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IBIS (Interferometric BIdimensional Spectrometer)(*)

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Summary. — IBIS is a new instrument for solar bidimensional spectroscopy, now under construction at the Arcetri Astrophysical Observatory. It essentially consists of two Fabry-Perot interferometers, piezo-scanned and capacity servo-controlled, which are used in classic mount and in axial-mode, in series with a narrow-band interference filter. This instrument will operate on a large field of view (80″) and on a large wavelength range (5800–8600 Å), with high spectral ($\lambda/\Delta\lambda \simeq 250000$), spatial ($\simeq 0.2''$) and temporal ($\simeq 5$ frames s^{-1}) resolution. When completed in 2002, it will be one of the leading instruments for solar research, well suited for a new generation telescopes such as THEMIS.

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1. – Introduction

At the end of 1999 the construction of a new instrument for solar bidimensional spectroscopy started in Arcetri, which has been called IBIS, an acronym for Interferometric BIdimensional Spectrometer. This instrument has been built with the contribution of the Arcetri Astrophysical Observatory, the Department of Astronomy and Space Science of the Florence University, and the Department of Physics of the Rome "Tor Vergata" University.

When completed, at the end of 2002, IBIS will replace the Italian Panoramic Monochromator (IPM) [1], installed at THEMIS, the French-Italian solar telescope operative at Tenerife (Canary Islands).

Notwithstanding their different name, the two instruments are very similar, at least in principle, since both have been designed to take monochromatic images of the solar

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surface. The question is: why a new instrument, so similar to another one, already operative and producing scientific results?

2. – The ideal bidimensional spectrometer

To answer the previous question, let us consider firstly the more relevant instrumental characteristics required to an ideal bidimensional spectrometer for solar physics.

1) High spectral resolving power: $\lambda/\Delta\lambda \geq 200000$, to analyse narrow photospheric lines.

2) High wavelength stability: a maximum drift of the instrumental profile ≤ 10 m s^{-1} on some hours, to ensure the repeatability of the wavelength selection.

3) Large useful spectral range: a useful spectral range of $\simeq 1000$ Å or more, to allow a large selection of spectral lines of high diagnostic value.

4) Large field of view: a field of view of $\simeq 1.5'$ or more, to allow the study of active regions, and the interaction between adjacent structures.

5) High spatial resolution: a spatial resolution of $\simeq 0.2''$, to study single, elementary structures, with sizes of $\simeq 100$ km on the solar surface.

6) High temporal resolution: an acquisition rate of several frames s^{-1}, to study the evolution of the observed phenomena on short time scale.

As already noted [2], IPM only partly satisfies these requirements. As a matter of fact, it has a high spectral resolution and a high wavelength stability, but also is affected by some limitations. So, the useful spectral range ($\simeq 200$ Å) and the field of view ($5''$) are too small. Moreover, mainly due to the Universal Birefringent Filter (UBF), used as *order sorter* for the interferometer, the overall transparence is low, imposing an exposure time of about 200–300 ms. This implies that, while IPM has been designed to completely exploit the spatial resolution allowed by the telescope ($\simeq 0.2''$ for THEMIS), due to the long exposure time, the effective spatial resolution is lowered by the seeing effects. Finally, due to the long exposure time and to the long wavelength setting time of UBF ($\simeq 1$ s), the acquisition rate cannot be higher than $\simeq 0.7$ frames s^{-1}.

Among the requirements detailed above, the high spatial resolution certainly is the most demanding, not often obtainable with ground-based observations.

On the other hand, no space-based instrument of this kind yet exists, as it requires a large telescope and a very large bandwidth to transmit the enormous data flux.

Special considerations must therefore be given to these characteristics when planning a new instrument.

There are two primary methods that are currently used in solar physics to correct the seeing effects that limit the spatial resolution obtainable from the ground: adaptive optics, and the so-called *phase diversity* technique.

As is well known, adaptive optics is a hardware technique that allows the correction, in real time, of the incoming distorted wave-front. Tests, recently carried out at the National Solar Observatory (Sacramento Peak), have shown the possibility of successfully using this method on a small solar field of view ($\simeq 10'' \times 10''$), in order to reach the diffraction-limited resolution of the telescope.

Phase diversity, instead, consists in the simultaneous acquisition of two images of the same solar region, one in focus and another out of focus, by a known amount. The *post-facto* comparison of the two images allows the determination, and subsequent correction, of the atmospheric wave-front over the whole field of view. The phase diversity method requires very short exposure times (less than about 40 ms), in order to freeze the seeing conditions in each single exposure. In turn, this requires a very high throughput of the telescope and instrument combination and, for this reason, recent results obtained with this method are limited to data acquired with broad-band filters, devoid of any spectral information.

Starting from these considerations, IBIS has been designed to allow very short exposure times (≤ 20 ms), so that the spatial resolution of 1 m class telescopes can be fully exploited by using the phase diversity technique.

In any case, if adaptive optics will become available in the future, IBIS can take advantage of it, using longer exposure times for a more accurate photometry, but still allowing very short total acquisition times.

