IBIS 2.0

System Design Description

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Sections 1 and 3.	Updates after review for submission to INAF Open Access repository.

Contents

1 Introduction

The Interferometric BIdimensional Spectrometer (IBIS) (Cavallini 2006, Reardon and Cavallini 2008, Righini, Cavallini and Reardon 2010) is an instrument for solar bi-dimensional spectroscopy and spectropolarimetry that was realized at INAF-OAA with contribution from the University of Florence and the University of Rome Tor Vergata and operated at the Dunn Solar Telescope (DST) from June 2003 to June 2019 [RD1]. The instrument is basically composed by two Fabry-Pérot (FP) interferometers and narrow band filters placed between them operating in classical mode. It consists of more than 40 optical components, including 4 lenses, 3 beamsplitters, 14 fixed mirrors, 4 moveable mirrors, 2 filter wheels, 2 CCD cameras, 5 TV cameras, 1 He-Ne laser, 1 halogen continuous lamp, 1 photomultiplier and others optical components. All the optical components are anchored in an optical table through holders on X95 rails. The instrument is composed by a main optical path and several secondary channels whose components are employed for instrumental calibration. Find details in [RD1]. IBIS acquires monochromatic images in the wavelength range 580-860nm with high spatial (0.2”), spectral (R>200000) and temporal (several frames per second) resolution. In spectral mode the circular Field-of-View (FoV) is 80” in diameter, in polarimetric mode the rectangular FoV is 80”x40”. The FoV is halved in the polarimetric mode observation in order to use the same detector to image the two orthogonally linear polarized beams that are produced by the Polarizing Beam Splitter (PBS) placed in front of the scientific detector (see [RD1] for the description of the IBIS polarimeter used at DST; see the description of the IBIS 2.0 polarimeter in Section 3.4). Find information about IBIS also in Cavallini et al. 2000, 2001, 2003, Cavallini 2002, Reardon and Cavallini 2003, Cavallini and Reardon 2006.

IBIS returned to Italy in July 2019. A group of researchers from the INAF-OAR, INAF-OATs, INAF-OACt, University of Rome Tor Vergata, INAF-OAB and University of Catania is working on the re-design of the optomechanics, electronics and software of the instrument in order to install it at a solar telescope of the Teide Observatory (Tenerife, Spain). Actually, the main candidate solar facility is the German Vacuum Tower Telescope (VTT).

IBIS 2.0 at VTT must satisfy some instrumental requirements that are similar to the ones of IBIS at DST, due to mostly unchanged main components of the instrument and scientific goals. The main IBIS 2.0 requirements are:

- High spectral resolution > 200000
- High spatial resolution ~ 0.2”
- High temporal resolution = several frames per second
- FoV sufficiently large (FoV > 60”) to study the solar photospheric and chromospheric phenomena in their entirety
- Extended spectral range of 580-860 nm
- High wavelength stability of the instrumental profile (with a maximum drift of the order of 10 m/s over 10 hours)
- Exposure time to freeze the Earth’s atmospheric seeing (~ tens of ms)
- Diffraction limited image on the final focal plane (image spots inside the Airy disk on the whole FoV)
- Pixel scale to appropriately sample the final focal plane image according to the Nyquist criterion
- Detector matrix large enough to image the whole FoV

The final error budget has not yet been estimated; it will be assessed during the final design phase when the final optical design of the instrument will be selected.

The proposed optomechanical design of IBIS 2.0 results from a trade-off analysis between costs and available optical and mechanical components, in order to reuse most of the components of IBIS employed at DST [RD1]. However, the new design also aims at replacing obsolete components with more modern devices.

The IBIS 2.0 design is also constrained by the scientific requirements discussed in [RD12]. The achievement of the expected spectral, spatial and temporal sampling is driven by the scientific cases, considering the diffraction limited spatial resolution and the photon flux provided by the VTT.

In this document, the preliminary designs for the instrument optomechanics, control electronics and control software are presented.

Two different instrument optical layouts are presented:

- **First optical layout**. Optical layout of the instrument operating at DST adapted to the VTT physical and environmental conditions (e.g. dimensions, height and orientation of the optical bench with respect to the telescope focus), with minimal changes with respect to the original one.
- **Second optical layout**. A simplified optical layout with respect to the first one (e.g. modifications of the redundant calibration optical paths).

Besides the two optical layouts, different automation levels for the control electronics and software are presented. In the next project phase only one of them will be selected as baseline. The following automation levels are defined:

- **Level 0**. First optical layout with no instrument control automation added with respect to the control of the instrument operating at the DST (e.g. most of the instrument calibration procedures manually performed).
- **Level 1**. Second optical layout with an increased number of instrument functions controlled by the control electronics and software.
- **Level 2**. Second optical layout with almost all the instrument functions controlled by the control electronics and software and automation of the calibration procedures.

In section 6 a description of the IBIS Science Software operating at the DST is presented.

1.1 Definitions, acronyms and abbreviations

ADS	Automation Device Specification
AO	Adaptive Optics
BB	Broad Band
BOB	Broker for Observation Blocks
BS	Beam Splitter
BST	Beam Steering
CCD	Charge-Coupled Device
CCS	Central Control Software
CL	Continuous Lamp
CLIP	Common Library for Image Processing
CMOS	Complementary Metal-Oxide Semiconductor
COTS	Commercial Off-The-Shelf
CS100	Control System 100
DCS	Detector Control Software

DM	Deformable Mirror
DST	Dunn Solar Telescope
ES	Electronic Shutter
ESO	European Southern Observatory
FITS	Flexible Image Transport System
FoV	Field of View
FP	Fabry-Pérot
FS	Field Stop
FW	Filter Wheel
GPIB	General Purpose Interface Bus
GUI	Graphical User Interface
IBIS	Intereferometric BIdimensional Spectrometer
IC0/FB	IC0 Field-Bus
ICE	Instrument Controll Electronics
ICOS	IC Optical Systems
ICS	Instrument Control Software
ICU	Instrumental Calibration Unit
IDL	Interactive Data Language
IWS	Instrument WorkStation
KAOS	Kiepenheuer-institute Adaptive Optic System
L	Lens
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LAN	Local Area Network
LCVR	Liquid Crystal Variable Retarder
m, M	Mirror
MS	Maintenance Software
NB	Narrow Band
NCPA	Non-Common Path Aberration

ND	Neutral Density
OLDB	On-Line DataBase
OPC-UA	Open Platforms Communications-Unified Architecture
OS	Observation Software
PBS	Polarizing Beam Splitter
PLC	Programmable Logic Controller
PMT	Photomultiplier
RL	Relay Lenses
SDK	Software Development Kit
S/N	Signal-to-noise ratio
TCCD	Technical CCD
TCP/IP	Transmission Control Protocol/Internet Protocol
Tcl/Tk	Tool command language/Tool kit
TDCS	Technical Detector Control Software
TV	TV video camera
USB	Universal Serial Bus
VEE	Virtual Engineering Environment
VLT	Very Large Telescope
VLTSW	VLT SoftWare
VTT	Vacuum Tower Telescope
W	Window
WFE	Wavefront Error
WL	White Light
WLCL	White Light Camera Lens

2 Related Documents

RD1 IBIS 2.0 - IBIS at DST: Optomechanical Layout and Instrument Control (IBIS-05)

RD2 VLT Software – Instrument Common Software Specification;
ESO-043174, VLT-SPE-ESO-17240-0385, Version 6, 15.06.2012)

RD3 IBIS 2.0 – Operation and Calibration Plan (IBIS-03)

RD4 VLT – Base ICS – Fieldbus Extension – User's Manual;
ESO-049361, VLT-MAN-ESO-17240-5597, Version 1, 08.06.2012

RD5 Base ICS – Fieldbus Extension – Device Drivers, Communication Interfaces & PLC Code - User's Manual;
ESO-049378, VLT-MAN-ESO-17240-5628, Version 2, 20.05.2016

RD6 ESPRESSO Instrument Software User and Maintenance Manual;
VLT-MAN-ESP-13520-0240, Issue 1.3, 17.09.2018

RD7 INS Common Software – Common Software for Templates – User Manual;
ESO-043556, VLT-MAN-ESO-17240-2240, Version 6, 20.03.2009

RD8 VLT – CLIP – Common Library for Image Processing – Software User Manual;
ESO-202150, VLT-MAN-ESO-17240-4170, Version 3, 01.08.2014

RD9 S. Criscuoli and A. Tritschler (2014) IBIS Data Reduction Notes V5 (08/04/2014)

RD10 T. Rimmele, T. Kentischer, and P.H. Wiborg (1993). Real Time and Post Facto Solar Image Correction, pp. 24-31

RD11 T. Kentischer – IBIS@VTT document: some information about the telescope, the optical lab, the available optical table for IBIS (private communication).

RD12 IBIS 2.0 - Science Description (IBIS-02)

3 IBIS 2.0 Optomechanics at VTT

In this section, we present the optical design of IBIS 2.0 that we are planning to deploy at the VTT.

3.1 The Vacuum Tower Telescope (VTT) and the Kiepenheuer-institute Adaptive Optic System (KAOS)

Figure 1: VTT building (left) and the coelostat (right).

The VTT (Schroeter, Soltau and Wiehr 1985) is a German solar telescope located at the Teide Observatory in Tenerife (Spain). The telescope tube is placed in a vertical position inside the building and it is completely evacuated in order to reduce the internal seeing (see Figure 1). The primary mirror has a diameter of 70cm, a focal length of 46m and so an aperture ratio of f/D=65.7. The angular resolution is between 0.17” at 580nm and 0.23” at 860nm, and the image scale in the prime focus is 4.48”/mm. The solar light is sent inside the tube by the coelostat (see Figure 1), made by two flat mirrors, placed on the top of the building. After entering in the telescope tube through the plane-parallel BK7 vacuum window, the solar light hits the primary concave spherical mirror, which converges the solar beam, and then the light is reflected down by a secondary flat mirror.

Since 2003 the VTT has been equipped with the adaptive optics system KAOS (Kiepenheuer-institute Adaptive Optic System, von der Luhe et al. 2003), which is placed in an evacuated tank just after the telescope tube (see Figure 2). The telescope prime focus is located after three flat folding mirrors. The collimator mirror sends the light to the tip/tilt mirror and the deformable mirror (DM). Then, a folding mirror, the camera mirror and other two folding mirrors send the light to the science focus, which is located in the optical laboratory. With respect to Figure 2, the wavefront sensor is now incorporated inside the KAOS vacuum tank between the first and the second folding mirrors, before the telescope focus.

The wavefront error (WFE) of KAOS is approximately 60nm with r0=11cm, the sampling frequency is 2100Hz, 0db-bandwith approximately 90-100Hz and an rms FoV of 12 arcsec. The stroke of the DM is large enough to compensate for low order Non-Common Path Aberrations (NCPAs) of at least 200nm WFE Peak-Peak. In addition, KAOS compensate for all the static aberrations of the telescope (von der Luhe et al. 2003 and private communication with T. Berkefeld).

KAOS is a 1:1 optical system, so it does not change the image size and the f-ratio of the telescope. Moreover, using an appropriate dichroic filter or a beam splitter, the solar beam after KAOS can be divided into two paths: one feeding the VTT vertical echelle spectrograph and the other feeding one instrument in the optical laboratory.

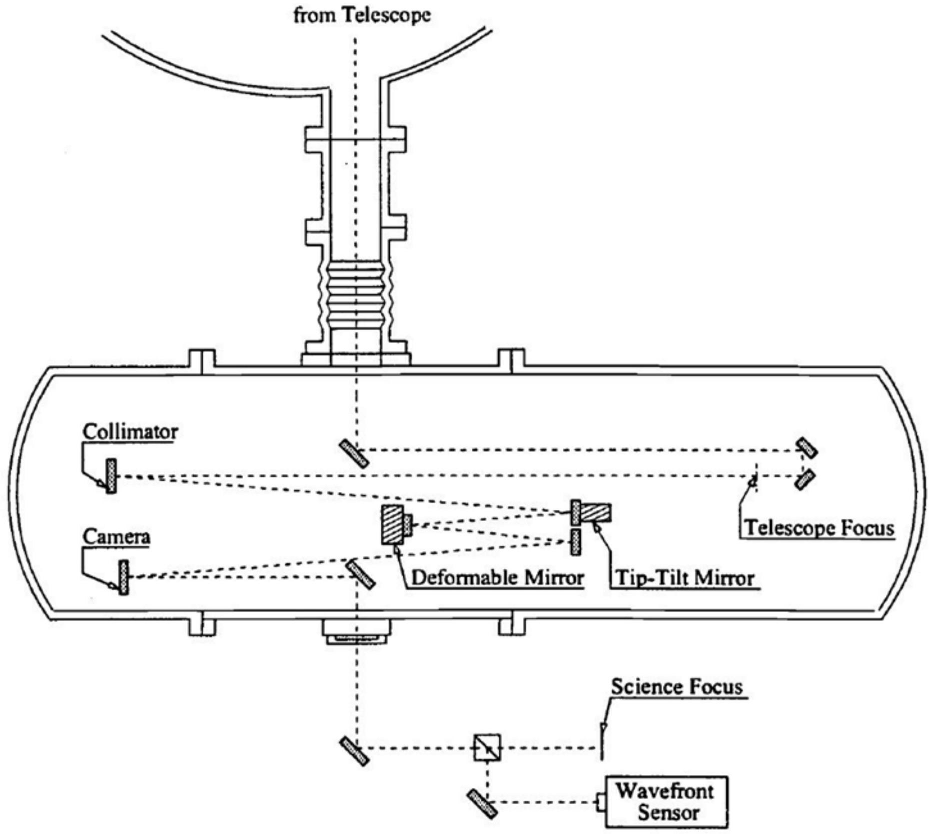

Figure 2: KAOS optical scheme.

3.2 The optical design of IBIS 2.0 at VTT

The optical scheme of IBIS 2.0 for the VTT keeps the previous optical scheme of IBIS at DST (see [RD1]) as unchanged as possible to fit all on the optical table available (3660x1200mm) in the instrumental laboratory of the VTT. The planimetry of the optical laboratory of VTT is reported in Figure 3. The planimetry of the available optical table for IBIS 2.0 at VTT and the adjacent optical laboratory is reported in Figure 4. The pictures of the available optical table for IBIS 2.0 are reported in Figure 5 and Figure 6. The pictures of the optical laboratory of VTT are reported in Figure 7 and Figure 8.

At DST, IBIS was mounted over X95 rails anchored in an optical table. IBIS 2.0 will be remounted by using the same X95 rails in order to maintain the old IBIS mechanics. Indeed, all the available optical components are mounted on mechanical stages that allow for fine tip/tilt regulation and x-y-z-axes translations using micrometers. For IBIS 2.0, a kinematic design that constrains the X95 rails to move along their length would be used to minimize the thermal stresses due to variations of the environmental temperature.

FP1, Filter Wheel 2 (FW2) and FP2 are encased in thermostatic boxes, which stabilize the temperature within +/- 0.1 °C, equivalent to a maximum spectral drift of 10 m/s over several hours.

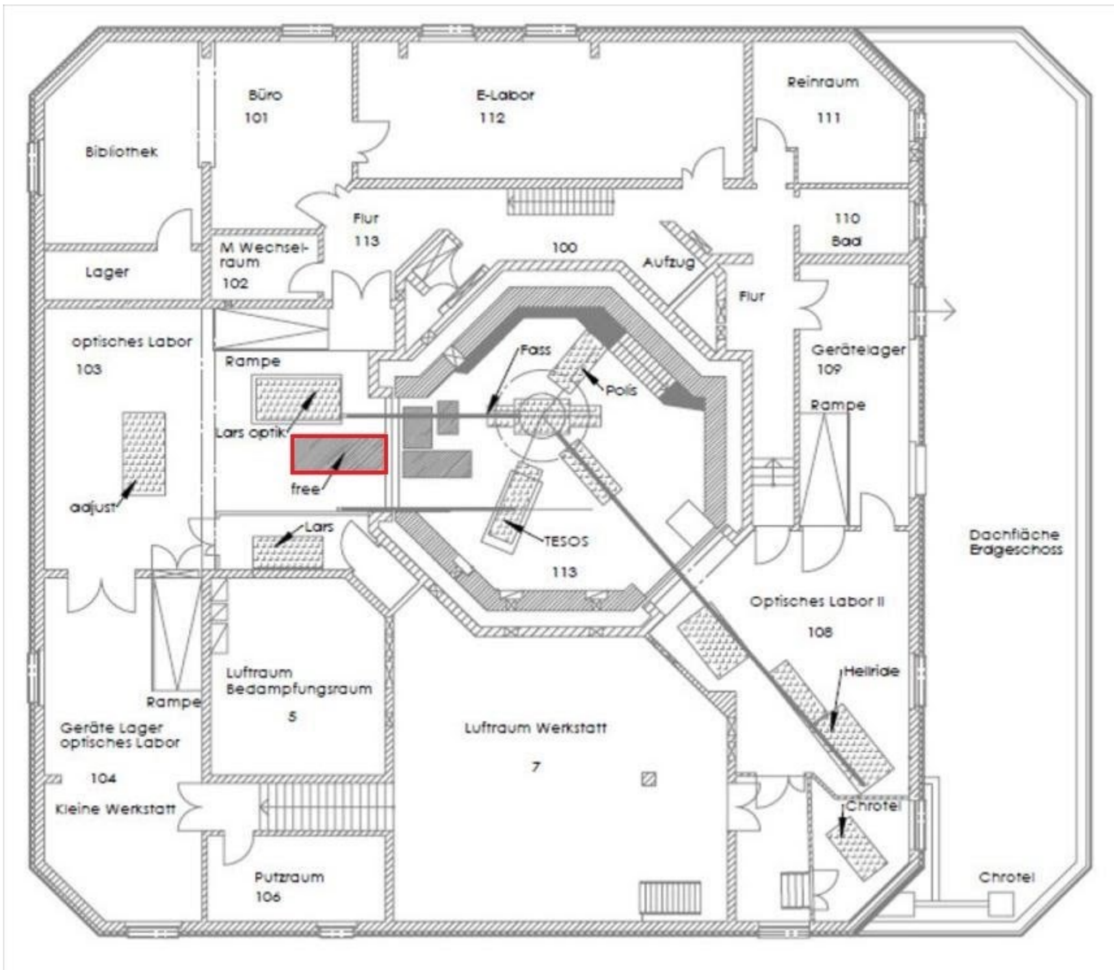

Figure 3: Planimetry of the optical laboratory of VTT. The available optical table for IBIS 2.0 is highlighted in red.

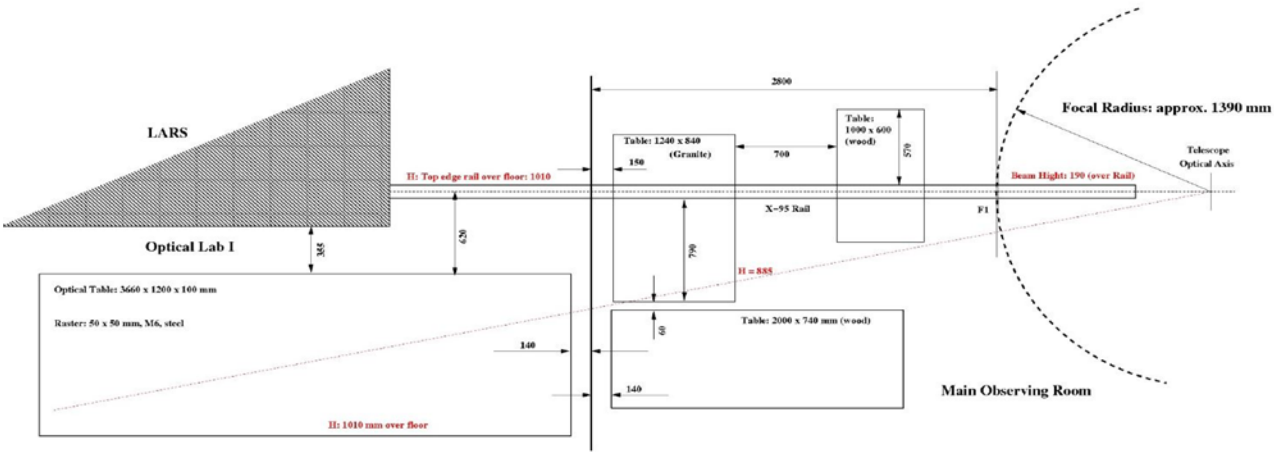

Figure 4: Planimetry of the available optical table for IBIS 2.0 at VTT (left) and the adjacent optical laboratory where the telescope focus is located (right).

Figure 5: Available optical table for IBIS 2.0 at VTT.

Figure 6: Available optical table for IBIS 2.0 at VTT.

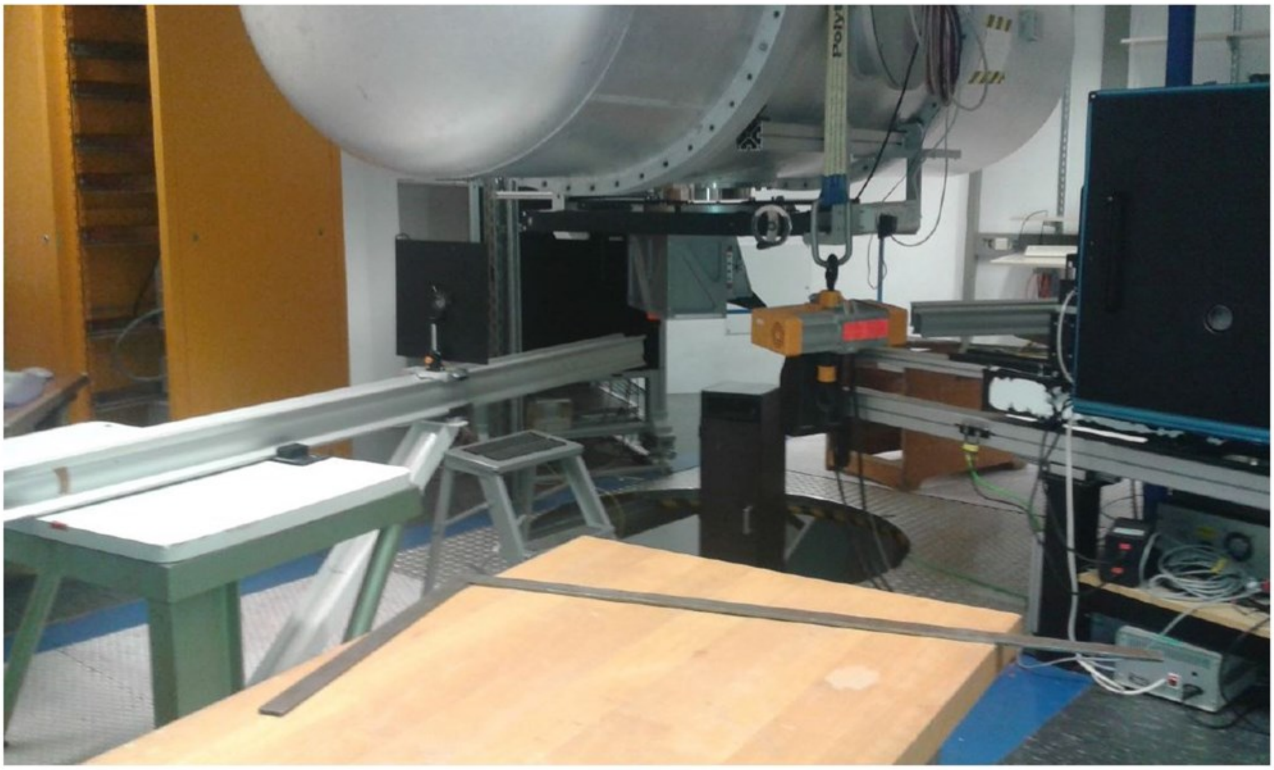

Figure 7: KAOS vacuum tank and folding mirror in the optical laboratory of VTT.

Figure 8: Available tables between the telescope focus and the IBIS 2.0 optical table.

