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ABSTRACT

A scientific and engineering team led by the Department of Astronomy of the IAG, at the University of São Paulo, is engaged in the development of a highly versatile, new technology, optical imaging interferometer to be used both in seeing-limited mode and at high spatial resolution using the SOAR Adaptive Optics Module (SAM: the GLAO facility for the SOAR telescope). Such an instrument opens up important new science capabilities for the SOAR astronomical community: from studies of nearby galaxies and the ISM to statistical cosmological investigations.

The Brazilian Tunable Filter Imager (BTFI) concept takes advantage of two new technologies that have been successfully demonstrated in the laboratory environment but have yet to be deployed in any astronomical instrument. The iBTF (imaging Bragg Tunable Filter) concept utilizes a Volume Phase Holographic Grating in double-pass configuration (Blais-Ouellette et al. 2006[1]) while the new Fabry-Perot concept involves the use of commercially available technology allowing a single etalon to act over a very large range of interference orders. Both technologies will be used in the same instrument. The combination allows for highly versatile capabilities. Spectral resolutions spanning the full range between 5 and 35,000 can be achieved in the same instrument through the use of iBTF at low resolution and scanning Fabry-Perots beyond R ~2,000 with some overlap in the mid-range.

The instrument is being developed in collaboration with several other Brazilian Institutions (Poli/USP, INPE, LNA and Unipampa) and international collaborations with

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the Laboratoire d'Astrophysique de Marseille and the University of Montreal. The reader is directed to the URL http://www.astro.iag.usp.br/~btfi/index.php for a full representation of the project and its current status. The instrument should see first light, mounted on the SOAR telescope, as a visiting instrument, on semester 2010B.

Keywords: Imaging Bragg Tunable Filter, Fabry-Perot, EMCCD

1. INTRODUCTION

The concept of the Brazilian Tunable Filter Imager came as a response to the need within the Brazilian community of a 3D-spectroscopy instrument able to make use of SAM's full field of view (Tokovinin et al., 2008[3]). The possibility of having an instrument working with SAM's enhanced spatial resolution over a relatively large (~3 arcminute) field of view was envisaged to be a powerful tool that would allow the SOAR community to conduct high impact scientific programs. In order to full realize the science potential that such an investment allows, it was necessary to utilize not just the superb image quality but also the field-of-view advantage of the SOAR plus GLAO configuration for spectroscopy, not just imaging. SOAR already possesses an optical imager (SOI) at the native bent Cassegrain focus and the SAM project has planned the construction of a dedicated GLAO-enhanced optical imager (SAMI). The BTFI concept, on the other hand, was proposal to develop a wide-field tunable filter imager as an effective means of doing area spectroscopy over a wide range of spectral resolving powers on SOAR and SAM, to fully exploit their science potential.

The BTFI project started in February 2007 and it successfully passed CoDR and PDR in September 2008 and June 2009 respectively. The system was designed to supply tunable filter imaging with a field-of-view of ~3 arcmin. sampled at ~0.12 arcsec. with an f/7 camera, for direct Nasmyth seeing-limited area spectroscopy and for SAM's Visitor Instrument port for GLAO-fed area spectroscopy.

Like many other instruments of its type, the BTFI employs Fabry-Perots (FPs) in order to achieve high spectral resolution, up to $R < 35,000$. In the scientifically compelling, low spectral resolution domain, exploited more recently by the Anglo-Australian Telescope's TAURUS Tunable Filter (TTF - Bland-Hawthorn, J., & Jones, D.H. 1998[2]), the BTFI will utilize a new double-pass Volume Phase Holographic (VPH) grating technology (the imaging Bragg Tunable Filter; or iBTF) to achieve ultra-low to intermediate ($5 < R < 4000$) spectral resolving powers in a highly efficient, cost-effective and compact configuration.

2. Instrument concept – the new technologies

The concept of a classical FP-based imaging interferometer for both kinematic work (high interference order) and tunable filter work (low interference order) is contrasted with the iBTF technology which allows for ultra-low spectral resolutions using very simple technologies.

2.1 The Fabry-Perot operating modes of BTFI

2.1.1 *The FP Tunable Filter mode (in the image plane)*

The BTFI uses FP etalons manufactured by SESO (Société Européenne de Systèmes Optiques - http://www.seso.com/) which allow a far greater range of spectral resolutions than available using the more traditional FPs. For the lower range of resolutions we chose to deploy a SESO etalon in the diverging beam of the f/16.5 input focus allowing us to dedicate the collimated beam to the higher end of the spectral resolution range. Although SESO etalons have the capability of spanning FP gaps of ~250μm, which would, in principle allow a spectral resolution range between 500 < R < 25,000, when used in the divergent beam, the higher end of this range is limited to R < 2,000.

