Image Motion Compensation

A tutorial including analysis of a catadioptric ultra-telephoto lens

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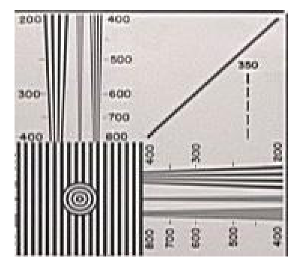
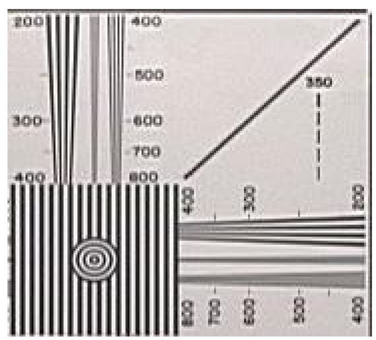


Introduction

- Imaging systems are subject to mechanical disturbances including vibration
- This results in a motion-induced blurring of the image called *smear*

Introduction

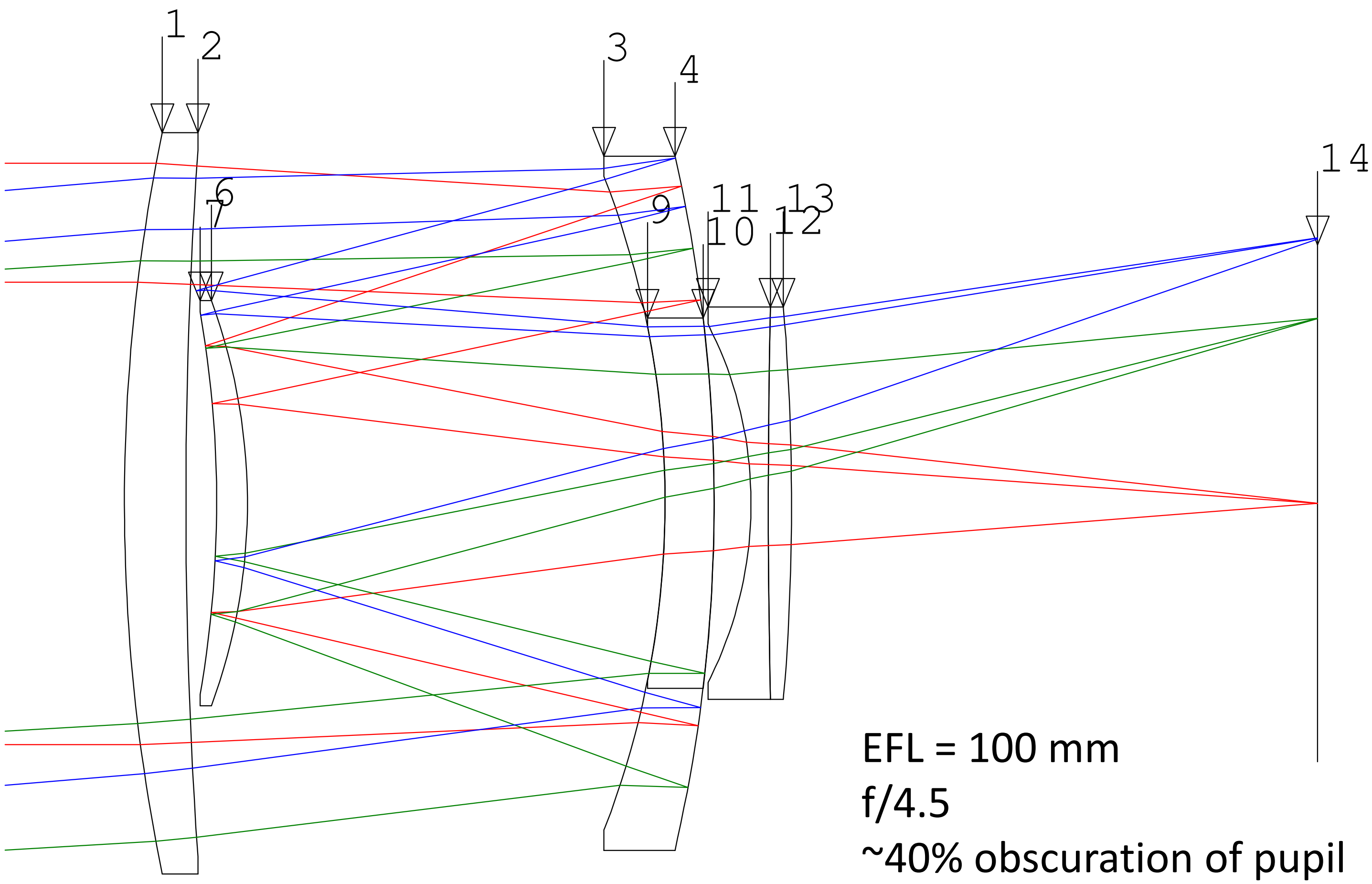
- Image motion compensation (IMC) refers to the active control of something to stabilize the object space line-of-sight (LOS) of the focal plane array
- Goal is to eliminate smear and thus have a sharper image



