The Wide-Field Imaging Interferometry Testbed: Progress and Plans

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Abstract

We describe the technique of wide field mosaic imaging for optical/IR interferometers and present early experimental results from a laboratory instrument designed to validate, experiment with, and refine the technique. A conventional single-detector stellar interferometer operating with narrow bandwidth at center wavelength λ is limited in its field of view to the primary beam of the individual telescope apertures, or $\sim \lambda/D_{tel}$ radians, where D_{tel} is the telescope diameter. Such a field is too small for many applications; often one wishes to image extended sources. We are developing and testing a technique analogous to the mosaicing method employed in millimeter and radio astronomy, but applicable to optical/IR Michelson interferometers, in which beam combination is done in the pupil plane. An $N_{pix} \times N_{pix}$ detector array placed in the image plane of the interferometer is used to record simultaneously the fringe patterns from many contiguous telescope fields, effectively multiplying the field size by $N_{pix}/2$, where the factor 2 allows for Nyquist sampling.

This mosaic imaging technique will be especially valuable for far IR and submillimeter interferometric space observatories such as the Space Infrared Interferometric Telescope (SPIRIT) and the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS). SPIRIT and SPECS will be designed to provide sensitive, high angular resolution observations of fields several arcminutes in diameter, and views of the universe complementary to those provided by HST, NGST, and ALMA.

1 Introduction

In order to fully explore the epoch of galaxy formation, high-resolution, far-infrared/submillimeter (FIR/submm) images are required, because half of the light emitted in the universe since the Big Bang is in the form of FIR/submm energy.

Such observations must also have high angular resolution to avoid confusion (multiple sources per resolution element) and probe the structure in distant objects. To achieve such high angular resolution, interferometric methods are required. However, to date, optical and infrared interferometers have had very narrow fields, making use of single detectors. In order to accurately characterize the early universe, we require broad fields of view. We must therefore develop new interferometric techniques to perform wide-field interferometric imaging.

The Wide-Field Imaging Interferometry Testbed (WIIT) is an optical testbed designed to explore imaging techniques needed for future space-based interferometers. Key elements of the design are multi-pixel detector arrays and a long delay stroke, which together enable wide-field spectral imaging. The standard output is a spectral array of images (i.e. a 3-dimensional data cube).

In Section 2, we discuss the goals of the WIIT experiment. In Section 2, we discuss the design and implementation of WIIT. Section 4 presents some of our results to date, and in Section 5 we briefly discuss some future goals for WIIT.

2 WIIT Goals

The purpose of WIIT is to develop understanding of the techniques necessary to employ wide-field imaging interferometry. There are a number of issues which we intend to address through WIIT. Some examples include

- What is the maximum practical field of view, and what limits it?
- What are the dominant error sources that limit photometric accuracy and dynamic range in the synthesized spatial-spectral data cube?
- What are the minimum tolerance requirements on various components?
- What are the short-term and long-term stability requirements?
- How can we best utilize data gathered "on the fly" by an interferometer with moving collector mirrors?
- What algorithm optimally expoits the information available in a double Fourier data set?
- Can we rely on a source or sources in the field of view for phase reference?
- What mission design considerations are suggested by our experience with WIIT?

3 The Instrument

WIIT uses a parabolic collimator to produce parallel beams from a an illuminated scene located at its focus. The parallel beam produced by the collimator enter the two collector mirrors (see Figure 1) which form the baseline of the interferometer. The baseline distance determines the angular resolution of the observation ($\theta = \lambda/2b_{max}$). The beam in one arm of the interferometer passes through a series of fixed flat mirrors to the beam combiner, while the beam in the other arm travels to the beam combiner via a pair of fixed flats and a pair of flats on a linear motion stage. The pair of flats on the stage provide the optical delay necessary for interferometry. The beams from the two arms of the interferometer rejoin at the beam combiner; this combination is in the pupil plane, characteristic of a Michelson interferometer. Following the beam combiner, the light is brought to a focus on the detector array by a single lens. This final path is baffled by a long tube in order to reduce stray light. In a classical Michelson interferometer, the combined light is brought to a focus on a single-pixel detector. This light comes from the primary beam of the individual telescope apertures. In the WIIT, however, a detector array (CCD camera) is used to sample simultaneously many contiguous primary beams.

