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IBIS 2.0: Optical Layout and Polarimetric Unit of the Interferometric BIdimensional Spectrometer 2.0

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ABSTRACT

The IBIS 2.0 Interferometric BIdimensional Spectrometer 2.0 instrument combines two tunable Fabry-Pérot interferometers, narrowband interference filters, a polarimetric unit, fast cameras, and a proper Instrument Control System to perform high-resolution solar spectropolarimetric observations at high cadence with short exposures. A previous version of the instrument, named IBIS, operated at the Dunn Solar Telescope (DST) of the National Solar Observatory (NSO) from 2003 to 2019. IBIS 2.0 is planned to enter operations over the spectral range 580-860 nm at the Teide Observatory in 2023. In this paper we describe the final optical layout adopted for IBIS 2.0 along with its polarimetric unit, which is realized with two Liquid Crystals Variable Retarders and a Wollaston prism acting as a Polarizing Beam Splitter. We also present the final design of the Instrument Control System, the expected performances of the IBIS 2.0 instrument, and the planned sequence of operations.

Keywords: IBIS 2.0, Fabry-Pérot Interferometers, Optical Design, Polarimetric Unit, Solar Spectropolarimetry, Solar Physics, Instrument Automation, ESO VLT Control Software.

1. INTRODUCTION

The IBIS 2.0 project[1] aims to realize an updated and upgraded version of the Interferometric BIdimensional Spectrometer (IBIS)[2–4], an instrument for high-resolution solar bi-dimensional spectropolarimetry. The instrument is planned to enter operations at the German Vacuum Tower Telescope (VTT) at the Observatorio del Teide in Tenerife in 2023.

The core of the instrument consists of two Fabry-Pérot (FP) interferometers and a set of narrow band interference filters (FWHM in the range 0.3-0.5 nm) operating in classical mount over the spectral range 580-860 nm. Find more information in[1] and references therein.

Here we present the final optical layout chosen for the instrument installation and the planned sequence of operations. We also describe the design of the IBIS 2.0 Polarimetric Unit (PU), which is expected to allow for observations with a polarimetric sensibility up to 10^{-3}. Finally, we describe the final design of the electronics and software of the IBIS 2.0 Instrument Control System.

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2. FINAL OPTICAL LAYOUT

The final optical layout of IBIS 2.0 is a variant of the "second optical layout" proposed in[1] . The adopted layout allows realizing a fully automated instrument that reuses most of the components of its previous version without decreasing the former instrumental capabilities. The final layout was studied with the Zemax OpticStudio software.

Figures 1 and 2 show the final optical layout adopted for the installation of the IBIS 2.0 at the VTT. The VTT has a diameter of 70 cm and a focal length of 46 m, therefore its focal ratio is 65.7. The image scale in the telescope focus is 4.48 arcsec/mm and the angular resolution varies from 0.17 arcsec at 580 nm to 0.23 arcsec at 860 nm. The VTT is equipped with an adaptive optics system, the Kiepenheuer-institute Adaptive Optic System (KAOS)[5] , which is a 1:1 optical system placed before the evacuated main optical tube of the VTT. The solar beam coming from KAOS is reflected by a folding mirror to instruments placed over optical tables in a laboratory. IBIS 2.0 will be diagonally placed on an optical table available there.

We decided not to use other folding mirrors with skew angles from the telescope focus to the IBIS 2.0 Field Stop (FS), in order to avoid the polarimetric spurious signals introduced by reflections on that type of mirrors. The telescope focus will be directly and telecentrically transferred 1:1 on the IBIS 2.0 FS by using two relay lenses (RL1 and RL2). The Entrance Shutter (ES) of IBIS 2.0 will be placed in the pupil between RL1 and RL2. The calibration Linear Polarizer (LP) and the modulator of the polarimeter, realized with two Liquid Crystal Variable Retarders (LCVRs), will be placed ~ 15 cm after the ES. To raise the VTT optical beam to the height of the IBIS 2.0 main optical axis, two periscope mirrors (M0 and M1) will be inserted between the FS and the lens L1. L1, L2 and L3 create the pupil between the two FPs, in the position of the Filter Wheel 2 (FW2), which will contain the narrowband prefilters (FWHM = 0.3-0.5 nm). The prefilters will be used to select one of the transmittance peaks of the tandem of the two FPs. They will be placed between the FPs in order to reduce spurious reflections and ghost images. Prefilters centered at 589.0, 589.7, 630.1, 617.3, 656.3, and 854.2 nm are planned for the IBIS 2.0 first-light. The two FPs and the FW2 will be enclosed in thermostatic boxes with a temperature control within $\pm 0.1^{\circ}$C, which is expected to ensure a wavelength stability of the instrumental profile with a maximum drift of 10 m/s over 10 hours[2] . L4 will create the scientific image (6.25 mm diameter) on the CAM1 camera. The spots are inside the Airy disk for all the positions of the Field-of-View (FoV) and for the whole instrument spectral range from 580 nm to 860 nm, therefore IBIS 2.0 will be a diffraction limited instrument. Beam Splitter 1 (BS1) will take part of the solar light and send it to the so-called White-Light (WL) channel, which will be used to acquire contemporary images to the ones acquired by CAM1. Those images will be employed to apply post-facto image reconstruction techniques that compensate for residual image degradation left by the adaptive optics KAOS. The image on CAM2 will be formed by the White Light Camera Lens (WLCL). The WL channel will be equipped with a broadband filter (BB, central wavelength 620 nm, FWHM 10 nm) and a neutral density filter (ND) in order to have the same exposure time on CAM1 and CAM2. After a trade-off analysis, the selected detectors for CAM1 and CAM2 are two Andor sCMOS Zyla 4.2 plus (2048×2048 pixels of 6.5 μm).

