# Partial Image Reconstruction of an Artificial Satellite in Real Time using Background Natural Stars

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## ABSTRACT

The images of artificial satellites in Low Earth Orbit (LEO) captured by ground-based telescopes are distorted due to atmospheric turbulence and motion blur. The major constituents of distortion are tip-tilt aberrations and the solution to partially improve the resolution is to develop a real time tip-tilt mirror control system on a ground-based telescope. The real-time tip-tilt correction system is developed and applied on sky at the University of Canterbury Mount John Observatory (UCMJO). The operation of the real-time closed-loop AO system is verified on sky with the update frequency of 20 Hz. Since a short exposure of between 0.2 and 0.5 ms is required to image a satellite without motion blur, the real-time closed loop AO system requires a closed-loop frequency of between 2000 to 5000 Hz, respectively.

## 1. INTRODUCTION

This paper details the on-sky performance of a real-time closed loop tip-tilt correction system using a natural source (star). The closed loop AO system corrects the wavefront of the background star in real-time, and in parallel, the International Space Station (ISS) is imaged with a short-exposure camera over the same optical path.

In Section 2, the concept of reconstructing images of a satellite using a guide star within a tilt isoplanatic patch, is detailed. In Section 3, the design, operation, and performance of a real time tip-tilt correction system is provided. In Section 4, operations of the optical telescope, detector, and observation methods are described. In Section 5, the results of the on-sky observation of the ISS using tip-tilt correction in real-time system are detailed. A conclusion is given in Section 6.

## 2. BACKGROUND

To reconstruct images of large, low-Earth orbit (LEO) satellites using ground-based telescopes, which are distorted due to the adverse effects of imaging through a turbulent atmosphere, concomitant imaging of a guide star, preferably within the isoplanatic *patch* [1] of a satellite's path, is required. Once an estimate of the distortion function, commonly referred to as the point spread function (PSF), is known *a posteriori*, either deconvolution from wavefront sensing [2], real-time adaptive optics [3], or a hybrid of both [4] can be applied. Given, however, the low probability that at least one bright natural source object can be located within an isoplanatic *patch* over the usable path of an expected satellite trajectory, laser guide stars have been used [5] in the form of projected sources that can be moved with the telescope during tracking. However, since such laser projections result in the generation of a relatively low-altitude source, distortion measurements contain incomplete cylindrical volumes of optical aberrations; the result of such inaccuracies is known as the *cone* and *focal* effects [6]. Such effects can be minimized by using more than one source object and atmospheric tomography [7], and a selection of natural and/or artificial guide stars, which can be applied over a wide field-of-view (FoV) to estimate the spatially variant PSF [8] for off-axis correction over the expected path of a satellite.

Due to restrictions on the use of laser guide stars in dark sky regions [9], in addition to their initial cost and maintenance, natural guide stars for turbulence measurements are often employed. However, the number of bright stars that may be suitable for wavefront sensing for image reconstruction and/or optical path correction is severely limited to <1% of the sky [10]. Given our group's resources, in terms of funding and local facilities, a low-order adaptive optics (AO) system was developed and is now used at the University of Canterbury Mt. John Observatory (UCMJO) for space situational awareness (SSA). Our current system was developed and has been used over a two year period from 2020 [11,12] to confirm the identity of large pieces of space junk in LEO. Some more recent extensions include identifying Geostationary orbiting spacecraft and, on a significantly more ambitious scale, to verify the presence of a satellite in cislunar space, which are on-going research projects. This paper is based on the earliest of our SSA research, i.e., the restoration of images of larger exoatmospheric objects in LEO.

## 3. REAL TIME TIP TILT CORRECTION SYSTEM

### 3.1 The Adaptive Optics System

The Adaptive Optics (AO) system at UCMJO provides low-order correction to image perturbations caused by atmospheric turbulence. The system has been designed to minimise PSF displacements of two orthogonal axes, i.e., tip and tilt, using a wavefront sensor and control system. It requires signals from two control channels to operate simultaneously. The proposed method of beam tilt is a linear process and operates individually on each axis and can be described using the schematic shown in Fig. 1.