2.1.2 *The classical Fabry-Perot mode (in the pupil plane)*

The raw data produced by a scanning FP system can be represented by a series of images of the studied object, obtained at different wavelengths (or velocities) emanating from the source. The different wavelengths are obtained by changing the spacing between the plates of the FP etalon. The observed wavelength range is isolated using an interference filter. Once calibrated, one has a spectrum for each pixel in the field.

For the BTFI we again use a SESO FP etalon but this time classical mounted in the collimated space. Again, the ability to enlarge the scan range of the piezo-electric from near zero up to 250μm, allows the BTFI to cover a large number of free spectral ranges.

2.1.3 *The use of both etalons in series*

The BTFI has two etalons, one in the divergent beam near the input focus (for low spectral resolutions) and the other in the collimated beam (for higher spectral resolutions). Since both etalons can be deployed independently into the optical beam it is possible to use these etalons in tandem with the first operating as an order sorter for the second. In this manner great flexibility is achieved in the ability to select a particular order for the higher resolution etalon, a job which is usually done by the use of a fixed interference filter. By using the low resolution etalon as an order selector, avoidance of the acquisition of multiple costly interference filters (and the necessity to mount these) is achieved. The disadvantage is that order selection is achieved with a single-pass Airy profile rather than a clean near top-hat interference filter profile. Nevertheless such a two-etalon capability is seen as a great advantage for BTFI.

The new SESO FPs can be used as a Tunable Filter (low order of interference: low resolution) and as a classical Fabry-Perot (high order of interference: high resolution) and may shift from one mode to the other in a fraction of second.

With BTFI we would target a resolution range which takes us from close to the resolution limit defined by the Tunable Filter elaton in the divergent beam (i.e. R ~2,000) to the upper end (R ~35,000). There will, inevitably be a spectral resolution "gap" between the low and high resolution domains which can be partially filled by the iBTF mode, under certain constraints and by our ability to stretch the gap range of the SESO etalons themselves. These limits are currently under investigation.

2.2 The iBTF operating mode

The iBTF employs two identical crossed VPH gratings which cancel each other's dispersion. The resultant output represents the blaze function, as defined by its Bragg condition at a specific angle of incidence. By changing the angle of incidence of the grating pair this blaze function can be scanned, thus achieving wavelength tunability over a wide range of wavelengths and spectral resolutions, as defined by the grating and the range of accessible angles.

This technique gives the ability to achieve an imaging tunable filter by simply changing the angle of the grating pair; the iBTF optical configuration can employ either transmission or reflection gratings thus increasing the range of resolutions obtainable. Resolutions are then limited to those achievable with current VPH grating materials.
Gratings made from dichromated gelatin (DCG) allow for very thin grating structures with high refractive index modulations giving resolutions in the range $5 < R < 500$, while thick, low refractive index modulation gratings can be made from doped-glass which can reach resolutions towards R ~4000.

2.3 The Detectors

When observing in wavelength scanning mode with a classical CCD, as is the case for all currently available tunable filters and Fabry-Perot systems, it can take several hours to complete a single scan and as such the observations are susceptible to changes in seeing and transparency between individual frames. The result is that the profile of the scanned line will be biased, unless the scan is rapid enough so that it can then be repeated several times to achieve the desired total exposure time. The changes in seeing and transparency will be averaged when adding all the individual frames corresponding to the same scanning step of the FP (or iBTF). The problem with classical CCDs is that their readout noise will be added on each individual frame and the resulting profile will be relatively noisy. Because of the read-out noise, it is impossible to scan rapidly through the channels (one has to wait for enough counts to be collected in the frame before reading it), with the result that only observations taken in highly photometric conditions are fully reliable since the changes in seeing and transparency cannot be averaged out.

In order to be able to scan rapidly through the channels, one has to work in photon counting (or electron amplification) mode with essentially no read-out noise. By far the best solution is the L3CCD (http://e2vtechnologies.com/technologies/l3vision_nojs.htm), an Electron Multiplying Charge Coupled Device (or EMCCD) in that it operates at essentially zero read-noise as compared to a classical CCD. EMCCDs can be operated in an amplification mode where gain-noise imposes an effective penalty of ~2 in quantum efficiency or in photon counting mode where gain-noise can be eliminated at the cost of a serious reduction in dynamic range. For classical, long exposure, imaging or spectroscopy these disadvantages generally out-weigh the EMCCDs advantages in background-noise limited observations. However, when short exposures are demanded or when detector noise is a limiting factor, then EMCCD can come into their own.