TV1 will be used to control the proper solar beam alignment on the FS, while TV4 will be used to control the alignment of the solar beam with respect to the main IBIS 2.0 optical axis. This will be done by regulating the tip/tilt of the second periscope mirror (M1).

Since the FPs are in classical mount, their orthogonality with respect to the incoming solar beam shall be secured in order to have the highest instrumental spectral purity. The BS2 will be inserted for this purpose: it will split the light into a direct and a reflected beam by one of the FPs and then it will recombine these two beams and sends the light to M4 and TV2. The orthogonality of the FPs (in succession) will be checked by overlapping the direct and the reflected images (observed on TV2), by regulating the tip/tilt of the two FPs.

The IBIS 2.0 laser path will be used to verify the parallelism of the FPs' plates. The laser path will be activated by rising the M7 mirror. The beam of a He-Ne stabilized laser will be sent to a beam steering system (BST), which will simulate a monochromatic incoherent source by rotating a circular opal diffuser. This component will be placed in the focus of L3, which will create a collimated laser beam in the FPs tandem. By alternatively inserting the FPs and selecting a suitable lens in the FW1, the CAM1 will be used to see the interference fringes produced by the FPs' plates. The piezo voltages of the FPs will be regulated until the fringes will be perfectly circular and with the first interference ring in the outer part of the FoV; in this way the parallelism of the FPs' plates will be regulated with an accuracy of $\lambda/2$.

The IBIS 2.0 tuning path will be used to perform the spectral calibration of the two FPs for each prefilter. This calibration implies the spectral alignment of one of the peaks of FP1 with respect to one of the peaks of FP2 and the spectral alignment of the total transparency peak of the two FPs with respect to the bandpass of each prefilter. The light of a continuous lamp (CL) will be sent by a suitable relay system (RL) inside the FPs with the same focal ratio of the solar light by inserting the M8 mirror, whose tip/tilt will be regulated to superimpose the direct and reflected images on TV3 created by the insertion of BS3; in this way the lamp beam will follow exactly the same path of the solar beam.

The above calibration procedures will be completely automated in IBIS 2.0 thanks to motorized stages and actuators. They will be repeated before each observational run to guarantee a stable instrument. A reduction of the time needed to perform the calibration procedures (lasting 70-80 min at DST with manual operation) is also expected in favour of the time available for scientific observation. After these calibration procedures, IBIS 2.0 in spectroscopic mode will acquire monochromatic images (with exposure times between 20 and 80 ms), with the FPs performing a scan of the spectral lines selected by the observer.

