The ST7 Interferometer

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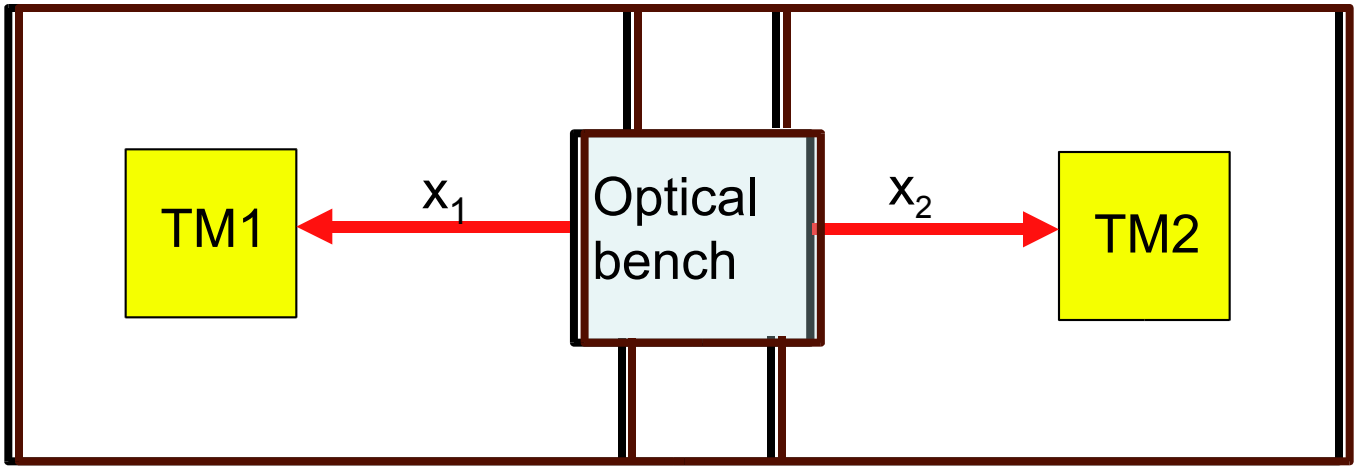
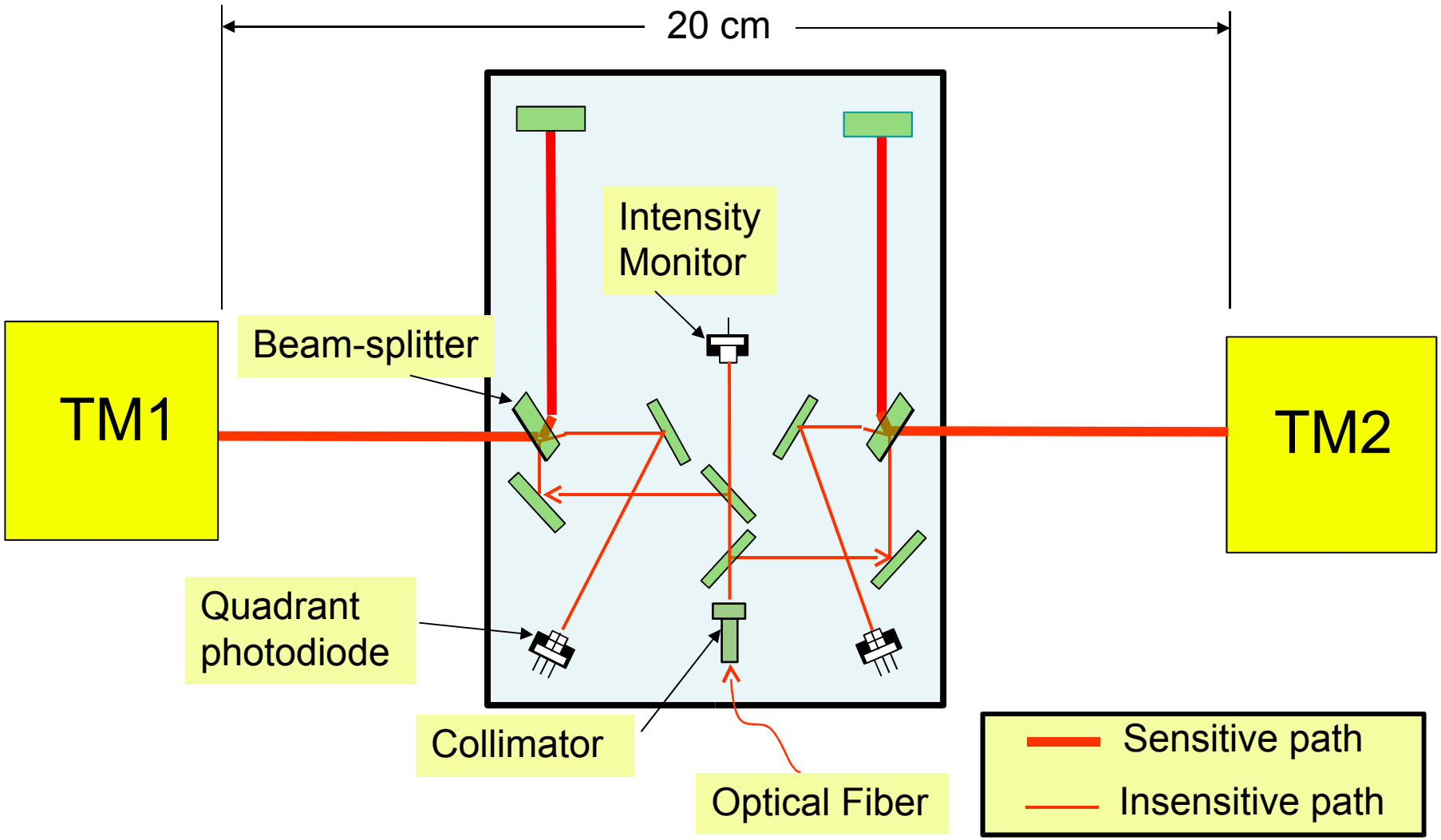
ST7 Concept

- Measure suspended masses within spacecraft
- Test thruster performance in drag-free control
- Hitch ride on LISA Pathfinder



- Interferometer optical bench fixed to spacecraft
- x_1 and x_2 measured separately; $x_1 + x_2$ is low-noise

Optical Bench



Interferometer Features

Beam diameter 1 mm, Rayleigh range 70 cm, sensitive path lengths 10 cm.

No modulators, phasemeters, intensity stabilization, or frequency stabilization.

Requires test mass to be positioned near mid-fringe.

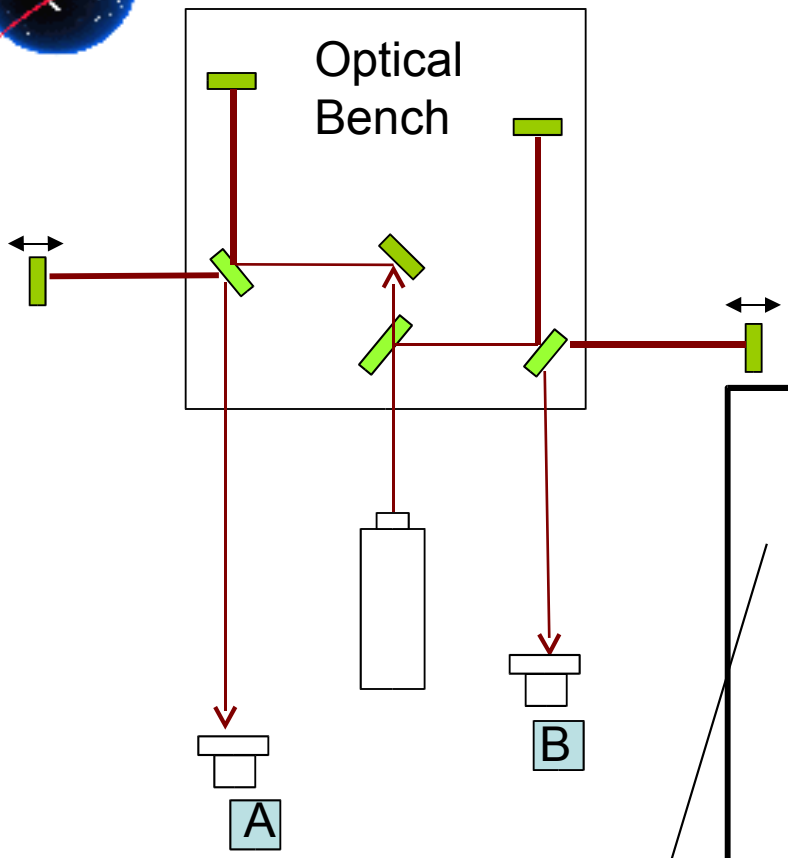
Intensity monitored, noise removed in data analysis.

Separate measurements of both bench/test-mass distances.

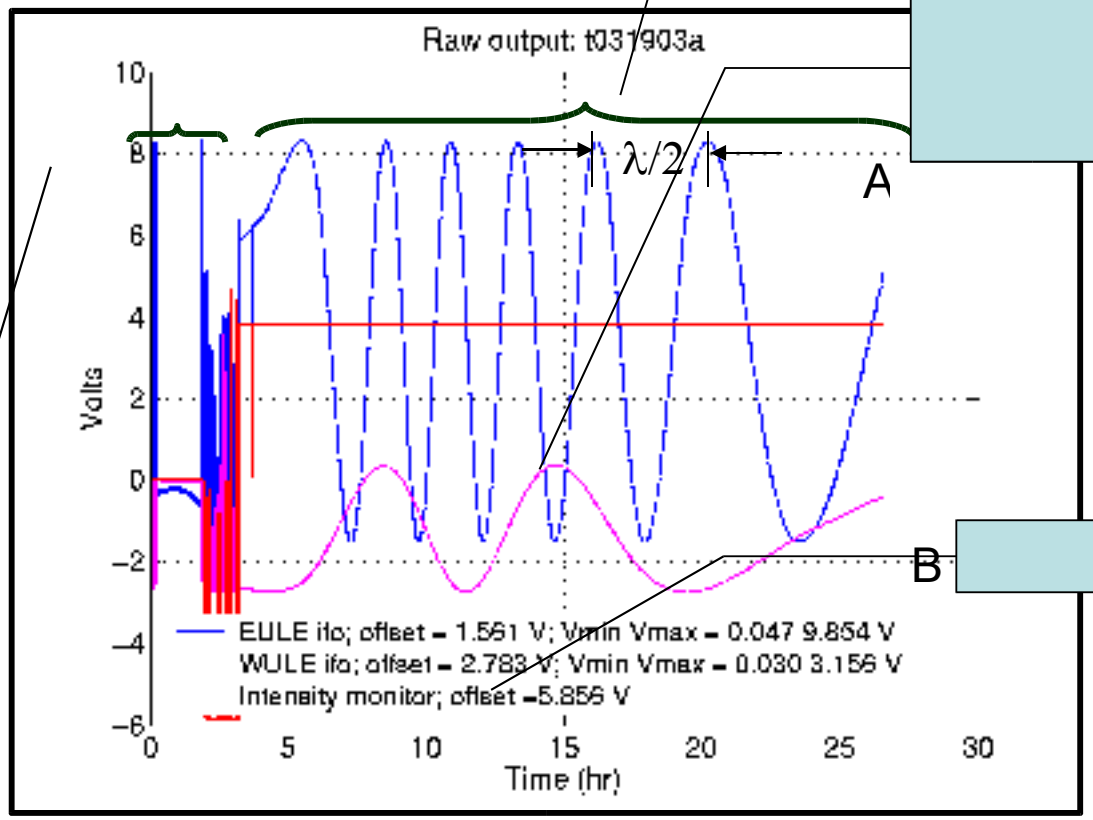
Quadrant photodiodes monitor total fringe signal, and two axes of alignment.

