Development of a Cryogenic Far-infrared Post-dispersed Polarizing Fourier-transform Spectrometer

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Introduction

The earliest stages of star and planetary formation can only be observed at far-infrared wavelengths which requires the use of a space-borne platform. The next generation of far-infrared space observatories will feature large (2 m to 3 m class), actively cooled (6 K) telescopes with high resolution spectroscopic capabilities provided by a Fourier transform spectrometer (FTS). The instrument concept that is widely considered by ESA, JAXA, and NASA to be the leading candidate for future missions is the Post-Dispersed Polarizing Fourier Transform Spectrometer (PDPFTS). In the absence of telescope self-emission and with access to ultra-sensitive detectors (noise equivalent power $\sim 10^{-19}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$) the former multiplex advantage of an FTS becomes a disadvantage if instantaneous broad spectral measurements are attempted. With the spectral noise density now determined by the astronomical source itself, the only way to reduce the total photon noise is by reducing the instantaneous spectral bandwidth observed by the FTS, typically to a fraction of one percent. In practice, this is accomplished by post-dispersing the output of an FTS using a diffraction grating. At high angles of incidence, reflection diffraction gratings operate with high and uniform efficiency ($\sim 80\,\%$) for transverse magnetic (TM) polarized light, but lower and variable efficiency (10 % to 40 %) for transverse electric (TE) polarized light. The polarizing encoding properties of a Martin-Puplett interferometer [1] can exploit this strong polarization dependence by ensuring that the interferometer output presents the TM mode to the grating. While the principles underlying the operation of the PDPFTS are well understood, to date a fully cryogenic integrated system has not been realized in the laboratory. In this poster, we describe the development of a cryogenic far-infrared PDPFTS to gain a better understanding of the challenges presented by this hybrid instrument.

PDPFTS Design & Overview

The PDPFTS is designed to operate over a wavelength range of 285 µm to 500 µm (35 cm^{-1} to 20 cm^{-1}), chosen to match available diagnostic test hardware, and consists of four separate modules: a cryogenic blackbody source (4 K), a cryogenic FTS incorporating a novel cryogenic scanning mechanism (4 K) [2], a reflection diffraction grating (4 K) [3], and a composite bolometer detector (0.3 K) [4]. Figure 1 shows a schematic of the PDPFTS. Red arrows indicate the direction light travels between modules.

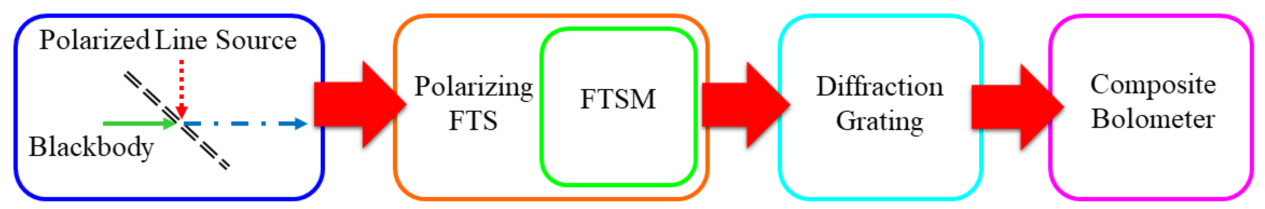

Figure 1: A schematic overview of the cryogenic PDPFTS highlighting the four principal modules.

Figure 2 shows a rendering of the optomechanical layout of the fully integrated PDPFTS; subcomponents use the same colour coding as in Figure 1. This layout consists of a source module (blue) featuring a modified flight spare of SCAL [5], the blackbody calibration source of the SPIRE instrument on the Herschel Space Observatory, and a tunable line source produced by a cryogenic THz photomixer. The FTS optics (FTSO) for a double-decker polarizing FTS (orange) incorporates a cryogenic scanning mechanism (FTSM) [2] (green) to produce a broadband interferogram of the source spectrum. The diffraction grating module (cyan) post-disperses the FTS output to produce a narrowband interferogram which is measured by the bolometer detector (magenta).