Introduction

- The example used in this tutorial is a catadioptric ultra-telephoto lens
- US Patent 4,264,136 (Ogino 1981) assigned to Minolta Corporation
- Original Japanese patent 61-48132

Introduction



EFL = 100 mm
f/4.5
~40% obscuration of pupil

Introduction

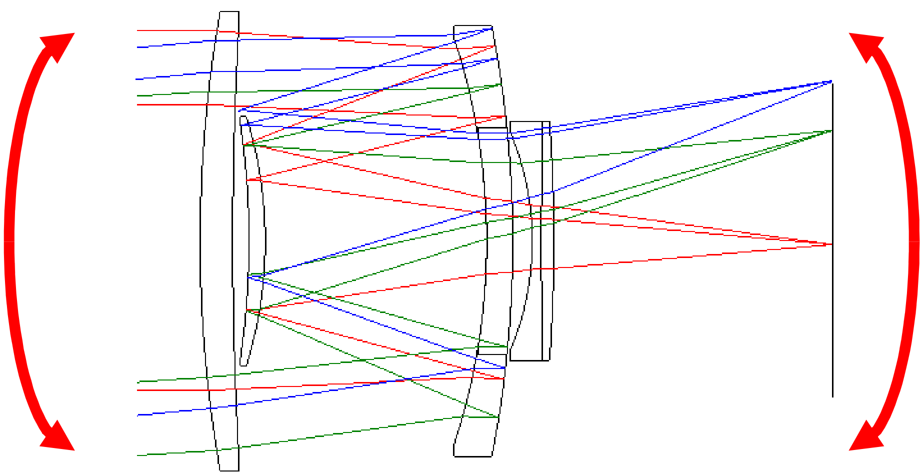
- Optical elements of system
  - Positive meniscus lens
    - Surfaces 1 and 2
  - Multiple-pass, primary negative meniscus lens/mirror
    - Surfaces 3—5, 9—10
  - Second-surface, secondary negative meniscus lens/mirror
    - Surfaces 6—8
  - Lens doublet
    - Surfaces 11—13

Common IMC methods

- There are four more-or-less common methods of compensating for image motion
  - Moving the entire optical system
  - Moving the focal plane array
  - Adding a flat, fast steering mirror (FSM)
  - Moving optical groups
- More exotic methods are possible in theory
  - Deformable optical surfaces
  - Variable index material

Common IMC methods

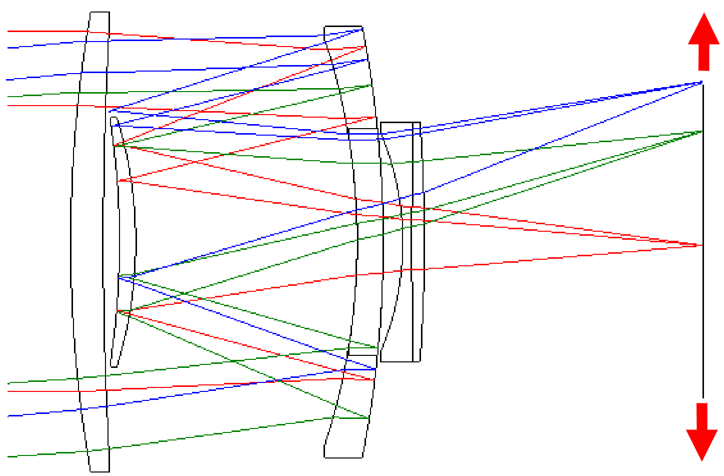
- Moving the entire optical system
  - Typically done with a serial gimbal mechanism
  - Bandwidth and thus performance is fundamentally limited



