Design, Operation, and Characterization of a Laboratory Spatial-Spectral Fourier Transform Interferometer

Jeremy P. Scott*[1], Chris S. Benson[1], Locke D. Spencer[1]

***Abstract*—A spatial-spectral interferometer is an important milestone for far-infrared astronomy. Here we present the design, operation, and characterization of a laboratory-based spatial-spectral Fourier transform interferometer.**

Keywords—spectroscopy, far-infrared, interferometry, instrumentation

I. Introduction

The Far-Infrared (FIR; 0.3 – 30 THz) remains one of the least explored bands of the electromagnetic spectrum in astronomy despite how crucial FIR observations are for studying some of the most important topics in astronomy including the formation and evolution of planets, stars, and galaxies, and the conditions for life sustaining planets [1, 2]. Research in this area has been limited in-part by insufficient spatial resolution due to the diffraction limit of FIR radiation. Spatial resolution is limited by the diameter of the entrance aperture for a conventional telescope and by the separation of input apertures for a spatial interferometer. Thus, a spatial-spectral Fourier Transform Interferometer (2FTI) is a promising technology in future FIR astronomy missions, providing enhanced spatial resolution over a broad spectral range [2].

Though spectral and spatial interferometry individually are mature, their combination within a single instrument is novel. Our instrument (Fig. 1) consists of two input apertures which sample the electromagnetic field at two points in space. The field under observation is generated by a source incident on an off-axis parabolic mirror producing planar waves that simulate a distant source. One aperture is positioned on a linear translation spatial-stage which modulates the distance between the two apertures setting the baseline separation of the spatial interferometer. Light is then relayed through a series of flats to a double-rooftop configuration on the spectral-stage. The spectral-stage modulates the optical path difference between the two beams and provides the functionality of a Fourier Transform Spectrometer (FTS). The beams are then combined at a beamsplitter and focused onto the detector plane using an off-axis parabolic mirror. The resulting signal is an interferogram with intensity modulation dependent on the optical path difference between the two beams and the aperture baseline.

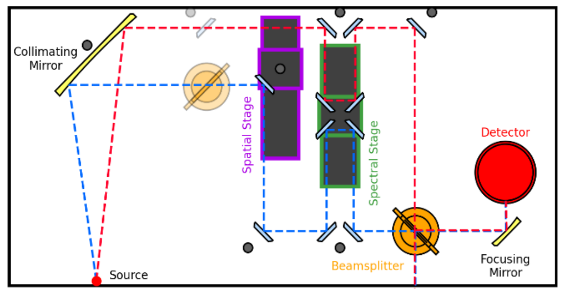

Fig 1. Diagram of 2FTI on laboratory optics table. FTS mode is obtained by adding the translucent components into the system.

II. Instrument Operation

An observation consists of setting a fixed baseline and slewing the spectral-stage in such a way that the resulting interferogram symmetrically samples both sides of zero-path-difference. Noise in the signals is averaged down either using a step and integrate method or by performing a series of rapid scans. The baseline is then changed and subsequent interferograms are recorded.

If the two input apertures overlapped, resulting in zero baseline, our instrument would be equivalent to an FTS. This configuration is achieved with our system by introducing the translucent components in Fig. 1. The resulting interferogram would then probe exclusively the temporal coherence of the source with its Fourier transform providing the spectral components (Fig. 2).

At non-zero baselines, a 2FTI probes the spatial coherence of the input radiation field in addition to temporal coherence. Spatial coherence manifests as the visibility of interference fringes and is determined by the intensity distribution of the source as related by the Van-Cittert Zernike theorem [3]. The Fourier transform of the resulting interferogram produces a spectrum with frequency dependent modulation determined by the spatial coherence of the radiation at the sampled baseline (Fig. 2). By measuring the modulation at a particular frequency at multiple baselines, it is possible to reconstruct a monochromatic intensity distribution of the source by use of the Van-Cittert Zernike theorem. Repeating this process for all frequencies produces a

[1]Institute for Space Imaging Science, University of Lethbridge, Lethbridge, Alberta, T1K 3M4, Canada

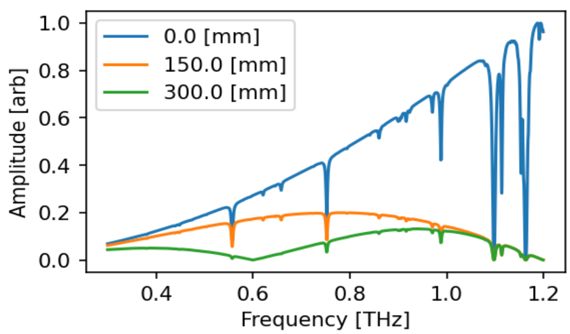

Fig 2. Model spectra of a 900 K blackbody with water absoption lines obtained for our 2FTI at various baselines viewing a 1 mm source. Modulation at non-zero baselines is due to the spatial coherence properties of the wavefront at the sampled baselines.

hyper-spectral image of the source with spatial resolution determined by the maximum baseline.

