Final Cleared version

Instrument Pointing Control System for the Stellar Interferometry Mission – Planet Quest

Paul B. Brugarolas, Bryan Kang
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099

ABSTRACT

This paper describes the high precision Instrument Pointing Control System (PCS) for the Stellar Interferometry Mission (SIM) – Planet Quest. The PCS system provides front-end pointing, compensation for spacecraft motion, and feedforward stabilization, which are needed for proper interference. Optical interferometric measurements require very precise pointing (0.03 as, 1-σ radial) for maximizing the interference pattern visibility. This requirement is achieved by fine pointing control of articulating pointing mirrors with feedback from angle tracking cameras. The overall pointing system design concept is presented. Functional requirements and an acquisition concept are given. Guide and Science pointing control loops are discussed. Simulation analyses demonstrate the feasibility of the design.

Keywords: pointing, tracking, control, interferometry.

1. INTRODUCTION

SIM-Planet Quest is a NASA mission under development at the Jet Propulsion Laboratory. It is a space observatory in an earth trailing orbit and it is designed to obtain micro-arcsecond class astrometric measurements in order to search and study Earth-like planets, investigate dark matter, and generate a 100 times more accurate star catalog. The SIM instrument executes those science objectives by utilizing 3 parallel Michelson Stellar interferometers[1,2]. Two guide interferometers are used to stabilize the interferometric baselines and provide the reference signals for the science interferometer as a mean of feedforward control. With the aid of feedforward, the science interferometer observes science target stars that can range from visibly bright stars to as dim as 20th magnitude stars

This paper is organized as follows. Section two presents a brief overview of the pointing system. Section three presents the pointing acquisition concept. Section four describes the pointing control loops and section five shows some preliminary simulations results. Section six summarizes the conclusions.

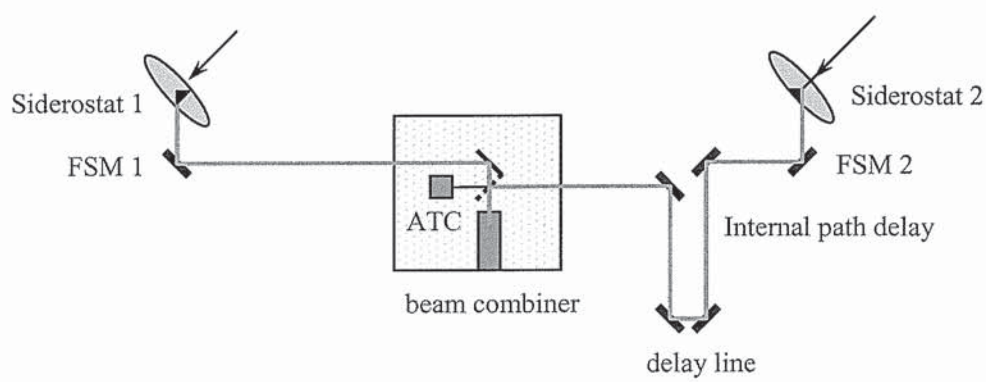

Figure 1.1 Pointing System for the Science Interferometer

2. SIM POINTING SYSTEM OVERVIEW

This section provides a brief overview of the pointing systems, their hardware and capabilities.

2.1 Pointing architecture

Figure 1.1 shows a schematic illustration of the science interferometer. The science interferometer has a 9 meter baseline. At the ends of the baseline, it has two steerable Siderostats (SID). The SIDs provide a 15 degree circular field of regard (FOR). In addition, it has two fast steering mirrors (FSM) to direct the collected and compressed star-lights into the astrometric beam combiner (ABC) where the two star-lights from each arm of the interferometer get interfered. The two guide interferometers (Fig. 1.2) are similarly equipped as the science except that they don't have the SIDs and they share the shorter baseline of 7.2m. Instead of the SIDs, the guide FSMs have a coarse stage that provides a FOR of 0.1×1.0 degree.

The main objective of the pointing system is to place the compressed star-lights from the two arms on the calibrated points of the angle camera, while rejecting internal structural jitter and ACS disturbances. When the star-lights are tightly controlled on the calibrated spots, then the desired interference can be assured. In addition to the main tracking function, the interferometer pointing system supports the following tasks: i) steer, search and find the target star, ii) identify and acquire the target star and iii) provide precision attitude estimates for feedforward functions and the spacecraft stabilization. In order to support the above functional requirements, the SIM instrument needs to provide a high precision pointing for line-of-sight stability (30 milli-arcseconds (1-σ, radial)) and minimize differential wavefront-tilt between the two interferometer arms (for each interfereometer) during observation periods that could be as long as 1 hour. To achieve such a high precision pointing stability requirement, a two stage approach is implemented:

- The Spacecraft Attitude Control System (ACS) points the spacecraft within the field of view of the instrument and brings the stability to 0.1 arcseconds (1-σ, radial), using the instrument as a fine guidance sensor.
- The Instrument Pointing Control System brings the stability to the desired performance of 30 milli-arcseconds.