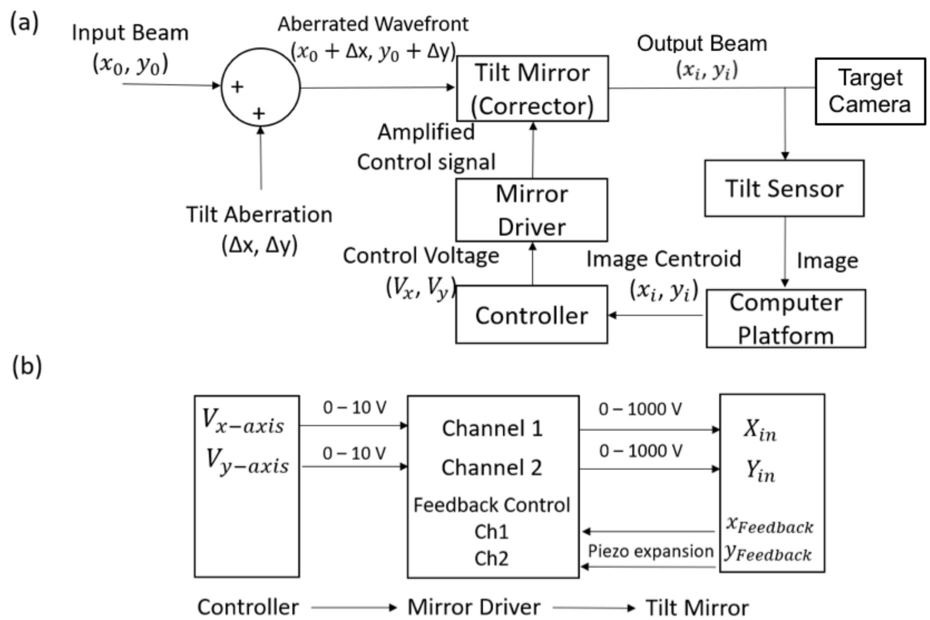


Fig. 1: Tip-tilt mirror control system: (a) overall block diagram of the system, and (b) details of the closed-loop piezo control and driver [13].

Figure 1 illustrates the design of the controller which is based on an iterative process and uses the difference between two captured frames, i.e., the first and each successive frame, to determine the degree of correction using a centroiding algorithm. Correction is an inverse response to variations from the input beam and second-order tilt aberrations, and corrections are achieved by a PID control algorithm and high-voltage actuator driver. The fundamental principle of the linear control system is shown in Figure 1, where the feedback of the tilt sensor-controller path is shown. Feedback and correction in the sensor-mirror loop compensates for a disturbance, improving the transient response and reducing the steady state error. The transient response is a significant factor in the design due to the frequent variation of tilt disturbances.

During field tests, such variability appeared to be directly related to wind speed, which is mathematically formalised by the refractive index structure constant, $C_n^2$ [4]. A $C_n^2(h)$ model and velocity profile and wind velocity model $v(h)$

have been developed for New Zealand's largest observatory, UCMJO [14]. The system has a sufficiently short transient time, but a sudden overshoot can cause system oscillation. Therefore, a compromise is necessary between large gain for rapid response and small gain for system stability, and our local model parameters reflect such changes. The tip-tilt mirror control system that is based on an optical breadboard design, is illustrated in Figure 2.

