Article

Characterization and Comparison of CubeSat and Drone Platform Jitter Effects on Laser Beam Pointing Stability

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Abstract: Adaption of laser communication terminals to airborne and lean-satellite platforms is now a vogue, made possible due to the progressing advancements in lightweight components and compactness of onboard electro-optical transceivers and control systems. This enables highly secured and superior data-transmission rates beyond multiple Gigabit/second on CubeSats and drones compared to Megabit/second rates offered by similar radio-transceivers form factors. However, laser-transmission links require a very stringent beam-pointing stability because they are easily perturbed by attitude variations and micro-vibrations generated by the host platform's propulsion system or other mechanically active subsystems in proximity with the transmitter's optical head. Severe line-of-sight jitter causes the downlink laser beam to drift from the targeted receiving system's field-of-view, inducing pointing errors, increasing signal outage probability and information loss. We experimentally examine the platform jitter generated by the propellers of an hexacopter drone during ground operation and the attitude-control unit's reaction wheels in a 6U CubeSat structure. We determined the vibration spectrum unique to these platforms and accordingly prescribe requirements for applicable optical fine pointing and disturbance isolation or suppression systems needed to achieve a high-fidelity laser-communication link.

Keywords: Laser Communications; Platform Jitter; Beam-pointing stability; Drone; CubeSat

1. Introduction

Small satellites and drones are projected to play crucial roles in the evolution of next generation 6G telecommunication systems. Due to the increasing demand of higher data transmission rates, it becomes imperative to adapt free-space optical (FSO)/laser communication (lasercom) links within existing RF networks [1]. Laser beams have higher directivity, suitable for long distance and high-capacity information transmission. However, this makes it also susceptible to beam pointing instability especially when the platform has persistent mechanical disturbances and continuous attitude variations. Nowadays, commonly used drones available off-the-shelf are the rotary-wing propeller type that generates substantial high-frequency mechanical jitter and audible sound from take-off to landing. Similarly, orbit bound CubeSats have problems with microvibration generated by the reaction wheels used for the satellite attitude control. Careful consideration of the impact of platform microvibration is a good reason to have sufficient margin for pointing losses in the optical link budget design. Microvibration or jitter are generally defined as structurally transmitted force disturbances generated from components such as servomotors, reaction wheel assembly (RWA), drive mechanisms and appendages of the platform.

 doi:10.20944/preprints202208.0206.v1

The CubeSat's RWA is the chief source of jitter on the platform which perturb the hosted optical instrument or lasercom payload line-of-sight pointing stability.

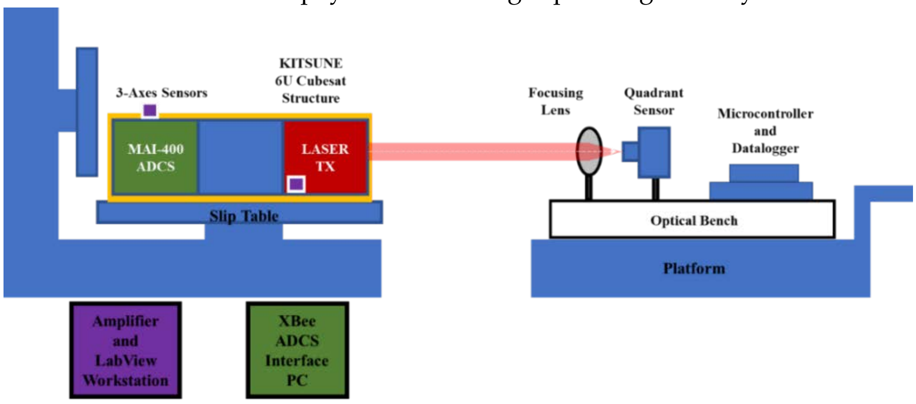


Figure 1. 6U CubeSat ADCS jitter measurement setup.

Figure 2. Drone with mounted Lasercom Module and an ad-hoc optical receiving system.