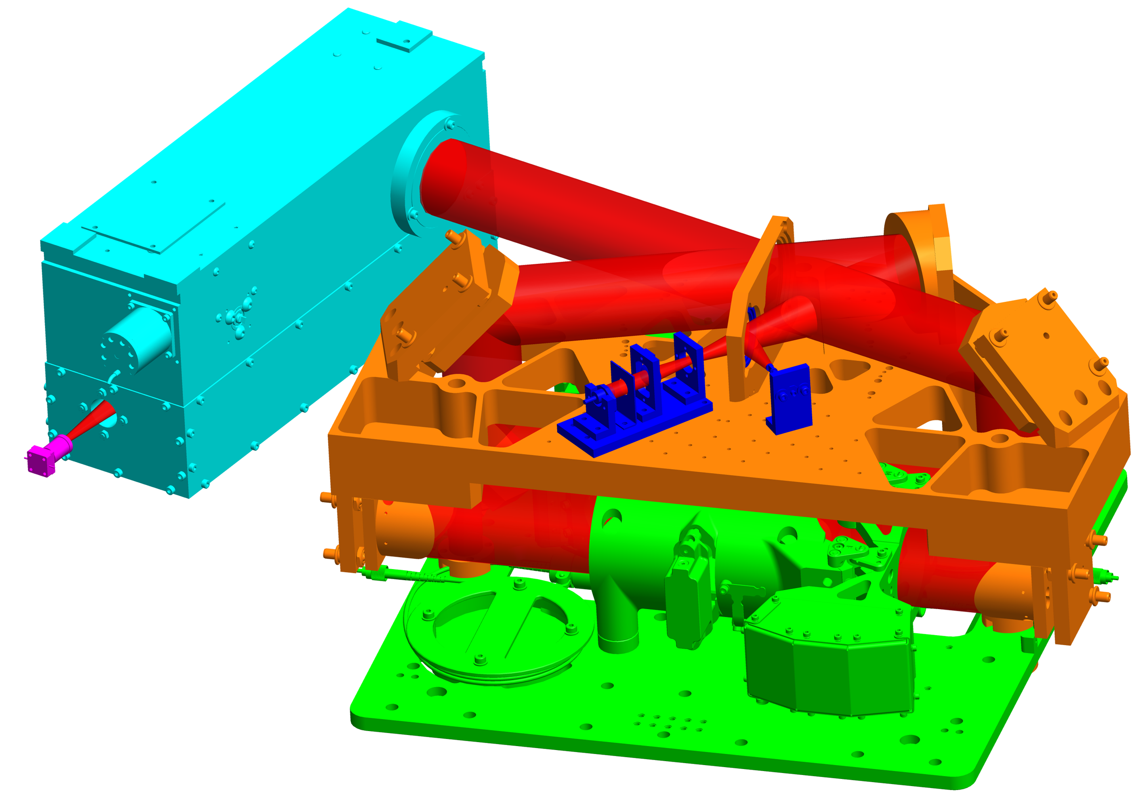

Figure 2: CAD rendering of the PDPFTS featuring all 4 modules of the prototype instrument following the colour coding in Figure 1. The PDPFTS will be integrated in a large volume 4 K facility cryostat.

To validate the prototype PDPFTS in a laboratory setting, a ground-based cryogenic test facility with a large working volume is required. A Large Facility Cryostat (LFC) developed by Blue Sky Spectroscopy Inc. features a 650 mm × 650 mm × 250 mm (25.6 in × 25.6 in × 9.8 in) 4 K volume and will allow the PDPFTS system to be fully integrated at cryogenic temperatures. Figure 3 shows a picture of the LFC with radiation shielding removed exposing the large 4 K working volume.