$$\Delta\theta_{\mathrm{Gimbal}} = \Delta\theta_{\mathrm{Field}}$$

Common IMC methods

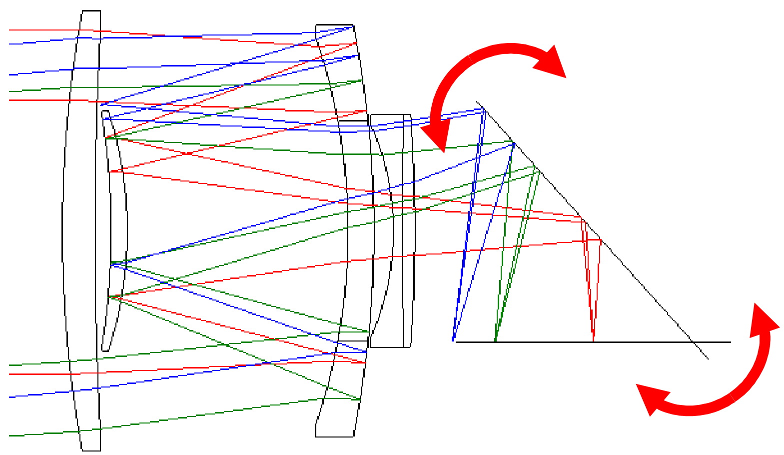
- Moving the focal plane array
  - Consumer camera manufacturers using this technique include Sony, Pentax, Olympus, Fujifilm, Samsung, Sasio, and Ricoh Capilio (Wikipedia, 2008)



$$\Delta\varepsilon_{\mathrm{FPA}} = f \cdot \Delta\theta_{\mathrm{Field}}$$

Common IMC methods

- Adding a flat, fast steering mirror

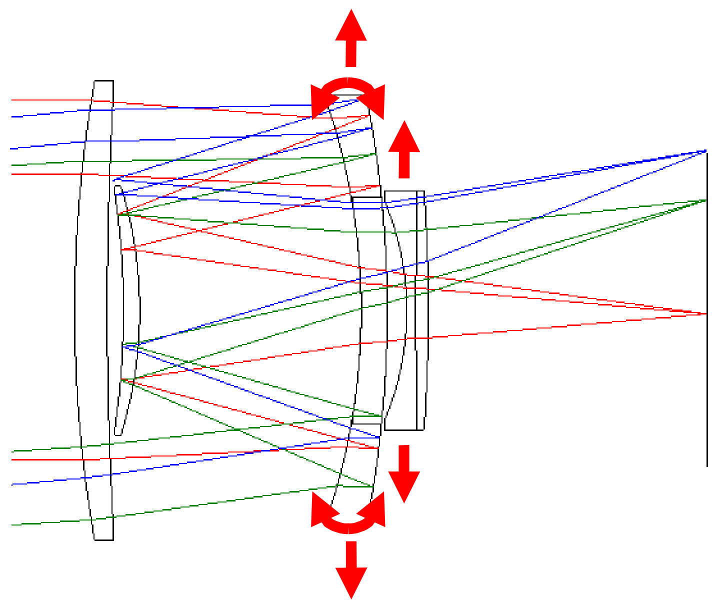


$$\Delta\theta_{\mathrm{FSM}} = \frac{f}{2 \cdot f/\# \cdot B_{\mathrm{FSM}}} \cdot \Delta\theta_{\mathrm{Field}}$$

- f/# is the (working) focal ratio
- B_{FSM} is the marginal ray bundle diameter at the FSM

Common IMC methods

- Moving optical groups
  - Used by Canon and Nikon
- For example system, three possibilities are
  - Tilt primary mirror (multi-pass, catadioptric element)
  - Decenter primary mirror
  - Decenter doublet



