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Exoplanet Detection and Characterization: Development and Results of a New Generation Imaging Fourier Transform Spectrometer

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ABSTRACT

Spectroscopy in exoplanet imaging has been used to characterize exoplanets in astronomy for the last two decades. To optimize new and promising techniques, such as using very high-spectral resolution to identify exoplanet molecules in a speckle-limited image, new imaging spectrograph technologies are needed. These new techniques are difficult to implement as they require both a large field-of-view (FOV) to search for hidden exoplanets, and a high-resolution spectrum for every resolution element of the FOV. The Subaru Pathfinder Instrument for Detecting Exoplanets & Retrieving Spectra (SPIDERS) will showcase a new generation imaging spectrograph, using an imaging Fourier transform spectrometer (IFTS) to acquire a wide FOV from low R40 to high R20,000 spectral resolution. Off-the-shelf devices have few options for scan speed and shape control as typical applications can provide a bright light source to take advantage of faster scan speeds with a high spectral signal-to-noise ratio. Implementing new imaging methods and faster techniques, SPIDERS requires an IFTS that can scan much slower than usual to minimize the impact of detector read noise whilst prioritizing scan stability. Using an off-the-shelf Michelson interferometer, a custom PCB was developed and implemented to facilitate a voice coil driving and metrology feedback circuit that will provide complete control over scan speed, length, and shape. A helium-neon laser provides fringe quadrature feedback that is used to determine Angstrom-level positional feedback for closed-loop control. The C-based controller generates a 16-bit current command at 100kHz to provide stable scanning and accurate positioning. Preliminary results are proving the success of the drive and metrology circuit design, the quadrature algorithm, and the closed-loop control. This paper will present the controller design and implementation, along with its performance and initial results on the bench.

Keywords: Imaging Fourier transform spectrometer, Michelson interferometer, fringe quadrature, closed-loop voice coil control, exoplanet imaging and characterization, adaptive optics

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1. INTRODUCTION

The NEW EARTH laboratory team at the National Research Council Canada (NRC) Herzberg Astronomy & Astrophysics (HAA) observatory in Victoria BC Canada have been working on new high-contrast imaging technologies and ideas [1]. The current project, the Subaru Pathfinder Instrument for Detecting Exoplanets & Retrieving Spectra (SPIDERS) [2] deploys many new technologies designed specifically for the detection and characterization of exoplanets using the 8.2m Subaru telescope on Maunakea, in Hawaii [3].

In addition to the identification of molecules in the atmospheres of exoplanets using mid to high spectral resolution, an imaging spectrograph can use low spectral resolution to optimize SDI post-processing and planet finding in a large field-of-view (FOV) with approaches like the fast atmospheric self-coherent camera technique (FAST) [4] and new self-coherent camera (SCC) algorithms [5]. Higher spectral resolution imaging around key bands, such as CH₄ or CO, could also be used to search for planets hidden in the star speckle noise. Furthermore, at very high spectral resolution the IFTS can be used to do velocity mapping of emission lines. With its low to high dynamic resolution capability, the IFTS is positioned to be a powerful tool to perform cutting-edge exoplanet science.

2. OPERATIONAL PRINCIPALS

Before its use in exoplanet imaging, Fourier transform spectroscopy was and still is a commonly used process in industries that require the precision measurement and analysis of a material, compound, or light source. Commercially available devices like ABB's Fourier Transform Near-Infrared Process Analyzer FT-PA2000-300 [6] use a bright internal source to create a strong signal for spectral analysis of any sample that light can transmit through. Using this device on SPIDERS, we instead use an exoplanet system as the input signal to perform spectral analysis of the star and its companions.

2.1 THE MICHELSON INTERFEROMETER DESIGN

At the heart of the IFTS is a Michelson interferometer with two retroreflector mirrors attached to an arm on a flexural hinge that facilitates interference of an image along a changing optical path difference (OPD), figure 1.