Static and dynamic imbalances, bearing friction, manufacturing or factory errors and operational degradation are responsible for the RWA jitter. Static imbalance is the misalignment of the wheel's center of gravity (CoG) from its main rotating axis while dynamic imbalance is defined as the cross product of the wheel's inertia caused by angular deviation of the principal inertia with respect to the spin axis. While most COTS RWA and drone propeller manufacturers seldom provide full jitter data [2], it is essential to characterize the device micro-vibrations to estimate the impacts of a lasercom payload and possible mitigation measures. In this paper, we describe the results of practical jitter experiments aiming to characterize the impact of a CubeSat's RWA and drone's propeller unwanted force propagation on a laser beam pointing setup. An historical perspective of the development microvibration analysis is presented in section 2. The methodology of conducted experiments, the results, and the platform comparison are described, and jitter mitigation measures are discussed in section 3. We summarized the importance of the study in section 4.

2. Microvibration Analysis

Drones are highly mechanically active airborne platforms, with significant vibrations and shock produced by the multiple brushless motor driven propellers. The vibrations are transmitted through the entire structural system in a fashion peculiar to the drone's airframe design. Not much material is available on disturbance characterization of rotary-wings, multi-rotor drones [3][4] as they have diverse configuration and aerodynamic designs. External factors such as weather, windspeed, and air turbulence contributes to the complex vibration pattern in drones. Reaction wheel technology is currently well developed and extensively adopted in satellite platforms for communication, imaging, and remote sensing applications. RWA jitter is modeled analytically, empirically or a combination of both. Origin of RWA disturbance modelling efforts dates to the 1970s with early mathematical/analytical approaches taking shape in the 90s while empirical modelling method came to limelight in the early 2000s [5]. The empirical modelling was first created for RWA vibration assessments of the Hubble Space Telescope [6]. It is a more robust scheme that make use of parameters recorded from a reaction wheel test or experiment. In the empirical approach, the steady-state jitter force or torque $\boldsymbol{J(t)}$, having an amplitude $\mathbf{A}_i$, $(\mathbf{N^2/Hz})$ is proportional to the square of the RWA speed, $\boldsymbol{\Omega}$ $(\mathbf{Hz})$ and contains discrete harmonics (n).

$$J(t) = \sum_{i=1}^{n} \mathrm{A}_i \Omega^2 \sin(2\pi h_i \Omega \mathrm{t} + \phi_i) \tag{1}$$

Where $\boldsymbol{h_i}$ is the harmonic coefficient and $\boldsymbol{\phi_i}$ is the phase of the harmonic with values range from 0 to 2π. Equation 1 provide insights to the nature of the microvibration forces and torques with respect to the speed of the RWA. Typically, different RWA produces different jitter patterns therefore it is essential to characterize the RWA in use at every given case. The power spectral density $\boldsymbol{P_j}$ of the RWA disturbance force is related to the root-mean-square (RMS) line-of-sight pointing error of the platform [7]:

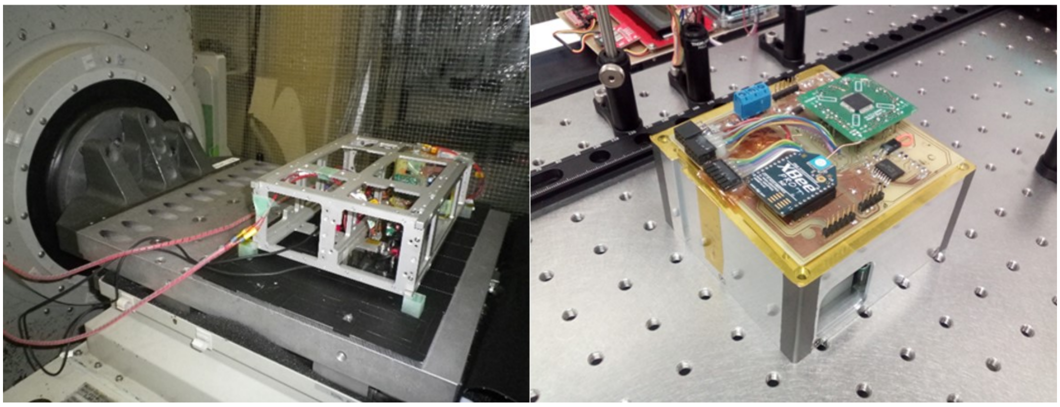
$$P_J(f) = \sum_{i=1}^{n} \frac{F_i^2(\Omega)}{2} \delta(h_i\Omega - f) \tag{2}$$