The optical scheme of IBIS 2.0 has been designed with Zemax software. In order to form a good pupil plane between the two IBIS 2.0 FPs, and so to have the best spectral performance, the solar image on the IBIS 2.0 Field Stop (FS) must be telecentric. To do that, we have to transport telecentrically the solar image from the telescope/science focus to the IBIS 2.0 FS. This telecentric relay system is made by two achromatic doublets with a diameter of 63mm and with a focal length of 800mm (see Figure 9). The solar image on the IBIS 2.0 FS is 19.38mm in diameter. We make use of the pupil plane between the two relay lenses, to insert the two Liquid Crystal Variable Retarders (LCVRs) of the polarization modulator, needed to perform polarimetric measurements with IBIS 2.0 (see Figure 9, Figure 10, Figure 11, Figure 12).

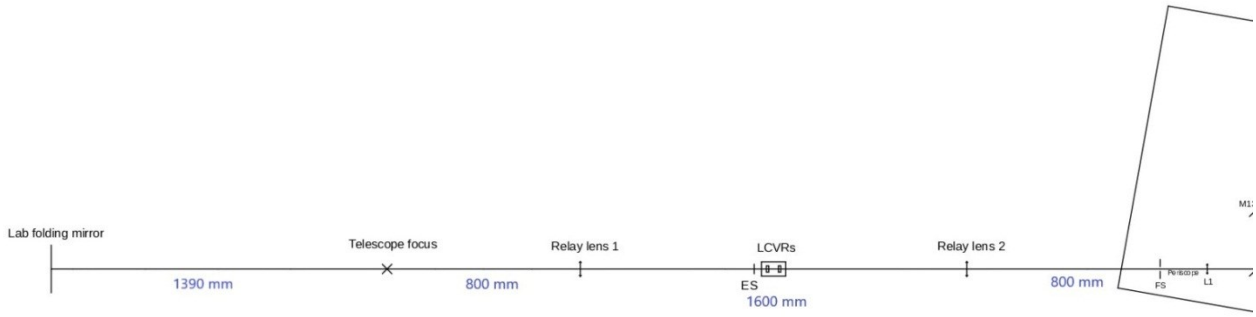

Figure 9: Relay optical system from the telescope focus to the IBIS 2.0 FS.

L1, L2, L3 and L4 are the same used in IBIS at DST (see [RD1] and Figure 13); therefore, the image on the CCD science camera is 6.25mm in diameter with an angular FoV of 80” (the same angular FoV of IBIS at DST) on the Sun. L4 can be moved ~12cm forwards in order to use it in “polarimetric mode”: in this way the final focal plane after M3 is moved ~12cm forwards thus obtaining the space to insert the polarization analyzer beam-splitter (PBS) between M3 and the science camera. The pupil between the two FPs is moved 10-20 cm forward (with respect to the pupil position between the two FPs of IBIS at DST) due to the telescope pupil and the presence of the LCVRs and the plates of BS1; therefore, it could be necessary to move forward the block of FP1, FW2 and FP2 in order to place them nearer the pupil between L3 and L4 (see Figure 13).

To raise the VTT optical beam at the height of the IBIS 2.0 optical axis, we insert a periscope between the FS and L1. The mirrors m1 and m2 of the IBIS design at DST will be reused for this periscope. The IBIS 2.0 main optical path is placed diagonally on the optical bench in order to avoid the use of folding mirrors, which would introduce undesirable extra spurious polarization in the instrument, and to simplify the optical alignment of the instrument. From L2 to the end of the optical train, IBIS 2.0 at VTT will have the same geometrical path/configuration as IBIS at DST. In our Zemax design, we modeled also the two optical plates of BS1, the plates of FP1, the plates of FP2 and the prefilter placed in the FW2. The IBIS 2.0 optical scheme is reported in Figure 10, Figure 11, Figure 12 and Figure 13. The Zemax Lens Data Editor of IBIS 2.0 at VTT is reported in Figure 14 and Figure 15. A table with the characteristics (semidiameters, radii of curvature, optical glasses, thickness, etc.) of the IBIS 2.0 optical components will be produced in the final design document.

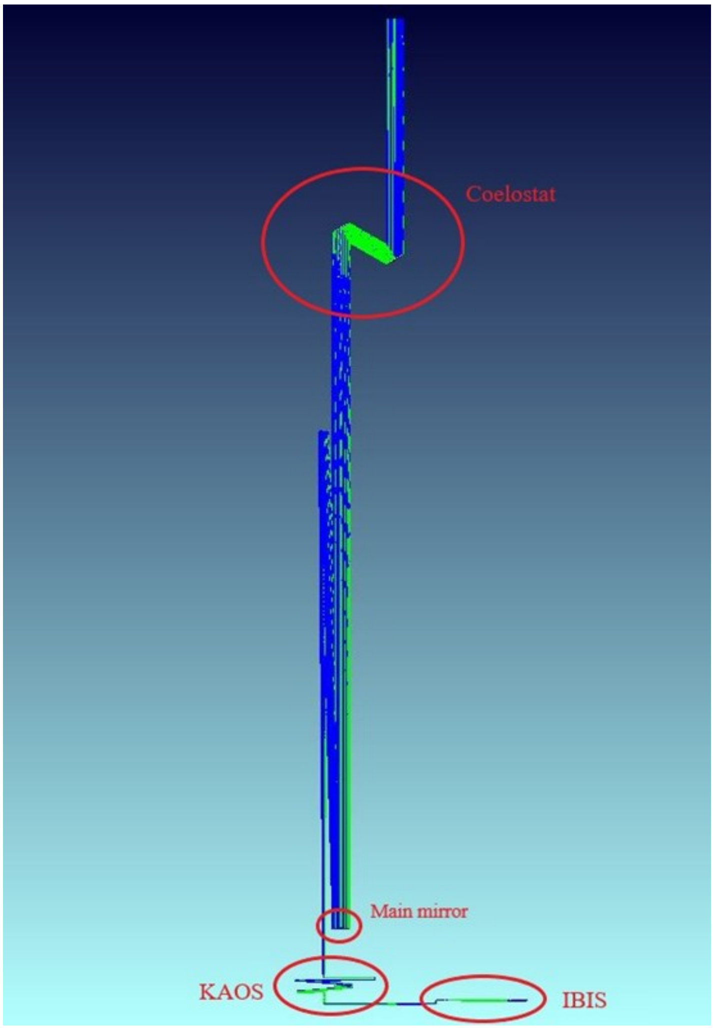

Figure 10: Overall side view of the optical scheme of VTT, KAOS and IBIS 2.0. The position of the coelostat, VTT main mirror, KAOS and IBIS 2.0 are highlighted in red.

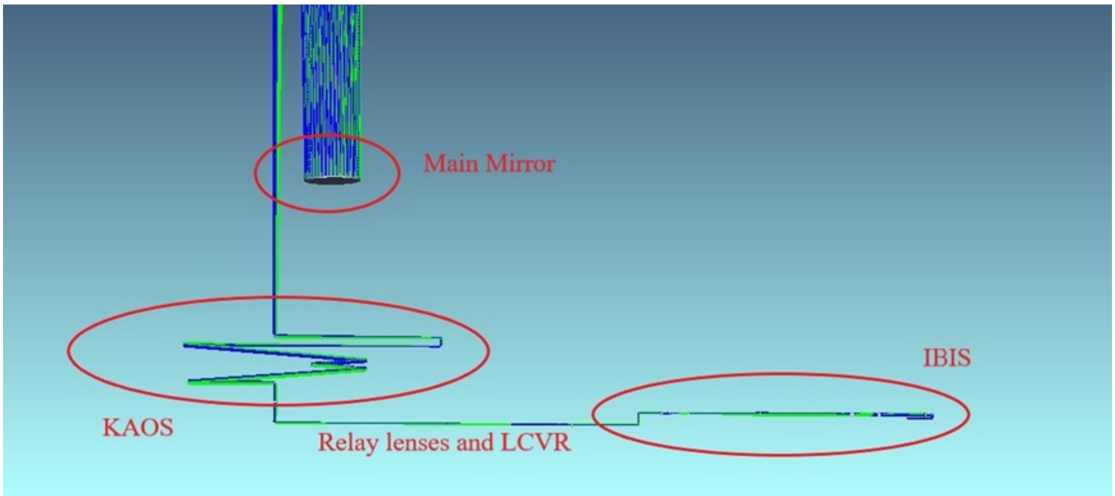

Figure 11: Zoom of the bottom part of the optical scheme, side view. The position of KAOS, relay lenses and LCVR, and IBIS 2.0 are highlighted in red.

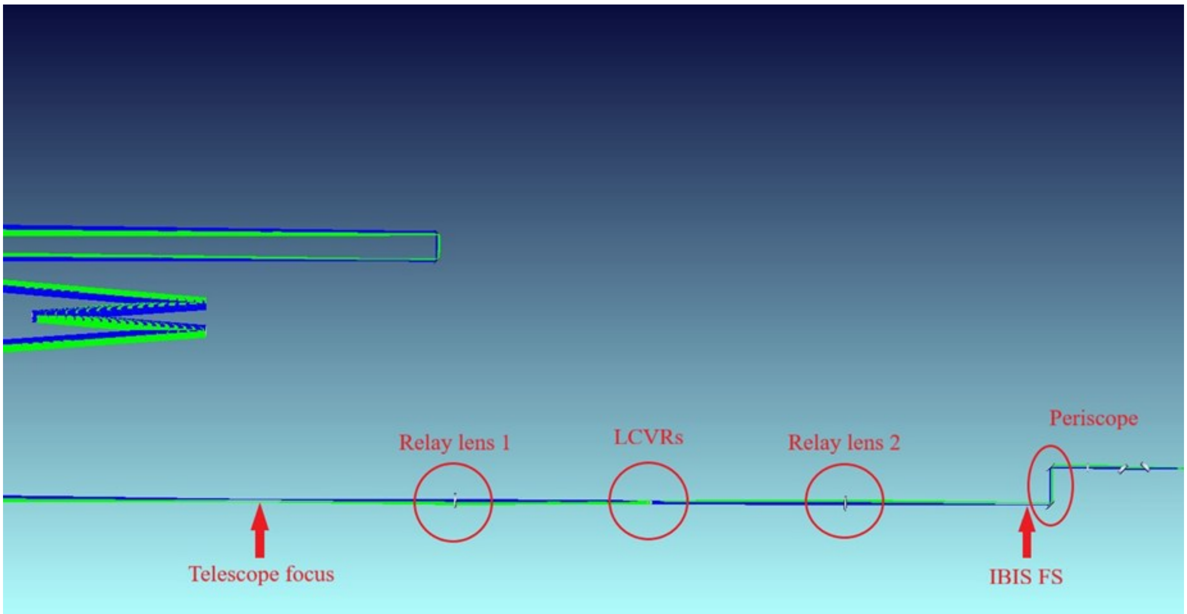

Figure 12: Side view of the optical scheme of relay lenses and LCVRs in the optical laboratory of VTT, and IBIS 2.0 FS and periscope on the available optical table.

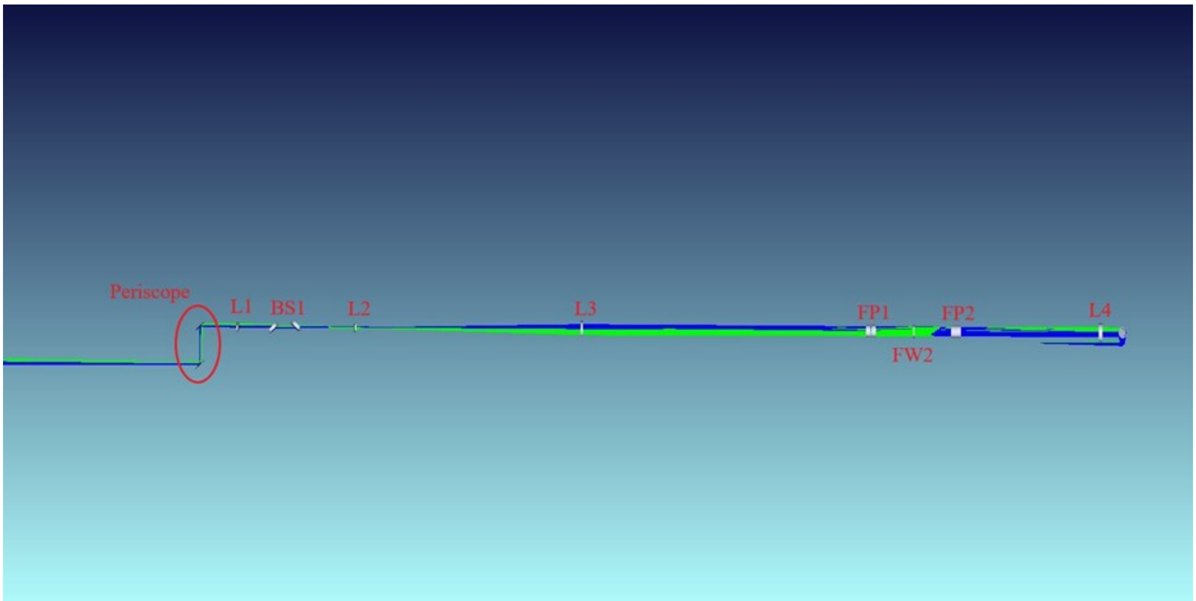

Figure 13: Side view of the optical scheme of the IBIS 2.0 principal components placed on the optical table: L1, BS1, L2, L3, FP1, FW2, FP2, L4 and folding mirrors.

Lens Data Editor

Edit Solves View Help

Surf	:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)	Par 2(unused)	Par 3(unused)	Par 4
OBJ	Standard		Infinity	Infinity		Infinity	0.000					
1	Standard		Infinity	1.000E+004		353.058	0.000					
2+	Standard	Coelostat	Infinity	-2600.000	MIRROR	405.209	0.000					
3+	Standard	M2	Infinity	2000.000	MIRROR	404.580	0.000					
STO	Standard	Window_1	-1.172E+006	70.000	BK7	350.000	0.000					
5	Standard	Window_2	-1.173E+006	2.712E+004		350.017	0.000					
6+	Standard	Main Mirror	-9.200E+004	-2.073E+004	MIRROR	355.766	0.000					
7+	Standard	Fold Mirror	Infinity	2.274E+004	MIRROR	199.769	0.000					
8+	Standard	AO_M1	Infinity	-2125.000	MIRROR	40.150	0.000					
9+	Standard	AO_M2	Infinity	120.000	MIRROR	17.706	0.000					
10+	Standard	AO_M3	Infinity	-288.561	MIRROR	16.688	0.000					
11	Standard	Telescope Focus	Infinity	-3000.000		9.657	0.000					
12+	Standard	AO Collimator	6009.000	2350.200	MIRROR	32.762	0.000					
13+	Standard	AO Tip Tilt	Infinity	-715.000	MIRROR	25.279	0.000					
14+	Standard	AO DM	Infinity	715.000	MIRROR	22.977	0.000					
15+	Standard	AO BS WFS	Infinity	-2285.000	MIRROR	25.147	0.000					
16+	Standard	AO Imager	6009.000	1109.500	MIRROR	32.359	0.000					
17+	Standard	AO_M4	Infinity	-240.000	MIRROR	33.576	0.000					
18	Standard	AO_Window_1	Infinity	-30.000	BK7	22.101	0.000					
19	Standard	AO_Window_2	Infinity	-247.582		21.951	0.000					
20#	Standard	Lab_Feed	Infinity	1391.505	MIRROR	40.000 U	0.000					
21	Standard	Focus	Infinity	800.000		9.685	0.000					
22*	Standard		1090.430	5.000	SF8	31.500 U	0.000					
23*	Standard		308.080	5.000	BACD9	31.500 U	0.000					
24*	Standard	L-AOC287	-711.138	784.726		31.500 U	0.000					
25*	Standard	LCVR 1	Infinity	5.000	SILICA	10.000 U	0.000					
26*	Standard		Infinity	10.000		10.000 U	0.000					
27*	Standard	LCVR 2	Infinity	5.000	SILICA	10.000 U	0.000					
28*	Standard		Infinity	790.000		10.000 U	0.000					
29*	Standard	L-AOC287	711.138	5.000	BACD9	31.500 U	0.000					
30*	Standard		-308.080	5.000	SF8	31.500 U	0.000					
31*	Standard		-1090.430	792.841 M		31.500 U	0.000					
32	Standard	IBIS Field Stop	Infinity	44.000		9.688	0.000					
33#	Standard	Periscope 1	Infinity	-156.000	MIRROR	25.000 U	0.000					
34#	Standard	Periscope 2	Infinity	150.000	MIRROR	25.000 U	0.000					
35*	Standard	L1-LA0277	942.120	3.000	SF8	20.000 U	0.000					
36*	Standard	L1-LA0277	156.530	4.000	SSK4A	20.000 U	0.000					
37*	Standard	L1-LA0277	-238.730	136.095		20.000 U	0.000					

Figure 14: Zemax Lens Data Editor of IBIS 2.0 at VTT (part 1).

38	Coordinat..	Element Tilt		0.000	-	0.000			0.000	0.000	45.000	
39*	Standard	BS1 A	Infinity	12.500	BK7	25.000 U	0.000					
40*	Standard		Infinity	-12.500 T		25.000 U	0.000					
41	Coordinat..	Element Tilt		12.500 P	-	0.000			0.000 P	0.000 P	-45.000 P	
42	Standard	Dummy	Infinity	80.000	P	6.942	0.000					
43	Coordinat..	Element Tilt		0.000	-	0.000			0.000	0.000	-45.000	
44*	Standard	BS1 B	Infinity	12.500	BK7	25.000 U	0.000					
45*	Standard		Infinity	-12.500 T		25.000 U	0.000					
46	Coordinat..	Element Tilt		12.500 P	-	0.000			0.000 P	0.000 P	45.000 P	
47	Standard	Dummy	Infinity	107.500	P	6.082	0.000					
48	Standard		Infinity	120.000		3.089	0.000					
49*	Standard	L2-LA0138	77.210	8.200	SK11	20.000 U	0.000					
50*	Standard	L2-LA0138	-54.090	3.000	SF5	20.000 U	0.000					
51*	Standard	L2-LA0138	-216.100	113.807 M		20.000 U	0.000					
52	Standard		Infinity	796.160		3.328	0.000					
53*	Standard	L3-LA0357	1090.430	5.000	SF8	31.500 U	0.000					
54*	Standard	L3-LA0357	308.080	5.000	BACD9	31.500 U	0.000					
55*	Standard	L3-LA0357	-711.138	1148.119		31.500 U	0.000					
56*	Standard	FP1 plate 1	Infinity	20.000	SILICA	25.400 U	0.000					
57*	Standard	FP1 spacing	Infinity	2.300		25.400 U	0.000					
58*	Standard	FP1 plate 2	Infinity	20.000	SILICA	25.400 U	0.000					
59*	Standard		Infinity	150.000		25.400 U	0.000					
60	Paraxial			100.000		0.000			100.000	1		
61*	Standard	FW2	Infinity	5.000	SILICA	25.400 U	0.000					
62*	Standard		Infinity	150.000		25.400 U	0.000					
63*	Standard	FP2 plate 1	Infinity	20.000	SILICA	25.400 U	0.000					
64*	Standard	FP2 spacing	Infinity	0.637		25.400 U	0.000					
65*	Standard	FP2 plate 2	Infinity	20.000	SILICA	25.400 U	0.000					
66*	Standard		Infinity	556.863		25.400 U	0.000					
67*	Standard	L4-L-APA130	455.789	11.000	BK7	38.100 U	0.000					
68*	Standard	L4-L-APA130	-336.814	6.500	SF5	38.100 U	0.000					
69*	Standard	L4-L-APA130	-1010.101	80.000		38.100 U	0.000					
70+	Standard	M2	Infinity	-330.000	MIRROR	22.891	0.000					
71+	Standard	M3	Infinity	331.759 M	MIRROR	11.774	0.000					
IMA	Standard		Infinity	-		3.124	0.000					

Figure 15: Zemax Lens Data Editor of IBIS 2.0 at VTT (part 2).

We have analyzed the spot diagram of IBIS 2.0 (at five positions on the FoV of 80", one at the center and the others at the four edges) simulating the light beam coming from the VTT, and we report the results in Figure 16. It can be noticed that the instrument at VTT and with KAOS turned off is not diffraction limited (spots outside the Airy disk, marked by the gray circle) because of the spherical aberration and other aberrations (on the telescope focus at 656.3nm: spherical aberration 870nm, coma –30nm, astigmatism 20nm and field curvature -80nm) introduced by the inclined main mirror of the VTT. These aberrations are compensated by KAOS turned on in closed loop (private communication with T. Berkefeld); therefore, IBIS 2.0 used at VTT will be diffraction limited. In fact, to characterize the optical quality of IBIS 2.0 alone, we analyze the spot diagrams obtained with an "ideal VTT", realized with paraxial optical surfaces. As it can be seen in the spot diagrams at 589.0nm, 617.3nm, 630.1nm, 656.3nm, 722.4nm and 854.2nm, reported respectively in Figure 17, Figure 18, Figure 19, Figure 20, Figure 21 and Figure 22, IBIS 2.0 fed with a beam without aberration ("ideal VTT") is diffraction limited (the point spread function spots are well inside the Airy disk, marked by the gray circle in the various figures).

The two new identical detectors of IBIS 2.0 are indicated as CCD1 and CCD2, referring to the old IBIS scheme at DST, but we are considering to use either CCD or CMOS detectors (find details in the following).

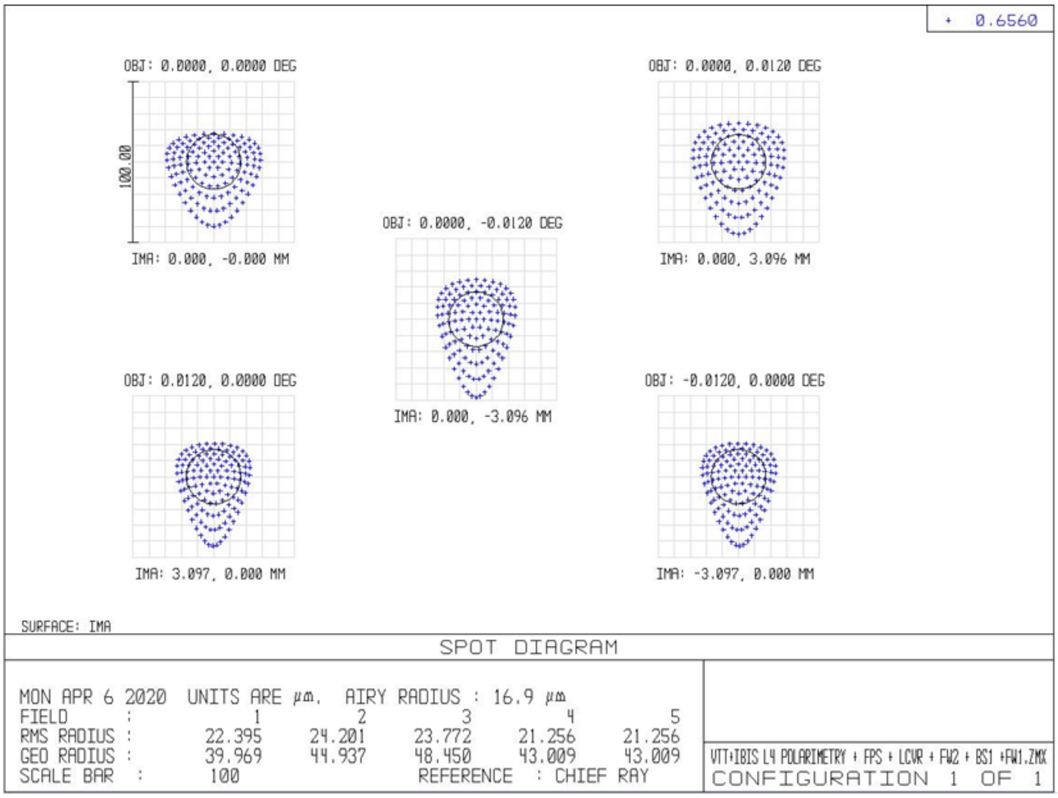

Figure 16: Spot diagram of IBIS 2.0 fed with the VTT at 656.0 nm.