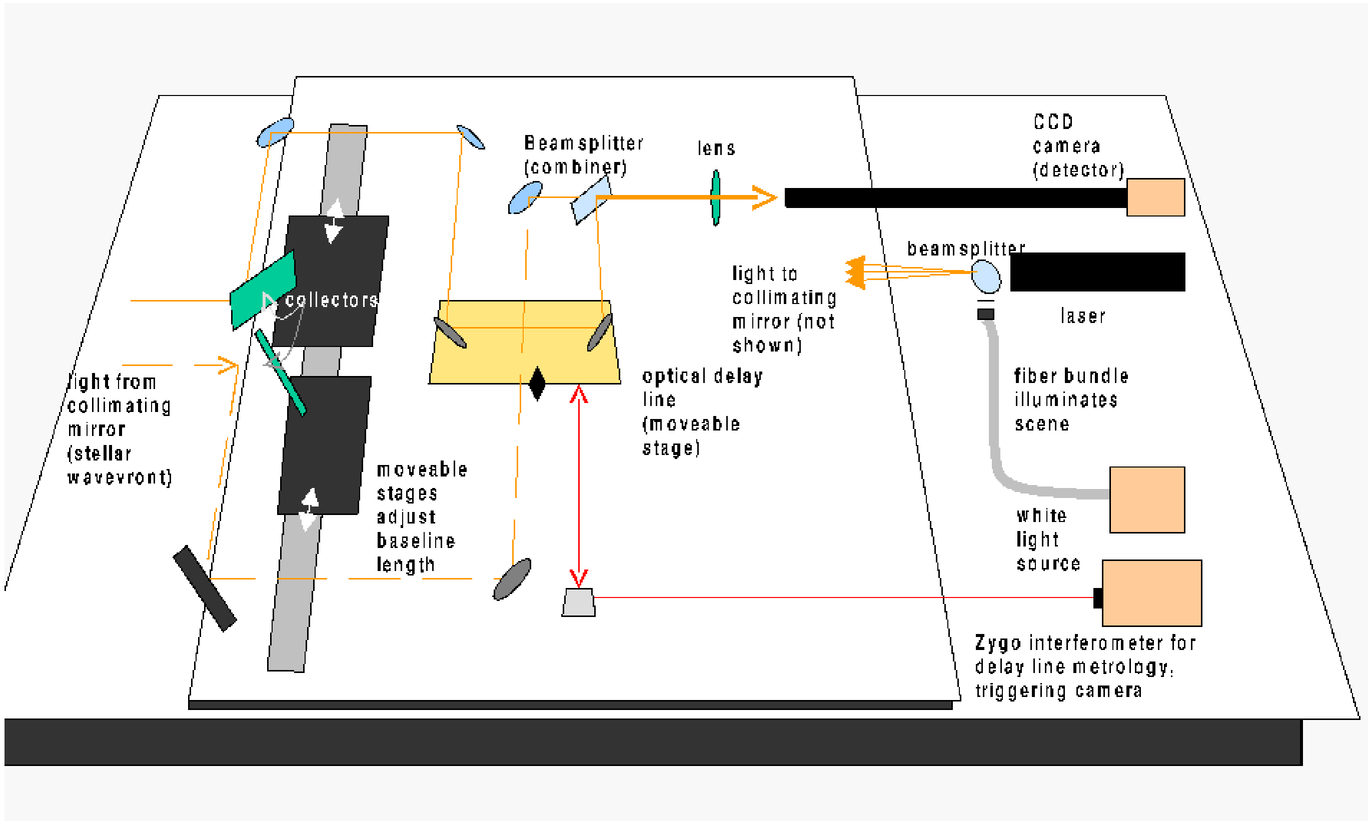

Figure 1: A schematic diagram of the Wide-Field Imaging Interferometry Testbed.

The key points of the WIIT design are:

1. Beam combination in the pupil plane.
2. Record fringe pattern in the time domain in each pixel, as in conventional Michelson.
3. Detector array sees multiple "primary beams" in parallel.
4. Add stroke to optical delay line to compensate for geometric delay across the field of view (FOV).
5. Total stroke provides both wider FOV and Fourier Transform spectroscopy (FTS).
6. Pixels Nyquist sample contiguous primary beams (analog to mosaic imaging used in radio interferometry).