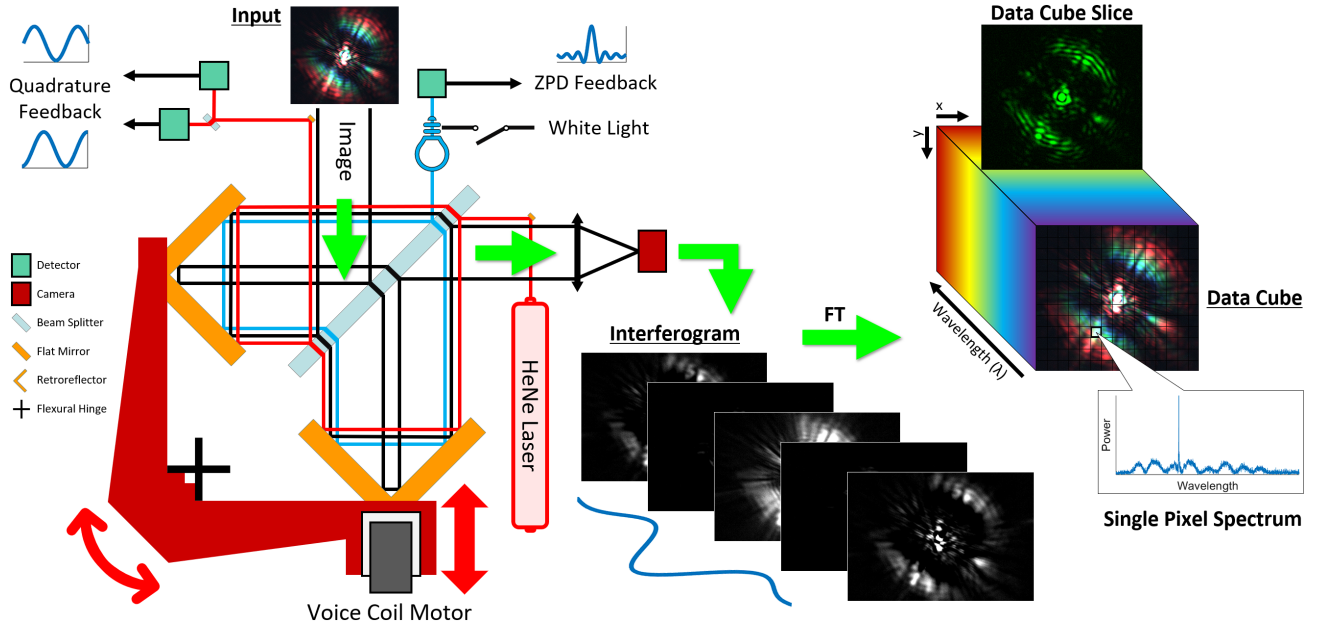


Figure 1. A scanning Michelson interferometer receives an image and outputs its interferogram.

The interferometer scans continuously over an OPD window using a voice coil motor to position the arm in space, a helium-neon (HeNe) laser to provide positional feedback, and an internal white light to find the scan

center (zero-OPD, or ZPD). An incoming chromatic (broadband) image is interfered with itself to produce an interferogram on the detector of a monochromatic camera. The interferogram recorded at each pixel is then Fourier transformed (FT) to recover the spectrum of the image for each pixel. The resulting wavelength specific images represent the spectral components (slices) of the input image and make up the data cube. Stacking and assigning colour to the data cube images can provide an insightful visualization of the original chromatic image.

2.2 CLOSED-LOOP VELOCITY CONTROL

Using the HeNe laser fringe signals, a quadrature algorithm was developed with the help of ABB to recover the OPD of the IFTS [7, 8], similar to the method used on SITELE [9]. With a robust method to recover the position of the IFTS along its scan, a closed-loop controller was designed to ensure scan stability and repeatability over long-term operation. Without closed-loop control, external disturbances such as mechanical vibration or turbulent air pushing on the IFTS arm will cause the system to deviate from the commanded trajectory and significantly deteriorate the IFTS scan performance. Keeping the velocity constant over the duration of the scan is critical to ensuring each camera image gets an equal exposure time and are captured at near-equidistant OPD. Because the voice coil is driven through discrete position commands proportional to the current it is drawing, the regulated velocity command must be changed into a position command before it is used. Ultimately, the constant-speed motion during a scan is achieved by providing small linearly increasing position commands to the voice coil while taking advantage of the heavy IFTS arm that increases inertia and filters the discrete step motion. The controller block diagram is shown in figure 4 below.

