LISA 19-DOF DRS Model

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Overview

- LISA dynamics and controls models are developed to:
  - Evaluate LISA requirements and verify that they can be met
  - Evaluate DRS control architectures and strategies
  - Perform trade studies
  - Support the integrated modeling effort

- A 19 degrees of freedom model of a LISA spacecraft has been developed

LISA 19-DOF Model

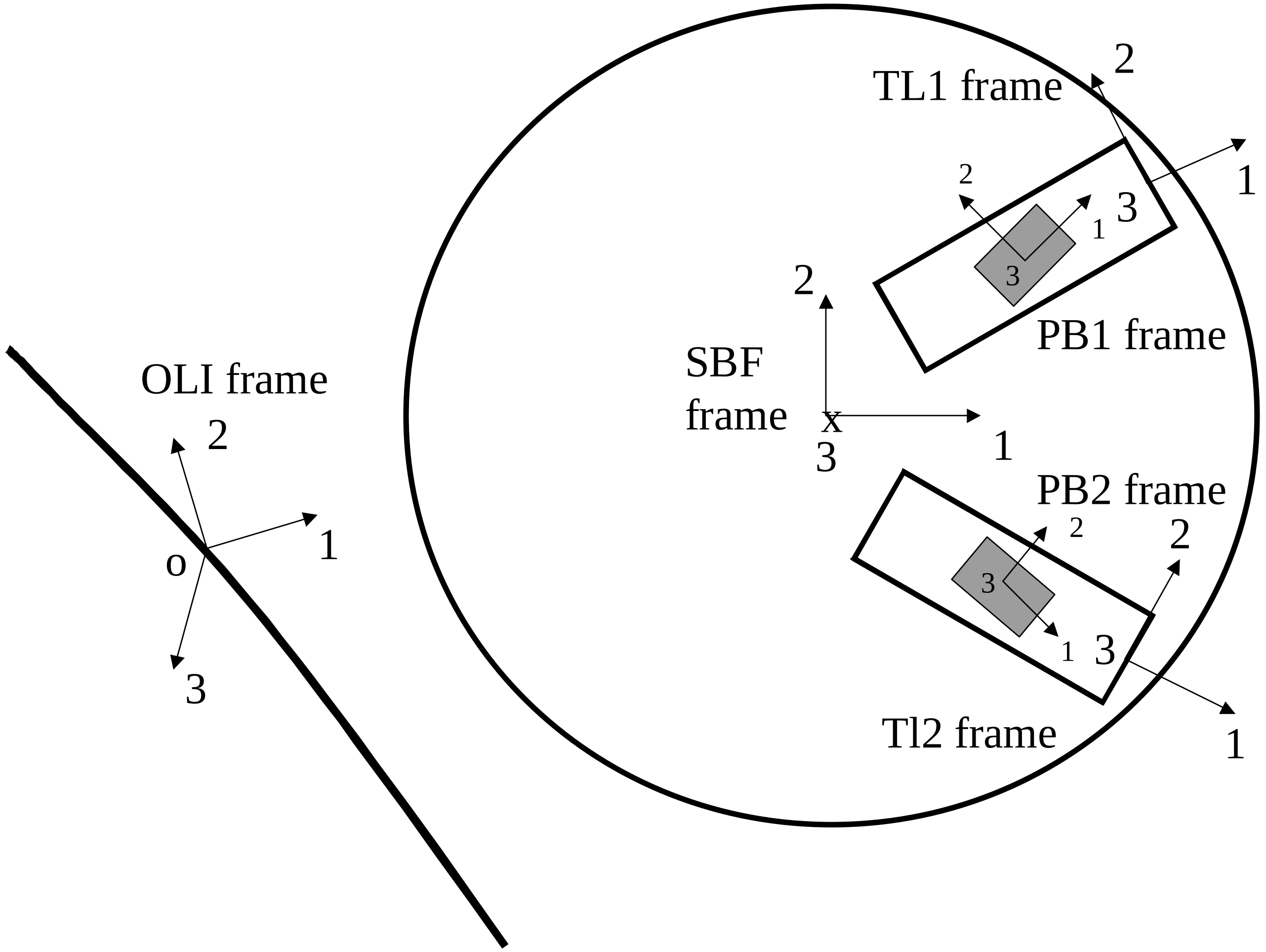
Model Overview

- Full LISA S/C model: S/C (6 DOF), two Proof Masses (6 DOF each), and telescope articulation
- Nonlinear translational and rotational kinematics and dynamics
- Preliminary designs for the four main control systems: Drag-Free control, Attitude control, Proof Mass suspension control, and telescope articulation control
- A decentralized approach to control is followed
- Realistic LISA orbits are brought in via ephemeris file: obtained from orbit design and optimization

Model Overview (Cont'd)

- Orbital ephemeris are also used to simulate incoming laser beam directions for S/C attitude control and telescope articulation control
- Point-ahead angle dynamics and its compensation are not considered
- Measurement and actuation noise models are included
- Approximations to nonlinear electrostatic forces and torques, as well as, those from self-gravity, are included
- Realistic gravity gradient forces (due to the Sun) and Solar radiation pressure forces/torques (bias and variations) are included

Coordinate Systems



Measurement and Actuation Models

- Model assumes that laser detector measurements provide unit vectors along the paths of the incoming laser beams.
- Detector noise model is included for S/C attitude control and telescope articulation control.
- Relative PM-S/C attitude and translation (GRS):
  - Noise models for sensing and actuation included.
  - Actuation forces and torques are applied in the proof mass housing frame.
  - Nonlinear electrostatic forces and torques, as well as, those from self-gravity, are modeled via a linear time-invariant system.
  - Actuation and sensing cross-talk is included.
- μN-thruster noise model is included.
- Actuator quantization for telescope articulation is included

Disturbance Reduction System Control

- DRS control comprises five control systems
    - S/C attitude control system (ACS): to orient the S/C to align the telescopes with incoming laser beams
    - Drag free control system (DFC): to maintain drag free motion of the proof masses in LISA measurement directions
    - Proof mass (PM) suspension control: to maintain relative attitude of the proof mass with respect to its housing an to maintain relative position of the proof mass with respect to its housing in the transverse directions
    - Telescope articulation (TA) control: to maintain the angle between the telescopes
    - Point ahead (PA) and acquisition control: to point the outgoing beam while sensing the incoming beam using communication from the other spacecraft