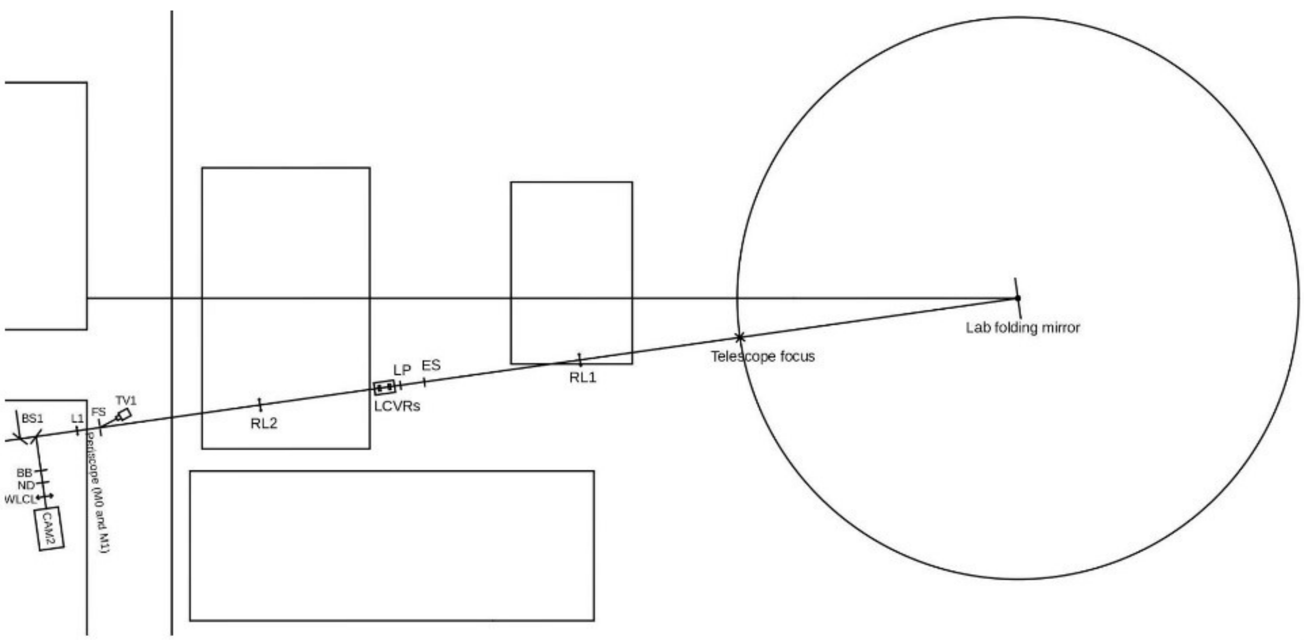

Figure 1. Optical relay system (RL1 and RL2) between the telescope focus at VTT and the IBIS 2.0 Field Stop (FS). The Entrance Shutter (ES) is placed in the pupil between the two relay lenses. The calibration Linear Polarizer (LP) and the two Liquid Crystal Variable Retarders (LCVRs), the modulator of the polarimeter, are placed $\sim$ 150 mm after the pupil image on the ES. The rectangles show optical tables, the circle indicates the position of the telescope focus rotating with the Lab folding mirror.

3. POLARIMETRIC UNIT

During the design process of the IBIS 2.0 Polarimetric Unit (PU), several solutions of solar PU have been investigated. In the last decades, solar PUs have been realized by using, e.g., dual-beam polarimetery (on one or two detectors) with a set of either two LCVRs or two Ferroelectric Liquid Crystals (FLCs) as a *polarimetric modulator*, and with a Polarizing Beam Splitter (PBS) as a *polarimetric analyzer*[6–8]. The LCVRs are optical devices with a fixed orientation angle and a retardance that can be varied with voltages; instead, the FLCs are optical devices realized with a fixed retardance and an orientation angle that can be varied with voltages. Several modulation schemes are used in solar PUs, e.g., six states with two LCVRs in IBIS at DST[2], four states with two LCVRs in TESOS[9], four states with two FLCs in LPSP and TIP[10–12]. The PBS has also been realized

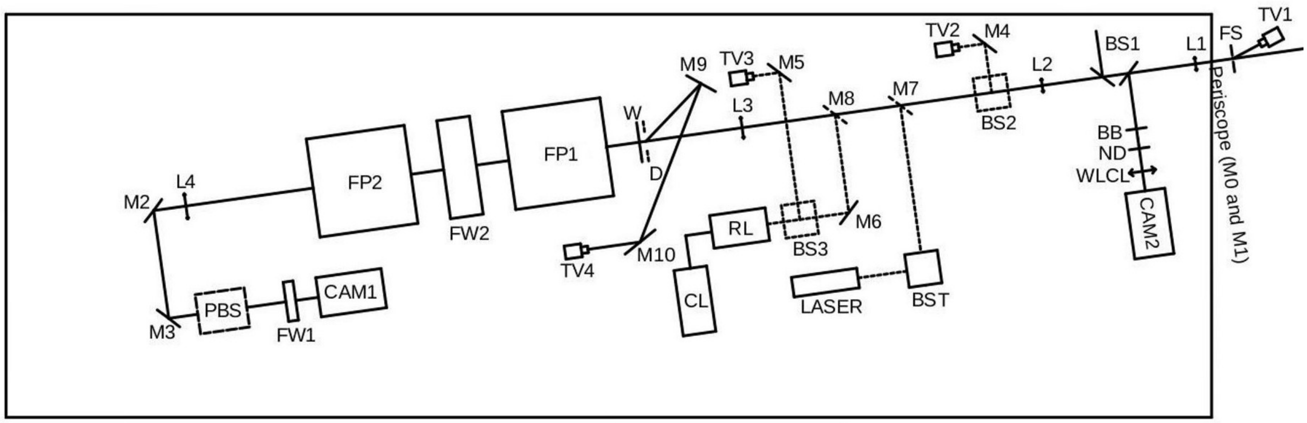

Figure 2. Optical layout of IBIS 2.0 at VTT. The instrument is mounted diagonally on the optical table available at the telescope (rectangle). FP1 and FP2 are encased in two thermostatic boxes, as well as the prefilter in the Filter Wheel 2 (FW2). FW1, instead, contains lenses used during the calibration phases and the Polarizing Beam splitter (PBS), showed separately from FW1 for the sake of clarity. CAM1 is the scientific detector, which acquires the narrowband images, CAM2 is the broadband camera (called white-light camera), equipped with the White Light Camera Lens (WLCL), broadband filter (BB), and neutral density filter (ND). TV cameras (from 1 to 4) are used during the calibration procedures. The Laser beam, passing through a Beam Steering (BST) is used to set the parallelism of the FP's plates, the Continuous Lamp (CL) beam passes through the Relay Lens box (RL) and it is used for the spectral calibration of the two FPs. The Beam Splitter (BS, from 1 to 3) are used to activate the various channels of the instrument. L are the lenses (from 1 to 4) and M are the mirrors (from 0 to 10). Solid lines are fixed parts of the instrument, while dashed lines denote moving parts.

with, e.g., modified Savart plate[11] , a Wollaston prism[9] , a set of cemented polarizing cube beam splitters[13] , and a simple cube beam splitter that splits the beam on two detectors[14] .

The instrumental requirements for the IBIS 2.0 PU are: FoV of $80{\times}80$ arcsec^2 in spectropolarimetric mode; distance between the centers of the two split images ~ 6.65 mm; image dimension in spectropolarimetric mode ~ 5.69 mm; beam diameter in the polarimetric modulator place < 50 mm; available space for the PBS $45{\times}18{\times}18$ mm (L$\times$W$\times$H). To reduce the number of actuators, the PBS will be inserted in the FW1, placed before CAM1.