3. Description of Experiments

3.1. CubeSat RWA Jitter Experiment

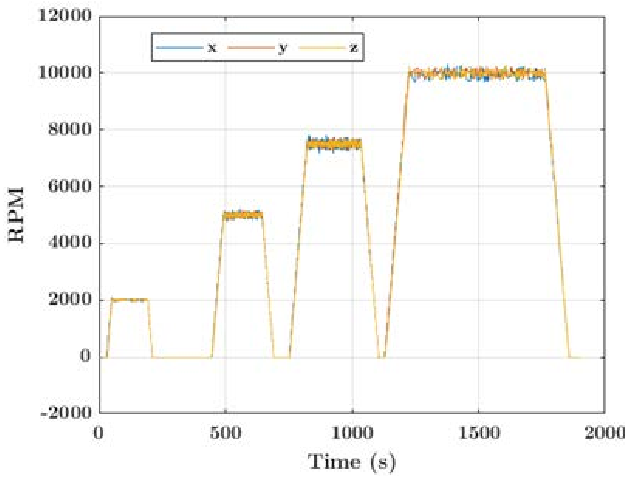
We assembled an experimental testbed at the Kyushu Institute of Technology's Centre for Nanosatellite Testing (CeNT) to determine the spectrum of jitter induced by the MAI-400 integrated attitude determination and control system (ADCS) unit's reaction wheel, with a line-of-sight laser transmitter in a 6U CubeSat structure as shown in Figure 1. The axial acceleration and gyroscope data from the ADCS internal sensors were obtained via an XBee radio interface between the MAI-400 and a laptop computer. To monitor the effects of the vibrations at different RWA speed, an optical beam position sensing system was incorporated at the receiving end. The RWA speed was incremented in steps starting from off position to its full capacity (10,000RPM) to study the impact on the magnitude of force projected to the optical components as well as the resultant instability of the laser beam. The unit's internal accelerometer and gyroscope simultaneously recorded the dynamics at each step. The recorded accelerometer and gyroscope data are shown in Figure 4. Three-axes external piezo accelerometers were mounted on various locations at the structure and the ADCS unit, connected to a pre-charge amplifier. The pre-charge amplifier converted the piezo-electric type accelerometer high impedance charge input into a low impedance voltage signal fed into a data acquisition system [8]. Piezo-electric sensors are an excellent choice for jitter measurement and characterization [9] given their high resolution, very high frequency response and wide dynamic range. Two units of the 3-

axes piezo sensors were used (shown in Figure 5 below), one at the Fine Steering Mirror (FSM) location and the other one close to the reaction wheel.

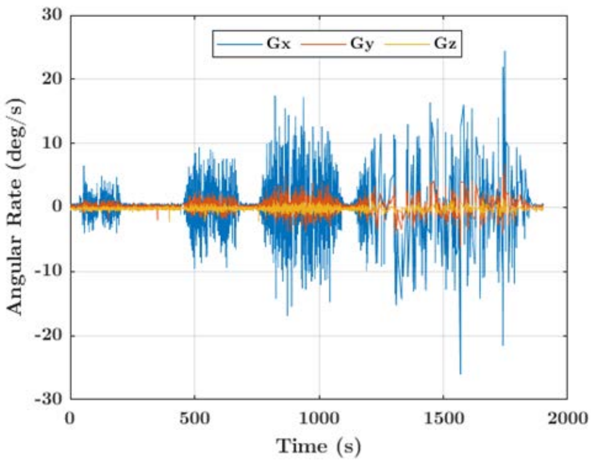


(a) (b)

Figure 3. (a) CubeSat structure placed on slip table; **(b)** MAI-400 ADCS Module.