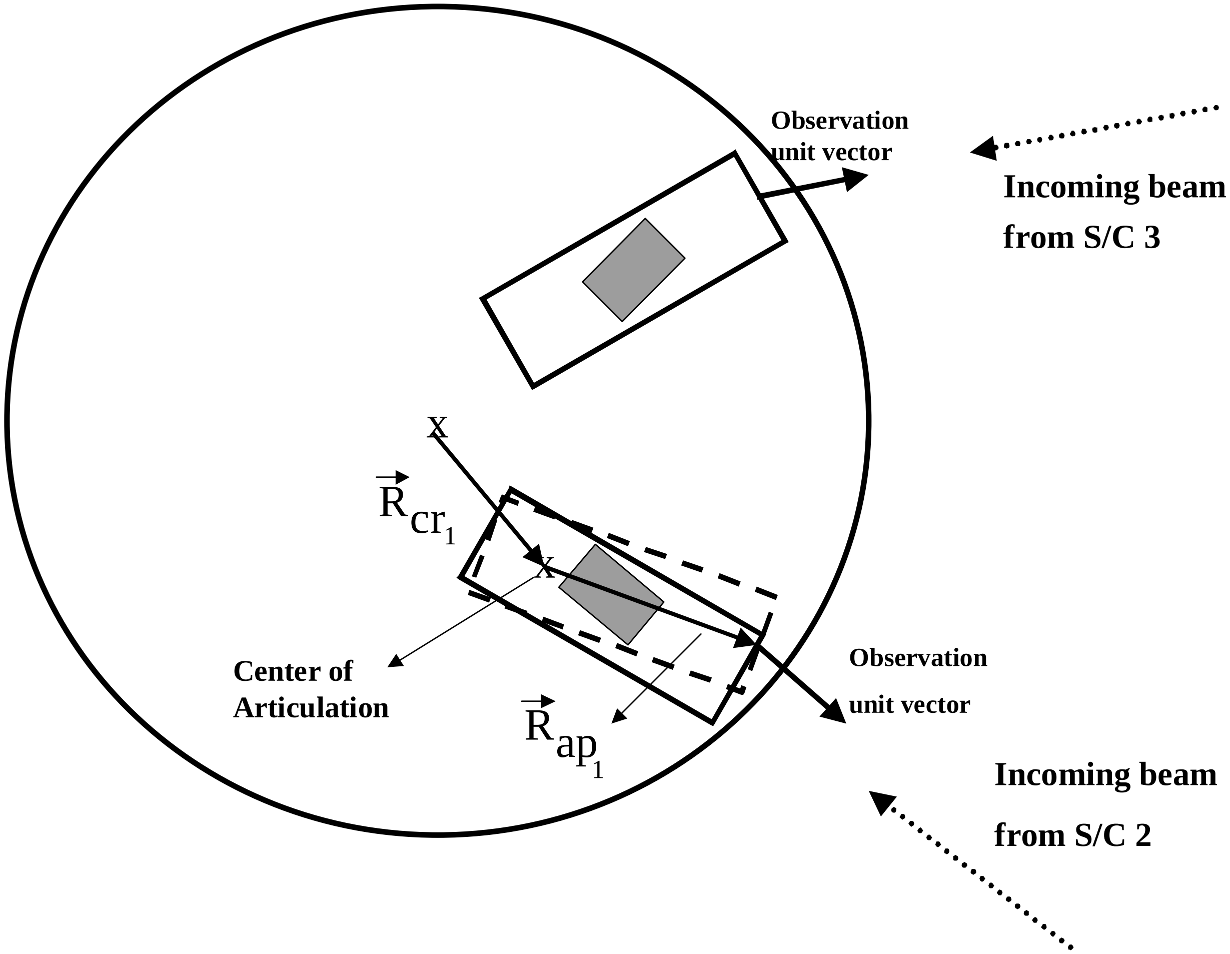
S/C Attitude Control System

- Detectors provide unit vector measurements corresponding to the incoming laser beams: based on instantaneous inertial positions of the telescopes and the other spacecraft
- S/C attitude control must be done in concert with telescope articulation
- Error distribution logic determines the spacecraft attitude error as well as telescope articulation angle error that aligns the telescope axes with the measured unit vectors.
- S/C attitude error is sent to the ACS for attitude adjustments
- ACS is a digital controller and designed using classical single loop approach

Telescope Articulation Control

- Telescope articulation device is assumed to be a torque device at the CM of the telescope, i.e., no reactive forces during articulations.
- Static or dynamic imbalances are not modeled for the telescope articulation.
- Model assumes that the articulation axis and the S/C z-axis are parallel
- Error distribution logic determines the telescope articulation angle error
- This error is sent to the articulation control for angle adjustments
- Articulation control is a SISO digital controller

LISA Attitude Control Concept



Observation unit vector

Incoming beam from S/C 3

x

$\vec{R}_{cr_1}$

x

Center of Articulation

$\vec{R}_{ap_1}$

Observation unit vector

Incoming beam from S/C 2

Attitude and Articulation Errors

- Observed unit vectors to the other spacecraft

$$\vec{o}_{m_1} = \begin{Bmatrix} \sqrt{1-\alpha_1^2-\beta_1^2} \\ \alpha_1 \\ \beta_1 \end{Bmatrix}; \quad \vec{o}_{m_2} = \begin{Bmatrix} \sqrt{1-\alpha_2^2-\beta_2^2} \\ \alpha_2 \\ \beta_2 \end{Bmatrix}$$

- The desired direction, in the respective telescope frame, is given by

$$\vec{o}_d = \begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix}$$

- The telescope articulation angle error is taken as $\alpha_1 - \alpha_2$
- The spacecraft attitude error computed from the required coordinate transformation that would align the measured unit vectors with the desired direction vector.

$$A_e A_{\alpha_1}^T A_1^T A_{\alpha_1} \vec{o}_{m_1} = A_{\alpha_1}^T A_1^T \vec{o}_d$$

$$A_e A_2^T \vec{o}_{m_2} = A_2^T \vec{o}_d$$

Proof Mass Attitude Control

- Uses relative attitude of the proof mass with respect to its housing from capacitive sensing
- Suspension torques are applied at the housing frame
- The relative attitude error is sent to the suspension control for proof mass attitude adjustments
- The attitude suspension controller is a digital controller designed using classical single loop approach

Drag Free Control

- The relative position of the center of mass of the proof mass from its housing is measured by capacitive sensing.
- Two strategies are considered for drag free control:
  - Both strategies do not allow proof mass translation control in the sensitive (measurement) axes (FTR Strategy 4): S/C translation will have to center the proof masses in these directions
  - First strategy permits commanding of the gravitational sensors (in the transverse directions) in a centralized manner: cross coupling between sensors
  - Second strategy does not allow for centralized commanding of the gravitational sensors : proof mass simply follows the housing (no coupling)

Drag Free Control (cont'd)

- The out-of-plane DOF of the 2nd proof mass is not suspended in both strategies: S/C translation will take care of it
- Error distribution matrix computes position errors for the S/C and the proof masses (in the transverse direction) to achieve drag-free motion in the measurement axes as well as to center the proof masses in the transverse directions
- S/C position error is sent to the Drag-free control for S/C translational adjustments
- Proof mass position error is sent to the translational suspension control for position adjustments
- Both DFC and suspension controllers are designed based on digital classical single loop designs.

First Drag Free Strategy

- The required S/C and PM translations

$$A_1(t)\vec{\delta}_s(t)-\vec{\delta}_{p_1}(t)+\vec{e}_{m_1}(t)=0$$
$$A_2\vec{\delta}_s(t)-\vec{\delta}_{p_2}(t)+\vec{e}_{m_2}=0$$

- Solution:

$$\vec{\delta}_s(t)=A_2^T\vec{\delta}_{p_2}(t)-A_2^T\vec{e}_{m_2}$$
$$A_1A_2^T\vec{\delta}_{p_2}-\vec{\delta}_{p_1}=A_1A_2^T\vec{e}_{m_2}-\vec{e}_{m_1}$$

- Note: the z component (out-of-plane) of 2nd proof mass is not suspended.

$$\begin{bmatrix} 0 & 0 & \bar{A}(1,2) \\ -1 & 0 & \bar{A}(2,2) \\ 0 & -1 & \bar{A}(3,2) \end{bmatrix} \begin{Bmatrix} \vec{\delta}_{p_1}(2) \\ \vec{\delta}_{p_1}(3) \\ \vec{\delta}_{p_2}(2) \end{Bmatrix} = \bar{A}\vec{e}_{m_2}-\vec{e}_{m_1}$$

Second Drag Free Strategy

- The required S/C translations are computed to provide drag-free motion in the sensitive axis and one transverse axis

$$
\begin{aligned}
&A_1(1,1)\vec{\delta}_s(1) + A_1(1,2)\vec{\delta}_s(2) + \vec{e}_{m_1}(1) = 0 \\
&A_2(1,1)\vec{\delta}_s(1) + A_2(1,2)\vec{\delta}_s(2) + \vec{e}_{m_2}(1) = 0 \\
&\vec{\delta}_s(3) + \vec{e}_{m_2}(3) = 0
\end{aligned}
$$

