Automatic Optical Image Stabilization system calibration, validation, and performance for the SkySat constellation

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ABSTRACT

Capturing Earth imagery from low-Earth orbit causes blur from the spacecraft's orbital motion. Planet's high resolution SkySat satellites utilize an Optical Image Stabilization (OIS) system to reduce motion blur by mechanical oscillation of the payload assembly. Automated on-orbit procedures and analyses are used for calibration and validation of the system across a fleet of 19 satellites. OIS actuation settings are configured for each image capture through automated optimization procedures. The benefit of the OIS system is demonstrated by an increased collection ground scan rate with no degradation to image quality, thereby improving fleet production capacity of the SkySat constellation.

INTRODUCTION

Planet operates a fleet of high resolution Earth imaging satellites called SkySats, which operate across a variety of polar sun-synchronous and inclined orbits. SkySats are tasked to image locations all over the globe in a step-stare fashion, where a long "strip" image consists of many frames taken in succession as the imager scans across the Earth's surface. Two primary metrics for the SkySat constellation's performance are the image resolution, which is a measure of image quality, and the area of Earth's surface for which imagery is collected over a given span of time, also known as the fleet's image collection capacity.

In pursuit of maximizing both image quality and collection capacity, motion blur is a critical part of this trade-space. Motion blur is a degradation of image quality caused by relative motion between the imager and the target. When the target, in this case the Earth's surface, moves across the camera sensor while it is collecting photons, detail is spread out across the focal plane and sharpness is lost in the resulting image frame. Motion blur is inherently present in images collected from an orbiting satellite due to the rapid speeds at which these satellites transit above Earth's surface, and is worsened by the relative motion of the camera's field of view as the spacecraft scans across an area on the surface.

Nineteen SkySats are equipped with an Optical Image Stabilization system that is used to cancel out the relative motion between the target and the image plane, reducing motion blur. This system, once calibrated, enables SkySats to collect higher resolution images and scan areas of the Earth faster, boosting the collection capacity of each spacecraft in the fleet.

THE MECHANICS OF MOTION BLUR

In Low Earth Orbit, SkySats have an orbital velocity of more than 7 km/s. In order to scan over an area on the ground to take an image the spacecraft slews at rates up to 5 deg/s. These factors are considered together as a metric called ground scan rate, which is defined as the speed at which the imager's line of sight moves across the Earth's surface. The geometric distance from the sensor to the target is called the slant range. For a given slew rate of the satellite, the scan rate is faster if the target is at a higher slant range from the sensor. An image becomes more blurry the faster the target moves with respect to the camera while it is integrating the signal.

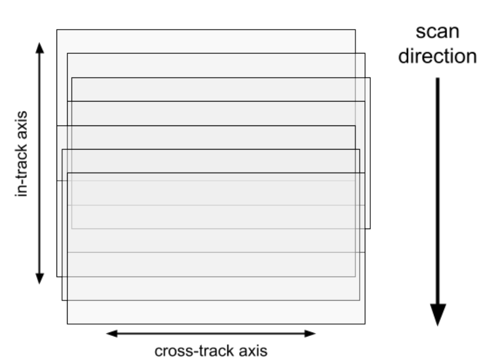

Figure 1: Footprint of image frames collected while scanning over a region.

SkySats reduce motion blur using a closed-loop controlled optical image stabilization (OIS) system. With the OIS system, controlled vibration of the telescope compensates for the relative motion of the scene during an image exposure.

As shown in Figure 2, the OIS system oscillations result in periods of very low relative motion in between periods of very high relative motion. The imager integrates an exposure during the period of low relative motion.

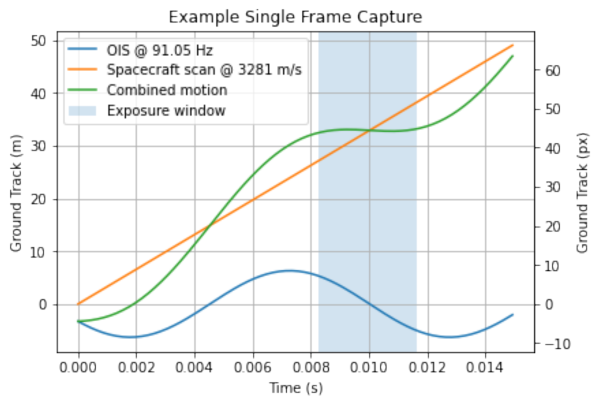

Figure 2: OIS cancels out scan motion during image exposure windows.