Analysis of catadioptric ultra-telephoto system

- Prescription

Surface #	Radius	Thickness	Index	Abbe #	Semi-Aperture
Object	Infinity	Infinity			
Stop	60.5720	2.0000	1.5176	53	11.1372
2	173.8170	15.6000			11.0649
3	-29.8250	1.6000	1.5168	64	10.2000
4	-51.1740	-1.6000	1.5168	64	10.4000
5	-29.8250	-13.6000			9.6902
6	-19.3730	-1.0000	1.5168	64	5.9000
7	-36.9270	1.0000	1.5168	64	5.7641
8	-19.3730	13.6000			5.8103
9	-29.8250	1.6000	1.5168	54	5.2979
10	-51.1740	1.2000			5.3649
11	-13.0150	0.5600	1.5168	81	5.3657
12	266.6470	0.7600	1.7400	62	5.6363
13	-77.9790	17.0322			5.7000
Image	Infinity	0.0981			8.6788

Analysis of catadioptric, ultra-telephoto system

- Performance metrics
  - Image location: Image height y_{image} (mm) of the ray going through the y_p = 0.65 pupil position for a 589 nm wavelength
    - Due to obscuration, 0.65 pupil position is "central"
  - Image quality: Weighted RMS of RMS wavefront error (waves)
    - RMS wavefront error across pupil computed for 656, 589, and 434 nm wavelengths
    - RMS across wavelengths computed thereafter

Analysis of catadioptric, ultra-telephoto system

- Comparison of performance for nominal system and with fields rotated by 0.1 deg due to system motion

Field	Weighted ΔW_{RMS}	y_{Image} of W2, y_p = 0.65
0.00	0.092406	-0.00169
0.71	0.630788	6.06034
1.00	0.832963	8.67177
AVE:	0.580905	

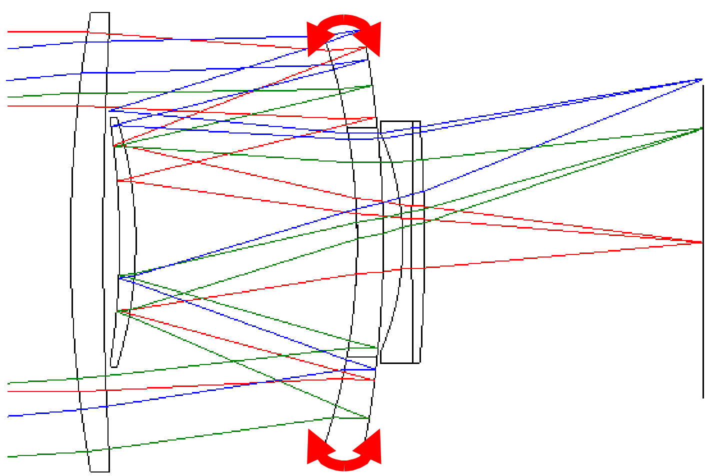
Reference system without field rotation

Field	Weighted ΔW_{RMS}	y_{Image} of W2, y_p = 0.65
0.00	0.094484	-0.17703
0.71	0.609964	5.87943
1.00	0.820255	8.48489
AVE:	0.568817	

Disturbed system with 0.1 deg field rotation

IMC via tilt of primary mirror groups

- First strategy: Tilt the primary mirror
- “Mirror” is really a multi-pass, catadioptric element
- Most image motion comes from rotation of surface 4
- Must consider surfaces 3, 5, 9 and 10 as well



IMC via tilt of primary mirror groups

- Define two groups of surfaces
  - Group G1: Surfaces 3, 4 and 5
  - Group G2: Surfaces 9 and 10
- Properties of G1
  - First and second principal planes coincident, $d_{G1} = d'_{G1} = 1.0$ mm to the right of S3 vertex
  - Power is $\varphi_{G1} = 0.026178\ \text{mm}^{-1}$, corresponding to a focal length of $f_{G1} = 38.2$ mm

IMC via tilt of primary mirror groups

- Properties of G2
  - First principal plane is d_{G2} = -1.5 mm to the right of S9 vertex
  - Second principal plane is d'_{G2} = -2.6 mm to the right of S10 vertex
  - Distance between principal planes is PP'_{G2} = 1.7175 mm
  - Power is φ_{G2} = -0.007044 mm^{-1}, corresponding to a focal length of f_{G2} = -142.0 mm

IMC via tilt of primary mirror groups

- Sensitivities of image motion to element motion can be computed using methods described in (Burge, 2006)
- Need following parameters
  - Marginal ray bundle diameters of groups G1 and G2 are B_{G1} = 19.9 mm and B_{G2} = 5.2 mm
  - Numerical aperture exiting groups G1 and G2 are NA_{G1} = 0.0624 and NA_{G2} = 0.1885
  - System numerical aperture is NA = 0.1114