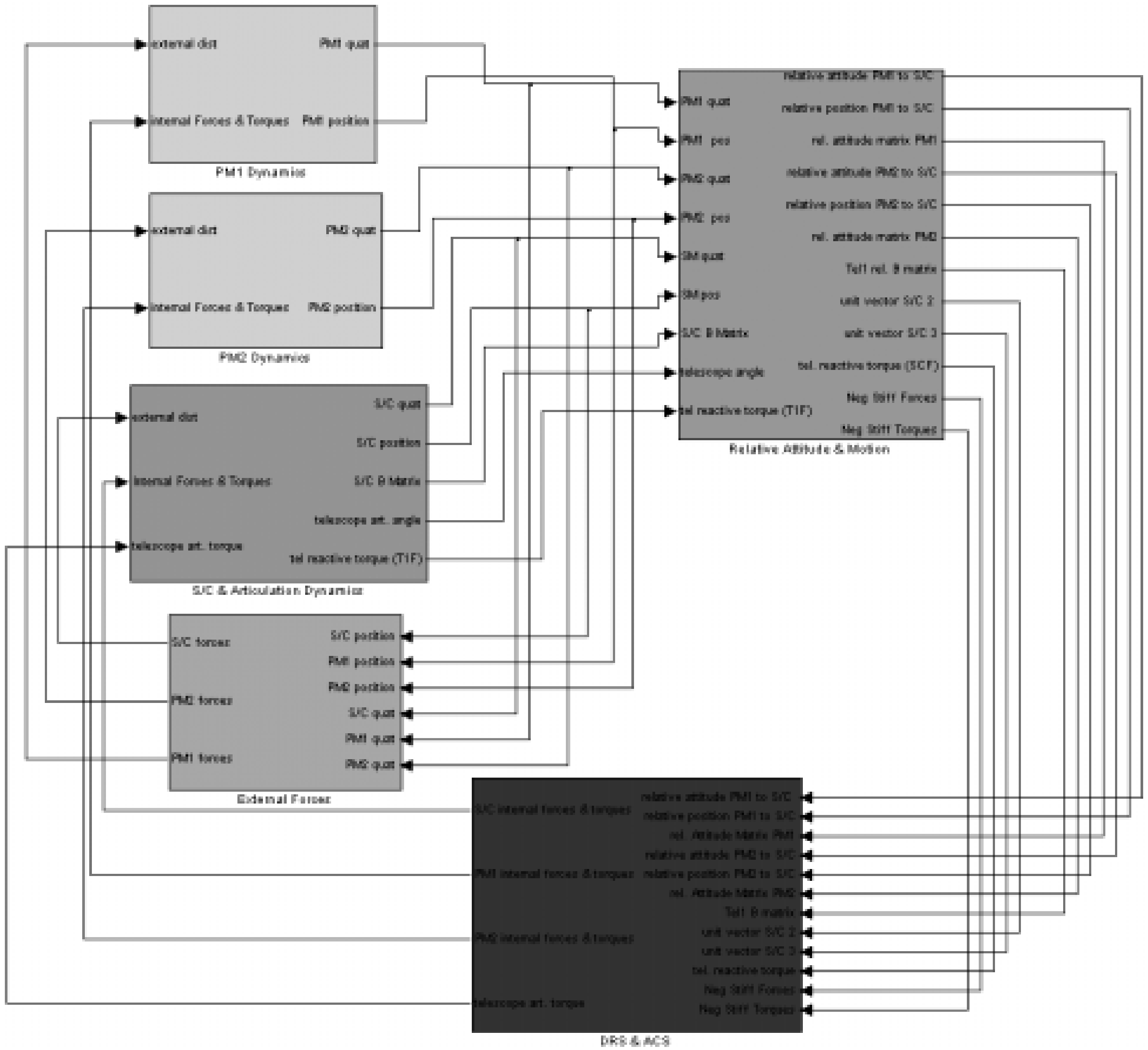
- The proof mass position errors in the transverse direction are computed as

$$
\begin{aligned}
&\vec{\delta}_{\mathrm{p}_1}(2)=\vec{\mathrm{e}}_{\mathrm{m}_1}(2) \\
&\vec{\delta}_{\mathrm{p}_1}(3)=\vec{\mathrm{e}}_{\mathrm{m}_1}(3) \\
&\vec{\delta}_{\mathrm{p}_2}(2)=\vec{\mathrm{e}}_{\mathrm{m}_2}(2)
\end{aligned}
$$

LISA Simulation Model

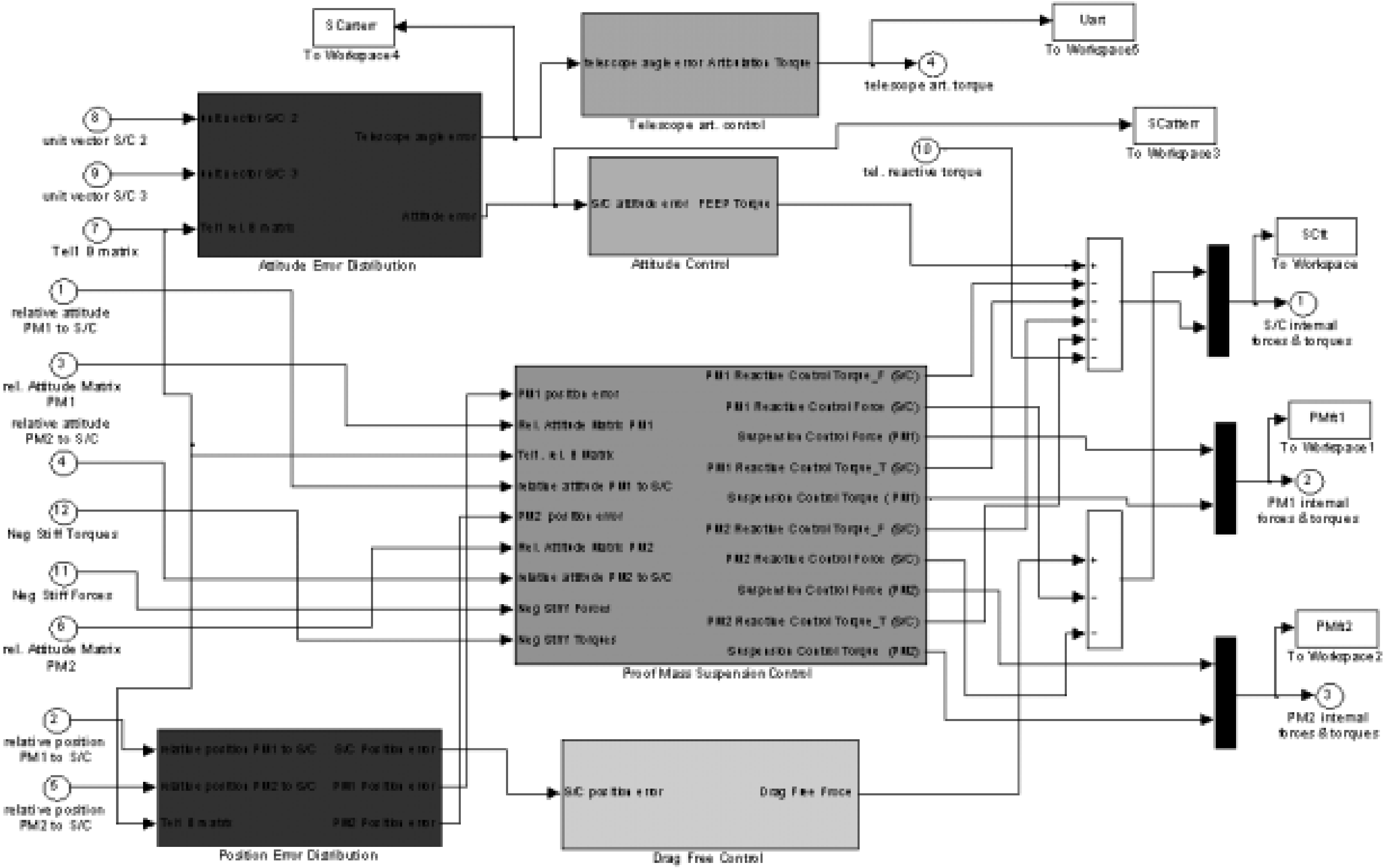
- Model is developed in SIMULINK environment with MATLAB script file driver
  - Different stiff and non-stiff solvers are available for integration
  - Hybrid systems and nonlinearities are fully treated
- Orbital ephemeris (obtained from optimization) are imported
- Realistic initial attitudes and rates (S/C & PMs) obtained from ephemeris data