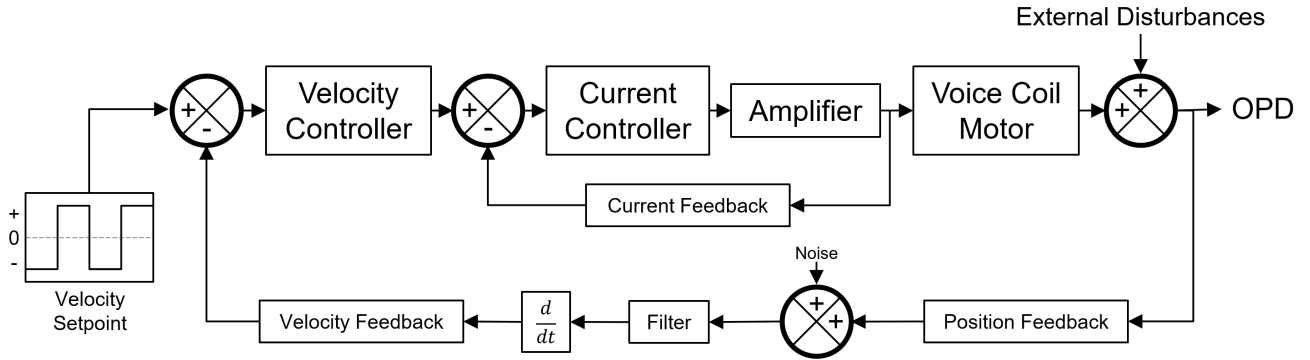


Figure 2. A closed-loop velocity-current cascade controller to regulate the voice coil motor scan speed.

Various controllers were explored in simulation and on the bench including position-velocity cascade and pole-placement, but in the end, the velocity-current cascade controller shown in figure 4 was the simplest to tune and optimize on the bench with a constant positive or negative velocity input. The inner current controller loop is implemented via hardware and does not require any tuning. Although some FTS devices operate in step-scan mode to increase integration time at specific OPD, this system is designed to work at a constant speed only, also referred to as the continuous-scanning mode.

3. IMPLEMENTATION, PERFORMANCE, AND EARLY RESULTS

To acquire the position feedback, drive the voice coil, and implement closed-loop control for the IFTS system, custom electronics and software were developed. A printed circuit board (PCB) was designed to mount off-the-shelf analog-to-digital converters (ADC) to measure the fringe signals, a digital-to-analog (DAC) converter to command the voice coil current controller, and support for a microcontroller unit (MCU) to control the system. Every $10\mu\text{s}$ (or at a rate of 100kHz) the 16-bit ADCs measure and sends the analog fringe signals to the MCU, the MCU determines the current position, a new command is sent to the 16-bit DAC, and the current controller provides a new position command to the voice coil. A sheet metal enclosure was designed to house a power supply, fan, and PCB assembly while fitting comfortably on a 1U server rack shelf ($< 1.75\text{in}$ tall). BNC connectors on the front allow the input or output of 3.3V triggers while a USB can be connected to set the scan speed and window

serially from any PC, figure 5 (left). A custom cable connects the IFTS controller to the ABB FTS voice coil and fringe signal detectors, mitigating any addition of heat or vibration from the controller by housing it away from the system.