Automatic alignment, autonomous operation.

Homodyne Signal

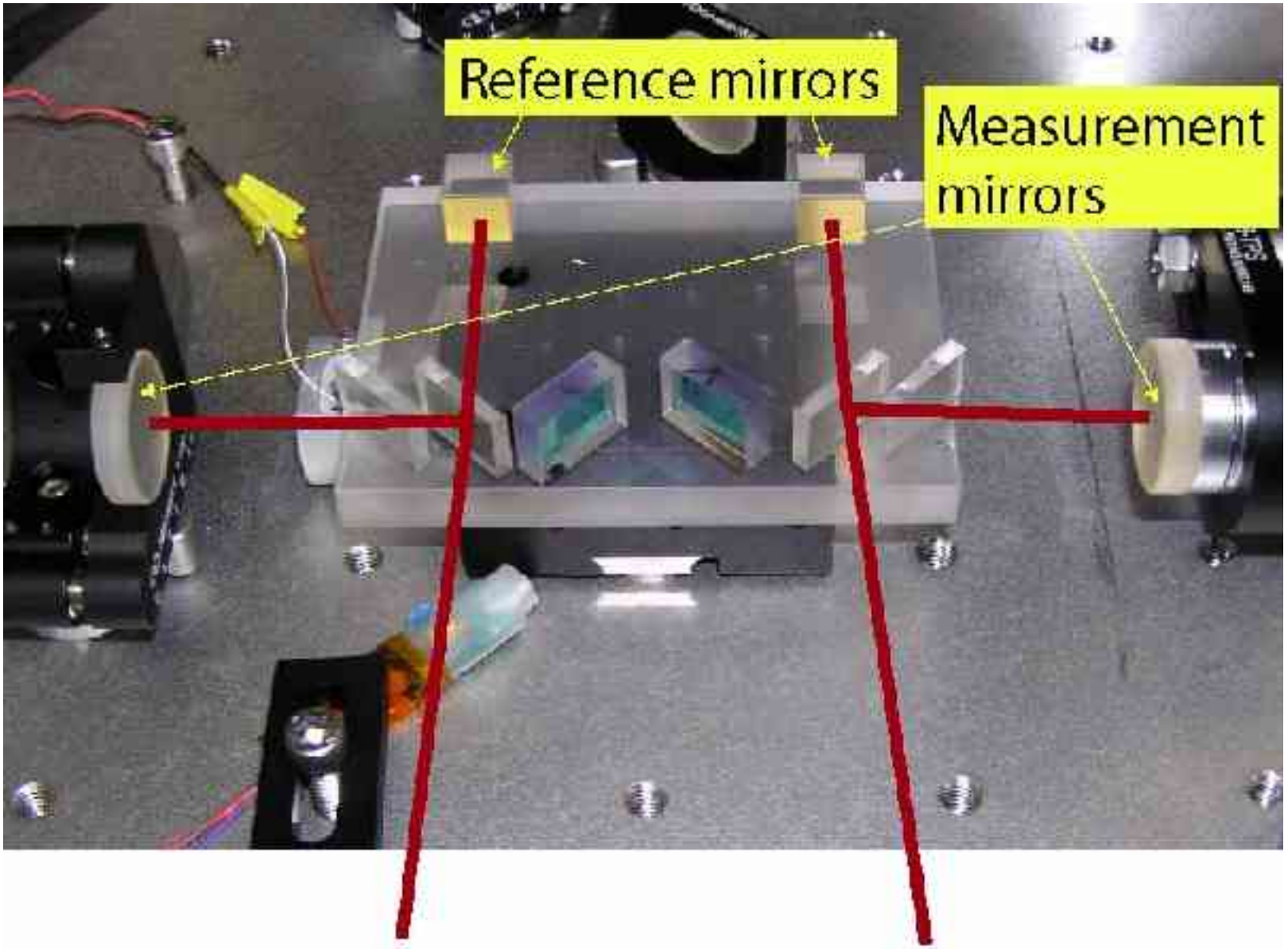


Thermal
Expansion

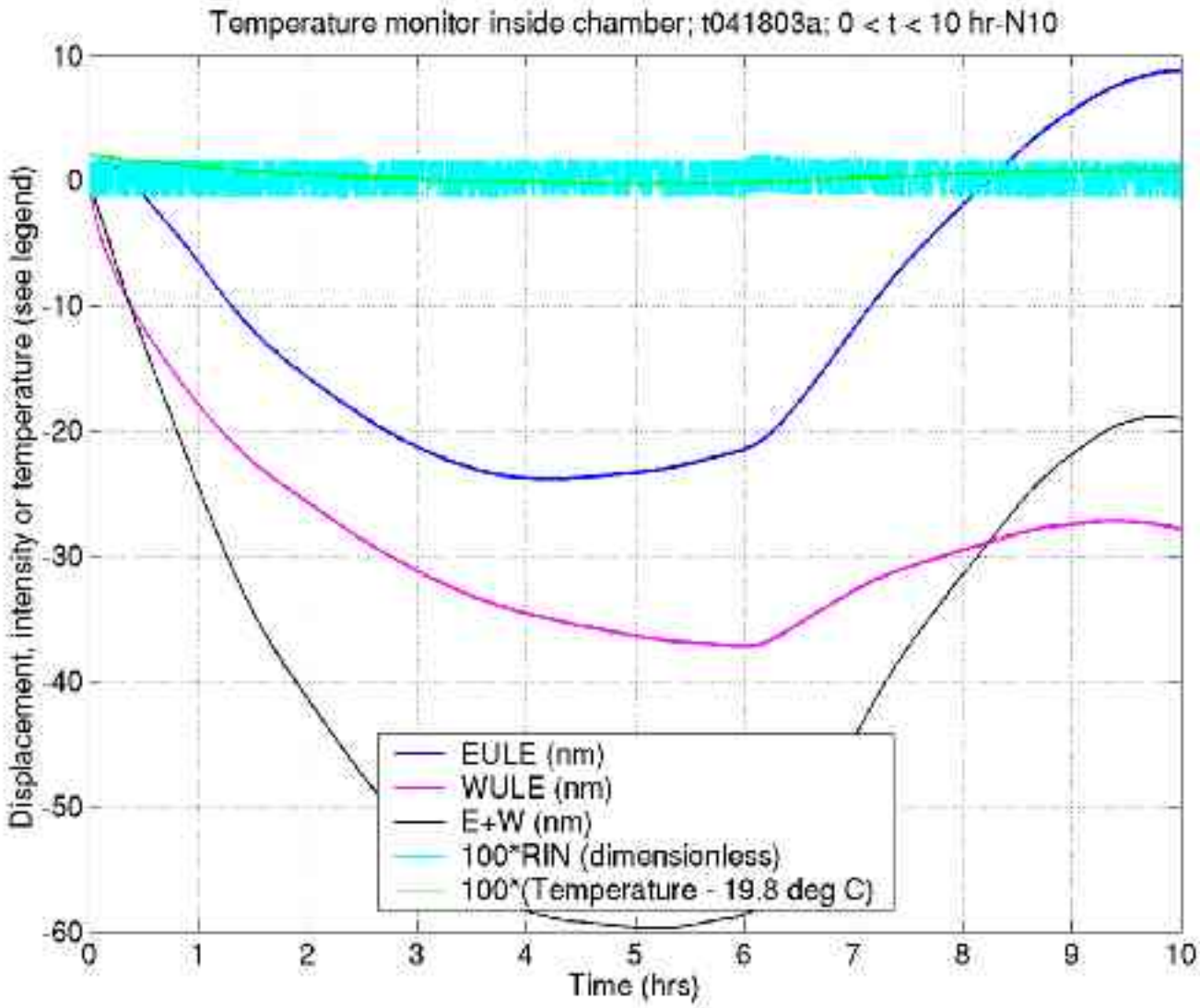


Manual
Alignment

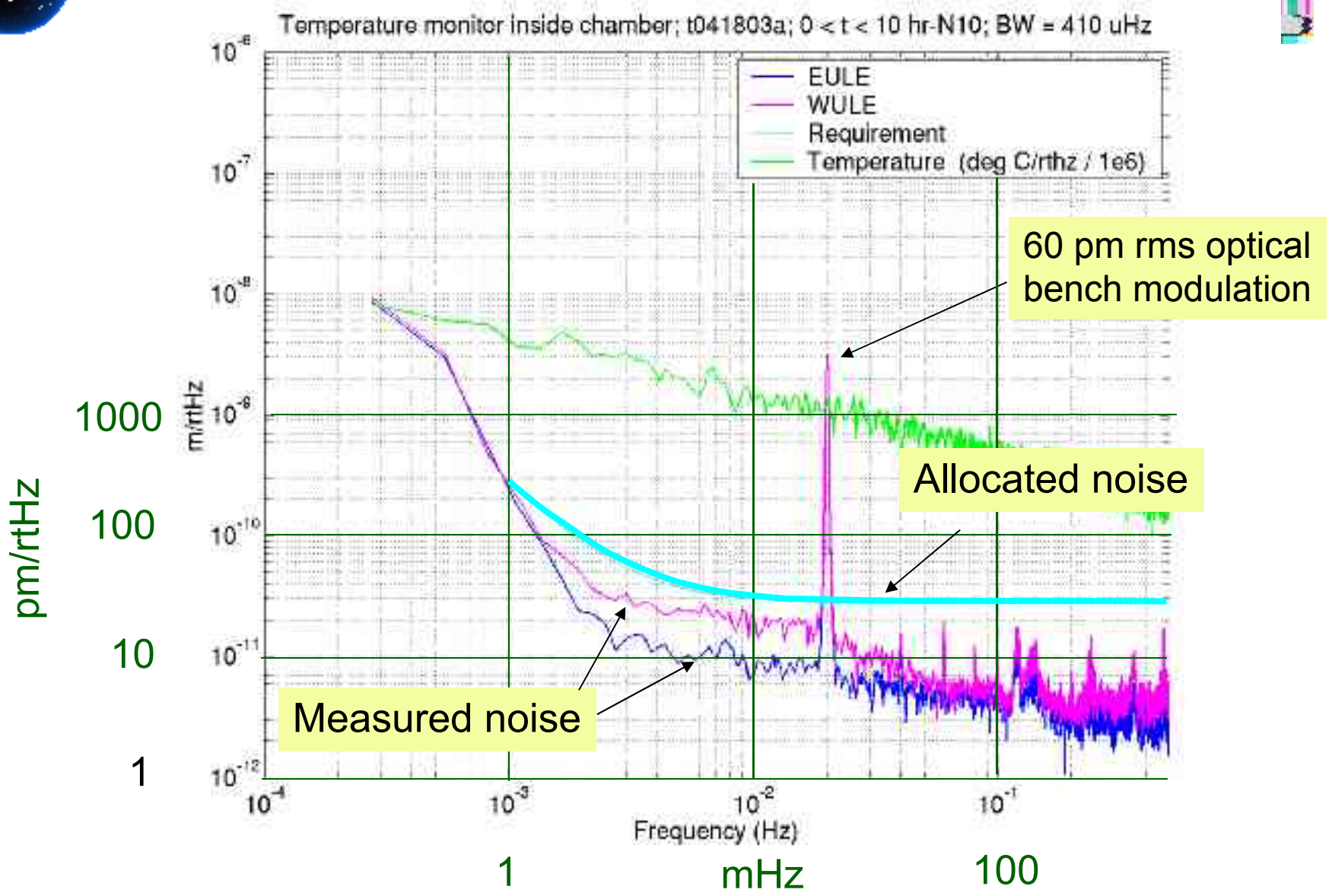
Contacted Optics in Vacuum Chamber



Testbed Drift

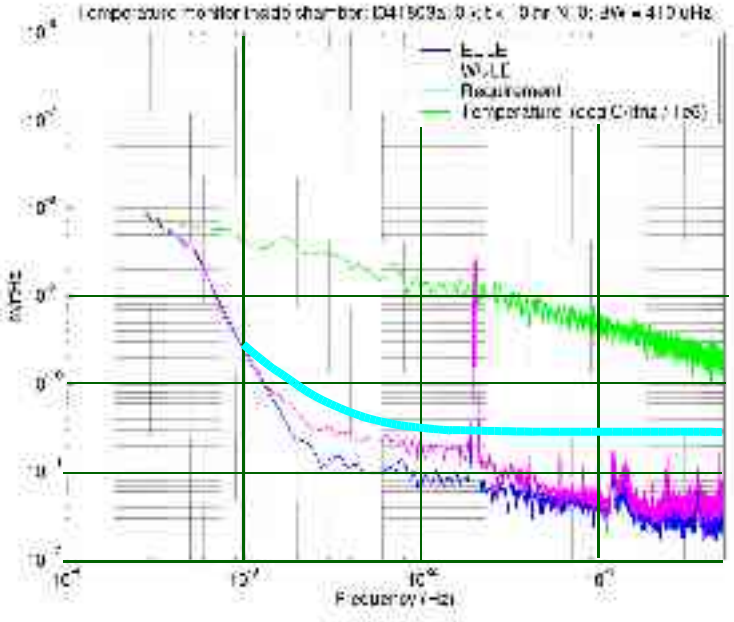


Testbed Noise

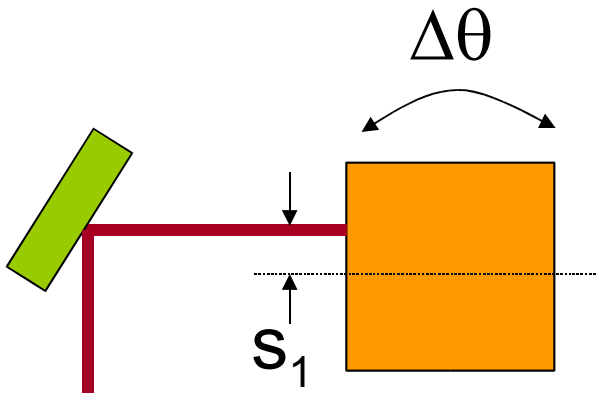


Measurements Demonstrate:

1. Analog electronics and ADC noise adequately low
2. Thermal sensitivity probably adequately low
3. Bench motion suppression typically x200, without calibration (x1000 needed)
4. Frequency stabilization not needed
5. Intensity noise can be suppressed in data analysis

