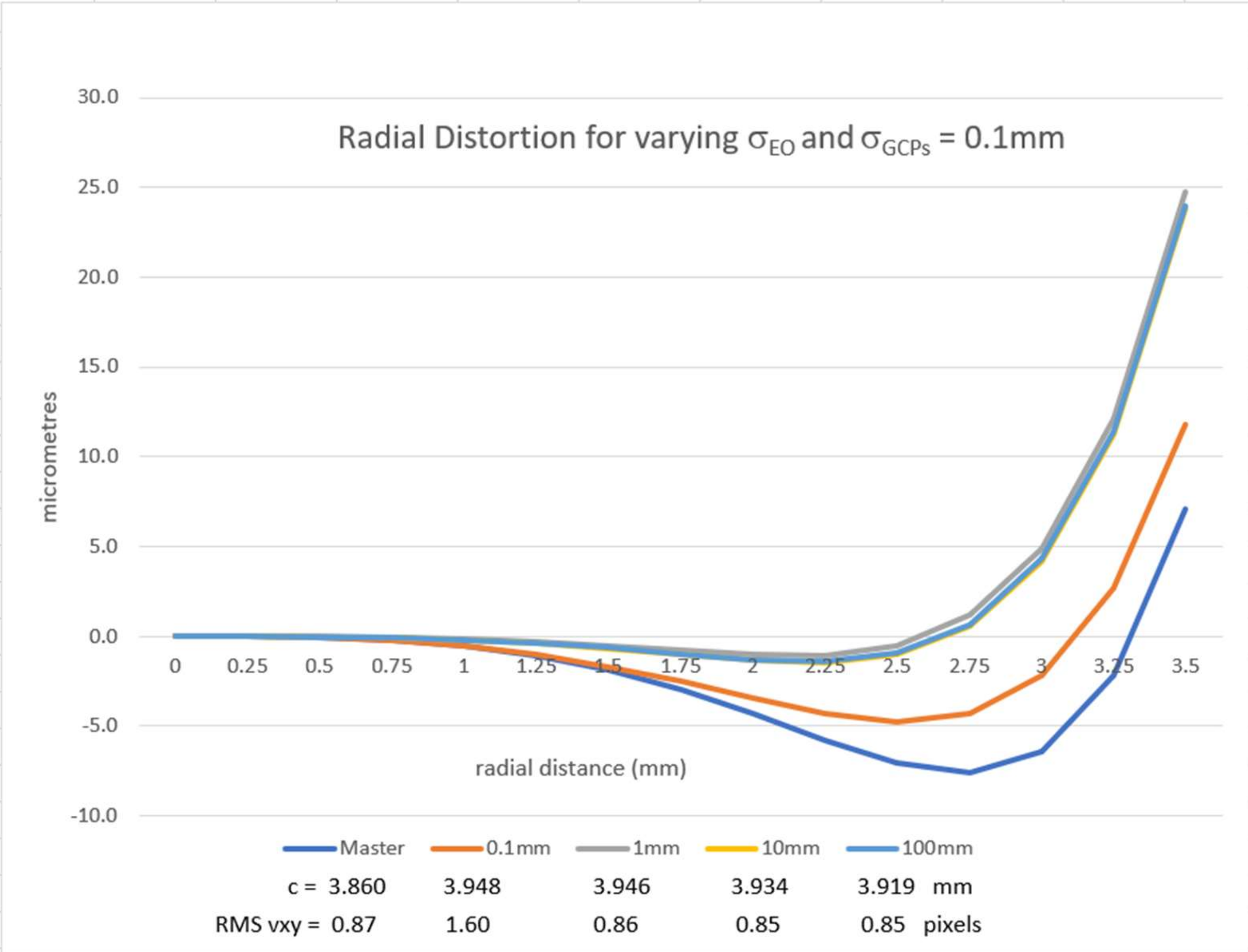
GENERALLY NOT RECOMMENDED!

