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DEEP-SPACE OPTICAL COMMUNICATIONS POINTING CONTROL DESIGN [*]

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This paper provides an overview of pointing control design for NASA's Deep Space Optical Communications (DSOC) system. DSOC is NASA's first deep-space laser communications system and includes both a ground system and a space terminal. This paper focus on the pointing control system design and related issues for the Flight Laser Transceiver (FLT), including its key subsystems and components that support the space terminal pointing and control, its operational concept and sequence design, and its control systems design and related analyses. The paper also provides an overview of the achievable system pointing performance that meets the DSOC pointing control design requirements.

INTRODUCTION

NASA has been developing space laser communication technologies to improve communications performance over RF based systems for many years now.[1,2] In particular, the purpose of the Deep Space Optical Communications (DSOC) flight demonstration project, led by NASA's Jet Propulsion Laboratory in Pasadena, California, is to develop and validate laser communications for deep space communications to support connectivity speeds needed for future human explorations of the solar system and to advance the support of future high-resolution scientific instruments, live-streaming of high-definition video and the use of virtual reality technology to remotely monitor and control machinery across deep space distances, with a capability of delivering information rates at least 10 times faster than conventional systems that use comparable mass and power.[3,4]

DSOC consists of a Flight Laser Transceiver (FLT) terminal and a ground system. The flight transceiver is scheduled to launch in 2022 on board NASA's Psyche spacecraft, set to study the giant metal asteroid known as "16 Psyche" in our solar system's main asteroid belt. As the Psyche spacecraft will travel to the asteroid belt, DSOC will have a chance to first test out NASA's deep space laser communications capability during the cruise phase of the Psyche mission. The DSOC ground system includes two ground stations: the Ground Laser Transmitter (GLT), located at JPL's Table Mountain Observatory (TMO) near Wrightwood in California, for transmitting the uplink laser signals to the FLT and the Ground Laser Receiver (GLR), located at Caltech's Palomar Observatory near San Diego in California, for receiving the downlink laser signals from the FLT.

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Compared to the near-earth cases, the deep space laser communication has its unique design challenges. As the communication distance increases, the received laser power becomes extremely limited at both ends of the communication link. This drives the pointing performance requirements for both the transmitting/receiving systems at both ends of the link. The precision pointing system of the DSOC FLT, which is the main focus of this paper, makes use of an accelerometer based active isolation system for the stabilization of the floating side of the terminal stabilization and uses the ground transmitted laser signal as a beacon for tracking and pointing purpose. At the same time, a set of relative position sensors are used to maintain a low bandwidth caging control loop in the non-pointing degrees-of-freedom (DOF) of the floating platform to prevent the floating side of the FLT from colliding with the stationary side of the FLT. In operation, the position control loop is used in conjunction with the uplink pointing direction knowledge, provided by Psyche's attitude control system in real-time (with the speed-of-light correction), to enable a spiral scan search pattern to find the laser beacon on the detector of a photon counting camera (PCC). Once the uplink laser beacon is acquired, the beacon is tracked via the closed-loop control of the uplink laser centroid on the PCC to support the uplink laser communication. At the same time, a separate downlink laser LOS control via a point-ahead mirror (PAM) on the stabilized floating platform to point the downlink laser at the GLR to support downlink laser communication. This paper describes the pointing system designs for the DSOC FLT, including topics related to the pointing control system architecture, components, operations, control design and stability analysis, and the achievable performance. The contents of this paper are based mainly on a set of DSOC pointing and control peer reviews and DSOC pointing and control Critical Design Review.[5,6]

The paper is organized as follows: Section 2 gives an overview of the DSOC uplink and downlink pointing system and the key optical and pointing components, as well as a high-level summary of the operational sequence design; Section 3 provides a more in-depth description of the key hardware components, including the sensors and the actuator, and the pointing control software (PCS) modules, used to support the pointing control system functionalities; Section 4 covers the dynamics models used in our analyses, the main control loops designs and analyses, and the stability results; Section 5 provided the detailed results of pointing control system performance in both frequency domain and time domain based on our analysis and simulation models; Finally, Section 6 provides some concluding remarks, current status and future work. Note that in this paper we are mainly concerned with the pointing control system design, and we shall leave topics such as system testing and operation experience to future papers.

POINTING SYSTEM ARCHITECTURE

There are two main requirements on the DSOC FLT pointing control system design: (1) The flight terminal shall acquire and detect uplink laser beacon via spatial search and initiate tracking of the beacon within certain time limit after receiving an uplink beacon signal that meets certain specified signal power and stability requirements; and (2) the flight terminal shall have downlink radial pointing jitter/bias performance as specified by the system level requirement documents under the influence of a set of specified host vehicle jitter profile defined at the interface location between the Psyche spacecraft and the DSOC FLT in order to support the DSOC downlink laser communication performance.

To support the DSOC FLT pointing control system operation, DSOC needs to have a ground system that transmits an uplink laser signal with the point-ahead angle correction and with enough power and stability to meet certain signal performance metrics at the FLT optical system entrance point at a long distance to support deep-space missions. For the flight terminal, DSOC relies on the Psyche spacecraft to point the FLT base to the GLT direction based on the real-time ephemeris information of the GLT and Psyche spacecraft. For this purpose, the Psyche spacecraft is required to maintain the guidance and control performance from Psyche's attitude control system and at the same time minimize the motion disturbance from ACS actuators to the base of the DSOC FLT. Most importantly, the FLT pointing control systems are critical in achieving the successful uplink beacon acquisition/tracking and downlink pointing performance.

System Description

The high level DSOC FLT system and its interactions with the DSOC ground system and the Psyche spacecraft are depicted in Figure 1.

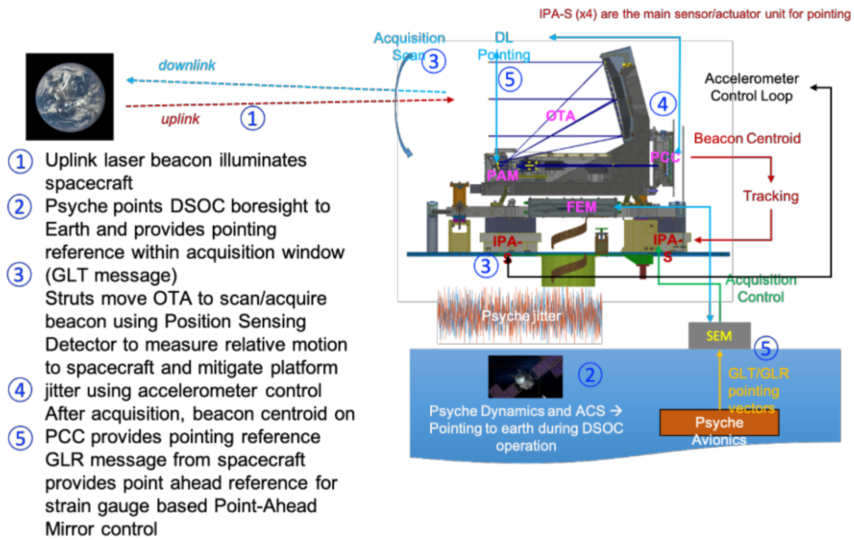

Figure 1. System Architecture of DSOC Flight Laser Transceiver with Key Components

Starting from the ground, we have the two ground stations GLT and GLR as mentioned before. The GLT hosts the uplink laser subsystem that generates and points the uplink laser. The uplink laser not only carries the communication information but also acts as the uplink laser beacon. The GLR is the laser receiver system that decodes the downlink laser signal from the FLT for communication purpose. It also provides laser power measurement capability to support the space-ground pointing calibration capability. The main components of the DSOC FLT are as follows:

- Isolation and Pointing Assembly - Struts (IPA-S): There are four identical IPA-S units that provides active isolation and pointing functions. Each of the IPA-S unit includes two accelerometers, a Position Sensor Diodes (PSD) that measures two-dimensional relative position offset, and a Lorentz Force Actuator (LFC) that provides control forces in two directions.

- Optical Transceiver Assembly (OTA): The OTA is the main optical assembly that consists of the primary mirror M1, the secondary mirror M2, a dichroic beam splitter, and a retro mirror, as well as the Point Ahead Mirror (PAM) that controls the downlink laser pointing direction.

- Photon Counting Camera (PCC): A single PCC provides photon counting capability for laser communication purpose. For pointing control, the PCC acts as the detector for the uplink laser beacon acquisition and tracking. The PCC is also used for downlink control to support the PAM strain gauge calibration.

- Stationary Electronic Module (SEM) and Floating Electronic Module (FEM): Those are the two main electronics boxes for the FLT. The SEM provides the necessary processing and software/firmware for the pointing control functionalities and interfaces to the sensors and actuator of the pointing control system. The FEM provides interface to the PAM and the PCC on the floating side of the FLT.

- Laser Transmitter Assembly (LTA): This unit generates the downlink laser signal.

