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3-D Spectroscopy: The Historical and Logical viewpoint

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Abstract.
The present review consists of two parts. The first is mostly of historical interest: the largely-forgotten Lippmann color-photography technique is recalled. The second part is wholly devoted to a critical comparative study of the recently- developed techniques.

1. The Lippmann plate seen as a 3-D spectrometer

The Lippmann interferential color-photography technique was introduced in 1892, and developed for about twenty years. As a practical tool, it was to be superseeded by the Lumière trichromatic process, followed by many others. Recent historical reviews are given by Connes, 1987 and Fournier,1991. We should also be aware that both the Lippmann ideas and the the specific have recently acquired great importance in holography: see Kubota, 1991 and Denisiuk, 1991.

We are concerned here solely because the Lippmann plate constitutes a 3-D spectrometer, indeed a remarkably simple and compact one, a point which was not, and still is not, widely realized. Lippmann himself was not a spectroscopist, and hardly an optician to boot; hence he did not pursue the kind of applications we have in mind. Neither did any of his contemporaries. However, two fellow scientists clearly understood the point (Connes, 1987), and stressed it when they nominated Lippmann for the Nobel prize (which he did finally receive in 1908). Marcellin Berthelot wrote that the Lippmann plates were important not merely as works of art, but also as research instruments. Henri Becquerel was more specific, explaining that all absorption bands and other spectral properties of the photographed object would be preserved in the plate. Nothing came out of these remarks at the time. Today, equipped with a far clearer understanding of basic limits in light detection, we may ask: Could the Lippmann technique become practical for 3-D spectroscopy?

Since the theory of interferential color photography is explained, at least briefly, in all textbooks dealing with wave optics, here we merely comment Fig. 1. A light beam coming from the right falls on the emulsion under quasi-normal incidence. A plane mirror, in optical contact with the emulsion, returns the beam to the right. A standing-wave pattern is formed, and duly impresses the plate. If the beam is monochromatic with wavelength λ, the optical distance between

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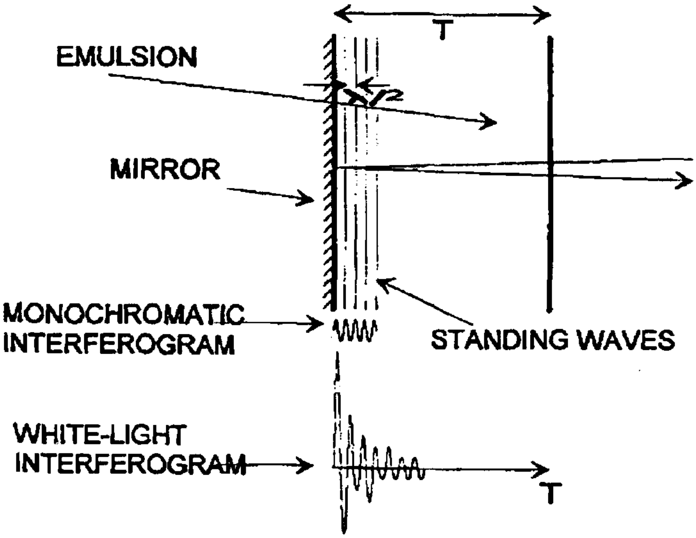

Figure 1. Principle of interferential color photography. T is the optical thickness of the emulsion.

nodes is $\frac{\lambda}{2}$. After developing and fixing, if the plate is viewed in white light under the same incidence, the same wavelength will be preferentially reflected. Today, the similarity with Fourier transform spectroscopy (FTS) is immediately obvious. If the exposing beam contains many different wavelengths, the standard pattern of a white-light interferogram (in three dimensions) is formed close to the mirror. Since there is a node on the mirror surface, the emulsion records a sine-transform interferogram (just as we do in the form of FTS that uses internal modulation). Resolving power R_0 will be equal to the number of recorded nodes, i.e. $\frac{2T}{\lambda}$. Permissible solid angle Ω will obey the standard Jacquinot formula $R_0 = \frac{2\pi}{\Omega}$. Well-known limitations of photon and/or detector noise for narrow- or broad-band spectra etc... will apply.