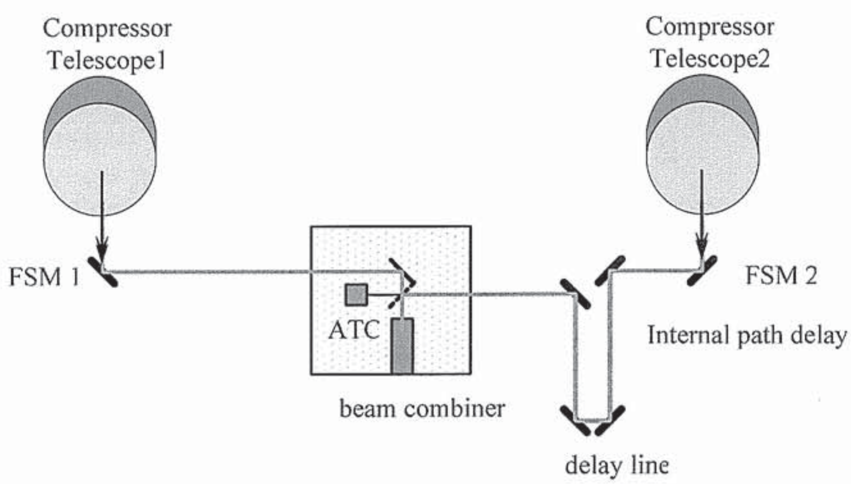

Figure 1.2 Pointing System for the Guide Interferometers

2.2 Main Pointing Requirements

The key pointing requirement demands that the starlight be stabilized to 0.03 as (1 σ, radial) over the tile duration for the guide interferometer and over science observations within a tile for the science target observation. This pointing requirement is relaxed for dim science targets (magnitude 15 and above). In such cases, the lack of photons reduces the effectiveness of the ATC feedback. In such cases, the science FSMs are controlled using an angle feed-forward signal estimated from the guide interferometers. However, thermal deformations during exposures introduce additional errors and require additional allocation depending on the star magnitude. The pointing control system that combines the camera feedback with the feedforward is explained in section five.

In addition to the pointing stability requirement, there is an additional driving requirement. A requirement on acquisition times to enable large numbers of science star observations. Interferometers have to acquire guide stars in less than five seconds or after two angle camera exposures for dim science targets. The acquisition approach is described in section three.

2.3 Spacecraft Attitude Control System (ACS)

The nominal pointing of the SIM instrument is performed by the spacecraft ACS. The spacecraft maneuvers via reaction wheels. It aim the instrument telescopes at their desired direction to roughly 25 arcsec (3σ). Once the spacecraft completes the maneuver, the spacecraft ACS uses the guide interferometer based fine attitude estimates to further stabilize the spacecraft. This stabilized orientation is maintained for up to about an hour or until when the science interferometer completes the observations. The spacecraft ACS has two star trackers and an IRU for attitude knowledge, and 6 reaction wheels for attitude control. The star trackers are mounted on the instrument to minimize thermo-mechanical drifts. In order to reduce the disturbance environment, the reaction wheels are mounted on isolators and operated within some wheel speed range. In addition, linear isolators are used at the interface between the spacecraft and the instrument to further reduce high frequency jitter transfer to the instrument.

2.4 Instrument Pointing Control System (PCS)

After the spacecraft completes a given attitude maneuver, the SIM instrument pointing system starts up by searching and acquiring the guide stars. Through the process of search, acquire and track, the pointing system transition from the 25arcsec, 3σ states to better than 0.09 arcsec 3σ conditions. The main objective of the instrument pointing system is to take out residual low frequency disturbances from the ACS (below 5 Hz). This requires the instrument pointing control system to have a closed loop bandwidth of about 12 Hz.

Fine Steering Mechanism (FSM)

The FSM is a three stage mechanism: fine, coarse, and retro. The fine stage has a range of motion of 100x100 arcsec in the sky with a required accuracy of 0.005 arcsec (1 σ). The coarse stage has a range of motion of 0.1x1 degree in the sky with an accuracy of 1 as (1 σ). The retro stage has one axis rotation and it is used for internal calibration of the instrument. Both the coarse and retro stages have brakes to hold them in position during science observations.

Siderostat (SID)

The siderostat (SID) is a two stage mechanism. The fine stage has a range of motion of 100x100 arcsec in the sky with an accuracy of 0.005 as (1 σ). The coarse stage provides a FOR of 15 degrees in the sky to an accuracy of 1 as (1 σ). The coarse stage has a brake to hold it in position during science observations.

Angle Track Camera (ATC) and Angle Image Processing (AIM).

The ATC employs a CCD frame transfer device with 80x80 pixels divided into 4 quadrants of 40x40 pixels. The ATC has the capability to provide multiple read options: full CCD read at a reduce rate (20 Hz) or windowed reads at faster rates (e.g., 8x8 pixel region at 500 Hz). The typical star image centroiding accuracies (for various incoming photo-electrons and location of the spot within a CCD pixel) are tabulated in Table 2.2. Note that near corner means within 15% of the cross hairs, the center corresponds to 70% and the other corresponds to the edges between corners. The pointing error is given in milli-arcseconds (1 σ, radial) and has two components: bias and random (denominated NEA, Noise Equivalent Angle).