III. Demonstration of Visibility Measurement

We demonstrate visibility measurements using a tunable THz coherent source. Sinusoidal interferograms for a selection of frequencies are obtained at multiple baselines using the method outlined above. Amplitudes extracted from the resulting power spectra are used as unnormalized visibility measurements. The source emits though a 10 mm diameter circular lens, and we model the source as a circular intensity distribution. The expected visibility curve is then given by the absolute value of the besinc function. Using this model, we fit and normalize our visibility measurements as shown in Fig. 3. The fitted curves are good approximations of the data with deviations attributed to additional structure in the source shape.

IV. Instrument Characterization

The primary collimating mirror has an effective focal length of 1,200 mm and can provide a collimated beam 415 mm in extent. Circular 135 mm diameter flats are used as input apertures and optical relays. When placed at 45 degrees with respect to the collimated beam, the interferometer achieves a minimum and maximum baseline of 135mm and 310 mm, respectively, resulting in a maximum spatial resolution of 1 mm at 0.55 THz. The 5x5 transition-edge-sensor detector array is housed within a ~4 K cryostat. The array is a square with 18 mm linear dimension and coupled to the radiation field through a f/4 feedhorn array that is matched to the focusing mirror with an effective focal length of 240 mm. A magnification of -0.2 is obtained through the combination of the collimating and focusing mirror, and given the size of the detector array, a 100 mm field of view is obtained at the source plane. With a nominal optical path length of 3,400 mm and an aperture stop 60 mm in diameter at the focusing mirror, a 26 mm unvignetted field of view is obtained at the source plane.

The maximum symmetric optical path difference for all possible baselines is 500 mm resulting in a spectral resolution of 0.3 GHz. The beamsplitter bandpass and detector spectral response limit the bandwidth to ~0.4 – 2.1 THz. Assuming a Nyquist frequency of 2.5 THz and using the measured detector cutoff frequency of 1.5 kHz, the spectral stage can be scanned at a maximum speed of 27 mm/s.

V. Conclusion

In this work we presented the design of a laboratory spatial-spectral Fourier transform interferometer and described its operation. The principles of visibility measurements were outlined, and a demonstration was provided for a circular laser source. Finally, we summarized the interferometer performance characteristics.

References

[1] Linz, Hendrik, et al., "Bringing high spatial resolution to the far-infrared." *Experimental astronomy*, Jun. 2021.

[2] Helmich, Frank P., et al., "FIRI—A far-infrared interferometer." *Experimental Astronomy*, Mar. 2009.

[3] Wolf, Emil. "A macroscopic theory of interference and diffraction of light from finite sources II. Fields with a spectral range of arbitrary width." *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, Jun. 1955.

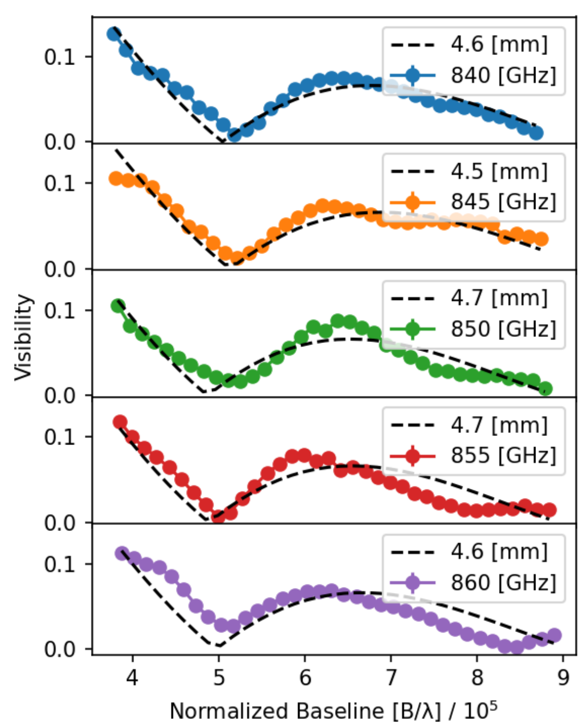

Fig 3. Measured (circles) and fit (dashed) visibility curves for a laser source at select frequencies. Values associated with fit indicate the radius of the circle that would produce the fit curve.