It will be noted that the domain of short exposure and low background noise is precisely that of the tunable filter. Not only is the back-ground noise suppressed to a greater or lesser extent by the narrow-band imaging but the requirement to mitigate against atmospheric variability implies the use of rapid scanning whereby very short exposures are taken to build up a data-cube through continuously cycling through wavelength space. A detailed analysis shows that for BTFI under a broad range of operating conditions, the EMCCD in amplification mode (even given the reduction of a factor of 2 in QE) gives higher signal-to-noise performance than a classical CCD when used for rapid scanning tunable filter work. Counter-intuitively, this is not the case for photon counting, despite the fact that the early use of imaging FPs used the Image Photon Counting System (IPCS). The fact is that photon counting has such a limited dynamic range that it is only useful under the most extreme of low light level condition across very limited flux levels; this despite the fact that it does not suffer from gain noise inherent in amplification mode operation of the EMCCD.

3. BTFI Instrument Description

3.1 Instrument Concept

In its simplest mode the BTFI instrument is a focal reducer with a single f/16.5 collimator and dual cameras allowing the simultaneous acquisition of the filtered (F_λ) and complementary ($T-F_\lambda$) images across the observed field-of-view (T represents the spectrum of pre-filtered light incident on the tunable filter having a tunable band-pass

F_λ). The simultaneous acquisition of filtered and complementary images permits a robust correction for transparency and PSF variations which otherwise plague the reconstruction of photometrically accurate 3D data-cubes.

As far as we are aware, all other FP-based imaging interferometers have done without such a facility, however accuracy of the photometric reconstruction of such data-cubes has been a severe limitation on the scientific utility of the resulting data. While high resolution kinematic data can, with care, be routinely obtained, an accurate, low resolution, tunable filter data cube requires not only superb photometric conditions over the time-frame of the spectral scan but also a stability of the image PSF to preserve spatial resolution through the data-cube. Immunity to such atmospheric instabilities can be mitigated to some degree with photon counting detectors (eg: the original TAURUS system using the Image Photon Counting System, the FaNTOMM fast scanning system or proposed systems using E2V's L3CCD technology,) however, at low resolution, where back-ground noise dominates, standard CCDs may still be required for ultimate sensitivity. Furthermore, the time spectrum of PSF variability as delivered by SAM's GLAO system, while it may have been modeled under the range of atmospheric conditions prevalent at SOAR, will not be confirmed until the SAM system has been commissioned. Hence for a system based on long time-scale sequential wavelength scanning, caution argues for acquisition of a complementary channel.

As defined above, the second, complementary, channel ($T-F_\lambda$) approximates to a continuum image of the observed field and hence offers a very deep, high signal-to-noise, image which can be used to monitor the atmosphere. However, this is not the only use of the second channel; the broad-band ($T-F_\lambda$) light can be further filtered with a FP to allow for simultaneous wavelength scanning at a secondary spectral resolution. Provided the second channel is at significantly lower resolution than the first, it can be used both as an atmospheric monitor channel and as a second science channel offering simultaneous wavelength scans at two resolutions and/or wavelengths.

The two cameras of the BTFI thus represent a highly versatile instrument concept. The primary channel can be used for high resolution (FP) scans or low to intermediate resolution (iBTF) scans. In both cases the secondary channel can be used for atmospheric monitoring. Alternatively the accuracy of atmospheric monitoring can be traded with scientific utility by using the second channel for the simultaneous acquisition of data-cubes at different resolutions and/or wavelengths. The actual usage of the BTFI will be highly dependent on the science objectives of the user. The two channel concept gives the BTFI a photometric robustness for data cube acquisition while allowing a scientific versatility that is unique amongst FPs and tunable filter imagers.

4. Current Status

The mechanical structure and mechanisms were built in São Jose dos Campos, Brazil with the optics being delivered in March, 2010. The preliminary assembly, integration and test optics, mechanics, electronics and software were subsequently completed in IAG/USP and the instrument is now in its final stages of assembly at the SOAR telescope. Assembly on the direct port of the SOAR telescope scheduled for July 2010 with commissioning following shortly thereafter.

5. Conclusion

The Brazilian Tunable Filter Imager (BTFI) represents an instrument strategy that optimizes the science potential for optical spectroscopy with the SOAR telescope, with its emphasis on high image quality and its use of Ground Layer Adaptive Optics for image enhancement in the optical over a field of view of 3 x 3 arcmins.

The instrument will be commissioned as a visitor instrument of SOAR at the beginning of 2010B and will hopefully become a regular users instrument after SAM is in use.

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