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Snapshot interferometric multispectral imaging using deconvolution and colorimetric fit

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HIGHLIGHTS

- New snapshot interferometric hyperspectral imaging technique.
- Improved compromise of the dualism between spatial and spectral resolution.
- Deconvolution and colorimetric fit emulates dispersion.
- Non-rigorous comprehensive sensing approach.

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ABSTRACT

Multispectral imaging techniques provide spatial and spectral information about a scene. Among them, the spatial Fourier transform interferometric approach is popular, because it does not use moving parts and has the signal advantage. But the inherent antagonism between the recording of spectral and spatial frequencies in such techniques is truly bypassed only in remote sensing by using the relative motion between the scene and the imager as a substitute for the scanning device. Snapshot techniques, which do not use any sort of scanning, were also developed, but at the price of sacrificing the overall spatial-spectral resolution. They use mapping, multiplexing, and filtering to spread the spatial and the spectral information over a large sensor array. Here, a snapshot interferometric multispectral imaging technique is presented, that does not sacrifice resolution. The whole spectral and spatial information is obtained from a small quantity of input data; this was made possible by the use of deconvolution in the Fourier spatial spectrum and colorimetric fit, which puts our technique in the vicinity of the compressive sensing approach. A severe limitation is that the technique can be applied only to scenes that can be divided into subscenes in which the dependencies of the light intensity on the spectral and the spatial variables respectively are separable, i.e. the input data has high sparsity. This shifts the burden of creating complex hardware capable of performing snapshot spectral analysis to finding algorithms for dividing the scene in spectrally uniform subscenes. Another difficulty is the fact that the subscenes need to be smooth enough so that the Fourier spectrum due to interference does not overlap the Fourier spectrum of the non-interfered subscene. However, solutions to these problems exist or they are in development. For instance, we propose a test of high probability for separability. The use of deconvolution and colorimetric fit eliminates the need for calibrated dispersive elements in the spectral analysis and may be separated from other considerations and construed as a contribution to spectral analysis.

1. Introduction

In this paper, we propose a novel snapshot multispectral imaging technique based on spatial Fourier transform interferometry and some non-rigorous compressive sensing strategies. Hyperspectral imaging (closely related to multispectral or spectral imaging) is an optical characterization and detection technique that combines imaging and spectroscopy [1–25]. The end product of hyperspectral imaging is the hyperspectral data cube, i.e. a set of images of a scene, each corresponding to a different wavenumber (or wavelength). Multispectral imaging is considered by Hagen [26] and others a diminished version of hyperspectral imaging, that presents the images for a number of spectral bands, rather than a contiguous spectrum. However, Hagen acknowledges there is no fundamental difference between the two types of techniques.

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An important problem in spectral imaging is finding the best compromise between antagonistic requirements such as A) scanning both the field of view of the scene and the spectrum without serious perturbation of the measurement process due to movement or without using moving parts at all in the system, and B) acquiring a large amount of data in a short time and with a not so large sensor array.

According to criterion A, one may classify the spectral imaging techniques in three categories: (1) *with internal moving parts* such as a motorized stage [11,14] or a vacuum pump [25]; (2) *internally static*, where the uniform movement of the scene removes the necessity of internal moving parts for the scanning; this is to be found usually in the field of remote sensing applications [1,2,4,9,10,12,13,16–18,22,24], but also for close range targets if, for various reasons, there is uniform, predictable relative movement between the spectral imager and the scene [1,10,12,21,23]; and (3) *snapshot*, where no scanning is performed at all, yet the whole spectral and spatial information is acquired in one single shot [1,3,5–8,15,20,24]. The first category was the first chronologically, and is still in use [25]. The second category takes advantage of the relative uniform motion between scene and imager, which replaces the role played by the internal moving parts of the system. The rather large amount of literature dedicated to this type of spectral imaging, especially for remote sensing purposes, proves that the advantage of not having internal moving parts, yet to benefit from scanning opportunities is by no means trivial. It provides experimental simplicity, compactness of design, robustness, autonomy; all sought for in spaceborne or airborne satellites. Many of these techniques are based on spatial Fourier transform interferometry [2,4,9,13,16–18,22,24], like our technique; this is in part what makes them static. Another, more general reason for which interferometric techniques are preferred, is the fact that they benefit from the Jacquinot and Felgett advantages, meaning high input and output signal. There is some debate about the signal collecting abilities of the spectral imagers because of their complexity [27]; also, in the special case of very sensitive shot-noise limited detectors, the Felgett advantage no longer applies.

