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Imaging Fourier Transform Spectrometer

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ABSTRACT

The operating principles of an Imaging Fourier Transform Spectrometer (IFTS) are discussed. The advantages and disadvantages of such instruments with respect to alternative imaging spectrometers are discussed. The primary advantages of the IFTS are the capacity to acquire more than an order of magnitude more spectral channels than alternative systems with more than an order of magnitude greater étendue than for alternative systems. The primary disadvantage of IFTS, or FTS in general, is the sensitivity to temporal fluctuations, either random or periodic. Data from the IRIFTS (ir IFTS) prototype instrument, sensitive in the infrared, are presented having a spectral sensitivity of 0.01 absorbance units, a spectral resolution of 6 cm^{-1} over the range 0 to 7899 cm^{-1} , and a spatial resolution of 2.5 mr.

1. INTRODUCTION

Imaging spectrometers acquire a "data cube" consisting of 2 spatial and 1 spectral dimension. There are a variety of means to this end, depending on whether spectra are dispersed in 0, 1, or 2 dimensions. Any non-imaging spectrometer may have its field of view rastered across a scene to produce a data cube, but this is very inefficient. The availability of focal plane image detectors enables highly efficient acquisition of spectrally and spatially resolved data. An imaging grating spectrometer (IGS) disperses light in 1 spatial dimension, and provides imaging in an orthogonal direction. By concatenation of a succession of 1 dimensional slices of a scene, a 2 dimensional image may be reconstructed. An Echelle grating spectrometer (EGS) uses 2 orthogonal directions for coarse and fine spectral resolution, and is intrinsically not well suited for imaging spectroscopy, other than by rastering. An imaging Echelle grating spectrometer (IEGS) is possible based on temporally multiplexing the openings of a programmable slit array at the entrance aperture. If each pixel element is varied at a discrete multiple of a fundamental frequency, then FFT can be used to efficiently disentangle the image in the focal plane. Such a scheme has high optical throughput, but is very cumbersome. An imaging Fizeau interferometer (IFI) produces a spatially extended interferogram in 1 dimension, and has imaging in an orthogonal

direction. A variable spectral filter spectrometer (VFS), such as a filter wheel or tunable filter acquires a full 2 d image each frame, with successive frames viewed through successive filters.

Fig. 1. IFTS raw data cube.

Finally, an imaging Fourier transform spectrometer (IFTS) acquires a full 2d image per frame, with successive frames associated with different positions of a moving mirror in an interferometer. This is illustrated in figure 1, where a set of frames of a complete 2D scene are shown in a stack. The variation of light intensity for a single pixel in the

scene is indicated by the curve to the lower right. The raw data cube for an IFTS consists of the interferogram in 1 dimension and the 2D scene in the 2 orthogonal directions. Fourier transformation of the interferograms for each pixel in the field of view then produce the spectral dimension of the data cube, as is illustrated by the curve in the upper right of figure 1. Most of the existing imaging spectrometers are IGS, e.g. HYDICE, ASAS, AVIRIS, CASI, with a few VFS systems, e.g. MUSIC, and some IFI systems, e.g. SMIFTS.

The number of spectral channels practical with either IGS, or IFI is limited by the width in number of pixels of the focal plane image. In practice the number of spectral channels is at most a few hundred. Similarly, VFS systems are limited in practice to a few hundred discrete filter elements. For applications where the spectral features are fairly broad, such resolution is sufficient, and indeed higher resolution can be disadvantageous. Most of the existing imaging spectrometers are sensitive in the visible, or near visible, and indeed do not require high resolution for their intended applications. For spectral regions where the spectral features are very narrow, and spread over a wide spectral range, it is advantageous to have higher resolution than is practical with IGS, VFS and IFI systems. In particular, in the infrared, molecular spectra of vapors in the atmosphere are often a fraction of 1 cm^{-1} in width, and it is important to have high resolution over a broad range of wavenumbers in order to discriminate chemical compounds. The great advantage of an IFTS system is the very large number of spectral elements combined with imaging. It is natural to develop IFTS for the infrared region, i.e. IRIFTS.