(a)



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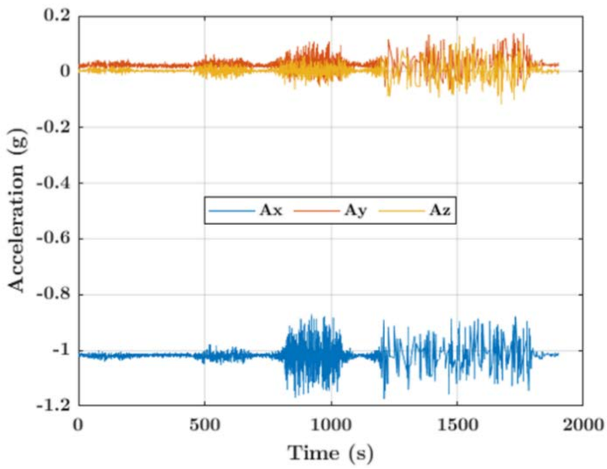

(c)

Figure 4. (a) CubeSat Reaction Wheel Tachometer profile; **(b)** ADCS module internal Gyroscope data; **(c)** ADCS module internal Accelerometer data.

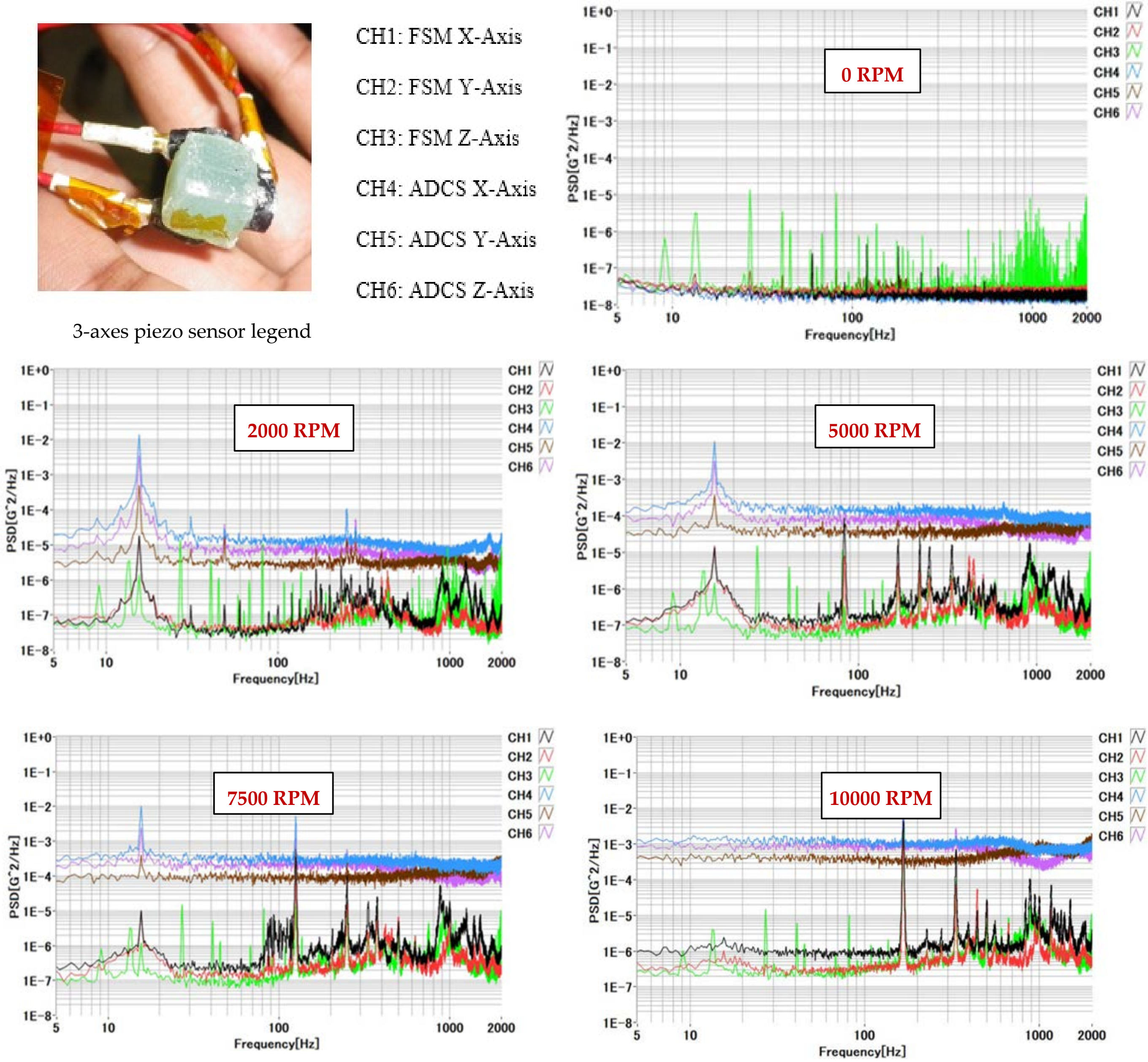

Figure 5. Vibration spectrum at ADCS and FSM locations during different reaction wheel speeds.