Constrained Single-Scale Self-Calibration: varying $\sigma_{X^c Y^c Z^c}$ & σ_{XYZ} = 0.1mm

a priori constraint	RMS v_{xy} (pixel)	$\bar{\sigma}_{XY}$	$\bar{\sigma}_{Z}$	RMS $v_{X^c Y^c}$	RMS v_{Z^c}	RMS Δ_{XY}	RMS Δ_{Z}	RMS Δ_{XY} (GCPs)	RMS Δ_{Z} (GCPs)
Free-net, fixed calibration	0.85	0.006m	0.015m	0.50m	0.43m			0.011m	0.013m
$\sigma_{X^c Y^c Z^c}$ 0.1m	0.85	0.006	0.015	0.49	0.18	0.008m	0.08m	0.006	0.004
$\sigma_{X^c Y^c Z^c}$ .01m	0.85	0.006	0.015	0.48	0.13	0.008	0.08	0.006	0.004
$\sigma_{X^c Y^c Z^c}$ .001m	0.86	0.006	0.014	0.42	0.13	0.017	0.10	0.007	0.004
$\sigma_{X^c Y^c Z^c}$ .0001m	1.6	0.010	0.026	0.14	0.11	0.13	0.19	0.033	0.012

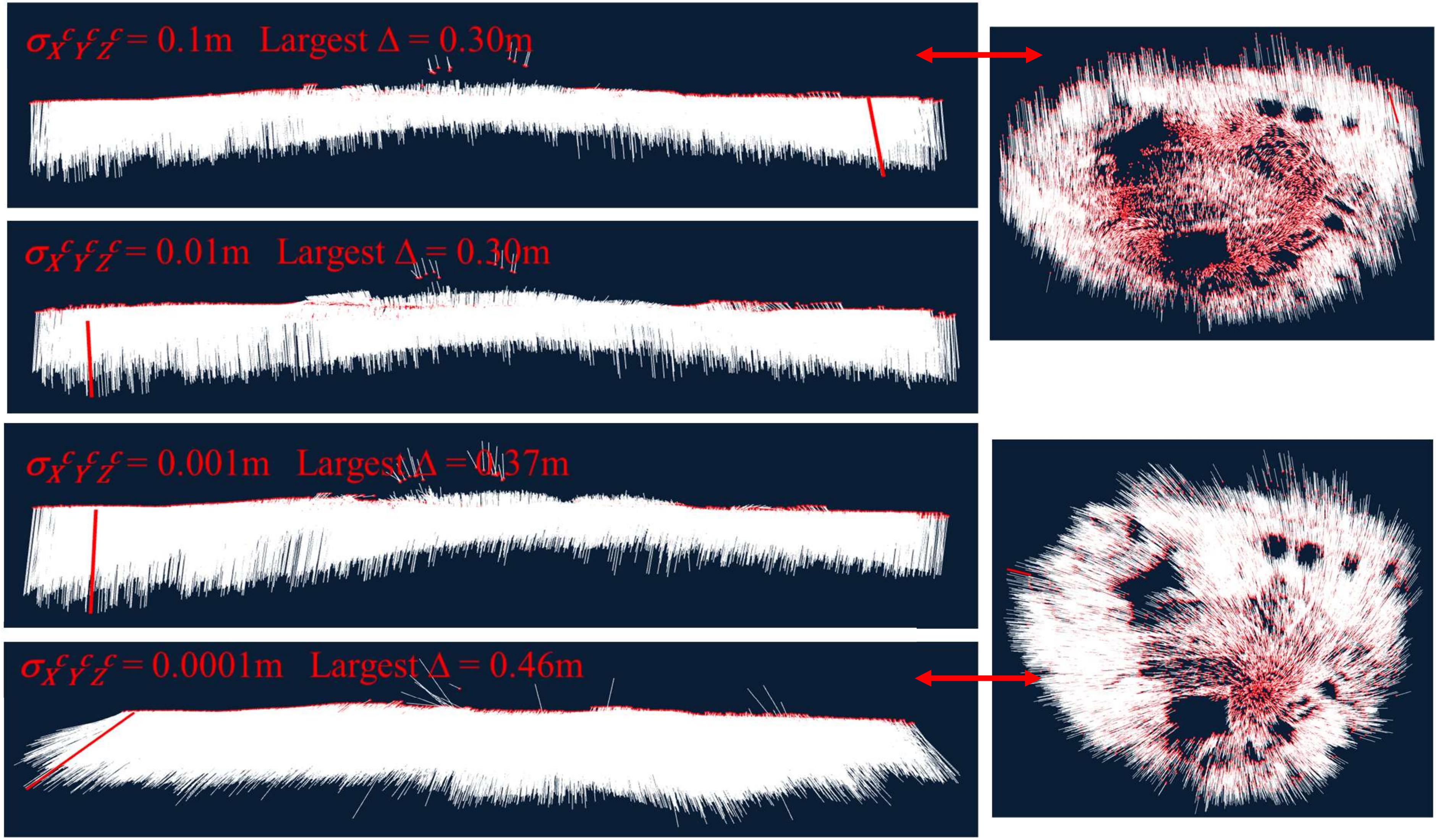
For σ_{XYZ} = 0.1 mm, there is basically no impact on object point precision and accuracy when varying $\sigma_{X^c Y^c Z^c}$, except for the case of camera stn. coords. being very tightly constrained $\sigma_{X^c Y^c Z^c}$= 0.1mm)