Using this technique, relative motion is drastically reduced for a period of time long enough to take an image with less than 1 pixel of motion blur, as shown in Figure 3.

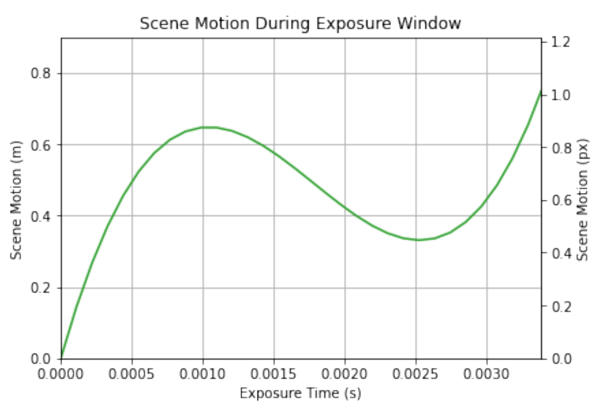

Figure 3: Scene motion with OIS is constrained to less than 1 pixel.

The OIS system allows for images to be collected with scan rates that would otherwise produce significant blurring. Figure 4 shows that for a given scan rate motion blur is reduced to less than 1 pixel with OIS enabled, compared to high amounts of blur when OIS is disabled. With OIS, SkySats are able to capture images more quickly without degradation to image quality.

Figure 4: Direct comparison of image collections at a given scan rate with OIS disabled (left) and enabled (right).

This paper will discuss the implementation, calibration, and performance of the SkySat OIS system.

SHAKE IT UP!

Nineteen SkySats are equipped with an OIS system. The OIS system is a mass-spring-damper with a feedback control algorithm based on repetitive control theory that produces desired sinusoidal motion of the payload in two axes.[1] Two voice coil actuators are used to produce sinusoidal forces on the bus, creating sinusoidal torques on the spacecraft. Coupling between the payload and the bus causes sinusoidal motion of the payload. Four accelerometers are used to estimate the payload angular motion, which is used as feedback for the control algorithm.

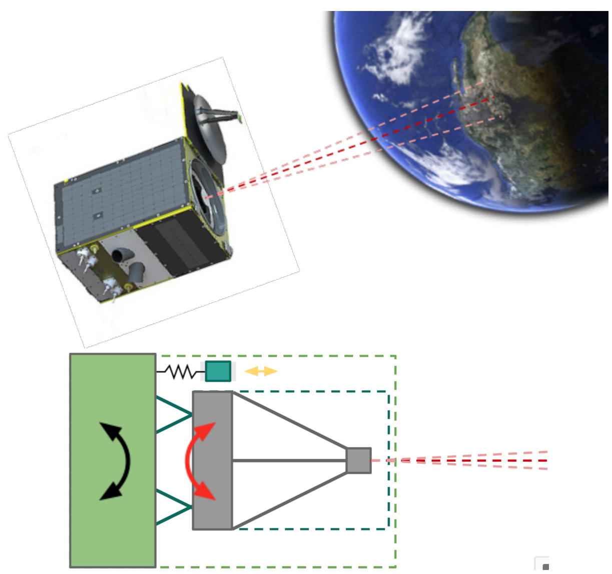

Figure 5: OIS oscillates the payload's line of sight by vibrating the payload bus.

The controller converges for sinusoidal inputs that repeat after a set number of control cycles. Desired angular accelerations of the in-track and cross-track payload axes are provided to the controller as inputs, along with the measurements from the four accelerometers. The controller output specifies the desired voltage for each voice coil actuator.

The resonant frequency of the SkySat payload bus is approximately 90 Hz. This is an integer multiple of the SkySat camera's nominal framerate of 45 Hz. Because of this relationship, the OIS efficiently oscillates the payload in sync with the payload's nominal imaging configuration at amplitudes large enough to counteract motion blur. A calibration is required because slight differences in the construction of each SkySat result in minor variations of the resonant frequency by a few Hz. This calibration must be performed in the microgravity environment of Low Earth Orbit.

CALIBRATION & VALIDATION

Key control system parameters must be calibrated in order to properly translate actuator effort into motion of the image plane before the feedback control algorithm can be commanded to effectively counteract motion blur. The calibration process uses a series of spacecraft activities that build upon one another in order to systematically determine the optimal control parameters. The overall calibration approach is to first build a transformation matrix that links actuator inputs to the measured vibration response, then to build a transformation matrix that links the measured vibration response to pixel-wise motion at the image plane.