General System Operation Concept

The sequence of the system level events for the DSOC space/ground systems is as follows: The ground laser transmitter at the GLT is controlled to point the uplink laser to the direction of the Psyche spacecraft with a point-ahead angle; The Psyche spacecraft uses the ephemeris information of both the Psyche spacecraft and the GLT to point the DSOC base on the Psyche spacecraft to the GLT direction and provides the pointing reference in the form of a line-of-sight (LOS) unit vector within acquisition time window; The IPA-S struts are controlled by the pointing control software to move the OAT to scan and acquire the uplink laser beacon using the PSDs to measure the relative motion of the floating platform relative to the FLT base (and the Psyche spacecraft). At the same time, a high-bandwidth accelerometer based control is mixed with the low bandwidth position control to mitigate the jitter motion of the floating platform; After a successful uplink laser beacon acquisition, the beacon centroid on the PCC provides the pointing reference required for the floating platform LOS control so that the floating platform in the two pointing DOFs is inertially stabilized against the uplink laser direction; Once the platform is stabilized, the GLR LOS message from the Psyche spacecraft is used, together with the uplink laser beacon LOS, to provides point ahead reference for strain gauge based Point-Ahead Mirror control of downlink laser pointing.

Pointing Control Operational Sequence

At the start of the DSOC operation, the Psyche spacecraft will send command to undock (or release the launch lock if it is the first time) the floating side of the DSOC FLT. Subsequently, the FLT is powered on and the DSOC pointing control is enabled by the DSOC FLT flight software after the initial checkup of the FLT is done. After the DSOC FLT pointing control is enabled, the PCS normal sequence of submodes are executed autonomously as follows:

- CENTER PLATFORM: In this submode, the pointing control system uses the PSDs together with the accelerometers within the IPA struts to move the floating platform to the ”center” position in the 6DOF sense, away from all the physical constraints imposed by the launch locks and the motion cages.

- MOVE PAM: In this submode, to prepare for the scanning of the uplink laser beacon, the PAM, which controls the downlink laser pointing direction as well as the retro laser centroid on the PCC, is moved such that the retro laser spot is out of the PCC detector to avoid any possible interference with the detected uplink laser beacon centroid on the PCC.

- SCAN FOR BEACON: In this submode, the IPA struts are controlled so that the tip/tilt angles of the uplink boresight of the OTA is performing either a square or circular spiral scan pattern to find the uplink laser beacon on the PCC. The sensors used in the pointing control in this submode are PSDs and the accelerometers inside the IPA struts.

- WALK BEACON: In this submode, after the beacon is initially detected by the PCC, the IPA struts are controlled to further move the beacon spot to a pre-selected location on the PCC detector. For the LOS tip/tilt control, the control sensor used is now the PCC which provides the detected uplink laser spot centroid location on the PCC. For motion DOFs other than the tip/tilt, the PSDs, together with the accelerometers, are still used to cage the motion of the floating platform.

- TRACK BEACON: In this submode, the pointing control system maintains the uplink laser beacon centroid at the selected location on the PCC using the same mixed PCC and PSDs based control as in the case of the WALK BEACON submode, with the exception that in this submode, the fine PCC centroiding mode, which is based on a 2-by-2 pixels window instead of a global search of the 3-by-3 pixels window with the maximum detected laser power, is used.

- TRACK BEACON AND DL: In this submode, the floating platform pointing control remains tracking the uplink laser beacon as in the last submode. At the same time, the PAM is controlled such that the downlink laser LOS is pointing to the direction specified by the point-ahead angle. This is the fully operational submode in which the full two-way laser communications become possible.

- DL POINTING CAL: In this submode, the floating platform pointing control remains tracking the uplink laser beacon as in the last submode. However, the PAM in this submode is controlled such that the downlink laser LOS is pointing to a set of predetermined directions around the point-ahead angle direction, with the purpose of projecting the downlink laser power at the close vicinity of the GLR direction so that the received power can be measured at the GLR. These power measurements are then used for the space-ground pointing calibration and the estimated downlink pointing corrections are eventually uploaded to the DSOC FLT for future downlink pointing corrections.

In addition to the main pointing control operational submode, the FLT provides some other diagnostic submodes for testings, model identifications, and other diagnostic activities. The main operational sequence and switch logics are shown in Figure 2.

Interface Requirement & Control Document (IRCD) Jitter

One of the main challenges of the DSOC FLT pointing control design is to reject the disturbance from the Psyche spacecraft. For the disturbance rejection requirement purpose, a set of jitter profiles is provided to limit the allowable jitter at the Psyche/DSOC interface point. The profiles are given in terms of jitter motion power spectral density for translational and rotational motions at the interface and are shown in Figure 3.

Laser Beacon Acquisition Region

If there is no error in the system, the Psyche spacecraft provided GLT LOS should point the FLT optical boresight to the GLT direction. Various errors in the system make the uplink LOS knowledge not represent the true direction of the required pointing, thus resulting the need for the uplink laser beacon acquisition process. Figure 4 shows a pictorial description of the control errors and the knowledge errors of the DSOC FLT uplink LOS pointing, as well as the required acquisition circle.

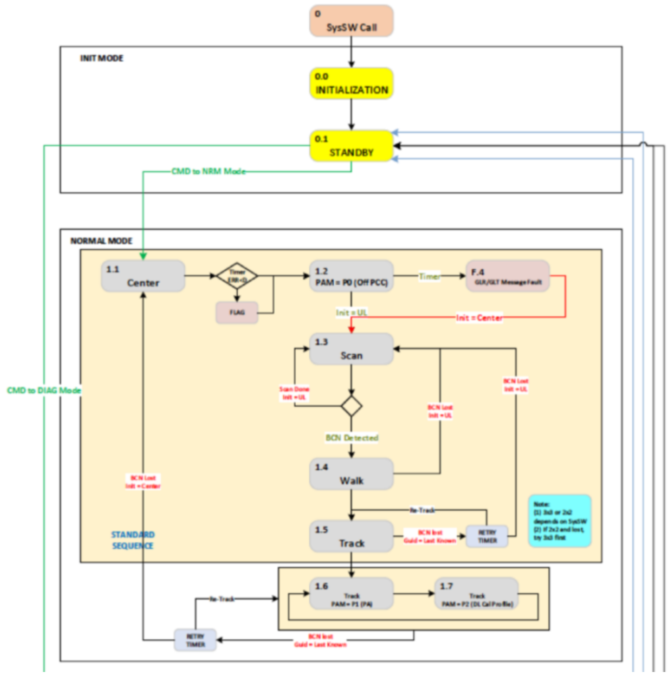

Figure 2. Operational Sequence Diagram of DSOC FLT

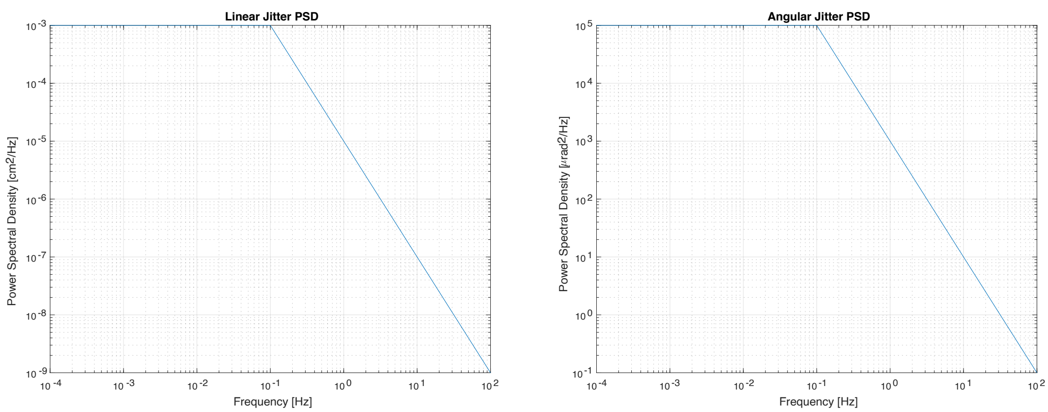

Figure 3. Translational and Rotational Interface Motion Jitter Power Spectral Density Profiles

POINTING CONTROL HARDWARE AND SOFTWARE

The pointing control system of the DSOC FLT mainly relies on the IPA-S, the PCC, the PAM and the control software/firmware to achieve both the uplink and the downlink pointing performance. The following subsections shall describe the key component of the pointing system and the main error sources associated with those components, as well as the approaches to minimize the errors at the individual component levels.

Optical Transceiver Assembly

The OTA is the optical subsystem of the FLT and consists of the M1-M4 mirrors, the dichroic beam splitter, the retro mirror, and the PAM. A simplified optical diagram is shown in Figure 5.

