SOLAR-B Solar Optical Telescope Image Stabilization System

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Image Stabilization System

- Scientific Requirements
- System Overview
- Functionalities
- Test Results

Scientific Requirements

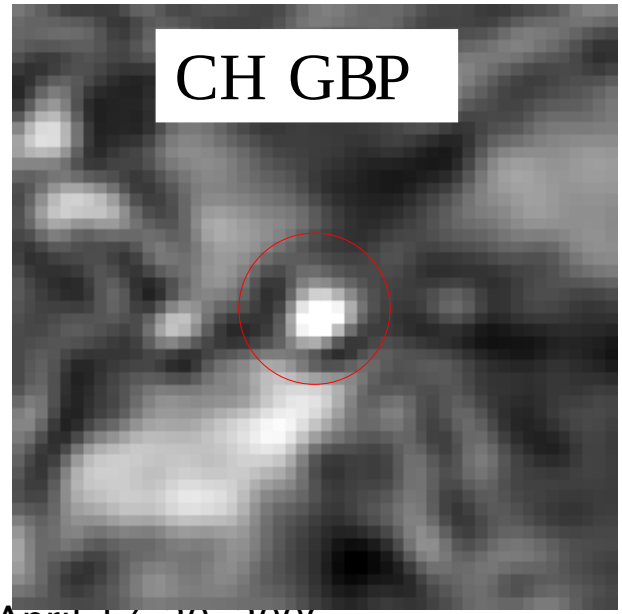
Image Stabilization System

Stability Requirement

Precise measurements of polarization with diffraction limited images (0.2- 0.3 arcsec.):

=> Stability requirements (0.09 arcsec. 3σ 10sec)

[Satellite body pointing: ~0.6 arcsec (3σ, 10sec)]



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Steiner et al. (1998)

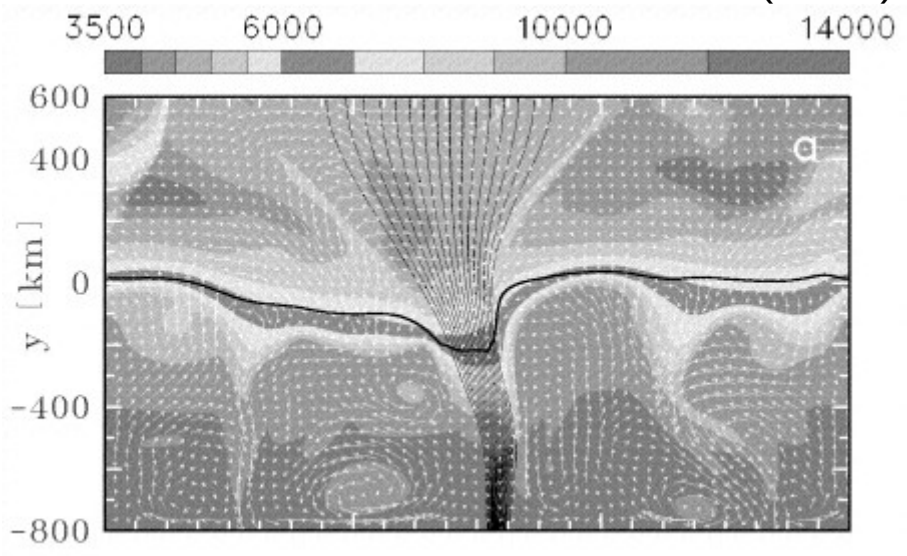
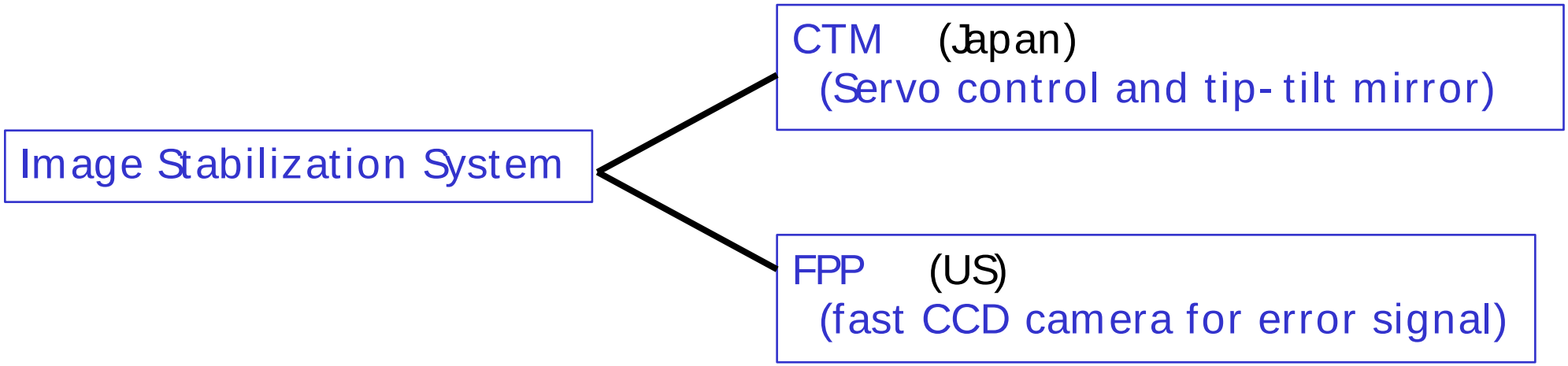


Image Stabilization System

Image Stabilization System

- Consists of correlation tracker (in FPP) and tip-tilt mirror
- Stabilize solar images on focal-plane CCDs



CTM = Correlation Tracker and Tip-Tilt Mirror package

Image Stabilization System

SOT Pointing Stability (10 [sec], 3σ)
Requirement: 0.090 arcsec, Goal: 0.040 arcsec

Current Estimate on Stability: 0.045 arcsec (3σ)

[RSS(jitter) + RSS(transient) + RSS(drift)]

Errors due to correlation tracker and CTM electronics

- Error in CT tracking signals: 0.018 arcsec (FPP ElCA, jitter)
- Error in CTM-E/CTM-TE: 0.012 arcsec (r.s.s.) (jitter)
  - Digital bit resolution of CT tracking signals: 0.0005 arcsec
  - Digital bit resolution in mirror drive electronics: 0.0071 arcsec
  - Electrical noise in mirror drive circuits: 0.009 arcsec

Residual Errors in Stability after jitter removal with CTM system

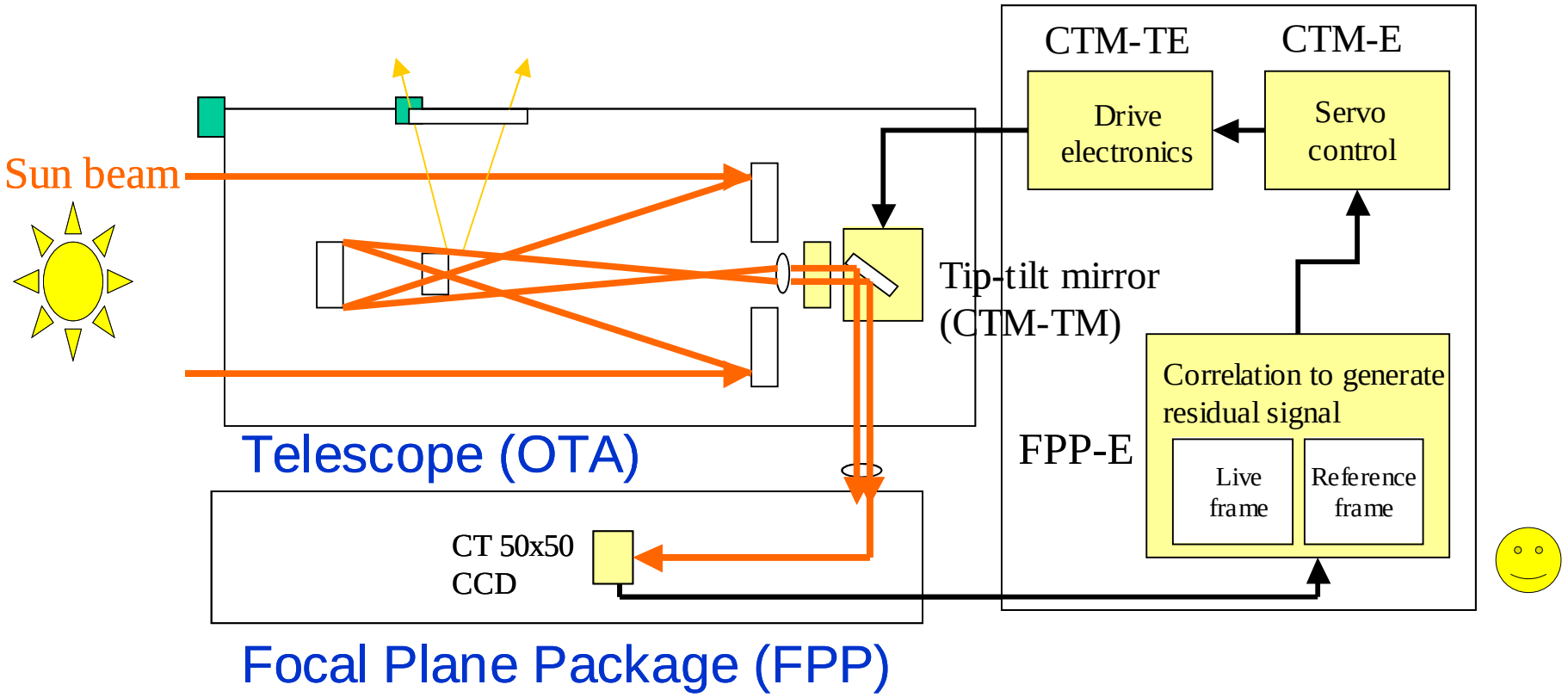
- Residual jitter caused by attitude control components (momentum wheels): 0.020 arcsec (jitter)
- Residual jitter caused by moving components in telescopes: 0.010 arcsec (transient)

Error due to Image rotation around Z axis

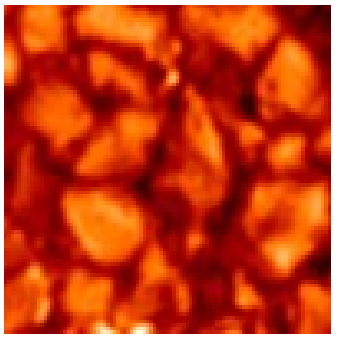
0.002 arcsec (jitter), 0.008 arcsec (transient), 0.003 arcsec (drift)