The trade-off analysis during the design process of the IBIS 2.0 PU pointed towards a unit similar to the one used at DST. The main advantages of the adopted design are:

- The combination of spatial and temporal modulation in the acquisition scheme allows to reduce the seeing-induced cross-talk and the gain-table uncertainties.
- The modulation scheme based on six states with two LCVRs is more efficient than other solutions[15] . Indeed, the data are characterized by a reduced cross-talk between the Stokes parameters, because the modulation states are linear combination of the Stokes parameters with integer coefficients.
- The PBS is placed immediately before CAM1 allowing to perform duam-beam polarimetry with the two images split on the same detector, reducing the polarimetry uncertainties, semplifying the calibration pipeline, and reducing the cost of the detectors needed.
- Largely tested calibration scheme of the PU and robust calibration scheme of the polarimetric signal introduced by the telescope.

In spectropolarimetric mode, IBIS 2.0 will acquire images with CAM1 for each polarimetric modulation state at each wavelength step of the spectral scan selected by the observer.

3.1 Polarimetric modulator design

The LCVRs were adopted because they can be used over a larger wavelength range than the FLCs. Indeed, the latter allow a good contrast and transparency only over a limited wavelength range of at maximum 100 nm. On the other hand, the setting time of LCVRs (milliseconds) is larger than the one of the FLCs (microseconds), but they are still compatible with the fast temporal resolution expected from the IBIS 2.0 observations. The LCVRs will be placed $\sim$ 150 mm after the pupil between the two relay lenses (see Figure 1) in order to avoid pupil aberration in the whole optical system. In fact the pupil aberration must be as low as possible to avoid contamination of the spectral instrumental profile since the FPs are placed near a pupil plane. The LCVRs will be protected by an UV-cut filter ($<$ 450 nm), in order to avoid UV damages of their liquid crystals. The LCVRs will have a clear aperture of 20 mm, in order to avoid vignetting of the beam and they will be temperature stabilized within $\pm$ 1°C because their retardance slowly depends on temperature.

Table 1 presents summary information on the modulation scheme of the two LCVRs that will be the same as the one used at DST. We studied this modulation scheme in combination with the PBS by using a code developed with the Interactive Data Language (IDL) that performs Mueller matrix calculations (for details, see[16]). This study allowed us to determine the orientation angles (with respect to the horizontal axis) at which the two LCVRs shall be mounted in order to obtain the correct modulation states with the LCVRs retardances listed in Table 1. The result of this study is that LCVR 1 and LCVR 2 shall have orientation angles of 90° and 135°, respectively.

Modulation state	**LCVR 1 retardance [deg]**	**LCVR 1 retardance [wave]**	**LCVR 2 retardance [deg]**	**LCVR 2 retardance [wave]**
I+Q	360	λ	360	λ
I+V	360	λ	270	$3/4\ \lambda$
I-Q	360	λ	180	$\lambda/2$
I-V	360	λ	90	$\lambda/4$
I-U	270	$3/4\ \lambda$	90	$\lambda/4$
I+U	90	$\lambda/4$	90	$\lambda/4$

Table 1. Modulation states and LCVRs retardances for the IBIS 2.0 PU.

Finally, during the PU design, we also analyzed the wavefront errors introduced by a sample LCVR manufactured by Thorlabs. The measurements, which were performed at the Optical Laboratory of the INAF Osservatorio Astrofisico di Arcetri with a WYKO RTI 4100 laser interferometer, showed that the rms wavefront errors introduced by the tested LCVR are consistent with those expected for the IBIS 2.0 polarimetric modulator.

3.2 Polarimetric analyzer design

A PBS must be inserted before the scientific detector to perform dual-beam spectropolarimetry. There are several alternatives for the PBS used in solar PUs. As stated before, they are based on: Wollaston prism, modified Savart plate, set of cemented polarizing cube beam splitters, and a single polarizing beam splitter. The design based on the latter has been discarded during the PU design because it requires two scientific detectors and it would strongly impact the calibration pipeline and the instrument realization costs. The design employing the set of cemented polarizing cube beam splitters has also been discarded due to geometrical problem, because this assembly does not fit the beam dimension with the sensor dimension. Furthermore, the Zemax OpticStudio analysis led to reject the alternative with the modified Savart plate, because it requires a considerably thick Calcite ($>$ 30 mm) to obtain the correct beam separation on the detector due to the alignment procedure of its three components (two calcites and one $\lambda/2$ set at 45°). The best solution resulted to be the one based on Wollaston prism. This is for the following reasons: 1) the separation angle can be tuned by varying the cutting angle of the prism; 2) it has only two optical surfaces; and 3) it is easy to align because it is made by only one optical element. The disadvantage of this solution is that the Wollaston prism must be used in collimated beam otherwise the two emerging beams are affected by different amount of spherical aberration and astigmatism that cannot be compensated with the same lens. Therefore, since the PBS will be placed in the converging beam coming from L4, the design of the component must include a corrective lens system to place the Wollaston prism in a collimated beam.

