An Imaging Fourier Transform Spectrometer for the Next Generation Space Telescope

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Abstract.

Due to its simultaneous deep imaging and integral field spectroscopic capability, an Imaging Fourier Transform Spectrograph (IFTS) is ideally suited to the Next Generation Space Telescope (NGST) mission, and offers opportunities for tremendous scientific return in many fields of astrophysical inquiry. We describe the operation and quantify the advantages of an IFTS for space applications. The conceptual design of the Integral Field Infrared Spectrograph (IFIRS) is a wide field (5′.3 × 5′.3) four-port imaging Michelson interferometer.

1. Introduction

When the Next Generation Space Telescope (NGST) begins observing towards the end of the first decade of the next millennium it will usher in a new era of infrared (IR) astronomy. The combination of a deployable 8-meter aperture and an L2 orbit, which will allow the telescope to cool to 30-50K, will enable zodiacal-light limited performance for \(\lambda < 10 \mu m\).

The rationale for placing NGST far from Earth and shielded from the Sun is reduction of the background by factors of up to \(10^6\) compared to terrestrial environments. This will enable studies of the origins of the structure in the universe, galaxies and quasars, stars, and planetary disks — core mission objectives of the NASA Origins Program. Many of these programs require IR observations: the light from distant galaxies seen at early epochs is redshifted by the expansion of the universe; regions of star formation in our galaxy are obscured by dust in the visible, but are penetrated by infrared radiation; and cool objects such as forming stars and proto-planetary disks emit in the IR.

2. What is IFIRS?

The goal of IFIRS is to obtain ultra-deep, wide field, diffraction limited imagery from near- to mid-IR wavelengths, with flexible spectral resolution (Graham et al. 1998). IFIRS is a Michelson interferometer configured as an imaging Fourier transform spectrometer (IFTS) (See Fig. [1] (Bennett 1993). An interferogram is recorded for every pixel in the field of view, and hence a spectrum can be obtained for every object. Since IFIRS is an FTS, it is both a high-throughput camera and a multi-object or integral field spectrometer. As a camera IFIRS has unusual flexibility of spectral resolution, and a unique pan-chromatic imaging
2.1. Design of IFIRS

On the object side a collimator illuminates the interferometer with parallel light. The interfering beams are collected by a camera, creating a one-to-one mapping between points in the object and image planes. By placing a detector focal plane array (FPA) at the focus of the camera, each pixel is matched to a single point on the sky. At any given optical path difference (OPD) the image of the sky is modulated spatially by the interferometer’s fringe pattern, which encodes the spectral information. By recording images of the sky at different OPDs, the spectrum of each pixel can be reconstructed. The OPD is scanned in discrete steps since FPAs are integrating detectors. The time series from each pixel forms an independent interferogram for every point on the sky within the field of view. These interferograms are Fourier transformed individually yielding a spectral data cube composed of the same spatial elements as the image. The sampling theorem establishes the number and amplitude of OPD steps necessary to recover the spectrum at a given spectral resolution.

The major components of IFIRS, shown in Fig. 2, are the collimator, interferometer, cameras, and FPAs and associated electronics. Two important ancillary subsystems, not shown are the metrology system and the calibration unit.

The collimator is a three mirror anastigmat (TMA) that illuminates a four-port Michelson. There are two input and two output ports. One input port is fed with the sky signal, and the other input can be illuminated by the calibration unit. The interferometer consists of a 50:50 reflecting/transmitting beam splitter, and two cube-corner retroreflectors. The appropriate beam splitter is
Figure 2. The optical layout of IFIRS. For simplicity only the near-IR FPA have been shown at the output ports. The final fold mirror is either a dichroic or flip-mirror which directs the mid-IR light to the mid-IR detectors. For clarity reimager # 2 has been rotated by 180 degrees. The actual design is symmetric about the beam-splitter.

selected using a filter-wheel mechanism. One cube-corner is located on a translation stage, which permits precision control of the OPD. The OPD is monitored using an interferometric metrology system. Each output port of the interferometer feeds identical TMA cameras. A final reflection (an articulated fold mirror or a static dichroic) directs short wavelength radiation to the near-IR FPA and long wavelength radiation to the mid-IR FPA. In summary, the properties of IFIRS are:

The absolute wavelength calibration is provided by the interferometer metrology system, which is referenced to a diode laser. The accuracy should be better than 7.5 GHz (0.25 wavenumbers). This provides the wavelength calibration for both pure and dispersed FTS modes.

| NIR Channel | MIR Channel |
|-------------|-------------|
| Bandpass/Detector | 0.6-5.6 µm/InSb | 5-15 µm/HgCdTe |
| Maximum Spectral Resolution | 1 cm$^{-1}$ | 1 cm$^{-1}$ |
| FOV/Array Format | 5/28×8k×8k | 2/64×2k×2k |
| Pixel size/Nyquist $\lambda$ | 0.0386/3 µm | 0.0726/6 µm |
| Wave front error/Strehl | 150 nm rms/0.8 | 150 nm rms/0.9 |
| Throughput | > 0.7 | > 0.6 |
| Sensitivity$^a$ for $R^b = 1/5/100$ | 0.2/1/35 nJy | 13/65/1300 nJy |

$^a$ SNR = 10 for a 10$^5$ s integration. All spectral channels are obtained simultaneously.

$^b$ $R$ is the number of simultaneous spectral channels in the band-pass.
3. Unique Attributes of an IFTS

The signal-to-noise (SNR) performance of 3-d imaging spectrometers equipped with 2-d FPAs is the same for all architectures, in the ideal case of photon shot noise limited operation (Bennett 1995, 2000). This is correct so long as the spectrometers are equipped with the same size FPAs, and the same spatial and spectral degrees of freedom of the astronomical scene are observed.