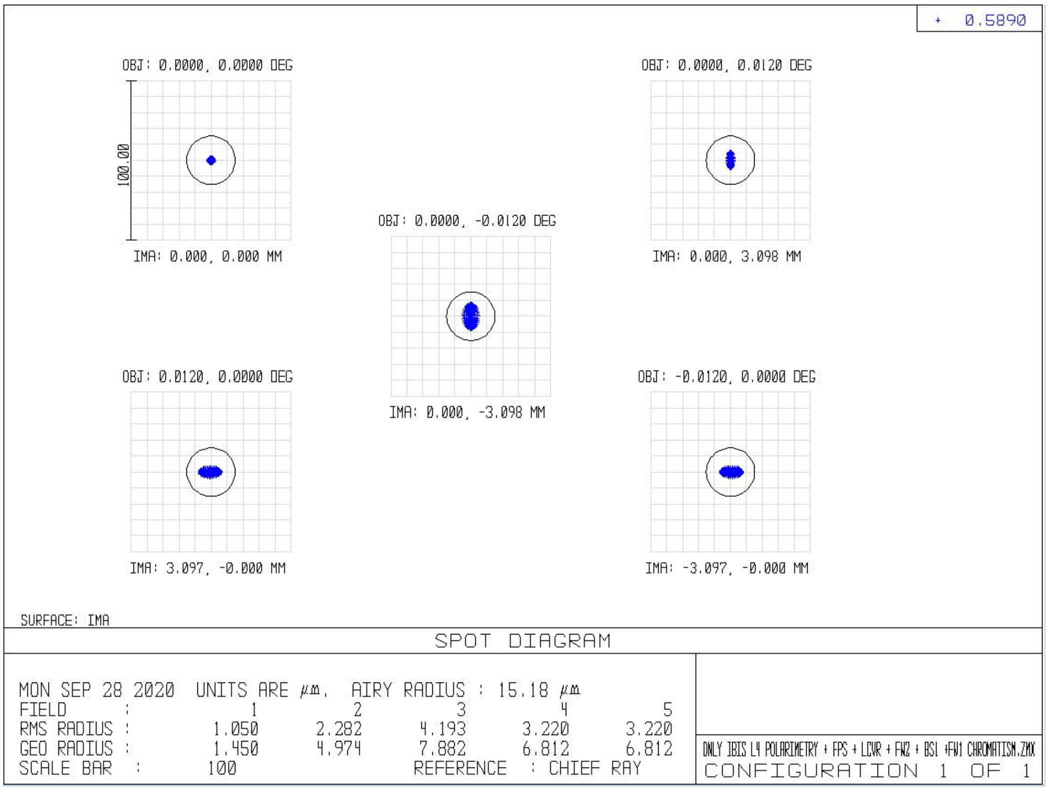

Figure 17: Spot diagram of IBIS 2.0 fed with an “ideal” (paraxial) VTT at 589.0 nm.

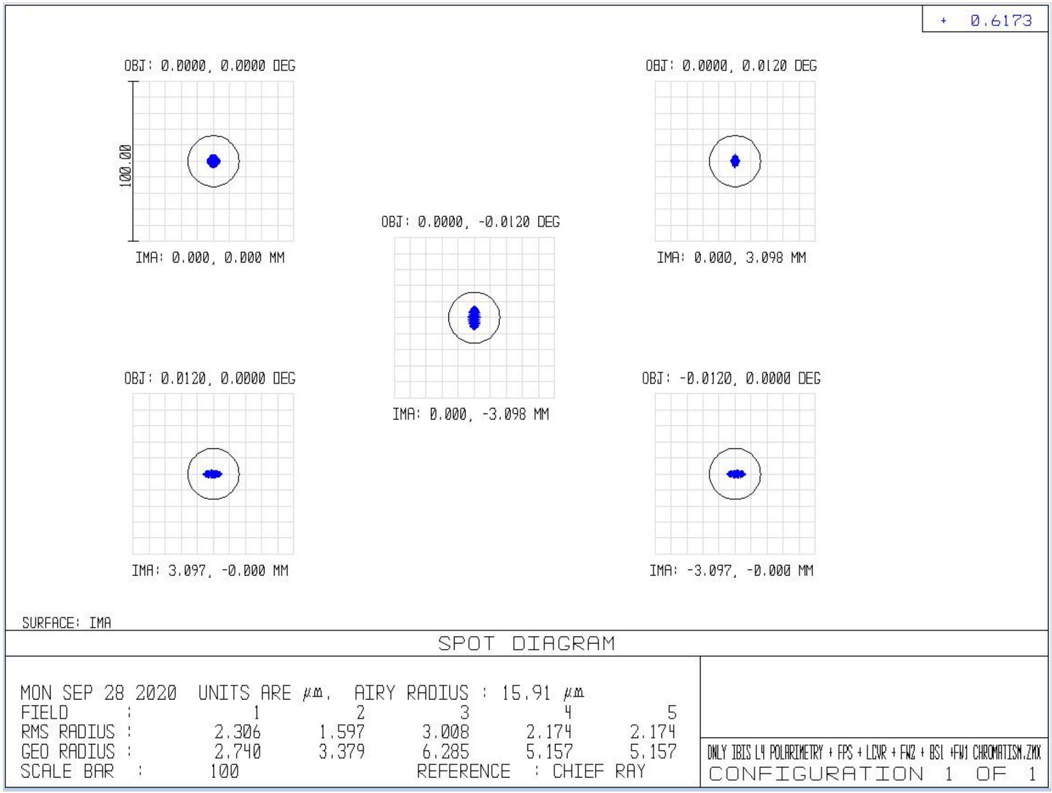

Figure 18: Spot diagram of IBIS 2.0 fed with an “ideal” (paraxial) VTT at 617.3 nm.

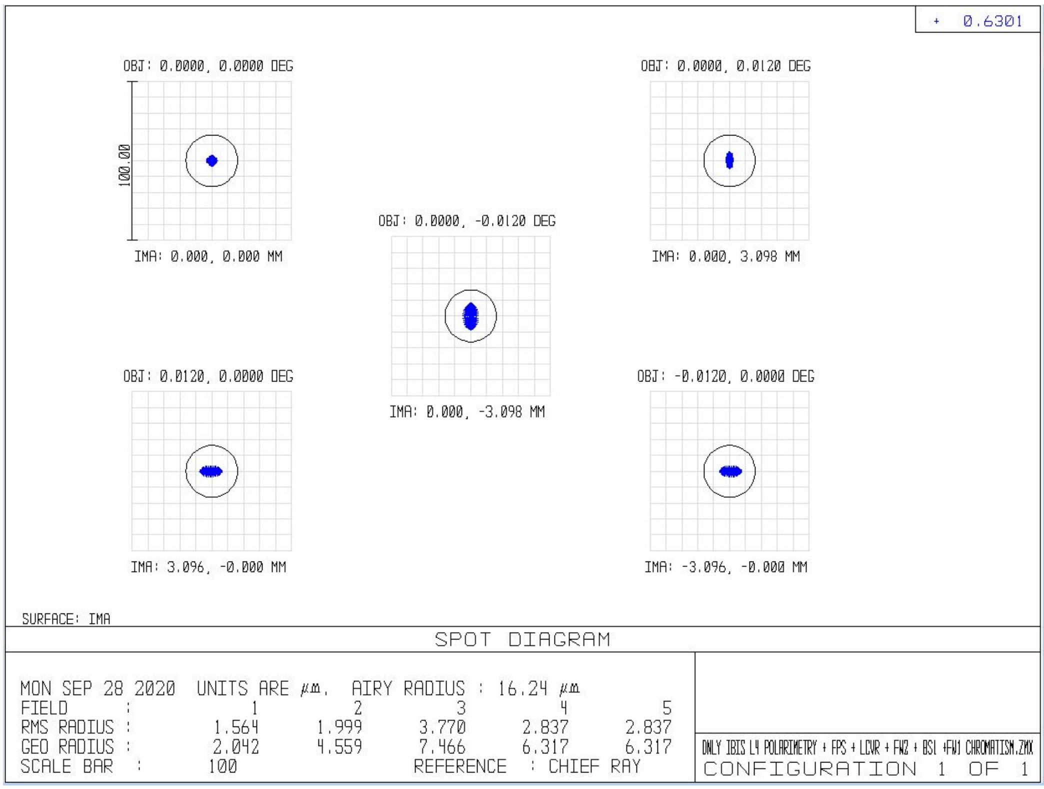

Figure 19: Spot diagram of IBIS 2.0 fed with an "ideal" (paraxial) VTT at 630.1 nm.

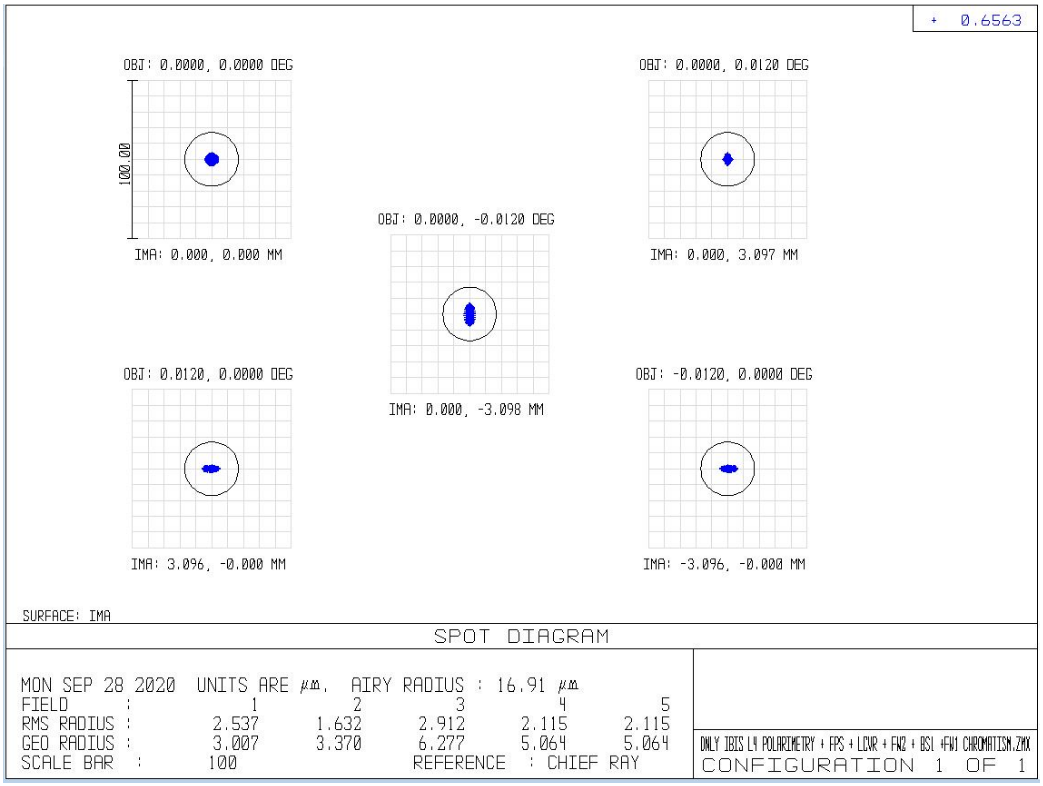

Figure 20: Spot diagram of IBIS 2.0 fed with an "ideal" (paraxial) VTT at 656.3 nm.

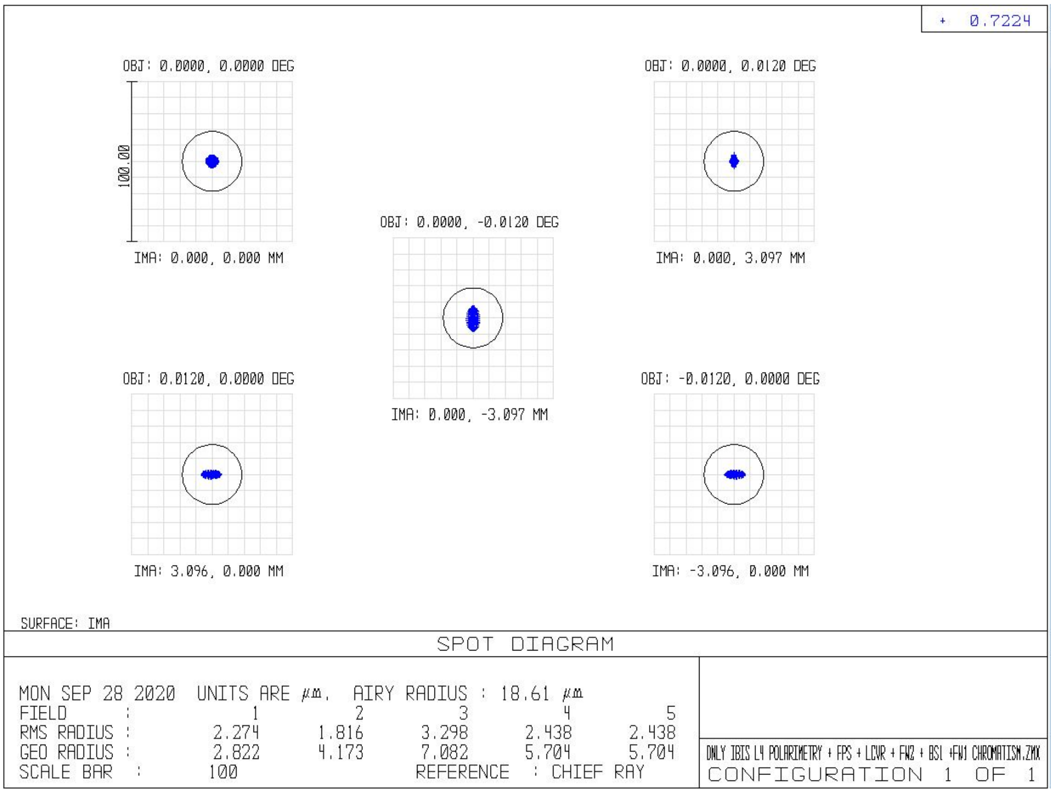

Figure 21: Spot diagram of IBIS 2.0 fed with an “ideal” (paraxial) VTT at 722.4 nm.

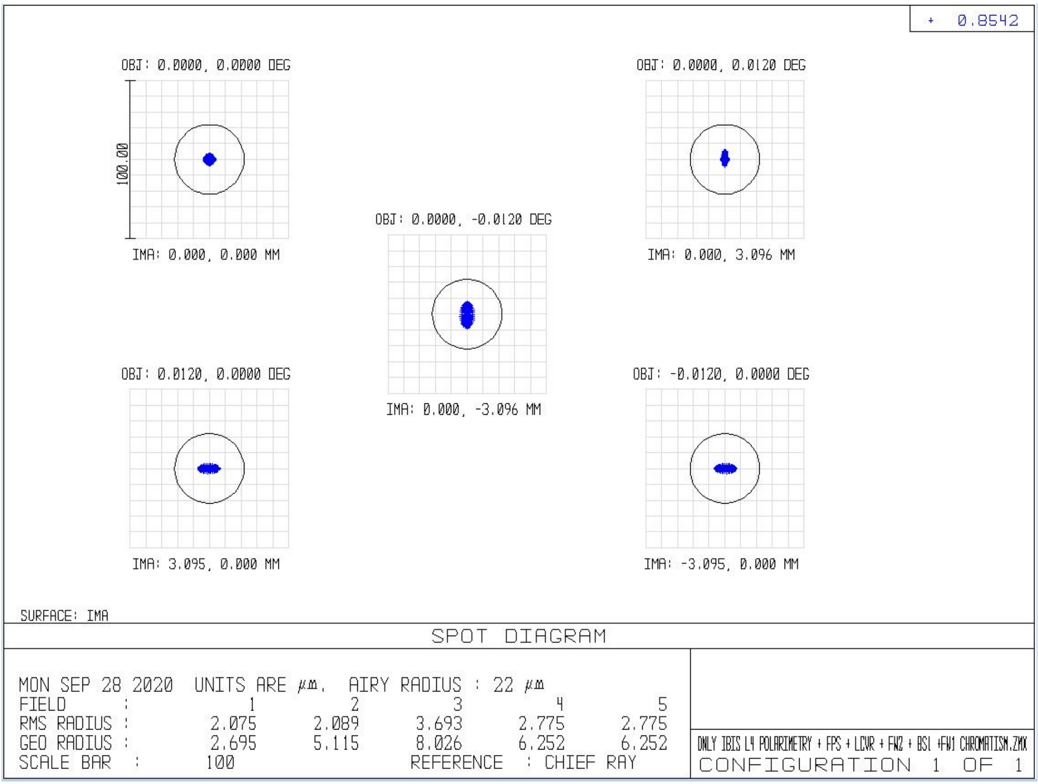

Figure 22: Spot diagram of IBIS 2.0 fed with an “ideal” (paraxial) VTT at 854.2 nm.

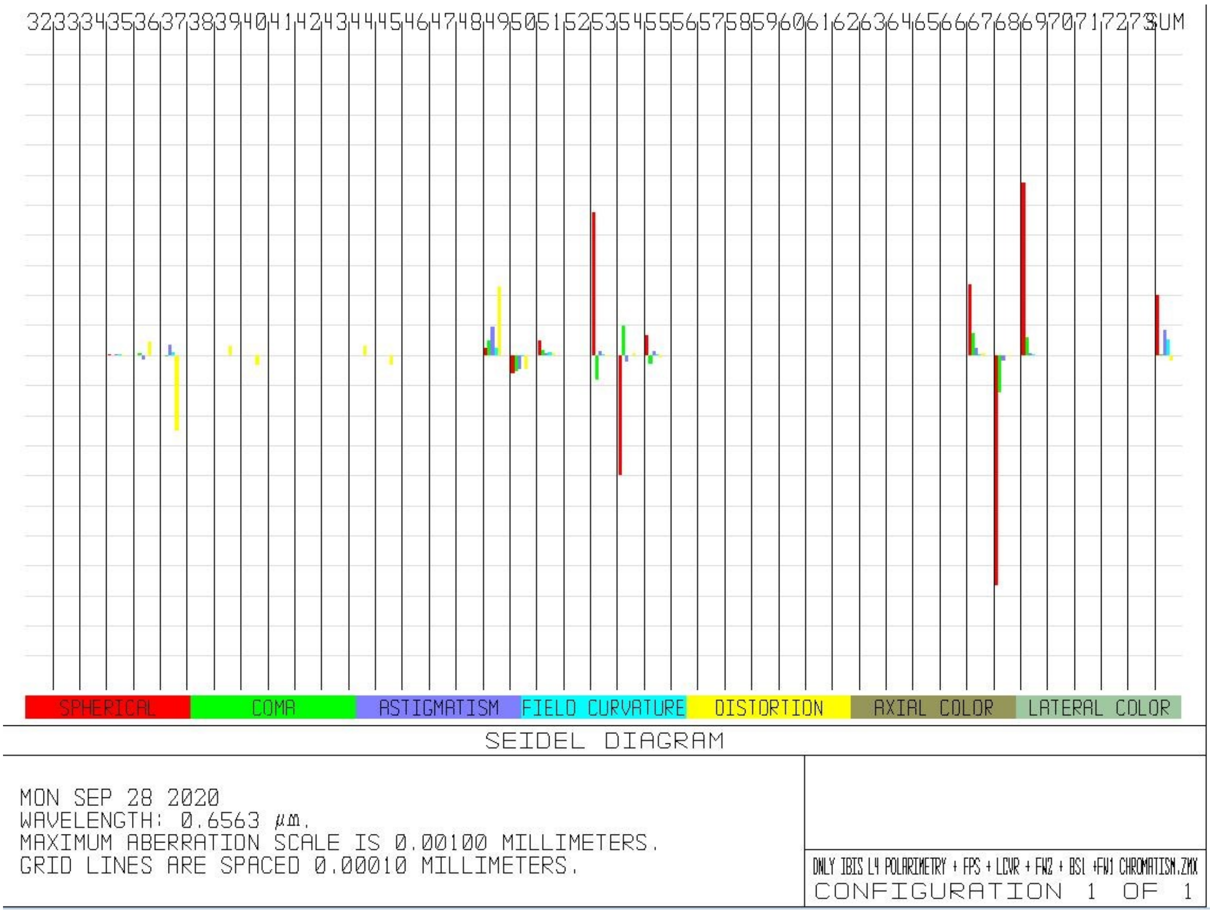

Figure 23: Seidel aberration diagram of IBIS 2.0 at VTT. The step of the horizontal grid is 100 nm.

The Seidel aberration graphics for the IBIS 2.0 fed with the “ideal VTT” at 656.3nm is shown in Figure 23, where the amount of the different aberrations introduced by the various optical surfaces is also reported. The distortions introduced by the two inclined plates of BS1 are self-compensating (optical surfaces 39-40 and 44-45); negligible aberrations are introduced by the lenses L1 (opt. surf. 35-37), L2 (opt. surf. 49-51), L3 (opt. surf. 53-55) and L4 (opt. surf. 67-69). According to the Zemax model, on the science focal plane (opt. surf. SUM), where CCD1 is placed, we have the following residual aberrations: spherical aberration 205nm, coma 5nm, astigmatism 85nm, field curvature 55nm and distortion -20nm. According to the Zemax analysis, the maximum distortion (<0.015%) and the coma are negligible. These aberration on the final focal plane of CCD1 are to be compared with the rms of 60nm and the total stroke of 200 nm of the DM of KAOS. In any case, the instrument spatial resolution is limited by the telescope diffraction limit. The effective image contrast of IBIS 2.0 will be evaluated in the final design phase.

Using the Zemax model, we also investigated the chromatism of IBIS 2.0, finding that a total focus range of ~5mm is needed to focus the instrument in the whole operational spectral range (580-860nm).

Also, we simulated the image on the CCD1 focal plane of a square FoV of 80”. We perform the image simulation for the detectors:

- Andor Zyla 4.2 plus: 2048x2048 with 6.5 µm pixels
- Andor Sona: 2048x2048 with 6.5 µm pixels
- Andor Marana 4.2: 2048x2048 with 6.5 µm pixels
- Andor Ixon Ultra 888: 1024x1024 with 13 µm pixels

The results of the image simulation including the IBIS 2.0 PSF are reported and compared in Figure 24 and Figure 25. It can be seen that only the central part of the detector is illuminated by the image formed by L4. In the details (zooms) of the simulations, the different sampling of the images due to the different pixel dimensions of 6.5 µm and 13 µm are visible.

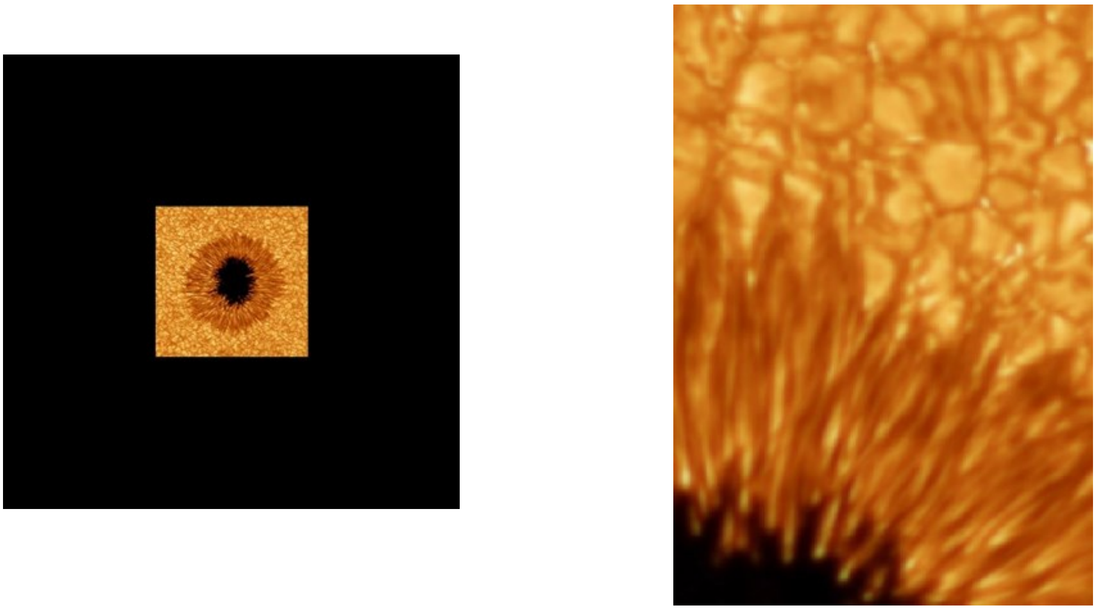

Figure 24: Image simulation with 2048x2048 detector and 6.5 µm pixels (left) and detail of this simulation (right).