2. BASIC PRINCIPLES OF IFTS

Fourier transform spectrometers are based on the Michelson interferometer, with one fixed mirror and one moving mirror. The light

transmitted through the interferometer is measured as a function of the displacement of the moving mirror from the zero phase difference (ZPD) position. The Fourier transform of this "interferogram" yields the spectrum. An imaging spectrometer is obtained by "looking through" the interferometer with a camera, and constructing the Fourier transform of the variations in light

Fig. 2. A sketch of the optics of an Imaging Fourier Transform Spectrometer

intensity at each pixel as a function of the position of the moving mirror. The optical layout of an IFTS is sketched in figure 2.

Typical rays emerging from two representative points are drawn. One point is located on the optic axis. The second point is displaced by a distance y from the optic axis. The object plane is located at a distance equal to the focal length f of the collimating lens. The object plane may be a real emitting surface, or may be the focal plane of a telescope or microscope. It is possible to merely have an entrance aperture of diameter D , rather than a lens, corresponding to the case $f = \infty$. The focusing lens, with focal length f' produces an image with magnification (or reduction) factor f/f' . The depth of field of the focusing

system should accommodate twice the maximum travel distance of the moving mirror in the interferometer in order to produce a sharp focus in the image plane. The beam splitter transmits a fraction T of the incident light and reflects a fraction R . These coefficients in general depend on polarization, the angle θ , and the wavelength. For monochromatic light of wavenumber $k=1/\lambda$, the intensity of light at the image point y' relative to the intensity emerging from the object point y is proportional to $R \cdot T \cdot \cos^2(\delta/2)$. The phase difference δ is determined by the round trip optical path difference x for the moving mirror with respect to its zero phase difference (ZPD) point, and the angle $\theta = y/f = y'/f'$, between the collimated rays and the optic axis,

$$\delta = 2\pi kx \cos(\theta). \quad (1)$$

A point source in the object plane produces an extended spot in the image plane. The Raleigh diffraction limit on the degree of focus is $1.22 \lambda f'/D'$. For reasonably fast optics, this limit is significantly smaller than the pixel size. Thus spatial resolution is limited by pixel size rather than by diffraction. For a non-monochromatic point source, the observed light intensity $I(x,y')$ in the focal plane is a function of both mirror position x and the distance from the optic axis y' . For a spectral distribution with intensity for wave numbers between k and $k+dk$ given by $S(k)dk$, and a detection efficiency E , the observed light intensity in the focal plane is given by

$$I(x,y') = \int S(k)/2 \cdot E \cdot R \cdot T \cdot (1 + \cos(2\pi k x \cos(\theta))) dk. \quad (2)$$

The light intensity at any given radius y' is thus simply related to the Fourier transform of the spectrum. Introducing the modified frequency

$$k' = k \cos(\theta), \quad (3)$$

and the modified spectrum $S'(k') \equiv E \cdot R \cdot T \cdot S(k) = E \cdot R \cdot T \cdot S(k' \sec(\theta))$, the observed intensity is

$$I(x,y') = \sec(\theta) \int S'(k')/2 (1 + \cos(2\pi k' x)) dk'. \quad (4)$$

By fourier transform of the $I(x,y')$ as a function of x , the spectrum $S'(k')$ can be recovered, and thus $S(k)$ itself. Ordinarily, a range of values of y' are integrated, which has the effect of broadening and shifting a monochromatic line in the spectrum which is recovered from the Fourier transform of $I(x)$. This is the origin of the Jacquinot limit¹ on the resolution of an FT

spectrometer. For a Jacquinot stop of radius r , to first order in r/f , the total width of the Jacquinot blurring is