An IFTS measures the spectrum of every pixel on the field of view and hence provides the only efficient means of conducting unbiased spectroscopic surveys of the high-z universe, i.e., without object preselection (e.g., using broad band colors) and without the restrictions imposed by spectrometer slit geometry and placement. Because there is no slit, an IFTS can record spectra for adjacent individual objects, down to the confusion limit (e.g., resolved stellar populations), and for moving targets (e.g., Kuiper Belt objects).

An IFTS also allows spectroscopy over a wide bandpass, typically three octaves, and affords flexibility in choice of resolution ($R = 1-10^4$). IFIRS uses all reflecting optics, and high-efficiency beam-splitters. The throughput is high and flat across the band-pass. For the near-IR channel the efficiency is approximately 75%, including optics, beam splitter, and detector QE (see Fig 3).

The IFTS has the brightest imagery of any imaging spectrometer design because the full band-pass is transmitted to the FPA. The summed signal from the two output ports is unmodulated and corresponds to the total broad-band photon flux entering the instrument. This pan-chromatic image is peculiar to a four port interferometer. Thus deep, broad-band imaging is acquired simultaneously with higher spectral resolution data over a broad wavelength range. A pan-chromatic image can be formed with a filter-wheel camera by summing the sequence of filter images, but the IFTS pan-chromatic image has a speed advantage factor that is equal to the number of filters used. The IFTS advantages due to broad-band operation are high SNR pan-chromatic imaging for science and also for telescope guiding, tolerance of cosmic rays hits, detector noise, and internal instrument background, and high SNR determination of flat-fields and detector non-linearity.

A four port Michelson interferometer is intrinsically a superb instrument from a calibration point of view. The measured interferogram results from the difference between spectra of sources at the two input ports. Calibration sources

\[ \text{Figure 3. The throughput of IFIRS for the near- and mid-IR channels.} \]
placed at the second input port act as transfer standards for full radiometric calibrations performed on the ground prior to flight. The mid-IR channel is calibrated by varying the temperature of a cold blackbody at the second input that fills the field of view. The near-IR channel is calibrated using a dilute, hot blackbody, that does not produce excessive heating of the instrument. In both cases, a full calibration of each FPA pixel’s offset, spectral responsivity, and non-linearity can be conducted by varying integration times or source intensities. This capability is invaluable should the system response change due to exposure to the space environment.

IFIRS also has a hybrid, or dispersed FTS mode. In a regular FTS, spectral information is encoded in the z-direction of the data cube, and there is no mixing of spectral and spatial information. The advantage is that a spectrum is recorded for every pixel on the sky. The penalty is that the photon shot-noise from all spectral channels is present at each frequency. This shot-noise can be reduced by masking the telescope focal plane around objects of interest with a programmable focal plane mask and inserting a prism into the collimated space. The dispersed FTS mode is used to obtain the highest possible sensitivity at high spectral resolution \( R = 600-10,000 \) \((\text{Bennett, 2000})\). The slit width does not determine the spectral resolution in the dispersed FTS mode, since the spectral resolution is derived from the interferograms. The dispersed FTS data-cube contains spectra which are tilted with respect to the z-axis. The tilt angle is the arc tangent of the ratio of spectral resolutions of the dispersive element and interferometer. The dispersed FTS has better SNR performance than the pure FTS, and the source density of object slits is higher than for the pure multi-object spectrometer.

4. Performance of IFIRS on NGST

IFIRS records a spectrum for every pixel in the field of view. This means that data produced by IFIRS is three-dimensional, i.e., it forms a data cube consisting of two spatial dimensions \((x, y)\) and one wavelength dimension \((z)\). A horizontal \((x, y)\) slice through a data cube corresponds to a monochromatic image. A line extracted from the data cube in the \(z\)-direction corresponds to a spectrum.

To estimate the performance of an IFTS in the NGST environment we have simulated data as follow. An astronomical scene is represented as a noise-free distribution of objects. This input data cube is convolved with the telescope point spread function (PSF). This is a 3-d convolution, since the PSF depends on wavelength. The spectra are then multiplied by the wavelength dependent throughput. From this spectral data cube the interferogram is calculated by a Fourier transform. At each OPD step noise is added. The noise sources treated are photon shot noise from the zodiacal light, photon shot noise due to thermal emission from the telescope, photon shot noise from the target, shot noise due to detector dark current, and detector read-noise. The noisy interferogram cube is then Fourier transformed back into a spectral data cube.

We have used Im & Stockman’s (1998) simulation of a blank field at very low flux levels to demonstrate the spatial multiplex advantage of IFIRS. In this simulation we show only 0.02% of the field of view of IFIRS. If we had simulated
Figure 4. IFIRS data cube for the Im & Stockman (1998) NGST deep field.

The entire IFIRS data cube it would contain spectra for tens of thousands of galaxies.

The spectral energy distributions omit nebular emission lines, so redshifts must be deduced from stellar absorption features and spectral breaks. Simulations of star forming galaxies show that a cluster forming stars at 2.5 $M_\odot$ yr$^{-1}$ for $10^7$ yr can be detected in Ly$\alpha$ emission to $z = 12$. In this example objects with $K = 31.3$ AB mags are detected with $SNR = 5$ per spectral resolution element, which is sufficient SNR to identify the Lyman break in objects as distant as $z = 12$.

I am indebted to the IFIRS team for their contributions to this report: M. Abrams, C. Bennett, J. Carr, K. Cook, A. Dey, R. Hertel, N. Macoy, S. Morris, J. Najita, A. Villemaire, E. Wishnow, & R. Wurtz. This work was support by NASA.

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