The above factors are fully independent of the actual spectral-reconstruction technique used. Lippmann's admirers were mostly struck by the automatic and near-perfect reproduction of original color realized by the simple device of white-light illumination. Today, that aspect of the case becomes unimportant: we have more precise ways of producing suitable Fourier transforms. Let us focus our attention on the Lippmann plate merely as a way to record a multipixel 3-D interferogram. What are the *strictly-basic limitations?*

Plate size is almost unlimited, hence very large number of pixels may be accommodated. As to resolving power, which is controlled by thickness T, it was demonstrated by H. Yves, 1908 that up to 250 nodes had been recorded with mercury lines; the expected line-like spectrum was reconstructed in the

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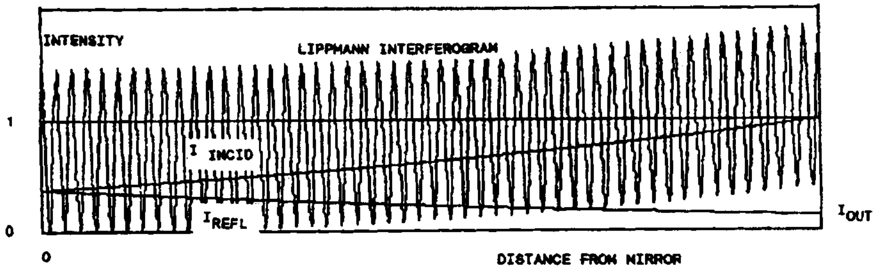

Figure 2. Intensity of recorded Lippmann-type interferogram as a function of optical distance from mirror (at left), in the optimal case.

standard way from white-light illumination. Clearly, that is no limit, and emulsion thickness could be increased at least to about 1mm, with a corresponding R_0 of a few thousand. Next, all types of Fourier spectroscopy suffer from a dynamic-range difficulty for the first few fringes when the recorded spectrum is wide (or, more exactly, contains a large number of spectral elements). This problem appears particularly severe when the recording medium is a photographic emulsion. However, we readily see that cutting off the first few fringes merely loses the very-low-resolution information, which is often not needed (e.g. already available from broad-band photometry). For color photography this is not acceptable, and the only way Lippmann could have his emulsion in optical contact with a mirror was to use mercury; silver was impossible for chemical reasons. Today, for moderate resolution spectroscopy, we would use any kind of mirror protected by a dielectric layer.

Efficiency is a more serious problem. The first question is: Even if we were given an ideal 3-D recording material, would it be feasible to match a Lippmann-type device to the incident wave so that most of the energy is indeed used to record the wanted interferogram? The answer is not immediately obvious. If absorption is very low, most of the energy escapes out after double-passing the layer: efficiency is inherently poor. If absorption is high, the energy is well-trapped indeed; but the intensities of the two beams differ widely, except at the mirror surface. However, a simple two-beam interference calculation establishes that an acceptable compromise exists; results are presented on Fig. 2.

As in Fig. 1, the incident beam enters from the right, and is reflected on the mirror at left. The two exponential curves represent intensities of the two beams taken separately, i.e. what one would get without the standing waves. T is measured in wavelengths, K is the absorption coefficient, the incident intensity is unity. When averaged over a broad spectral band, the intensity of the outgoing (lost) beam is $I_{out} \otimes = e^{-2KT}$. An optimum case is easily found by selecting $K = \frac{1}{T}$; then $I_{out} = 0.13$; hence a fraction 0.87 of the incident beam has been trapped. The intensity of the corresponding "Lippmann interferogram" is represented. It is the sum of two terms. The first is exponentially rising, and would be easily filtered out in the reduction procedure. The second is the useful modulated term, with a constant amplitude. Peak intensity is 1.46. Let us compare with standard FTS. A perfectly absorbing detector located at one output