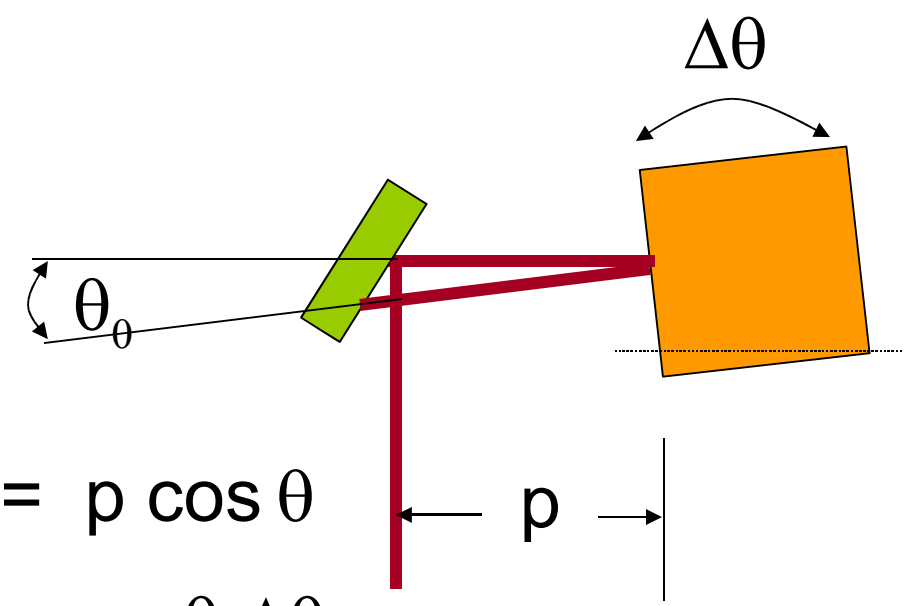


Alignment Sensitivity 1: Geometric error



$x_S = s_1 \sin\theta$

$\Delta x_S = s_1 \Delta\theta$



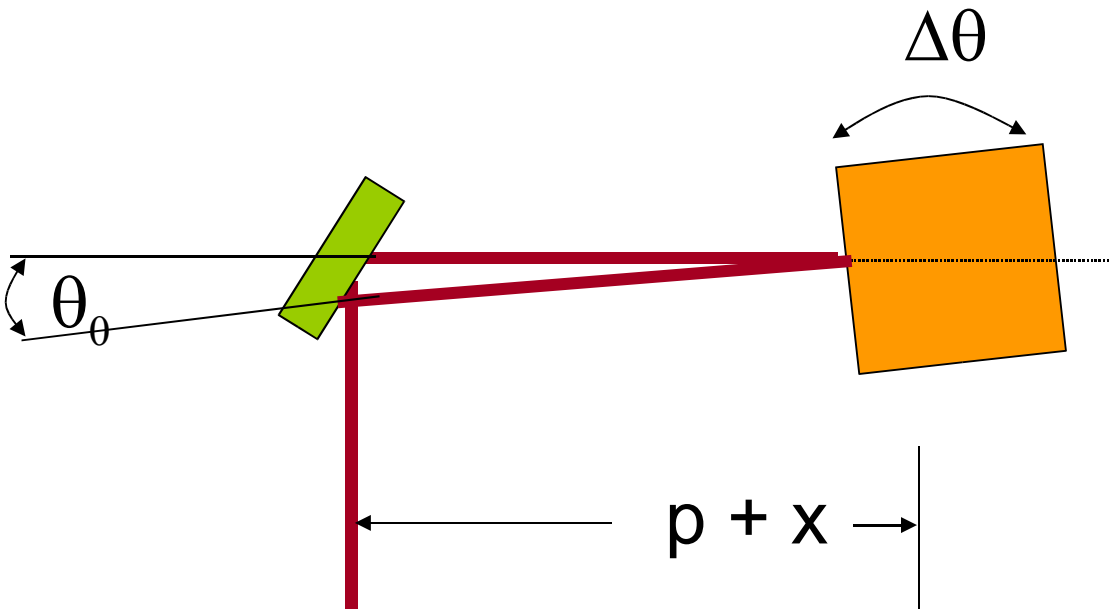
$x_c = p \cos\theta$

$\Delta x_c = p\,\theta_0 \Delta\theta$

$s_1 = 40\ \mu$; $p = 10$ cm; $\theta_0 = 400\ \mu$rad

Errors are correlated, and of same order: $s_1 \sim p\,\theta_0$

Alignment Sensitivity 2: Fringe position error

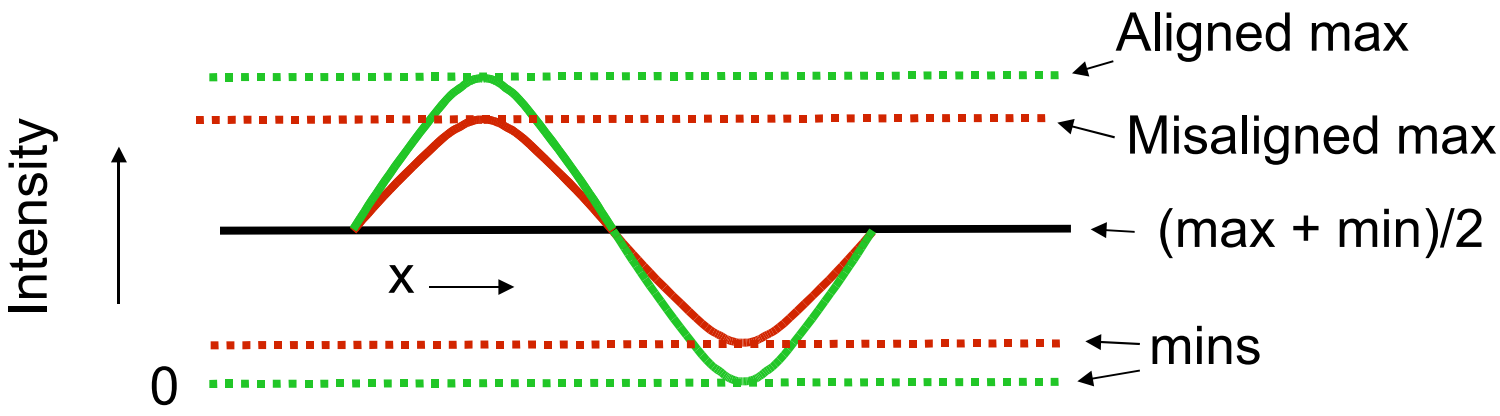


$\Delta x_x = \alpha x\ \theta_0 \Delta\theta,$

$\alpha = (\pi w/\lambda)^2 = 2.2 \times 10^6,$

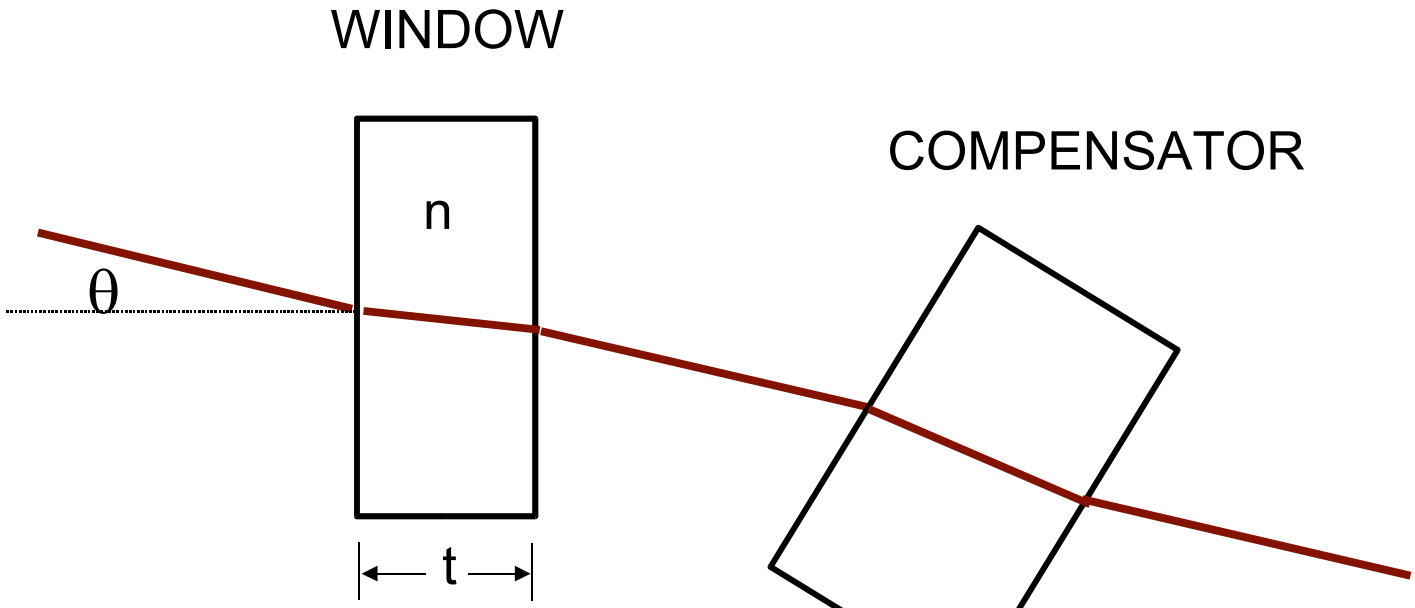
w=beam radius

Alignment Sensitivity 3: Half-intensity operating point



At the x = 0 half-intensity operating point, detected intensity is independent of alignment θ.

Alignment Sensitivity 4: Refraction through window



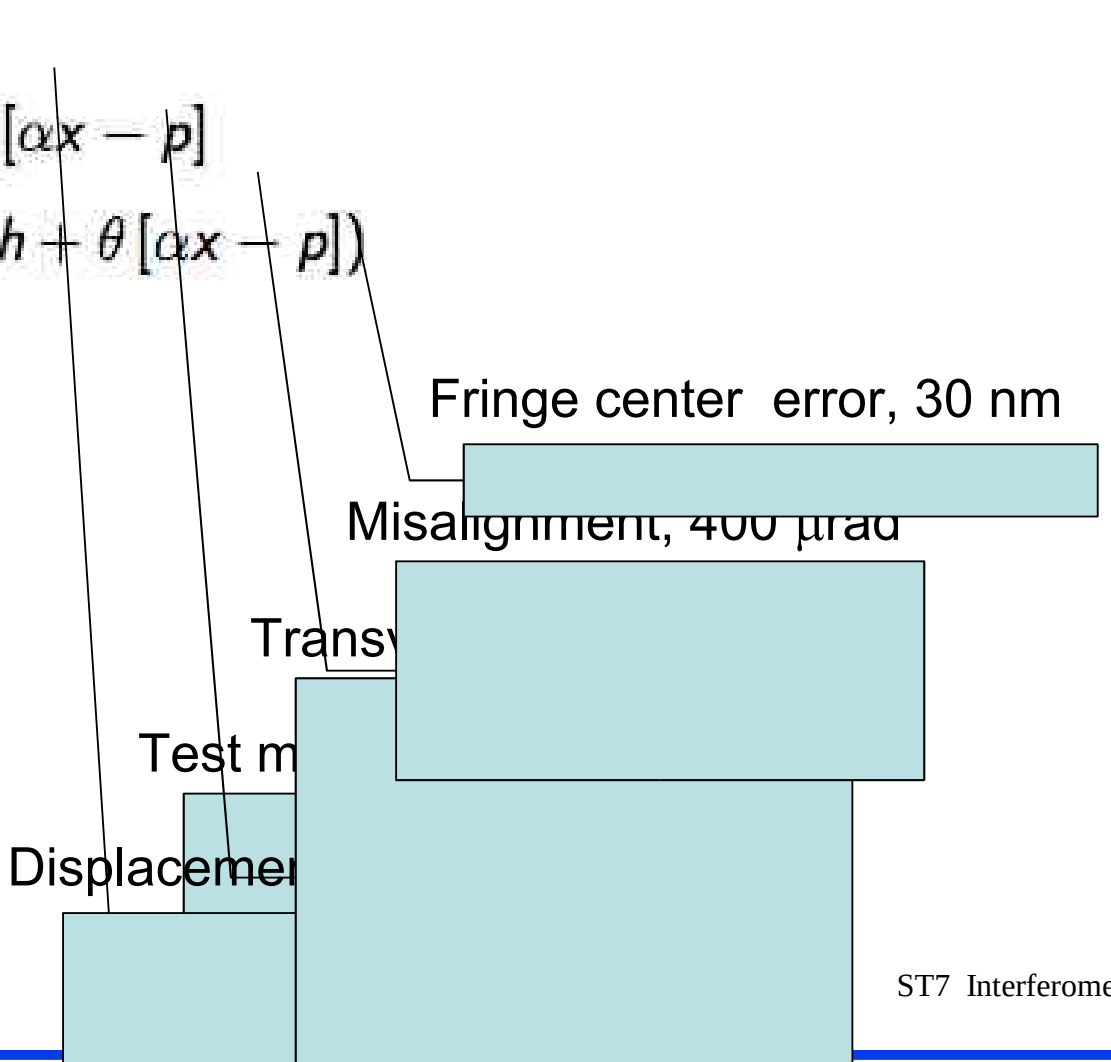
$dx/d\theta = \theta t(n-1)/n$

- Window tilted by ~ 2 deg to avoid spurious interferometer
- Compensator thickness and angle adjusted to cancel $dx/d\theta$

Total angle-jitter noise

$$\frac{dx}{d\theta} \approx h + \theta\,[\alpha x - p]$$

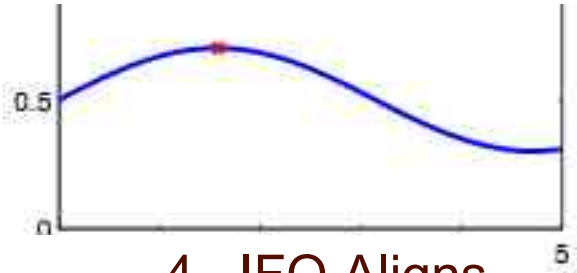
$$\tilde{x}(f) \approx \tilde{\theta}(f)\,(h + \theta\,[\alpha x - p])$$