IMC via tilt of primary mirror groups

- Sensitivities of image motion to angle for each group

$$\frac{d\varepsilon_{\mathrm{G1}}}{d\theta_{\mathrm{G1}}} = 2 \cdot f\,/\# \cdot B_{\mathrm{G1}} = 179.1\,\mathrm{mm/rad}$$

$$\frac{d\varepsilon_{\mathrm{G2}}}{d\theta_{\mathrm{G1}}} = \varphi_{\mathrm{G2}} \cdot \left(d_{\mathrm{G2}} - d_{\mathrm{G1}}\right) \cdot f\,/\# \cdot B_{\mathrm{G2}} - PP'_{\mathrm{G2}} \frac{NA_{\mathrm{G2}}}{\mathrm{NA}} = -2.5\,\mathrm{mm/rad}$$

- Combined sensitivity

$$\frac{d\varepsilon}{d\theta_{\mathrm{G1}}} = \frac{d\varepsilon_{\mathrm{G1}}}{d\theta_{\mathrm{G1}}} + \frac{d\varepsilon_{\mathrm{G2}}}{d\theta_{\mathrm{G1}}} = 176.6\,\mathrm{mm/rad}$$

IMC via tilt of primary mirror groups

- Rotation required to compensate for a field change of $\Delta\theta_{\text{Field}} = 0.1$ deg is then

$$\theta_{G1} = \left(\frac{d\varepsilon}{d\theta_{G1}}\right)^{-1} f \cdot \Delta\theta_{\text{Field}} = -988.14\ \mu\text{rad}$$

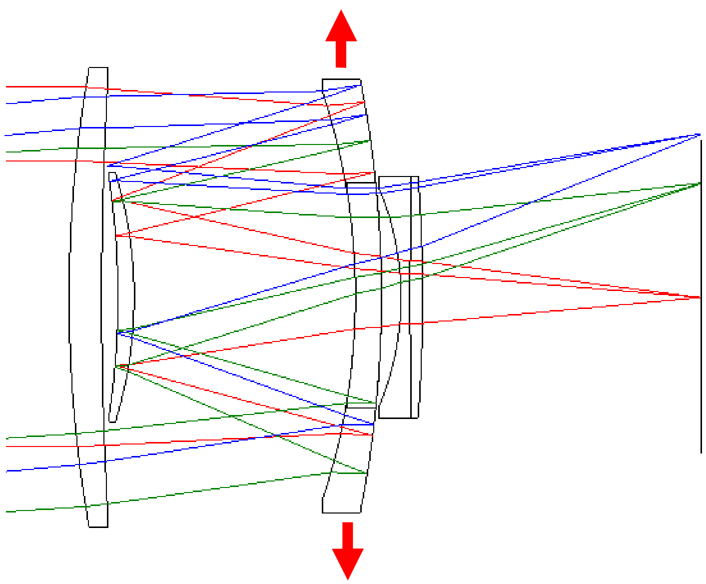
- Apply and run Code V to get

Field	Weighted ΔW_{RMS}	y_{Image} of W2, $y_p = 0.65$
0.00	0.096466	-0.00015
0.71	0.617780	6.06217
1.00	0.824420	8.67363
AVE:	0.572908	

WFE and image position given compensatory rotation of primary mirror groups

IMC via decenter of primary mirror groups

- Second strategy: Displace the primary mirror laterally (decenter)



IMC via decenter of primary mirror groups

- Sensitivities of image motion to decenter for each group

$$\frac{d\varepsilon_{\mathrm{G1}}}{ds_{\mathrm{G1}}} = \varphi_{\mathrm{G1}} \cdot f/\# \cdot B_{\mathrm{G1}} = 2.34\ \mathrm{mm/mm}$$

$$\frac{d\varepsilon_{\mathrm{G2}}}{ds_{\mathrm{G1}}} = \varphi_{\mathrm{G2}} \cdot f/\# \cdot B_{\mathrm{G2}} = -0.17\ \mathrm{mm/mm}$$