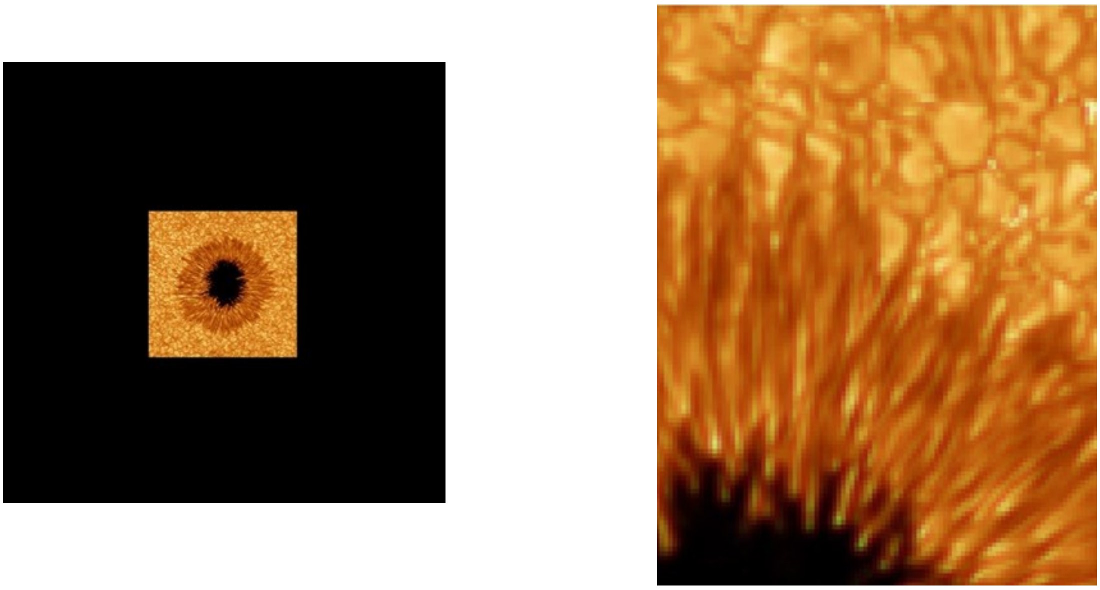

Figure 25: Image simulation with 1024x1024 detector and 13 µm pixels (left) and detail of this simulation (right).

3.2.1 First optical layout (Level 0)

In Figure 26 we report the first optical layout proposed for the IBIS 2.0 optical scheme at VTT with automation Level 0. We describe here the IBIS 2.0 optical path before L2, which is the only part of the instrument that has been rearranged for the VTT, reusing the optomechanical components of IBIS at DST. The initial path between FS and L2 has been aligned with the main optical path in order to avoid folding mirrors, which could get more difficult the polarimetric calibration, and to fit the dimensions of the optical table. The white light channel (M13+CCD2) and the M12+TV5 channel have been also reorganized in order to fit the optical table dimensions and encumbrances of the mechanical parts. The beam splitter BS1 is still positioned near the pupil between L1 and L2. Mirrors M12 and M13 were maintained in order to center the images on the TV5 and CCD2 detectors. A set of neutral density filters (ND) or a set of variable crossed polarizers, placed before the White Light Camera Lens (WLCL, 70-200mm zoom lens) can be used to regulate the photon flux on the chip of CCD2, so that CCD2 has the same exposure time as CCD1. The broad-band filters (BB) are placed immediately after the ND filters. The image on CCD2 is formed by the WLCL, see [RD1] for details. The remaining IBIS 2.0 optical path is unchanged with respect to the one used at DST. The proposed new CCD or CMOS cameras are discussed in Section 3.3.

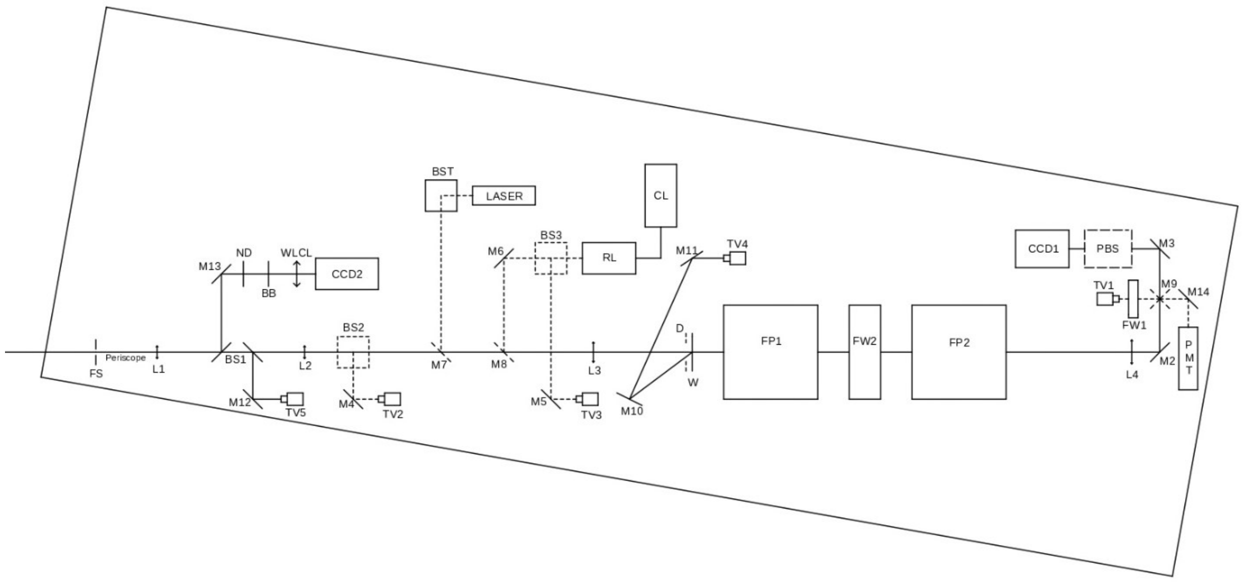

Figure 26: First optical layout proposed for the IBIS 2.0 optical scheme. The external rectangle is the optical table.

A manually-removable diaphragm (D) is placed in front of the window (W). A linear stage is used to insert/remove the PBS and another linear stage (or alternatively a filter wheel) is used to change the circular FS with the rectangular FS.

The instrument shutter (which is used to remove the solar light during some calibration phases) can be placed before the LCVRs. If necessary, this shutter could be equipped with a heatsink in order to avoid the heating caused by the solar light. This shutter is manually controlled.

In this optical layout, we propose to use the same optomechanical components of IBIS at DST, therefore leaving the IBIS 2.0 calibration procedures in manual mode. The reference (BS1, M13, CCD2, M12, TV5), tuning (CL, RL, BS3, M8, M6, M5, TV3) and laser paths (laser, BST, M7) are realized with the same hardware used at DST, but reorganized [RD1].

3.2.2 Second optical layout (Level 1 and Level 2)

The scheme of the second proposed optical layout for IBIS 2.0 at VTT with automation Level 1 and Level 2 is reported in Figure 27. Most of the changes that are proposed are to make the optical design simpler and more efficient, and to realize a semi-automatic system (highlighted in red in Figure 27). The path between FS and L2 is aligned with the main optical path.

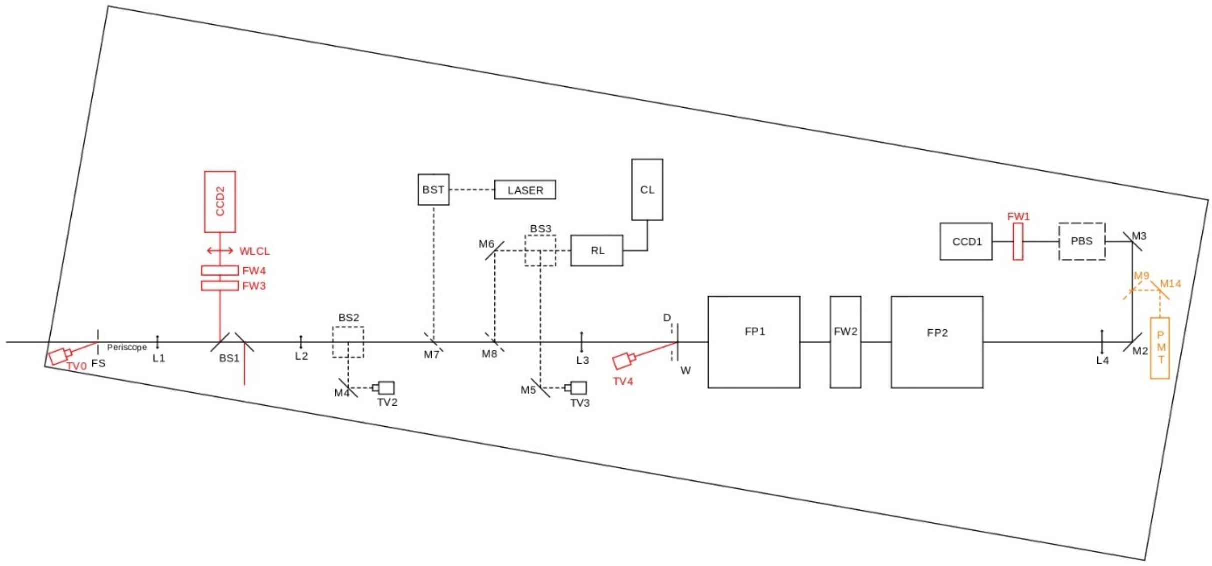

Figure 27: Second optical layout proposed for the IBIS 2.0 optical scheme. The external rectangle is the optical table. New reference path is highlighted in red. M9+M14+PMT are highlighted in orange (tuning path).

A TV0 camera (equipped with a suitable lens) is used slantwise to observe the proper illumination of the IBIS 2.0 FS with the solar light coming from the folding mirror after KAOS. The mirrors M10 and M11 are removed and the TV4 camera watches slantwise the window W. IBIS 2.0 will be correctly fed by the solar beam coming from the VTT when FS and W are uniformly illuminated. We propose to use an electronic shutter also for this second optical layout placed before the LCVRs. In this case it will be managed by the control system (ICE and ICS, see sections 4 and 5).

The initial path before L2 is simplified. We removed the TV5 camera and the M12 mirror since we use the quick view of CCD1 or CCD2 to look at the region of interest on the Sun. The mirror M13 is removed and the white light camera CCD2 looks directly at the first plate of BS1. We can use two filter wheels FW3 and FW4 to change the BB filters and the ND filters, if it is necessary. The image on CCD2 is formed by the WLCL. The other plate of BS1 is used to avoid the beam shift produced by a single plate and to compensate for the aberration induced by the first plate. The light coming from the second plate of BS1 is unused, but it is available for other future broadband channels.

The TV1+FW1 channel of IBIS at DST is integrated in the CCD1 main optical path, so the laser path is slightly modified [RD1]. FW1 placed in front of CCD1 is used during the laser calibration and during the verification of FPs plates parallelism. Selecting the clear position in FW1, we obtain an image of the opalescent disk of BST on CCD1, which is used to check the laser beam alignment with respect to the solar beam. Inserting a lens with a focal length of 100mm in FW1 and refocusing CCD1 of ~7mm, we obtain alternatively an image of FP1 plates or PF2 plates on CCD1, which can be used to check the plates parallelism.

We also include a linear stage to change the diaphragms (D) placed in front of the window (W), a linear stage to insert and remove the PBS and another linear stage (or alternatively a filter wheel) to change the circular FS with the rectangular FS.

The M9+M14+PMT channel (highlighted in orange in Figure 27) is activated only for the spectral tuning of the FPs. After making laboratory measurements, we can decide to include the spectral tuning path into the main optical path, using CCD1 instead of PMT. In this case, a telecompressor can be used to reduce the image of the calibration lamp on the CCD1 in order to increase the number of counts, especially with darker prefilters. The telecompressor can be made using three equal lenses (19mm of focal length, 12.5mm of diameter, Thorlabs) to reduce the image from 6mm to ~1mm of diameter, or using two equal lenses (14mm of focal length, 11.25mm of diameter, Edmund Optics) and another lens (19mm of focal length, 12.5mm of diameter, Thorlabs) to reduce the image from 6mm to ~0.6mm of diameter.

In this second optical layout of IBIS 2.0 at VTT, we propose to use some of the optomechanical parts used at DST and we plan to use functions controlled by the control software. The lamp path is the same used at DST.

3.3 IBIS 2.0 scientific detectors for VTT

The choice of the IBIS 2.0 scientific cameras is dictated by the science requirements described in [RD12]. The first limiting parameter for high resolution solar observations is the number of photons per pixel, which depends on the transparency and reflectivity of the various optical components, on the spectral sampling, on the spatial sampling and on the temporal sampling. The spatial sampling and the temporal sampling are connected by the characteristic evolution velocity of the observed phenomenon. The spatial sampling must satisfy the Nyquist criterion (at least two pixels per resolved element) and the temporal sampling must be less than the proper evolution time of the phenomenon itself. Considering that the angular resolution is L=0.2” approximately (corresponding to 145 km on the solar atmosphere) and that the typical characteristic velocity of the plasma in photosphere has values from v=1 km/s and C_s=7 km/s (sound velocity in the photosphere), the characteristic evolution time L/C_s is between 145 s and 20 s, which should be the maximum time needed to perform a complete spectral scan. In the chromosphere the phenomena are more rapid, with a velocity up to C_s=40 km/s, so we expect that the characteristic evolution time of the structures is of the order of ten of seconds or less (the more rapid chromospheric phenomena are nowadays addressed with Integral Field Unit instruments and not with FP-based instruments). In order not to observe a smearing of the solar scene, the spatial and the temporal sampling must be correctly rescaled according to the number of photons per pixel and in order to have a reasonable suitable signal-to-noise ratio (S/N), and this imposes some requirements on the choice of the scientific cameras.

The IBIS 2.0 CCD1 and CCD2 detectors must be identical, in order to use the CCD2 detector for the image reconstruction post-facto techniques on the CCD1 images. The detectors must satisfy the following requirements:

- At least 800x800 pixel array to sample correctly (Nyquist criterion) the image on the focal plane, since the FoV is 80” and the angular resolution between 0.17” at 580nm and 0.23” at 860nm;
- Pixel smaller than 16μm to satisfy the Nyquist criterion, since the image has a diameter of 6.25mm;
- QE > 30% over the whole wavelength range of IBIS 2.0 (580-860nm);
- Suitable exposure times of the order of 50-100 ms in order to be as close as possible to frozen seeing conditions but also to have an adequate S/N (seeing refreshing time of 10-20 ms at 580 nm);
- Read-Out-Noise (RON) < 10 e- ;
- Possibility of frame rate > 10 fps to have a large number of images to perform post-facto reconstruction techniques;
- High pixel well depth (dynamics) in order to have a good number of counts in the darker regions (sunspots, pores) while at the same time not saturating in the brighter regions;
- Signal-to-Noise Ratio (S/N) > 5 in the sunspot (darker region of the solar atmosphere) and at the spectral line center (more absorption).

Analyzing some datasets of IBIS acquired at the DST with 80ms of exposure time and gain=2.5, we were able to estimate the photon flux on the detector from the umbra of a sunspot observed in the darkest spectral positions available with IBIS prefilters and from the photospheric granulation observed in the spectral continuum. We found an average number of 100 counts in the spectral line center of the sunspot umbra pixels and an average number of 3000 counts in the spectral continuum of photospheric granulation pixels.

Among the large number of detectors available in the market, we found that the Andor Ixon 885 (the one used at DST), the Andor Zyla 4.2 Plus, the Andor Marana and the Andor Ixon Ultra 888 are possible candidates for the IBIS 2.0 detectors.

Table 1 summarizes the most relevant specifications for the selected replacement detectors compared to the original IBIS detector iXon 885:

MODEL	pixel [μm]	# of pixels	ron [e-]	QE @ 543	QE @ 588	QE @ 620	QE @ 656	QE @ 854
Ixon 885	8.0	2048x2048	15	0.60	0.65	0.64	0.62	0.35
Zyla	6.5	2048x2048	1	0.82	0.82	0.81	0.78	0.35
Marana	6.5	2048x2048	1.6	0.94	0.95	0.93	0.88	0.50
Ixon Ultra 888	13.0	1024x1024	6	0.90	0.90	0.90	0.90	0.55

Table 1: Relevant specifications for the new proposed IBIS 2.0 detectors.

The expected S/N for the different candidates, in the darker region of the typical IBIS 2.0 image, is then compared in Figure 28, Figure 29 and Figure 30, where the instrument performance is analyzed along several important wavelengths typical of IBIS 2.0 science cases:

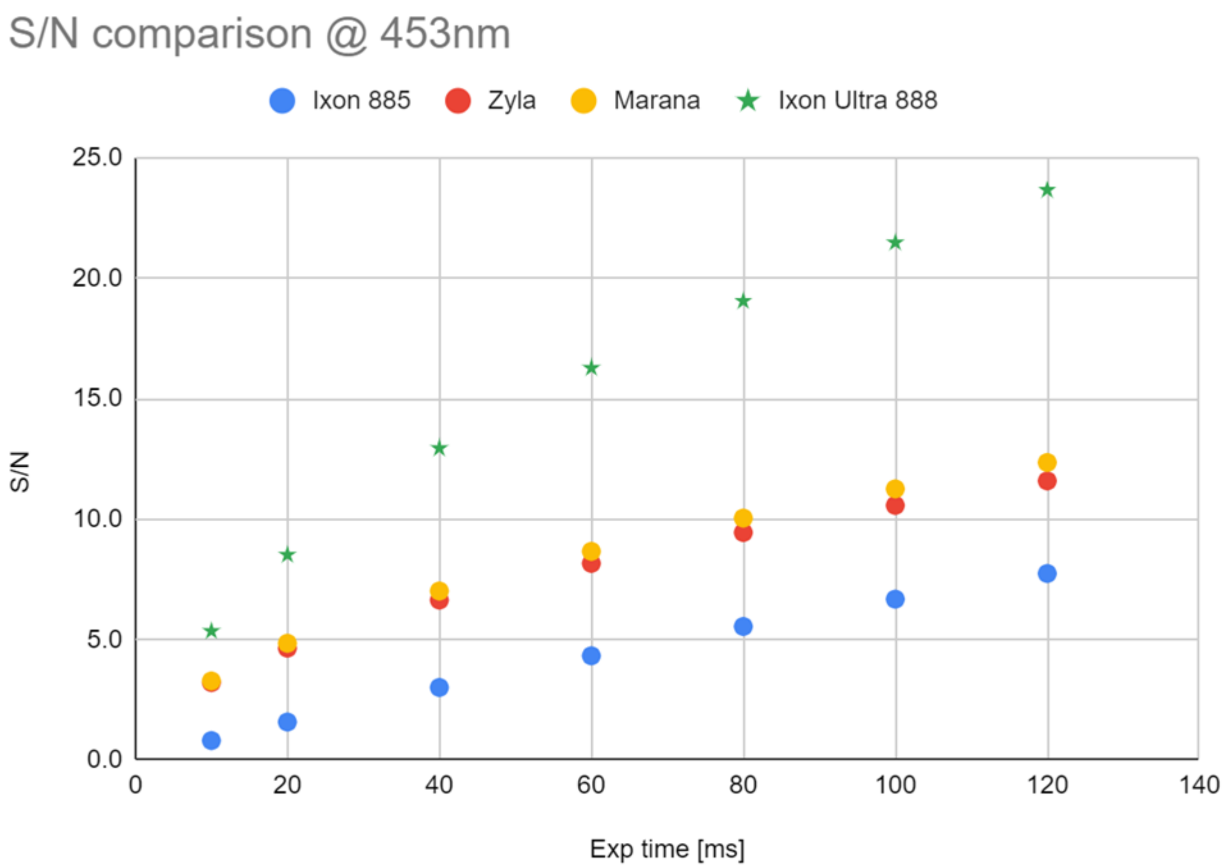

Figure 28: S/N comparison for the various proposed detectors at 453nm.

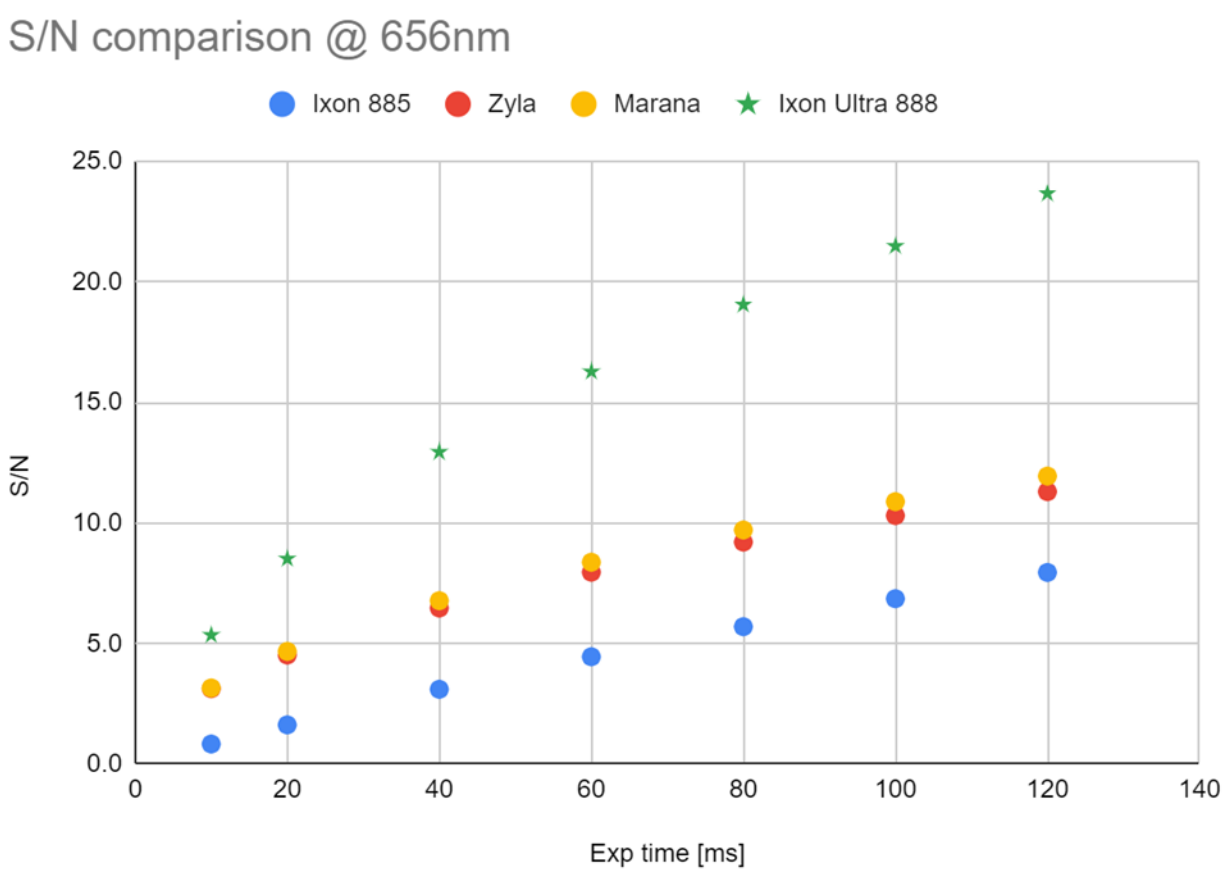

Figure 29: S/N comparison for the various proposed detectors at 656nm.