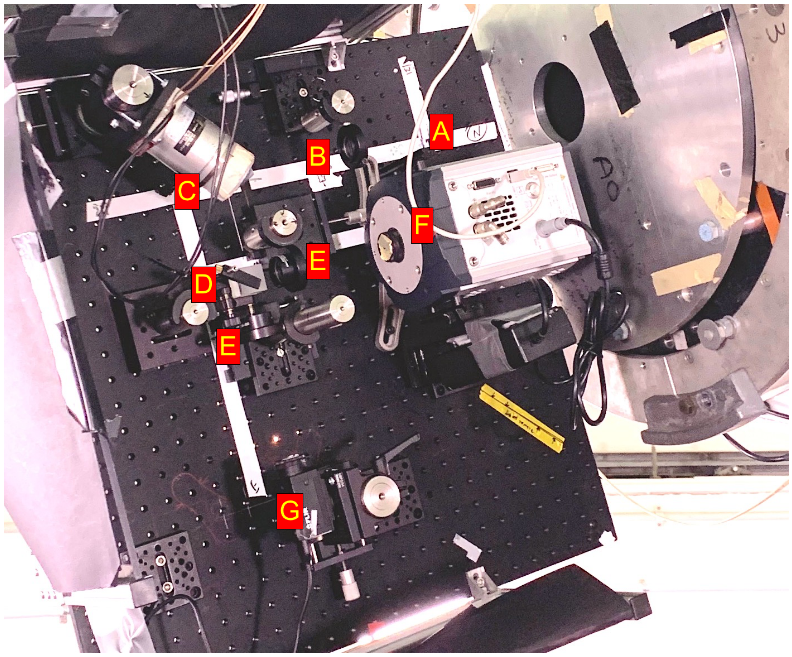


Fig. 2: On-sky optical system: **A**: f/6.25 telescope focal point; **B**: Collimating achromat lens; **C**: S-915.106 tip-tilt mirror; **D**: Beam Splitter; **E**: f/6 plano-convex achromats; **F**: Andor iXon WFS camera; **G**: FLIR Grasshopper science camera; **H**: and **I** (not shown**)**: P-865.30 Piezo Controller-Driver, and Tip-tilt Controller.

A controller, implemented as an embedded system module, calculates the difference in centroid position between two captured frames, and the inverse of the corresponding control signal will be applied to the Piezo Mirror driver. A list of major components used for low-order tip/tilt correction, include:

A. Approximate focal point from an f/6.25 Schmidt Cassegrain 0.61 m Boller and Chivens telescope.
B. f/6, 150 mm Achromat doublet collimating lens.
C. Physik Instrument S-915.106 Tip-Tilt mirror, which is a two-channel controlled deflection mirror. The piezo driver (Item-H) uses two of three 1000 V driver signals to drive the mirror. Internal feedback is supported through two leads, which are compatible with our driver (Item-H).
D. Non-polarised, 20 mm, 400-700 nm, 50/50 beam-splitter.
E. Two f/6, 150 mm Achromat doublet focusing lenses.
F. Andor iXon Ultra 897, electron-multiplying, wavefront sensor camera, supporting a 512 × 512 pixel, Peltier cooled (to -100º C), 16-bit monochrome, USB 2.0/Camera-Link interfaces.
G. FLIR Grasshopper (NIR) USB3.0 target camera, supporting a 2048 × 2048 CMOS sensor.
H. Physik Instrumente P-865.30 Piezo Driver (not shown), is a joint driver-controller for PZT position systems. Inputs are 0V-10V and generates three outputs of 0-1000V; two inputs are used for mirror position feedback.
I. Tip-tilt Controller (not shown), is a UC designed customised hardware module comprising a 2-channel, 16-bit Digital to Analog device (DAC) AD5752, Atmel ATSAM4S8BA micro-controller and Microchip $I^2C$ 512 k Bit EEPROM.

### 3.1 AO Performance

Initial laboratory measurements of our AO system on a 633 nm laser source showed that the full-width half-maximum (FWHM) long-exposure PSF was improved by up to 23% [15]. On-sky FWHM performance showed an improvement of 16.7% for a sampling frequency of 40 Hz, and after an independent channel scaling system [15]. Our on-sky results using a natural point source (star), $\delta$ Cru, over moderate seeing, is shown in Table 1. By applying tip-tilt image correction, up to 87% of total distortion can theoretically be corrected using 2$^{nd}$-order Zernike polynomials [4].