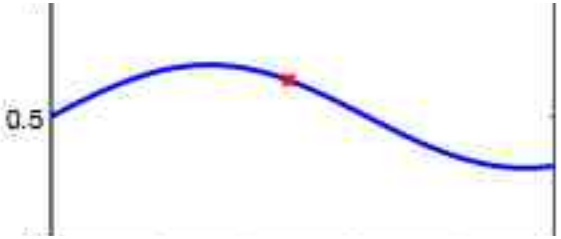
Initialization

1. Starting state

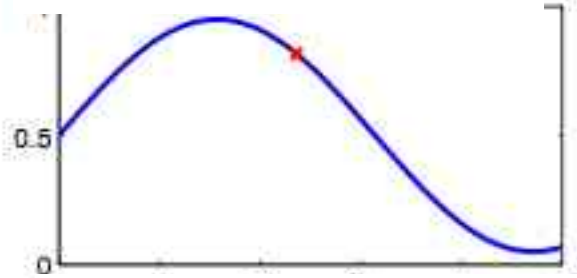
2. IFO finds bright fringe



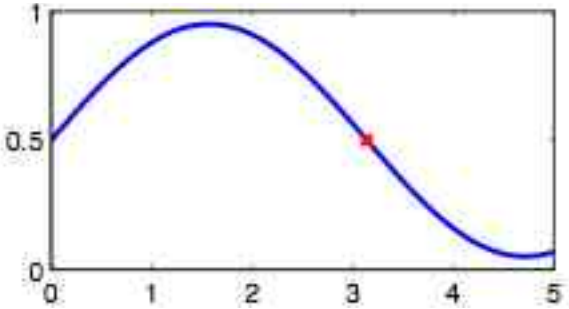
3. GRS moves to quarter fringe



4. IFO Aligns



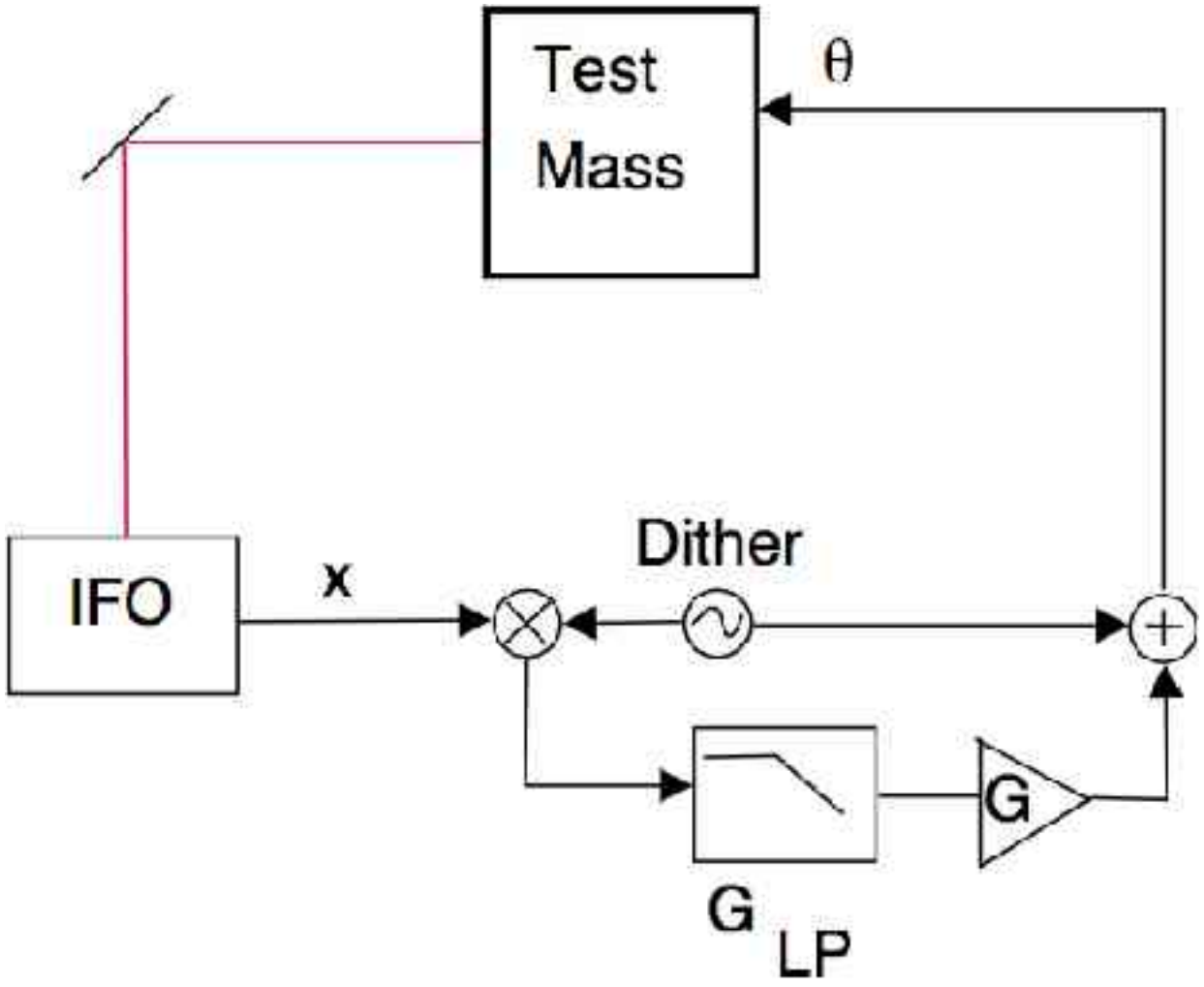