SIMULINK Model

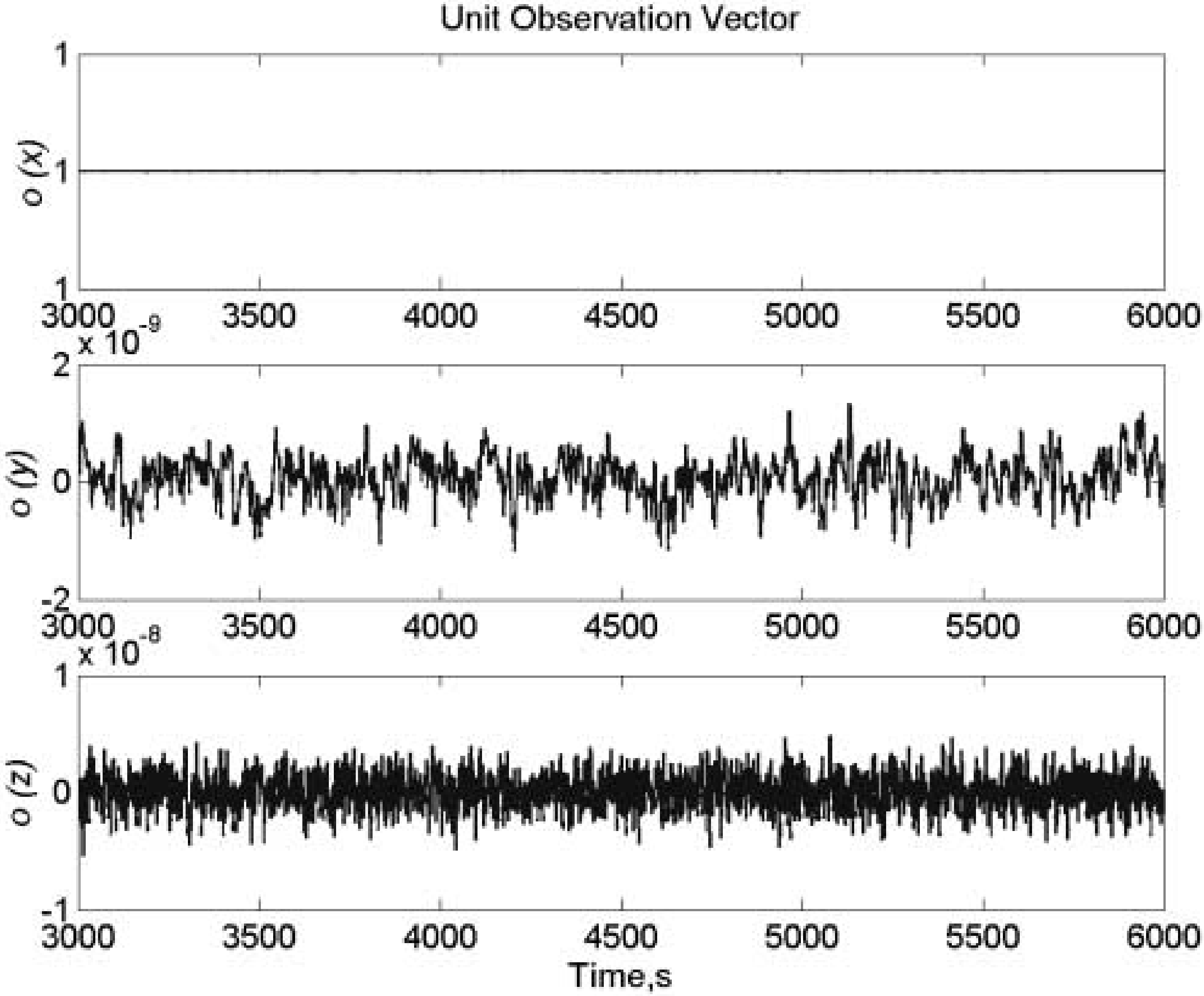


LISA

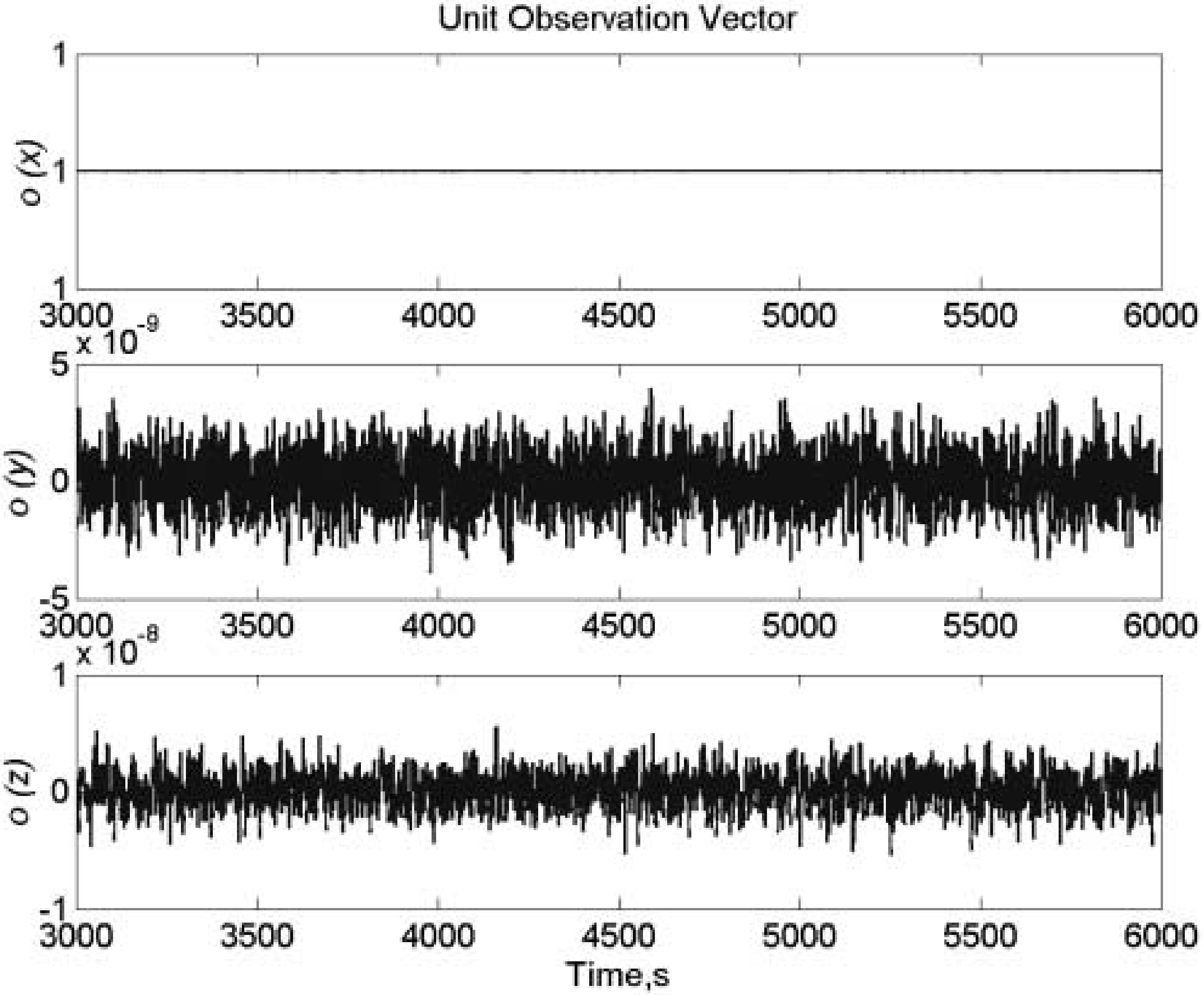
DRS Controller



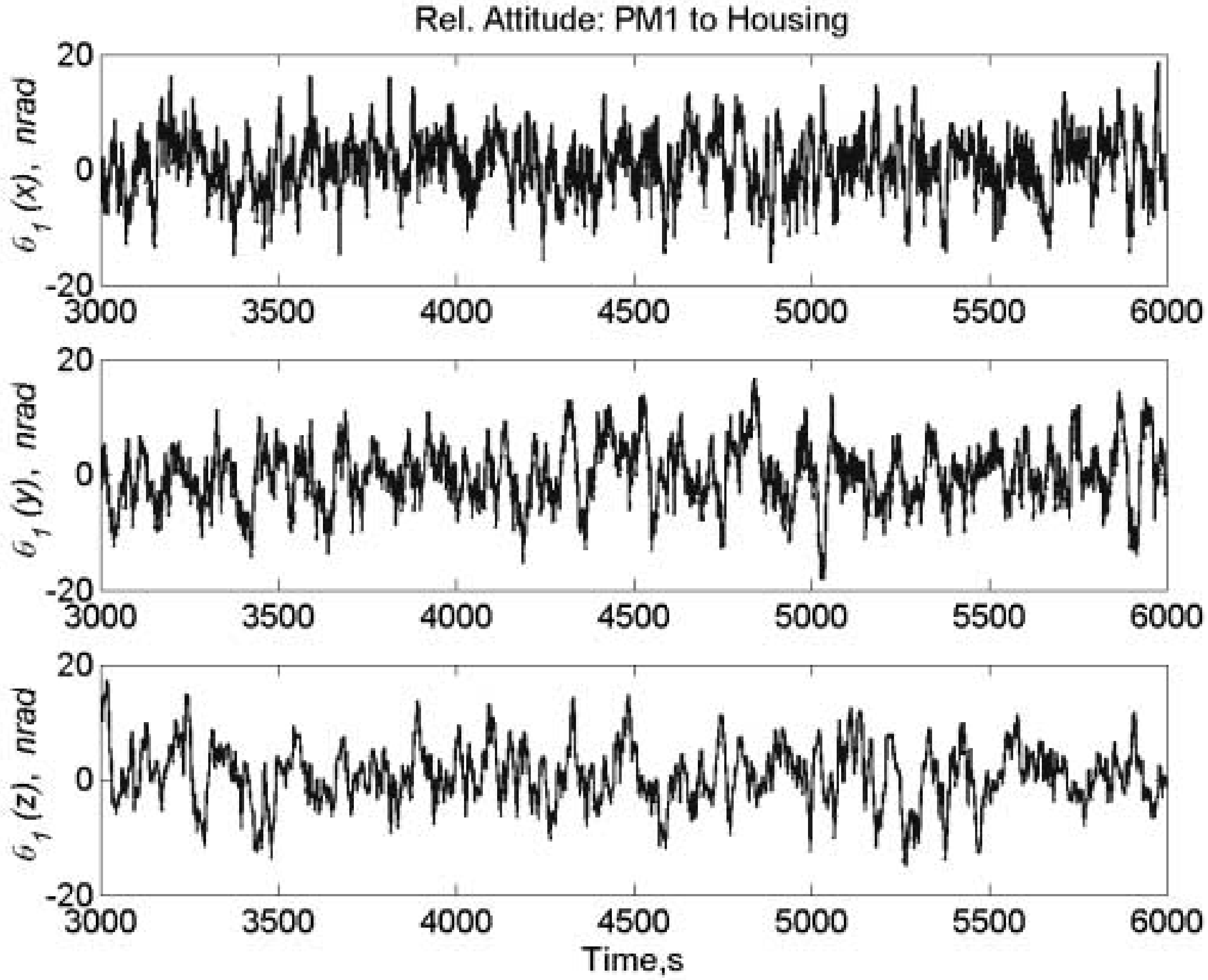