System Overview

Image Stabilization System



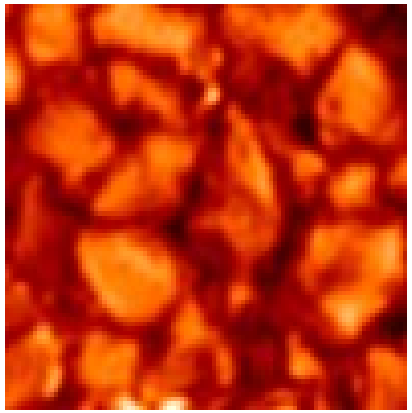
CTM-E :CTM Electronics (servo loop controller)
CTM-TE :CTM Tip-tilt mirror drive Electronics
CTM-TM :CTM Tip-tilt Mirror unit (mounted inside of OTA)
FPP :Focal Plane Package
CT-CCD: high-speed camera for correlation tracking of solar granules
FPP-E :FPP Electronics



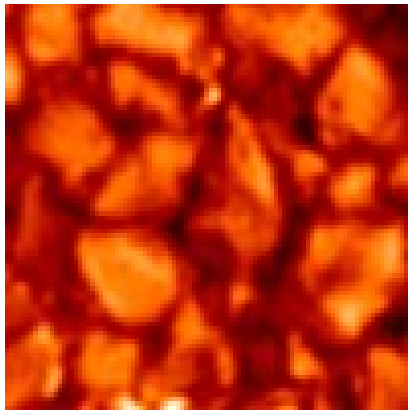
Solar Granules

FPP CT Signal: Correlation Algorithm

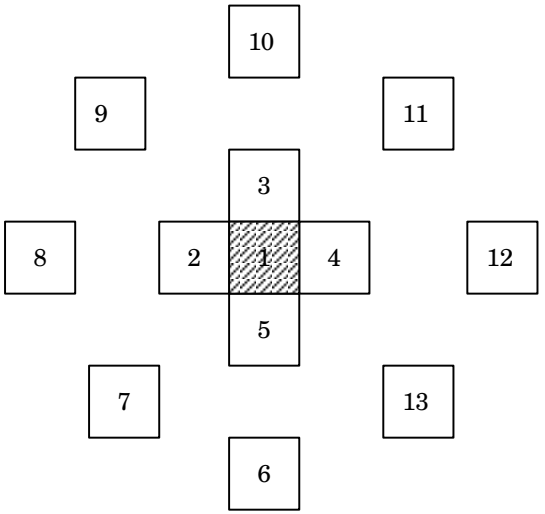
Live Image: I_L



Ref. Image: I_R



Shifted Positions



Frame rate: 580 Hz

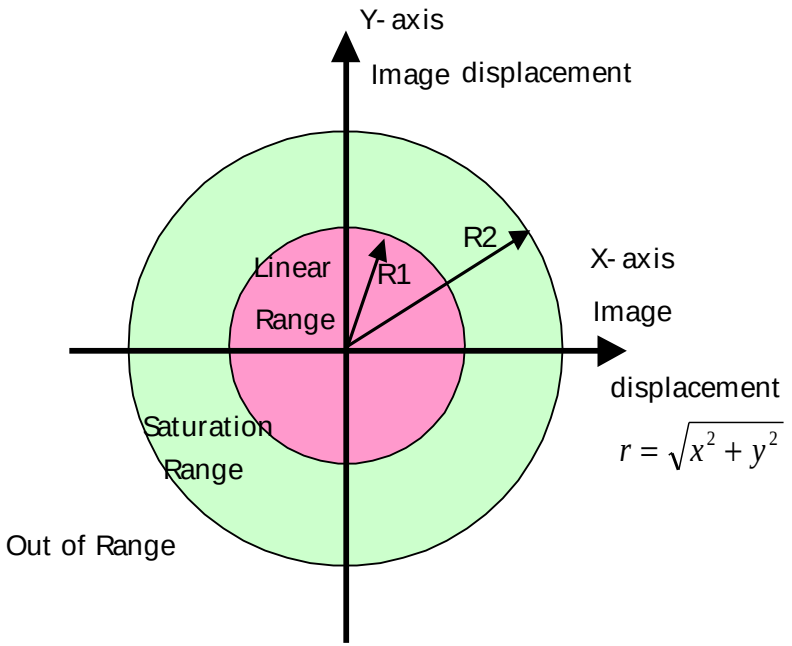
Updated every 40s

Residual: $$\delta I = \sum_{pix} |I_L - I_R|$$

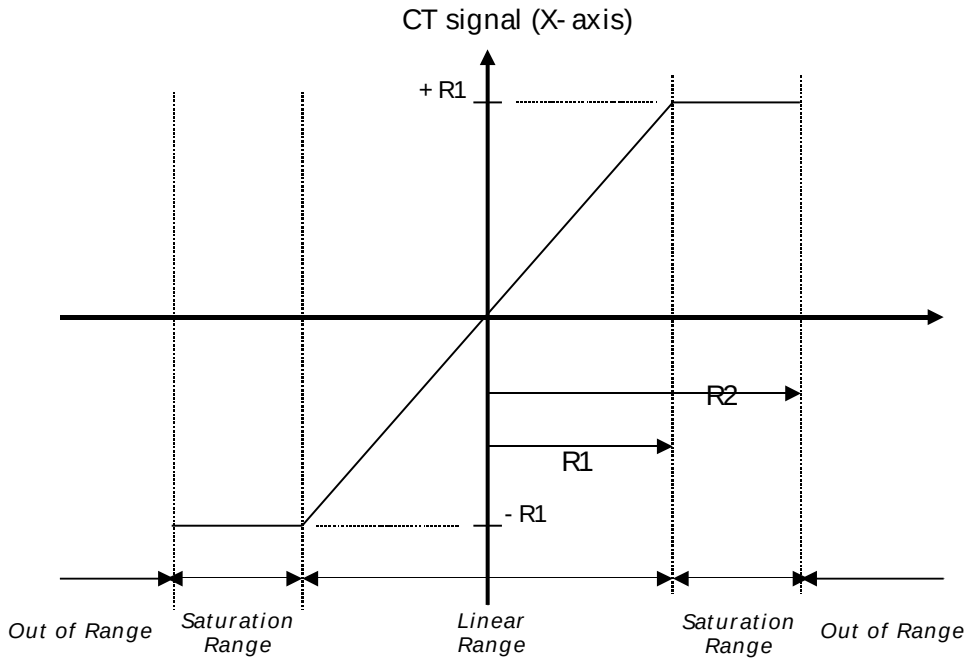
- Residual is calculated with 13 shifted positions.
- CT signal (dx,dy) is calculated from sub-pixel polynomial fit for minimum residual position.

Image Stabilization System

2D Map of CT Signal



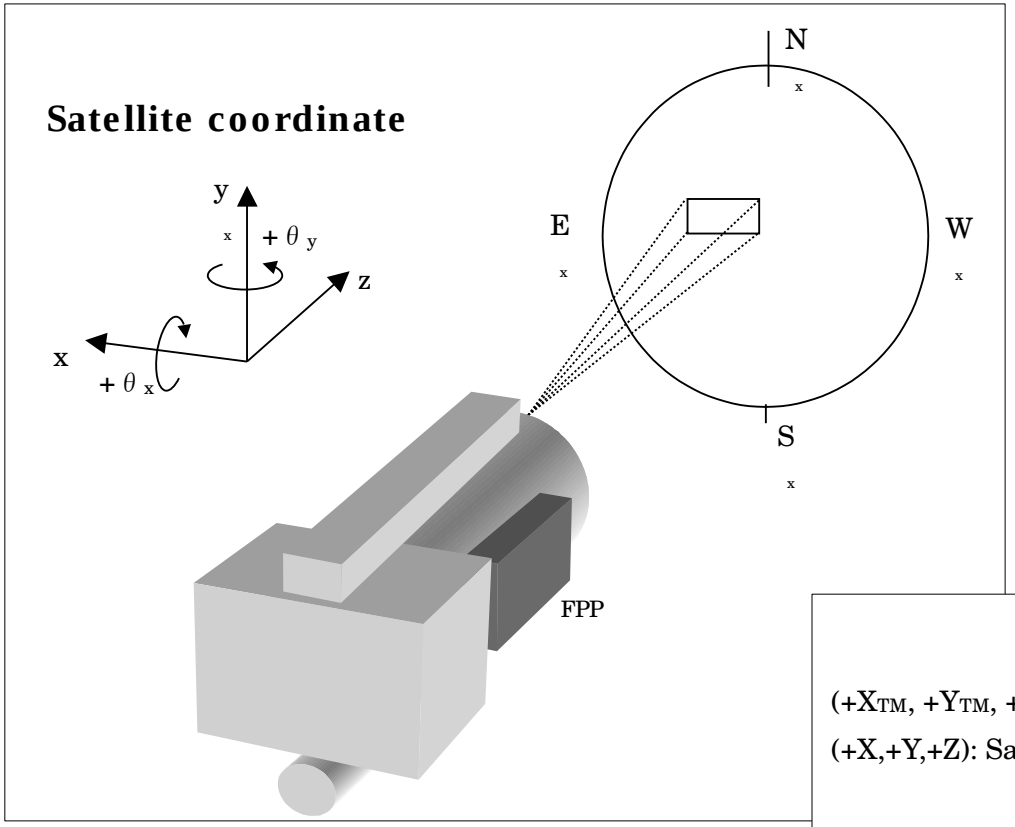
CT Signal Condition on X- axis



R1 = 0.44 arcsec; R2 = 1.1 arcsec (for normal granule). R2 depends on the target.