As shown in Figure 5, the uplink laser passes though the M1/M2 and the dichroic beam splitter and then though the M3/M4 (not shown) and is projected onto the focal plane array (FPA) of the PCC. The downlink laser is reflected by the PAM and is then split into two beams: the downlink beam gets reflected by the dichroic mirror and then passes the M2/M1 toward the GLR on the ground while a small portion of the laser energy passes though the dichroic beam splitter and is

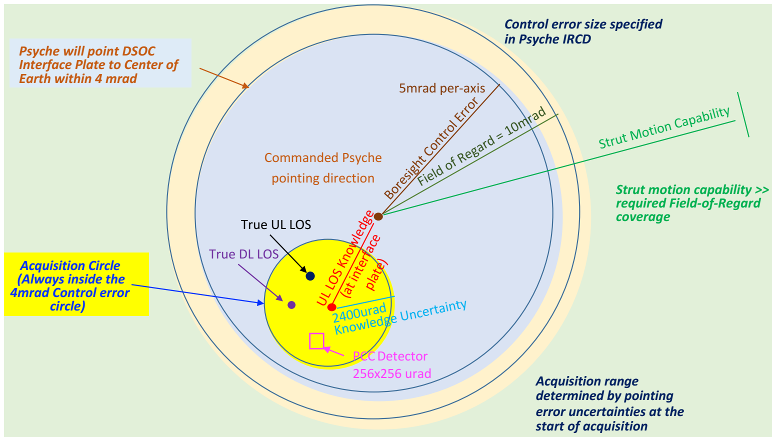

Figure 4. Pointing Uncertainties Associated with Initial Uplink Beacon Acquisition

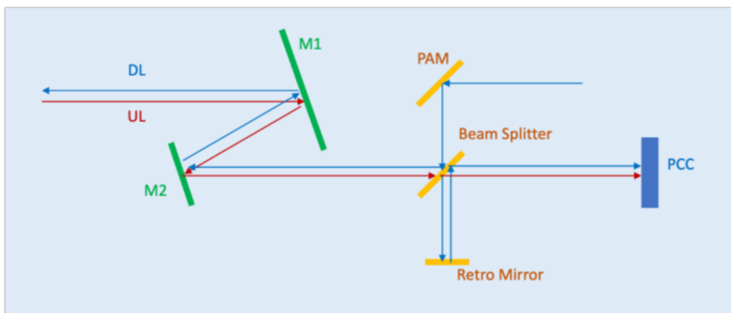

Figure 5. Flight Terminal Optical Transceiver Assembly

subsequently reflected by the retro mirror and the dichroic mirror and then passes the M3/M4 and is eventually also projected on the FPA of the PCC. Clearly, the point-ahead mirror can be steered to control the downlink laser pointing direction, as well as the retro laser spot on the PCC. All the alignment errors of the optical components of the OTA can cause pointing error in both the uplink and the downlink directions. However, the optical system calibrations are used to reduce the raw errors to the calibration residuals which need to be absorbed by the system pointing error budget or further improved by the system level space/ground calibration planned for in-space operation.

IPA-S and Inertially Stabilized Platform

The four IPA struts provide the main pointing control actuators and the key sensors for inertially stabilizing the floating platform, consisting of the OTA, PAM, FEM, and other components of the FLT, and are a critical part of the DSOC FLT pointing control system. The IPA struts control consists of a fast inner control loop based on the embedded accelerometer measurements and a slower position control loop based on the beacon centroid on the PCC and the relative position measurements from the embedded PSDs. In the operation, only 3 out of the 4 available IPA struts are used at any given time to provide the control. Figure 6 shows the IPA struts as part of the FLT one the left and a single IPA strut unit on the right.

The strut has three main components: the Lorentz force actuator employs a pair of magnets on the floating side that provide a permanent magnetic field. A pair of coil windings placed within the magnetic field can be controlled with varying currents. The control currents in the two windings interact with the magnetic field to provide control forces in the two orthogonal (horizontal and

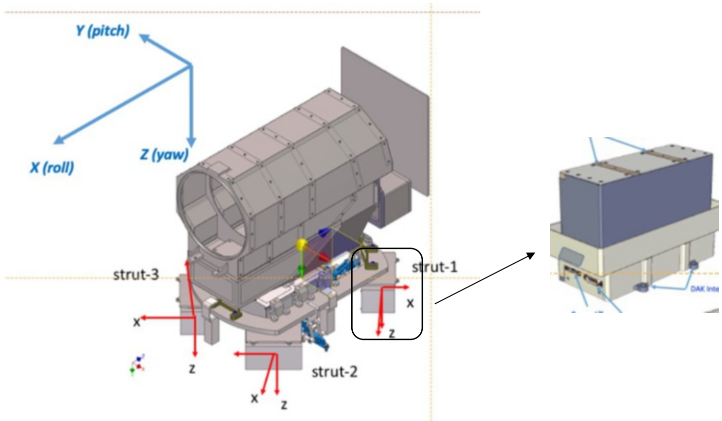

Figure 6. Isolation and Pointing Strut (IPA-S) and Their Placement on DSOC FLT

vertical) control directions, which are shown in Figure 6 on the struts as parallel to the Y-axis and the Z-axis. For sensing, a single PSD consists of a laser diode on the floating side that projects a low-power laser onto a two-dimensional detector on the stationary side, with the centroid of the laser on the detector providing a reading of the horizontal and vertical rEq. (elative positions between the floating side laser and the stationary side detector at the local strut PSD location. A pair of high-precision/low noise accelerometers on the floating side provides the inertial motion reference in the horizontal and vertical control directions for the direct acceleration feedback control.

The four IPA struts are placed in a daisy-chain pattern with each providing two-dimensional sensing and control. When the three out of the four IPA struts are used, they provide six individually controllable actuators. These six individual controls from the three IPA struts result in the full desired 6DOF floating platform body motion control via a geometric mapping. As a matter of fact, the desired pose (6DOF motion) can be computed uniquely from the desired delta PSD values from a known pose (such as a GSE-fixed pose for ground survey of 6DOF pose of floating platform relative to base) and vice versa. Note that the PSD deltas for each individual strut for the known pose are determined before launch and the "center" pose can be determined by the required delta PSD values based on the strut selection configuration (123, 124, 134, or 234). In mathematic terms, denote the F-Frame as the coordinate frame attached to the floating platform at any given time and the L-Frame as the F-Frame at the time when the floating platform is fixed by the GSE on the factory floor and denote the GSE-fixed platform position relative to the FLT base frame as ${}^{B}\Delta_{LB}$, the direction cosine matrix from the base frame to the L-Frame as C_{LB}, and the corresponding PSD measurements at the GSE-fixed pose as $psd_{h,i}$ and $psd_{v,i}$, $i = 1, 2, ..., 8$. If the delta PSD readings from those at the GSE-fixed pose are $\Delta psd_{h,i}$ and $\Delta psd_{v,i}$ for the three IPA struts of a particular strut configuration, the new 6DOF pose can be related to the GSE-fixed pose using the delta PSD readings as follows (using strut configuration 123 as an example):

$$\begin{cases} \Delta psd_{h,1} = [u'_{h1}][{}^{B}\Delta_{FL}] + [u'_{h1}](C_{BF} - C_{BL})[r_{l,1}] \\ \Delta psd_{v,1} = [u'_{v1}][{}^{B}\Delta_{FL}] + [u'_{v1}](C_{BF} - C_{BL})[r_{l,1}] \\ \Delta psd_{h,2} = [u'_{h2}][{}^{B}\Delta_{FL}] + [u'_{h2}](C_{BF} - C_{BL})[r_{l,2}] \\ \Delta psd_{v,2} = [u'_{v2}][{}^{B}\Delta_{FL}] + [u'_{v2}](C_{BF} - C_{BL})[r_{l,2}] \\ \Delta psd_{h,3} = [u'_{h3}][{}^{B}\Delta_{FL}] + [u'_{h3}](C_{BF} - C_{BL})[r_{l,3}] \\ \Delta psd_{v,3} = [u'_{v3}][{}^{B}\Delta_{FL}] + [u'_{v3}](C_{BF} - C_{BL})[r_{l,3}] \end{cases} \tag{1}$$

where u_{hi} and u_{vi} are direction cosines of the PSD sensing axes for the i-th strut in the base frame and $r_{l,i}$ are the position vector of the PSD laser diode of the i-th strut relative to the floating platform center of mass. Eq. (1) can be used to derive the pose measurements from the delta PSD measurements. Conversely, it can be used to determine the desired delta PSD given the desired delta pose from the GSE-fixed reference pose. For instance, the Center submode pointing control guidance can be calculated as

$$^B\Delta_{FB,guid} = {}^B\Delta_{FL} + {}^B\Delta_{LB}$$

for the translational DOFs of the floating platform relative to the base while the rotational DOFs guidance given by either quaternions or roll, pitch and yaw Euler angles can be calculated from the solution of C_{BF} from Eq. Eq. (1), either by small-angle approximation or by iterative nonlinear equation solvers.

The accelerometer noises, the PSD noises and the LFA noises are the pointing error contributors we need to consider. The sensor/actuator alignment errors also need to be considered in the pointing performance analyses.

Photon Counting Camera

As easily seen from Figure 5, the Photon Counting Camera can capture both the uplink beacon centroid and the downlink retro laser centroid if the PAM angles are in the range. The main functionalities of the PCC are to provide the uplink laser beacon detection and the uplink laser signal photon counting capability for the uplink communication purpose. In addition, as the downlink laser is also retro projected onto the PCC, the PCC can potentially be used to control downlink laser centroid to support the PAM strain gauge calibration against the PCC.