At first, the solution based on a single Wollaston prism was studied by placing it in the converging beam coming from L4. This study aimed at identify the crystal type and its reasonable optical thickness to produce the correct beam separation ($\sim$ 6.65 mm) on the detector of CAM1 (13.3 mm large). This preliminary analysis was in favor of using Calcite crystals instead of Quartz crystals, because a thick Quartz crystal (around 40 mm) would be needed to get the correct separation.

The corrective lens system was designed for the Calcite Wollaston prism in order to place it in a collimated beam, by using a diverging lens before the prism and a converging lens after it, with these lenses having same focal length but with opposite sign. We developed two optical designs for this corrective lens system: one based on two achromatic doublets and the other on two singlet lenses. Both these designs allow to obtain a diffraction limited instrument. The final design will be adopted during the trade-off analysis at the procurement and assembly phases.

Figure 3 shows the design of the IBIS 2.0 PBS realized by using two achromatic doublets (-100 mm and +100 mm of focal lengths) as a corrective lens system; find the design based on the two singlets in[16]. Figure 4 shows spot diagrams at the center and at the four edges of the FoV for both the split beams at 720.0 nm, which is in the middle of the IBIS 2.0 spectral range. Similar spot diagrams were obtained over the whole IBIS 2.0 spectral range from 580 nm to 860 nm. Therefore, we can conclude that the final optical design is diffraction limited also in spectropolarimetric mode, because all the spot diagrams are inside the Airy disks. Find more details in[16].

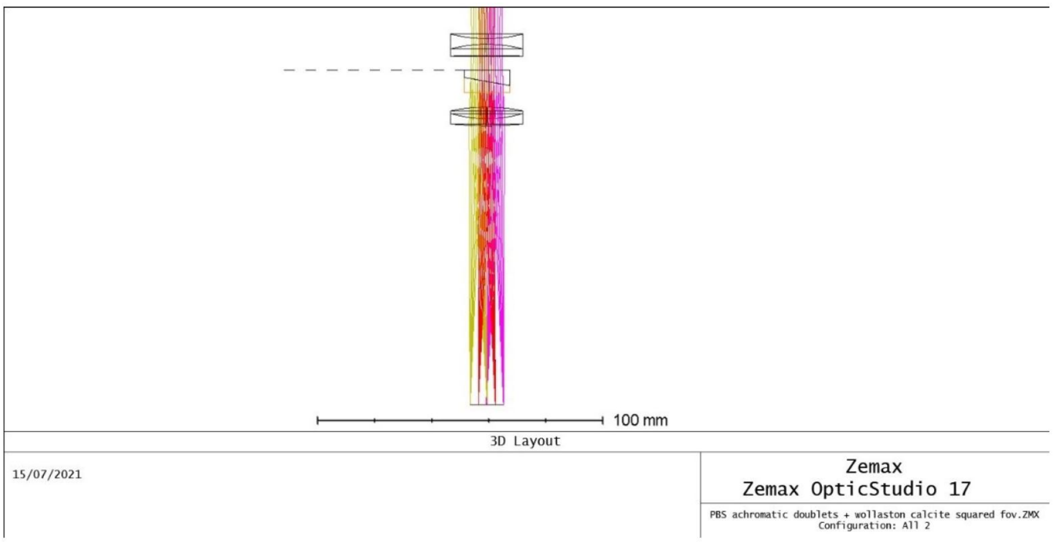

Figure 3. Design of the PBS of IBIS 2.0: Calcite Wollaston prism inserted in the collimated beam between the two corrective achromatic doublets.

3.3 Polarimetric calibration of IBIS 2.0

The polarimetric calibration of the IBIS 2.0 PU is a critical procedure to acquire spectropolarimetric observations with a sensitivity up to 10^{-3}. There are two fundamental steps that must be done for this purpose: 1) calibration of LCVRs voltages; 2) data calibration for the polarimetric X-matrix and T-matrix. The latter calibration account for the polarimetric spurious signals introduced by the instrument and telescope, respectively.

The LCVRs voltages calibration, which associates the voltages applied to the LCVRs with the corresponding retardances, shall be repeated before each observing run because of second order terms introduced by e.g. telescope misalignments, beam wobble, deterioration of liquid crystals, etc. As done with the IBIS PU at DST, the LCVRs voltages calibration will involve the use of a calibration linear polarizer (LP) inserted before the two LCVRs during this calibration. It will be done for each LCVR at the time by applying on it a set of increasing and decreasing voltages. We developed an IDL code to simulate the whole optical polarimetric train in order to determine the orientation angles of the LP during the calibration of each LCVR. The study showed that the LP must be set with an orientation of 90° and that the LCVR 1 must be set at 0λ during the voltages calibration of