5. GRS to half fringe



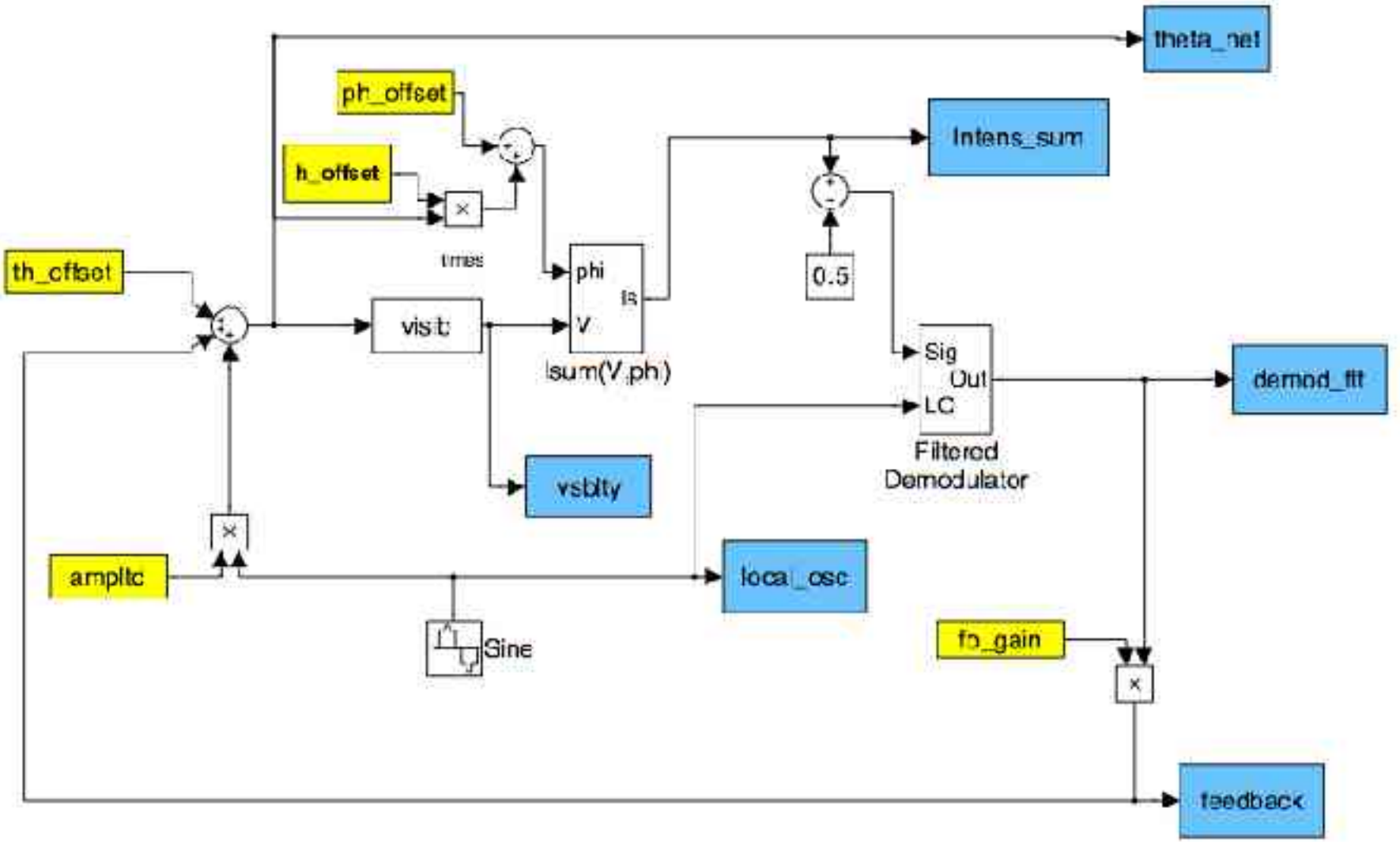
Intensity ⟶

Position ⟶

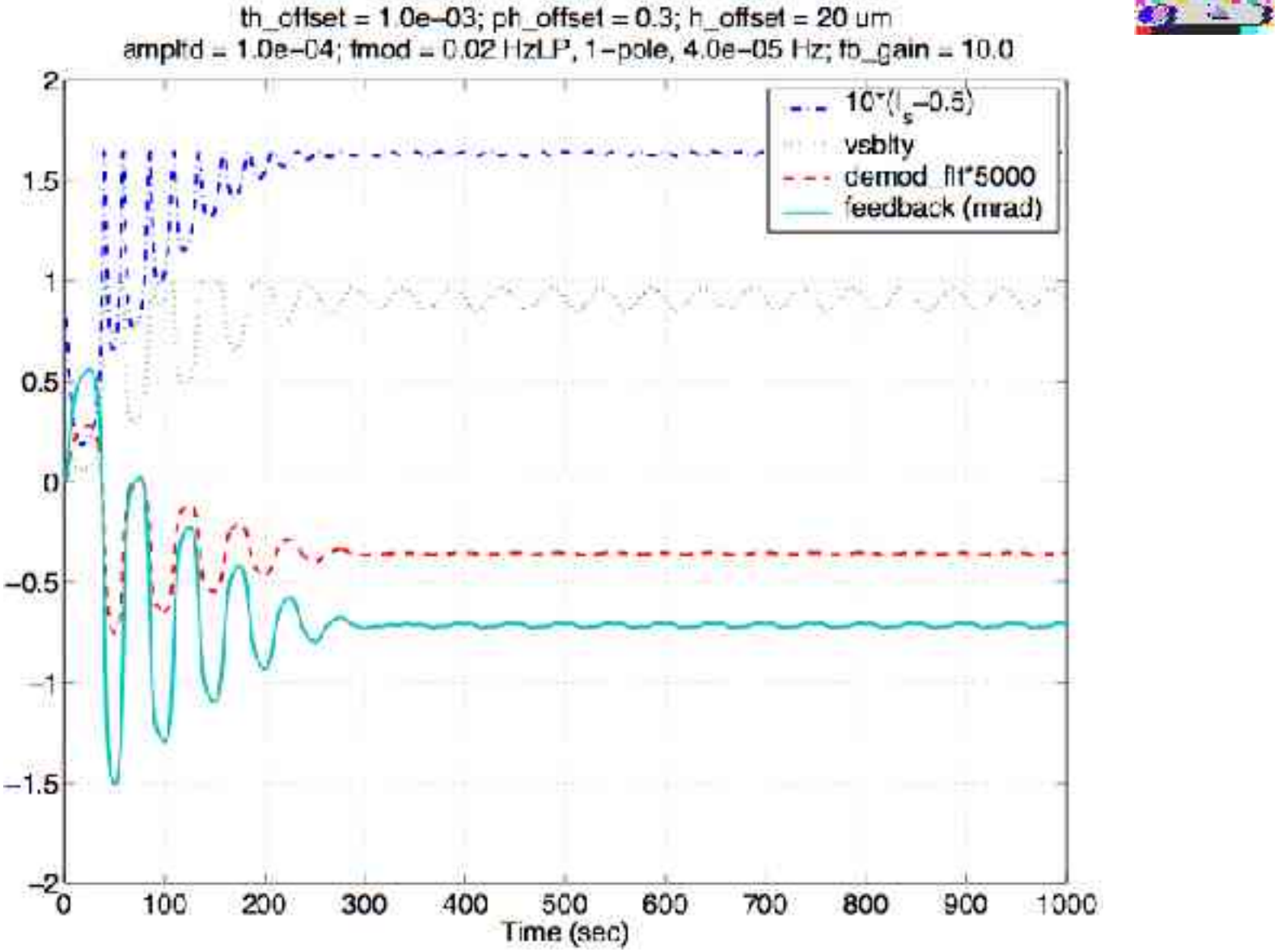
Dithered alignment -- concept



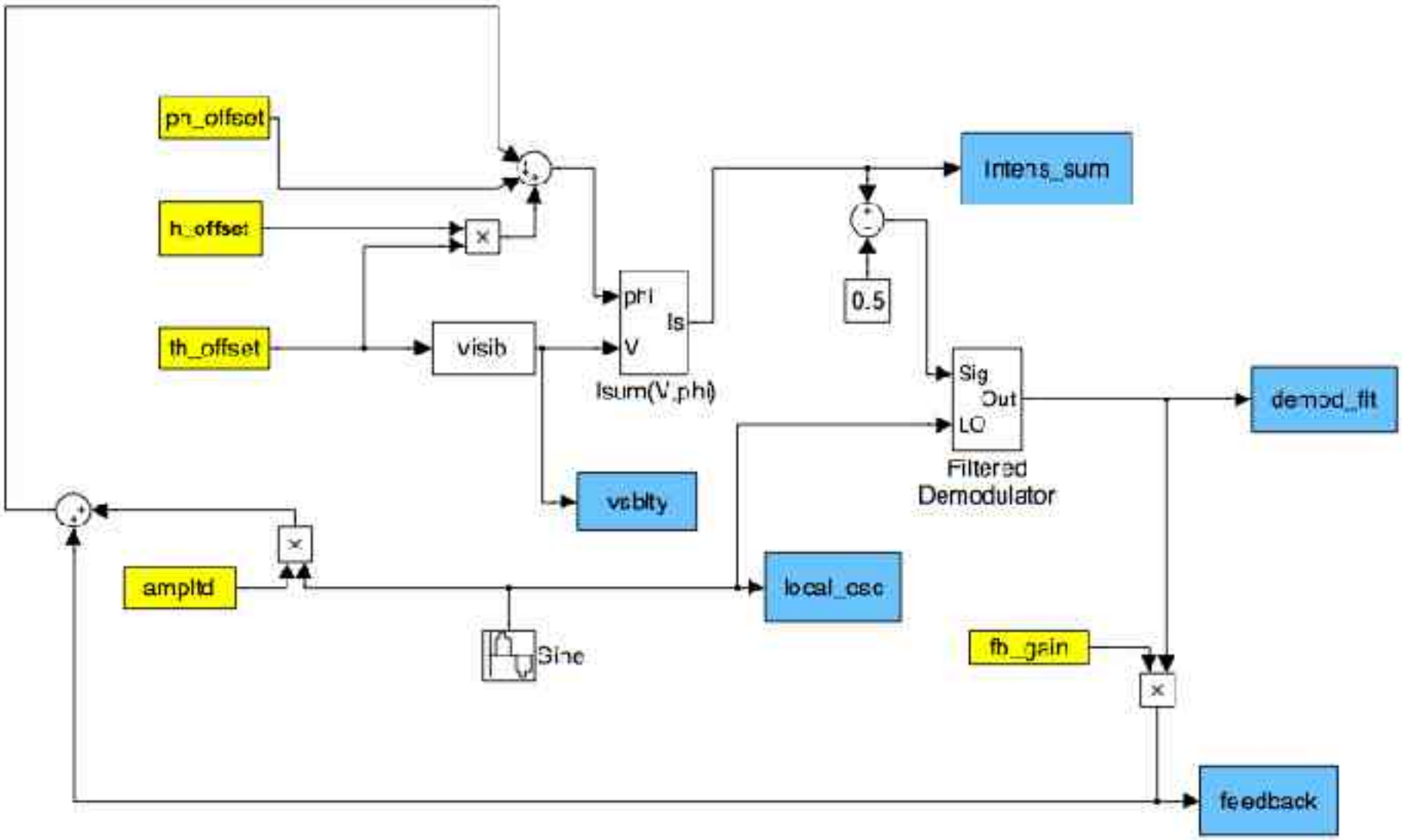
Dithered alignment -- Simulink model



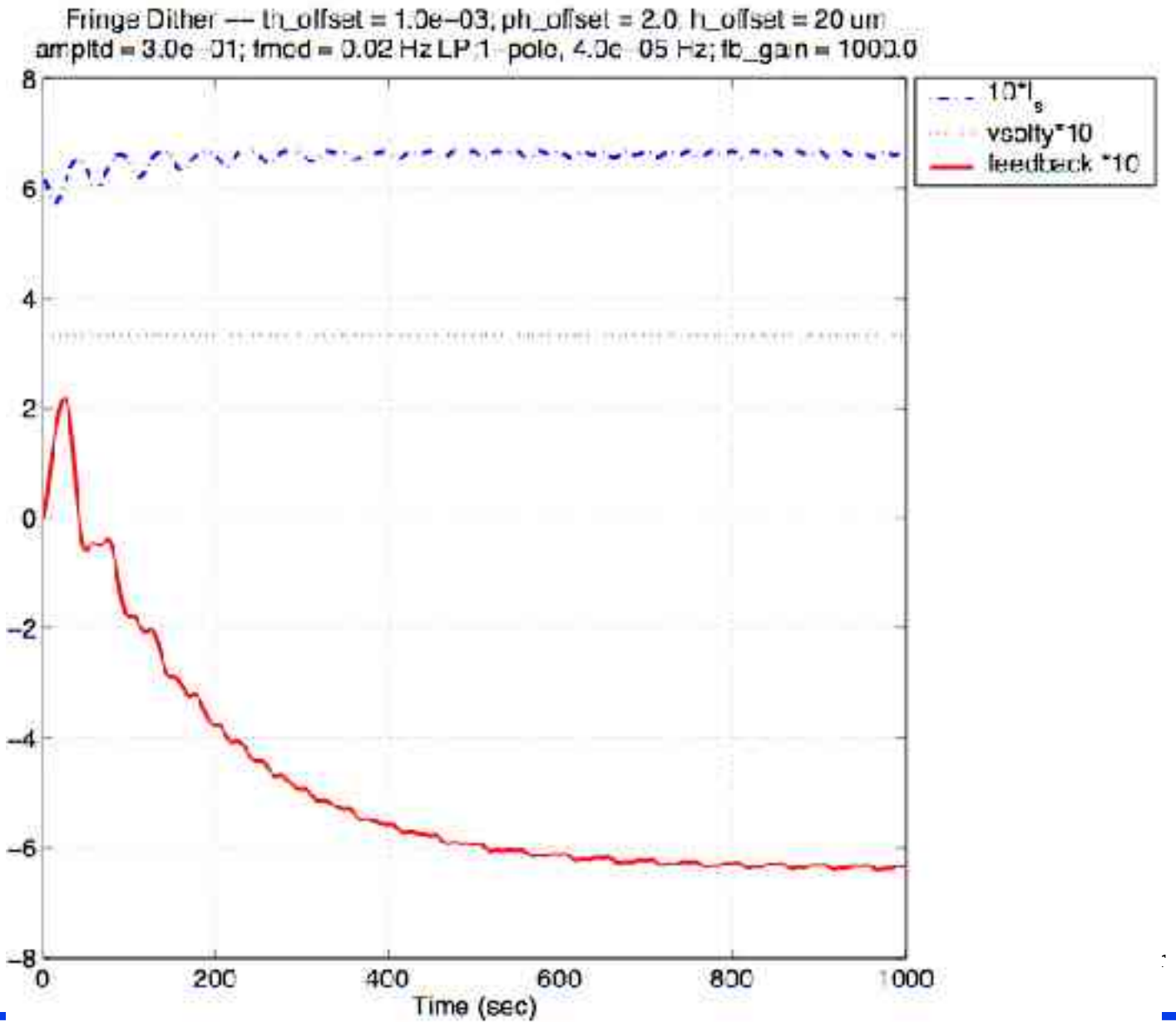