Table 2.2: Sensitivity of AIM centroiding accuracy (milli-arcseconds, 1 σ radial)

	Near Corner			Center			Other		
	Bias	NEA	**Total**	Bias	NEA	**Total**	Bias	NEA	**Total**
1260 e	4.9	28.4	**28.8**	10	54.7	**55.7**	7.9	43.7	**44.4**
3150 e	2.9	16.4	**16.7**	5	29.7	**30.1**	4.2	24	**24.4**
6000 e	2.7	11.6	**11.9**	3.6	20.2	**20.5**	3.2	16.4	**16.8**

3. INSTRUMENT POINTING ACQUISITION

SIM science observations are divided into a grouping of stars called a tile. A tile is a collection of stars located within a circular area on the sky covered by the SID F.O.R. such that those stars can be observed without moving the spacecraft from a parked attitude. The acquisition process for each tile is done in two main phases:

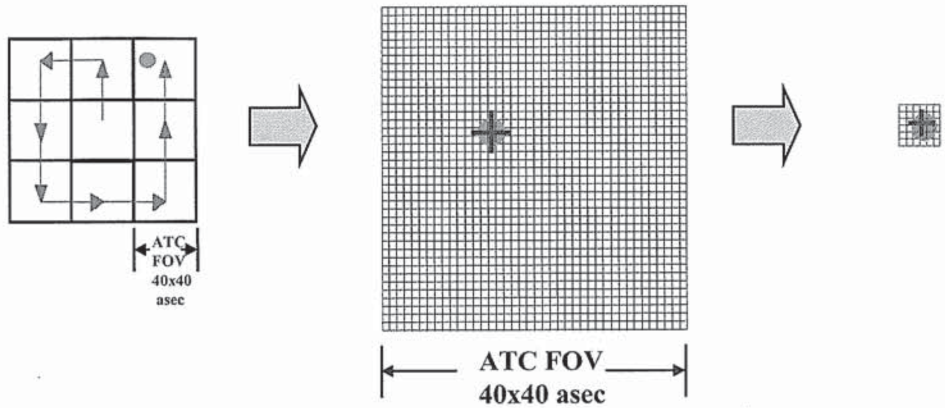

Figure 3.1 Guide interferometer search and acquisition. Figure depicts a 3x3 mosaic search, acquisition and transition to a 6x6 pixel window tracking mode in the Angle Track Camera. Not to scale.

- *Tile preparation phase:* This phase is entered right after the spacecraft terminates the ACS maneuver and parks into an attitude that supports the particular tile observations. During this phase, the pointing system performs acquisition for the guide stars. Both the science and guide pointing system acquires guide stars to allow alignment of the science pointing system with respect to the guides. While in the tile preparation phase, the spacecraft bus points the interferometer compressor telescopes to an accuracy of 25 as (3 σ) and the coarse stages of the FSM and SID are position at the pre-calculated positions associated with the target stars to an accuracy of about 1 as (3 σ). The resulting pointing error is in the order of 25 as (3 σ). Since the ATC has a FOV of 40x40 as, to cover a 50x50 as area will require performing a spiral search (depicted in Figure 3.1). Once the target stars are found the ATC is switch to a window mode and the FSM high rate loop is enabled. The FSM stabilize the star-light to 0.09 as (3 σ). Once all guide interferometers are tracking their respective guide stars, the instrument attitude estimator receives the measurements of the FSM fine stage angles and computes the attitude motion changes for the spacecraft ACS. These estimates are accurate to 0.09 as (3 σ). The spacecraft ACS uses these estimates to damp rates and stabilize the spacecraft bus to an accuracy of 0.3 as (3 σ) for the duration of the tile. Successful completion of this process allows the interferometer to enter the fringe search and detection process.
- *Retargeting phase:* Once the spacecraft ACS and the guide interferometers are stabilized to the required level, the science intereferometer starts the scheduled observations by sequences of SID maneuver and the follow up acquisitions. Each acquisition, stars with positioning the SID to the pre-computed location and the science FSMs to their home position to accuracies of about 1 as (3 σ). The FSM tracking loops are engaged using angle feed-forward (see section four for more detail) and the Science ATC exposure durations are setup to accumulate at least 1260 e-. The first centroid may have a degraded performance (~0.05 as 1 σ) since the center of the point spread function may fall more than 15% away from the cross hairs of four pixels. However, after an initial SID fine stage correction is performed the subsequent centroids will fall within 15% of the cross hairs of 4 pixels allowing to meet the desired accuracy of 0.03 as per exposure (vid. Table 2.2).

4. INSTRUMENT POINTING CONTROL SYSTEM

This section describes the Guide and Science Pointing Control Systems.

4.1 Guide Pointing Control

The objective of the Guide pointing control loop is to compensate for the spacecraft ACS residual pointing errors. The ACS residual acts as a disturbance with a magnitude of about 0.1 arcseconds (1 σ) and a spectrum between 0.005 and 5 Hz. The Guide pointing loop uses the ATC to measure the position of the star and the FSM to correct for pointing errors. A block diagram of the guide pointing loop is depicted in figure 4.1.