The PCC has a 32-by-32 pixels FPA with an 8 μrad pitch angle. The main outputs from the PCC for pointing purpose are the three sets of centroid measurements. For the uplink laser beacon acquisition purpose, all the possible 3-by-3 pixels sub-windows are integrated and a centroid is calculated using the 3-by-3 pixels sub-window with the maximal power and meeting certain signal power and noise conditions. For the uplink laser beacon tracking purpose, a directed 2-by-2 pixels sub-window is used to generate the fine centroid. For the downlink retro laser, a directed 2-by-2 pixels sub-window is also used to generate the downlink retro laser centroid.

For the DSOC FLT design, as the size of the PCC detector is rather limited, the potentially large point-ahead (PA) angles required for the DSOC FLT downlink pointing to the GLR can make the retro spot centroid go off the PCC detector. For this reason, the PAM strain gauges, rather than the PCC retro centroid, are the main measurements used for the downlink pointing control, while the PCC is only used periodically to calibrate the strain gauges against the PCC centroid positions using the following linear model:

$$\begin{bmatrix} v_{sgx} \\ v_{sgy} \end{bmatrix} = \begin{bmatrix} m_{sg,11} & m_{sg,12} \\ m_{sg,21} & m_{sg,22} \end{bmatrix} \begin{bmatrix} x_{pcc} \\ y_{pcc} \end{bmatrix} + \begin{bmatrix} b_{sg,1} \\ b_{sg,2} \end{bmatrix} \equiv M_{sg/pcc} \begin{bmatrix} x_{pcc} \\ y_{pcc} \end{bmatrix} + B_{sg/pcc} \tag{2}$$

where v_{sgx} and v_{sgy} are the strain gauge voltages corresponding to the pitch and yaw angles of the downlink LOS in the floating platform frame, x_{pcc} and y_{pcc} are the downlink retro centroid pixel location on the PCC corresponding to the downlink LOS. For the PAM strain gauge calibration, a set of pre-selected crosshairs (defined as the center of the four adjacent pixels) are used as commanded pixel locations and the PAM is controlled to put the retro laser on those crosshairs using the PCC centroid feedback.

The main error contributor from the PCC is the PCC detection noise. The noise size is mainly a function of the received laser power, the distance from the ground (for uplink) and the pointing error coherence time. Analysis models and tests are used to characterize the PCC noise. The PCC noise is a large contributor to the uplink tracking error for the DSOC FLT and as such is also a large contributor to the downlink pointing error.

Point-Ahead Mirror

The PAM is a two-axis fast-steering mirror that is used to control the downlink LOS. Each axis of the PAM employs a pair of piezo actuators to provide the required angular motion with a pair of dedicated strain gauges to provide the angular measurements. Figure 7 shows the conceptual PAM.

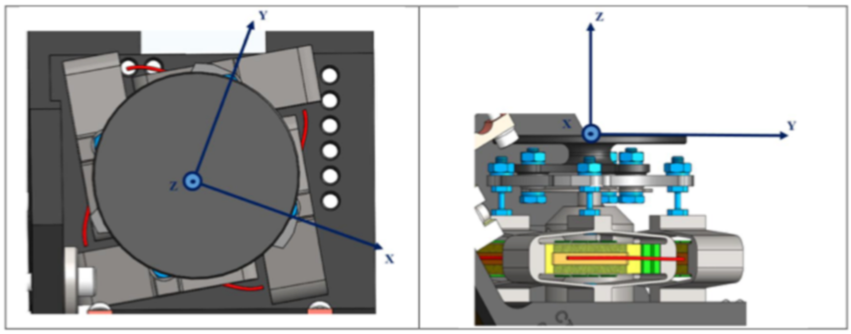

Figure 7. Point-Ahead Mirror

Errors in the PAM can directly impact the downlink pointing accuracy. Those errors include the strain gauge reference voltage errors and processing errors and the piezo actuator hysteresis, as well as the mechanical thermal distortions. Various calibration schemes are used to reduce the effect the thermally dependent errors and a possible compensation of the piezo actuators hysteresis on top of the strain gauge based closed-loop control is also studied and reported.[7]

Pointing Control Software (PCS)

The PCS is part of the DSOC flight system Operational Software (OpSW). In the DSOC FLT operation, the PCS is called by OpSW at a 60Hz interrupt frequency and relies on the shared memory to exchange information with OpSW. This includes inputs from the hardware, outputs to the hardware, other dynamic variables generated and/or propagated by the PCS, and parameters used by the PCS. The information exchange is facilitated by a data structure for the PCS variables and a separate data structure for the parameters, both of which are defined by the PCS/OpSW Interface Control Document (ICD), and are accessible by two pointers from either the PCS or OpSW side.

Within PCS, the PCS Mode Commander controls the execution of the PCS based on a limited set of commands from OpSW and the autonomous switching logics. Depending on the current mode that the PCS is operating in, the Mode Commander calls a sequence of autonomously switched submode executives to perform the various pointing control tasks required by that mode. A pointing control executive typically calls the guidance, measurement, and control methods to complete the tasks defined for the submode. The PCS telemetry is provided to OpSW which manages the telemetry to the ground via the Psyche spacecraft using the shared memory. The top-level PCS structure diagram is shown in Figure 8.

For the floating platform control, the PCS takes the relative position measurements from the PSDs embedded in the struts and the centroid measurements from the PCC to compute the control signals in terms of the required acceleration in the directions of the local LFA actuation axes. The

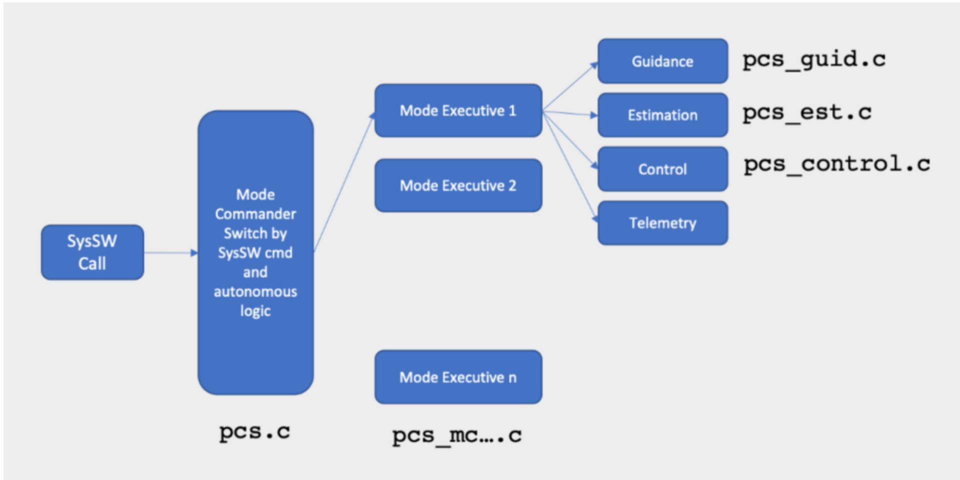

Figure 8. PCS Software Execution Diagram

local acceleration commands are then sent to the three operating struts to become the reference commands for the local accelerometer control loops. For the downlink control, the PCS takes the tip/tilt measurements from the PAM strain gauges to compute the control signals in terms of the required PAM piezo-drive voltages and send the voltages commands to the FEM to move the PAM in the desired directions. In addition to interfacing with the necessary sensor and actuator hardware, the PCS also takes in the guidance commands originated from the Psyche spacecraft at an 8Hz sampling rate to assist the uplink laser beacon acquisition process, as well as other commands originated from OpSW. It also provides telemetry points as part of the dynamic variable data structure, including several PCS execution fault flags. The main PCS interface diagram is shown in Figure 9.