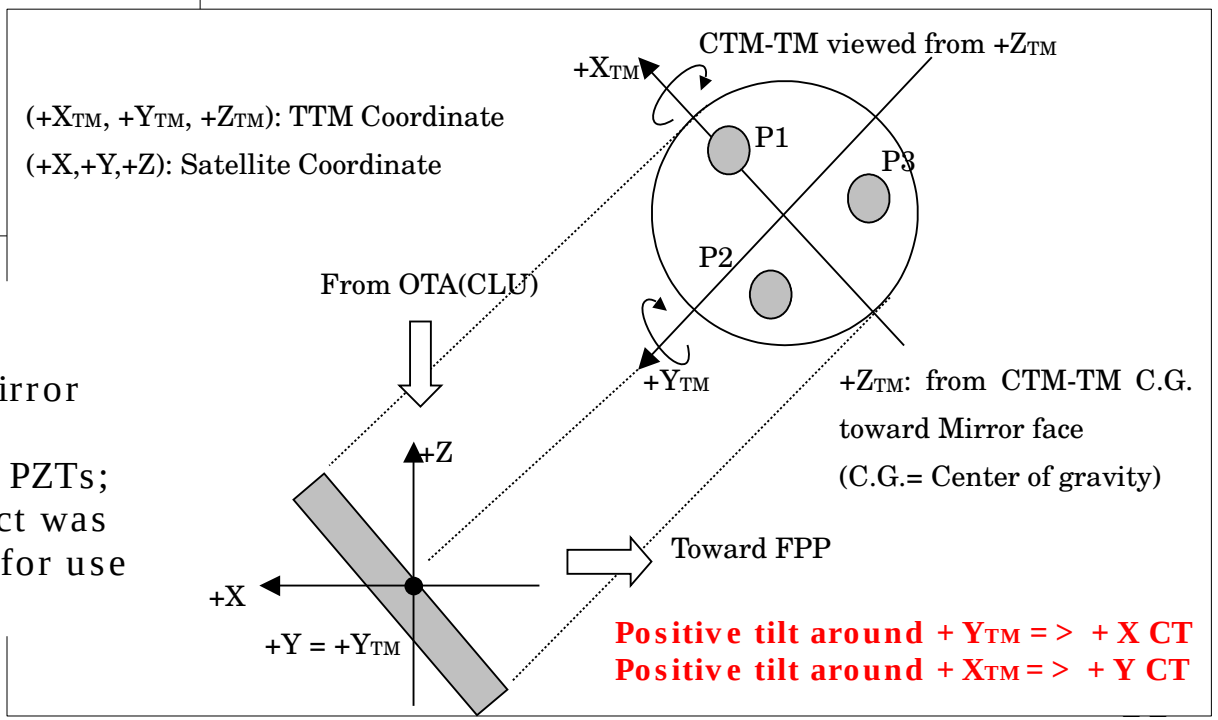
CT Status	CT Signal Properties	CTM-E Control
Out of Range	Not defined.	CTM-E keeps CTM_SERVO_ON mode, but holds the last TM position until CT signal returns into Linear or Saturation ranges.
Saturated Range	CT signal has magnitude R1 with the correct direction of the image displacement.	CTM-E keeps CTM_SERVO_ON mode
Linear Range	CT signal is proportional to the image displacement on CT CCD in FPP	CTM-E keeps CTM_SERVO_ON mode

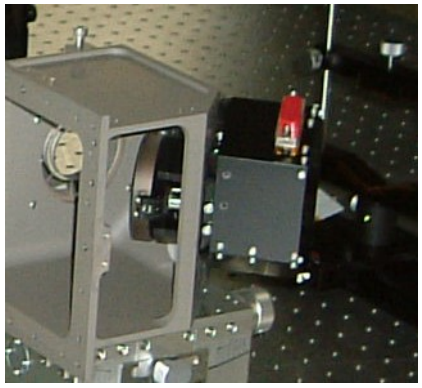
Image Stabilization System



The satellite pointing is changed
around X (+ θx) = > FOV moved toward S
around Y (+ θy) = > FOV moved toward E

The solar feature on CT CCD
is displaced toward NW
direction (+ θx, + θy).





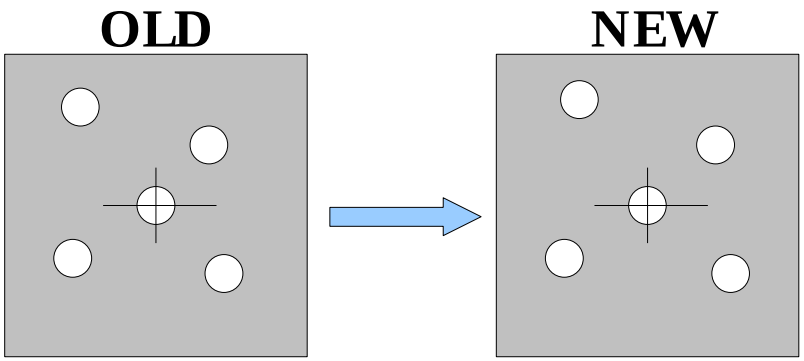
CTM- TM

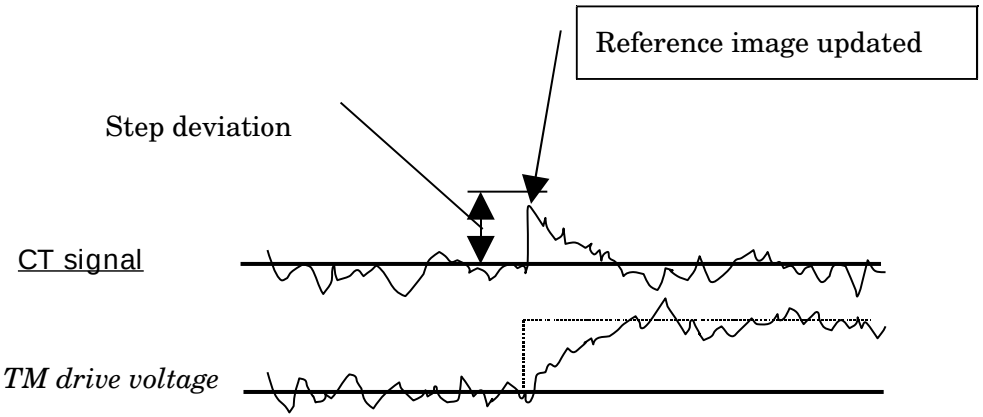
- 60mm diameter mirror
- Located near pupil
- Actuated by three PZTs; commercial product was qualified by NOAJ for use in space.

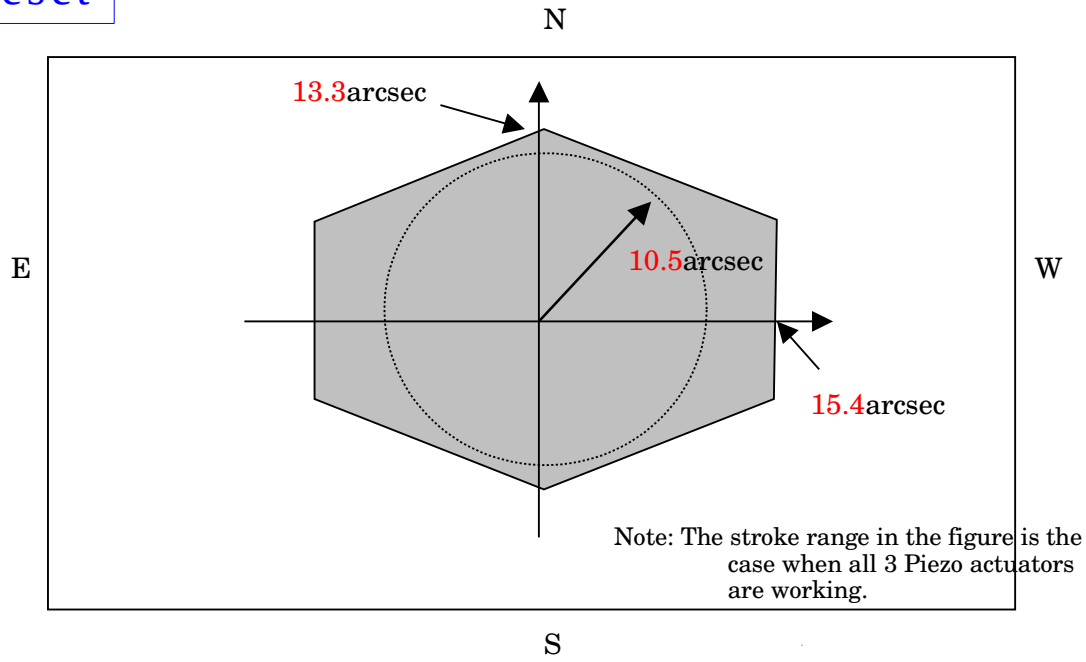
Image Stabilization System

Reference frame update and CTM- TM reset

When reference image is updated, CT signal may have a small step deviation on the order of 0.01 to 0.02 arcsec.