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of a lossless Michelson interferometer, with 50/50 beamsplitter, would trap on the average half of the incident energy. Peak intensity is 2. However, a second detector at the complementary output may trap the second half. Altogether, compared with the ideal 2-detector FTS case, the efficiency of the Lippmann device (which incorporates detector and interferometer in a single unit) is 0.63, which is not absurdly low; however, after selecting T which controls R_0, one must also be able to choose K at will. Furthermore, a full comparison of expected SNR in both cases is more complex, and will not the attempted here. Next, what about quantum efficiency? The single main reason why the Lippmann plate was superseeded by trichromatic processes around 1910, is that it required much longer exposures, hence earned a reputation for very low sensitivity. However, no comparison has ever been made under proper conditions, nor has given results relevant to our quest. First, the $KT = 1$ relation should be obeyed; second, the comparison should be made for the same R_0, since the resolving power of any 3-color emulsion will be considerably lower than that of any Lippmann plate. If the relevant laboratory tests were undertaken today, we have no reason to believe that the Lippmann-type emulsions would prove less sensitive, in the above meaning, than any others; however, rushing to the sky to make half-backed tests with just any available emulsion would be naïve indeed.

Unfortunately, we have no reason either to believe they would prove any better, and in the days of CCD's etc..., no astronomer is bound to feel great enthusiasm for reintroducing photography in any guise whatsoever. Hence, the next question is: What about possible non-photographic detectors? The detection of standing waves with a photoelectric device has been achieved by Ives and Fry, 1933, in a classical experiment. Using modern techniques, a multipixel 3-D semiconductor detector, incorporating a mirror, might conceivably be fabricated. However, it may very well be that no suitable semiconductor will ever be found: the necessary condition of being able to choose K at will across a broad spectral range may prove impossible to fulfill. For instance, silicon would be suitable only within very narrow ranges close to the absorption edge.

If no solution to this basic problem is found, despite its appealing simplicity, no Lippmann-type device will ever supersede the obvious competitors, i.e. the FTS or FP spectrometers followed by a standard multipixel detector.

2. A review of modern 3-D spectrometers

2.1. The detectors: "true" 3-D's, "sequential" 3-D's and 2-D's

The images available to astronomers mostly are three-dimensional, with two spatial dimensions plus a spectral one. The "data cube" is also called the "Courtès data cube". A thorough acquisition of the information content would require 3-D detectors. However, no truly good one exists, and one must resort to a host of various tricks. First, one may project all three dimensions on present 2-D detectors (CCD, ICPS), with an attendant loss on the total simultaneously-acquired information; alternately, one tries to acquire the data sequentially, which leads, for a given observing night, to a reduction of available time for each elementary exposure.

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True 3-D detectors Supraconductor-based detectors. These transducers make use of supraconducting junctions, at a temperature of 0.1 K. One visible photon creates about 1000 Cooper-pairs somewhere on the surface of the supraconducting electrode; these may be detected at the electrode edge. The number of pairs gives the information about the photon energy, while the travel times of pairs in the substrate gives the position of impact. These detectors have not yet reached the stage of practical usefulness, but one may expect rapid progress in the field. Should they become available in mosaic form, they would provide large-format detectors usable from near UV to far IR. Their spectral resolution will be adequate for sorting the orders of échelle gratings or low-resolution Fabry-Perots, and for directly implementing wide-band photometry. They are also very useful when used in a photon-counting mode with wide dynamic range and high speed (up to 10^7 counts/s) in systems like wavefront sensors.

Sequential 2-D detectors The idea is to read several times a monochromatic-light-illuminated detector, while scanning the spectrograph in order to reconstruct the spectral information. CCD-type detectors are affected by readout-noise, and one must try to reduce the number of readouts. Fabry-Perot interferometers are well-suited as long as the finesse is reasonable (of the order of 20), which means a significant elementary integration, and a photometrically-stable overall sequence.

Wide-field interferometric spectrometers (type: Taurus et al.) The spectral range is selected by an interference filter; the data-cube is scanned by changing path difference while keeping the same interference order. These are well-suited to the study of an emission line.