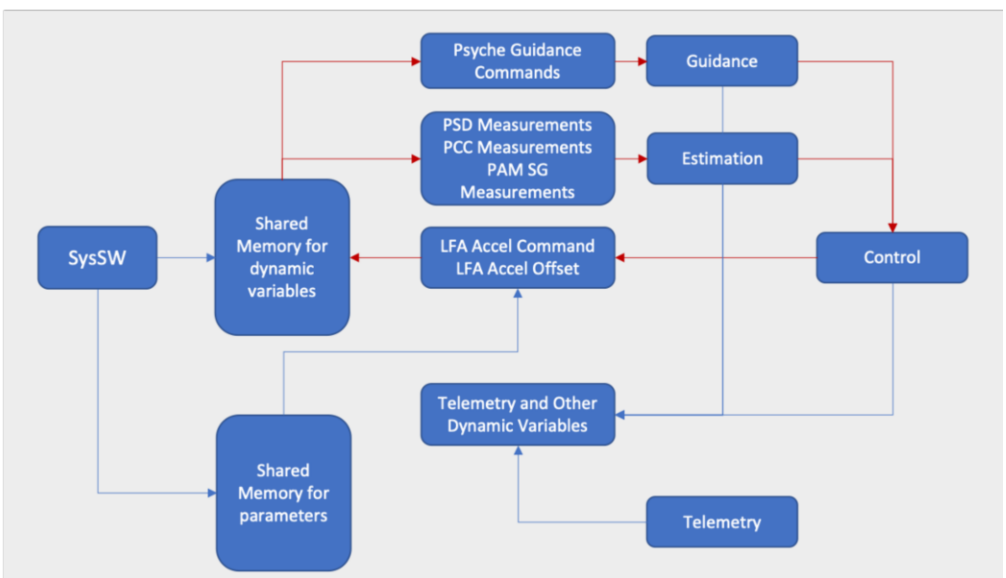

Figure 9. PCS Software Interface Diagram

CONTROL DESIGN AND PERFORMANCE

The DSOC pointing control tasks are divided into two parts: (1) the floating platform control that supports the operations of centering, scan, walk and tracking control and (2) the downlink LOS control using the PAM. As the mass and the inertia of the PAM is extremely small as compared to the floating platform, the two control systems are designed and analyzed as two decoupled control systems. However, as we shall see later, the time domain performance simulation uses a model that includes both systems. The entire DSOC FLT control system diagram with a very simplified Psyche ACS loop is shown in Figure 10.

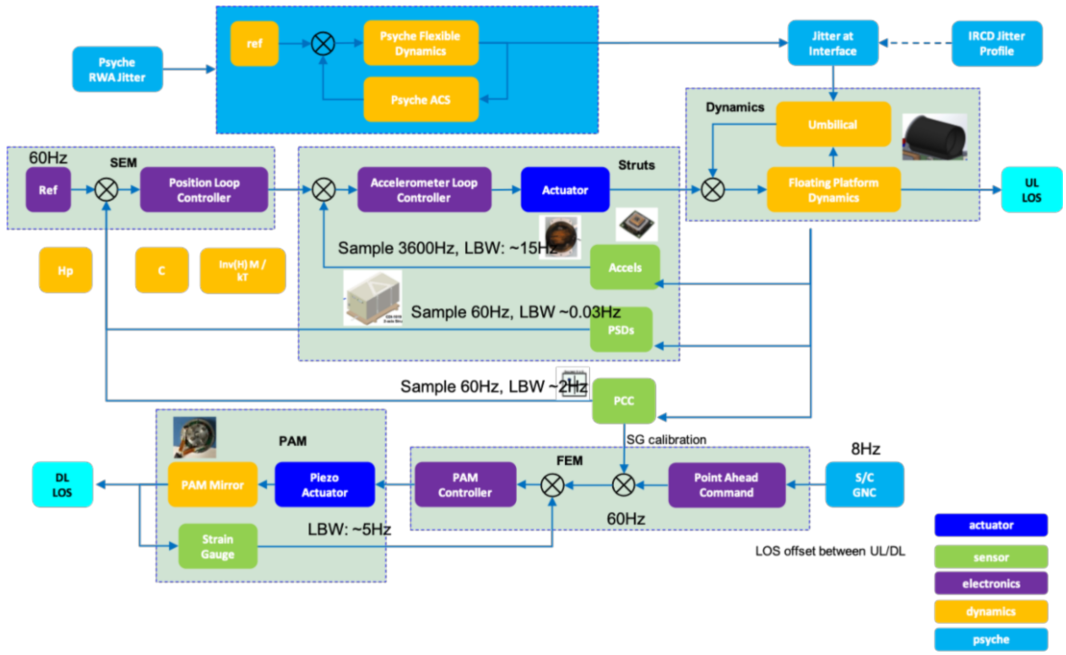

Figure 10. DSOC Platform Control and Downlink LOS Control Diagram

Floating Platform Control

The floating platform control includes a fast accelerometer based inner loop and a position sensor and/or the PCC based position loop, as shown in the middle portion of Figure 10. The accelerometer loops employ a set of high bandwidth and low noise accelerometers to provide the direct acceleration feedback control locally at the IPA struts location to reject mid- to high-frequency motion jitters of the floating platform. The outer loop consists of two switchable slower position control loops, one based on the PSDs embedded in the struts to provide the relative position control and to support the floating platform LOS search motion for the uplink laser beacon acquisition, and the other based on the mix of the PSDs and the PCC to provide the uplink laser beacon tracking control. In the tracking control phase, the floating platform's LOS motion in the tip/tilt directions are directly controlled using the measured uplink beacon centroid position from the PCC, while the other 4DOFs of the motion are controlled by the PSDs.

The guidance for the floating platform LOS control is provided by the Psyche spacecraft based on the real-time ephemeris information of the GLT and the Psyche spacecraft, corrected by the speed-of-light correction to account for the uplink laser traveling from the GLT to the DSOC FLT. The guidance information for the uplink control is provided to the DSOC FLT at the frequency of 8Hz. For the downlink laser LOS control, the GLR pointing direction (corrected by the point-ahead angle) is also provided by the Psyche spacecraft, together with the uplink laser beacon direction information. Both the uplink and downlink guidance commands are provided in the form of pointing direction unit vectors and unit vector velocities given in the DSOC FLT base coordinate frame defined at the Psyche/DSOC mechanical interface plate.

For the uplink laser beacon acquisition, the floating platform is controlled to perform a two-dimensional spiral scan in the platform's tip/tilt directions with the Psyche spacecraft provided uplink laser beacon direction as the starting pointing direction, while the other four non-pointing motion DOFs of the floating platform are loosely controlled to avoid collision with the stationary side of the FLT. Once the uplink laser beacon is detected by the PCC, the PSDs based acquisition control is switched to a mixed PSDs and the coarse PCC centroid based control to perform the walk operation that moves the beacon to a pre-selected PCC detector pixel crosshair location. If the detected beacon centroid at the chosen pixel location passes certain persistence checks, the walk phase is switched to the beacon tracking control using the fine mode of the PCC based on the measured centroid from the 2-by-2 pixels window around the pre-selected crosshair pixel location. The floating platform tracking mode is when the downlink LOS control can be carried out.

Downlink LOS Control

The DSOC FLT downlink LOS control aims to point the downlink laser at the GLR. The downlink LOS control guidance is computed based on the known offset between the uplink and downlink LOS unit vectors provided by the Psyche spacecraft, corrected by the detected true uplink LOS direction derived from the PCC centroid measurement. Since the downlink LOS is not directly measurable in object space, the control measurements are provided by the PAM strain gauges. The correlation between the strain gauge readings and the true downlink LOS in the floating platform frame through various calibrations at factory and in-space guarantees that the strain gauge based control can project the downlink laser in the desired LOS direction. The control of the PAM is through four piezo actuators with a relatively low bandwidth controller.

CONTROL LOOPS DESIGNS

In this section, we summarize the control designs for the floating platform. We will start with the discussion of the methodology for the control system design, followed by the description of the modeling of dynamics and the major components of the system. We will also address the system stability consideration and stability margins of the closed-loop system.

Integrated System Analysis Methodology

The DSOC FLT control system design problem was originally treated as a standalone control design problem, independent from the possible host-vehicle dynamics and its attitude control system. The interface to the host-vehicle is simply captured by the translation and rotational motion jitter power spectral density profiles defined shown in Figure 3. These jitter profiles were chosen to encompass the various motion jitters profiles exhibited by a large set of spacecrafts and are used to define the standard disturbance rejection requirement to test out a particular laser communication terminal's disturbance rejection capability. The broadband nature of the jitter profiles in Figure 3, however, can make the requirements rather conservative as they can drive an unnecessarily difficult control design problem. For DSOC's first flight, with the Psyche spacecraft selected as the host spacecraft for the DSOC FLT, we consider several different approaches to address the disturbance rejection problem, with varying levels of conservatism.

The simplest case for the control design analyses is when the DSOC FLT is treated as a rigid body and no host-vehicle dynamics is considered. In this case, the jitter is fully characterized as prescribed 6DOF motions described by the power spectral density profiles in Figure 3. This model is used for the preliminary control design and performance evaluation purpose.

To further evaluate the system performance, flexible dynamics of the DSOC flight terminal is used. To see the interaction of the jitter source and flexible dynamics of the DSOC terminal and the pointing performance, three types of the analysis methodologies are used. Figure 11 shows the three cases of the jitter and system modeling approaches.