Furthermore, the *tip isoplanatic angle* can be considerably larger than the isoplanatic angle [4], which is associated with corrections of higher-order Zernike polynomials [16]. Correspondingly, this allows the isoplanatic patch for tip correction to be much larger than the isoplanatic patch required for high-order correction, and we apply this relaxation when targeting natural point source guide objects along the path of a target satellite. When imaging large extended objects, such as the ISS, second order aberrations and corresponding corrections result in small displacements in the image plane of the science camera, and subsequently show corrections of the extended object along its trajectory. The application of low-order adaptive optics to minimise displacement errors over the path of large artificial objects in LEO, such as the ISS, are discussed in the following sections.

Table 1: Improved AO performance with 40 Hz loop frequency and independent channel scaling [15]

| Conditions | Open-loop FWHM (arcsecs) | Closed-loop FWHM (arcsecs) | FWHM Improvement |
|---|---|---|---|
| Different Channel Scaling | 3.7398 | 3.1148 | 16.7% |
| Identical Channel Scaling | 4.0536 | 3.5665 | 12% |

## 4. SATELLITE OBSERVATION

The Boller and Chivens (B&C) telescope at the University of Canterbury Mount John Observatory (UCMJO) is used for imaging artificial satellites at LEO. The primary aperture and focal length of the B&C are 0.61 m and 3.85 m respectively, and the NIR detector (FLIR GS3-U3-41C6NIR-C) employs a sensor format of 1” × 1”, and supports a pixel width of 5.5µm. The telescope Field of View of (FoV) is 10 arcminutes, is operated at the Sidereal rate, and is pointed to a guide star that has a proximity which coincides with part of the trajectory of a satellite or the ISS. During the estimated time of contact, multiple frames of the satellite with a reference star are imaged [15,16].