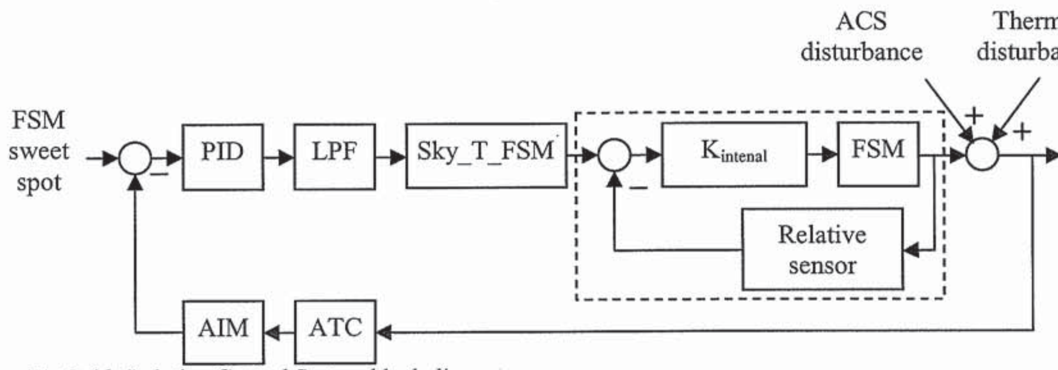

Figure 4.1. Guide Pointing Control System block diagram.

The elements of this block diagram are:

FSM sweet spot: Calibrated point that maximizes visibility
ATC: Angle Tracking Camera, it provides 8x8 pixel image at 500 Hz.
AIM: Angle Image Processing, it generates (u,v) centroids for every camera frame at 500Hz.
PID: 2-dim. PID controller in (u,v) coordinates (projected angles on the sky)
LPF: 2-dim. 2^{nd} order low pass filter in (u,v) coordinates
Sky_T_FMS: Transformation that maps control commands in (u,v) coordinates in the sky to FSM mechanical frame.
$K_{internal}$: Local controller to linearize FSM fine stage response with a closed-loop bandwidth of 125Hz.
FSM: FSM dynamics
Relative Sensor: position sensors used in the internal local loop.

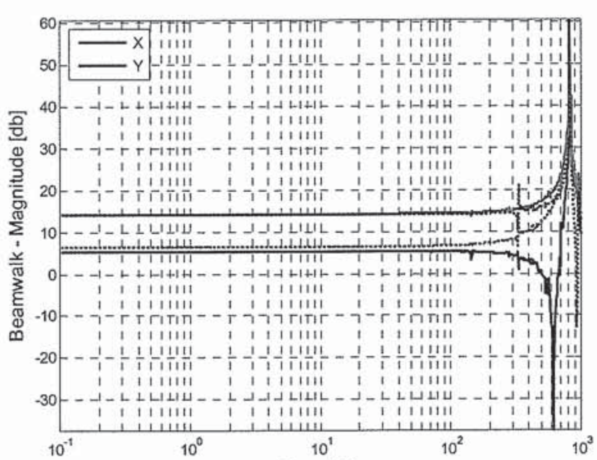

Figure 4.2 Bode plot of transfer function from FSM fine stage actuator to beamwalk in Science Angle Track Camera.

The current concept has the Guide pointing loop running at a 500 Hz. The Guide interferometer only observes bright stars (below visible magnitude 7). In such cases, the ATC can produce windowed frames at 500 Hz. The AIM process this frames and generates star centroid estimates. The FSM is also commanded at 500 Hz, but it has an equivalent open loop bandwidth of 125Hz. The FSM achieves such a large bandwidth with the use of momentum compensation and a local closed loop which uses a relative position sensor to linearize the actuator dynamics and roll-off high frequency jitter. Figure 4.2 shows the bode plot of the transfer function from one of the FSM fine stage actuators to the beamwalk in the Science Angle Track Camera. This transfer function has been extracted from a high fidelity integrated model[3]. It does not contain the internal control loop. The internal control loop with a closed loop bandwidth of 125Hz will roll-off the high frequency jitter.

The Pointing Controller reference signal is the denoted as the 'FSM sweet spot'. It corresponds to a calibrated set point that leads to maximum fringe visibility. The controller works in projected angles in the sky. The controller is made of a PID compensator and 2nd order low pass filter. The closed loop bandwidth is 12 Hz. This bandwidth is adequate to track the ACS disturbances below 5 Hz and noise reduction of the ATC-AIM sensor-measurement noise. Simulation results which illustrate this control system design are given in section 5.

4.2 Science Pointing Control

The science pointing system has two pointing control devices: A Siderostat collocated at the aperture and a Fine Steering Mirror collocated after the compressor optics. The siderostat provides a 15 degrees field of regard, whereas the FSM has a 0.1x1 degree field of regard. The siderostat function is for science target pointing and to compensate for thermo-mechanical drifts. The FSM function is to compensate for the ACS disturbance as in the Guide interferometers. Figure 4.3 shows a block diagram of the science pointing control system. It also includes the pointing control system for the Guide 1 interferometer because when observing dim science targets (V>10), the Guide 1 interferometer, which has a baseline almost parallel to the science interferometer, provides an Angle Feed-Forward command to the science FSM. With the current optical design it takes up to 120 seconds (V=19) to collect enough photons at the Science Angle Camera to produce reasonable centroids. Guide 1 AFF estimates are used to drive the Science Fine Steering Mirror, and Science ATC centroids are used to drive the SID to compensate for thermo-mechanical drifts. The AFF and ATC centroids are complementary filtered to achieve the desired performance.