$$dk/k = r^2/2f^2. \quad (5)$$

For points off the optic axis, this blurring varies linearly with distance from the optic axis. In terms of the angular position θ and spread $\delta\theta$ of a given pixel, this limit to the spectral resolution is given by

$$dk/k = \tan(\theta) \delta\theta. \quad (6)$$

Except for extremely high resolution instruments, this limitation is small compared to the limit on the resolution from the total travel distance of the moving mirror. For our prototype instrument in particular, $\theta < 0.15$, $\delta\theta = 0.0025$, so that this resolution limit is 0.4 cm^{-1} at 1000 cm^{-1} for objects at the extreme edge of the field of view, while at the center of the field of view, this resolution limit is only 0.003 cm^{-1} .

3. IFTS ADVANTAGES

In non-imaging FT spectrometers, high resolution can only be obtained with the use of a relatively small aperture for the Jacquinot stop. A small Jacquinot stop then limits the étendue of the conventional FT spectrometer. To first order, the étendue for a conventional FT spectrometer whose limiting aperture area (usually determined by the beam splitter) is A , is given by

$$2\pi A dk/k. \quad (7)$$

In contrast, a conventional grating spectrometer, with entrance slit of height h , having the same resolution dk/k , and the same focal length f , has an étendue which is less than that of a conventional FT instrument by the factor^{2,3}

$$h/2\pi f. \quad (8)$$

Since the slit height is usually substantially less than the focal length in a grating spectrometer, a non imaging FT spectrometer enjoys 2 or 3 orders of magnitude larger étendue than a grating instrument. This advantage is known as the Jacquinot advantage of conventional FT Spectrometers. For imaging spectrometers, the étendue per frame of the focal plane detector is less for IGS than for IFTS by approximately the same factor as for non-imaging spectrometers. The number of frames per data cube for the IGS is simply the number of angular resolution elements per total field of view. The number of

frames per data cube for the IFTS is instead the number of spectral resolution elements. For equal volume data cubes, the IFTS throughput relative to IGS throughput is still given by approximately the ratio in equation (8). However, in an IFTS, the pixel size represents an effective Jacquinot stop, and the spectral resolution can be greatly increased with no sacrifice of étendue. Thus in an IFTS, a much larger volume data cube can be acquired for a given scene, with the extended dimension being the spectral dimension.

Another well known advantage of FT spectrometers, the Connes advantage, is that the wavenumber scale and instrumental line shape are precisely determined, and are independent of wavenumber. Because the off axis distortion of the spectra is given by the simple (and slight) linear shrinking of the wavenumber scale expressed by eq. (3), the Connes advantage of FT spectrometers is maintained in the imaging implementation. It is practical to readily compare, or subtract, even very complex standard reference spectra taken with different FT spectrometers. In contrast, the instrumental line shape of grating spectrometers in general, and a fortiori IGS, is dependent on wavelength and position in the focal plane. It is therefore much more difficult to compare IGS data with complex standard reference spectra without extensive and precise calibration.

4. IFTS DISADVANTAGES

The sensitivity of FT instruments depends on the signal to noise ratio of the interferogram, the number of resolution elements N , and the form of the spectrum. For a one sided interferogram consisting of N points, the corresponding spectrum will contain N spectral channels equally spaced extending from 0 up to the Nyquist sampling limit, $k_{\max} = 1/(2\Delta x)$, where Δx is the sampling interval. Let M be the ratio of the total observed intensity to the average intensity per channel. M is roughly the ratio of the width of the spectrum to the spectral resolution, or the number of significant channels. If there is white noise in the interferogram, there will be white noise in the spectrum. Let f be the ratio of the rms noise in the interferogram to the maximum intensity in the interferogram. The rms spectral noise relative to the typical intensity in the spectrum is approximately given by $f \cdot M/\sqrt{N}$. For high resolution and high sensitivity it is important to have a Nyquist limit significantly greater than the extent of the detected spectrum.