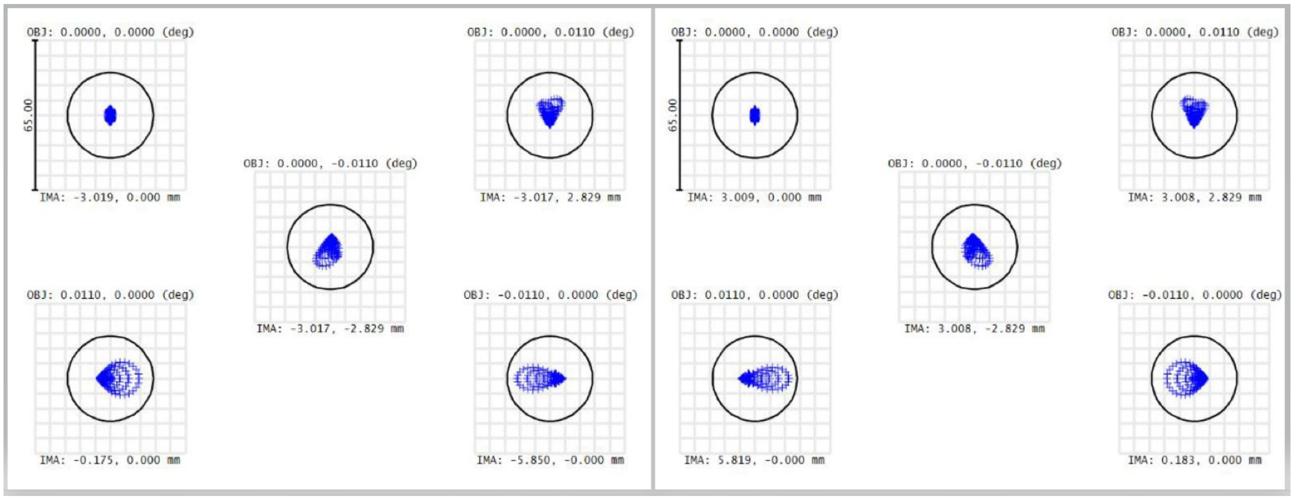

Figure 4. Spot diagrams at 720.0 nm of both the split beams by the Calcite Wollaston prism and the corrective lens system based on two achromatic doublets.

LCVR 2; instead the LP must be set with an orientation angle of 45° and the LCVR 2 must be set at $\lambda/4$ during the voltages calibration of LCVR 1. In fact, the insertion of the LP will allow to send purely linear polarized light into the LCVRs module that will be converted in either horizontal or vertical linear polarized light or circular polarized light by the tandem of the LCVRs with the PBS. This will produce two images on CAM1, one bright and one dark, or vice versa, or two images with the same halved intensity as the bright one. The association between these image conditions and the corresponding voltages applied on the two LCVRs will allow to determine the exact voltages at which the LCVRs have a retardance of $\lambda/4$, $\lambda/2$, $3/4\ \lambda$, and λ. It is worth noting that, this calibration shall be repeated for each prefilter employed for the solar observations because it is wavelength dependent.

The measured Stokes vector S_{out} will be related to the incoming Stokes vector from the Sun S_{in} by the equation $S_{out} = X \cdot T \cdot S_{in}$, where the X-matrix and the T-matrix describe the polarimetric influence of the instrument and of the telescope, respectively. The evaluation of the X-matrix will be performed by using the Instrument Calibration Unit (ICU) of the VTT, which is located inside the telescope vacuum tank before the adaptive optics KAOS. It consists of a linear polarizer and a retarder (approximately a quarter wave plate) as the one used at DST. Therefore, the X-matrix and the T-matrix describe the polarimetric behaviour of all the optical elements which are placed after and before the ICU, respectively. To evaluate the X-matrix, IBIS 2.0 will acquire images with CAM1, with the PBS and the ICU inserted, while the linear polarizer and the retarder of the ICU will be rotated in 16 configurations. In this way, the ICU will send known polarization states into the whole optical assembly of KAOS, relay lenses and IBIS 2.0. These states will be influenced by the mirrors, optical windows and the other optical components. The new pipeline of IBIS 2.0 at VTT will extract the X-matrix from a theoretical model of the ICU interpolated by the images acquired with CAM1 during the calibration phase. This procedure has been validated with a dedicated IDL code that performs Mueller matrix calculations of the whole polarimetric train of the IBIS 2.0 PU including the linear polarizer and the retarder of the ICU set in the 16 configurations. This procedure shall be repeated for each prefilter because the spurious signals introduced by the mirrors are wavelength dependent.

The T-matrix takes into account all the polarimetric spurious signals originated in the telescope optics before the ICU due to reflections on the mirrors and tensions on the vacuum windows. A telescope model has been developed[17] to simulate the polarimetric behaviour of the VTT. The entire telescope can be divided into three blocks that contribute to the polarimetric spurious signals accounted by the T-matrix as follows:

- The Mueller matrix of the two coelostat mirrors can be evaluated through an IDL procedure, which reconstructs the beam geometry starting from observation input parameters (year, month, day and hour of observation, the angle of the first coelostat mirror around the telescope tube and the height of the second coelostat mirror) and from the optical properties (complex index of refraction and angle of incidence) and geometry (angles and distances) of the coelostat mirrors.

- The two entrance and exit vacuum windows behave altogether as a slow retarder with an orientation angle that varies during the day. This behaviour is typically measured with an array of linear polarizers mounted in front of the telescope entrance window and rotated with a fixed angular step. These measurements allow to reconstruct the cumulative Mueller matrix of the vacuum windows.
- The polarimetric signals introduced by the telescope primary concave and secondary flat mirrors are negligible, because their inclination angle is less than 1°.

