A Hybrid Adaptive Optics System for Space Situational Awareness

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INTRODUCTION

We are developing and will commission a space debris and object detection system in New Zealand that will provide high resolution imaging capability to examine orbiting satellites using a simplified, low-cost approach. A hybrid system is proposed and will comprise a closed-loop tip/tilt mirror to remove low-order aberrations in real-time. An open-loop deconvolution from wavefront sensing system will determine the spatially variant distortion function from multiple natural guide stars over a wide field-of-view. To achieve this, a geometric wavefront sensor will provide estimates of phase distortion from multiple source objects, i.e, three or more background stars. We currently use images of the International Space Station, such as shown in Fig. 1, for comparative, system testing.

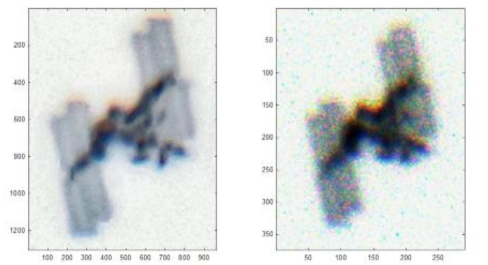

Fig. 1: *Inverse high- (left) and low- (right) resolution ISS images taken from Canterbury University Mt. John Observatory.*

Orbiting satellites and large space debris objects are detected within a wide field-of-view, and over such a field, a few natural stars may also be imaged. At large observational sites, laser guide stars are typically used to measure wavefront distortion from turbulence. However this is not possible at our premier University of Canterbury Mt. John Observatory in New Zealand, since it is registered as a dark sky reserve. We will employ atmospheric tomography [1] as a complementary sub-system. A system model has been defined to describe our hybrid configuration.

SYSTEM OVERVIEW

Our method to improve image resolution of large space debris objects and satellites for space situational awareness uses natural stars as reference objects. Firstly, wave front perturbations due to air turbulence within a spatially invariant region are determined using a Shack Hartmann wavefront sensor. Estimated low-order optical aberrations within an isoplanatic patch are removed, lowering the residual wavefront error, ϵ.

Fig. 2 shows how the forward path of a wave front from a single star **f** is convolved by distortion function **h**, the perturbations measured in the presence of additive noise η, and lastly, aberrations corrected in real-time using a closed loop tip/tilt AO control system.

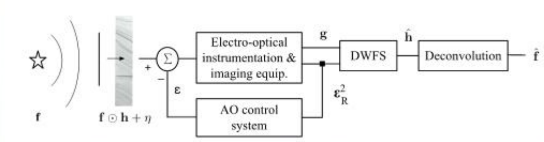

Fig. 2: *A partially compensated deconvolution from wavefront sensing model for improved satellite imaging.*

The spatially invariant point spread function $\hat{\mathbf{h}}$ can be estimated using deconvolution from wavefront sensing from remaining non-AO corrected wavefront errors defined by **g**, resulting in image restoration, $\hat{\mathbf{f}}$.

Secondly, additional background stars (not shown) can be used over a wide field to determine off-axis estimates using atmospheric tomography. Simulations using reservoir computing to estimate the spatially variant point spread function have been developed [2], and on-sky use is planned.

NATURAL STAR ESTIMATES FOR ATMOSPHERIC TOMOGRAPHY

The ability to detect multiple, faint background stars for wave front sensing is a key part of this project. Fig.3 shows the average number of stars per square degree in the galactic plane, galactic pole, and entire sky. If the image sensor detects stars with 9th magnitude then the number of stars per square degree in the galactic plane, galactic pole and entire sky is 12.8, 1.99, and 4.1 respectively. Given our FoV of 20 arc minute, it's possible to have four stars when pointing our telescope with in the galactic plane.

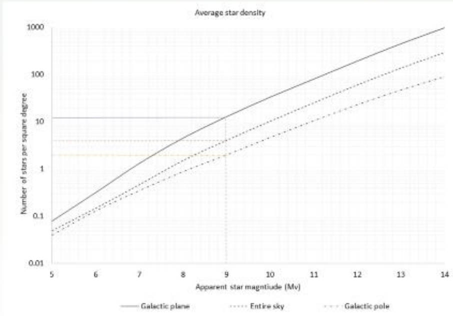

Fig. 3: *Average star density over the spectral band: 250 - 1050 nm.*

WAVEFRONT SENSING FOR ANISOPLANATIC IMAGING

Our work has focused on adapting sparse transforms to represent optical wavefront aberrations for minimizing image distortion by deconvolution. For example, using slope measurements from two defocused planes, our geometric wavefront sensor can also provide estimates of Zernike terms using ridgelets. This not only reduces processing time and also improves performance over low photon flux levels, as shown in Figure 4.

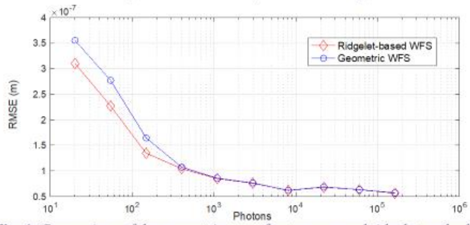

Fig. 4: *Comparison of the geometric wave front sensor and ridgelet method* [3].

The method is accomplished by first decomposing the image into a set of wavelet bands, and then analyzing each band by a local ridgelet transform.

CONCLUSIONS

An acquisition and signal processing system that uses multi-object adaptive optics to improve the resolution of satellite and large space debris object imaging, and without the need for laser guide stars, has been presented. Our simulation and laboratory test results are encouraging and our group plans to implement this system on-sky for evaluation late in 2019.

REFERENCES

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