3.2. Drone Jitter Experiment

CubeSats and drones are both very attractive for lasercom terminal adaption because they are low-cost, have rapid manufacturing time and suitable for several application scenarios. Drone propellers are an active vibration sources that needs to be damped to host sensitive optical payloads such as LiDAR and lasercom terminals. In the framework of the NICT-Kyutech collaborations, we conducted a drone jitter experiment at the NICT's Space Communication Systems Laboratory in Tokyo, utilizing the DJI M600 Pro Hexacopter fitted with a lasercom module and an active Ronin-MX gimbal stabilizer. As shown in Figure 2, the drone was firmly fixed to the ground the entire duration and separated from the ad-hoc receiving system by 15meters direct line-of-light. The gimbal was stabilized while the propellers where operated at full speed. Accelerometer and gyroscope sensor in the lasercom module recorded the vibrations of the platform while a laser position sensor at the receiver monitored the displacement of the beam footprint at the receiver.

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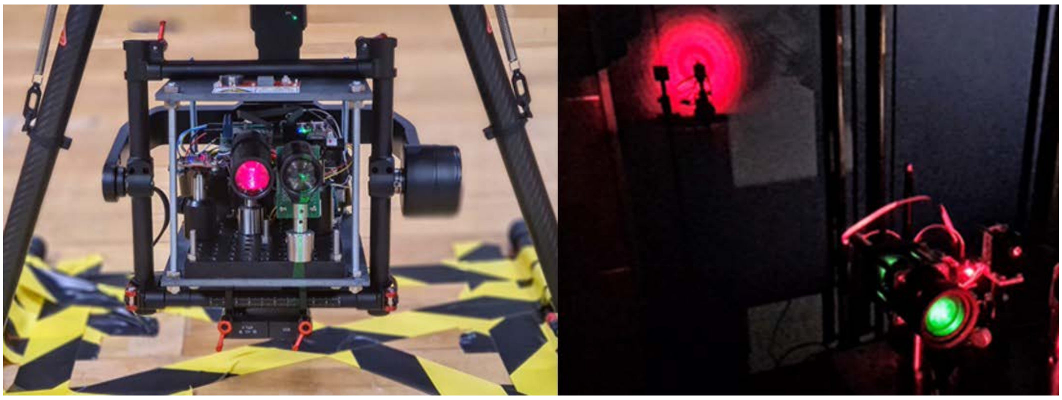

Figure 6. (a) Lasercom module with downlink laser beam switched on; (**b)** Footprint of the laser beam at the receiver.