4. INSTRUMENT CONTROL

The proposed control system for the IBIS 2.0 is based on Beckhoff's Programmable Logic Controller (PLC). This brand offers a broad choice of base components that are the building blocks to design a fully automatic control system. The main CPU (CX2030 series) is the control unit, whose I/O capability is extended by employing Analog, Digital I/O and temperature acquisition modules for PT100 sensors. Additionally, the low power motors (steppers) are controlled by special function motion control modules. With this configuration, all the IBIS 2.0 functions can be controlled.

Beckhoff PLCs run in a TwinCAT3 software environment with added OPC-UA library through which the IBIS 2.0 hardware communicates with the high-level control software, based on the ESO VLT Software (VLTSW) that runs on the Instrument Workstation.

The IBIS 2.0 control architecture follows the standard architecture for the VLTSW based instruments and is divided in the following standard packages: Instrument Control Software (ICS), responsible for the control of all low-level functionalities of IBIS 2.0 (motors, lamps, sensors), Detector Control Software (DCS), which takes care of the control of the scientific detector CAM1 and white light camera CAM2, Observation Software (OS), responsible for the coordination of the wholes scientific exposure, and Maintenance Software (MS), which provides tools to maintain the configuration of the instrument and to check the instrument health.

Figure 5 shows the IBIS 2.0 Control Software architecture based on the VLT Control Software. The OS subsystem (OS Control process) receives commands from BOB, the Broker for Observation Blocks, which oversees executing the instrument templates and dispatches each instruction to be executed to the different software subsystems: ICS Control (for the device control part) and DCS. The ICS Control process forward the received commands to the ICS processes responsible for the interface with the real hardware. These processes are based on the IC0/FB (IC0/FieldBus) Extension, the VLT Control Software architecture that allows to control devices not only via "classical" field-buses like EtherCAT but also e.g. via Ethernet. A Super DCS process coordinates the acquisition of the scientific detector and white light camera. At the end of the scientific exposures, OS collects the final detector images, merges them with the header information coming from the different instrument subsystems and triggers the OS Archiver which oversees the creation of the final FITS file and its archiving. Dedicated TCCD processes coordinate the acquisition of the instrument technical cameras (Basler brand). It has still to be defined if the Instrument Workstation will be interfaced to the existing Telescope Control System.

5. CONCLUSIONS

The IBIS 2.0 project aims to realize an updated and upgraded version of the Interferometric BIdimensional Spectrometer in light of its installation at the German Vacuum Tower Telescope. In this work, we presented the final optical layout that will be adopted for IBIS 2.0 at the new telescope. We also described the design and the calibration of the modulator and the analyzer of the new polarimetric unit of the instrument, which will allow high resolution spectropolarimetric observations of the solar atmosphere with a diffraction limited optical quality and a polarimetric sensitivity up to 10^{-3}. Finally, we described the new Instrument Control System based on ESO VLT Control Software and motorized linear stages and actuators, which will allow the full automation of the calibration and operation procedures.

Find information about IBIS 2.0 at www.ibis20.inaf.it

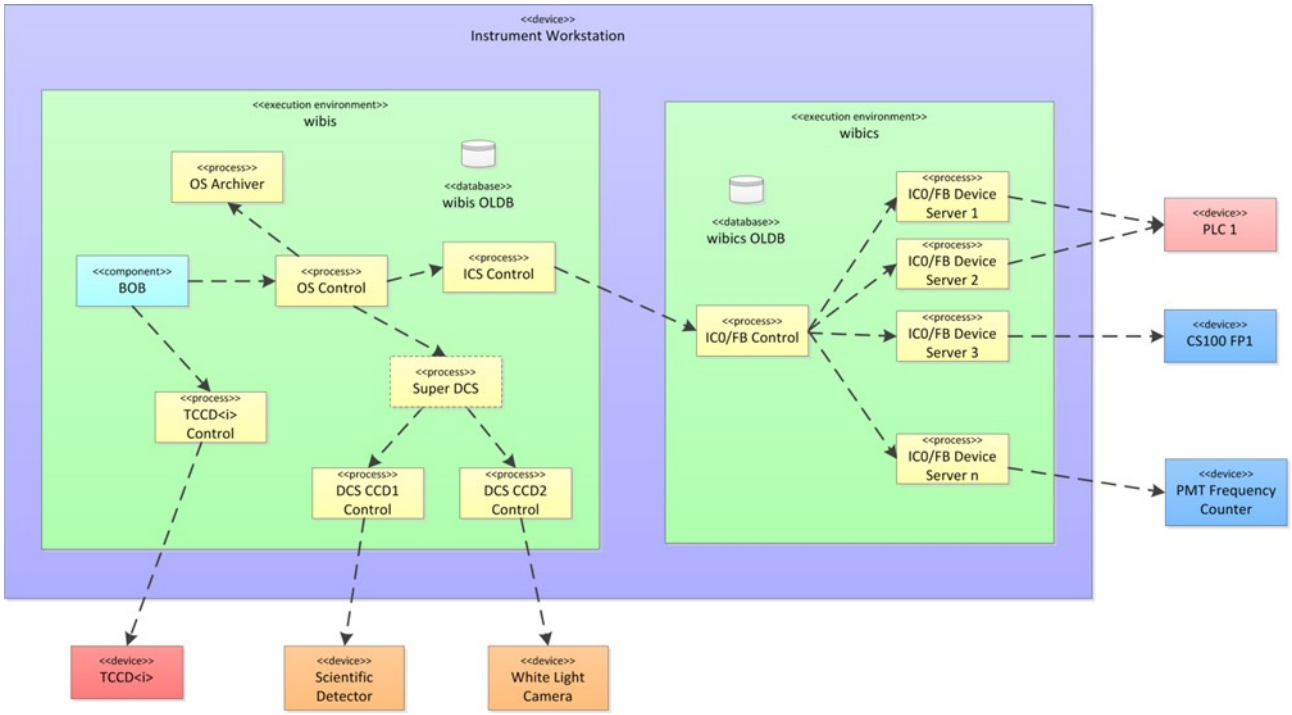

Figure 5. IBIS 2.0 software architecture.