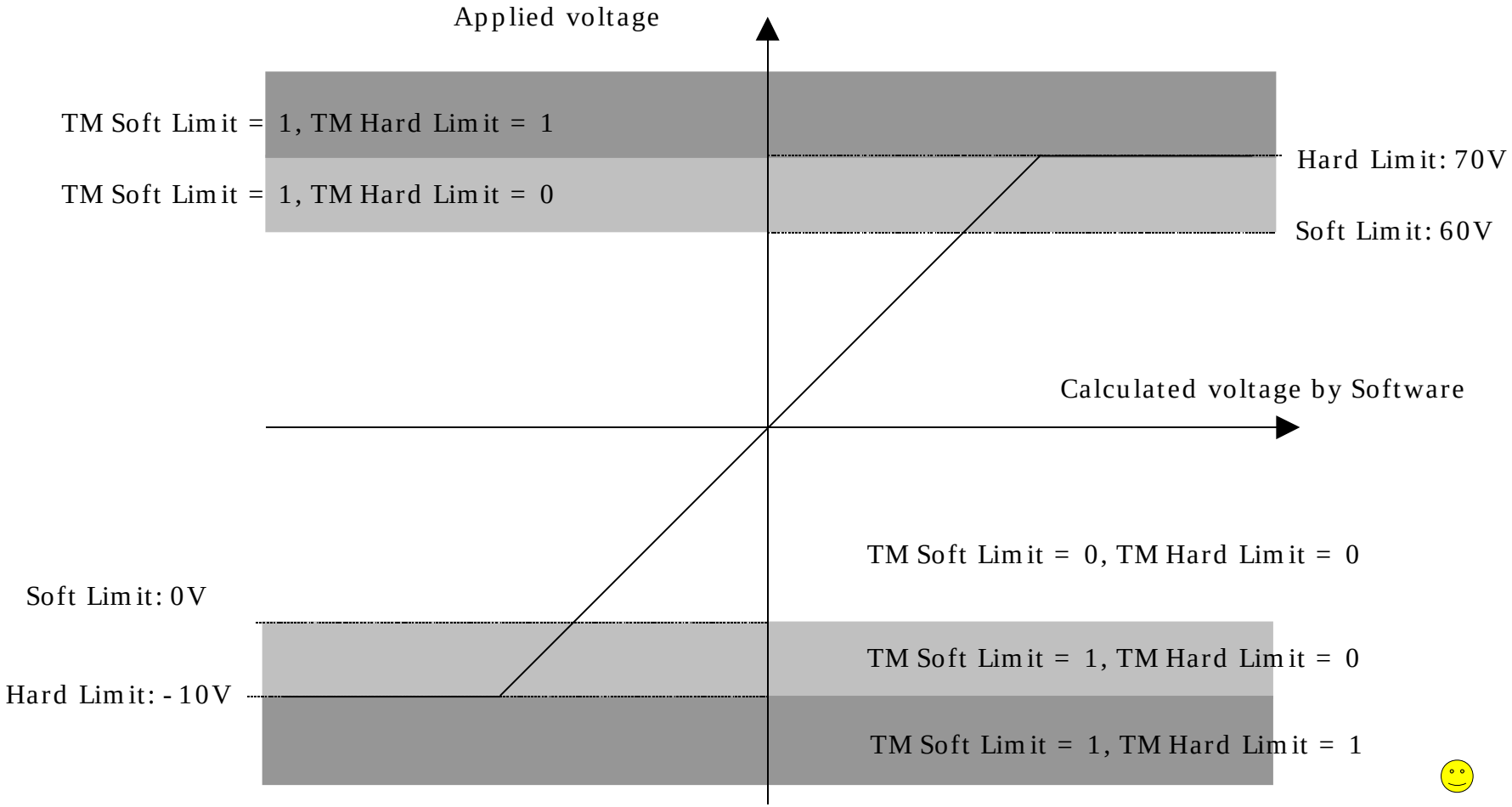






- The tilt range that the tip- tilt mirror can move is a hexagonal area defined by the triangle station of three PZTs shown above.
- The voltage applied to PZTs are limited; applying high voltage may reduce the lifetime of PZTs.
- When hard limit is detected, **FPP CT software resets tip- tilt mirror position to home position** and goes back to normal servo operation.
- Expected reset interval 1- 2 hours; during the reset operation, SP/ FG observation is paused.

Image Stabilization System



Limits are nominal (can be changed on board)

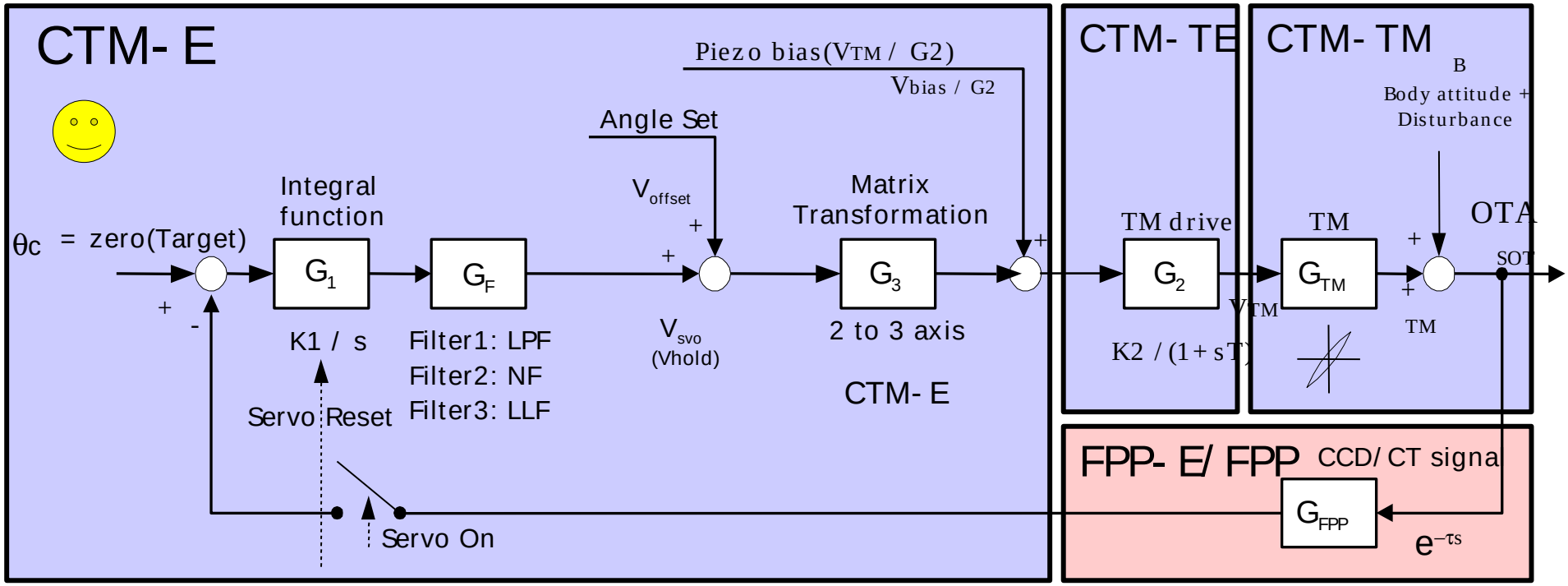
Image Stabilization System

Image Stabilization System Basic Properties

Correlation Tracker (CT) in FPP		
	- Producing displacement error for feeding back to CTM tip-tilt mirror control	
	CCD	50x50 pixels, 0.22 arcsec/pixel
	Frame rate	580Hz
	Spectral range	629-634nm
	Displacement Range	+/- 5 pixels
	Error signal accuracy	~ 0.01 arcsec
Tip-tilt mirror and its controller (CTM)		
	Signal used for closed loop control	Residual signal from correlation tracker
	Actuator	3 Piezo actuators
	Tilt range	10.5 arcsec in radius on the sky
	Control crossover frequency	14 Hz (nominal gain)
	Stability	<0.007 arcsec (3σ, a test result)

Functionalities

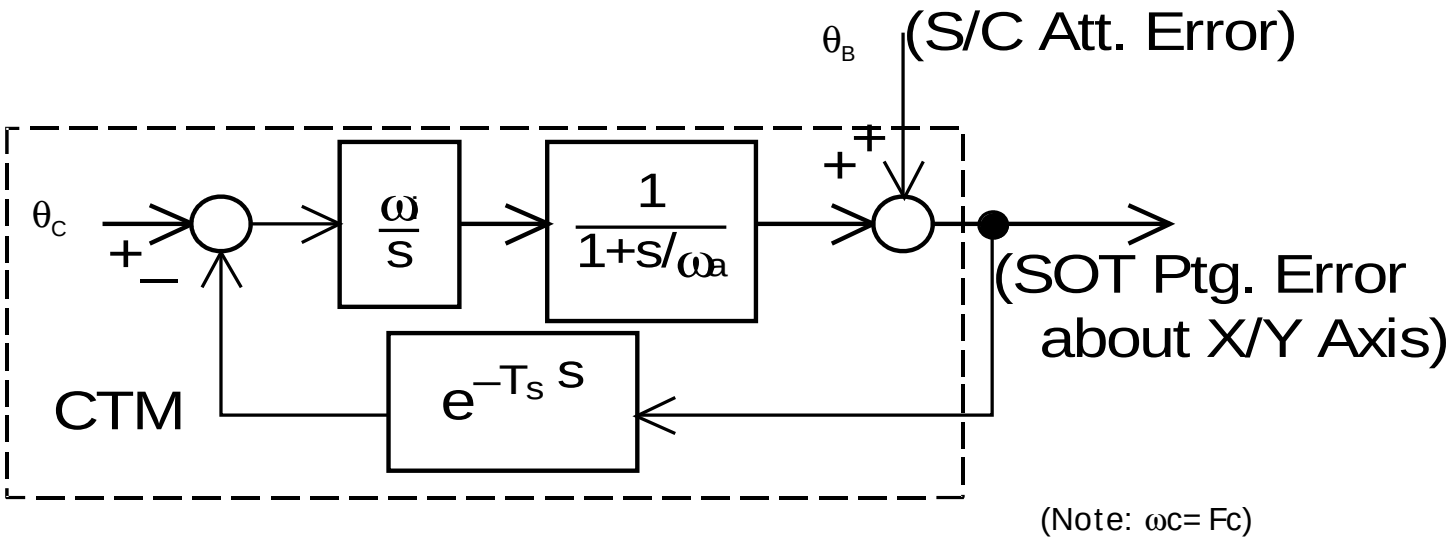
Image Stabilization System



Servo loop gains can be optimized by onboard diagnostic software in CTM- E

symbol	description	realized by
G1	Integral function for compensation of the Gain margin	software
G_F	Sequential three filters	
	filter1: Low Pass Filter for noise reduction	software
	filter2:Notch Filter for for mechanical resonace	software
	filter3:Lead-Lag Filter for compensation of the Phase ma	software
G3	Transformation from 2 to 3 axis	software
G2	Transfer Function of Tip-tilt Mirror Drive Circuit	CTM-TE Hardware
G_{TM}	Trasfer Function of Tip-tilt Mirror	CTM-TM Hardware
G_{FPP}	CT signal Characteristics(FPP-E)	FPP-E

CTM Servo Block (simplified model)



- Tip-tilt mirror is closed-loop controlled using CT signal generated by correlation tracker in FPP.
- Closed loop control is to stabilize CT signal into zero.

Image Stabilization System

The overall transfer function is expressed as follows:

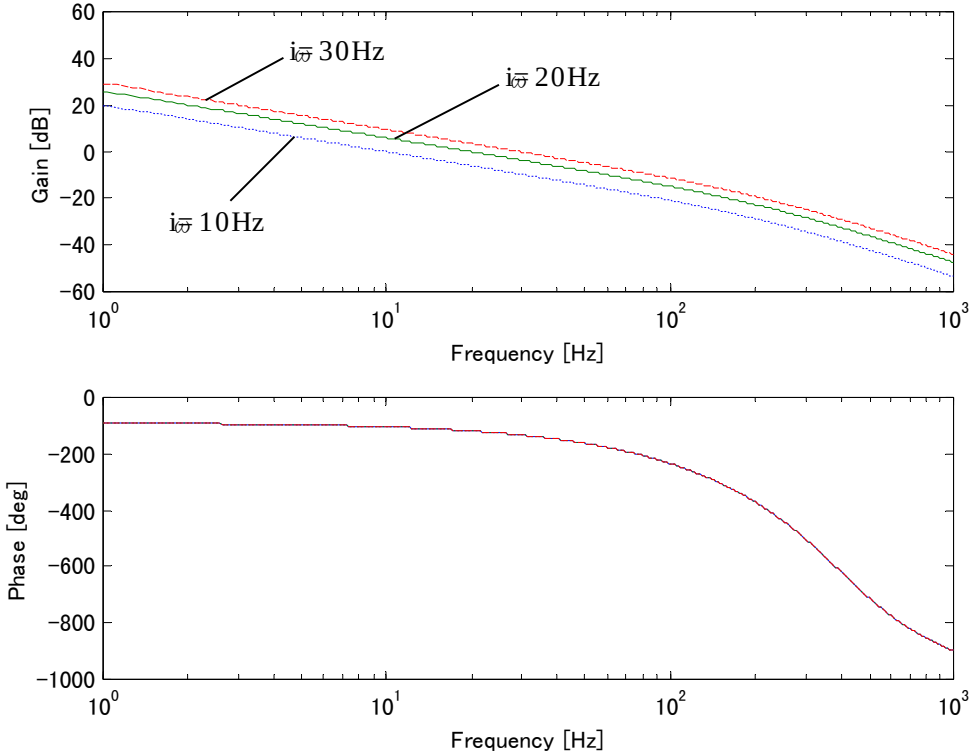
$$G(s) \simeq \frac{K_1}{s} \frac{1}{(1+Ts)} \exp(-\tau_c s), \quad s = j\omega .$$