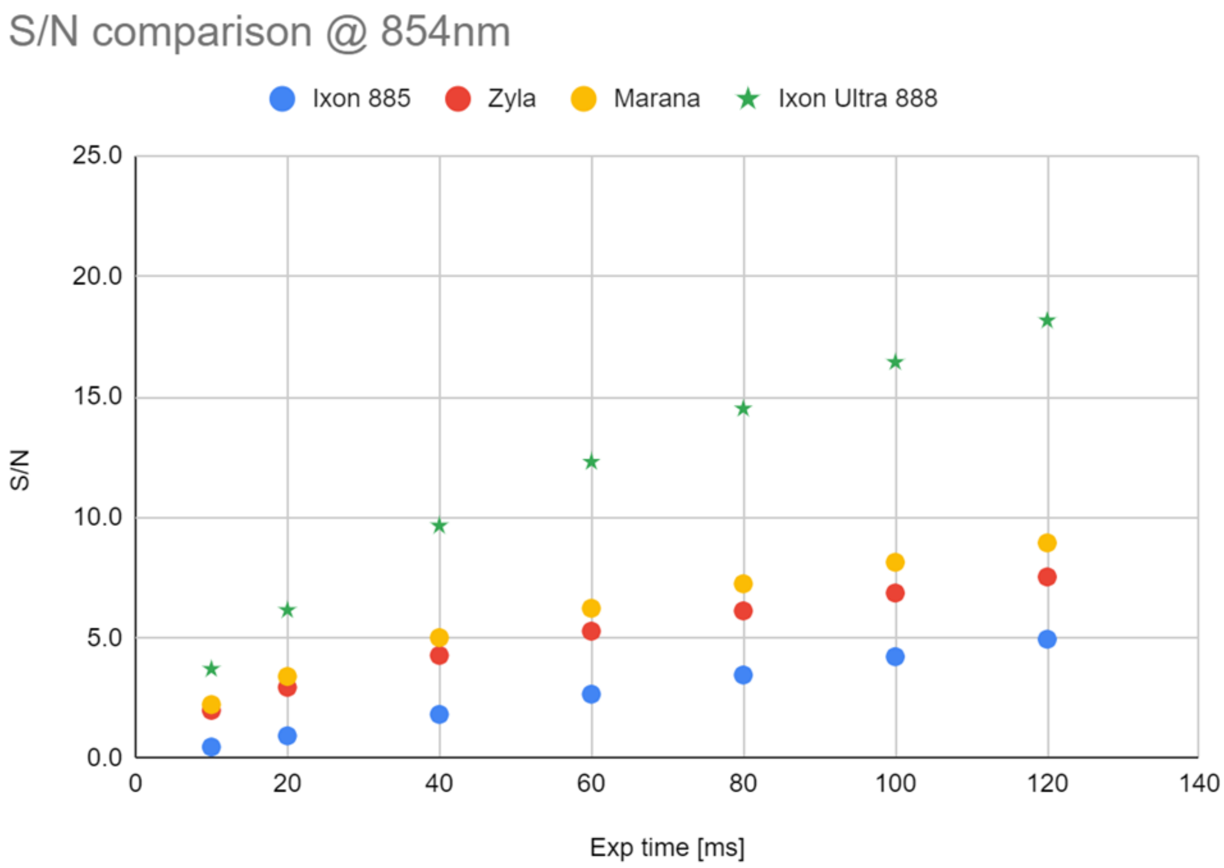

Figure 30: S/N comparison for the various proposed detectors at 854nm.

Note that the excellent performance of the iXon 888 is mainly due to the larger pixel that is slightly undersampling the IBIS 2.0 PSF. For a comparison at the same sampling it has to be divided by a factor 2 at least. Figure 31 shows the iXon 888 performance rescaled to achieve the same angular resolution sampling as the other cameras.

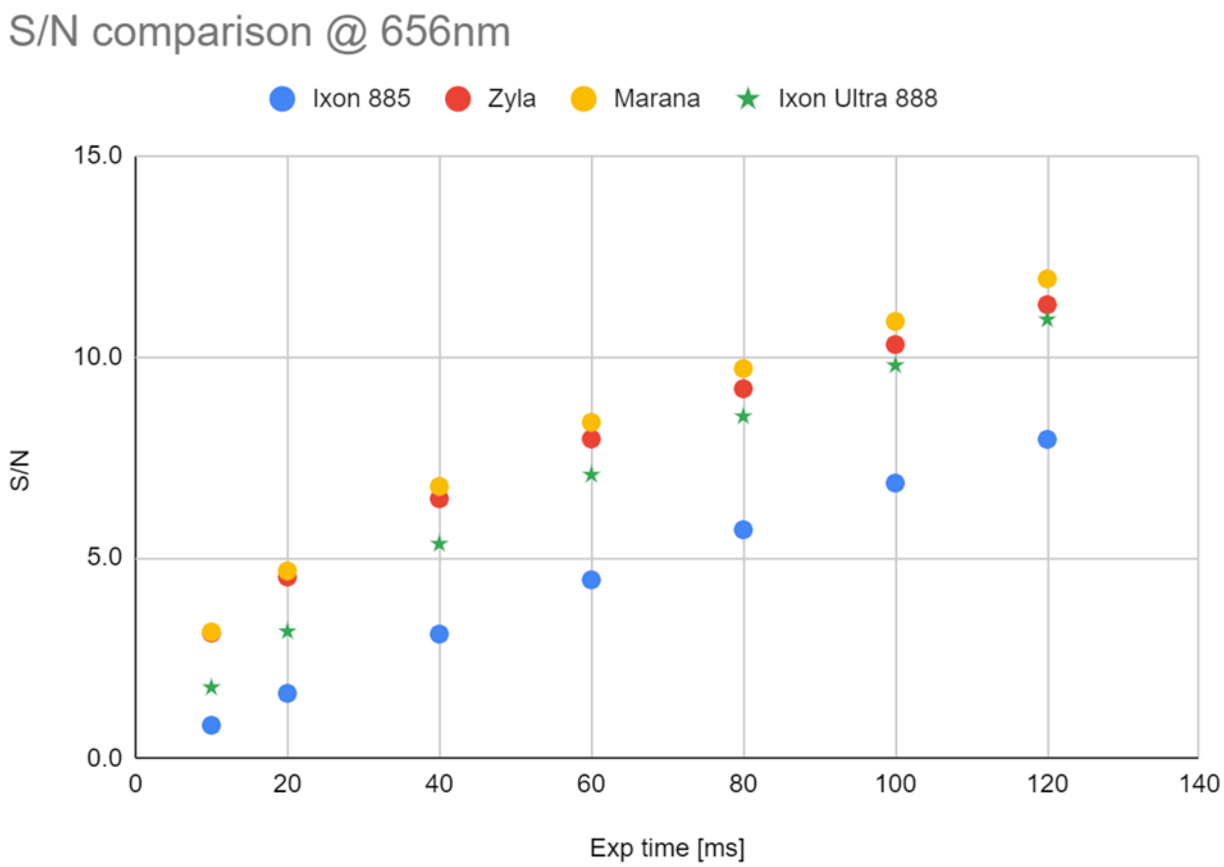

Figure 31: S/N comparison for the various proposed detectors at 656nm with the iXon 888 at the correct IBIS 2.0 sampling.

In Figure 32, we show the Zyla Signal and the S/N on dark and bright regions of the Sun photosphere at Halpha in comparison with the original iXon 885 used in IBIS at DST. The vertical axis is both representing the counts for the Signal and the S/N ratio for this last thanks to its logarithmic scaling.

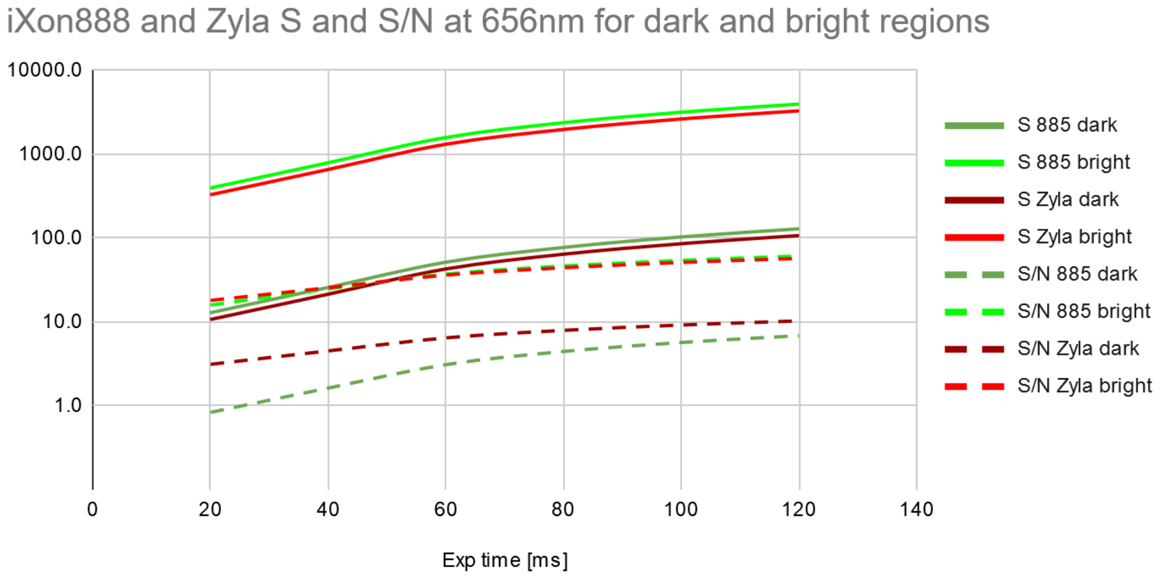

Figure 32: Signal and S/N comparison of bright and dark solar regions for the iXon 888 and Zyla detectors.

3.4 Spectropolarimetry with IBIS 2.0 at VTT

IBIS 2.0 at VTT can be also used to perform solar spectropolarimetry. The IBIS 2.0 polarimeter could be similar to the one used at DST based on LCVRs and employed with the same modulation strategy (6 modulation states). A new design based on Ferro-Electric Liquid Crystals with a new modulation strategy based on 4 states could be realized as well (Keller 2002). It could also be investigated a solution with the same polarimetric strategy of IBIS at DST but without reducing the FoV and imaging two identical FoV of 80"x80" into the same detector, taking advantage of the larger dimension of the detector with respect to the one used at DST. The detailed design of the polarimetric unit will be addressed in the next project phase.

Following the approach of the polarimeter of IBIS at DST, the LVCRs can be placed in the pupil between the two relay lenses (pupil diameter 15mm) and they should be preceded by a suitable blocking filter (UV cut < 450nm) to protect them from UV-damage. The PBS (to be designed) will be still placed between M3 and the science camera: it will split the vertical field stop (40"x80") into two vertical images, both imaged on CCD1 by L4. In the first instance, the same modulation scheme of IBIS at DST will be maintained for IBIS 2.0 at VTT. Assuming that the optical axis of the LCVR2 is set at 0° and that the optical axis of the LCVR1 is set at 45°, the modulation scheme is reported in Table 2:

Modulation state	LCVR 1 retardance [deg]	LCVR 2 retardance [deg]
I+Q	360	360
I+V	360	270
I-Q	360	180
I-V	360	90
I-U	270	90
I+U	90	90

Table 2: Modulation states and LCVR retardances for IBIS 2.0 polarimeter at VTT.

3.4.1 The polarimetric calibration of IBIS 2.0 at VTT

To obtain high polarimetric accuracy during IBIS 2.0 observations, a precise polarimetric calibration must be performed. Polarimetric spurious signals are originated by reflection on the mirror, the inclination angles of the mirrors and the tensions on the vacuum windows, the polarizers, the retarders, etc. We describe here a brief overview on the polarimetric calibration that IBIS 2.0 might have at the VTT following previous works on the polarimetric calibration for instruments at VTT (Beck 2002, Beck et al. 2005a, 2005b).

The effects of the polarimeter are taken into account by the **X**-matrix or the polarimeter response function. The **X**-matrix is a 4x4 matrix which describes how the input Stokes vector and the output Stokes vector are related at the position of the Instrumental Calibration Unit (ICU) provided by the VTT.

The effects of the telescope, such as the mirror reflections and the vacuum windows stresses, are taken into account in the **T**-matrix. The **T**-matrix is a 4x4 matrix which describes the polarimetric behaviour of the optical elements which are placed before the ICU.

These two matrices are Mueller matrices which relates the input Stokes vector coming from the Sun $\mathbf{S}_{\mathbf{in,sun}}$ with the output Stokes vector $\mathbf{S}_{\mathbf{out}}$ which comes from the demodulation procedure:

$$\mathbf{S}_{\mathrm{out}} = \mathbf{X} \cdot \mathbf{T} \cdot \mathbf{S}_{\mathrm{in,sun}}$$

3.4.2 The polarimeter calibration

The **X**-matrix is assumed to be constant for hours, so the polarimeter calibration should be done on a daily basis, usually after the observing run. The ICU is placed between the VTT and KAOS (inside the vacuum tank) and it is made by a linear polarizer and a retarder which can be inserted into the solar beam and they can be rotated at different angles. The ICU is used to generate different known polarization states to retrieve the instrument response function described by the **X**-matrix.

A series of measurements will have to be done with IBIS 2.0 in order to determine the 16 elements of the **X**-matrix. Assuming a non-polarized solar input $(I_0\ 0\ 0\ 0)^T$, the measured Stokes vector during the calibration is given by: $\mathbf{S}_{\mathrm{out}} = \mathbf{X} \cdot \mathbf{M}_{\mathrm{ret}}(\theta_{\mathrm{ret}}) \cdot \mathbf{M}_{\mathrm{pol}}(\theta_{\mathrm{pol}}) \cdot \mathbf{T} \cdot (I_0\ 0\ 0\ 0)^T$, where θ_{ret} and θ_{pol} are respectively the rotation angles of the retarder and of the linear polarizer of ICU, $\mathbf{M}_{\mathbf{ret}}$ and $\mathbf{M}_{\mathbf{pol}}$ are the Mueller matrices for the rotated optical elements. Usually the polarimeter calibration is performed keeping fixed the linear polarizer angle at $\theta_{\mathrm{pol}} = 0°$ (in order to simplify the procedure), and doing an half-rotation of the retarder at 5°-step. Using an analytical or a numerical algorithm, it is possible to extract the **X**-matrix from the precedent formula. For further details, see Beck 2002 and Beck et al. 2005b.

3.4.3 The telescope calibration and the telescope model

The telescope calibration is a procedure able to take into account the instrumental polarimetric signal introduced by the optics before the ICU, which are the two mirrors of the coelostat (C1 and C2), the main entrance window E1, the main spherical mirror M3, the deflection mirror M4 and the exit window E2 (see Figure 33). To evaluate the polarimetric properties of the VTT, a telescope model has been introduced in Beck 2002 and Beck et al. 2005a (see for further information). The telescope polarimetric calibration datasets are adjusted on this specific telescope model. Instead the **X**-matrix, the telescope **T**-matrix varies considerably during the time, day and months due to the movements of the Sun and of the coelostat mirrors. Following the notation of Figure 33, the Mueller matrix **T** of the telescope can be obtained from:

$$\mathbf{S}_{\mathrm{out}} = \mathbf{T} \cdot \mathbf{S}_{\mathrm{in}} = \mathbf{W}_{\mathrm{E2}} \cdot \mathbf{R}(\theta_4) \cdot \mathbf{M}_{\mathrm{M4}} \cdot \mathbf{M}_{\mathrm{M3}} \cdot \mathbf{W}_{\mathrm{E1}} \cdot \mathbf{R}(\theta_3) \cdot \mathbf{M}_{\mathrm{C2}} \cdot \mathbf{R}(\theta_2) \cdot \mathbf{M}_{\mathrm{C1}} \cdot \mathbf{R}(\theta_1) \cdot \mathbf{S}_{\mathrm{in}}$$

where **R** matrices are referred to the rotation of the reference frames between subsequent optical elements, **W** are the Mueller matrices of the vacuum-stressed windows and **M** the Mueller matrices of the mirrors. The **T**-matrix therefore depends on the geometry of the beam (the incidence angles on the mirrors and the rotation angles of the various optical elements), on the material properties (refraction indices and extinction coefficients of the mirrors, effective phase shift and angle of the optical axis of the windows). Using analytical and numerical methods, the **T**-matrix can be extracted from the previous equation. The telescope model can be improved performing instrumental measurements mounting an array of linear polarizer in front of the telescope entrance window or in front of the first coelostat mirror C1. From previous measurements, the VTT telescope (E1, M3, M4 and E2) behaves like an ideal retarder with an effective retardance of 3° at 630nm and an angle for the fast axis between 20° at 8:00 UT and 0° at 20:00 UT. The coelostat, instead, behaves as a variable retarder depending on the time.

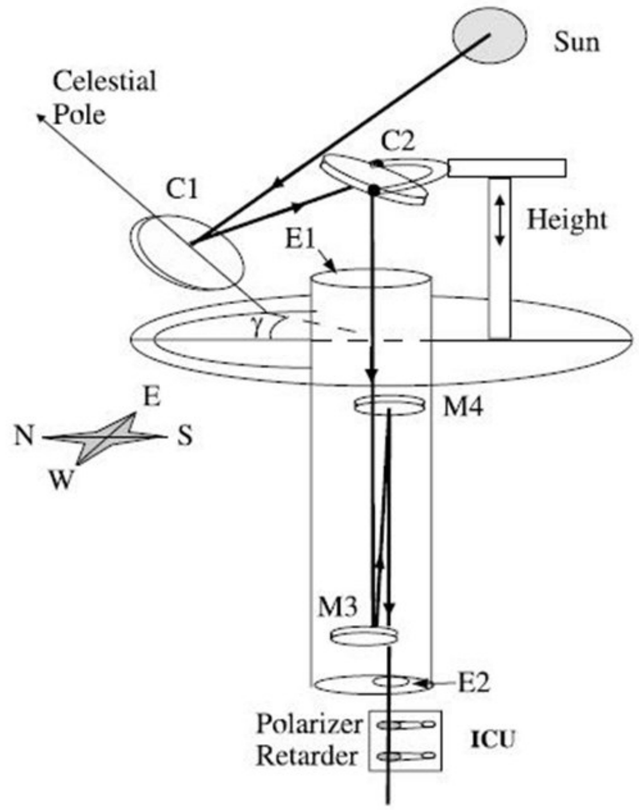

Figure 33: Geometry of the VTT coelostat and telescope vacuum tube.

3.5 Planned instrumental performances

Both the proposed optomechanical designs of IBIS 2.0 at VTT satisfy the instrumental requirements listed in Section 1. Indeed, the conceived IBIS 2.0 will reach high spectral (>200000), spatial (around 0.2") and temporal resolution (of the order of 10 fps). The FoV will be 80" in spectral mode and 40"x80" in polarimetric mode. The wavelength range of 580-860 nm will be the same of IBIS at DST since the coating of the FPs' plates will not be changed. The high spectral stability of IBIS 2.0 is maintained by using the same thermostatic chambers for the two FPs and the FW2 used at DST, allowing to reach a maximum drift of the instrumental profile of 10 m/s over 10 hours. The dimension of the pixels of the detectors will be less than 13.0 μm and the array of the sensor will be at least of 1024x1024 pixel, ensuring the correct spatial sampling of the final focal plane image, which will have a dimension of 6.25 mm and an angular resolution of approximately 0.2". The exposure time will be of the order of tens of ms, which is a reasonable value to freeze the Earth atmospheric seeing having a good S/N in the solar darker regions; the effective exposure time will be evaluated accurately in the final design phase taking into account the total throughput of the instrument at different wavelengths, the number of spectral points in the scan, the modulation strategy and the desired SNR. The final focal plane image of IBIS 2.0 will be diffraction limited since the spots are inside the Airy disk for different wavelengths (see section 3.2). The contrast of the image will be estimated in the final design phase in order to evaluate how the optical aberrations degrade the instrumental PSF, especially for polarimetric measurements.

In Table 3, a summary of the achieved (highlighted in green) and the TBC (highlighted in orange) instrumental requirements is reported.

Requirements	**Status**
High spectral resolution > 200000	200000-270000
High spatial resolution ~ 0.2”	From 0.17” at 580nm to 0.23” at 860nm
High temporal resolution = tens of frames per second	~ 10 fps (TBC in the final design phase)
Large FoV > 60”	80” in spectroscopic mode and 40”x80” or 80”x80” (TBC) in the spectropolarimetric mode
Large spectral range 580-860nm	580-860nm
High wavelength stability ~ 10 m/s over 10 hours	~ 10 m/s over 10 hours
Exposure time of the order of 50ms	Tens of ms (TBC in the final design phase)
At least 800x800 pixel array detector with a pixel dimension to correctly sample the final focal plane image	1024x1024 detector with 13µm pixels or 2048x2048 detector with 6.5µm pixels
Diffraction limited image	Image spots inside the Airy disk over the whole spectral range

Table 3: IBIS 2.0 achieved and TBC instrumental requirements.

4 IBIS 2.0 Instrument Control Electronics at VTT

4.1 Upgrade of IBIS 2.0 ICE for the first optical layout (Level 0)

The purpose for the Instrument Control Electronics (ICE) of IBIS 2.0 for the first optical layout is to leave the instrument as much as possible with manual control. The aim is to make IBIS 2.0 work at the conditions similar to the ones it was working before, at the lowest possible expense. Many of the devices are manually controlled and require about 2 hours to perform all the calibrations (see description of ICE at DST in [RD1]). The design of ICE aims to recover the old configuration, without adding further automations. The control and setup of the instrument is therefore mainly done on site by trained operators, doing manually all the optical alignment for the calibrations and observations procedures. The upgrade of the control system in this case covers only the replacement of the Virtual Engineering Environment (VEE) control software with a more updated and maintainable system (see section 5.8). The changes made to the control electronics hardware, compared to the old design are minimal and are listed hereafter:

- repair CS100
- check FP1
- new General Purpose Interface Bus (GPIB) to Local Area Network (LAN) interface are required for CS100, CCD focus motor and Frequency counter
- polarimeter (LCVR + PBS + corrective lens)
- a gateway device for controllers of Filter Wheels 1 and 2

4.2 Upgrade of IBIS 2.0 ICE for the second optical layout (Level 1 and Level 2)

In the second optical layout case, as said before, the proposed control architectures are the following:

1. **Level 1**, with the automation of some functionalities, which are used often or that require long time to complete during manual calibration operations.
2. **Level 2**, with the automation of almost all the functionalities, with the exclusion of the optical elements that are fixed or moved only for alignment.

The new optical design and the two automation options require the use of a unique control system, reliable, maintainable in the long term and interfaceable with the high level software.

The proposed control system for the IBIS 2.0 in both automation cases for the new optical design is based on Programmable Logic Controller (PLC) Beckhoff, since this is also conformant to the Very Large Telescope (VLT) software baseline.

Beckhoff brand offers many solutions to develop a fully automatic control system. The main CPU can be equipped with Analog and Digital I/O control modules, Analog modules for the PT100 monitor, and many options for the control of low power motors (DC and stepper). With these possibilities all the IBIS 2.0 functions in the Level 1 or Level 2 can be controlled.

Beckhoff PLCs are programmed via TwinCAT Software System and can be equipped with the OPC-UA library though which IBIS 2.0 hardware can communicate with the high level control software, based on VLT Software (VLTSW) (see section 5). Control panels can be added to the design if necessary, to monitor and control some IBIS 2.0 function directly near the device.

Table 4 shows the list of controllable IBIS 2.0 functions and the proposed level of automation where they are implemented. It is shown also which type of electronic/software function they represent. The devices present in the optical scheme but not listed in the table are not considered to be software/hardware controlled but just a fixed element (e.g. lens, window,..).