3.1 Recent Developments

Accurate knowledge of the delay line (and baseline) position is critical for interpretation of data from an interferometer. The first white light fringes were detected with the WIIT in August 2001 (Figure 2). Artifacts seen in the measured interferograms suggested the presence of jitter and drift in the delay stage. Subsequently, we have worked to install an independent metrology system and couple the CCD camera exposures to the delay stage position. Recently we have installed an optical encoder system to accurately measure the absolute position of the delay line stage. We have also implemented camera triggering using the signal from the Zygo interferometer. This ties the camera exposures to the position of the delay line stage with an accuracy of roughly 10nm.

We are also in the process of implementing two housekeeping systems. First, sixteen temperature sensors are being deployed around the optical table and the interferometer. Monitoring the temperature over time will help us to understand the environment in which we operate. Second, we are installing a pair of power meters in the system. One of these will be used to measure the amount of light in the parallel beam, determining the stability of our source and providing information for accurate calibration of images. The second power meter will be placed on the second arm of the beam-combiner. This will allow us to measure the relative amounts of light traversing each arm of teh interferometer (by blocking one arm at a time). Any imbalance in the throughput could limit the achievable fringe visibility.

4 Results to Date

Version one of the testbed has been constructed and utilized. In Figure 2 we show a "white light" fringe, compared to a model calculation based on the optical properties of the system components. In Figure 3, we show a similar figure taken using a 10 nm wide bandpass filter. To date, we have measured fringes with both laser light and white light, and through a number of narrow band filters. These interferograms agree qualitatively with system models, and show that the

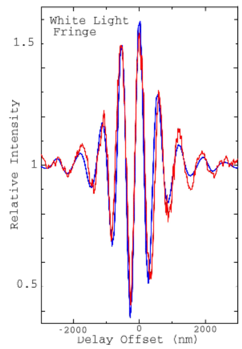

Figure 2: Measured and calculated fringes for WIIT at full bandwidth, 4500 to 6800 Angstroms extent at half intensity, 4000 to 7200 Angstroms at 10%. The red curve is the data, the blue curve is a model based on independent measurements of the source spectrum and the system spectral response function. Compison of the red and blue curve peaks suggests that the true system bandwidth is a little narrower than the model prediction. However, errors in our knowledge of the delay line stage position limited the detailed fringe comparison until recently, when the independent metrology system was introduced.

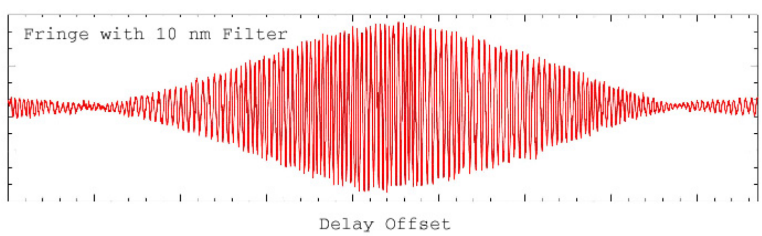

Figure 3: Measured fringes for WIIT with a 10 nm bandpass filter.

system is stable optically and mechanically over periods of weeks. We have also determined that the major limitation on the quality of our data is the uncertainty in knowledge of the position of the delay line. Environmental effects, such as air turbulence, vibrations, and temperature changes might turn out to be significant, but are much less important than jitter and drift in the delay line stage. We have taken steps to mitigate all the significant error sources.

5 Future Plans

There are several improvements underway and planned which we expect will greatly improve WIIT performance. First, when we finish the implementation of Zygo-triggered images and synchronization with the optical encoders, we will drastically improve our knowledge of delay line position. Second, our light level monitoring will provide level correction data for use during data reduction.

In addition, by using the Zygo to measure turbulence around the testbed and the temperature sensors, we will attempt to understand environmental effects. Following this, we will endeavor to provide greater isolation from these effects. With these improvements, we will attempt to systematically characterize the noise of the system and determine noise contributions from different sources within the system.

Once the system noise is well-understood, we will produce, reduce, and analyze data, building toward synthesis of increasingly complex scenes. We will begin with 1-D imaging; a single point source, then moving to more complicated scenes (including multiple point sources, extended sources, extended sources with non-uniform brightness, etc.).

Following these data, we will proceed to develop the next version of WIIT by installing source and camera rotation stages to enable 2-D imaging. We will then conduct analogous experiments, using multiple 2-D scenes of varying complexity. We will use these data to test reduction algorithms and to optimize baseline movement of filling the synthetic aperture. The same procedure will be used again for 2-D spectral imaging, using scenes which have both spatial and spectral structure.

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