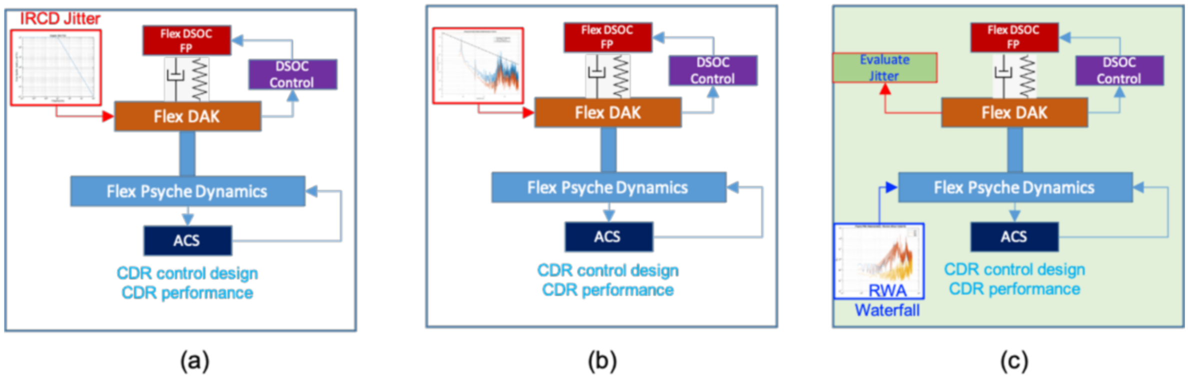

Figure 11. DSOC Platform Modeled as Flexible Body - Three Cases to Evaluate Jitter Influence on Pointing

Case (a) in Figure 11 is a case where both the Psyche spacecraft and the DSOC FLT flexible dynamics models are used. The IRCD jitter motions shown in Figure 3 are injected into the system at the Psyche/DSOC interface location as prescribed external motions. This is a rather conservative approach as the broadband motions jitter is injected to excite both the DSOC FLT and the Psyche spacecraft.

Case (b) is very similar to Case (a) in that the same flexible dynamics models are used. However, instead of using the IRCD jitter profiles, the motions used at the interface are the motion jitter independently predicted by the Psyche project using the flexible Psyche dynamics model with a rigid-body DSOC FLT mass model, excited by the reaction wheel (RWA) force/torque jitter provided by the RWA vendor and modified by adding a model uncertainty factor (MUF). This approach serves mainly as an intermediate step that supports independent analyses carried out by the Psyche project and the DSOC project.

Case (c) is a more realistic case in which the integrated Psyche/DSOC flexible dynamics model is used, and most importantly, the RWA jitter is directly injected at the four RWA locations on the Psyche spacecraft as the 6DOF force/torque (with MUF).

These approaches are used to predict the DSOC FLT floating platform LOS pointing motion power spectral density in the frequency domain or LOS pointing motion time profile in the time domain. For the frequency domain analysis, the corresponding cumulative root-mean-square (CRMS) are used to identify the large contributors against the RMS pointing requirement. The remaining part of the section is devoted to the stability analysis of the integrated model approach.

Stability Results

There are two control design problems for the FLT floating platform stabilization. The inner loop deals with the accelerometer based control. The transfer functions from the local strut LFA forces to the measured acceleration from the accelerometers are used as the design model for the controller design. These transfer functions include not only the effects of the flexible dynamics of both the DOSC FLT floating platform and the Psyche spacecraft, but also the effects of the umbilical and the strut internal cables connecting the floating side to the stationary side. As an example and a comparison, the transfer functions between the strut #1 horizontal force to the strut #1 horizontal acceleration for two versions of integrated flexible dynamics models (two different model deliveries from the mechanical team) and the rigid-body model are shown in Figure 12. The transfer functions show the true flexible dynamics as well as the low-frequency modes introduced by the umbilical and the strut internal cables connecting fixed side and floating side of the DSOC FLT. The Psyche spacecraft model in these cases is closed-loop with an ACS controller provided by the Psyche project GN&C team.

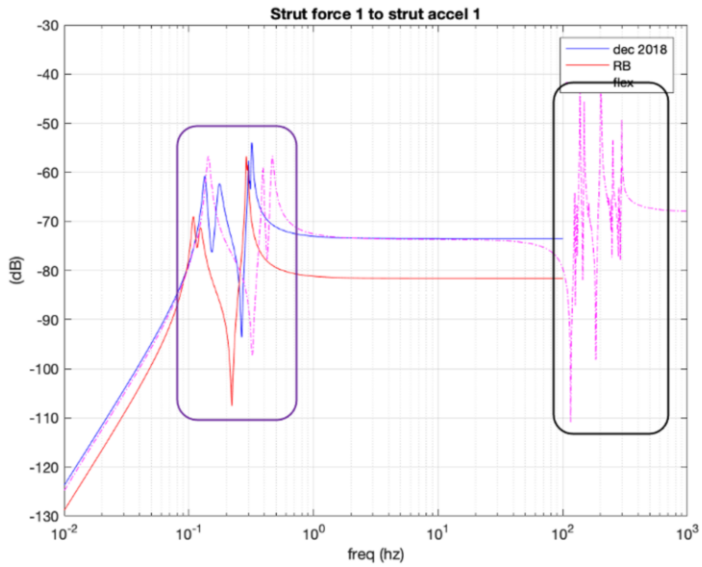

Figure 12. DSOC Flexible Dynamics Model and Comparisons

The accelerometer loop controls are designed as six decoupled single-input single-output (SISO) loops for each strut locally due to their simplicity and physical limitation of no cross-strut interfaces. The control loop bandwidths are chosen such that there is a clear separation from the 100 Hz of the DSOC flexible dynamics high-frequency modes. The SISO stability results for the 6 decoupled loops are shown in Figure 13. Each SISO loop meets the 6 dB and 30 degrees of gain and phase stability margin requirements.

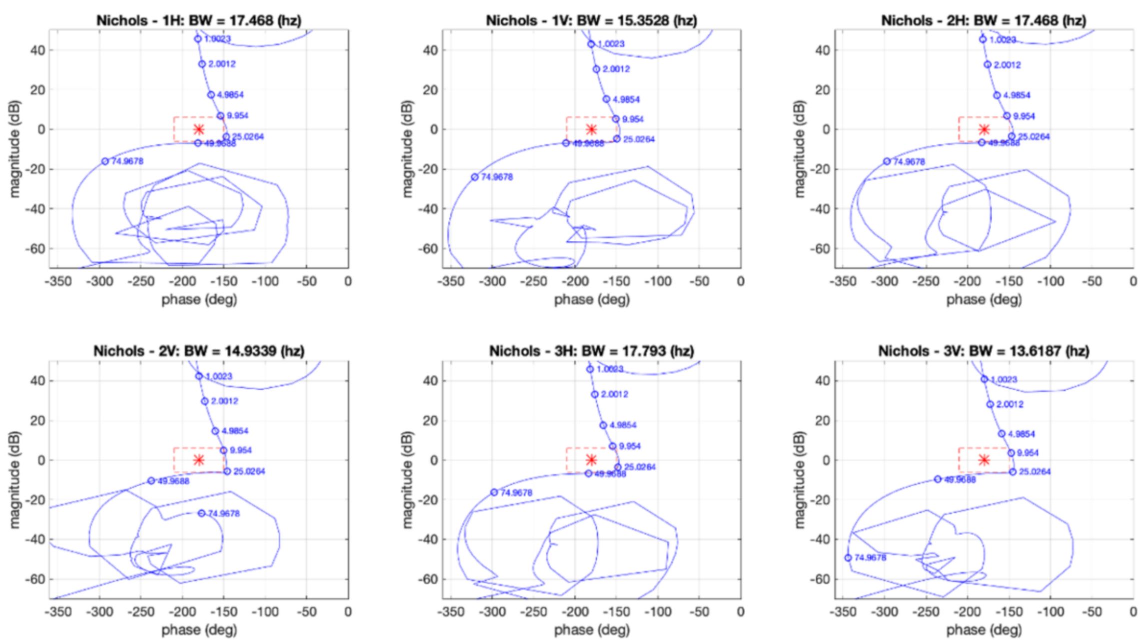

Figure 13. SISO Accelerometer Loop Stability Results

The outer loop can be either a pure relative position control or a mix of relative position control and LOS control. The control design dynamics model for the outer loop is the transfer function between the reference strut accelerations and the PSD measurements or the mix of PSD and PCC measurements, with the closed-loops of the inner accelerometer control. The position control is designed for the 6DOF body motions of the floating platform center of mass (CM), with the outputs of the controller being the body translational and rotational accelerations at the CM. Those body acceleration commands are then mapped to the translational accelerations at the strut locations to serve as the reference inputs for the inner accelerometer loops. As mentioned before, the two performance critical pointing loops (tip/tilt) are tightly controlled with relatively high control bandwidth while the other 4DOFs are loosely controlled with much lower bandwidth. The SISO stability results for the 6 decoupled position loops with the accelerometer loops all closed are shown in Figure 14. Again, each SISO loop meets the 6 dB and 30 degrees of gain and phase stability margin requirements.