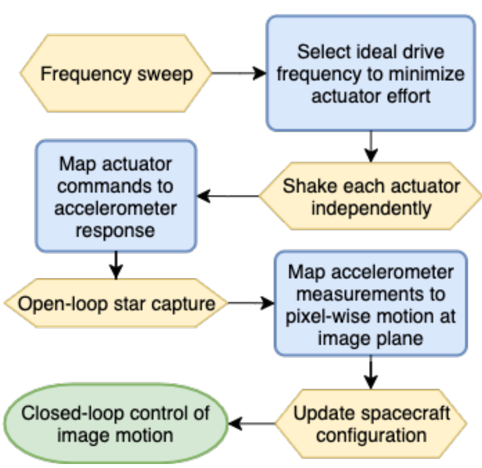

Figure 6: OIS calibration workflow.

For each activity, high fidelity on-orbit telemetry is collected from actuators and accelerometers for the duration of the activity and then downlinked to ground stations after the activity is completed. This high fidelity telemetry is analyzed procedurally with code to determine calibration parameters. The calibration activities are simply scheduled to occur on-orbit according to a procedure and the system may be calibrated without requiring a subject matter expert to be involved in the process.

Map Actuator Commands to Accelerometer Responses

The frequency of oscillation, or drive frequency, of the OIS controller is calibrated to be as close as possible to the resonant frequency of the payload bus. The controller allows for one of 8 drive frequencies to be selected.

An activity is scheduled on the spacecraft to oscillate each actuator at 88–96 Hz in 1 Hz intervals. Figure 7 shows accelerometer voltages, which indicate angular motion of the payload bus, are analyzed with respect to the magnitude of actuation commanded of the voice coils.

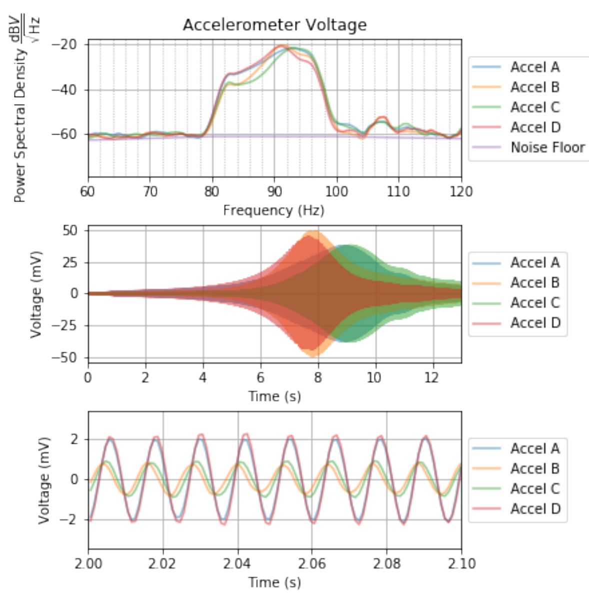

Figure 7: Accelerometer response from OIS actuatation during frequency sweep.

Figure 8 shows the actuator effort required to drive the OIS system at each available drive frequency. The drive frequency is selected as the frequency where the command magnitude required for nominal operation of OIS control is minimized for both actuators. A cost function is used to procedurally select the ideal drive frequency from this analysis.

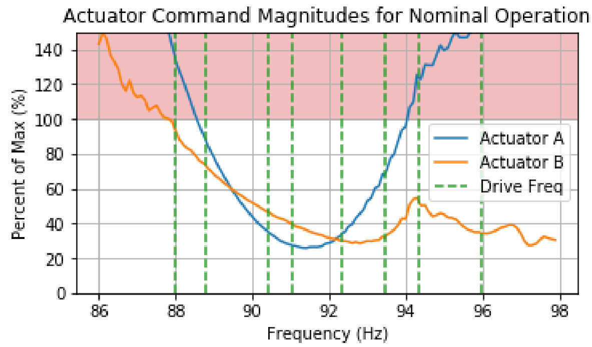

Figure 8: Actuator effort vs OIS frequency. Dotted lines indicate drive frequencies.

Next, an activity is executed on orbit in which accelerometer data is collected for system identification using the selected drive frequency for each actuator independently, as shown in Figure 9. These two datasets contain a large amount of energy at the drive frequency and are long enough to allow the system to reach steady state. They can be used to calculate the amplitude and phase shift between the actuators and the accelerometers at the drive frequency. This information is crucial for commanding the OIS system to produce controlled motion in both the in-track and cross-track axes.