Image Stabilization System minimize pointing jitter(θ_B), and the remaining jitter(θ_{SOT}) in FPP images is related to pointing jitter with the transfer function G(s):

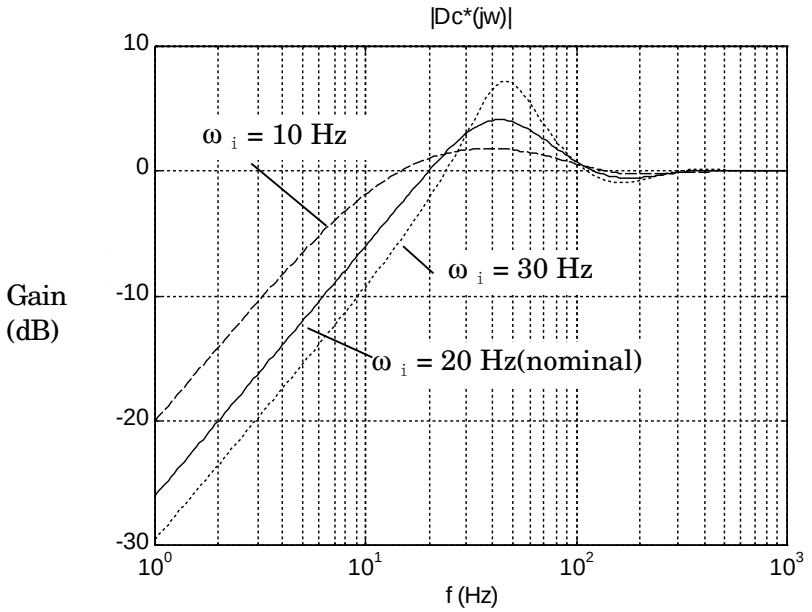
$$\frac{\theta_{SOT}}{\theta_B} = H(s) = \frac{1}{1+G(s)}$$

Image Stabilization System

Overall Transfer Function



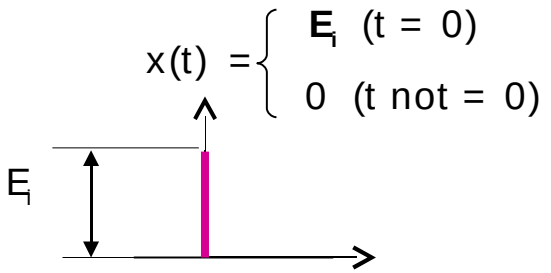
Reduction Performance



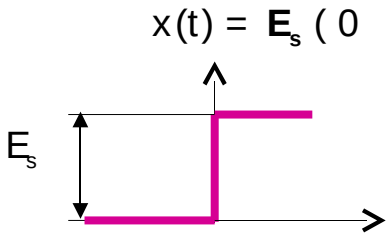
CTM overall delay time τ_s = 3 ms

Image Stabilization System

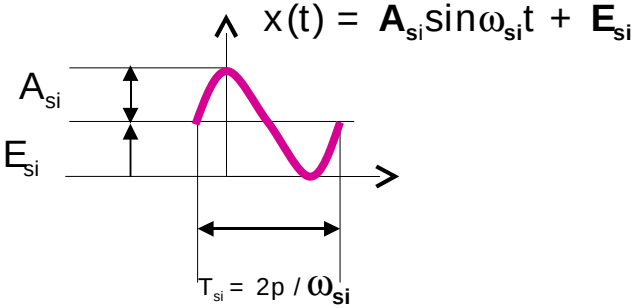
- The diagnostics mode allows us to diagnose transfer function of servo loop.
- The diagnostics mode has a capability to input a signal pattern in the servo loop:The three signal patterns are available.



Impulse



Step



Sine Wave

Image Stabilization System

The diagnostics mode produces diagnostic telemetry data, which allows to monitor the status in high rate (580, 290 or 145 Hz): 36 points can be monitored.

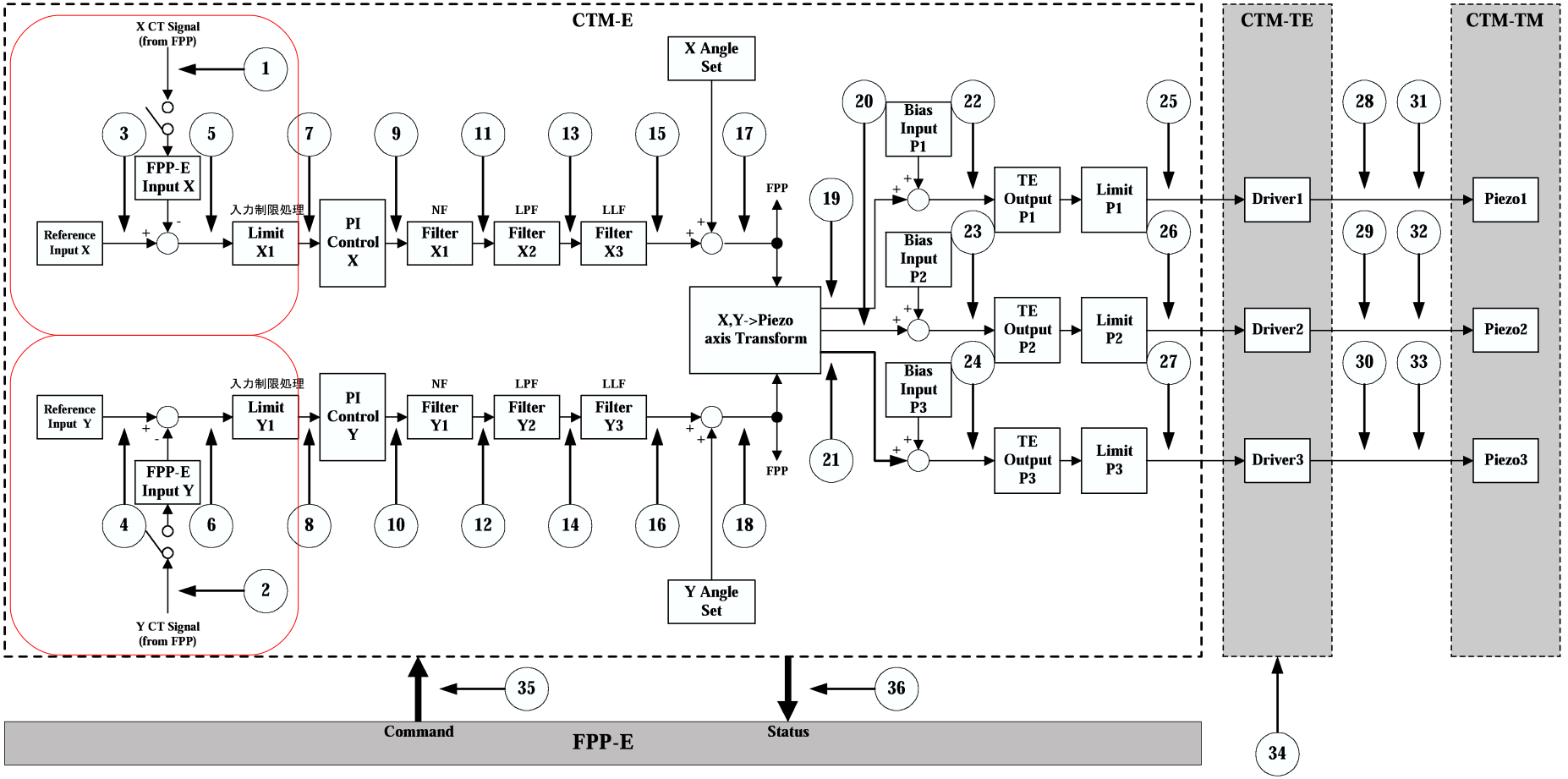
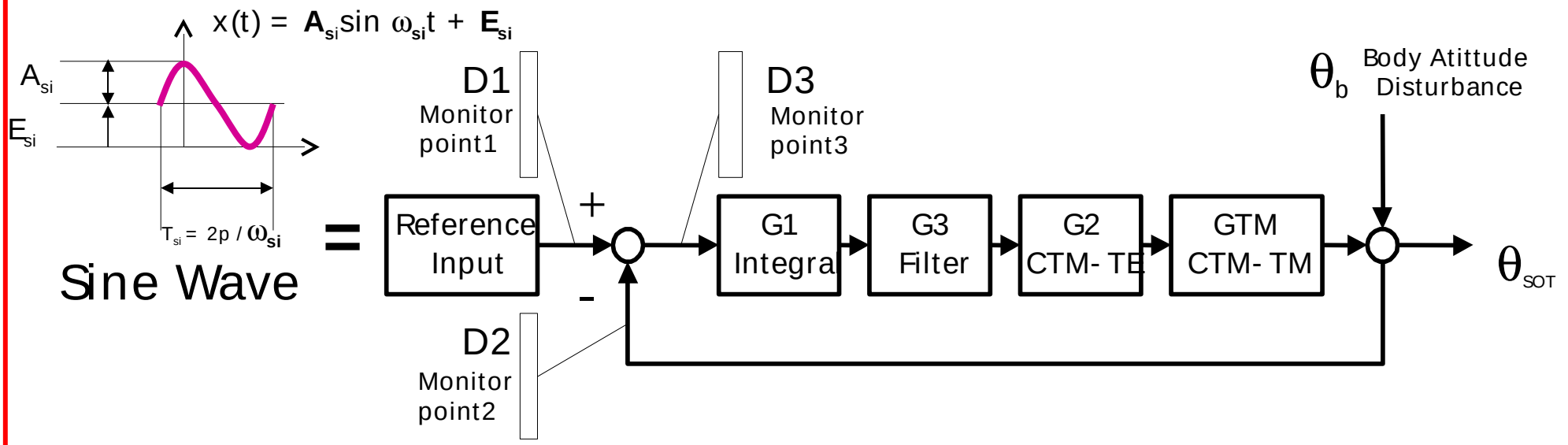