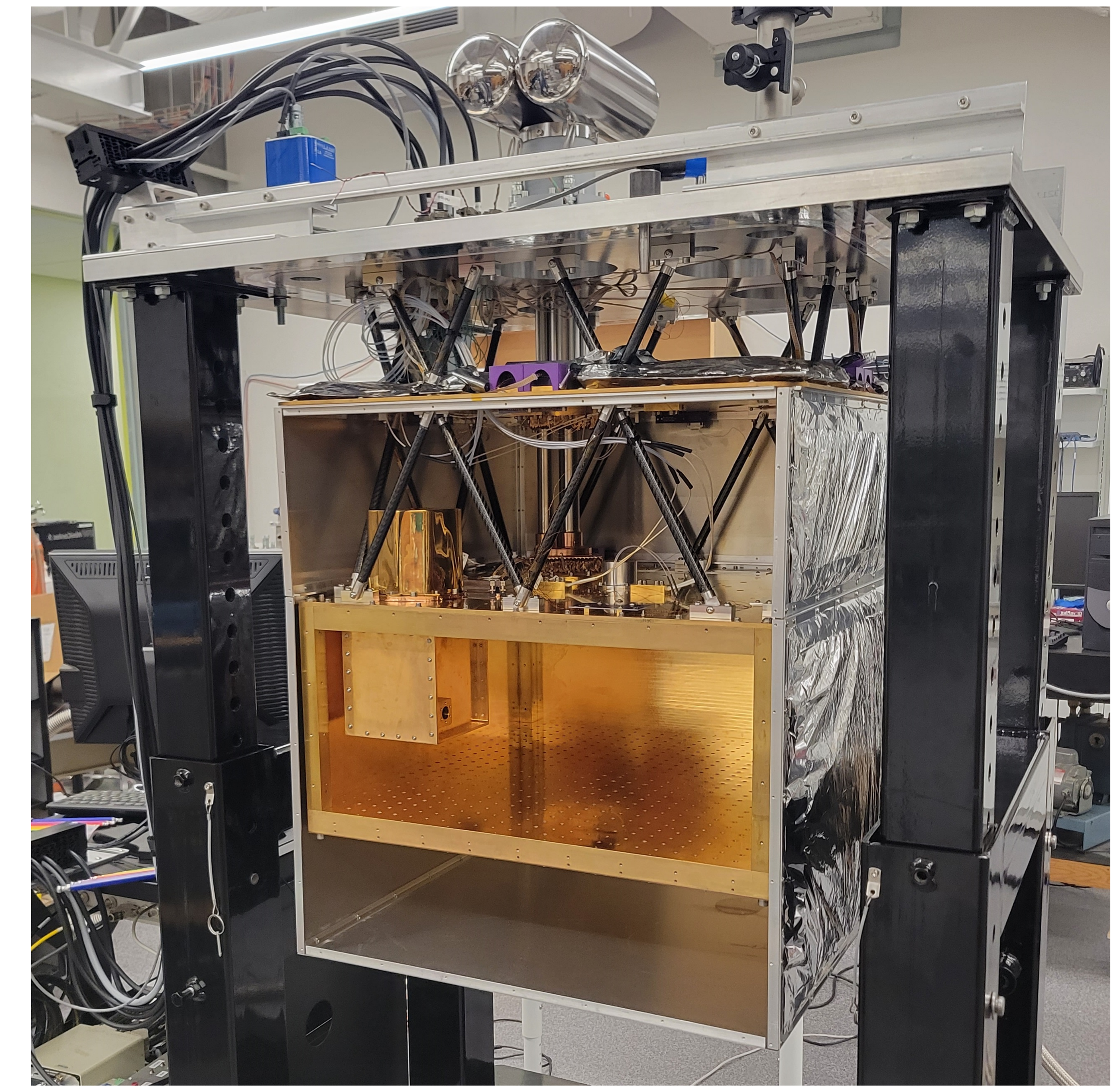

Figure 3: The Large Facility Cryostat developed by Blue Sky Spectroscopy Inc. with its radiation shielding opened.

Room Temperature Integration & Results

While working towards a fully cryogenic integration, the PDPFTS was tested at room temperature. This room temperature configuration features a higher power line source capable of producing narrow banded spectral features over the 300 GHz to 400 GHz range (1000 µm to 750 µm) and a lower-sensitivity pyroelectric detector in place of a cryogenic bolometer detector. Due to the line source's wavelength range exceeding the diffraction grating module's original design specifications of 285 µm to 500 µm, a custom diffraction grating was machined in-house to better match the available tuning range. Figure 4 shows the room temperature PDPFTS integration. While components in the four separate modules of the PDPFTS have been swapped out, the photon path remains identical to the cryogenic integration.