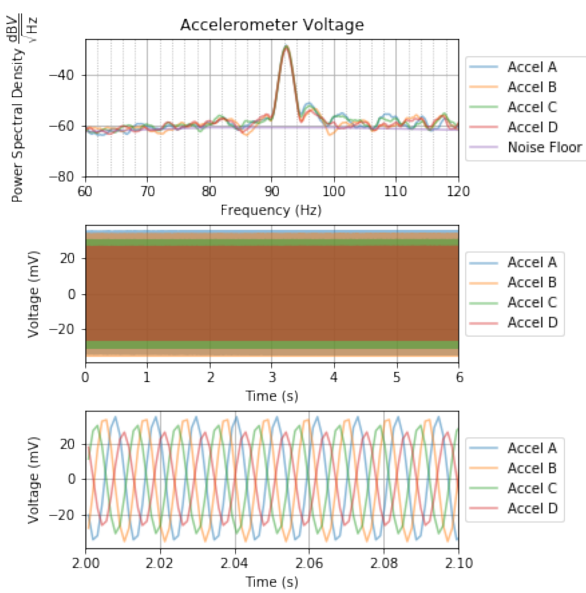

Figure 9: Accelerometer spectra and time series during actuation.

The transfer functions from actuators to accelerometers, evaluated at the drive frequency, are assembled into a matrix, C. C is used to derive actuator commands that will produce a desired oscillation of the payload bus.

Map Accelerometer Measurements to Pixel Motion at Image Plane

A new set of transfer functions is needed to describe 2-D motion of the image on the focal plane for a given 3-D oscillation of the payload bus. Image motion at the focal plane is measured by taking exposures of stars while commanding the OIS system to oscillate the payload bus. The star acts as a point source target which traces the image motion on the focal plane as the sensor integrates the signal over time.

With C defined, the OIS system is used in open-loop control mode in which the payload is oscillated with a given amplitude and phase between the actuators without using feedback from the accelerometers. The actuators are commanded such that the payload oscillates in both axes and two orthogonal directions.

The exposure of the star forms an ellipse in the captured image. The ellipse is essentially a trace of the sinusoidal motion of the payload projected onto the image plane. This means that coefficients for sinusoidal motion can be obtained from the eccentricity, amplitude, and phase of these ellipses.

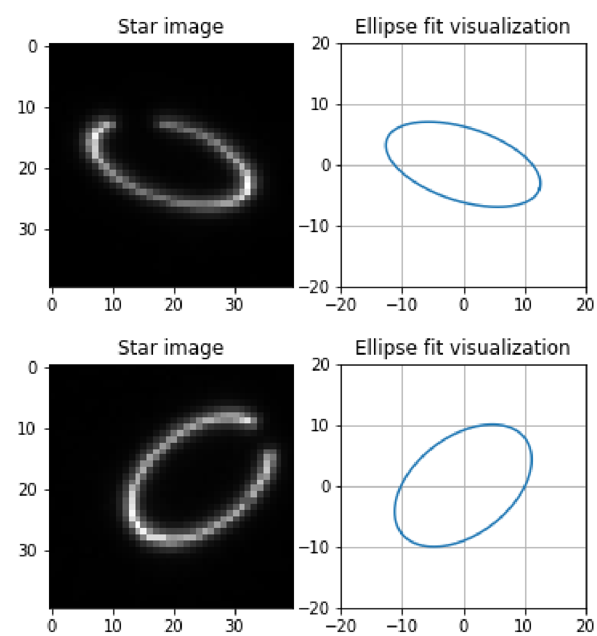

Figure 10: An ellipse is fitted to the pixel data from the star trace on the image plane.

A matrix, D, is defined to relate actuator inputs with motion at the image plane. While the C matrix mapped actuator inputs to time series data from the accelerometers, the D matrix maps the actuator inputs that produce corresponding ellipses on the image plane. Since the image motion cannot be directly measured by the control system, a new matrix, M, is created to relate the motion of the image plane to motion at the accelerometers. Since the system is approximately linear for small angles, we are now able to relate actuator inputs to motion at the image plane with real-time feedback from sensor measurements.

At last, a transfer function is fully defined to link feedback from accelerometer measurements to actuator commands in order to control motion on the focal plane in the in-track and cross-track directions for closed-loop control. Motion on the image plane can now be oscillated along in-track and cross-track image axes with sinusoidal motion in order to counteract motion blur.