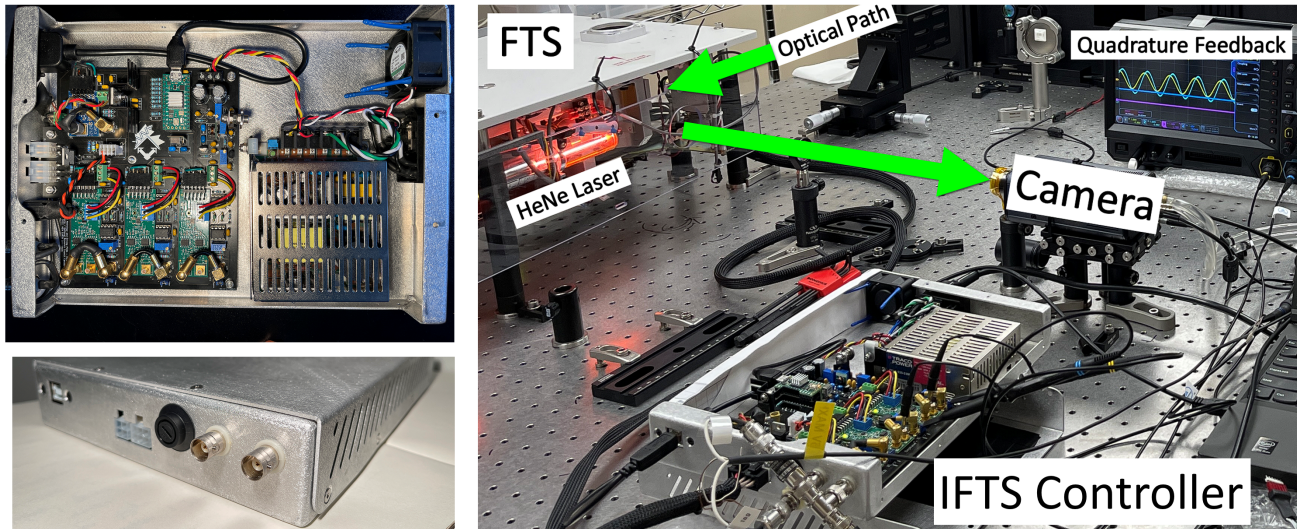


Figure 3. The custom IFTS controller system (left) and early experimental setup in the NEW EARTH lab (right).

The closed-loop controller was developed first in the NEW EARTH lab before being optimized on the SPIDERS bench for speeds between 0.36mm/s and 1.2mm/s , scanning back and forth indefinitely over ZPD. An OPD window from -10mm to 10mm or as small as $100\mu\text{m}$ anywhere within that range can be utilized for double-sided or single-sided scans. Using a scan speed of 0.36mm/s in an OPD window from -3mm to $+3\text{mm}$, the IFTS position and velocity response are shown in figure 6 below from left to right, respectively, for the system in open and closed-loop control.

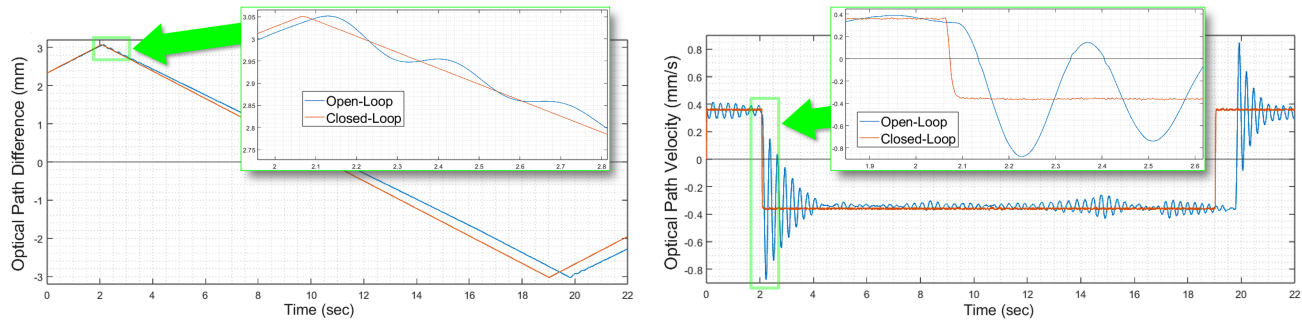


Figure 4. The open and closed-loop response in position and velocity for a 0.36mm/s continuous-scan.