Pointing Error: Telescope 1



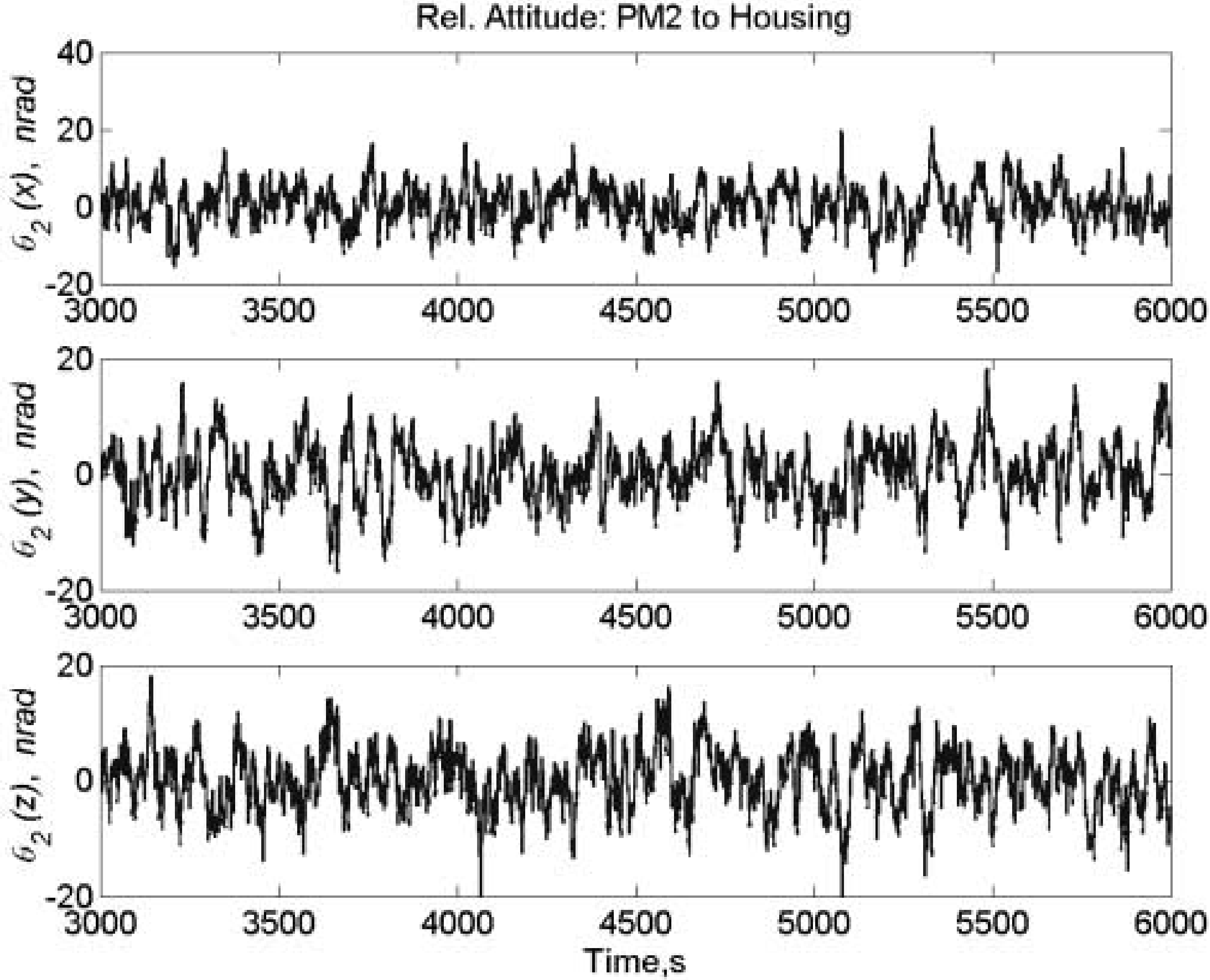
Pointing Error: Telescope 2



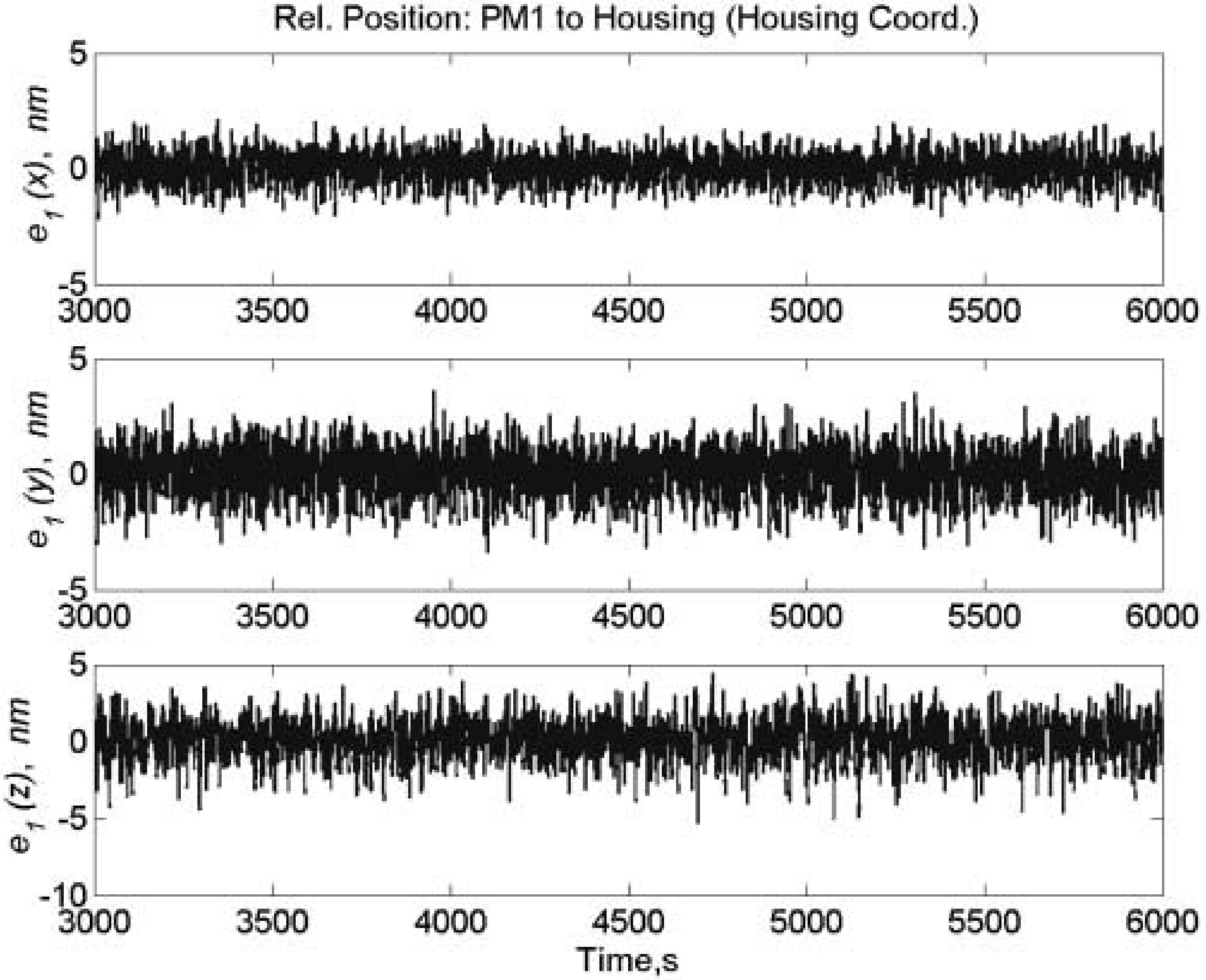