PEPSIOS. The principle is the same, but the spectral range is selected by a set of interferometers with increasing orders of interference, which are simultaneously scanned; see Mack et al. (1963), Reynolds et al. (1990).

PYTHEAS. This device combines a grating and a Fabry-Perot; several interference orders are simultaneously available for all the points within a small field, selected by a grid of microlenses.

FTS. This is the most versatile device, since the observer may adjust resolution at will. However, a long scan is required if one wants both a high spectral resolution and a large spectral range (in the case of absorption spectra an no readout noise detector).

"Simultaneous" 2-D devices These systems produce simultaneously a few monochromatic images of a given field upon one or several detectors.

BPM G. Courtès (1964) described a multi-bandpass system which sends several images of the same field simultaneously to separate detectors, with medium spectral resolution (illustrated on fig 3).

Spectrographs Integral spectrography. Provided one requires only a few spectral elements, it is feasible to do spectroscopy on all contiguous pixels within a given small field. Instruments of the ARGUS type (Vanderriest 1984) use a compact bundle of fibers which spread out along a slit, while the TIGER-type

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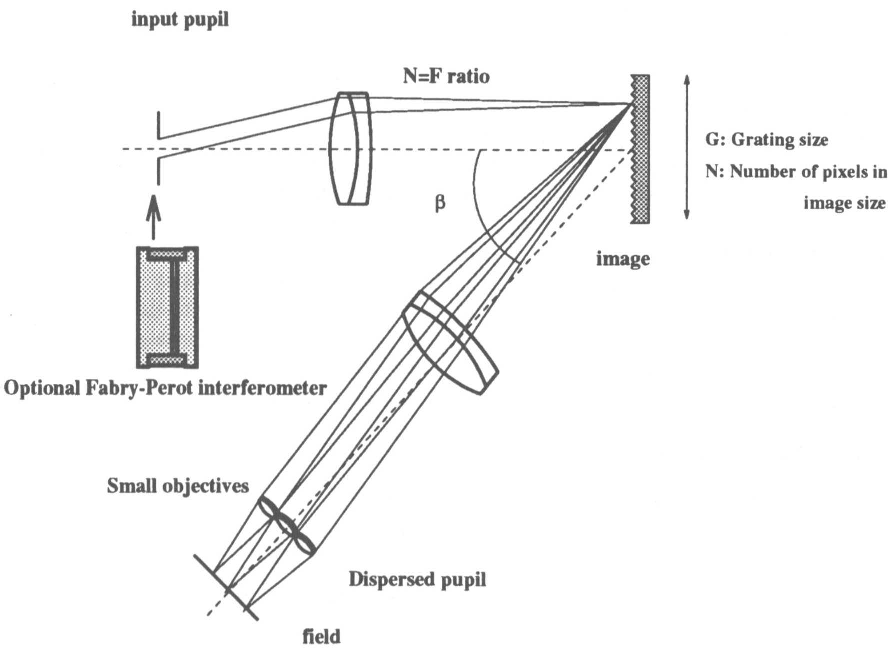

Figure 3. The "Bande Passante Multiple " mounting (Courtès 1964) The image of field is projected over the grating where the focal ratio number $N = \frac{f}{D}$ gives directly the limiting spectral resolution $R = N\ tg\ \beta$. Small objectives placed on the dispersed pupil make an image for each selected color. It is possible to add a Fabry-Perot interferometer in front of the BPM in order to boost the spectral resolution

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(Courtès 1982) starts from a microlens array; these convert an enlarged image of the field in small elementary slit pupils spread out in the field.

Multi-object spectrography. In the same situation (a few spectral elements), one may produce spectra of several point sources randomly located anywhere within the field. Again we have two distinct families of spectrographs: the first, of the "medusa" type (Courtès 1984) use fibers to reunite the beams along a slit; the second require a multi-slit mask in the image plane, followed by a focal reducer.