When the speed setpoint changes sign (the system reaches the edge of a scan window), the open-loop system takes over 2 seconds to settle and never fully settles due to external vibrations combined with its highly under-damped response. Furthermore, the open-loop control suffers from steady-state error and on average does not reach the scan speed setpoint, leading to longer than expected scan times. In contrast, the closed-loop system settles in about 35ms (or under $15\mu\text{m}$ of OPD) and minimized the benchtop vibrations seen in open-loop.

Linking the camera images to the OPD, the IFTS controller can either output a 3.3V trigger at equidistant OPD intervals with non-uniformly triggered camera exposures, or a non-equidistant OPD can be output in Angstroms over serial communication with uniformly triggered camera exposures. In either the equidistant OPD or non-equidistant OPD case, the camera images from a complete scan produce the raw interferogram. The

interferogram at equidistant OPD intervals can utilize a standard fast Fourier transform (FFT) to recover the spectrum, while the uniform triggering at non-equidistant OPD intervals require a non-uniform FFT (NUFFT) to interpolate the interferogram and resample to use the standard FFT. Details on these operations are not discussed in this paper but can be found in publications such as [10] and [11].

To evaluate the spectroscopic performance of the IFTS system, a SuperK COMPACT supercontinuum white light laser [12] was used as a source on the SPIDERS bench with a C-RED 2 infrared camera [13]. The camera took images at equidistant OPD locations every 400nm along a -3mm to $+3\text{mm}$ window at a constant speed of 0.36mm/s , requiring an average frame rate of 900Hz . The 15,000 images recorded by the monochromatic camera produce the interferogram - a subset of black and white images around the ZPD shown in figure 7 on the left - where each pixel is Fourier transformed (FT) to produce a wavenumber spectrum at each pixel in the FOV. The data cube of wavenumber (or wavelength) specific images can be stacked and coloured to produce the original chromatic input image (figure 7, right), with wavelength from red (long) to blue (short).

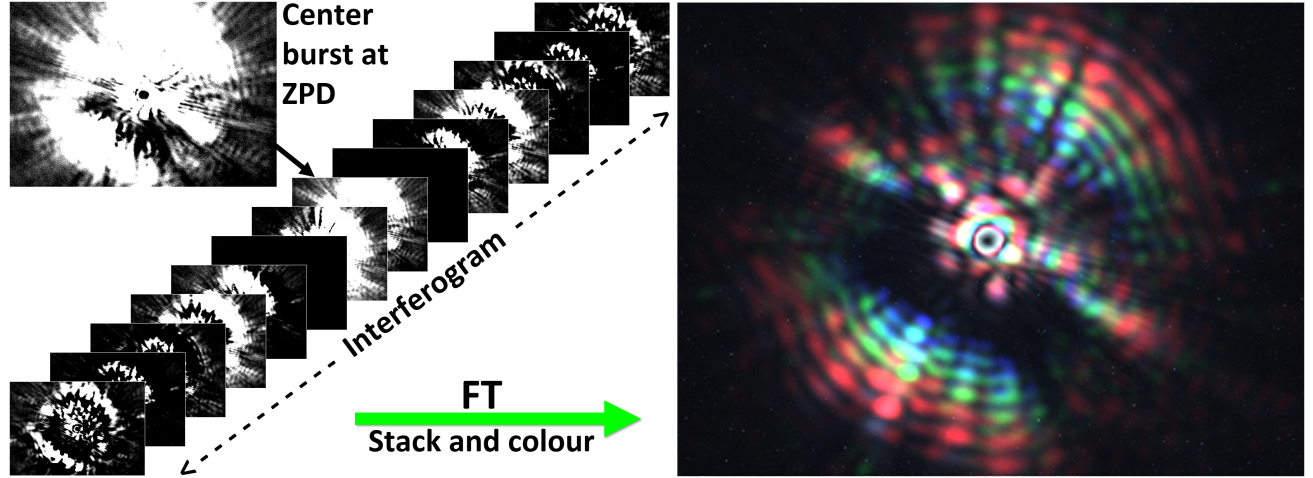


Figure 5. The interferogram produced and recorded by the IFTS (left) and the processed broadband image (right).