Rel. Attitude PM1 to Housing



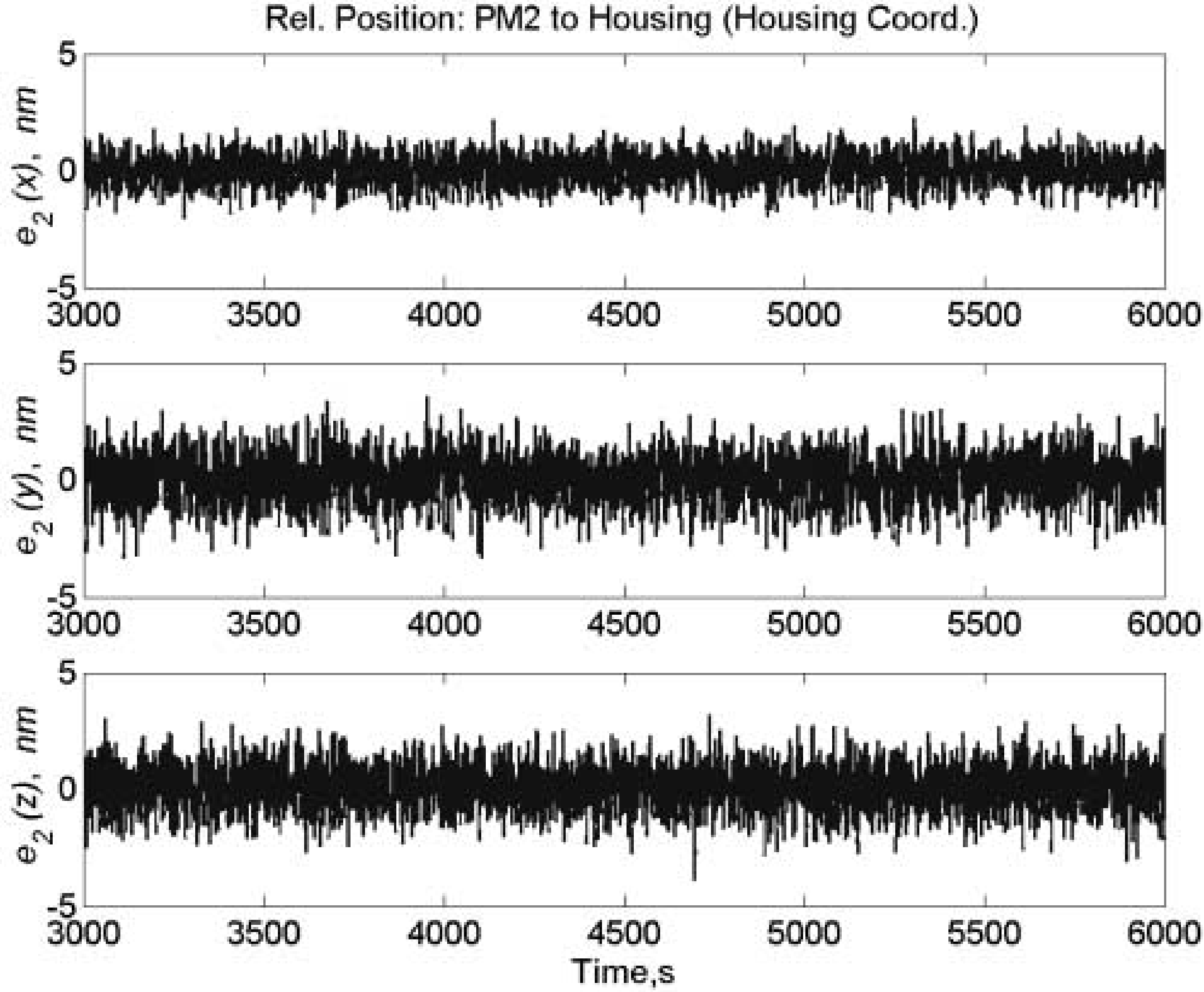
Rel. Attitude PM2 to Housing



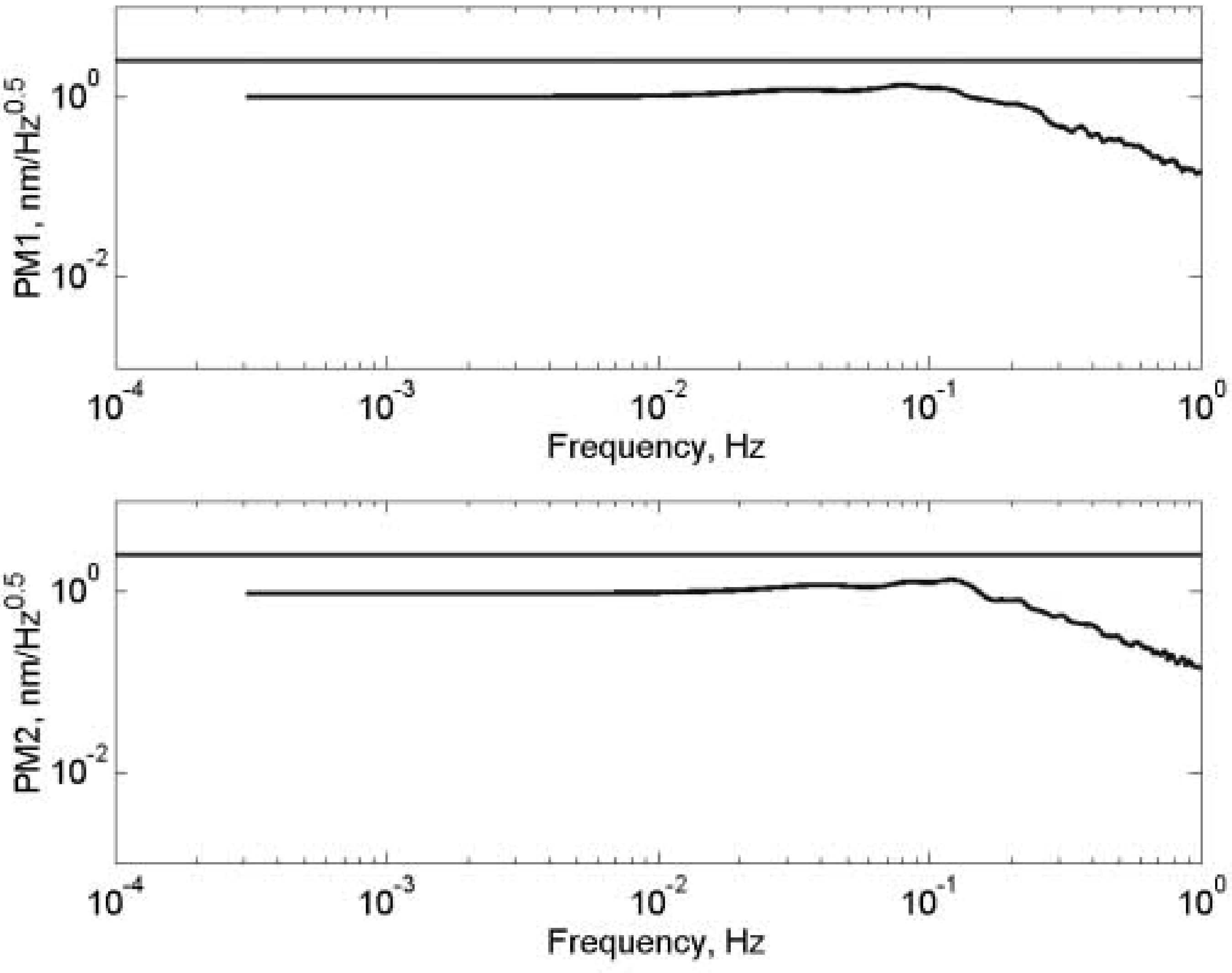
Rel. Position PM1 to Housing