FUNCTION	AUTOMATION LEVEL	TYPE OF FUNCTION (sensor, motor, ..)
A.O. folding mirror	2 (TBD)	TBD
M3	1, 2	tip/tilt
M7 (lin)	1,2	lin (dig I/O)
M7 (tip/tilt)	2	tip/tilt
M8 (lin)	1, 2	lin (dig I/O)
M8 (tip/tilt)	2	tip/tilt
M9	1,2	lin
FS	1,2	lin or filter wheel
D	1,2	lin
NEUTRAL DENSITY	2	rot (TBC)
BROADBAND FILTER	2	rot (TBC)
ES	1,2	dig I/O
BS2	1,2	Lin
BST	1,2	dig I/O
LASER	1,2	dig I/O
BS3	1,2	lin
CL + LIC + RPS	1,2	dig I/O
FP1 lin	1,2	lin (dig I/O)
FP1 tilt	2	tip/tilt
FP2 lin	1,2	lin (dig I/O)
FP2 tilt	2	tip/tilt
FW2	1,2	rot
CS100 (x2)	1,2	
FW1	1,2	rot
PMT Voltage Supply	1,2	dig I/O

FREQUENCY COUNTER	1,2	
CCD focus	1,2	lin
FP1 TEMP int control	1 (only monitor),2	sens (analog I/O) + dig
FP1 TEMP int monitor	1,2	sens
FP1 TEMP ext	2	sens (analog I/O) + dig
FP2 TEMP int control	1 (only monitor),2	sens (analog I/O) + dig
FP2 TEMP int monitor	1,2	sens
FP2 TEMP ext	2	sens (analog I/O) + dig
FW2 TEMP	2	sens (analog I/O) + dig
LCVR voltage control	1,2	TBD
PBS	1,2	lin or rot (TBD)
LINEAR POLARIZER insertion	1,2	lin
LINEAR POLARIZER rotation	1,2	rot

Table 4: IBIS 2.0 PLC controlled functions in case 1 or 2.

4.2.1 PLC local control unit

The core of the control system is represented by the PLC CPU. The baseline for IBIS 2.0 control system is the Beckhoff CPU of CX2030 series. Table 5 shows the main features of this CPU.

Technical data	CX2030
Processor	Intel® Core™ i7 2610UE 1.5 GHz
Number of cores	2
Flash memory	20 GB or 40 GB CFast flash card (depending on the operating system), optionally extendable
Main memory	2 GB DDR3 RAM (expandable ex factory to 4 GB)
Persistent memory	128 KB NOVRAM integrated
Interfaces	2 x RJ45 10/100/1000 Mbit/s, 1 x DVI-I, 4 x USB 2.0, 1 x optional interface
Cooling	passive cooling, optionally with active cooling ex factory
Diagnostics LED	1 x power, 1 x TC status, 1 x flash access, 2 x bus status
Clock	internal battery-backed clock for time and date (battery exchangeable)
Operating system	Microsoft Windows Embedded Compact 7 (TwinCAT 3 supports only one CPU core), Microsoft Windows Embedded Standard 7 P, Microsoft Windows 10 IoT Enterprise 2016 LTSB
Control software	TwinCAT 2 runtime TwinCAT 3 runtime (XAR)
I/O connection	via power supply module (E-bus or K-bus, automatic recognition)
Power supply	24 V DC (-15 %/+20 %)
Max. power consumption	27 W
Dimensions (W x H x D)	144 mm x 99 mm x 91 mm
Weight	approx. 1165 g
Operating/storage temperature	-25…+60 °C/-40…+85 °C

Table 5: CPU CX2030 main features.

The functions to be controlled, listed in Table 4, are of different types. Hereafter a brief overview of them:

Motorized functions

lin or rot functions on IBIS 2.0 design are existent motorized stages or new motorized stages. In any case the type of motor is a low power stepper motor, which can be controlled by a Stepper Motor terminal (e.g. Beckhoff EL7031), with no encoder and with digital inputs for they limit switches (e.g. Beckhoff EL1084). Figure 34 shows the IBIS 2.0 design with the position of the motorized stages (total automation case).

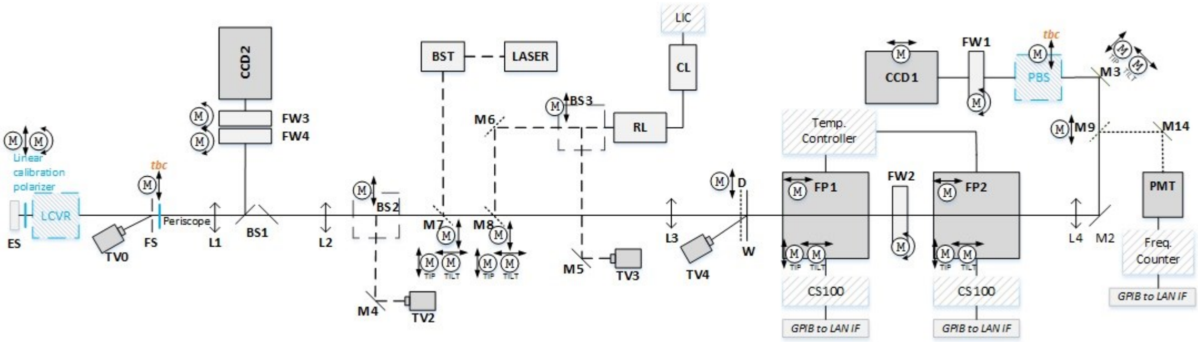

Figure 34: Overview of IBIS 2.0 motorized functions in case of full automation.

Digital I/O functions

Digital I/O functions are required for the switch on/off of the devices, or to drive some stages with just in/out commands (e.g. with Beckhoff EL1084, EL2004 modules).

Analog I/O functions

Analog I/O are required for the control of Continuous Lamp (CL) system (e.g. with Beckhoff EL3062 module).

Temperature sensors

Analog Inputs (e.g. EL3202) are required for the reading of the PT100 temperature sensors.

Figure 35 shows a possible control architecture. The Beckhoff CPU can be equipped with several series of modules. The communication between the PLC modules is via EtherCAT interface. In case of necessity the modules can be decentralized from the CPU thanks to EtherCAT interfaces.

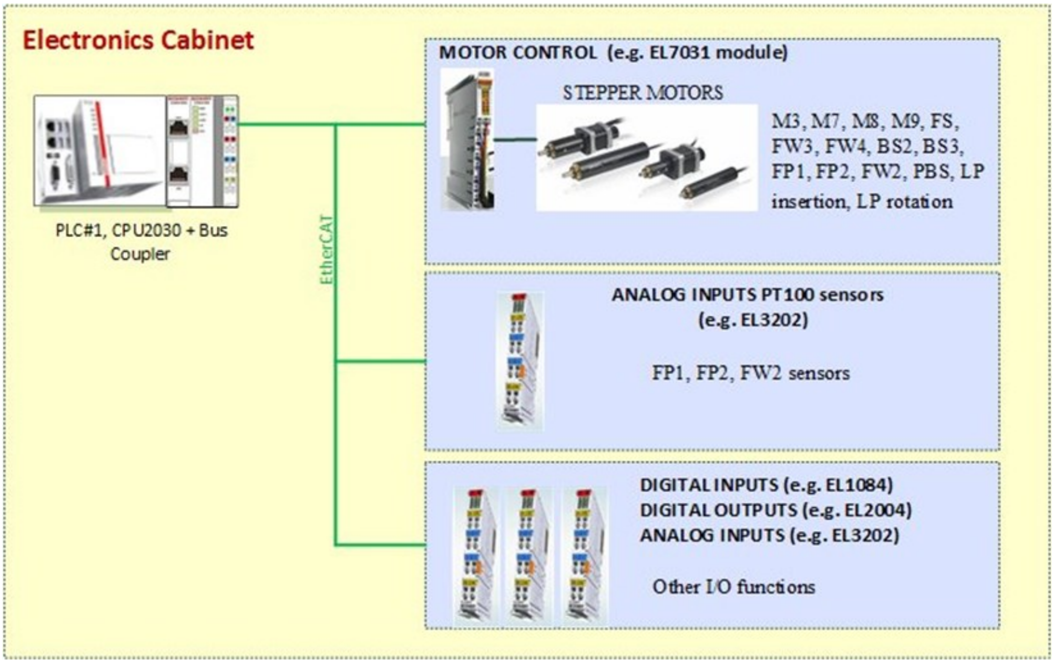

Figure 35: Beckhoff control architecture overview.

Table 6 gives an overview of the number of PLC modules and components required for the control of IBIS 2.0 functions in both partial and total automation cases.

Beckhoff component	Level 1 n.	Level 2 n.
CPU CX2030	1	1
Power supply module CX2100	1	1
Control Panel	1	1
Bus Coupler - EK1100	1	1
EtherCAT Extension -EK1110	1	1
Stepper motor terminal 24 V – EL7031	10	20
Digital Input – EL1084	6	11
Digital Output – EL2004	6	5
Analog Input – EL3062	1	1
Analog Input PT100	4 (TBC)	7 (TBC)

Table 6: Preliminary evaluation of Bekchoff PLC components for the control of IBIS 2.0 in case automation 1 and 2.

The CS100 and the Frequency counter in both automation cases can be controlled directly from the VLTSW through a dedicated GPIB-to-LAN interface and do not require the PLC control.

The PLC CPU can be installed in a dedicated rack, as the one shown in Figure 36. If necessary, the PLC modules can be decentralized and placed in different cabinets that may be placed close to the controlled function. If necessary, fan system can be installed to allow better air circulation inside the racks. All the cabinets can be placed under the optical bench with no need of further space in the room.

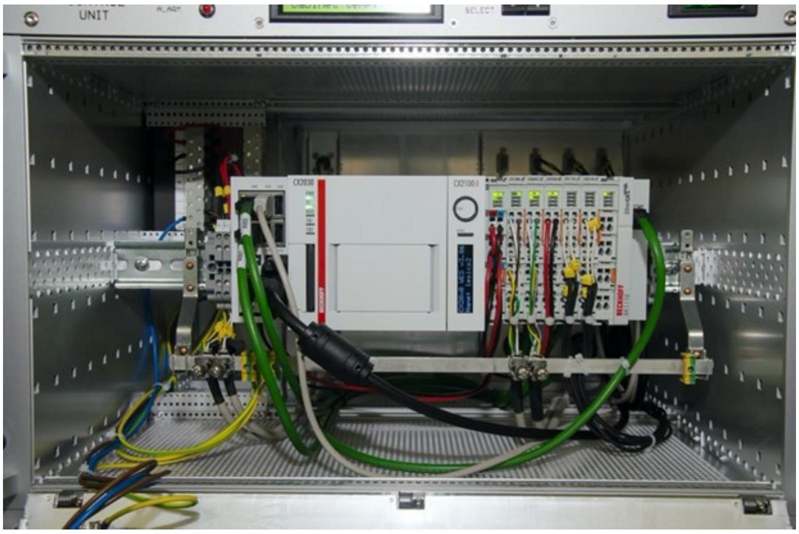

Figure 36: PLC CPU mounted in a rack.

The original power supply system will be completely reworked and be part of the PLC system, since all the devices will be connected to this unit in the proposed design.

4.2.2 Motorized stages and motors

In both proposed automation levels, the majority of the motors currently employed will need to be replaced in order to obtain a better degree of uniformity, improved performance and be completely compliant with the PLC control system. In a few cases of translational movements (FP1, FP2, M7 and M8), they will be upgraded to provide also a feedback to the control system of the position. In all the other cases, the motors and stages will be of the stepper type.

An example of proposed linear actuators from Newport-Mks (model TRA12PPD) and linear stage from Physik Instrumente (model M-413) are shown in Figure 37.

Figure 37: Example of actuator and stage.

4.2.3 Technical cameras

The proposal in both automation levels is to replace the original TV cameras with CCDs or CMOS cameras that offer a digital interface, while still maintaining the Type-C attachment on the optical side allowing a straight replacement.

At Level 1, the ThorLabs DCC1545M with a 1024x1048 sensor and maximum 25fps are proposed. These cameras offer a USB connection and an additional USB hub will be provided for the connection to the Instrument workstation. The purpose of this camera is only to show a real-time image to the operator on the control system monitor, replacing old TV monitors.

At Level 2, the Allied Vision Technologies Manta G-235B with 1936x1216 sensor and maximum 50 fps is proposed. These cameras have a Gig-E compliant Ethernet interface with PoE that allow a connection to the Instrument Workstation through LAN. With better specs and higher frame rate they should be better suited for closed loop control of the functions via image analysis.

4.2.4 Interfaces with the VTT environment

IBIS 2.0 control electronics requires the following interfaces from the VTT/VST environment:

- 230 Vac Single phase normal power supply (about 3 kW), UPS preferred
- LAN connection to the observatory network, access to Internet not mandatory but preferred

5 Control Software of IBIS 2.0

For the control of the instrument, two solutions are presented, according to the different optical layouts.

The control software architecture related to the second (simplified) optical layout will be described first. The choice for this option is to adopt a software framework for the instrument control, namely the VLT Control Software (see [RD2]) developed by the European Southern Observatory (ESO). The VLT Control Software is a distributed system connecting a set of workstations, dedicated to high level operations and, in the latest versions, Programmable Logic Controllers (PLCs), dedicated to the control of sub-systems hardware. The chosen programming language for the workstation applications (running the Linux operating system) is mainly C++, except for the Graphical User Interfaces, as well as High-Level Operations Software (e.g. Broker for Observation Blocks - BOB), which are based on the scripting language Tcl/Tk (Tool command language/Tool kit). The communication between the low level software and the hardware controlled by the PLCs is performed by means of the Open Platforms Communications-Unified Architecture (OPC-UA) communication protocol, an industry accepted and vendor independent architecture.

This choice is also driven by the refurbishment of the instrument control electronics for this simplified layout (see section 4.2), that will replace the control of some instrument function with the latest industry standards (PLCs), automating at the same time some movements that were controlled manually (e.g. manual micrometers) or via manual handsets in the original instrument control operating at DST. For this architecture, two different automation levels are considered, following the two automation levels of the control electronics (see section 4.2), a “partial automation” (Level 1) and a “full automation” (Level 2). The latter automation level, besides the automatic control of a greater number of functions, includes also the automation of the instrument calibration/alignment procedures described in [RD3]) (see section 5.7.1).

The choice of using the VLT Control Software as a software framework for the control of IBIS 2.0 has been driven by the following considerations:

- It is software framework used for the control of astronomical instrumentation (all the instrument currently installed at the ESO VLT are controlled by the VLT software), ranging from the control of the low level functions to the tools to implement in an easy way the Graphical User Interfaces (GUIs).
- Even if the first versions of the VLT Control Software date to the end of the nineties, over the years it has be extended to include the latest technology and industry standards (e.g. Programmable Logic Controllers for the hardware control and use of the OPC-UA communication protocol).
- INAF - OATs has a twenty-year experience in the use of the VLTSW, having developed the control software for several VLT instruments (UVES, FLAMES, X-SHOOTER, ESPRESSO).

The control software architecture related to the second (simplified) optical layout is described from section 5.1 to section 5.7 included.

The control software architecture related to the first optical layout (layout used during the operations at DST adapted to the physical environment of the VTT) will be presented in section 5.8. From the control software point of view, the solution proposed in this case to maintain as much as possible the same functions existing at DST (from a control point of view), replacing only the components that can be no longer maintained (e.g. VEE software).

5.1 IBIS 2.0 control software for the second optical layout (Level 1 and Level 2)

The control software architecture for this optical layout is based on the VLT Control Software.

The IBIS 2.0 Control software proposed architecture follows the standard architecture for the VLTSW based instruments and is divided into the four standard packages:

- **Instrument Control Software (ICS).** It is responsible for the control of all the vital, low-level functionalities of IBIS 2.0 (motors, lamps, sensors).
- **Detector Control Software (DCS).** It takes care of the control of scientific detector systems (scientific detector and white light camera).
- **Observation Software (OS).** It is responsible for the coordination of activities of the DCS and ICS. It also interfaces with the telescope control system (the interface with the telescope control system at the VTT has to be confirmed). It also interfaces with the instrument data flow, in particular with Broker for Observation Block (BOB), which delivers the next observation block to be executed, and the Archive, which saves the results at the end of each observation.
- **Maintenance Software (MS).** It provides tools to maintain the configuration of the instrument and to check the instrument health.

5.2 Control architecture

The IBIS 2.0 control architecture can be defined as composed by the following main blocks:

- **Main optical path**. It is composed by the entrance shutter, LCVR, field stop linear stage, Beam Splitter 2, Fabry-Pérot 1, Filter Wheel 2, Fabry-Pérot 2, M9, M3, Filter Wheel 1 and CCD focus linear stage. The temperature sensors/heaters for the two Fabry-Pérot and the Filter Wheel 2 are included in this path.
- **White light camera path**. It is composed by the Filter Wheels 3 and 4.
- **Calibration path**. It is composed by the Laser, M7, the Continuous Lamp, Beam Splitter 3 and M8.
- **PMT path**. It is composed by the PMT Power Supply and Frequency Counter.
- **Polarization optics**. This block is composed by the linear polarizer linear stage and PBS.

The following detectors are foreseen:

- Scientific detector (CCD 1)
- White Light Camera (CCD 2)
- Technical CCD (TCCD) (x 4)

Figure 38 gives an overview of the IBIS 2.0 control architecture. This description takes into account the “full automation” option. The devices that will not be controlled in the “partial automation” case are highlighted in the last column of Table 7 (“Remarks”).

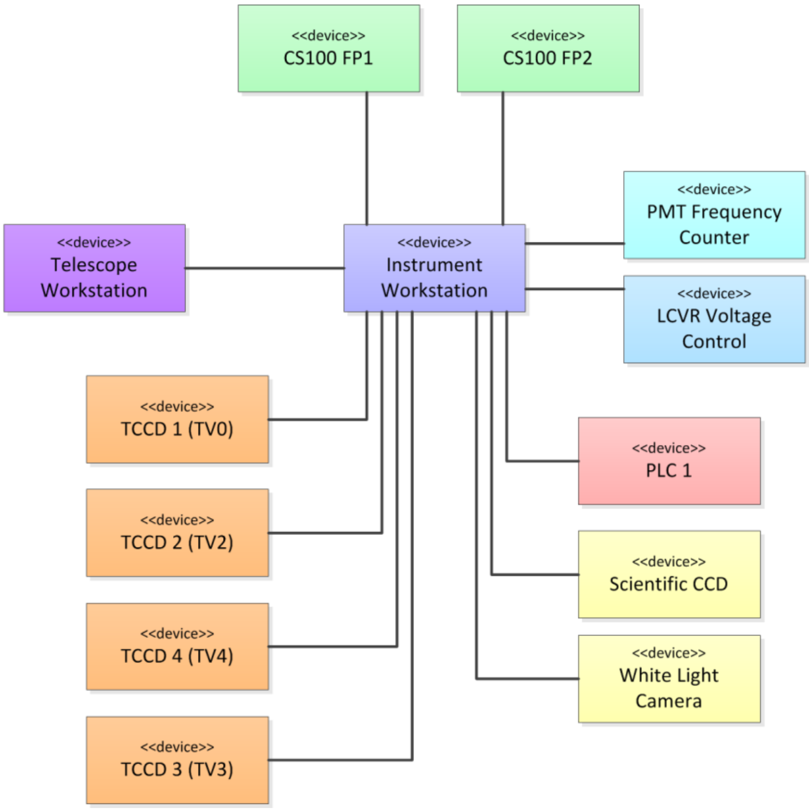

Figure 38: IBIS 2.0 control architecture.

On the Instrument Workstation (IWS) runs the high level control software that controls the instrument devices and detectors. At the VTT the IWS is located in the optical laboratory near the optical bench (TBD).

One PLC (PLC 1), located in an electronic cabinet, controls the following devices: entrance shutter, field stop linear stage, Beam Splitters 2 and 3, CCD focus linear stage, Filter Wheels 1, 2, 3 and 4, the linear and tilt movements of the two Fabry-Pérot, the linear and tilt movements of the mirrors (M7, M8, M9 and M3), the linear stage of the diaphragm placed in front of W, the calibration lamps (Laser and Continuous Lamp), the PMT power supply, the linear stage for the linear polarizer and the linear stage for the PBS. PLC 1 controls also all the temperature sensors and heaters used in the inner and outer shells of the two Fabry-Pérots and in the Filter Wheel 2.

The CS100 controller of the two Fabry-Pérots, the LCVR Voltage Control and the PMT Frequency Counter are controlled directly by the IWS.

The Scientific Detector and the White Light Camera are directly connected to the IWS via an USB 3.0 interface.

The four TCCDs are connected to the IWS either via an USB 3.0 interface or via Ethernet, depending on the camera model proposed for the automation levels 1 and 2 (see section 4.2.3).

It has to be defined if the IWS will be interfaced to the VTT telescope control software (if any).

5.2.1 Instrument LAN

The two CS100 and the PMT Frequency Counter are connected to a switch by means of a GPIB to LAN interface. The PLC1 is connected to the same switch, which connects also the Instrument Workstation. The Scientific Detector and the White Light Camera are directly connected to the IWS through an USB 3.0 interface, as well as the LCVR Voltage Control. Depending on the model proposed for the automation levels 1 and 2, the TCCD are either directly connected to the IWS through an USB 3.0 interface (Level 1) or have an Ethernet connection to the switch (Level 2). The connection to the telescope workstation (if any, or to the device running the telescope control system) has to be verified.

Figure 39 shows the IBIS 2.0 network layout. In Figure 39 the four TCCD are connected to the IWS through an USB 3.0 interface (Level 1).

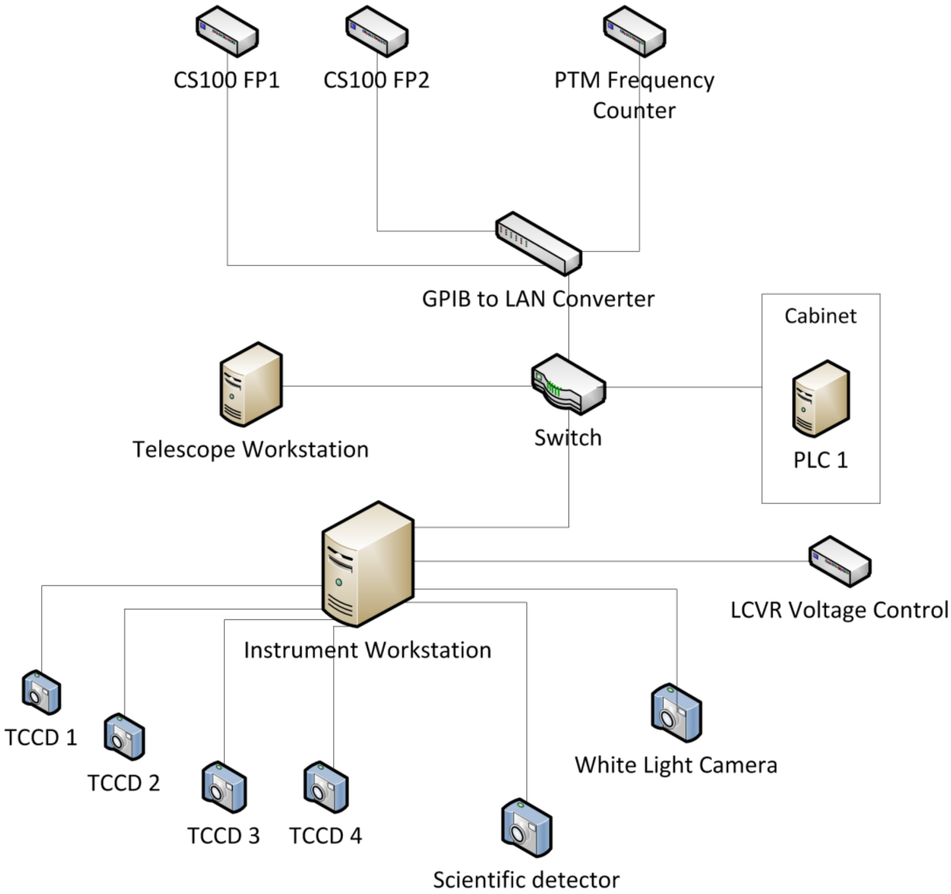

Figure 39: IBIS 2.0 network layout.

5.3 Software architecture

The IBIS 2.0 software architecture is based on the VLT Control Software. In the VLT Instrument Control Software architecture part of the software runs on the IWS and part on the PLCs.