For a broad band spectrum, with a series of absorption lines, the noise equivalent absorbance varies as $\sqrt{N}$, whereas the depth of the absorption line varies linearly with the resolving power, and is therefore proportional to N , up to the point that the resolution is approximately equal to the line width. Thus it is advantageous to operate with spectral resolution matched to the width of the spectral features of interest. For relatively broad spectral features for

which the resolution of an IGS or VFS is adequate, the sensitivity of an IFTS is likely to be inferior. For narrow spectral features, however, the sensitivity of an IFTS can be substantially larger than that of an IGS or VFS.

The greatest disadvantage of the IFTS is the difficulty of observing fluctuating sources. Since an FTS inherently uses time domain multiplexing of the spectral data, with spectral intensity vs. modulation frequency translated into spectral intensity vs. wavenumber, any significant temporal fluctuations in the observed light intensity within the frequency range corresponding to the spectral features of interest represents noise in the derived spectrum. Furthermore, periodic fluctuations produce line shifts of the observed spectral features, with the implication that it is very difficult, for example, to measure ac modulated calibration sources. Under certain circumstances however, this aspect of an IFTS may be used to advantage. For example, it is possible to use the broadening of ordinarily narrow spectral features as a measure of the degree of temporal fluctuation of the source term, and this can be used to distinguish transient or erratic spectral features.

5. PROTOTYPE DATA

We have constructed a prototype of IRIFTS, however, since the inner workings of this instrument, and subtleties not mentioned in the above theoretical discussion, are the subject of a patent⁴, technical details of the instrument will be published at a later date.

In order to illustrate both the spatial and spectral resolution simultaneously, a set of gas cells 6 inches long by 2 inches in diameter, containing various vapors, were positioned 1 foot from the entrance aperture of the IRIFTS instrument. A hot plate set at 350°C was positioned 2 feet behind the gas cells to provide ir back lighting. The gas cells had silicon windows which were nearly transparent to the ir. The instrument total field of view was approximately 9°, and contained about 3,000 spatial pixels. The volume of the data cube was nearly 5×10^6 points. By fourier transform of the interferogram dimension of the raw data cube, a processed data cube consisting of 2 spatial and 1 spectral dimension was obtained.

Representative data from 3 different **single** pixels, located within parts of the image corresponding to the Acetone, Propanol, and Methyl Ethyl Ketone gas cells are shown in figure 3. The spectral band pass of the system for this data extended over the range from 800 to 2500 cm^{-1} . The Nyquist upper limit on wavenumber was 7899 cm^{-1} . The spectral resolution was 6 cm^{-1} , independent of wavenumber. The spectral noise observed was "white", at an rms level for various pixels in the different samples ranging from 1% to 2% relative to the intensity at the peaks of the spectra. Averaging of the interferograms for N neighboring pixels within a region corresponding to a given spectrum reduces the spectral noise in proportion to $\sqrt{N}$. In the spectra,

prominent absorption of the hot plate emission by ambient water vapor and CO_2 present in the 3 feet of air between the hot plate and the IRIFTS has been indicated in the figure. Note that the spectra for the three different chemicals are very distinct, especially in the "ir fingerprint region" between 800 cm^{-1} and 1600 cm^{-1} .

Figure 3. Spectra for 3 different pixels in the field of view of IRIFTS.

6. APPLICATIONS

For applications to imaging spectrometry of the terrestrial environment, a passive instrument such as IRIFTS must make use of available light. In the thermal region of the ir, it is necessary to have a radiance contrast between the subjects of interest and the background, which generally means a temperature contrast. For ground based observations, the sky serves as a cold background in the ir window regions, $8\text{ }\mu\text{m}$ to $12\text{ }\mu\text{m}$ and $3\text{ }\mu\text{m}$ to $5\text{ }\mu\text{m}$. The presence of foreground vapors at nearly the ambient ground temperature then produces thermal emission lines when viewed with the sky in the background.

7. ACKNOWLEDGMENTS

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