- Combined sensitivity

$$\frac{d\varepsilon}{ds_{\mathrm{G1}}} = \frac{d\varepsilon_{\mathrm{G1}}}{ds_{\mathrm{G1}}} + \frac{d\varepsilon_{\mathrm{G2}}}{ds_{\mathrm{G1}}} = 2.18\ \mathrm{mm/mm}$$

IMC via decenter of primary mirror groups

- Displacement required to compensate for a field change of $\Delta\theta_{\text{Field}} = 0.1$ deg is then

$$s_{G1} = \left(\frac{d\varepsilon}{ds_{G1}} \right)^{-1} f \cdot \Delta\theta_{\text{Field}} = 0.0801\, mm$$

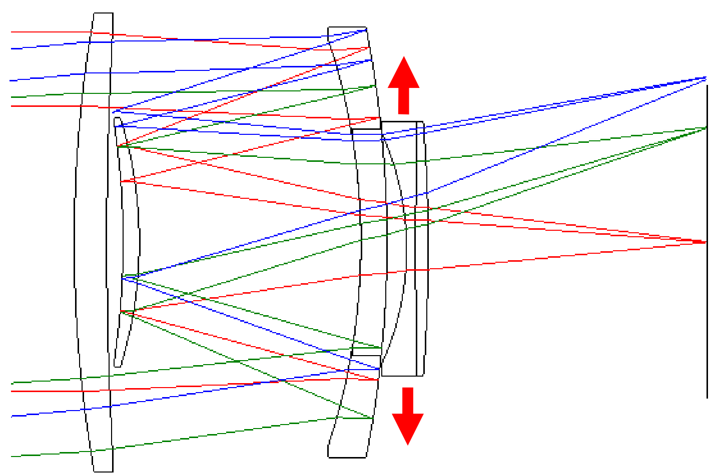
- Apply and run Code V to get

Field	Weighted ΔW_{RMS}	y_{Image} of W2, $y_p = 0.65$
0.00	0.204793	-0.00624
0.71	0.523547	6.05752
1.00	0.741858	8.66957
AVE:	0.516871	

WFE and image position given compensatory displacement of primary mirror groups

IMC via decenter of lens doublet

- Third strategy: Displace the lens doublet laterally (decenter)



IMC via decenter of lens doublet

- Group G3: Surfaces 11, 12 and 13
- Properties of G3
  - First principal plane is d_{G3} = -0.27 mm to the right of S11 vertex
  - Second principal plane is d'_{G3} = -1.09 mm to the right of S10 vertex
  - Distance between principal planes is PP'_{G3} = 0.506 mm
  - Power is φ_{G3} = -0.029069 mm^{-1}, corresponding to a focal length of f_{G3} = -34.4 mm
- Marginal ray bundle diameter B_{G3} = 4.0 mm

IMC via decenter of lens doublet

- Sensitivity of image motion to decenter

$$\frac{d\varepsilon}{ds_{\mathrm{G3}}} = \varphi_{\mathrm{G3}} \cdot f/\# \cdot B_{\mathrm{G3}} = -0.5267 \text{ mm/mm}$$

IMC via decenter of primary mirror groups

- Displacement required to compensate for a field change of $\Delta\theta_{\text{Field}} = 0.1$ deg is then

$$s_{\text{G3}} = \left(\frac{d\varepsilon}{ds_{\text{G3}}}\right)^{-1} f \cdot \Delta\theta_{\text{Field}} = -0.3313\, mm$$

- Apply and run Code V to get

Field	Weighted ΔW_{RMS}	y_{Image} of W2, $y_p = 0.65$
0.00	0.315091	0.01273
0.71	1.038235	6.10751
1.00	1.277895	8.74154
AVE:	0.932778	