Image Stabilization System



- Open Loop Characteristics:

$$G_{open}(s) = G1 \times G2 \times G3 \times G_{TM} = \frac{D2}{D3}$$

Gain: $$|G(\omega)| = \left|\frac{D2(\omega)}{D3(\omega)}\right|$$

Phase: $$\angle G(\omega) = \angle D2(\omega) - \angle D3(\omega)$$

- Closed Loop characteristics:

$$G_{closed}(s) = \frac{G_{open}}{1+G_{open}} = \frac{G1 \times G2 \times G3 \times G_{TM}}{1+G1 \times G2 \times G3 \times G_{TM}} = \frac{D2}{D1}$$

Gain: $$|G(\omega)| = \left|\frac{D2(\omega)}{D1(\omega)}\right|$$

Phase: $$\angle G(\omega) = \angle D2(\omega) - \angle D1(\omega)$$

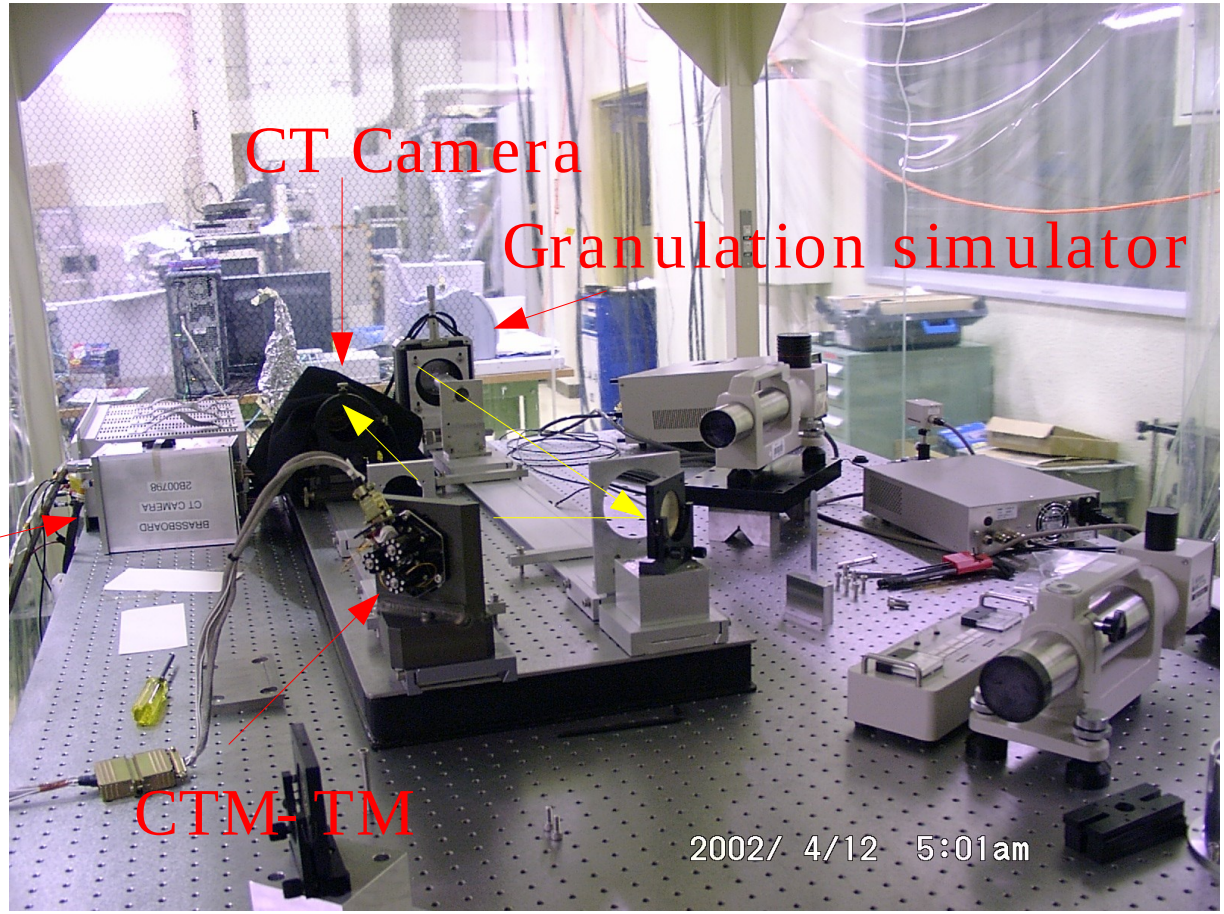
Test Resulsts

Image Stabilization System

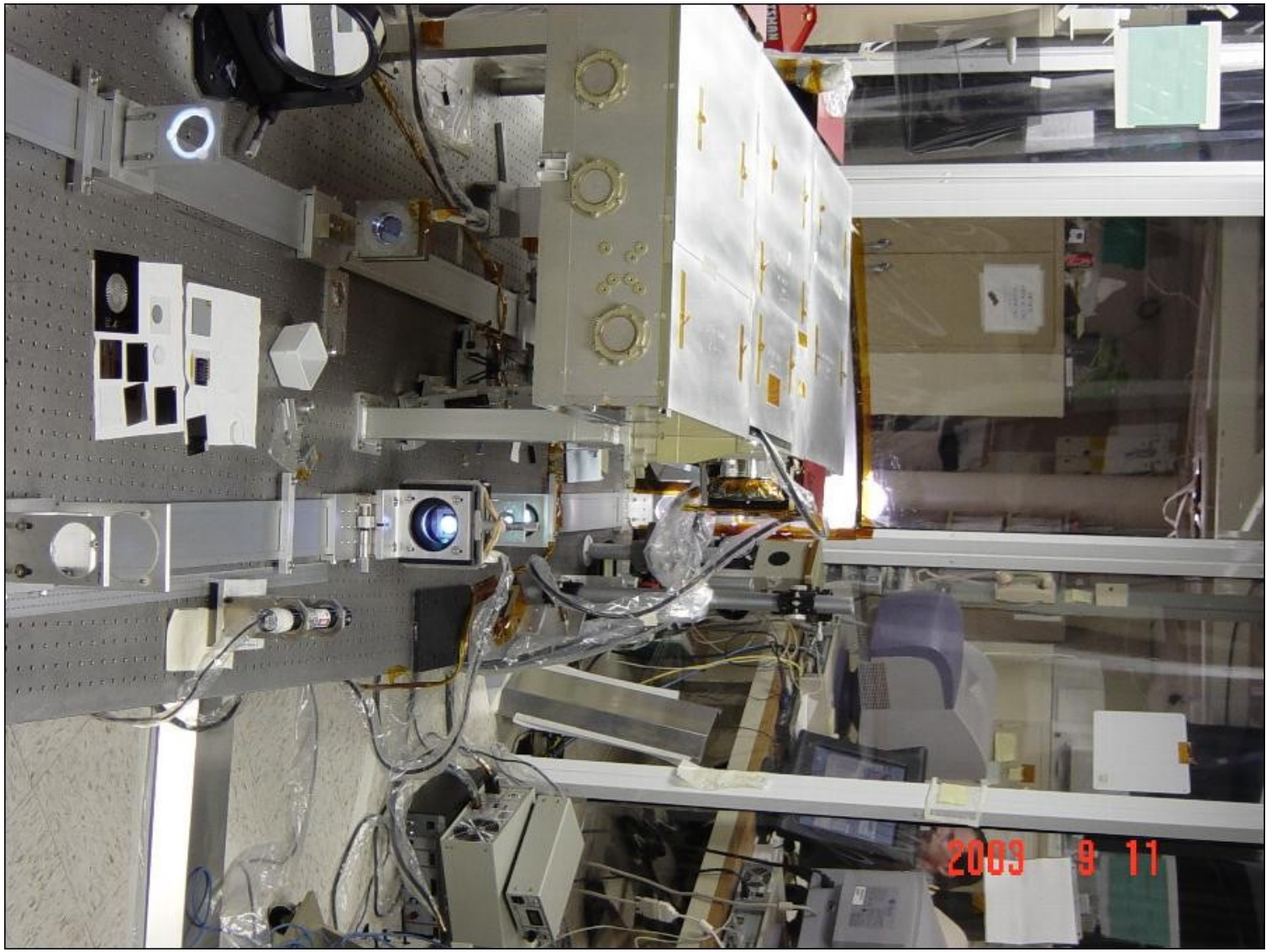
FM Combination Test:

- Tested in Sep. 2003 at LMSAL
- Confirmed stability of 0.001-0.002 arcsec (f<20Hz).