The third category, the snapshot spectral imagers, might not always be preferable, because of their increased complexity, but especially because most of them have a serious difficulty with criterion B. In order to better understand this difficulty, we have to turn to a key article in the joint fields of spectroscopy and imaging. We refer to the seminal article of Stroke and Funkhouser from 1965 [28], about using interferometric imaging, specifically holography, as a method of spectroscopy. Their paper presents a way to visualize the spectrum of a radiation source as the playback of the hologram formed by the interference of an object and the reference waves that are duplicates of the source differentiated by an optical path difference having a linear gradient. Analyzing the results, Stroke and Funkhouser noticed the dualism (or trade-off) between recording the spectral and spatial frequencies. Logically, since the sensor ability to record information is limited, one has to sacrifice either spectral or spatial resolution, or both in part. Roughly speaking, what all these methods have in common, is that a point of the scene is put in correspondence to multiple cells of the sensor array (say N); hence the resulting spatial resolution is the resolution of the sensor array divided by N, and the spectral resolution is proportional to N. This is why snapshot techniques oftentimes require large sensor arrays. (We see again the reason why the existence of a uniform relative movement between the spectral imager and the scene is so useful: in order to have both high spatial and spectral resolution, one needs several shots of the scene taken at different viewing angles, and the relative movement supplies these angles. Then the spectral and spatial information is obtained by comparing the shots). For a more detailed explanation of this fundamental limitation of snapshot techniques see Hagen's review [26].

Snapshot spectral imagers use a variety of methods to determine the entire spectral and spatial information from one shot. They spectrally decompose every point of the scene using dispersive means and then the rays corresponding to different wavenumbers are sent to different cells of the sensor array (mapping) [3,5,6], they multiply the entire image of the scene or the individual points of the images and then they spectrally filter each image or point with different filters before reaching the sensor array (filtering) [7], or they record in various areas of the sensor array various nontrivial combinations of the spatial and spectral information (multiplexing) [1,8,20]. We found in literature only one snapshot method which uses spatial Fourier transform interferometry as a means for obtaining the spectral information [15], as we do.

Unlike most of the snapshot techniques mentioned above [3,5–7,15], our method does not sacrifice any kind of resolution, spatial or spectral. It may be classified together with a recent but fast-growing class of spectral imaging techniques, which are snapshot, yet they do not sacrifice resolution, because they use compressive sensing strategies [1,8,20,24]. (Ref. [19] uses compressive sensing but is not snapshot). We did not use the formal theory of compressive sensing, we just exploited some opportunities to obtain all the required output data from the processing of a small amount of input data. This approach cannot be implemented to all scenes, but only to a subclass defined by the fact that the scene can be divided in subscenes in which the spatial and the spectral dependencies of the light intensity are separable. In other words, in the subscenes all pixels have the same spectrum and only their overall intensity varies. This limitation is similar to the compressive sensing requirement of redundancy of the output data, i.e. the spectral and spatial information must be compressible. The processing of data consists mainly of applying deconvolution to the Fourier transform of the interferogram and colorimetric fit based on the knowledge of the colorimetric properties of monochromatic light.

A technique such as ours is useful when one cannot physically separate or isolate the areas of spectral uniformity from the scene for spectral analysis or when a spectrometer is not readily available or convenient to use. It is a purely imagistic method. The very purpose of our work was to shift the burden of creating complex hardware able to perform snapshot spectral analysis to finding algorithms of image preprocessing consisting in dividing the scene into areas of spectral uniformity, after which very simple hardware can perform the measurements.

The separability limitation deserves further discussion. It should be noted that the assumption of spectral uniformity, despite being apparently very restrictive, was made by other authors working in the field of spectral imaging using static Fourier transform interferometers. Soncco et al. [29] recently presented a technique for separating the fringes due to interference from the panchromatic image of the scene that uses a variational multiplicative model. “Multiplicative” here means separability of the spatial and spectral dependence in the interfered image, or spectral uniformity. In their own words, “The assumption that all points have the same spectrum is then obviously a simplification, but it is verified at first order for remote sensing images.” Their hypothesis is even more restrictive, since it applies to the whole scene, not just the subscenes. The assumption of the separability of the spectral and spatial component is strong in theory but, apparently, not so strong in the practice of remote sensing. Moreover, in Section 6 we propose a test for separability that can be used also as means for dividing the scene in spectral uniform subscenes.

Another problem with our method is that the analyzed subscene must be smooth enough so that the Fourier orders do not overlap. For the case of a complex subscene, when there is overlap, the formalism of Soncco et al. [29] can be used for separating the Fourier spectrum due to interference from the Fourier spectrum due to the scene itself.

The static interferometric spectral imagers [2,4,9,13–19,21–23] use a variety of interferometers: Sagnac [2,17,21], Michelson [4,16], Mach-Zehnder [22], wedge interferometer [9,18], image plane interferometer [13], a polariscope Savart [23], a grating interferometer [19], or even holography [14], as in the seminal experiment of Stroke and Funkhouser [28]. We preferred to use a Mach-Zehnder interferometer for its simplicity; not a modified Mach-Zehnder, but a classical one with