The Science FSM's fine stage dynamic behavior is very similar to the Guide behavior described in the previous section. The Science Siderostat is a larger optic and its fine stage is not momentum compensated. It has a equivalent open loop bandwidth of 2 Hz. It also has a local control loop to linearize the fine stage actuators and to roll-off high frequency jitter. Figure 4.4 shows the bode plot of the transfer function from one of a SID fine stage actuator to beamwalk in the Science Angle Track Camera. It does not contain the actuator and local loop dynamics.

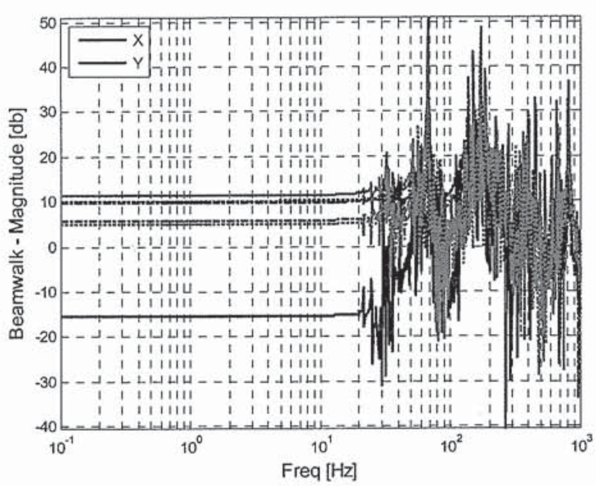

Figure 4.4 Bode plot of transfer function from Siderostat fine stage actuator to beamwalk in Science Angle Track Camera.

The Science pointing loops also runs at a sample rate of 500 Hz. The Science ATC runs at the needed rate to collect 1260 photons, which is the minimum number of photons needed to provide the necessary centroid accuracy (vid. Table 2.2). The centroid measurement signal gets complementary filtered to extract the thermo-mechanical component of the pointing error. This complementary low pass filter, CLPF, is located after the AIM and it is a two-pole low-pass filter with a frequency of 0.001 Hz. It extracts the thermo-mechanical drift component of the pointing error and feeds it to the SID controller, and sends the rest of the pointing error to the science FSM controller.

The FSM controller has another set of complementary filters to combine the information from the Angle Track Camera and AFF. This complementary filter has a different cut-off frequency for each star magnitude. This allows adding AFF information as needed to compensate for the ACS disturbances. However, when exposure gets over 20 milli-seconds the ACS motion which could have energy up to 5 Hz will produce centroids where the ACS motion got smeared over the exposure duration. In such cases, the FSM controller will be set to run in open loop and the complementary filter in the AFF path will be set to complement the SID complentary filter. The science FSM and SID controller have similar design as the Guide FSM controller. Simulation results which illustrate the science pointing performance are given in section 5.