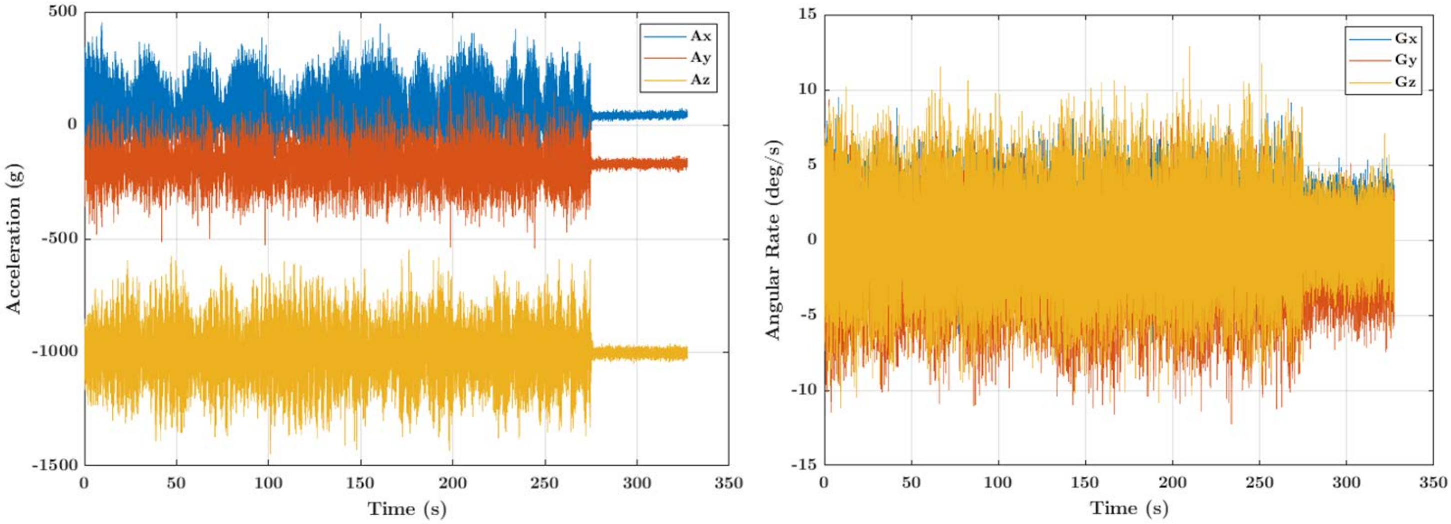

Figure 7. (a) Drone accelerometer data with gimbal smooth tracking mode activated; **(b)** Drone gyroscope data with gimbal smooth tracking mode activated.

3.3. Platforms Jitter Comparison

In this study, we collected both vibrational data using attitude sensors as well as optical detector to monitor the impact of the disturbances on the direct line-of-sight beam pointing at the receiver. This combination offers a unique discernment of the similarities and differences between the two platforms. The DJI M600 pro drone uses six E2000 propulsion motor drive, each attached to a twin blade foldable propeller providing up to 30,600g thrust. During flight, the microvibration generated on the drone are a resultant effect of the propeller motion, windspeed, drone structural configuration, appendages, and movements of the gimbal/payload. The drone propulsion system generated much stronger force and torque; therefore, much beam instability was observed at the receiver optical position measurement device as shown in Figure 8. Despite activating stabilization function of the drone gimbal, drifting of the laser beam could still be seen, indicating high frequency jitter in the system. Up to 90mrad angular displacement of the beam was recorded. The maximum speed of the CubeSat RWA was 10,000 RPM but the force amplitudes were quite lower with the beam angular displacement at 1mrad. CubeSats operate at longer link range compared to drone, hence the effect of the micro-disturbances is very

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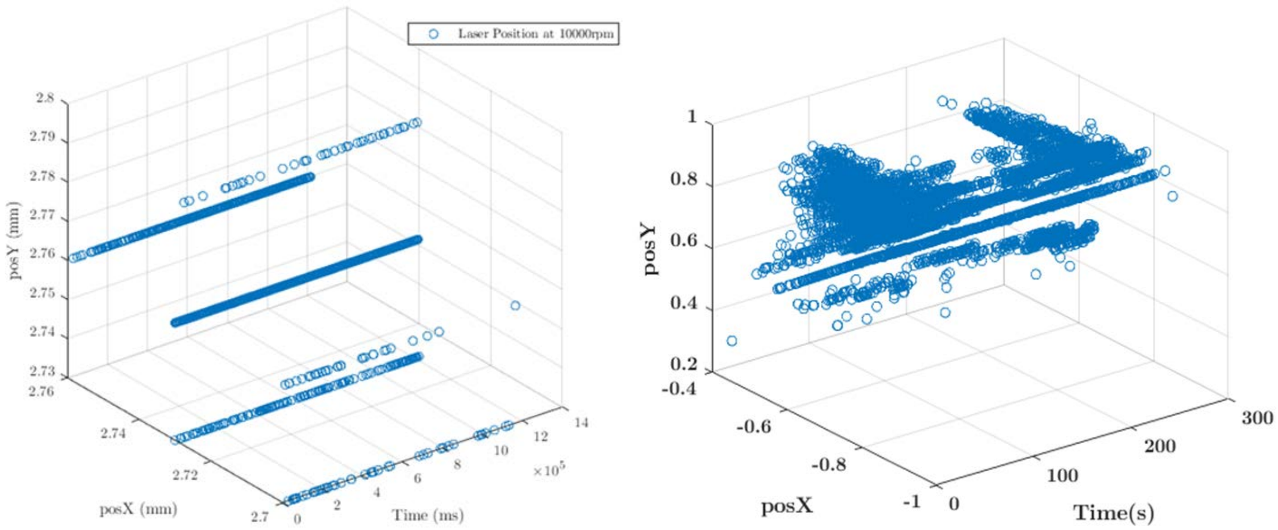
well pronounced because of the diverging beam and its footprint size at the receiver. Amateur drones are typically permitted to fly at 100 meters altitude, but the communication



range could be up to few kilometers for a horizontal link.