2.2. Beam throughput and invariant quantities in optical instruments.

Following G. Monnet (1970), we may state that all the above instruments will exhibit the same overall efficiency for a given 2-D detector fully-filled all the time. Inversely, one may easily find cases where the detector is but poorly used. Here are two examples: if the objects are widely dispersed within the field (e.g. galaxy clusters), the spatial information density is low; if emission spectral lines are similarly spread- out far apart, one suffers from low spectral information density. The observing problem reduces to selecting the type of imaging spectrograph which bests projects all the spectral/spatial information on a finite detector within a finite time. Moreover, for a given detector pixel size, the average seeing at a given site constrains the solid-angle of the beam falling on the detector. All these invariants proceed from the conservation of throughput ("étendue") which governs all optical instruments.

2.3. Field and Pupil

Any optical beam possesses two privileged planes:

- The field, a maximum-contrast plane where the image may be analyzed.
- The pupil, a minimum-contrast plane, interesting for photometry because of intrinsic stability and uniformity.

Fabry (1910) made good use of this last feature by imaging the pupil on the plate ("plage de Fabry"), in order to get the total flux of stars within the field, and deduce the integrated Milky- way flux. Jacquinot and Dufour (1948) used the same principle in their interferometric spectrometer: they imaged the pupil on the photomultiplier. Along any optical beam, pupil and field unavoidably alternate. For instance, with a slit spectrograph, we find in succession the collecting mirror pupil, the field at the telescope focus where the slit is located, a pupil image on the grating, and a field image on the detector. The original point in the Courtès set-ups has been the field-pupil inversion produced by the microlens grid over very short distances (a few mm), as in TIGRE and PYTHEAS. Hence we get a pupil image on the slit, then a superposition of multiple fields seen by each microlens on the grating and dispersed pupil images on the detector. The greatest advantage of this inversion is a thorough decoupling of the spatial/spectral informations; by contrast, in a slit spectrograph illuminated in the normal manner, the spectrum is convolved with the image of the object on the slit. Other spectrographs use fibers or image slicers in order to illuminate the slit uniformly; however there is some increase of the beam size, and the pupil is

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not uniformly illuminated. In the BPM set- up of Fig 3, a much-enlarged image of the object is projected in the afocal space, while the pupil image is dispersed by a concave grating, and several "monochromatic pupils" are generated on the Rowland circle. Finally we get several images of the field on separate detectors, with the ability to select the colors at will.

2.4. Input and output sampling

In most cases, image sampling is performed by the detector pixels at the output of the entire optical system. Even with the most carefully designed optics, image quality suffers from accumulated imperfections of all the elements. We know that the very best images are obtained by anti-blooming CCD's directly located at the telescope focus. Similarly, in the spectral information case, the accuracy of sampling will depend on the place where it is actually implemented, and of the various upstream/downstream elements which may degrade spectral resolution: slit, collimator, camera lens and sampling by CCD pixels . Some optical set-ups accomplish the sampling at the instrument input, because they separate and sample the informations right away. This is the case for a microlens grid or fiber bundle when it is located directly at the telescope focus (e.g. as in TIGRE and ARGUS), and also for the interferometers which filter the beam without any deviation. We are allowed to say either that they do not degrade the image (or the spectrum), or that their sampling accuracy is wholly independent of the optical train properties. This is particularly true in the case of PYTHEAS, with the interferometer located at the system input: then we do get the theoretical interferometer resolution, i.e. the local reflecting- power finesse, irrespective of planeity or parallelism errors (Chabbal 1958). Fig. 4 summarizes these properties and attempts to list the instruments depending of the quality of information sampling.

2.5. Focal reducer as a toolbox

In the focal reducer we have two privileged regions which we may call the slit space and the afocal space; within these, highly diverse tools may be located. In the following table we list some of instruments who can be used with the same focal reducer. The number and the letter in the table refer to the Fig. 5 which shows various devices in focal plane and afocal space.