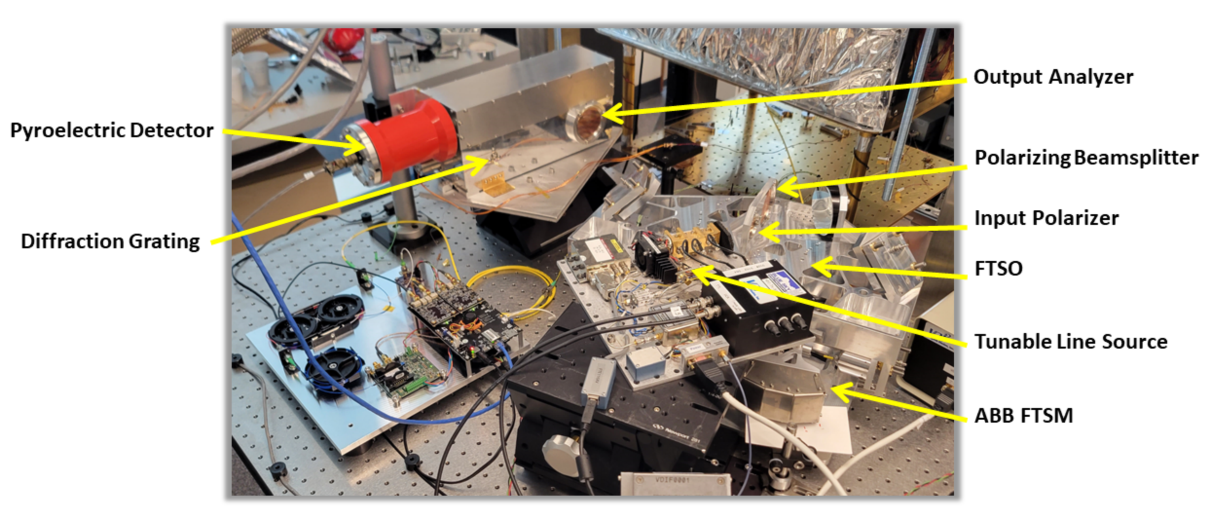

Figure 4: Room temperature integration of the PDPFTS featuring a longer wavelength line source and a lower sensitivity detector.

The Czerny-Turner monochromator configuration of the diffraction grating module allowed the $m = \pm 1$ and the zeroth order of the grating to be observed. Figure 5 shows the results of the diffraction grating spectrometer scans looking at the gratings orders at various line source tunings A close-up view of the m=1 order is also shown. The custom grating achieved a resolving power of 57.8(4) at 938.1 µm and a resolving power of 53.4(1) at 856.7 µm. The three closely packed line features centered around 935 µm were chosen such that the low resolving power of the grating would be able to distinguish any of the three lines from the feature at 855 µm, but not from each other.

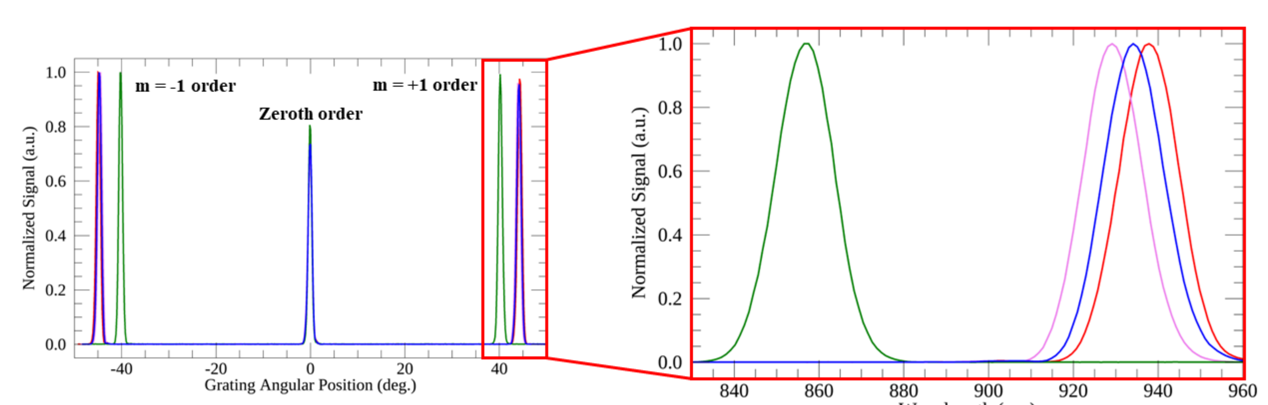

Figure 5: Room temperature PDPFTS diffraction grating spectrometer scans. Left: Grating scans showing the $m = \pm 1$ and zeroth order Right: A close-up look at $m = 1$ grating order scans. The lower resolving power ($R < 60$) of the diffraction grating is not able to resolve the tightly packed line features from each other.