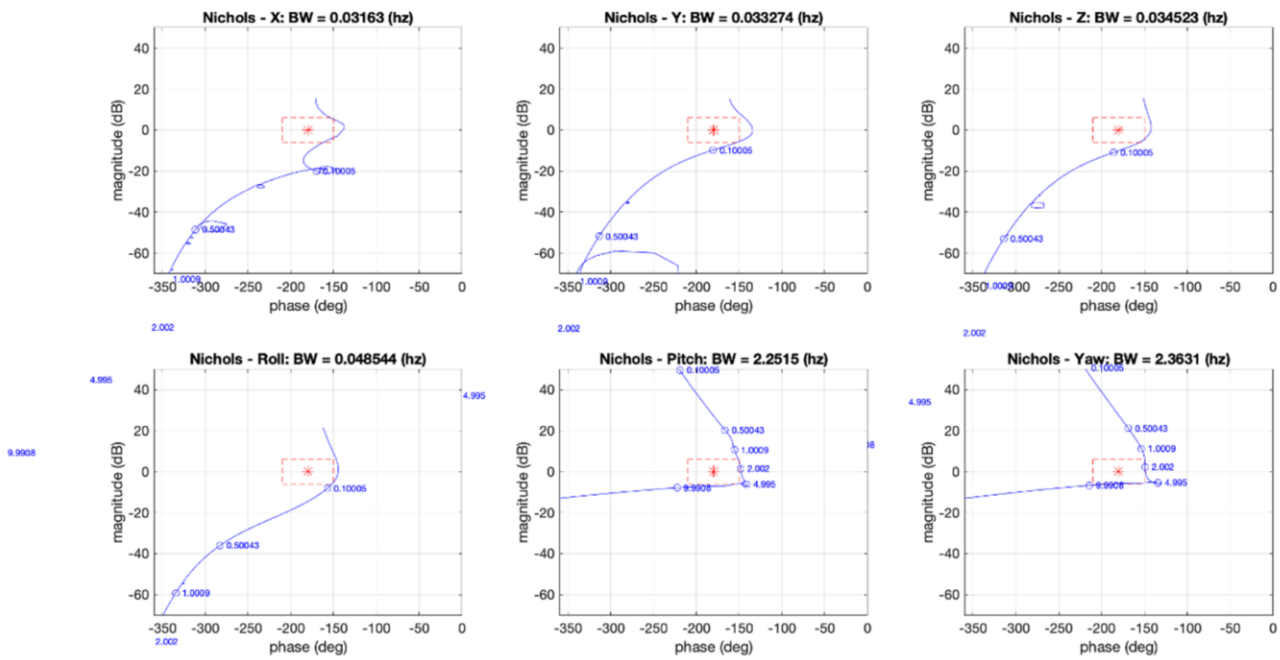

Figure 14. SISO Position Loop Stability Results

Additional stability cases are also analyzed. Those include the one-loop-at-a-time SISO cases stability analyses for the accelerometer loops and the position loops, for which all loops other than the loop under study are closed. In addition, the multiple-input multiple-output (MIMO) stability margins for both inner and outer loops are calculated as well.

SYSTEM PERFORMANCE

The system pointing performance is analyzed in both the frequency domain and the time domain. In the frequency domain analyses, we are mainly concerned about capturing the main contributors of the pointing errors and their sensitivities to LOS pointing performance. In the time domain analyses, the performance is predicted using a high-fidelity dynamics model that includes the flexible dynamics and nonlinear kinematics, actuator/sensors models with the flight design sampling rate and worst-case time delays, together with the current version of the PCS flight code. All models are built into Simulink blocks, with the C-code PCS encapsulated by a Simulink S-function block.

Frequency Domain Analysis

For the frequency domain analyses, the relevant transfer functions are generated directly from a slightly simplified Simulink model shown in Figure 15.

The frequency domain analysis model is used to evaluate the sensitivities of the various error sources on the floating platform LOS pointing errors during tracking. The list of errors for evaluation purpose includes the RWA jitter, the accelerometer noise, the PSD noise, the PCC noise, and the LFA noise. As all the noise performance for those hardware components are specified and known,

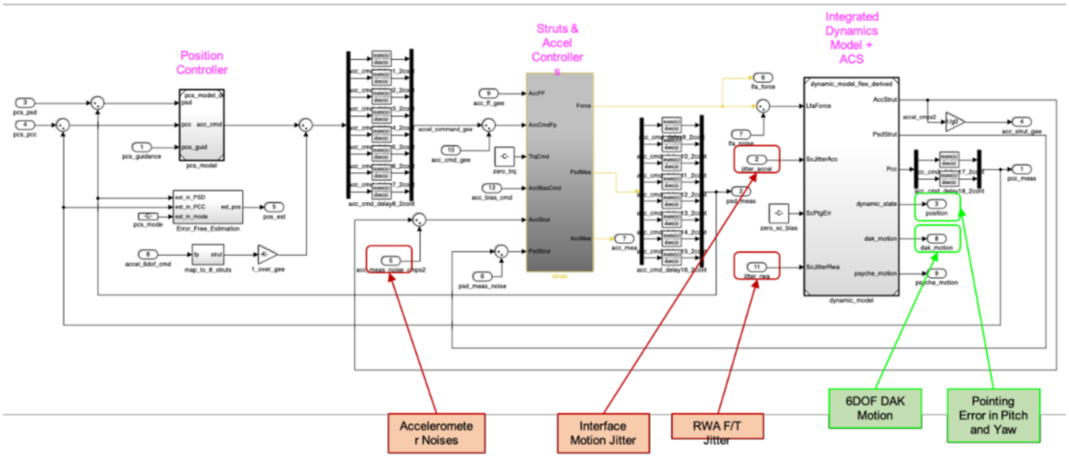

Figure 15. Frequency Domain Sensitivity Analysis Model

the LOS performance evaluation in the frequency domain amounts to the evaluation of the corresponding transfer functions. As an example, the transfer functions from the 24 (4 RWAs, 6DOF each) RWA jitter motions to the tip and tilt (pitch and yaw) of the floating platform are shown in Figure 16.

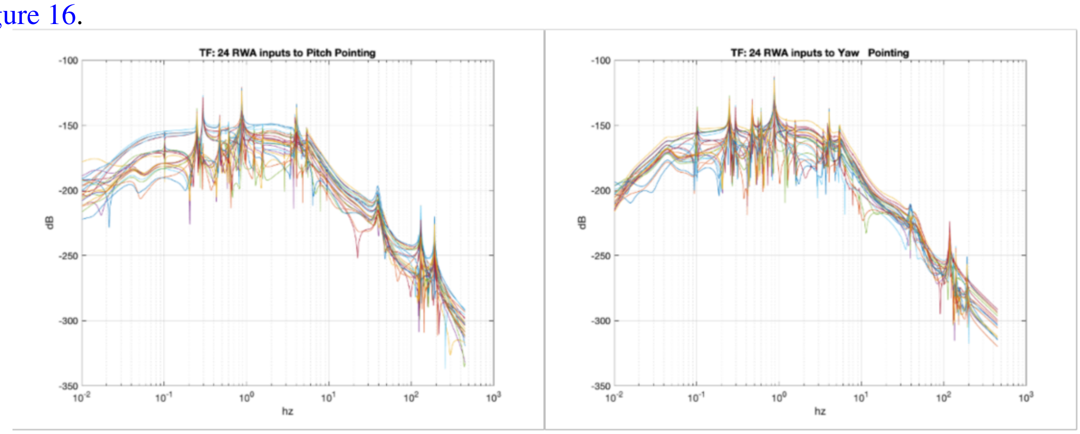

Figure 16. Transfer Functions from RWA Force/Torque to LOS Pointing

All frequency domain sensitivity results, including those for the conservative case of using the Psyche project predicted motion jitters directly at the interface location, show pointing errors below the requirements.

Time Domain Analysis

For the time domain analyses, the Simulink link model includes both the DSOC FLT and the Psyche spacecraft flexible dynamics. It also includes the DSOC pointing guidance model from the Psyche spacecraft interface. Within the DSOC model, various components, including the IPA struts, the PCC, and the OTA/PAM are included. For the PCC, two different models can be used. One is a full model that runs at the native PCC sampling rate, used to evaluate the PCC performance at different operating conditions/configurations. The other one is a simplified model that captures the main pointing/control characteristics but runs at the same sampling rate of the selected Simulink run step to enable much faster simulation runs. The simulation model supports direct interface with the DSOC PCS flight software as an embedded S-function block. The time domain high-fidelity simulation model is shown in Figure 17.