Constrained Single-Scale Self-Calibration: varying $\sigma_{X^c Y^c Z^c}$ & σ_{XYZ} = 0.1mm



Note the significant biases in the estimated focal length!

Constrained Single-Scale Self-Calibration: varying $\sigma_{X^cY^cZ^c}$ & $\sigma_{XYZ} = 0.1\text{mm}$



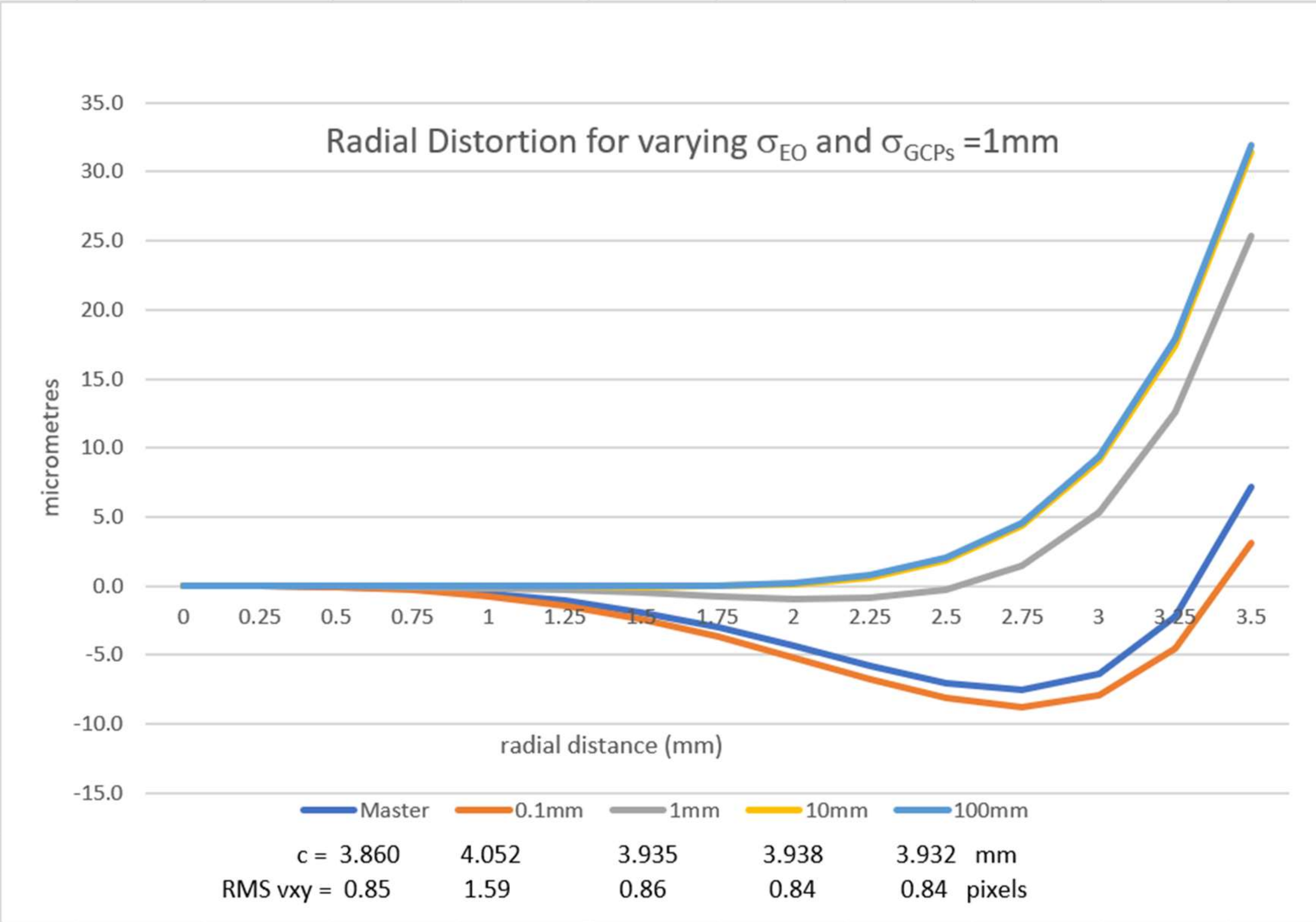
Plots of very large distortion in object space for varying camera station weights