Narrow-banded FTS scans were performed on the same line features. Figure 6 shows the results of the post-dispersed FTS scans. The spectra are very well fit by Sinc profiles. The FTS achieved a 0.038 35(2) cm^{-1} resolution of the scans ($R \sim 300$) with a theoretical resolution of 0.038 49 cm^{-1}. The higher resolution of the FTS enables the tightly packed spectral features to be resolved from one another.

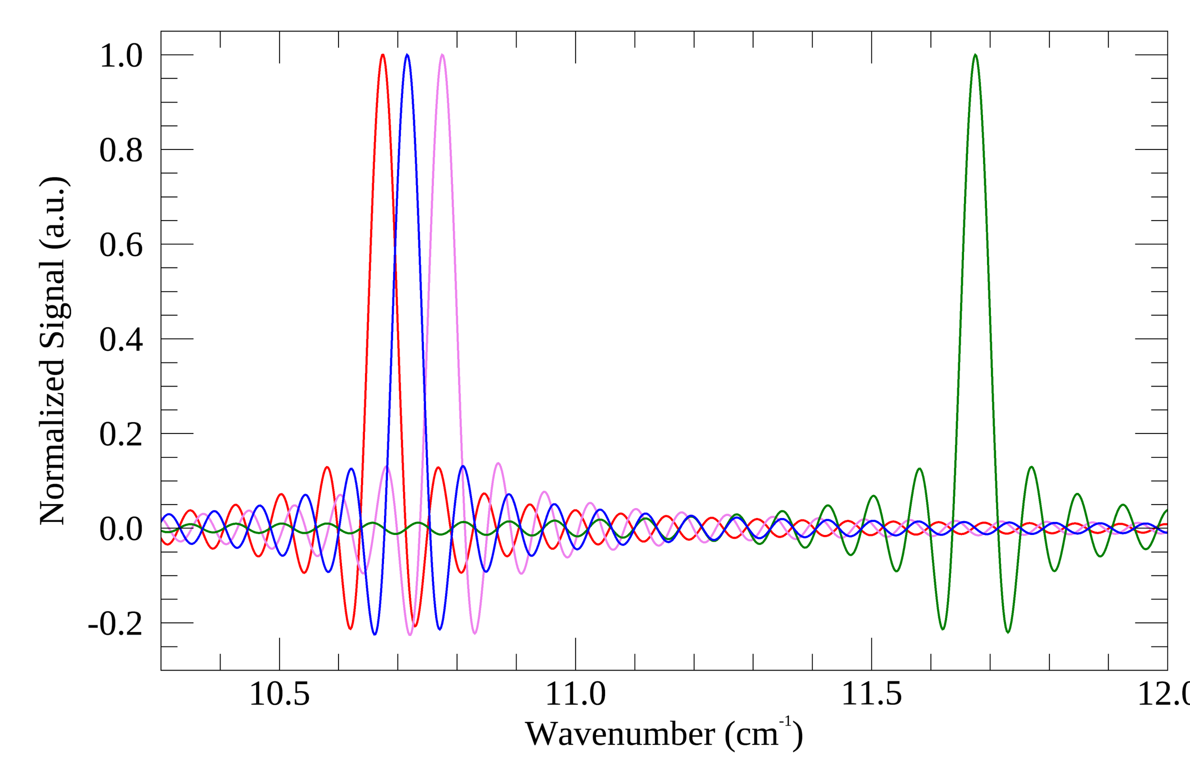

Figure 6: Room temperature FTS scan results. The higher resolving power of the FTS ($R \sim 300$), when compared to the grating, can resolve the tightly packed spectral features.

Conclusions

The FTS and scanning mechanism together with the auxiliary optics and hardware that constitute the four modules shown in Figure 2 are currently being integrated into a large facility cryostat. Results obtained from this system will be used to inform the design of such hybrid spectrometers and investigate the calibration challenges associated with combining the thousands of individual narrow-band spectra produced by a PDPFTS to reconstruct a single broad-band high-resolution spectrum.

References

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