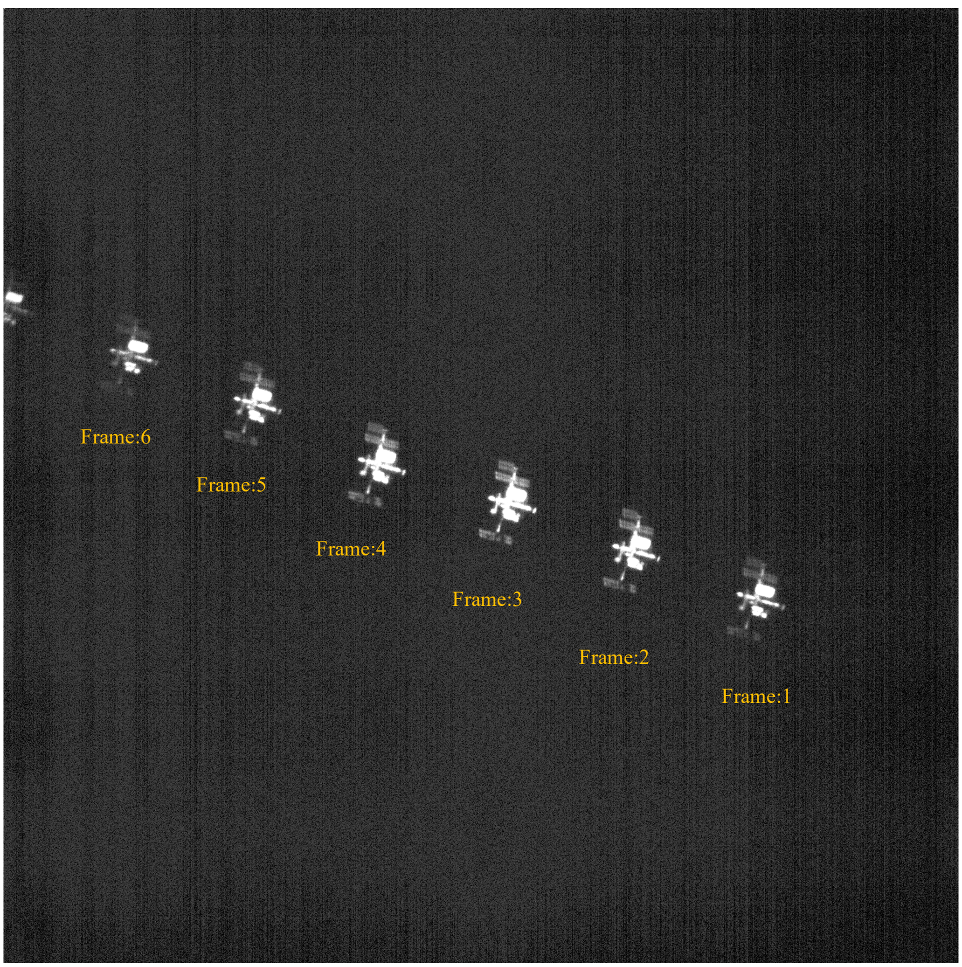


Fig.3 Stacked images of ISS.

The ISS in Figure 3 was imaged by the Grasshopper camera (G) shown in Figure 2 on 14 February 2022. During the observation the visible magnitude of the ISS was -3.8, elevation was 85 degrees, the slanting distance was 440 km, and the required exposure time to image and minimize the satellite motion blur was 0.17 ms. The ISS is shown in Figure 3 as several stacked images. The telescope was pointed to the star HIP35020, and the visible magnitude of the star is 4.8. The star is not visible in the stacked image (Figure 3) due to the short exposure period used for the wavefront sensor camera, but was confirmed prior to capture to be in the center of the FoV, i.e., at approx., [1023, 1023]. When the satellite enters the FoV with the star at the center, the Grasshopper camera (G) images the satellite in the foreground, which is in open loop. A magnified image of the ISS (from Frame 4) is shown in Figure 4.

The operational frame rate of the Grasshopper at 40 frames per second is based on the orbital velocity of ISS (7.6 km/s), slanting distance (440 km) between telescope and target, and the image sensor size (11.3 mm). The time taken for the ISS to cross the FoV of the imaging system is estimated to be 170 ms. Hence, six frames of ISS can be captured when it passes within the FoV of telescope which is shown in Figure 3. The AO system containing the iXon camera (F) and tip-tilt mirror (C) shown in Figure 2, partially corrects the distorted wavefront from the star in the background of the closed loop system, as the ISS passes through the FoV. Since the Grasshopper camera (G) is in the optical path of the AO system, it receives the reconstructed images of the artificial satellite in real time.

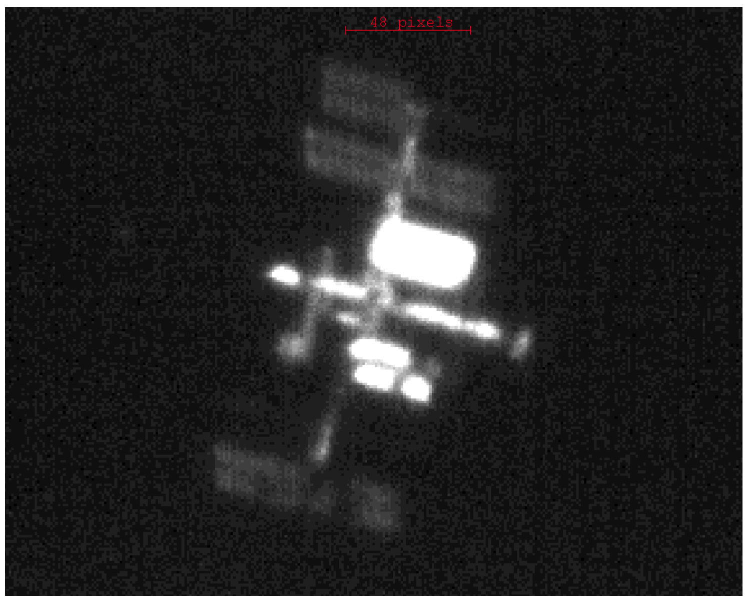


Fig.4 Image of ISS (from Frame 4).