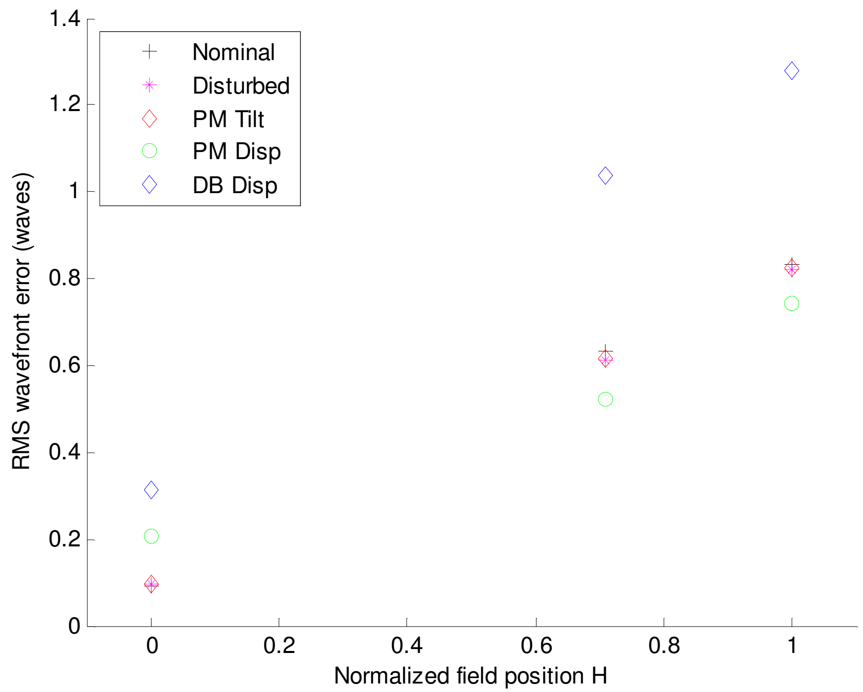
WFE and image position given compensatory displacement of lens doublet

Performance comparison

- Not enough analysis performed to make grand conclusions
- Still, it is interesting to compare performance

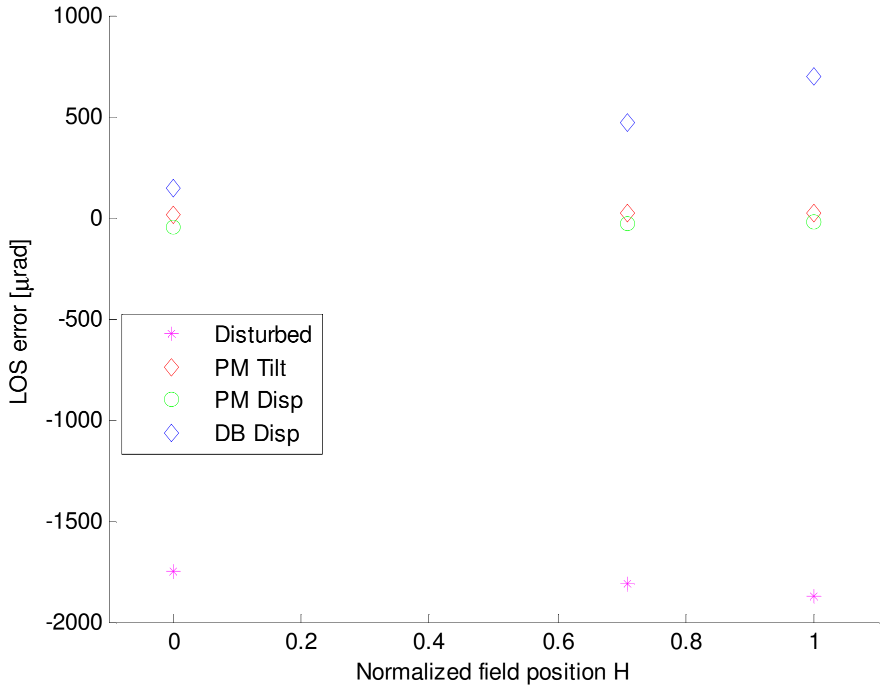
Performance comparison

- Wavefront errors



Performance comparison

- LOS errors
  - Evidence of over-compensation for doublet displacement



Conclusion

- An overview was given of four more-or-less common methods of compensating for image motion
  - Moving the entire optical system
  - Moving the focal plane array
  - Adding a flat, fast steering mirror (FSM)
  - Moving optical groups
- Special attention was given to the latter method of moving optical groups
- The optical performance (RMS WFE, LOS pointing error) will depend on which elements are moved and how

Bibliography

- Burge, J. (2006). An easy way to relate optical element motion to system pointing stability. *Current Developments in Lens Design and Optical Engineering VII. 6288*, pp. 62880I-1--12. San Diego: SPIE.
- Ogino, S. (1981). *Patent No. 4,264,136.* United States of America.
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