3. – IBIS

The instrumental layout has been already described in detail [2] and only some general characteristics will be reported here.

IBIS essentially is formed by two Fabry-Perot interferometers, piezo-scanned and capacity servo-controlled (see table I), which are used in classic mount and in axial-mode, in series with a narrow-band interference filter (FWHM = 3 Å).

At the end of the principal optical path there are one or two CCD cameras (see table II), depending on the use of the phase diversity technique. Near the entrance of the instrument, a beam-splitter picks off a small amount of light ($\simeq 0.25\%$), which then passes through a second set of broad-band interference filters (FWHM = 50 Å), centered at the same peak wavelength of the narrower ones. A suitable optical system then forms a "white light" image of the same solar region on a further CCD camera, identical to the other ones. Thanks to the use of only one electronic shutter, placed near a pupil image, the two CCD cameras simultaneously take a monochromatic and a "white light" image of the same solar area.

Additional secondary optical paths are provided to continuously monitor the selected solar area, to find the initial tuning conditions, to verify and to adjust the parallelism of the interferometer plates and their orthogonality to the optical axis.

In table III the more relevant instrumental characteristics of IBIS are compared to those of IPM. As may be seen, IBIS has a high spectral resolving power and a high wavelength stability, as IPM, but also a larger wavelength range (2800 Å *vs.* 200 Å of IPM), a larger field of view ($80''$ *vs.* $51''$ of IPM), a shorter exposure time (5–20 ms *vs.* 200–300 ms of IPM) , and a higher acquisition rate (5 frames s^{-1} *vs.* 0.7 frames s^{-1} of IPM).

4. – The choice of the optical mounting

4˙1. *A single interferometer.* – As said before, the two interferometers of IBIS are used in classic mount and in axial mode, and this choice is relevant to assure the best instrumental performances. Let us discuss, therefore, in more detail advantages and disadvantages of different optical mountings.

As well known, a Fabry-Perot can be used for imaging in classic or in telecentric mount.

In classic mount the interferometer is placed in a pupil space where the image is collimated: each image point is therefore formed by a cone of rays, normally incident

TABLE I. – *Fabry-Perot interferometers characteristics.*

Manufacturer	Queensgate Instruments Ltd.
Type	Mod. ET50
Clear aperture	50 mm
Plate separation	2.300 mm, 0.637 mm
Wedge angle	20′
Coating	Multilayer broad-band
Reflectivity	92–94%
Wavelength range	5600–8600 Å
Defects of each plate at 6328 Å	$\lambda/150$ maximum after coating

on the interferometer, containing all the directions allowed by the optics, and covering a small area of the plates.

In telecentric mount, instead, the interferometer is placed in an image space where the pupil is collimated: each image point is therefore formed by a beam of rays incident on the interferometer at an angle less or equal to the maximum one allowed by the optics, and covering a large area of the plates.

Each mounting shows advantages and disadvantages.

Let us consider firstly only one perfect interferometer (an interferometer the plates of which are perfectly parallel and without defects) used in axial mode.

In classic mount, in this case, each interference order (hereafter assumed as the instrumental profile) is generally narrower than in telecentric mount, but it shows a systematical blue-shift when moving from the optical axis towards the edge of the field of view.

On the other hand, in telecentric mount the wavelength of the instrumental profile is the same on all the points of the image plane, which can be therefore considered as spectrally homogeneous, and this is the reason why this mount is often preferred for imaging.

However, if we consider now a real interferometer, the effect of plate defects (generally more relevant than the parallelism errors) is different on different mounts.

In telecentric mount, due to the plate defects, the spacing on the small area covered by each cone of rays generally differs from the mean interferometer spacing. As a con-

TABLE II. – *CCD and camera characteristics.*

Camera manufacturer	Princeton Instruments Inc.
Camera type	Pentamax
Maximum acquisition rate	5 MHz
Dynamic range	12 bits
CCD manufacturer	Kodak
CCD type	KAF-1400
CCD format	1317 × 1317 pixels
Pixel size	6.8×6.8 μm
Active area	8.98 × 7.04 mm
Full well capacity	45 ke$^-$
Readout noise	20 e$^-$ at 5 MHz

TABLE III. – *Comparison between IPM and IBIS characteristics.*

	IPM	IBIS
Wavelength range	4600–6800 Å	5800–8600 Å
Calibrated ranges	5184 Å (Mg b1), 5380 Å (C I), 5576 Å (Fe I), 5890 Å (Na D2), 6438 Å (Cd red line), 6563 Å (H_α)	No calibration is necessary
Full Width at Half Maximum (FWHM)	17–26 mÅ	21–42 mÅ
Spectral resolving power ($\lambda/\Delta\lambda$)	260000–270000	205000–320000
Wavelength drift	≤ 10 ms^{-1} on 10 h	≤ 10 ms^{-1} on 10 h
Field of view (circular)	$51''$	$80''$
Transparency	0.7–2.0% (H_β–H_α)	10.0–16.2%
Exposure time (S/N $\geq$ 100)	200–300 ms	≤ 20 ms
Wavelength setting time	1 s	$\simeq 1.5$ ms
Acquisition rate	$\simeq 0.7$ frames s^{-1}	$\simeq 5$ frames s^{-1}

sequence, the wavelength position of the instrumental profile ramdomly changes when moving from a point to another point of the image plane, which therefore cannot be considered as strictly spectrally homogeneous.