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REFERENCES

[1] Ermolli, I., Cirami, R., Calderone, G., Del Moro, D., Romano, P., Viavattene, G., Coretti, I., Giorgi, F., Baldini, V., Di Marcantonio, P., Giovannelli, L., Guglielmino, S. L., Murabito, M., Pedichini, F., Piazzesi, R., Aliverti, M., Redaelli, E. M. A., Berrilli, F., and Zuccarello, F., "IBIS2.0: The new Interferometric BIdimensional Spectrometer," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11447**, 114470Z (Dec. 2020).

[2] Cavallini, F., "IBIS: A New Post-Focus Instrument for Solar Imaging Spectroscopy," **236**, 415–439 (July 2006).

[3] Reardon, K. P. and Cavallini, F., "Characterization of Fabry-Perot interferometers and multi-etalon transmission profiles. The IBIS instrumental profile," **481**, 897–912 (Apr. 2008).

[4] Righini, A., Cavallini, F., and Reardon, K. P., "Imaging performance of multi-etalon bidimensional spectrometers," **515**, A85 (June 2010).

[5] van der Luehe, O., Soltau, D., Berkefeld, T., and Schelenz, T., "KAOS: Adaptive optics system for the Vacuum Tower Telescope at Teide Observatory," in [*Innovative Telescopes and Instrumentation for Solar Astrophysics*], Keil, S. L. and Avakyan, S. V., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4853**, 187–193 (Feb. 2003).

[6] Collados, M., "High Resolution Spectropolarimetry and Magnetography," in [*Third Advances in Solar Physics Euroconference: Magnetic Fields and Oscillations*], Schmieder, B., Hofmann, A., and Staude, J., eds., *Astronomical Society of the Pacific Conference Series* **184**, 3–22 (Sept. 1999).

[7] del Toro Iniesta, J. C., "Introduction to Spectropolarimetry," *Cambridge University Press* (2003).

[8] Collados, M., "Polarimetry in the visible and near infrared," in [*Modern solar facilities - advanced solar science*], Kneer, F., Puschmann, K. G., and Wittmann, A. D., eds., 143 (Jan. 2007).

[9] Beck, C., Bellot Rubio, L. R., Kentischer, T. J., Tritschler, A., and Del Toro Iniesta, J. C., "Two-dimensional solar spectropolarimetry with the KIS/IAA Visible Imaging Polarimeter," **520**, A115 (Sept. 2010).

[10] Gandorfer, A. M., "Ferroelectric retarders as an alternative to piezoelastic modulators for use in solar Stokes vector polarimetry," *Optical Engineering* **38**, 1402–1408 (Aug. 1999).

[11] Bello González, N. and Kneer, F., "Narrow-band full Stokes polarimetry of small structures on the Sun with speckle methods," **480**, 265–275 (Mar. 2008).

[12] Mártinez Pillet, V., Collados, M., Sánchez Almeida, J., González, V., Cruz-Lopez, A., Manescau, A., Joven, E., Paez, E., Diaz, J., Feeney, O., Sánchez, V., Scharmer, G., and Soltau, D., "LPSP & TIP: Full Stokes Polarimeters for the Canary Islands Observatories," in [*High Resolution Solar Physics: Theory, Observations, and Techniques*], Rimmele, T. R., Balasubramaniam, K. S., and Radick, R. R., eds., *Astronomical Society of the Pacific Conference Series* **183**, 264 (Jan. 1999).

[13] Collados, M., Lagg, A., Díaz Garcí A, J. J., Hernández Suárez, E., López López, R., Páez Mañá, E., and Solanki, S. K., "Tenerife Infrared Polarimeter II," in [*The Physics of Chromospheric Plasmas*], Heinzel, P., Dorotovič, I., and Rutten, R. J., eds., *Astronomical Society of the Pacific Conference Series* **368**, 611 (May 2007).

[14] Scharmer, G. B., "Comments on the optimization of high resolution Fabry-Pérot filtergraphs," **447**, 1111–1120 (Mar. 2006).

[15] del Toro Iniesta, J. C. and Collados, M., "Optimum Modulation and Demodulation Matrices for Solar Polarimetry," **39**, 1637–1642 (Apr. 2000).

[16] Viavattene, G., Briguglio Pellegrino, R. A., Giorgi, F., Oliviero, M., Pedichini, F., and Terreri, A., "IBIS-TRE-01: Conceptual design of the IBIS 2.0 polarimetric unit," (2022).

[17] Beck, C., Schlichenmaier, R., Collados, M., Bellot Rubio, L., and Kentischer, T., "A polarization model for the German Vacuum Tower Telescope from in situ and laboratory measurements," **443**, 1047–1053 (Dec. 2005).