Using the adaptive optics (AO) system within SPIDERS, speckle suppression methods like *Thompson 2023* [14] can be used to remove the bright light directly surrounding the star (or benchtop light source in this case) to see potentially hidden planets that might exist. The coloured image in figure 7 illustrates how a deformable mirror (DM) can statically correct the image and allow us to see closer to a bright source, discussed in *Thompson 2023* along with an approach to dynamically corrected atmospheric effects during a real observation.

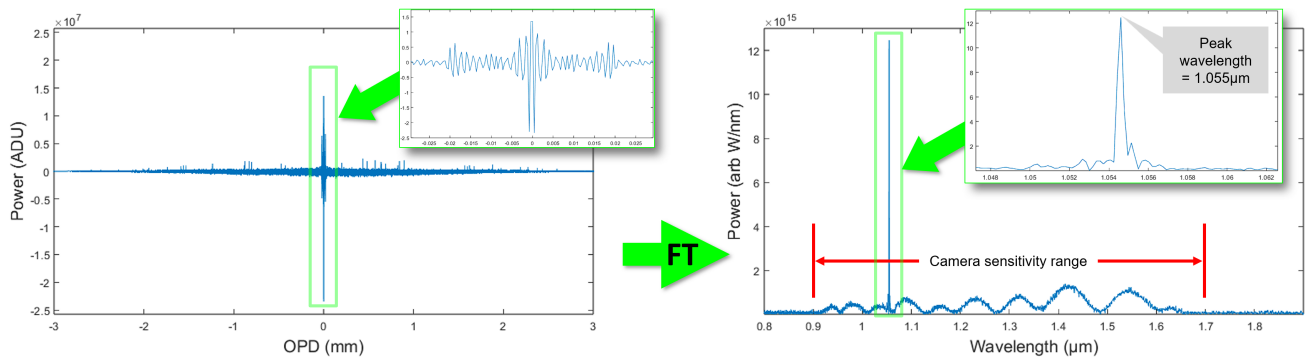


Figure 6. The 2D interferogram (left) and wavelength spectrum (right) of a benchtop supercontinuum white light source.

Analysing the bright regions in the FOV surrounding the core of the image (to negate chromatic effects caused by the coronagraph removing the central core light, currently installed on SPIDERS), an average 2D

interferogram and wavelength spectrum of the light source can be acquired, shown in figure 8 above, respectively. The obtained spectrum confirms that the C-RED 2 camera is only sensitive between 0.9 and $1.7\mu\text{m}$, with a peak intensity around $1.06\mu\text{m}$. The spectral resolution of this 3mm scan is around $R6,000$, where a possible 10mm scan could produce an $R20,000$ spectrum, or $R100$ for a $100\mu\text{m}$ scan. The interferogram can always be trimmed in post processing to reduce the resolution, but a longer scan must be performed to increase it. During this initial test on the SPIDERS bench, it was discovered that the final folding mirror was not optimal for the infrared waveband we were imaging in and resulted in the strange and lumpy spectrum we see in figure 8, rather than the unique spectrum published by the laser manufacturer [12]. Verifying the measured peak intensity and confirming the camera sensitivity range shows that the IFTS controller and system are working as expected.

4. CONCLUSIONS AND FUTURE WORK

Initial results of the IFTS system on SPIDERS indicate that we are able to recover high-resolution spectra over a large FOV on the bench. Tests using a supercontinuum white light source and equidistant OPD intervals proved the success of the new IFTS system and its ability to provide highly-stable motion for long-term continuous-scanning operation. With the ability to reprogram the scan speed and window for use with different triggering modes (equidistant or non-uniform OPD), the system is able to provide unique capabilities for current state-of-the-art and future high-contrast imaging instruments to use for exoplanet imaging and characterization. Current development with non-equidistant OPD serial output and uniform triggering is proving to be easier to integrate with cameras and the rest of the system, while adding some complexity to the post processing. With the planned commissioning of SPIDERS in 2024, we are refining the data cube processing algorithm and system for use over long observing nights and more detailed performance and analysis publications.

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