Constrained Single-Scale Self-Calibration: varying $\sigma_{X^cY^cZ^c}$ & σ_{XYZ} = 1mm

a priori constraint	RMS v_{xy} (pixel)	$\bar{\sigma}_{XY}$	$\bar{\sigma}_{Z}$	RMS $v_{X^cY^c}$	RMS v_{Z^c}	RMS Δ_{XY}	RMS Δ_{Z}	RMS Δ_{XY} (GCPs)	RMS Δ_{Z} (GCPs)
Free-net, fixed calibration	0.85	0.006m	0.015m	0.50m	0.43m			0.011m	0.013m
$\sigma_{X^cY^cZ^c}$ 0.1m	0.84	0.011	0.019	0.48	0.14	0.008m	0.10m	0.013	0.053
$\sigma_{X^cY^cZ^c}$ .01m	0.84	0.010	0.018	0.48	0.13	0.009	0.10	0.014	0.053
$\sigma_{X^cY^cZ^c}$ .001m	0.86	0.008	0.016	0.42	0.12	0.09	0.07	0.079	0.043
$\sigma_{X^cY^cZ^c}$ .0001m	1.6	0.010	0.028	0.13	0.11	0.21	0.90	0.18	0.71

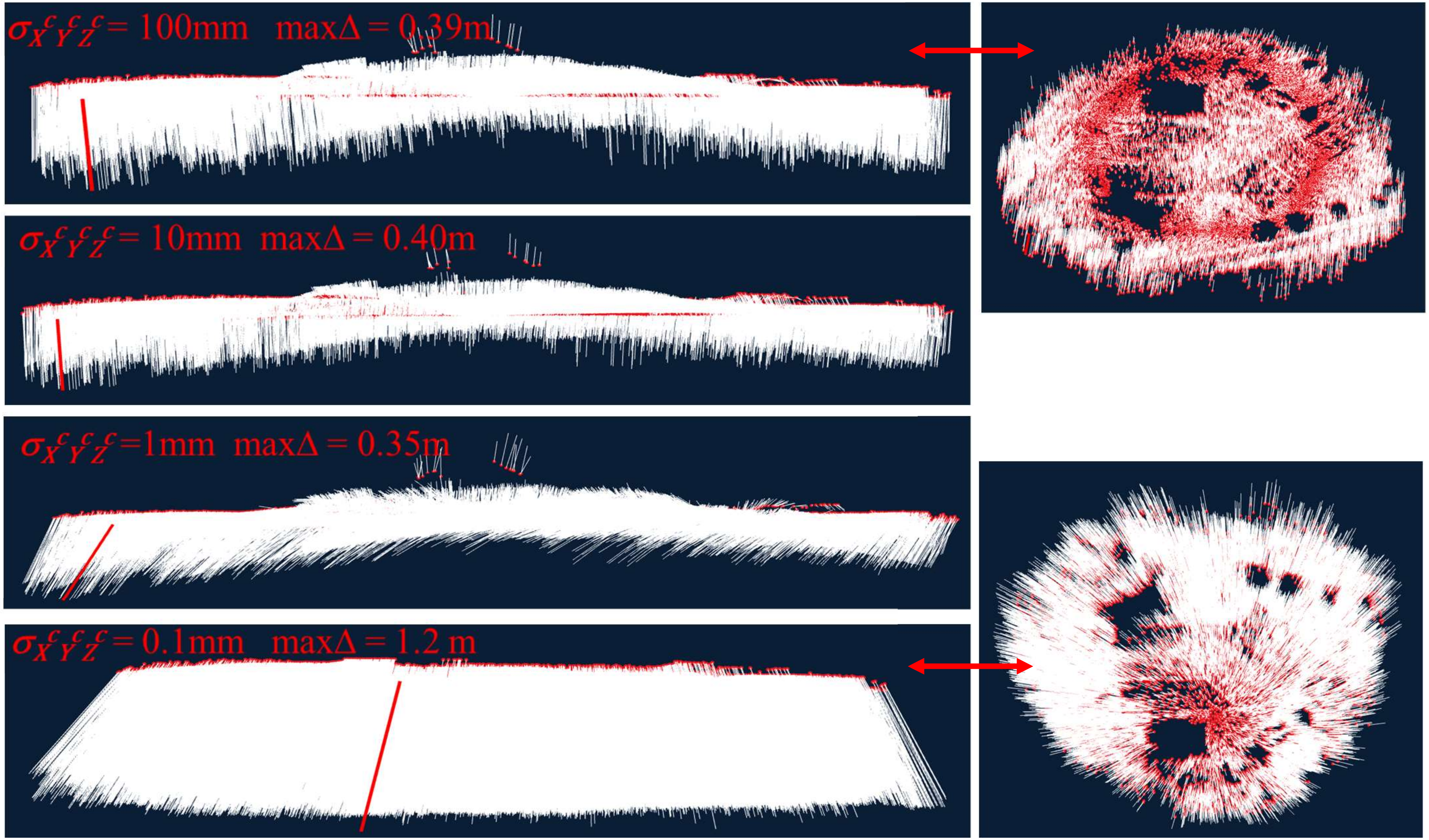
For σ_{XYZ} = 1mm, significant impact on object point planimetric precision and accuracy occurs when $\sigma_{X^cY^cZ^c} \leq \sigma_{XYZ}$; impact on vertical accuracy occurs for all constraint values.

Constrained Single-Scale Self-Calibration: varying $\sigma_{X^c Y^c Z^c}$ & σ_{XYZ} = 1mm



Note the significant biases in the estimated focal length!

Constrained Single-Scale Self-Calibration: varying $\sigma_{X^cY^cZ^c}$ & $\sigma_{XYZ} = 1$mm



Plots of very large distortion in object space for varying camera station weights

Concluding Remarks

- The network geometry rules regarding self-calibration apply to UAV/UAS networks – there are no shortcuts!
- Consider comprehensive pre-calibration & assessment of calibration stability; multi-scale networks preferred over constrained single-scale
- Not only IO calibration is problematic for near-nadir UAS networks w/o EO constraints, self-calibration of radial distortion also a problem
- GPS camera stn. constraints in self-calibration are generally useful in UAS networks only when GPS accuracy is cm level – not yet common
- Biases & distortions in point positioning are not necessarily removed through the use of moderately to tightly constrained GCPs
- Covariance matrices only realistic when datum & configuration defects removed – helped by control sigmas << image point sigmas*
- Object point biases & distortions can be >> magnitude indicated by object point XYZ sigmas

Thank You

To ensure successful self-calibration: Maximise image scale variation within and between images forming the network … and utilise roll angle variation