## 5. Results

Given this configuration, two objects are imaged. The first is the background star, which appears stationary due to Sidereal rate tracking; the second is a satellite, which is in rapid motion in the foreground. The telescope and target camera allow both objects to be captured, hence the grasshopper has as a short exposure of 0.17 ms to image the ISS without motion blur. However, the wavefront sensor camera supports a smaller detector than the Grasshopper, and therefore, its FoV only allows imaging of the background star. The update frequency of the closed-loop AO system is 20 Hz. This corresponds to an AO system update for wavefront correction of the target every 50ms, which is considerably slower when compared to the exposure time of the ISS (0.17 ms). Currently, the AO system is more suited for low-order turbulence corrections of celestial objects, such as stars and planets, which move at a relatively slower rate. The images of the ISS shown in Figure 2 and Figure 3 are due to very short exposures that attempt to reduce the effects of atmospheric decorrelation.

Centroids of the ISS over six frames is shown in Figure 5 and estimation of centroids are detailed in the authors previous publications [11,12]. Since the time taken for the ISS to cross the FoV of telescope is 170 ms, and given the update rate of closed loop AO is 20 Hz (50 ms), the displacement of the ISS centroid observed is given in only three frames, which is shown from Frame 3 to 5 in Figure 5. This verifies that closed loop AO is operational but with low frequency. By determining the centroid of the ISS in each frame, the displacement of the ISS in vertical and horizontal axes of each frame with reference to previous frame is estimated, which is shown in Figure 6 and Figure 7, respectively. In Figure 6, the displacement of the ISS in the vertical axis is validated at Frame 3 to 4 and in Frame 4 to 5. In Figure 7, the displacement of the ISS over the horizontal axis is verified in Frame 3 to 4 and Frame 4 to 5.

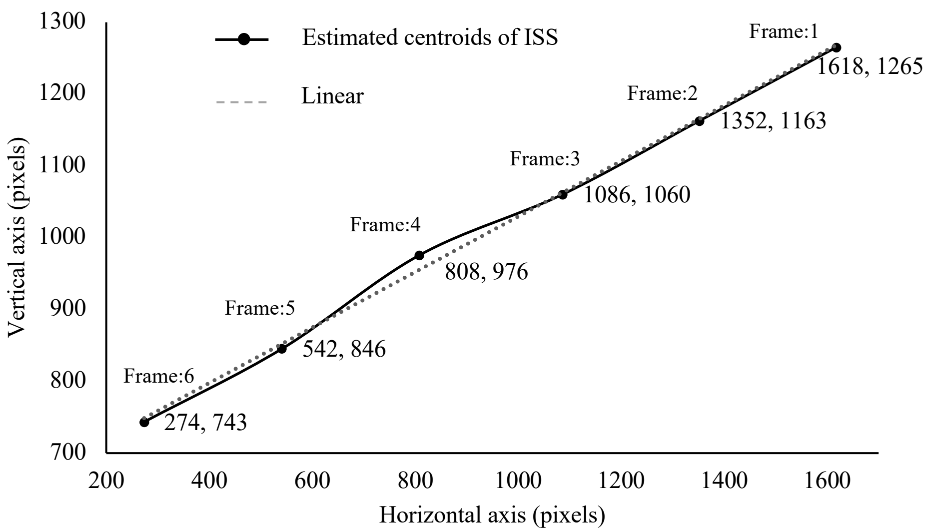


Fig.5 Centroid of ISS in the stacked frames.