Dithered alignment -- Simulink run



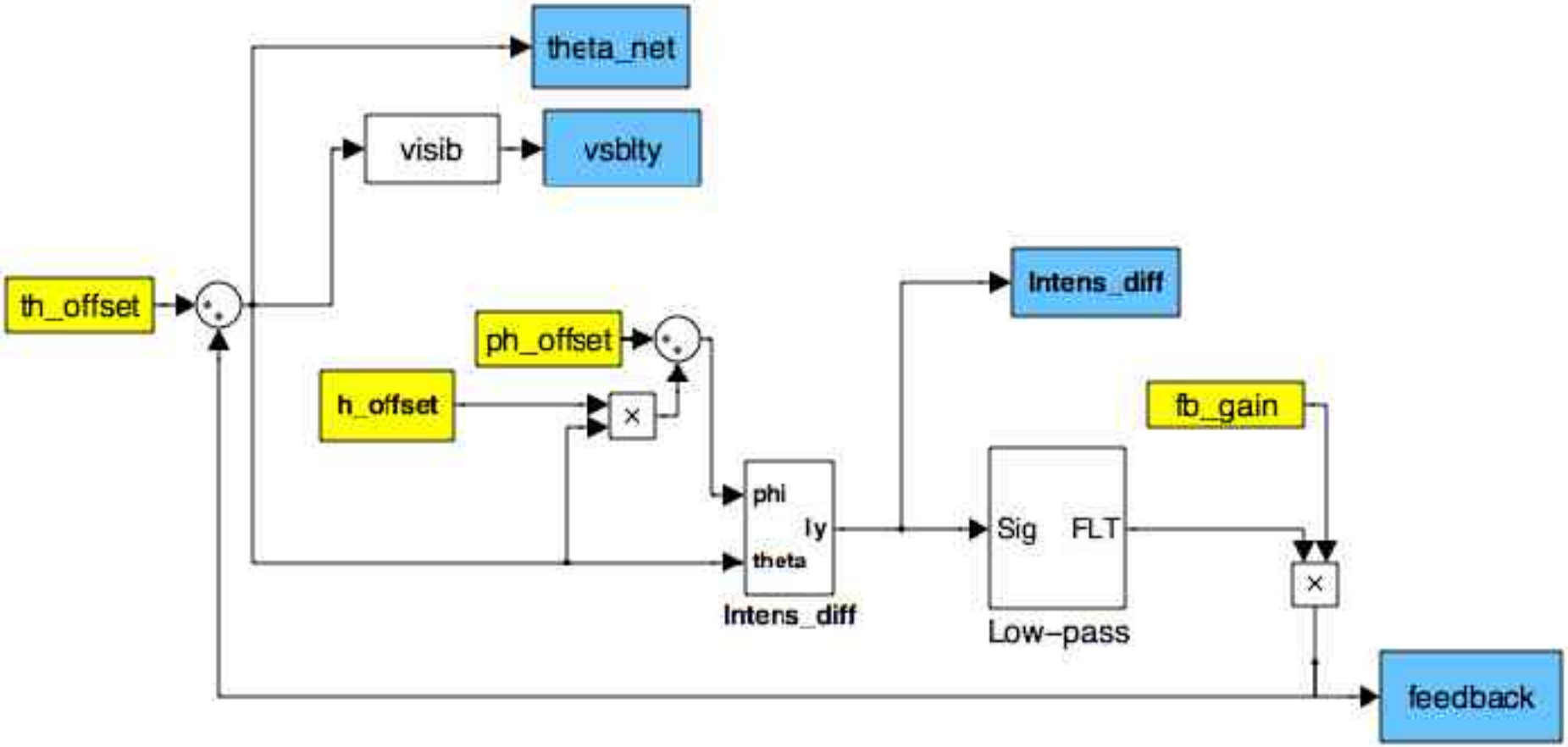
Bright fringe finder -- Simulink model



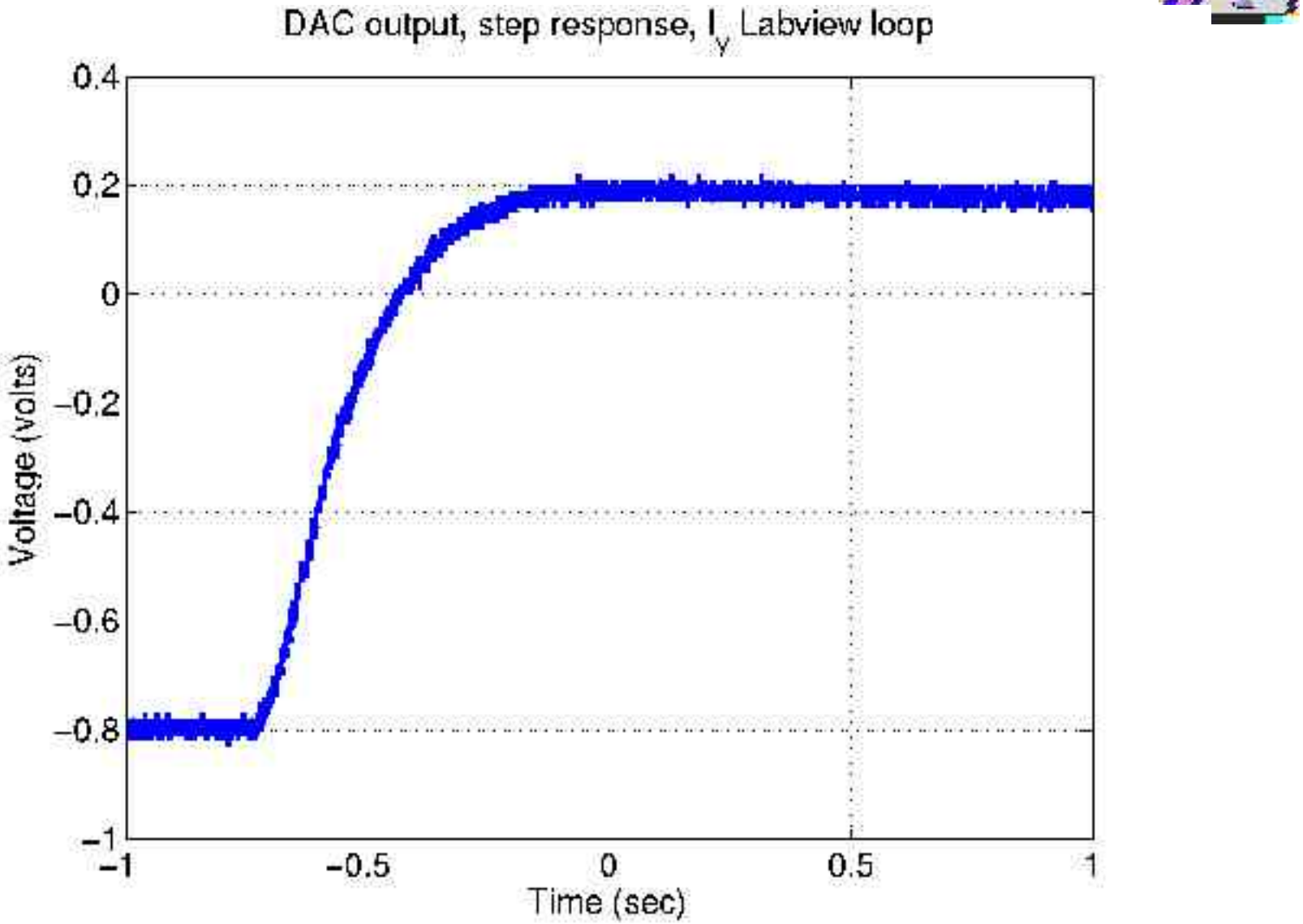
Bright fringe finder -- Simulink run



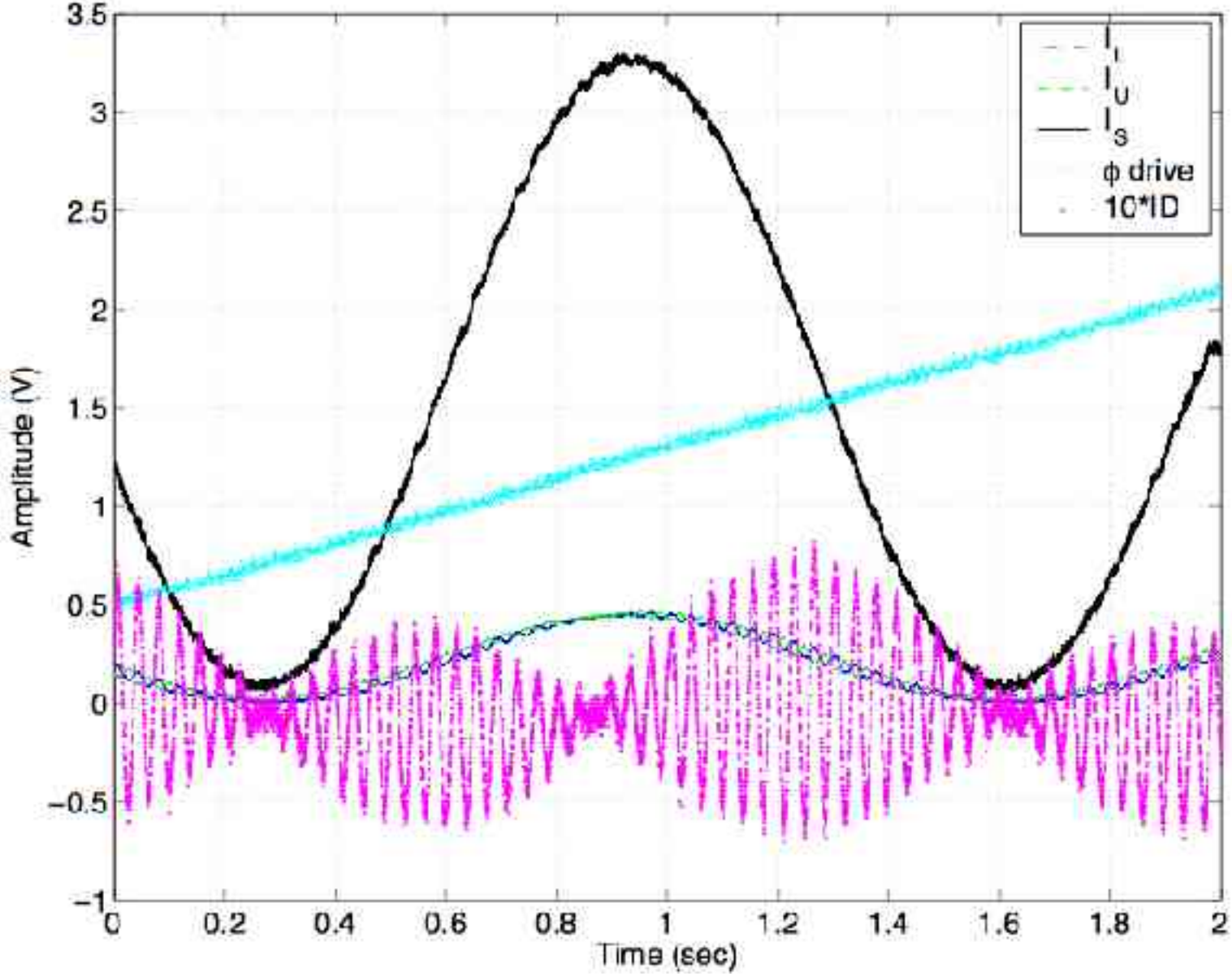
QPD difference alignment -- Simulink model