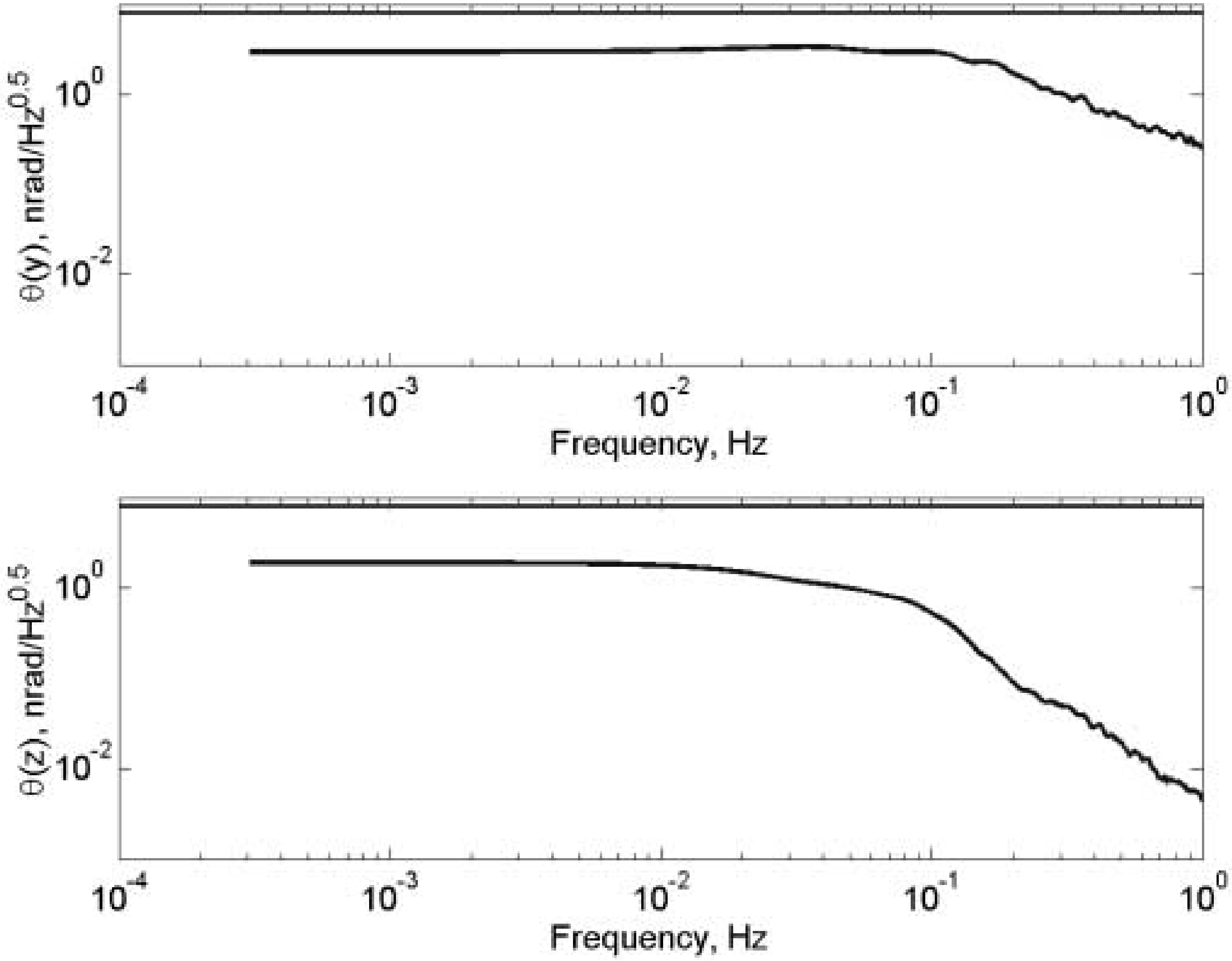
Rel. Position PM2 to Housing



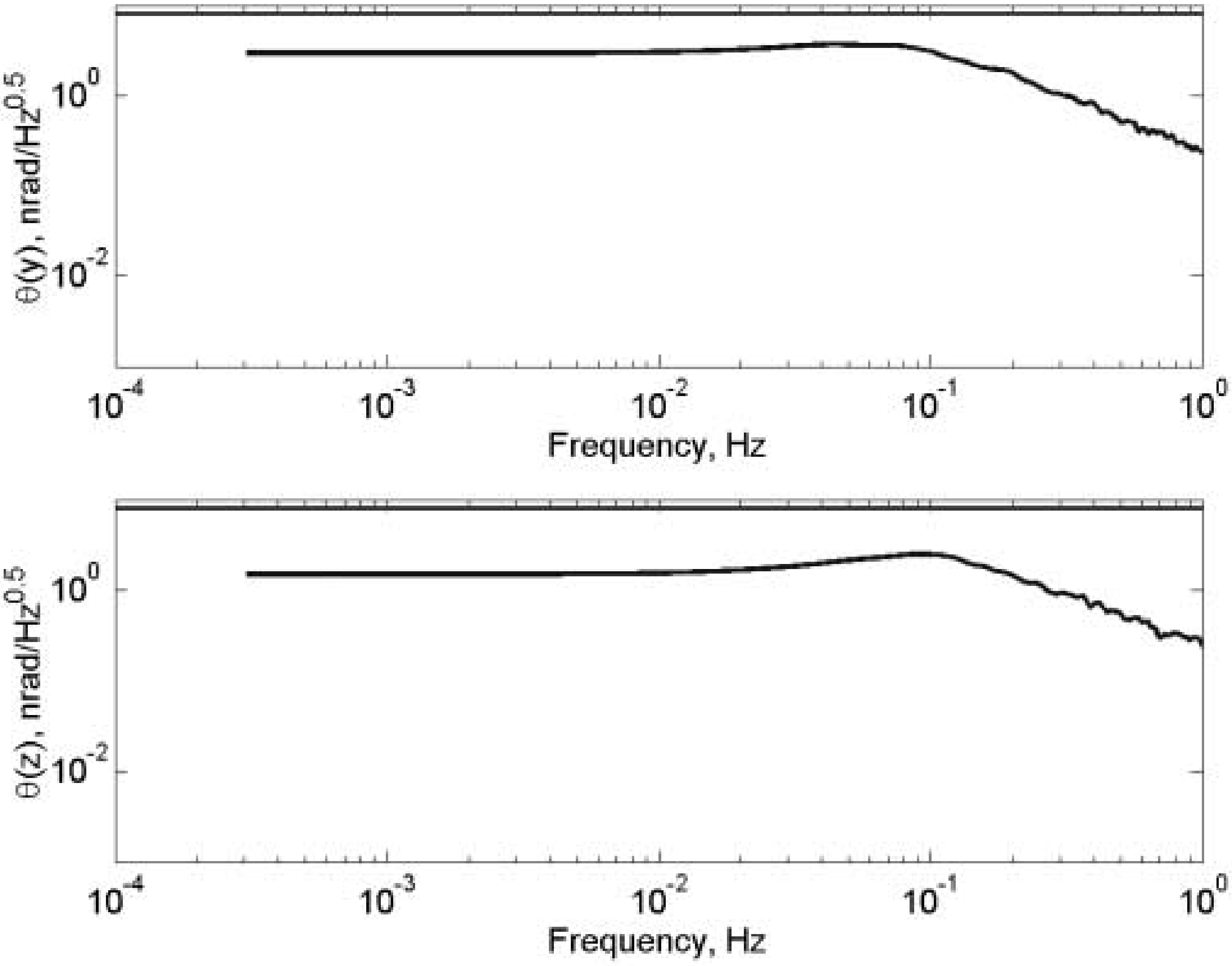
ASD of PM position in measurement direction