2.6. Channelled spectra

Crossing a grating and a Fabry-Perot in a spectrograph Fabry 1905. In this mode there is no way to get the full data cube: the entire spectrum is recorded, at very high resolution and within a large range, but some lines appear at some points of the field and others at other points. The system may be very compact; it was first demonstrated by Fabry in 1905 with R=300 000, and Perot used it in 1921 for the first check of the Einstein shift ($2.12\ 10^{-6}$) on the Sun.

Kulagin 1980. With a Fabry-Perot used under high incidence, the fringes become almost parallel and may be fitted to the grating dispersion; in this way Kulagin builds a very luminous spectrometer giving $R = 10^6$ without the need of a slit sharp enough to fit the telescope diffraction pattern.

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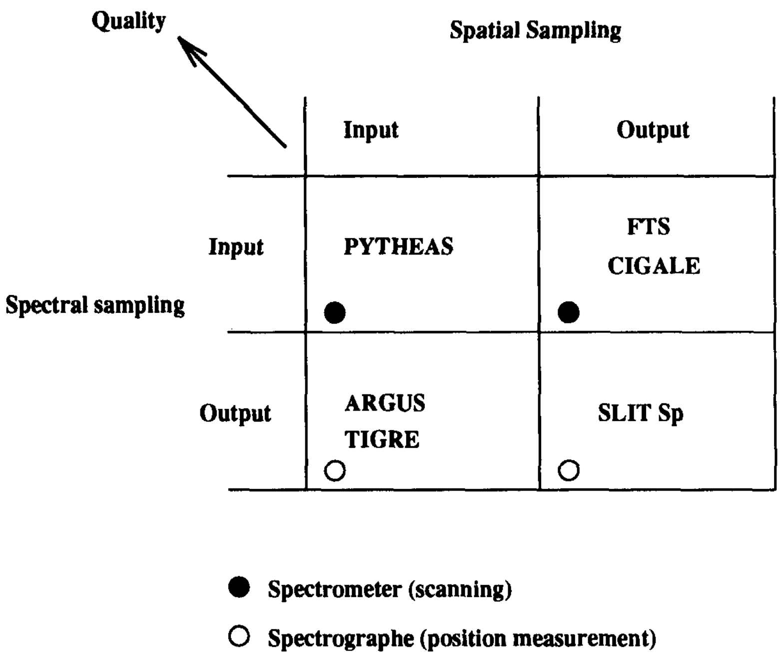

Figure 4. Various forms of information sampling

Table 1.

slit space		afocal space	Instrument	Publication
0	+	0	Wide Band Imaging	Fabry-Buisson (1911)
1	+	0	Narrow band imaging	Courtès Thesis (1952)
0	+	A	Prism-objective	Courtès (1964)
0	+	0	Insecte Eye	Courtès-Georgelin (1967)
1	+	D	Wide field spectrometer Taurus	Atherton (1982)
3	+	B	Integral field spectrograph	Courtès (1982)
4	+	B	Fiber bundle spectrograph	Vanderriest (1984)
5	+	B	multi-object fiber spectrograph	Vanderriest (1984)
6	+	B	Multi-slit Spectrograph	Fort (1986)
7	+	B	Pythéas	le Coarer (1992)
6	+	E	Multi-slit spectrometer	le Coarer (1992)