The VLTSW is based on the concept of *environments*, where processes can run and exchange messages with other processes, either in the same environment or in other environments. The messages have the form of *keyword-value* pairs (e.g. INS.LAMP1.ST TRUE for switching on a lamp). To each environment is associated one On-Line Database (OLDB), which contains relevant information for the environment processes. On the IWS runs one *main* environment (*wibis* in Figure 40). It hosts *BOB*, the Broker for Observation Blocks, which is in charge of executing the *instrument templates* forwarding each instruction to be executed to *OS Control* or to the TCCD processes.

OS Control is the process in charge of managing the scientific exposure. It receives commands from BOB and dispatches them to the processes of the different subsystems: *ICS Control* (for the device control part) and the *Super-DCS* (for the scientific detector and white light camera control). The use of a Super-DCS process is under investigation and will be confirmed in the final design. At the end of the scientific exposures, *OS Control* collects the final detector images, merges them with the header information coming from the different instrument subsystems and triggers the *OS Archiver* process which is in charge of the creation of the final FITS file and its archiving.

In the VLTSW architecture, the ICS subsystem controls the low level devices. It consists of one process running in the main environment *wibis* (*ICS Control*), which receives commands from *OS Control*, and a set of other processes running in a second environment (*wibics*). This design is imposed by the IC0/FB architecture used for the low level instrument control (see section 5.4.3). In the *wibics* environment the *IC0/FB Control* process receives commands from *ICS Control* and dispatches them to the *IC0/FB Device Server* processes. These processes encapsulate the software device drivers used for the communication with the real hardware (e.g. devices controlled by the PLC 1, the CS100 FP controllers, the PMT Frequency Counter, etc.).

The *Super-DCS* process (to be confirmed in the next project phase) manages the control and the synchronization of the scientific detector and white light camera. It receives commands from *OS Control* and dispatches them to the actual processes that communicates with the two detectors. A typical command sequence for the detectors is: START the acquisition and WAIT until the acquisition is finished.

In IBIS 2.0, the Technical CCDs are used for the alignment and calibration procedures, and are not involved in the scientific exposure. The corresponding processes running in the main *wibis* environment (TCCD<i> Control, i=1,4) receive commands directly from BOB (during the execution of the calibration/maintenance templates).

The software PLCs libraries include a set of Function Blocks. Function Blocks are software routines that implement the interface with the hardware to control instrument devices and to expose the status information to the device servers running on the IWS through the OPC-UA protocol. In the case of Beckhoff solution (see section 4.2), PLCs are equipped with an embedded OPC-UA server running on the Windows side of the PLC. This OPC-UA server communicates with the hardware through a vendor specific protocol called Automation Device Specification (ADS).

Figure 40 shows the IBIS 2.0 software architecture.

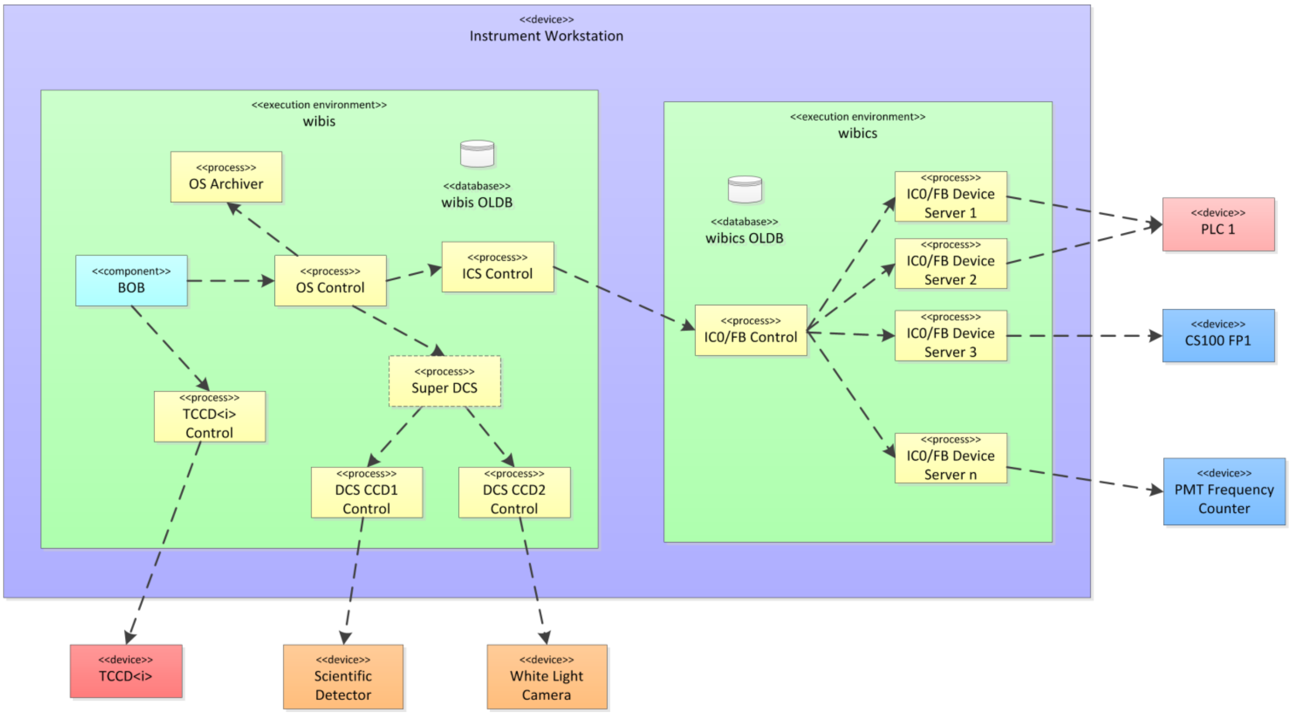

Figure 40: IBIS 2.0 software architecture.

5.3.1 Instrument users

Two users will be dedicated to the instrument on the IWS:

- *ibismgr*: responsible for building and installing the software
- *ibis*: responsible for starting/stopping and running the instrument environments and software

5.4 Instrument Control Software (ICS)

ICS is the low-level software package responsible for controlling all the instrument hardware components (motors, lamps, sensors and other functions). For the control of the instrument devices ICS uses the IC0/FB extension architecture (see [RD4] and [RD5]), a VLTSW standard that allows to interface and control devices connected to different kind of field-buses (see section 5.4.3).

5.4.1 Devices

Table 7 describes the devices seen by the control electronics and related software, i.e. those devices that are to be controlled or sensors whose output is to be monitored. The list of devices refers to the “full automation case”. For the devices that are not controlled by the PLCs in the “partial automation” case a note is added in the last column (“Remarks”).

The IC0/FB extension architecture provides automatically the device drivers for the devices that present a “standard” behavior (e.g. most of the lamps, motors and sensors). If a specific hardware component is not supported by any of the standard VLT device drivers, it is necessary to write a special software device to access this specific instrument hardware (see section 5.4.2).

All the devices controlled the instrument PLC (see section 4.2) are standard. The OPC-UA communication protocol is used for the communication between the device servers (that encapsulate the device drivers) running on the IWS and code running on the PLC that interfaces directly with the real hardware.

In Table 7, the column “FITS keywords” reports the keywords needed by the software to identify the devices for the configuration / setup. Some devices need more than one keyword in order to be controlled (e.g. linear polarizer, Fabry-Pérots, M7, M8, etc.). In order to simplify the interface with the higher level software, ICS provide a special mechanism to handle this case and a detailed description will be provide in the final design. The keywords presented in Table 7 are provisional and will be defined in the next project phase.

#	Device	Type	FITS keywords	Values	Remarks
1	Entrance shutter	SHUT	INS.SHUT1	Open / Closed	
2	Calibration linear polarizer linear stage	LIN	INS.POS1	In / Out	
3	Calibration linear polarizer rotational stage	ROT	INS.POS2		
4	LCVR Voltage Control		INS.LCVR		Special device
5	FS linear stage	LIN	INS.POS3	POS1 / POS2	
6	ND filter wheel (FW 3)	ROT	INS.FILT1	TBD	Not controlled in Level 1
7	Broadband filter wheel (FW 4)	ROT	INS.FILT2	TBD	Not controlled in Level 1
8	Beam splitter 2 linear stage	LIN	INS.POS4	In / Out	

9	M7 linear stage	LIN	INS.POS5	In / Out	
10	M7 tilt X	LIN	INS.POS6		Setup value in mrad. Not controlled in Level 1
11	M7 tilt Y	LIN	INS.POS7		Setup value in mrad. Not controlled in Level 1
12	M8 linear stage	LIN	INS.POS8	In / Out	
13	M8 tilt X	LIN	INS.POS9		Setup value in mrad. Not controlled in Level 1
14	M8 tilt Y	LIN	INS.POS10		Setup value in mrad. Not controlled in Level 1
15	Diaphragm linear stage	LIN	INS.POS11	1 or 2 positions (TBD)	
16	Fabry-Pérot 1 linear stage	LIN	INS.POS12	In / Out	
17	Fabry-Pérot 1 tilt X	LIN	INS.POS13		Setup value in mrad. Not controlled in Level 1
18	Fabry-Pérot 1 tilt Y	LIN	INS.POS14		Setup value in mrad. Not controlled in Level 1
19	Fabry-Pérot 1 – CS100 interface		TBD		Special device.
20	Filter wheel (FW2)	ROT	INS.FILT3	8 positions	
21	Fabry-Pérot 2 linear stage	LIN	INS.POS15	In / out	
22	Fabry-Pérot 2 tilt X	LIN	INS.POS16		Setup value in mrad. Not controlled in Level 1
23	Fabry-Pérot 2 tilt Y	LIN	INS.POS17		Setup value in mrad. Not controlled in Level 1
24	Fabry-Pérot 2 – CS100 interface		TBD		Special device.
25	M9 linear stage	LIN	INS.POS18		

26	M3 tilt X	LIN	INS.POS19		Setup value in mrad
27	M3 tilt Y	LIN	INS.POS20		Setup value in mrad
28	PBS linear stage	LIN	INS.POS21	In / Out	Maybe a filter wheel can be used.
29	Filter wheel (FW1)	ROT	INS.FILT4	6 positions	
30	CCD1 focus	LIN	INS.POS22		
31	BST linear stage		TBD	On / Off	
32	Laser	LAMP	INS.LAMP1	On / Off	
33	BS3 linear stage	LIN	INS.POS23	In / Out	
34	Continuous lamp	LAMP	INS.LAMP2	On / Off	
35	PMT voltage supply		INS.LAMP3 (?)	On / Off	
36	PMT frequency counter	SEN	INS.SENSOR1		
37	FP1 internal temperature control - monitoring	SEN	INS.SENSOR2		
38	FP1 internal temperature control - heater		TBD		Not controlled in Level 1
39	FP1 internal temperature monitor	SEN	INS.SENSOR3		
40	FP1 external temperature control - monitor	SEN	INS.SENSOR4		Not controlled in Level 1
41	FP1 external temperature control - heater				Not controlled in Level 1
42	FP2 internal temperature control - monitoring	SEN	INS.SENSOR5		
43	FP2 internal temperature control - heater		TBD		Not controlled in Level 1
44	FP2 internal temperature monitor	SEN	INS.SENSOR6		
45	FP2 external temperature control - monitor	SEN	INS.SENSOR7		Not controlled in Level 1
46	FP2 external temperature control - heater		TBD		Not controlled in Level 1
47	Filter wheel 2 (FW2) temperature control –	SEN	INS.SENSOR8		Not controlled in Level 1

	monitor				
48	Filter wheel 2 (FW2) temperature control – heater		TBD		Not controlled in Level 1

Table 7: IBIS 2.0 ICS devices.

5.4.1.1 PLC Libraries

For the communication between the IWS IC0/FB processes and the actual devices that are controlled by the Beckhoff PLCs, the OPC-UA communication protocol will be used. ESO VLTSW PLC libraries include a set of Function Blocks (FBs) that implement the interface with the hardware to control instrument devices and to expose the status information to the IC0/FB Device Drivers through the OPC-UA protocol.

5.4.2 Special devices

The IC0/FB extension architecture provides the device drivers for the devices that present a “standard” behavior. Some IBIS devices are “not-standard” and for them it is necessary to provide a dedicated implementation. The IC0/FB architectures provides the basic framework to implement these special devices. The IBIS 2.0 devices that need a special implementation are:

- LCVR voltage control
- FP1 CS 100 interface
- FP2 CS 100 interface
- PMT voltage control

A detailed design of these special devices will be given in the next project phase.

5.4.3 ICS architecture

In the IC0/FB architecture all the ICS software runs on the IWS (see Figure 41). The *ICS Control* process, running in the *wibis* main environment, acts as a front-end for all incoming commands, both from higher level software (e.g. the *OS Control* process) or directly from the ICS stand-alone GUI panel (see section 5.4.11). *ICS Control* communicates with the *IC0/FB Control* process running in the *wibics* environment. This last process exchange messages with the *IC0/FB Device Server* processes that encapsulates the devices drivers for the controlled devices and are responsible for the interface with the instrument hardware. The *IC0/FB Device Servers* communicates either with the real hardware (PLC1, CS100 FP controllers, etc.) or with the *IC0/FB Device Simulators*, that allows to run the devices in simulation.

For the communication between the *IC0/FB Device Servers* running on the IWS and PLC, the OPC- UA communication protocol is used.

ICS provides also an engineering GUI (see section 5.4.11).

Figure 41 shows the IBIS 2.0 ICS architecture, which reflects the standard IC0/FB one.

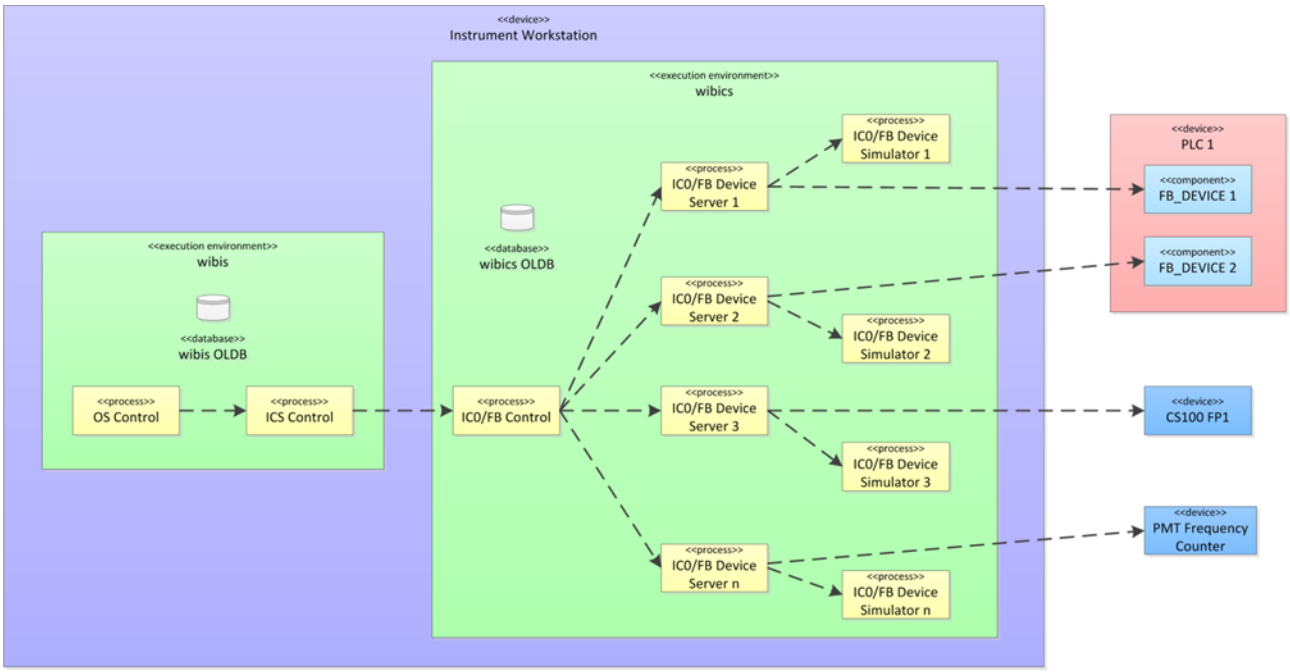

Figure 41: IBIS 2.0 ICS architecture.

5.4.4 Protocols

The communication between the IBIS 2.0 IWS and the controlled devices is performed through the following protocols:

- TCP/IP Ethernet connection for the four TCCDs (Level 2), two CS100 FP controllers and the PMT Frequency Counter.
- OPC-UA for the Beckhoff PLC hardware.
- USB 3.0 for the four TCCDs (Level 1) the Scientific Detector, White Light Camera, the four TCCDs and the LCVR voltage control.

Figure 42 summarizes the protocols that the IBIS 2.0 Control Software has to manage.

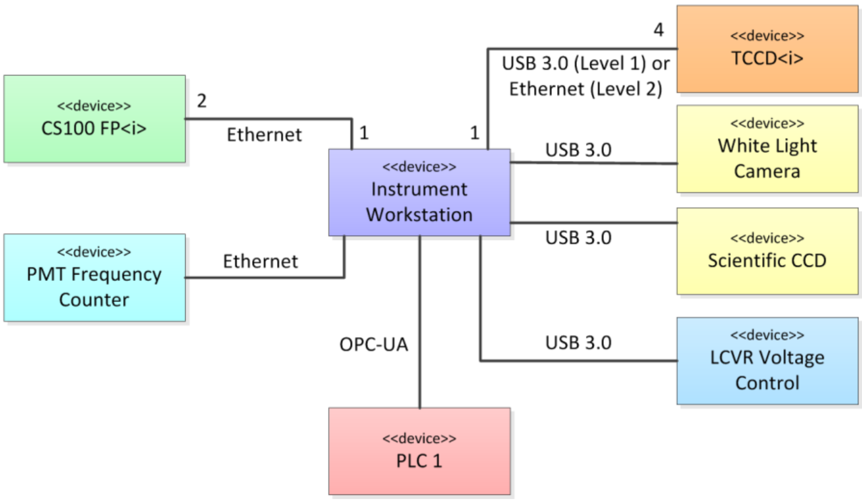

Figure 42: Protocols managed by the IBIS 2.0 Control Software.

5.4.5 States

The VLTSW architecture implements a well defined state machine.

Each device controlled by ICS can be in one of the following states:

- **OFF**: The corresponding device server is not running. The device is powered off.

- **LOADED**: The device server is running and ready to receive commands. The device is not initialized.
- **STANDBY**: Typically, in this state the motors are powered off, lamps are switched off, shutters are closed and the sensors are periodically monitored.
- **ONLINE**: The device is initialized. In this state it is possible to perform action commands on the device, such as SETUP.

5.4.6 Configuration

In the VLTSW architecture, all the ICS configuration parameters are stored in dedicated configuration files.

5.4.7 FITS header keywords

After the exposure, ICS provides its FITS header part to OS, which is in charge of merging them.

5.4.8 Logging and errors

The logging and error services are automatically provided by standard VLTSW packages.

5.4.9 Alarms and warnings

Alarm and warnings will be implemented using the standard VLT CCS Alarm System.

Monitoring of alarm conditions will be active also when the instrument will be in the STANDBY state. Warnings will be clearly displayed on the OS Control GUI (see section 5.6.4) and also on the standard alarm tool common to all VLT applications.

Alarms and warning shall be clearly shown to the user/operator by means of the OS status GUI (see section 5.6.4).

5.4.10 Simulation

When simulation is required, the IC0/FB Device Servers communicate with the IC0/FB simulator processes (see Figure 41). Simulators are provided by the IC0/FB extension architecture for the standard devices. For the special devices, dedicated simulator that mimic the desired behavior have to be implemented.

5.4.11 GUIs

ICS provides the mean to create a GUI for stand-alone engineering operations in an almost-automated way. As an example, an ICS engineering GUI for the ESPRESSO instrument is shown in Figure 43 (see [RD6]).

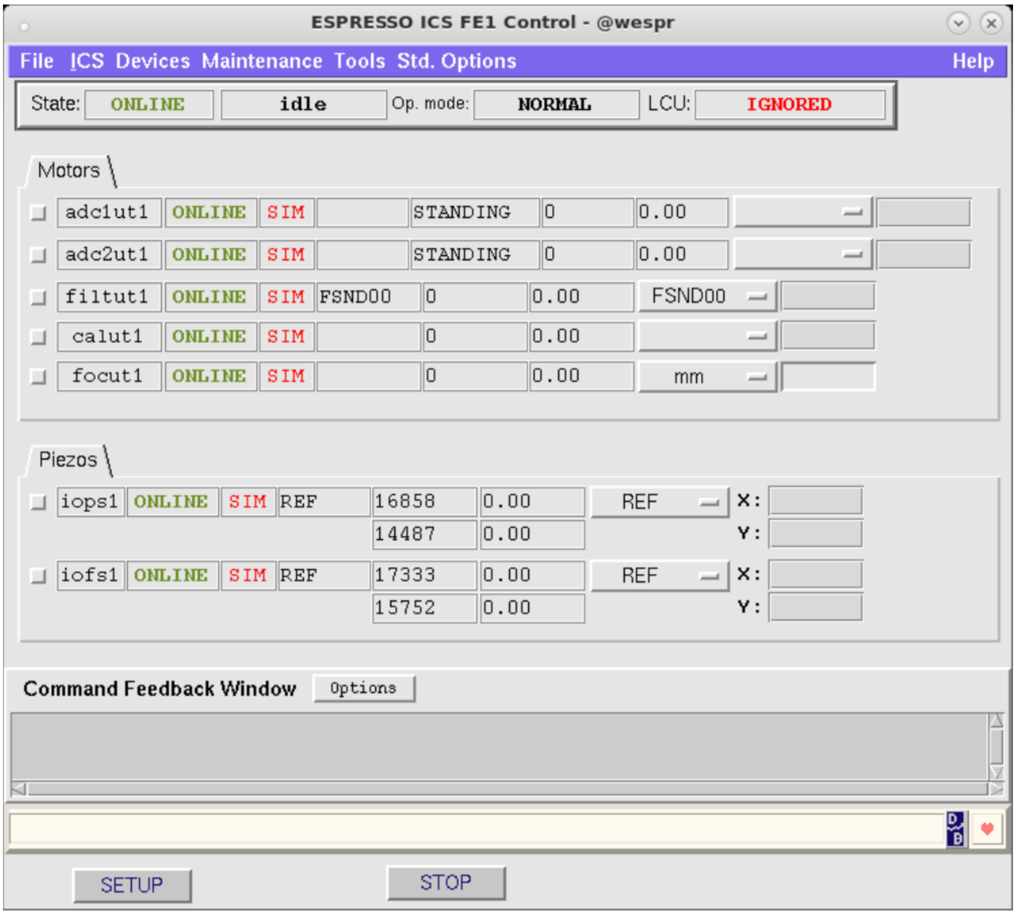

Figure 43: ICS engineering panel (taken from ESPRESSO, see [RD6]).

For IBIS 2.0, a dedicated ICS engineering GUI will be implemented in the next project phases.

5.5 Detector Control Software (DCS)

The operations of the IBIS 2.0 scientific detector (CCD1) and white light camera (CCD2) have to be synchronized during the scientific exposure. For each detector, a dedicated DCS control process will run on the IWS for managing its operations. The use of a Super-DCS process for the coordination of the operations of the two DCS processes is under investigation and will be confirmed in the next phase. As an alternative, the coordination of the two DCS processes will be managed by *OS Control*.

5.5.1 Data

The final FITS file format and keywords will be conform to the specifications expected by the existing IBIS 2.0 Data Reduction Software and will be detailed in the next project phases.

5.5.2 Stand-alone mode

Dedicated GUIs will be provided in order to operate the Scientific Detector and the White Light Camera in stand-alone mode. They will provide all the needed functionalities.

5.5.3 Configuration

The configuration of the Scientific Detector and the White Light Camera will be stored in dedicated configuration files.

5.6 Observation Software (OS)

The Observation Software (OS) is the highest layer of the control software and will run on the IWS.

5.6.1 OS architecture

The IBIS 2.0 OS consists of:

- An *OS Control* process, responsible for the execution of single exposures.
- An *OS Archiver* process, responsible for archiving the results of exposures in FITS files.
- Templates, defining and running sequences of exposures. Generally, the OS includes also the calibration and observation templates.