ASD of Telescope no. 1 Attitude



ASD of Telescope no. 2 Attitude



Future Work

- Obtain a linear 19-DOF model
  - Frequency-domain analysis
  - Robustness and stability analysis
- Perform trade studies on DRS control
  - Control strategies and architecture
  - MIMO and robust control designs
- Integrated modeling and analysis
  - Couple DRS simulation with optics
- Investigate point-ahead and acquisition controls
- Improve model fidelity
- Develop a full 57 DOF LISA formation model

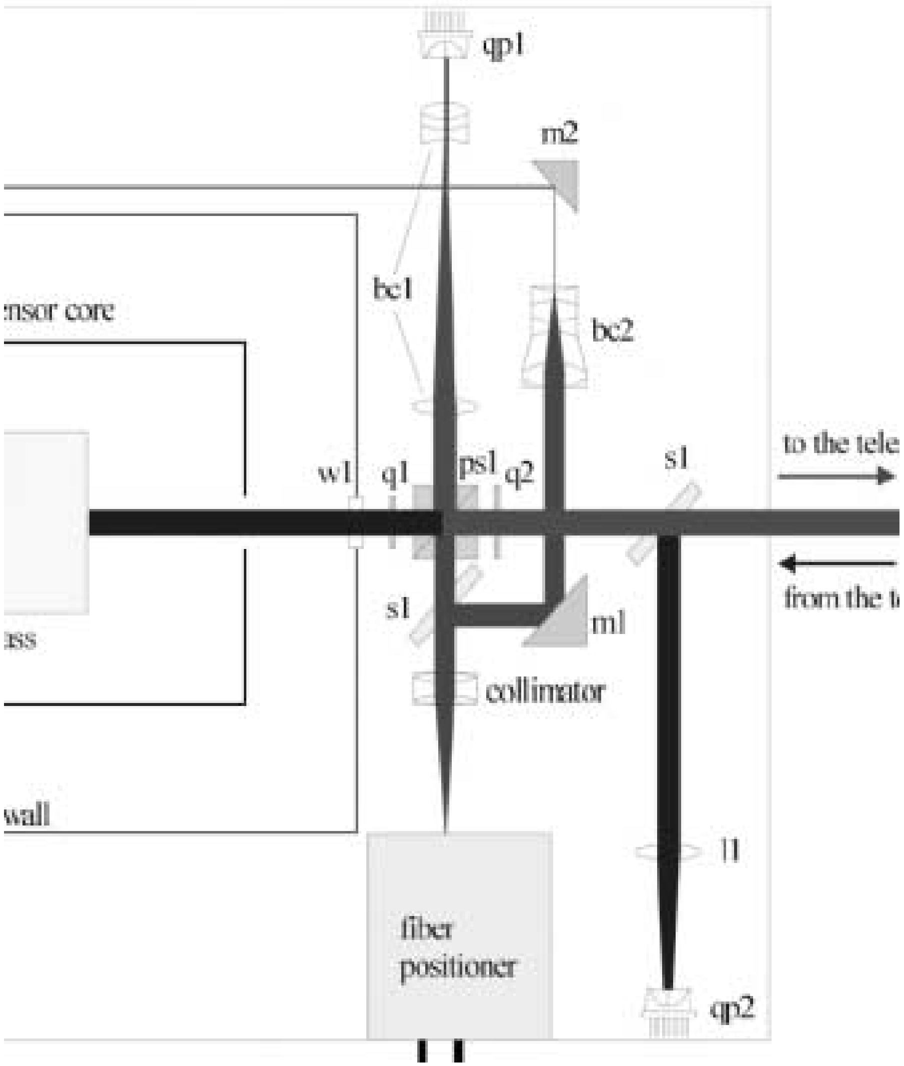
Point Ahead Angle

- So far, the 19 DOF model or control does not address point ahead or acquisition.
- Point ahead angle is the difference between outgoing and incoming beams due to speed of light
- From FTR Section 3-3, the PAA (in object space) are…

In plane	3.3 μrad +- 55 nrad
Out of plane	85 nrad +- 5.75 μrad

Component Angles

- Object space (30 cm beam)
- Compressed space (0.5 cm beam)
  - M_{tl}=60
- Detector space (0.5 mm beam)
  - M_{bc1}=10
- PAA= ~$6x10^{-6}$ rad max (object)
- Θ_{tl} = telescope rel bench (object)
- Θ_{out} = outgoing (object)
- $\Theta_{in} = \Theta_{out}$ - PAA (object)
- Θ_{ps1} = beamsplitter (comp)
- Θ_{pm} = proof mass (comp)
- Θ_{fa} = fiber aligner (comp)
  - Includes fiber aligner and collimator
- Θ_{err}= diff WF tilt (detector)



Point Ahead Equations

- Output Beam Angle
  - $\Theta_{out} = (1/M_{tl})(\Theta_{fa} + 2\Theta_{ps1}) + \Theta_{tl}$
- Wavefront tilt difference on detector
  - $\Theta_{err} = M_{bc1} \{ M_{tl} (\Theta_{in} + \Theta_{tl}) + 2\Theta_{pm} + 2\Theta_{ps1} - \Theta_{fa} \}$

- Conditions for lock…Telescope boresights outgouting beam
  - $\Theta_{out} = 0$, $\Theta_{tl} = 0$, $\Theta_{in} = -PAA$
  - $\Theta_{fa} = -2\Theta_{ps1}$

- Results in the following condition
  - $\Theta_{err} = M_{bc1} \{ M_{tl} (-PAA) + 2\Theta_{pm} + 4\Theta_{ps1} \}$
  - $\Theta_{err} = -600\ PAA + 20\ \Theta_{pm} + 40\ \Theta_{ps1}$

Options for Point Ahead Control

- Use PM (FTR baseline)
  - $\Theta_{err} = -600$ PAA $+20\ \Theta_{pm} +40\ \Theta_{ps1} = 0$
  - When $\Theta_{pm} = 30$ PAA $=\sim 180\ \mu$rad max
  - and $\Theta_{ps1}=0$

- Use beamsplitter and fiber aligner
  - $\Theta_{err} = -600$ PAA $+20\ \Theta_{pm} +40\ \Theta_{ps1} = 0$
  - When $\Theta_{ps1} = 15$ PAA $=\sim 90\ \mu$rad max and
  - $\Theta_{fa} = -2\Theta_{ps1} = -30$ PAA $= \sim -180\ \mu$rad max

- Live with error in tilt
  - $\Theta_{err} = -600$ PAA $+20\ \Theta_{pm} +40\ \Theta_{ps1} = -600$ PAA $= \sim 1.8\times10^{-3}$ rad
    - Problem: Loss of fringe visibility at qp1. At beam edge: 1.8×10^{-3} rad * 0.25×10^{-3} m $= 0.45\times10^{-6}$ m $= 0.45$ wave > lamda/20
  - When $\Theta_{pm} = 0$
  - and $\Theta_{ps1}=0$

Summary

- Conclusion:
  - Steering proof mass remains baseline for now
    - requires ~ 180 microradians max, what are implications for calibrations at other than “zero”

- To do:
  - Use real optics math
    - Include other downstream optics (cavity, backside, etc.) and beam walk.
  - Look at acquisition and calibration
  - Look at mechanisms for beamsplitter and fiber aligner