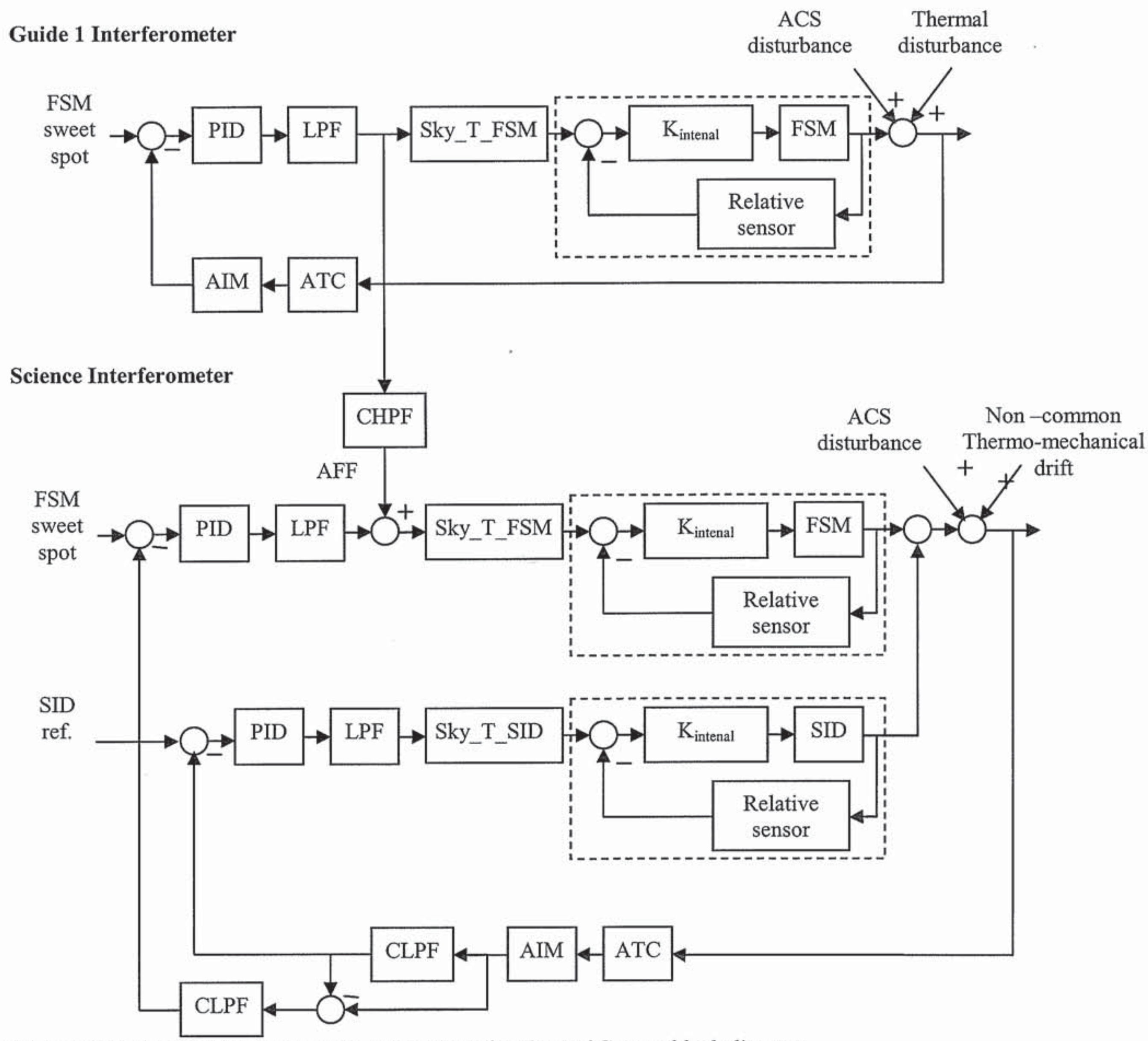

Figure 4.3 Guide 1 and Science Interferometers Pointing Control System block diagram.

The elements of this block diagram are:

FSM sweet spot: Calibrated point that maximizes visibility.

SID ref.: SID reference command.
ATC: Angle Tracking Camera, it provides 8x8 pixel image at 500 Hz at the Guide 1 interferometer and at as low as 0.0042Hz at the Science interferometer.
AIM: Angle Image Processing, it generates (u,v) centroids for every camera frame.
PID: 2-dim. PID controller in (u,v) coordinates (projected angles on the sky)
LPF: 2-dim. 2^{nd} order low pass filter in (u,v) coordinates
Sky_T_FMS: Transformation that maps control commands in (u,v) coordinates in the sky to FSM mechanical frame.
Sky_T_SID: Transformation that maps control commands in (u,v) coordinates in the sky to SID mechanical frame.
$K_{internal}$: Local controller to linearize FSM or SID fine stages response with a closed-loop bandwidth of 125Hz or 2Hz respectively.
FSM: FSM dynamics
SID: SID dynamics
Relative Sensor: Strain gauges or capacitative sensors used to closed the local loops.
CHPF: Complementary High Pass Filter
CLPF: Complementary Low Pass Filter

5. SIMULATION RESULTS

This section shows some preliminary simulation results which illustrate the Guide and Science pointing tracking control systems. The simulation results show the tracking performance of the Guide 1 interferometer, and the tracking performance of the Science interferometer while observing a dim star (V=15).

This simulation has been developed in the MATLAB-Simulink environment and includes a simplified optical configuration, kinematic models for the pointing mechanisms, actuator and sensor noise models with nonlinearities, disturbance models, and control algorithms.

Figure 5.1 shows the spacecraft ACS disturbance. This ACS disturbance is a prescribed trajectory that was obtained from realistic ACS simulations[4]. It meets the spacecraft pointing stability requirement of 100 milli-arcseconds (1 σ) for science observations. It also shows that it has energy within the spectrum of the ACS, which is 0.005-5 Hz. Figure 5.2 shows the Guide 1 interferometer ATC centroids. Figure 5.3 shows the Guide 1 FSM pointing commands projected in the sky. Since the Guide 1 is tracking the ACS disturbance, the FSM commands projected onto the sky are a mirror image of the ACS disturbance. Figure 5.4 shows the Guide 1 pointing error. This RMS of the pointing error is 7 milli-arcseconds. It satisfies the 14 milli-arcseconds (1 σ) pointing requirement.

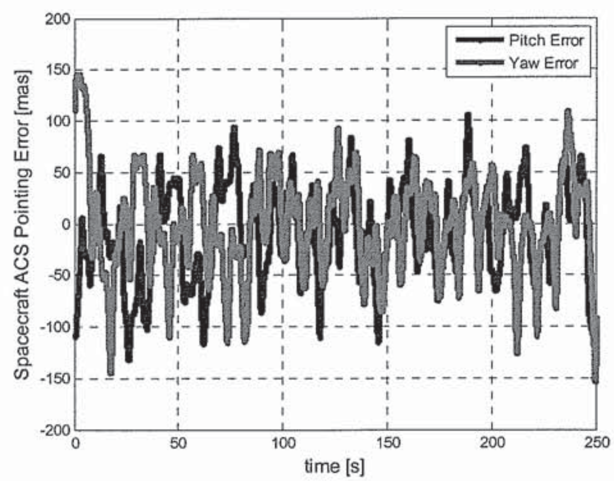

Figure. 5.1. Spacecraft Attitude Control System residual pointing error.