While the frequency domain model supports only the steady-state tracking performance of the floating platform, the time domain model can be used for various phases of DSOC pointing control submodes and the transitory behaviors when submodes change. It is also used to evaluate

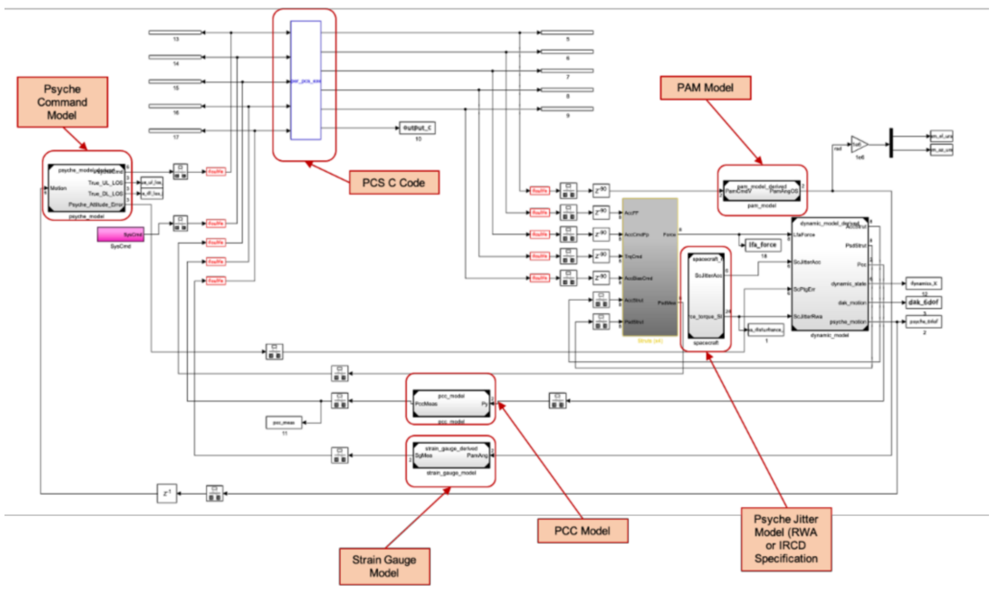

Figure 17. Time Domain Performance Simulation Model

the downlink LOS pointing performance as it includes both the floating platform control and the PAM/downlink control. Figure 18 shows the uplink acquisition sequence simulation results where the scan, walk and track submode results are plotted:

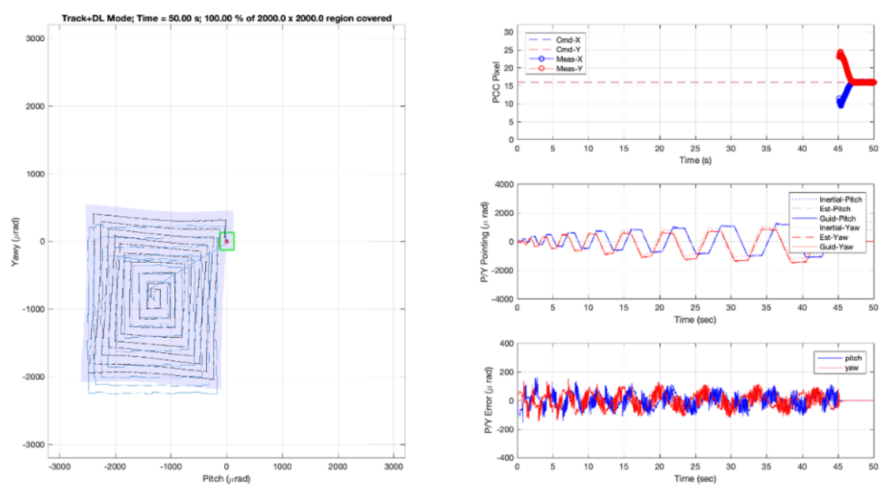

Figure 18. Time Domain Performance Simulation - Acquisition

The simulation is with the RWA jitter force/torque implemented as inputs to the Psyche spacecraft dynamics model. The offset of the starting acquisition pointing direction from [0,0] shown on the left plot represents the modeled pointing knowledge uncertainties in the guidance information provided by the real-time Psyche spacecraft commands. This particular case makes use of a square spiral scan profile while a hexagonal spiral scan profile is also implemented in the PCS flight software.

Calibration for Performance Improvement

To guarantee the overall FLT system pointing performance, several pointing related calibrations are planned both on the factory floor and in s pace. For the purpose calibrations discussion, Figure 19 shows the various coordinate frames defined and used for the DSOC FLT pointing control design considerations.

For the OTA base pose (defined on the One-Ring shown in Figure 19) with respect to the FLT

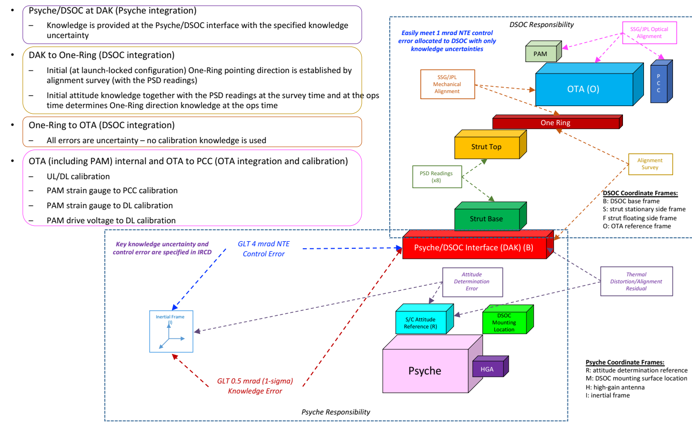

Figure 19. Pointing Related Coordinate Frames

base coordinate frame, the factory floor alignment surveys are performed to correlate the pose with the PSD readings at the GSE-fixed configuration. Based on Eq. (1), the OTA base pose (and the pointing direction) can be fully and uniquely determined by the delta PSD readings.

For the optical system defined relative to the One-Ring, the factory calibration will measure the uplink optical boresight in the One-Ring frame. By taking various measurements simultaneously, the factory calibrations also establish the correlations among the uplink laser LOS, the uplink PCC centroid location, the downlink LOS, the downlink retro laser centroid on the PCC, the PAM strain gauge readings, and the PAM piezo-drive voltages. Those correlations are implemented in the PCS as a series of 2-dimensional mappings, similar to Eq. (2), with their parameters determined from processing the OTA calibration measurement data. Those parameters become a part of the flight software parameter database and are used to support the DSOC FLT initial in-space operations.

Several in-space pointing related calibrations are also planned, as shown in Figure 20. The first is the PAM strain gauge calibration for the purpose of re-establishing the correlation between the downlink retro laser centroid locations and the strain gauge readings. This can be necessary if the strain gauge properties change over time due to temperature variations and long-term aging. In this calibration, the PCS is commanded to execute a strain gauge calibration procedure in which the PAM is controlled to move the retro laser to a set of predetermined PCC detector crosshairs while the measurements of the strain gauges are taken. The parameters in the linear mapping between the strain gauge and PCC centroid location (Eq. (2)) can be updated using the calibration results. The second in-space calibration involves a space-ground coordinated operation in which the PCS controls the PAM to follow a parametrized hexagonal scan patten while the GLR is configured to take the power measurements of the downlink laser. The determined downlink laser LOS direction corresponding to the peak laser power can be compared to the knowledge of the GLR LOS direction to produce an estimate of the downlink pointing offset that can be converted into the two-axis offsets in the PAM strain gauges. These offsets are then uploaded from the ground to the DSOC FLT via the Psyche spacecraft for the future downlink pointing corrections.

CONCLUDING REMARKS

This paper summarizes the pointing control design of the Deep-Space Optical Communications space terminal as an isolation and pointing device. The DSOC FLT will be on board of NASA's

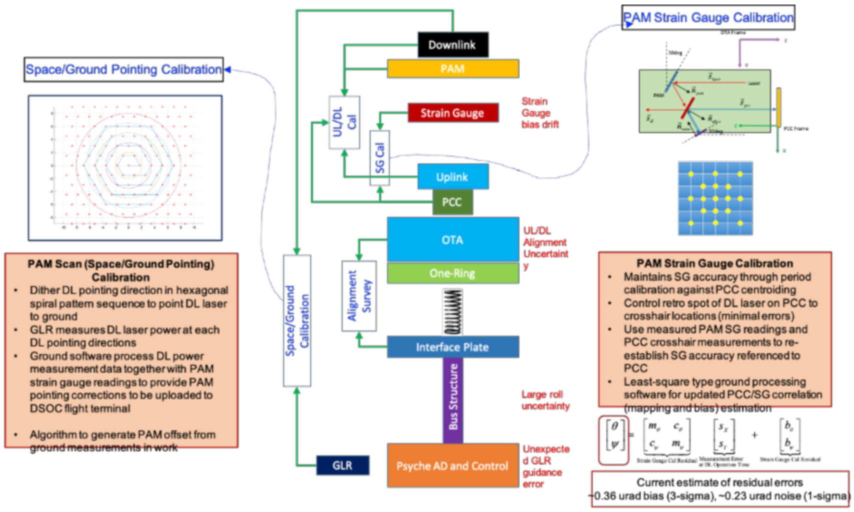

Figure 20. In-Space Pointing Related Calibrations

Psyche spacecraft which is scheduled to launch in 2022. The information presented in this paper is based on the results from a series of the pointing and control peer reviews and in particular the Critical Design Review of the DSOC pointing and control system. The results show that the pointing and control design meets the pointing performance requirements of the DSOC FLT system.

The DSOC pointing and control design benefited from a long history of space laser communications development activities at JPL and benefits from the supports from the key pointing and control related hardware vendors. As a summary paper, many other aspects of the pointing and control design, including the detailed operational design, various other calibration schemes and approaches, the system level pointing budget and allocations, and the verification and validation activities, are not discussed in this paper. Those topics may be the subjects of future reports.

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