Note: this is PM combination test

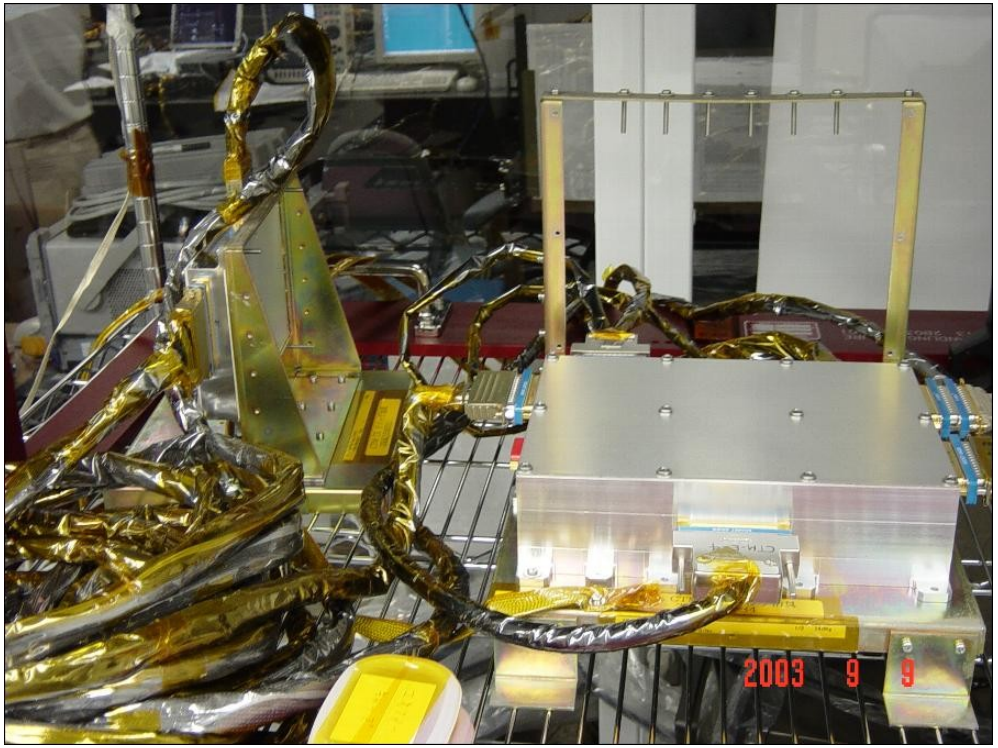


Test Scenes

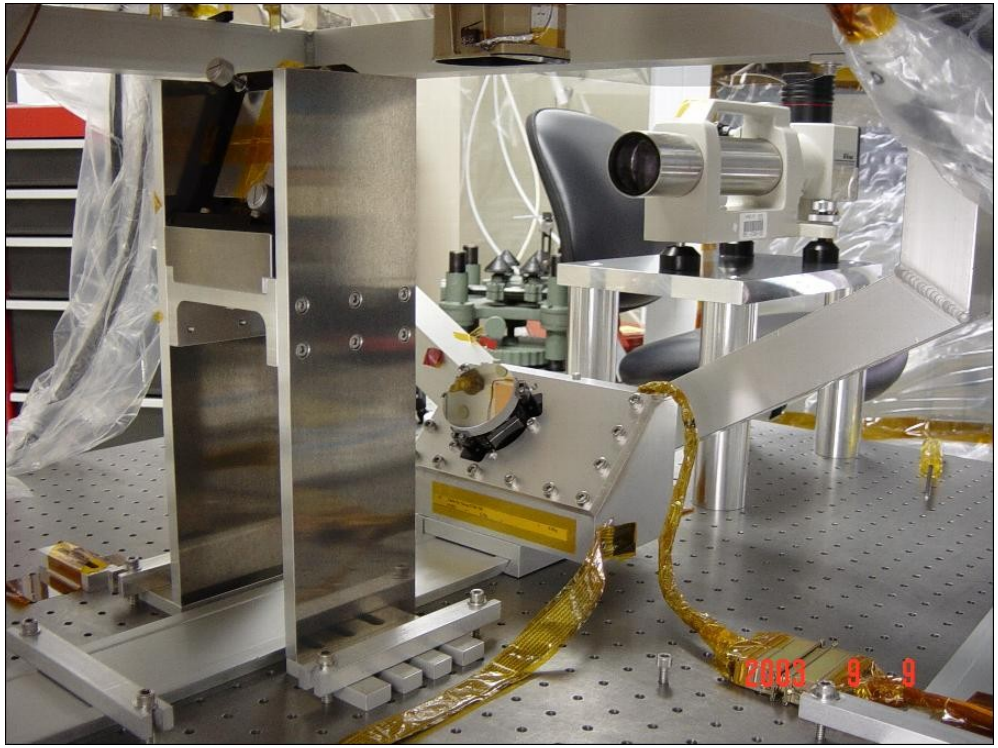


FPP and test optical layout in clean booth

Test Scenes

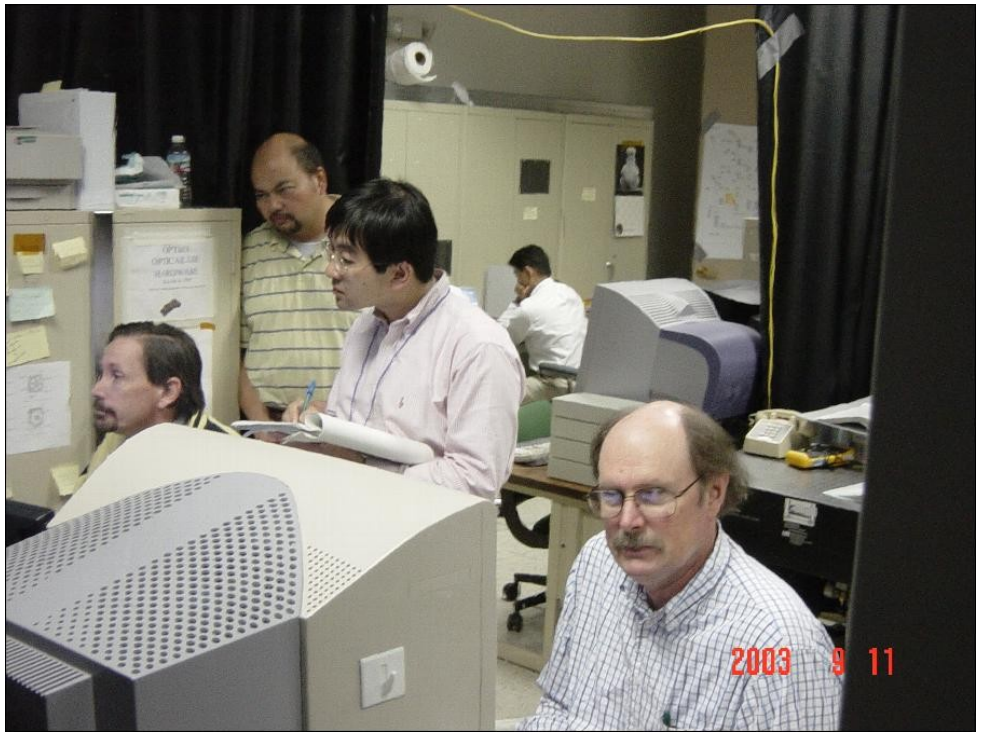


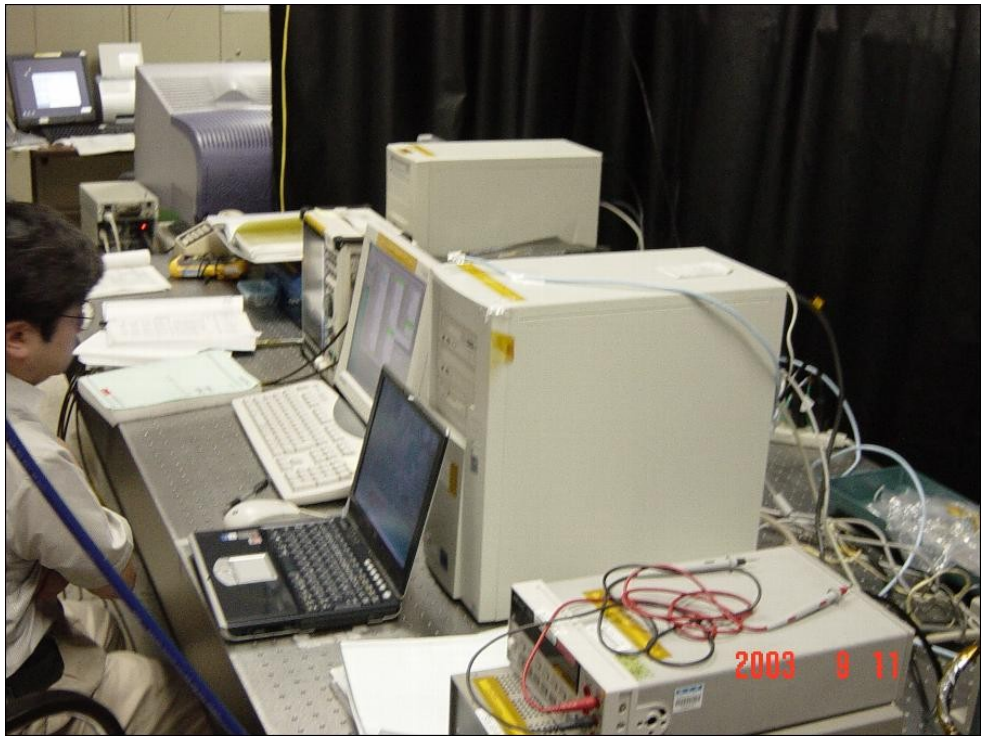
CTM-E and CTM-TE flight model



CTM-TM(PM) and auto-collimator

Test Scenes





FPP and CTM GSEs outside clean booth

Image Stabilization System

Transfer Function: Measurement (red circle) agrees well with model (green line)