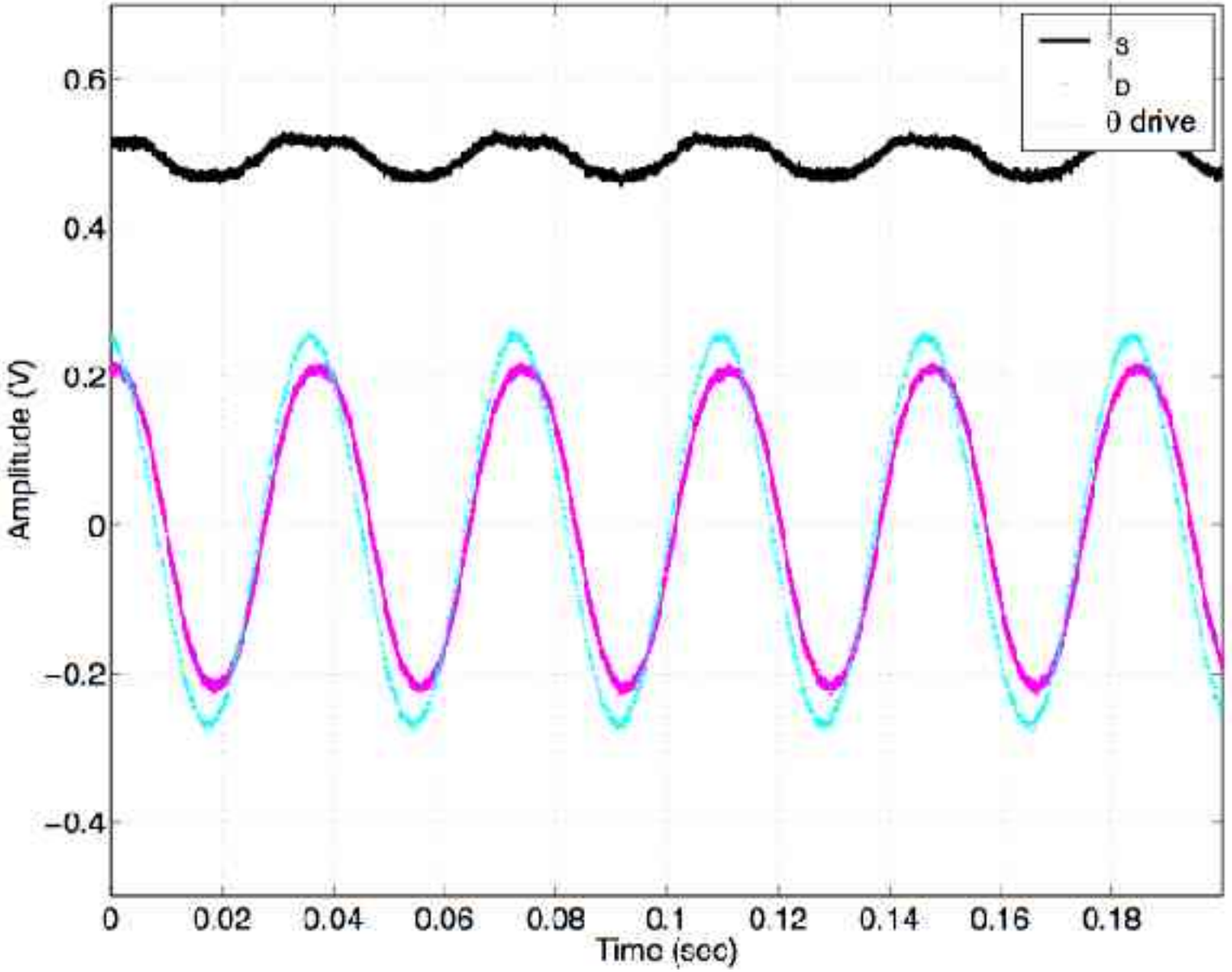
QPD difference alignment -- Experiment



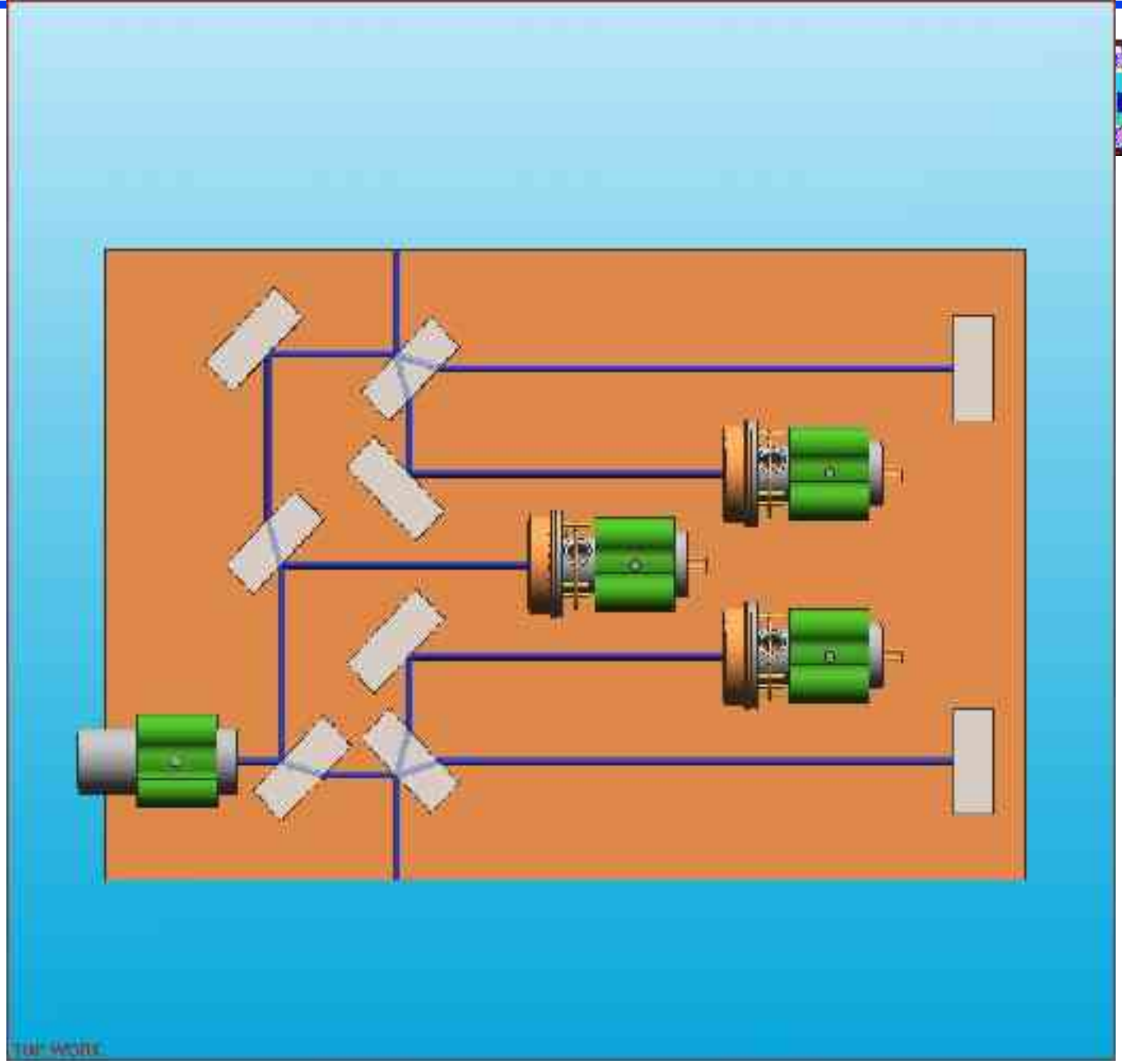
QPD difference signal alignment sensitivity



Sum vs. difference signals at half-fringe



ERROR SOURCE	TERMS	VALUE	pm/rthz	Corrltn
Intensity Noise			0.2	A
Equation 6	RIN I_0(f) (1/rthz)	1.0E-02		
	Non-simultaneity tau (sec)	5.0E-04		
	Frequency f (Hz)	3.0E-02		
Frequency Noise			5.3	A
Equation 10	Arm length diff Delta L (m)	1.5E-04		
	Frequency Noise nu (f) (Hz/rthz)	1.0E+07		
Analog Electronic Noise			0.8	
Equation 7	Half-max point V_0 (V)	2.0E+00		
	Voltage noise V(f) (V/rthz)	1.0E-05		
Digitization Noise			1.2	
Equation 9	Sample rate fs (Hz)	1.0E+00		
	ADC quantization (V)	5.0E-05		
Mirror angle sensitivity			13.2	
(Running,	Angle jitter theta(f) (rad/rthz)	1.0E-06		
Equation 12	Mirror-splitter distnace p (m)	1.0E-01		
	Mis-centering h (m)	2.0E-05		
	Drift from half-fringe x (m)	3.0E-08		
Mirror angle sensitivity			10.0	
(Initialization error)	Misalignment theta_0	1.0E-04		
Transverse displacement			0.2	B
Equation 14	Beam displcmnt y0 (m)	2.0E-04		
	Transverse motion y(f) (m)	1.0E-08		