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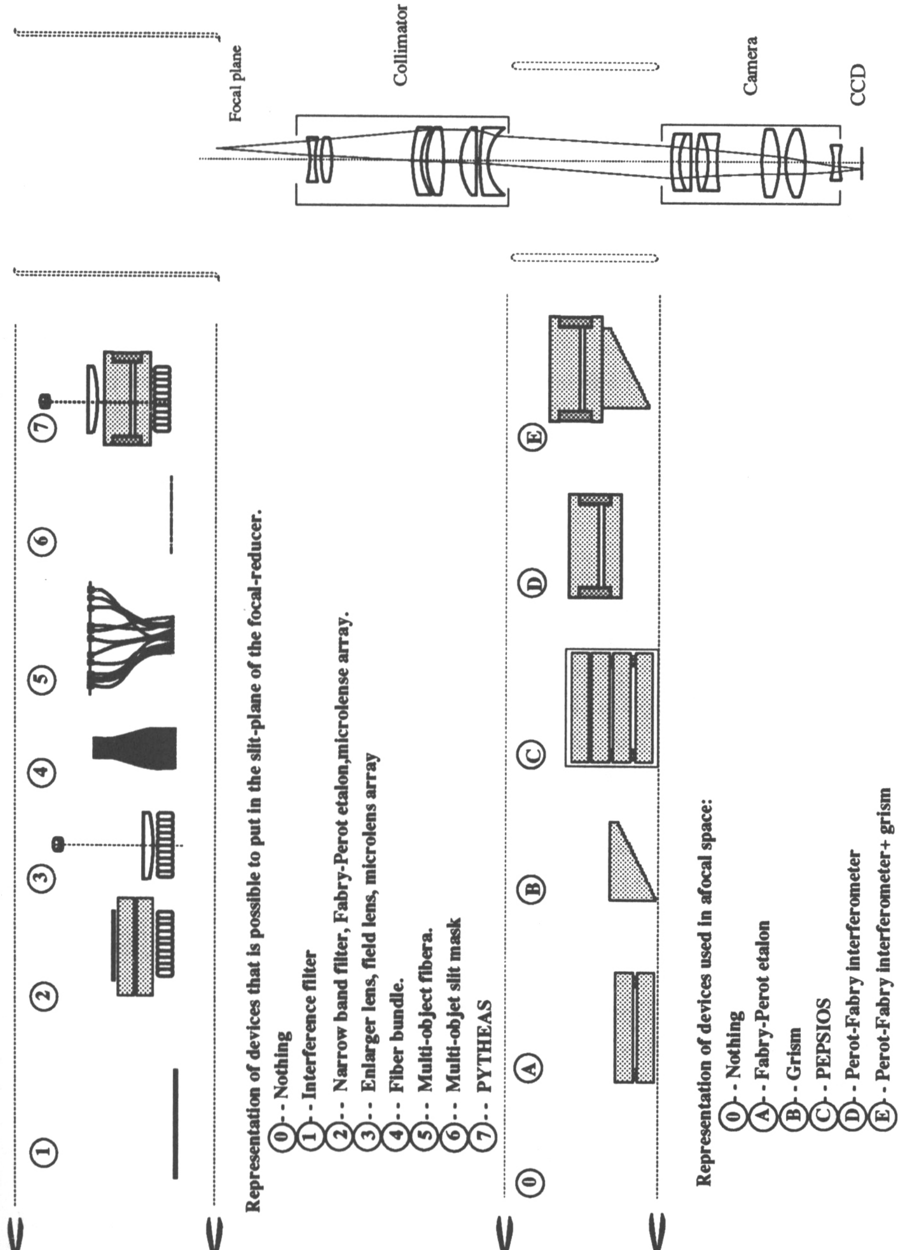

Figure 5

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Crossing a grating and a Fabry-Perot in a spectrometer By scanning the optical path between plates of Fabry-Perot, we may get the whole spectrum for the whole field, hence build up a large data cube. All the points in the field are simultaneously observed; the pack of grating-plus-Fabry-Perot channelled spectra is imaged on the detector XY plane. During the FP scan, the channelled spectrum slowly shifts, and at the end of the scan the whole spectrum has been recorded.

PYTHEAS. This is a crossed-grating-FP spectrometer with a microlens grid, which records all points within a small field.

MORGANE. Again a crossed-grating-FP device, but one with a multi-window mask; it simultaneously records many small windows within a wide field.

BPM-Fabry. Fig 3 presents one example of a BPM system to which a Fabry-Perot interferometer has been added for scanning line profiles.

Conclusion The lack of efficient three-dimensional detectors obliged physicists to develop some complicated optical devices. Theoretically, quantum mechanics authorizes us to hope in detectors able to detect the position, the energy and the arrival time of the photon with accuracy higher than necessary...

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