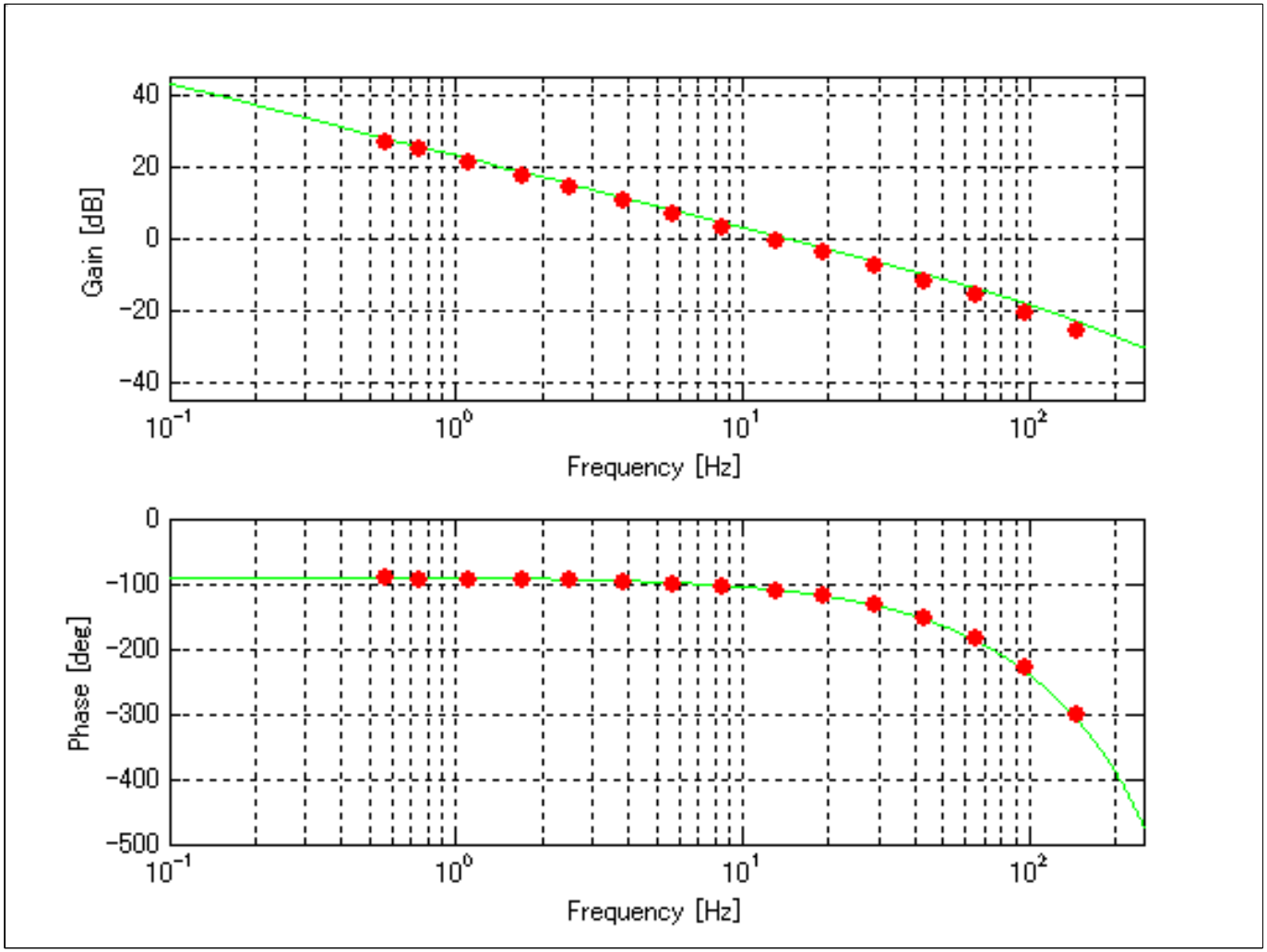


Image Stabilization System

SERVO OFF

X axis

Y axis

Time Profile

Histogram

PSD

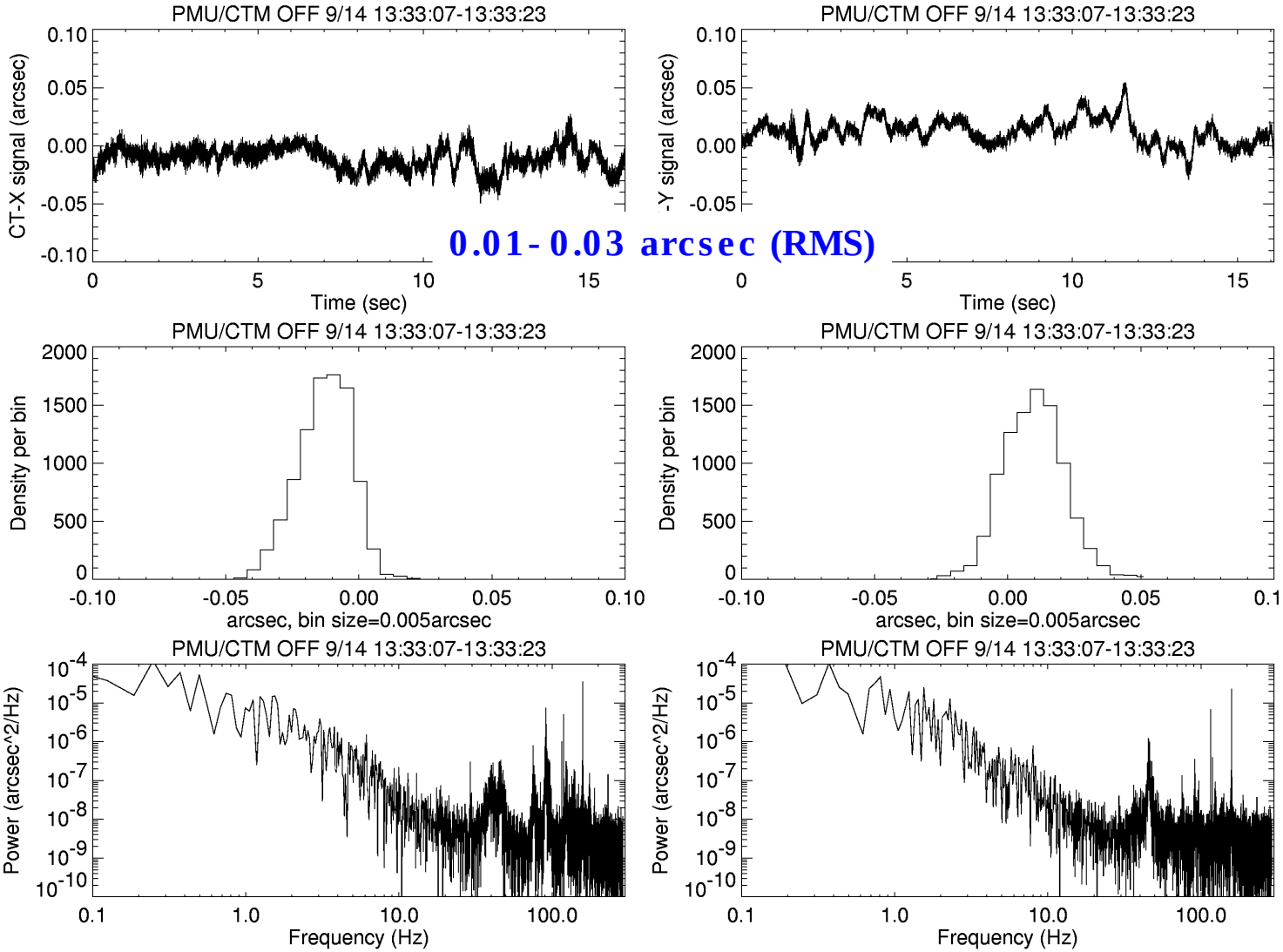


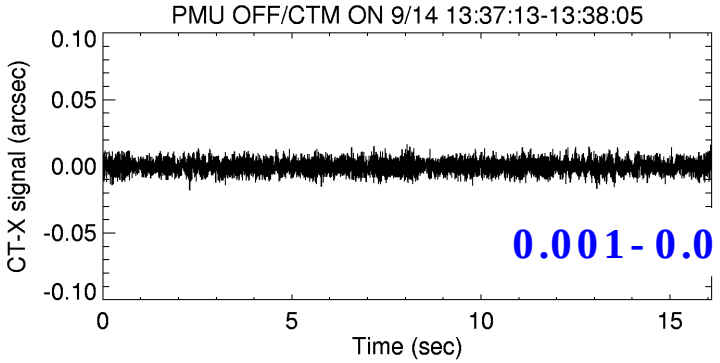
Image Stabilization System

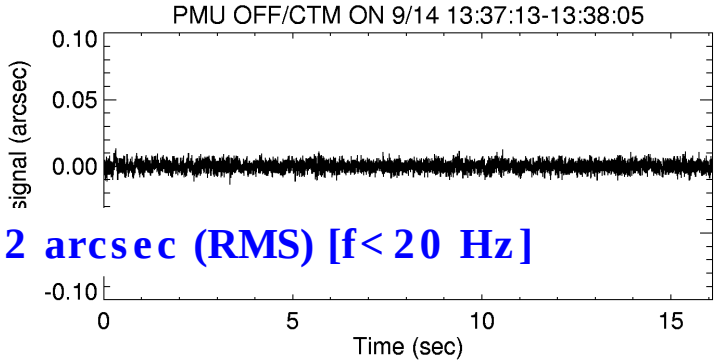
SERVO ON

X axis

Y axis

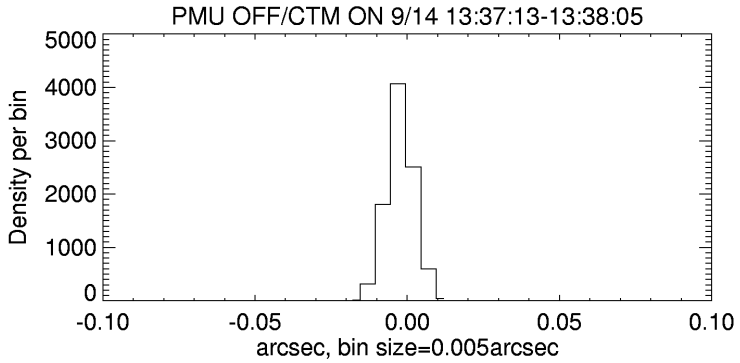
Time Profile

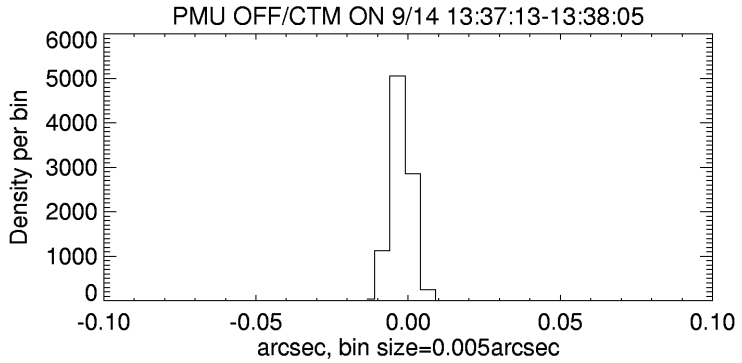




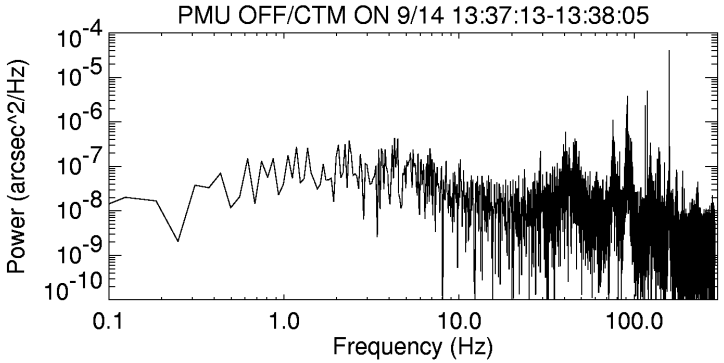
0.001-0.002 arcsec (RMS) [f<20 Hz]

Histogram





PSD



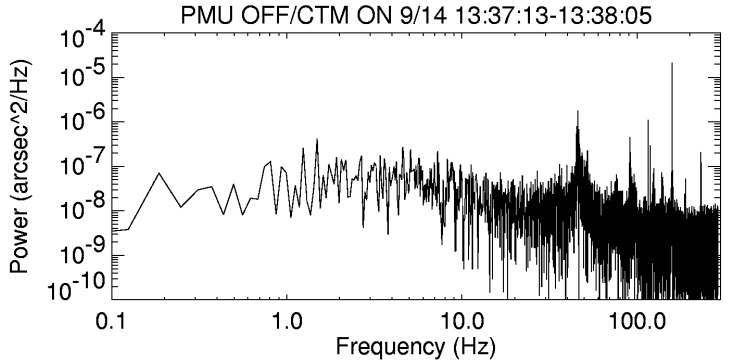


Image Stabilization System

END