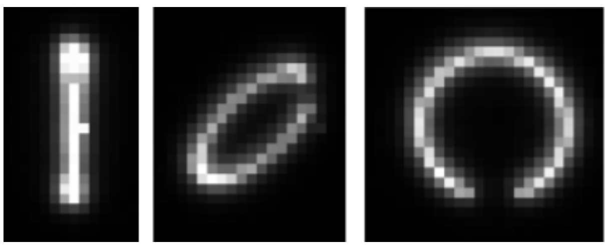

Figure 11: Two-axis control of motion at the image plane.

Figure 11 shows traces of stars captured on the panchromatic sensor, demonstrating two-axis control of motion at the image plane and the projection of orthogonal sine waves from OIS motion as the sensor integrates over time. In practice, the OIS system is used to produce a line so that motion blur is reduced along the in-track axes, while minimizing motion in the cross-track axis.

SCALING WITH AUTOMATION

Calibration procedures are packaged as sets of commands uplinked to the satellite, which are executed on orbit between accesses with a ground station. During the next available access, the satellite downlinks relevant telemetry, which is used to determine system parameters. Automation plays a key role in preparing calibration activities, scheduling them for execution, and interpreting the results.

We enable this calibration process to be turn-key and scaled across a fleet of 19 SkySats by proceduralizing all analysis as a set of code functions that operate on the raw telemetry data collected on orbit. These functions are organized into shell commands that correspond to each step in a written procedure. The analysis codebase is distributed as a virtual container. This allows satellite operators to simply execute steps of a procedure without requiring in-depth knowledge of the OIS system in order to produce a good calibration.

An interactive shell allow these automated analysis steps to be executed quickly for any satellite, and pairs the code, plots, and results in context with text explaining what the results mean and what to do next. Calibration parameters are stored in our Mission Control software, which is an internal web API that serves as a single source of truth for these values. This interface also includes a "commit history" of all past values and when changes were made.

The result is a simple, repeatable, and traceable calibration process for the OIS system.

IMPACT OF THE OIS SYSTEM

A calibrated OIS system allows us to operate the SkySat constellation at increased capacity compared to without OIS, without degradation to image quality. This can be seen in Figure 12 which shows the distribution of image capture duration and signal to noise ratio when operating with and without OIS for a set of image collections taken by SkySat-C14 between October 1, 2020 and February 1, 2021. OIS allows us to reduce capture duration time, while maintaining SNR. We use the definition of SNR as given in GIQE-5,[23] measured at the blue band of the SkySat's multispectral cameras.

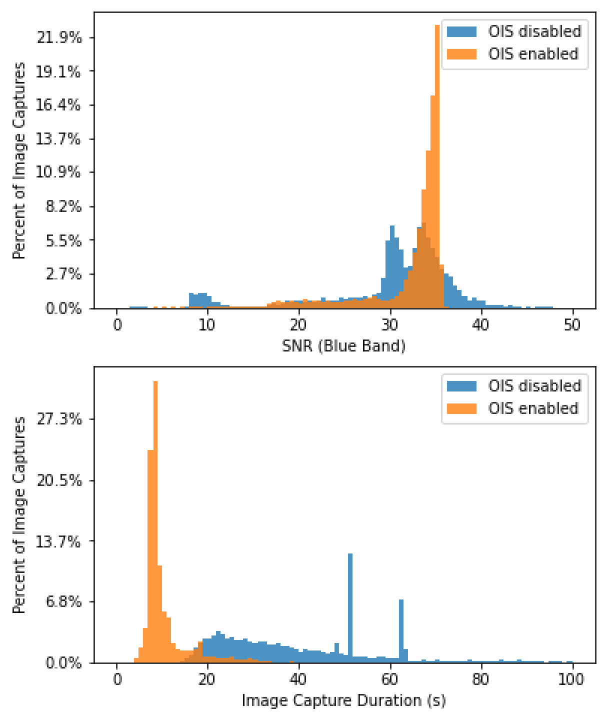

Figure 12: OIS drastically increases capture rate while maintaining sufficient SNR.

The system resolution is also maintained in the presence of increased ground scan rate as can be seen from the resulting image quality shown in Figure 13.

Figure 13: SkySat imagery captured with image stabilization. Motion blur is constrained to less than one pixel.

Automated calibration procedures enable each SkySat to use an optimized OIS configuration, and can easily deploy new calibrations to the fleet with minimal impact to nominal operations.

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