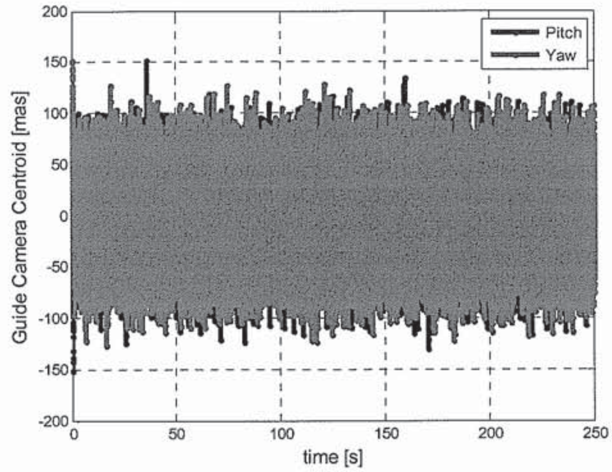

Figure 5.2 Guide 1 Angle Track Camera centroids

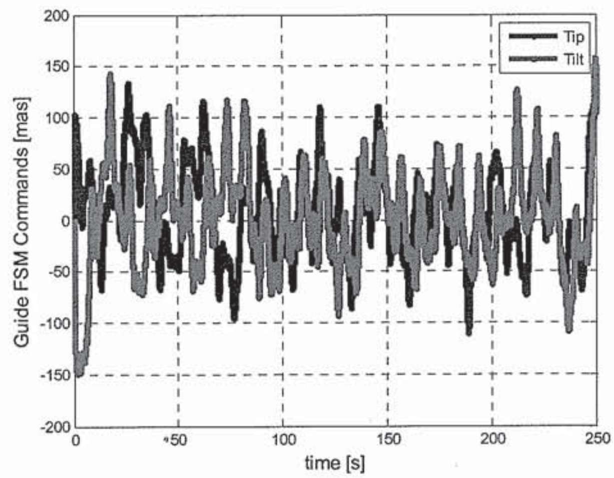

Figure 5.3 Guide 1 FSM pointing commands

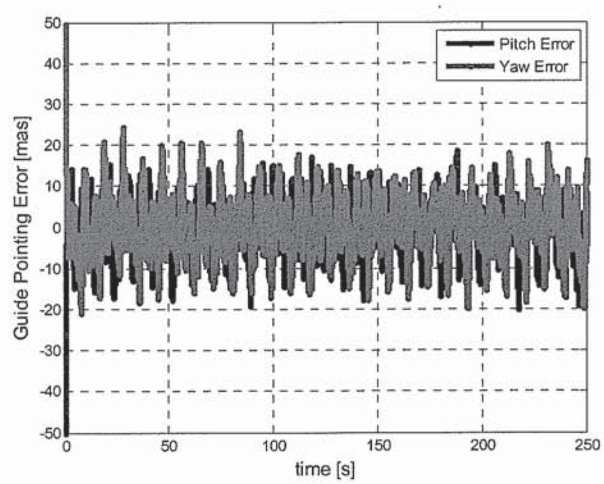

Figure 5.4 Guide 1 Interferometer pointing errors.

The simulation corresponds to a science observation of a dim star (visible magnitude V=15). As described in section 5, the pointing objectives are as follows: the Siderostat should track the thermo-mechanical drifts, while the FSM should tracks the ACS disturbances. Since we are observing a dim star, the science ATC is set to run at a 0.33 Hz frame rate and the AFF complementary filters is set to complement the ATC low-pass filter. Figure 5.5 shows the Science interferometer ATC centroids. Figure 5.6 shows the non-common thermo-mechanical drift. This is the drift that the Siderostat control system needs to correct. Figure 5.7 shows the Siderostat commands. To compensate for the drift the Siderostat commands should be a mirror image of the drift. We see that because of the smearing of the ATC images and time delays that the Siderostat tracks the thermo-mechanical disturbance with an error of less than 10 milli-arcseconds. Figure 5.8 shows the AFF to the science FSM loop. These signals correspond to the Guide 1 angle commands filtered by the high pass complementary filter and delay by one computational delay. Figure 5.9 shows the Science interferometer pointing errors. It includes the FSM control errors and the SID control errors. The error has an RMS of 14 milli-arcseconds, which meets the pointing requirement.