Transversion test mass			3.0	B
Equation 16	Coupling constant mu	3.0E-04		
Thermal optical bench			10.0	C
Equation 17	Temperature T_b(f) (k/rthz)	1.0E-04		
	Arm length (m)	2.0E-01		
	Tempo kappa_b (/K)	5.0E-07		
Thermal, transmissive			11.8	C
optics, Equation 18	BK7 total K_BK7 (1/K)	9.0E-06		
	Window thickness, t_W (m)	4.0E-03		
	Fused silica total K_FS (1/K)	1.2E-05		
	Algnmnt cube thckns, t_A (m)	5.0E-03		
	Splitter thickness t_S (m)	6.0E-03		
	Splitter index, nS	1.4E+00		
	Splitter t_sO (calculated, m)	6.9E-03		
Diffrntl Thrml, DiffTh			10.0	
SUM				**29.9**

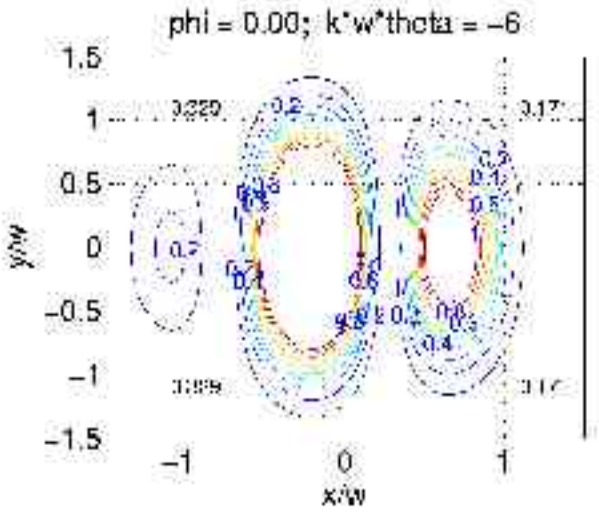


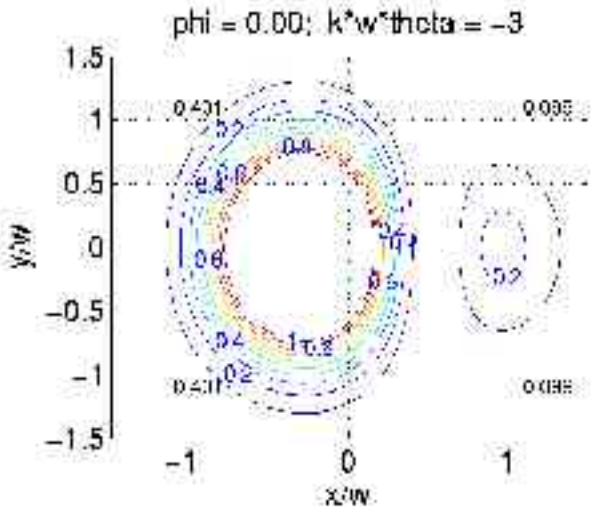
Backups

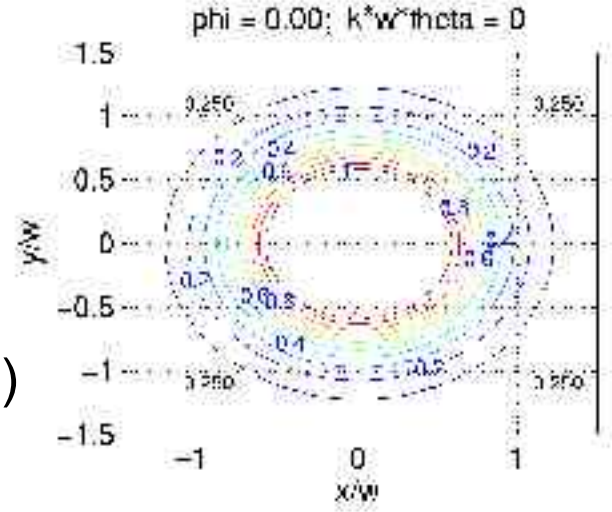
Intensity Pattern with Misalignment

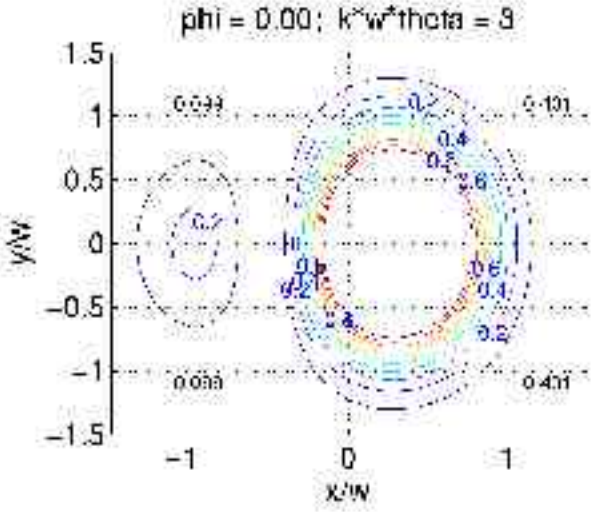
- Horizontal misalignment shown.
- Pattern insensitive to fringe offset near mid-fringe.
- Sample with 4 pixels (quadrant photodiode). Difference/sum response:

$$dQ/d\theta = \mathrm{sqrt}(8kw/\pi^3)$$



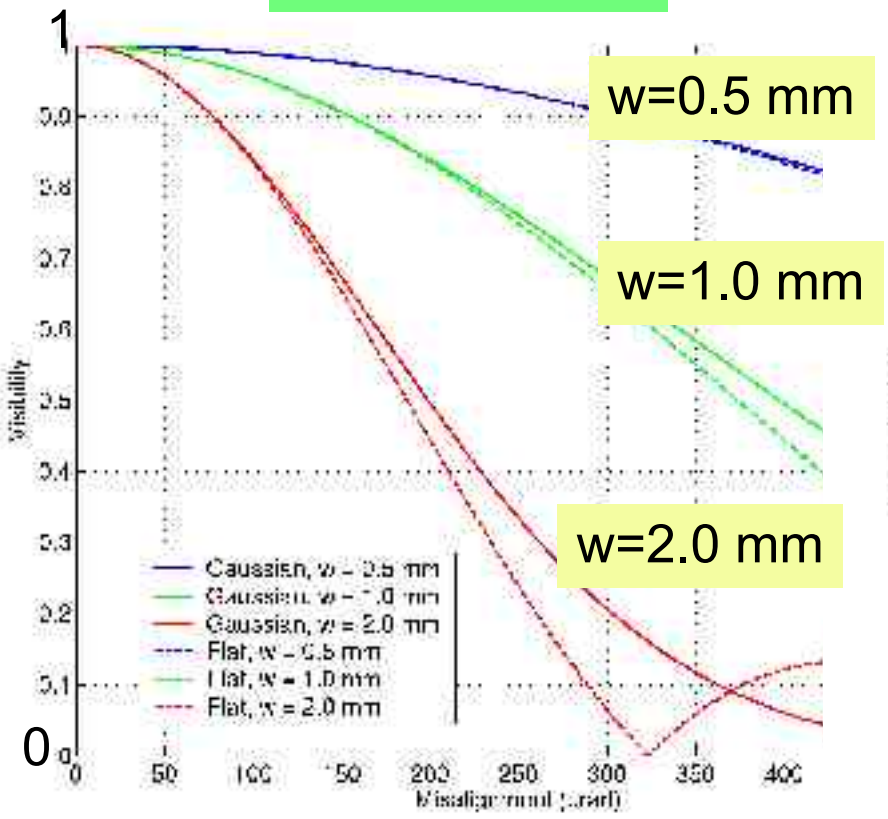






Static Misalignment and Static Longitudinal Error

Fringe Visibility



Error Sensitivity