Figure 8. (**a**) CubeSat laser beam drift at the receiver; (**b**) Drone Laser beam drift at the receiver.

3.4. Jitter Mitigation Measures

Microvibrations must be dampened or isolated to achieve a high performing optical system on a platform susceptible to internal or externally generated disturbances. The simplest approach is to locate the laser optical head as far away as possible from the dominant jitter source (RWA). Careful and compact arrangement of the platform subsystems and minimization of flanges and appendages on the structure is a passive means of reducing the impact of micro-vibrations in lasercom systems. However, high-frequency disturbances are easily transmissible and can permeate through the entire structural system which therefore necessitates more proactive countermeasures. A self-tuning feed-forward jitter compensation strategy applicable to laser link was described by Skormin et. al [10][11]. The method featured coupling the output of an accelerometer to an electrical RLC circuit for jitter signal reconstruction and utilization in the feed-forward control system. However, the drawback with feed-forward control scheme is that set-points tracking of the controlled variable is not always guaranteed [12], because the controller acts ahead of time before the jitter can disrupt the actuation device (e.g., Fine Steering Mirror). Lasercom nodes usually require an initial search and scan using a beacon beam to orient and align the optical heads. Jitter interference is noticeable in the link acquisition and beam scanning procedures (raster, spiral etc.) between for example, a microsatellite having ADCS module and a receiver. A previous work [13][14] suggested interpolation algorithm to alter the scanning beam by compensating for the platform vibrations. A dual-beam scan method was proposed by [15] as more advantageous compared to the single-scan because it provides double speed and more resilient against the scan beam jitter. The ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) 6U imaging CubeSat [16][17][18] featured an active jitter mitigation system providing pointing stability of up to 0.5arcsecond for precision photometry application; a two-axis piezo-electric positioning stage, implementing fine pointing by taking reference directional information from an onboard CMOS star tracker. Such a system can be applied to a lasercom payload to provide very good laser beam pointing stability. However, piezo-electric actuators often demand high voltages and have limited field of regard compared to a more flexible option of using micro-electromechanical (MEMS) FSMs.

 doi:10.20944/preprints202208.0206.v1

4. Conclusions

The need for multi-platform compatible optical communication transceivers is driven by demand for low-cost, mass produced, ready-to-fly COTS lasercom solution that can support ubiquitous multi-layer laser and hybrid (plus RF) communication network. A cross-platform lasercom terminal that is adaptable to both drone and CubeSat platforms must be capable of operating within the baseline performance despite differences in spectrum and amplitude of jitter experienced in the two cases. We have characterized the microvibration experienced in a 6U CubeSat with an integrated ADCS module and a heavy lift hexacopter drone. Determination of the peak and harmonic vibrational frequencies are important requirements to implementing an active fine pointing system with sufficient bandwidth. Since different platform gives different vibrational profiles, it is an indispensable task to conduct the kind of experiments described in this paper in a bid to achieve a high quality and reliable laser communication link.

Author Contributions: Conceptualization, F.I.; methodology, F.I. and M.C.; software, R.C.; validation, A.C., P.T., H.M., and M.C.; formal analysis, F.I. and M.C.; investigation, F.I.; resources, Y.M. and H.M.; data curation, F.I. and R.C.; writing—original draft preparation, F.I.; writing—review and editing, F.I. and A.C.; supervision, M.C., T.F. and H.T.; project administration, M.C., T.F., H.T.; funding acquisition, M.C., Y.M., T.F., H.T. and M.T. All authors have read and agreed to the published version of the manuscript.

Funding: The work reported in this paper was facilitated by the NICT-Kyutech matching research fund.

Conflicts of Interest: The authors declare no conflict of interest.

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