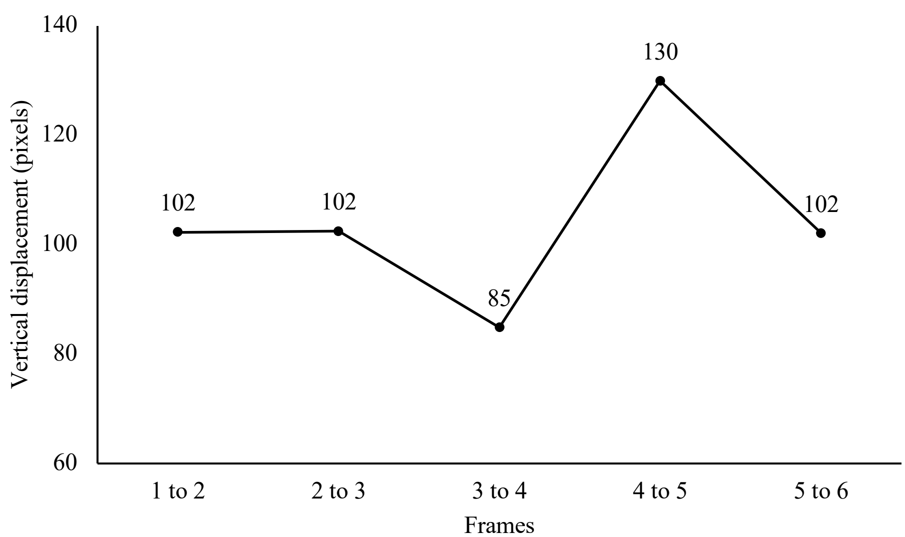


Fig.6 Vertical displacement in the centroid of ISS over the stacked frames.

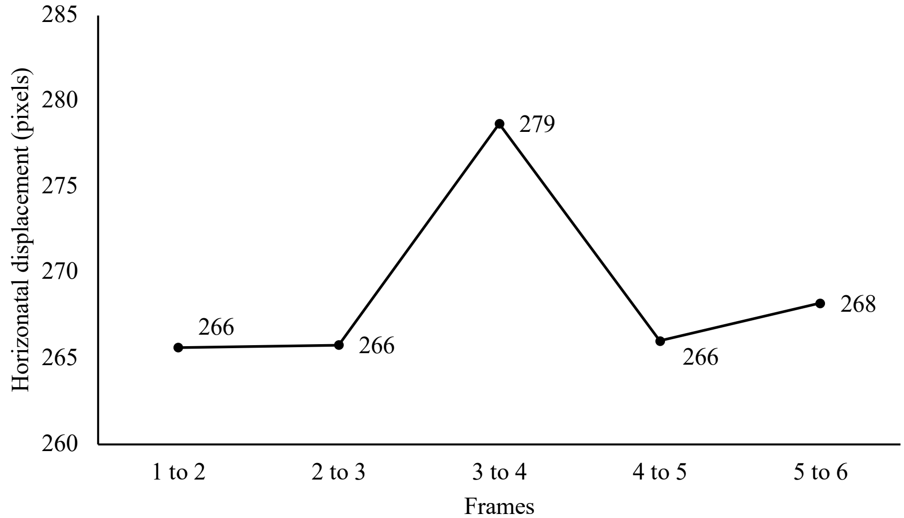


Fig.7 Horizontal displacement in the centroid of ISS over the stacked frames.

## 6. CONCLUSION

A new approach has been developed and implemented on sky to partially reconstruct the image of artificial satellites in Low Earth Orbit using a natural star in real time. Since this method requires images of two objects (star and satellite), both moving at different velocities in real time, the current update frequency of our closed loop AO system is currently sufficient to provide effective real-time correction. In this method, the telescope tracks a natural source (star) at the Sidereal rate over which the satellite will transit at an estimated time. To overcome the effect of motion blur when imaging satellites moving at relatively high velocity in LEO, the target camera, operating over short exposure times, i.e., from 0.2 to 0.5 ms, will require an AO system operating at a closed-loop frequency of between 2000 Hz and 5000 Hz for wavefront correction in real time. Therefore, due to the low closed-loop frequency from our current system, real-time reconstruction of artificial satellite images using a natural background source has yet to be achieved. However, the operation of our closed-loop AO low-order system has been verified on-sky using a low closed-loop frequency.

## ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the staff at University of Canterbury Mt. John Observatory. This research was supported by the Marsden Fund Contract (MFP UOC1803), administered by the Royal Society of New Zealand.

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