In classic mount all the collimated beams associated to the image points cover a large area of the plates. Consequently, the defects are equally averaged, and they produce a widening of the instrumental function which is the same in all the points of the final image plane.

In table IV is shown, as an example, the instrumental profile ($\lambda = 7200$ Å, *f*-number $= 110$) of one of the interferometers used for IBIS (spacing = 2.300 mm, see table I), when used in classic and in telecentric mount.

We may conclude that, for a single interferometer used in axial mode (as for IPM), the choice between classic and telecentric mount is only a compromise between spectral resolution and spectral homogeneity of the image plane.

TABLE IV. – *Instrumental profile of a single Fabry-Perot (axial-mode).*

	Classic	Telecentric
Peak transparency (%)	81.3	43.2
FWHM (mÅ)	32.3	79.1
Equivalent width (mÅ)	40.9	40.9
Shift (mÅ)	−74	±13

4·2. *A multi-interferometer.* – The situation is completely different when two or more Fabry-Perot in series are used for imaging. Let us consider, for example, a double-interferometer in telecentric mount and in axial mode. In this case, the random wavelength fluctuations of the instrumental profile produced by the first Fabry-Perot randomly add to those produced by the second one. The result is that on each point of the final image plane the instrumental profile not only changes in wavelength, as for a single Fabry-Perot, but also in shape. In table V is shown, as an example, the instrumental profile ($\lambda = 7200$ Å, f-number $= 110$) of IBIS, when used in classic and in telecentric mount. It may be seen that, as said before, the instrumental profile changes in wavelength, but also in transparency, in width, and in equivalent width. Moreover, all the instrumental profiles are asymmetric, except those corresponding to equal shifts produced by both interferometers.

We have to note that the strong fluctuations of the equivalent width (±34%) will produce equally strong fluctuations of the radiation flux on the final image plane. So, a field uniformly lighted by a continuous source will be reproduced at the exit of the instrument as a dishomogeneous field, with dark and light patterns. The flat field can remove this effect from images obtained on the continuum, but cannot obviously remove the effect produced by the shape fluctuations of the instrumental function from images obtained on a line profile.

In classic mount, instead, the radial blue-shift only depends on the wavelength and on the incidence angle, which is the same for each image point and for both interferometers, securing the tuning over all the field of view. The resulting instrumental profile, simply obtained as a product between the single instrumental functions of the two interferometers, has therefore the same shape over all the final image plane.

We may conclude that, while for a single interferometer both classic and telecentric mounts can be used, for two or more interferometers, telecentric mount so heavily affects the instrumental profile, that classic mount seems to be the only possible solution.

TABLE V. – *IBIS instrumental profile (axial mode).*

	Classic	Telecentric
Peak transparency (%)	66.1	17.7–39.7
FWHM (mÅ)	30.4	76.6–80.5
Equivalent width (mÅ)	26.1	15.8–32.1
Shift (mÅ)	−74	±28

5. – The ghost images

The proposed solution of a double-interferometer used in classic mount and in axial mode does not consider a problem, typical of any multi-Fabry-Perot: the ghost images produced by inter-reflections between different interferometers.

This problem generally is solved by tilting one or more Fabry-Perot of a small amount, sufficient to allow ghost images to clear the field [3, 4]. However, this solution also produces some serious, unwanted effects. In telecentric mount the tilt gives rise to a strong asymmetry of the instrumental function; in classic mount it produces different instrumental profiles in different points of the image plane.

Moreover, both in classic and in telecentric mounts, the tilt also yelds an equal, strong loss of the overall transparence ($\simeq 46\%$ for IBIS). In particular, while in telecentric mount the tilt produces a dishomogeneous darkening of the pupil and a homogeneous darkening of the image, in classic mount it produces opposite effects.

In any case, the final conclusion is depressing: the result of these considerations, in fact, is that, both in classic and in telecentric mounts, a multi-interferometer is always characterized by a bad instrumental profile and a heavy loss of transparency.

This impasse has been solved for IBIS by using the two interferometers in classic mount and in axial mode, and solving the problem of ghost images by placing the interference filter between the two Fabry-Perot. A filter with a so narrow passband, in fact, also has a small peak transparency of $\simeq 30\%$, and reduces therefore the ghost images from an intensity of $\simeq 10\%$ to $\simeq 1\%$ of the principal one.

In this way we obtain a double interferometer with a good instrumental profile and without any loss of light. The only remaining problem, that is the radial blue-shift of the instrumental function, can be easily solved by extending the spectral scanning of the same amount towards the red.

This solution, obviously, cannot be also used for three or more Fabry-Perot, and this is the reason why we preferred for IBIS two interferometers and a narrow-band interference filter, which limits the useful wavelength range to $\simeq 2$ Å, to more interferometers in series, whith a wider interference filter [5].

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