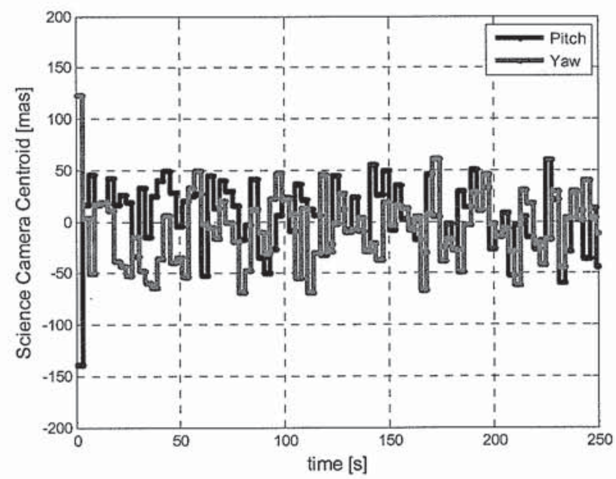

Figure 5.5 Science Angle Track Camera centroids

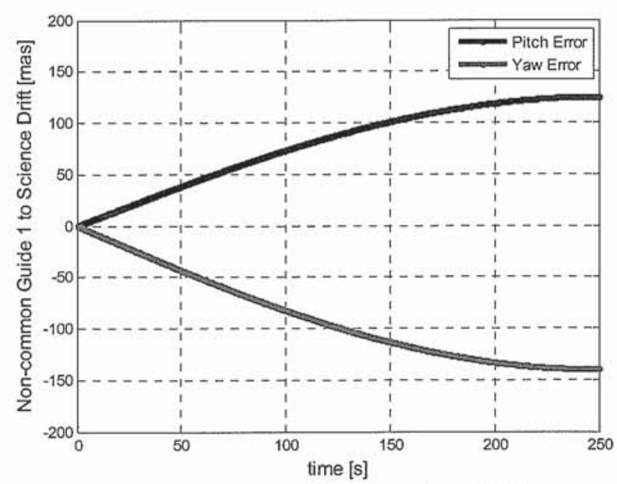

Figure 5.6 Guide 1 to Science Interferometer non-common thermo-mechanical drift.

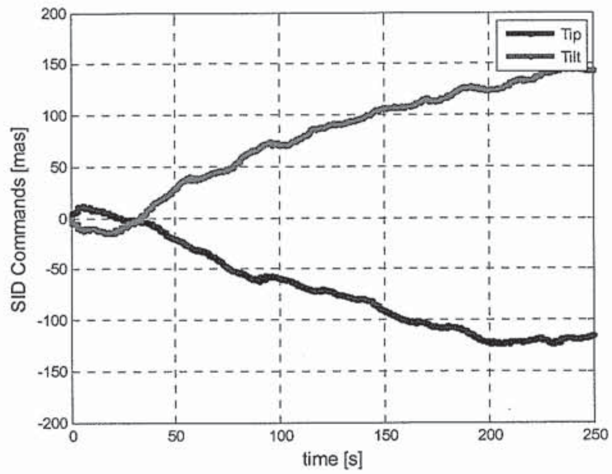

Figure 5.7 Science Siderostat commands.

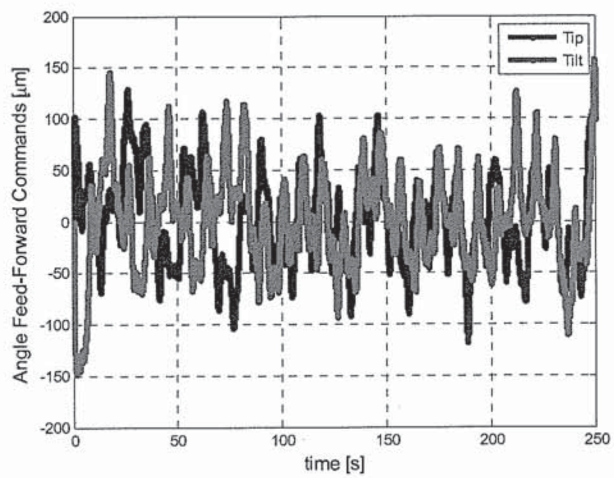

Figure 5.8 Guide 1 to Science Interferometer Angle Feed-Forward command

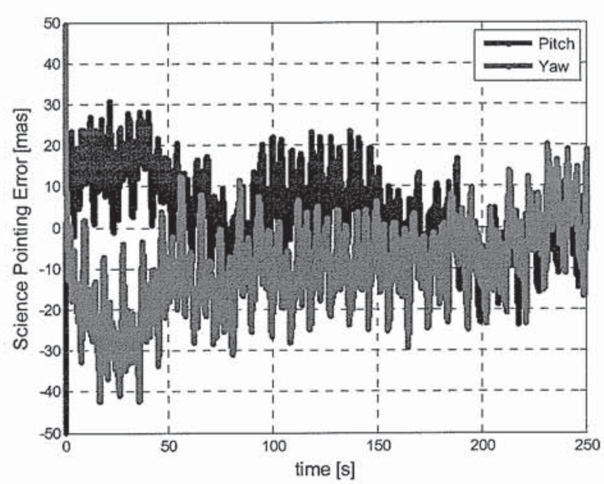

Figure 5.9 Science Interferometer pointing errors.

6. CONCLUSIONS

This paper discusses the high precision instrument pointing control system for the Stellar Interferometry Mission – Planet Quest. It briefly presents the pointing requirements, architecture, acquisition, and the capabilities of the pointing cameras and mirrors. It discusses the pointing control design for guide and science interferometers. It addresses pointing during science observations of dim stars, which are a challenge because of the reduced Angle Tracking Camera frame rate associated with observing dim stars. For such cases, the design includes an angle-feedforward implementation using complementary filters. The accuracy and feasibility of this approach is demonstrated by simulation.

ACKNOWLEDGMENTS

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

1. J.C. Marr IV, "Stellar Interferometry Mission – Plantet Quest progress report" SPIE Astronomical Telescopes and Instrumentation 2006, Orlando, FL, May 24-31, 2006.
2. R.A.Laskin, "Successful completion of Stellar Interferometry Mission – Plantet Quest technology" SPIE Astronomical Telescopes and Instrumentation 2006, Orlando, FL, May 24-31, 2006.
3. S. Sirlin, "Integrated Model Delivery to RTC, Model 1a" JPL Internal Document, March 20, 2006.
4. D.O'Connor, G. Neat, and R. Hejal, "ACS Pointing and Maneuvering Status" JPL Internal Document, Sim-lib file #98020. Nov. 29, 2004.