The OS processes (Server and Archiver) will be based on the standard VLT package *boss*.

Templates will be based on the standard VLT package *tpl*. The calibration and observation templates will define the sequence of commands to be executed by the Broker for Observation Blocks (BOB) and, according to the VLT standards, will be implemented in Tcl/Tk.

5.6.2 States

The OS states will be the VLT standard OFF, LOADED, STANDBY, ONLINE states (see section 5.4.5).

5.6.3 Instrument modes

The VLTSW embeds the concept of "instrument modes" for its operations. To each instrument mode correspond a list of involved instrument subsystems involved (e.g OS, ICS, TCCDs, etc.).

For IBIS 2.0 two instrument modes are foreseen, one for spectroscopic observations and one for polarimetric observations.

All the instrument mode configurations parameters will be stored in dedicated configuration files.

The IBIS 2.0 instrument modes will be detailed in the final design phase.

5.6.4 GUIs

The OS GUIs will be implemented using the standard *VLT panelEditor* tool.

For IBIS 2.0, two OS GUIs are foreseen:

- **OS Control GUI**. This panel will provide a general overview of the instrument operations, giving information on the instrument state, mode, exposure status of the detectors, device status and a summary of instrument warnings (see Figure 44).
- **OS Status GUI**. This panel will provide information on the position of all active devices, sensors values and alarms and warnings conditions (see Figure 45).

As an example, Figure 44 shows the OS control panel of the ESPRESSO instrument (see [RD6]).

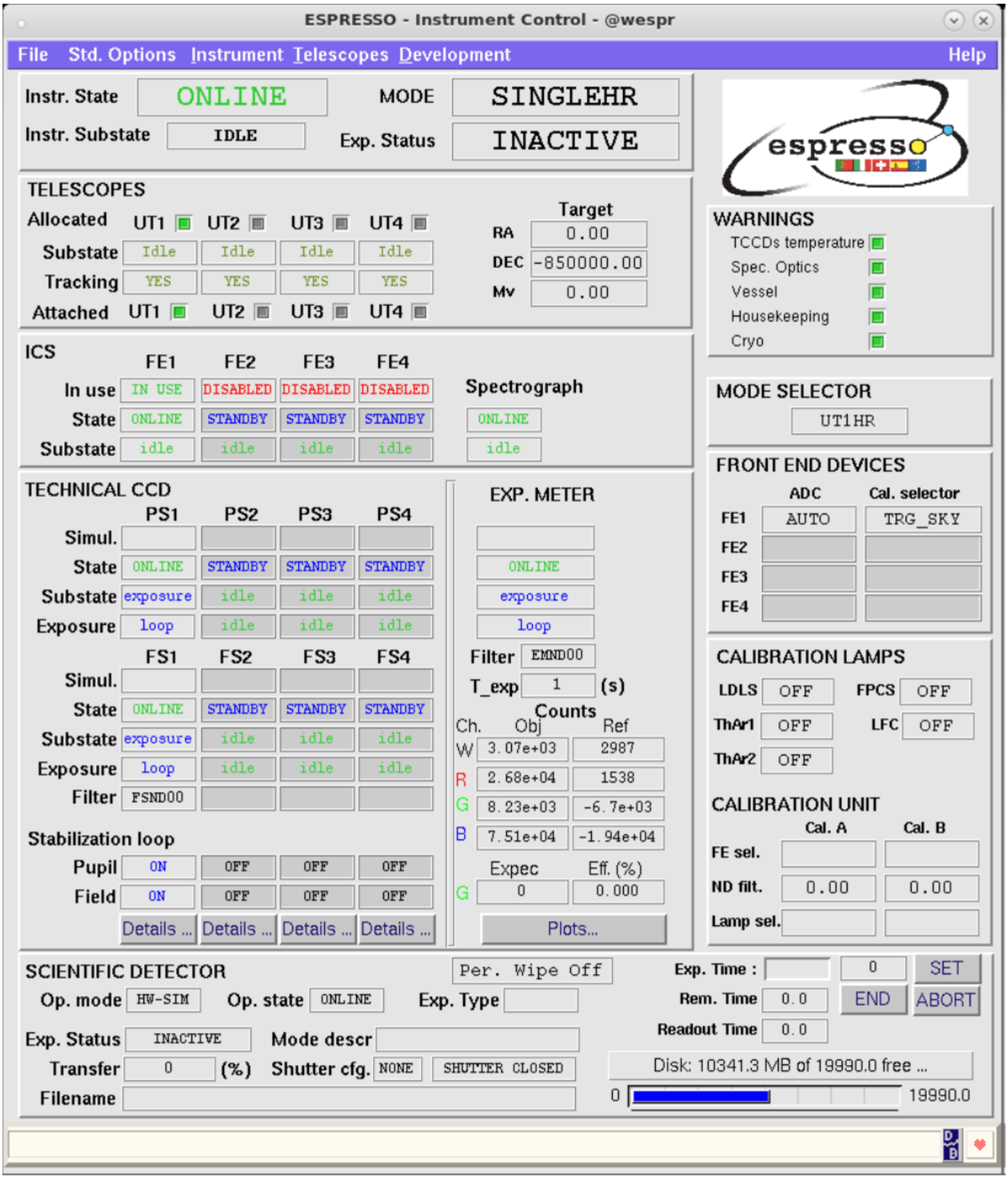

Figure 44: OS Control panel (taken from [RD6]).

Figure 45 shows the OS Status Panel for the ESPRESSO instrument (see [RD6]).

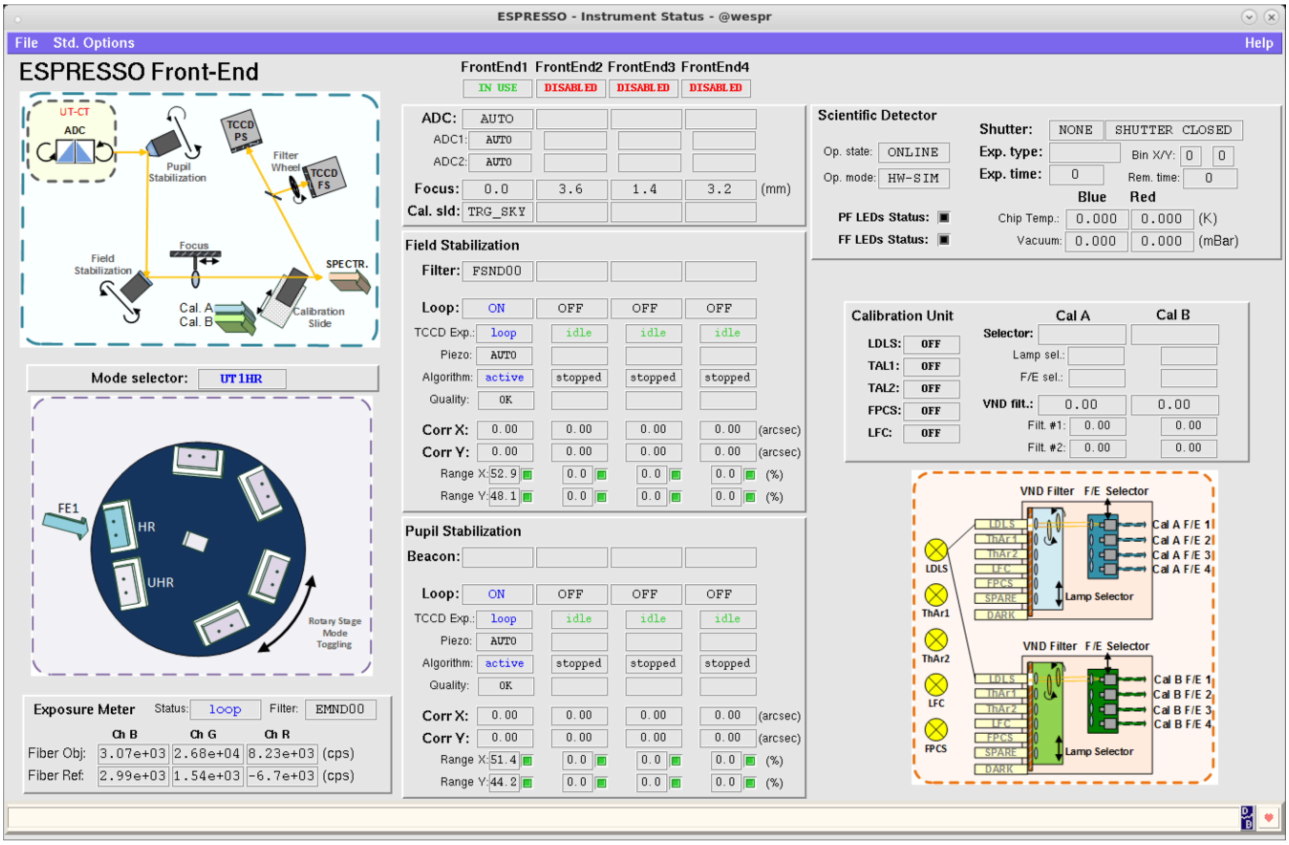

Figure 45: OS Status panel (taken from [RD6]).

5.6.5 Templates

Templates will be based on the standard VLT package *tpl* (see [RD7]). The calibration and observation templates will define the sequence of commands to be executed by the Broker for Observation Blocks (BOB) and, according to the VLT standards, will be implemented in Tcl/Tk.

The logic of the VEE code running at the DST will be re-implemented in the calibration and observation templates. The IDL routines called by the VEE code can be also called by the template code.

The complete list of the observing and calibration templates will be provided in the next project phase.

5.7 Technical CCDs

The second (simplified) optical layout foresees four technical cameras (TV0, TV2, TV3 and TV4 in Figure 27). They are interfaced to the IWS through an USB 3.0 interface.

From a control software point of view, a dedicated package is provided by the VLTSW for the control of COTS technical cameras, the Technical Detector Control Software (TDCS). This package provides the architectural framework for developing technical camera applications. In the TDCS application, two “communication adapters” allows the communication both with a real camera and a simulator. The TDCS SKD provides a base class for these communication adapters. This feature makes it possible to adapt the TDCS to be deployed with new types of cameras, without changing the core business logic.

For IBIS 2.0 it will be necessary to implement a new “communication adapter” for the operating the technical cameras that wraps the TCCD device driver and to implement a simulator.

5.7.1 Automatic calibration/alignment procedures

In the "full automation" case, it is possible to exploit a dedicated TDCS feature to implement the logic for the calibration/alignment procedures that has to be performed analyzing the images produced on the technical cameras. In this regard the TDCS framework provides image processing plug-ins, that allows to extend TDCS with new processing capabilities, without modifying the core of the system. Dedicated algorithms that analyze the TCCD images can be implemented (the VLT Common Library for Image Processing, CLIP, can be used for this purpose, see [RD8]) and the calculated corrections sent to the devices involved in the calibration/alignment procedures.

A general sequence can be the following (the operations can be implemented in dedicated templates):

1. Setup the instrument to send the light beam (calibration light or solar beam, according to the selected procedure) to the proper TCCD.
2. Start the TCCD acquisition (set an appropriate exposure time).
3. For each acquired image:
   a. The proper TDCS algorithm analyzes the image and calculates the offset/correction for the device to be controlled (e.g. mirror tilts/FP tilt).
   b. The offsets are sent to the device.
4. The loop a.-b. is repeated until the alignment condition (to be defined) is satisfied.

Some procedures require that the image is acquired on the Scientific Detector (e.g. the procedures that involved the use of TV1 in the DST opto-mechanical layout) instead of a TCCD. Also these procedures can be implemented in dedicated templates. The involved devices and the Scientific Detector can be coordinated by OS and the algorithms needed to perform the image analysis can be implemented at template level.

5.8 IBIS 2.0 control software for the first optical layout (Level 0)

For a control software point of view, for this layout the proposal is to upgrade only the control of the functions formerly controlled with the VEE software, namely the CS100 controllers of the two Fabry-Pérots, Filter Wheel 1, Filter Wheel 2, the CCD focus, the LCVR (TBC) and the detectors. All the other functions are not upgraded, and remain either manually controlled (micrometers and manual component insertions) or controlled via handsets or manual switches.

5.8.1 Control architecture

For the control of the devices formerly controlled by the VEE software three options are proposed:

1. VLT Control Software. This case is covered in the sections 5.1-5.7. In this scenario, the VLT Software runs on the Instrument Workstation and IC0/FB Special Devices need to be implemented for the control of the devices (see section 5.4.2). The calibration and observation procedures are implemented as calibration and observation templates (see section 5.6.5).

2. LabVIEW. Using LabVIEW offers the possibility for a smooth transition, since the programming paradigm is very similar to VEE. The LabVIEW environment offers a simplified control for the devices, since many of them have a specific LabVIEW driver available that encapsulates the low level communication protocol. As in the original implementation, some calibration task may still be made with IDL, called by LabVIEW. As in the other cases, the software runs on the Instrument Workstation and has direct access to the devices.

3. A scripting language (e.g. Python) is used for the implementation of the software procedures formerly implemented in VEE. The device drivers for the communication with the hardware are implemented in dedicated classes/routines (depending on the choice of the scripting language). The code runs on the Instrument Workstation.

The control architecture is shown in Figure 46.

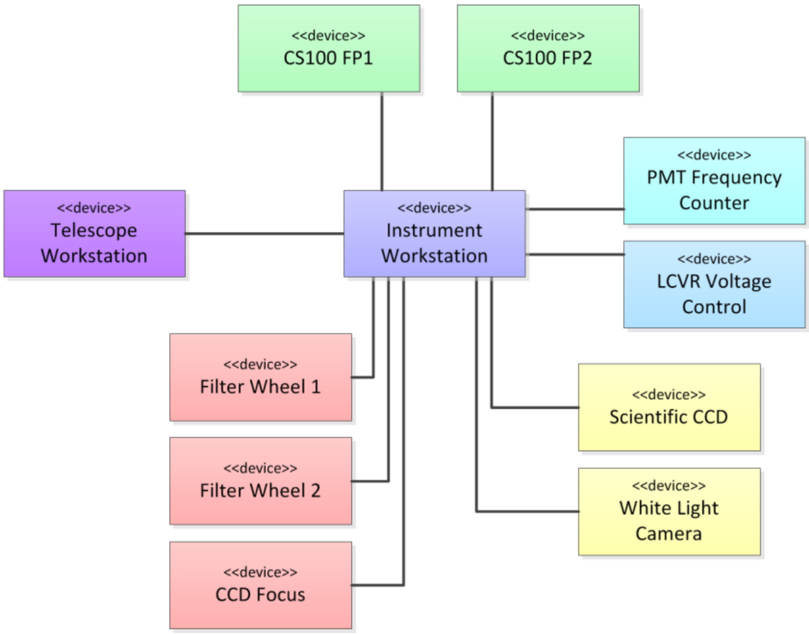

Figure 46: IBIS 2.0 control architecture for the instrument opto-mechanical layout used at DST.

Figure 47 shows the IBIS 2.0 network architecture foreseen for this scenario.

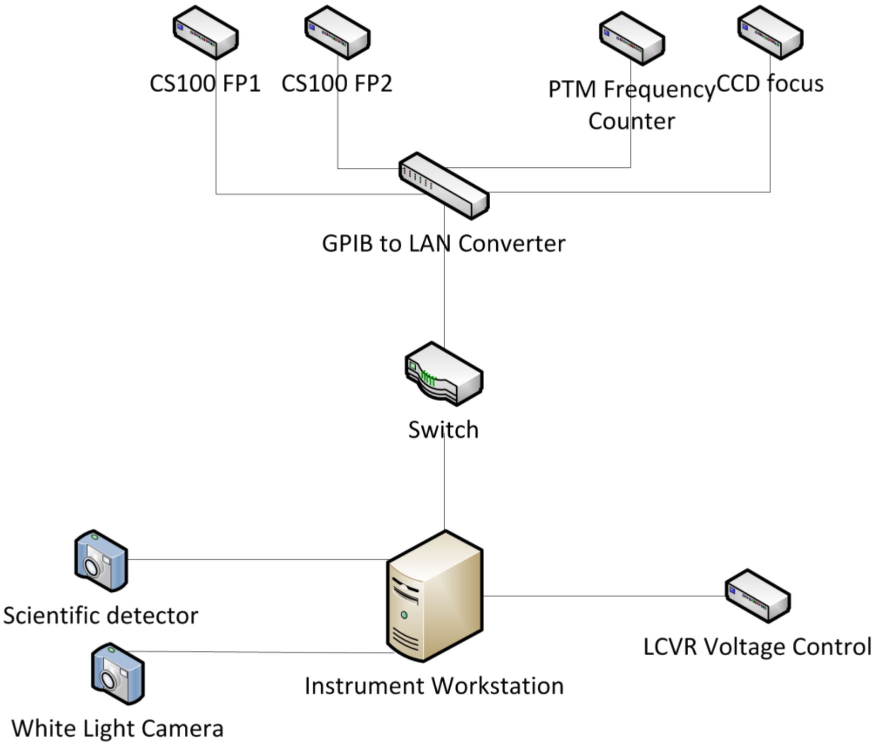

Figure 47: IBIS 2.0 network architecture for the instrument opto-mechanical layout used at DST.

6 Science Software

In this section we present a brief overview of the software reduction package, developed by A.Tritschler and S. Criscuoli (see [RD9]), which allows the user to calibrate the data obtained with the IBIS instrument at DST. The instrument can be operated in two different operational modes: spectroscopic and spectropolarimetric mode. In the instrument configuration operating at DST, switching between the two modes required manual intervention, so observing campaigns were performed in either spectroscopic or spectropolarimetric mode.
The user was allowed to specify explicitly, in the wavelength definition file, what spectral lines had to be modulated or not. All reduction steps were implemented sequentially and could be executed independently. There were only a few places where the software would pause and halt the execution as input from the user was required to proceed.
Since IBIS 2.0 will be implemented at VTT at first with the same operating mode used at DST, with minor changes to the optical scheme, no substantial changes to the reduction software are planned at this phase of the project. For the next phases we plan to make the reduction software more user friendly by interfacing it with a GUI and minimizing the user interactivity required during the data calibration.

6.1 IBIS science data structure

Science data obtained with IBIS, as well as all data necessary for the calibration and information about the observations, are stored in folders whose structure is shown in Figure 48. The data and the log files are stored in sub-directories whose name corresponds to the start of the acquisition of each dataset. The format name is YYYYMMDD_hhmmss, where "YYYY" is the year, "MM" the month, "DD" the day, "hh" the hour, "mm" the minutes and "ss" the seconds. For the NB channel the data are stored in a folder named 'Ibis' and for the BB channel in a folder named 'Whitelight'.

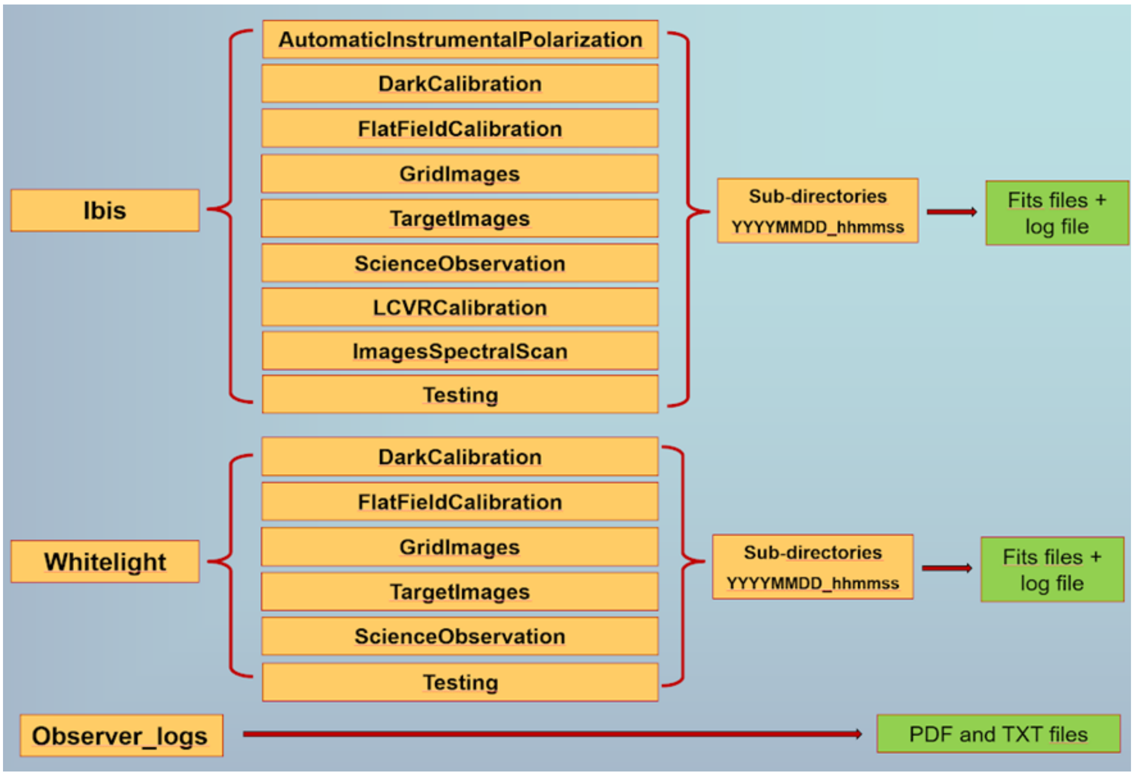

Figure 48: Folder structure of the science data obtained with IBIS.

6.2 Folders description

In this section we give a brief description of the folders used to store the IBIS data, as shown in Figure 48.

Observer_logs: contains information about the daily calibration of IBIS (the linearity of the CCD, the setting of the LCVR Voltage, and the spectral tuning) and a file containing handwritten notes by the observers, as the seeing level, the cloud coverage and some preliminary estimate of the quality of the acquired data. The log also contains the times of acquisition of the calibration and of the scientific data, as well as of the solar targets of the observations.

AutomaticInstrumentalPolarization: stores the data necessary for the spectropolarimetric calibration.

DarkCalibration: stores dark calibrations.

FlatFieldCalibration: stores gain calibrations.

GridImages: stores target calibrations (i.e. line grid and the dot targets). Note that the data reduction software makes use only of the line grid data.

ImagesSpectralScan: stores data acquired during the spectral calibration of the FPs.

LCVRCalibration (spectropolarimetric data only): stores data acquired during the calibration of the LCVRs. These data are not employed by the data reduction software.

ScienceObservation: stores the scientific IBIS data.

TargetImages: stores images acquired with the Air Force resolution chart. These data are not employed by the data reduction software.

Testing: stores test data acquired at the same wavelength positions as the observations, for checking exposure times, cadence, etc. These data are not employed by the data reduction software.

The content of each folder is the following:

log_YYYYMMDD_hhmmss.txt: ascii file for each acquired image that stores the acquisition time, the Voltages sent to the FPI1 and FPI2, the relative wavelength position (with respect to the line center as defined during instrument's tuning), the exposure time, the type of Stokes parameter, the central wavelength of the prefilter and its position within the filter wheel. It also stores more general information as the total number of sequence repetitions attempted, the start and end times of each sequence, and the type of observation. Note that some information stored in this file is needed as input to the reduction software (mostly the position of the prefilter in the pre-filter wheel).

lcvr_YYYYMMDD_hhmmss.txt: ascii file (spectropolarimetric data only). This file contains information about the temperature of the two LCVR at the beginning and end of each scan, the time of acquisition of each frame and the Voltages sent to LCVR1 and LCVR2. This information is not used by the data reduction software.

sXXX.TypeOfObservation.fits: extended FITS files storing the data acquired by IBIS. Each file corresponds to a single sequence, i.e. one iteration of all prefilters and wavelengths. General information about the data that is common to all prefilters is stored in the main FITS header while all information that is particular to a single image (acquisition time, wavelength position, exposure time, telescope pointing, polarization state, etc) is stored in the individual extension FITS headers.

Figure 49 shows the standard structure of a scan acquired for three different spectral lines: two in spectropolarimetric mode (Fe I 6302 Å, Fe I 6173 Å) and one in spectroscopic mode (Ca II 8542 Å).

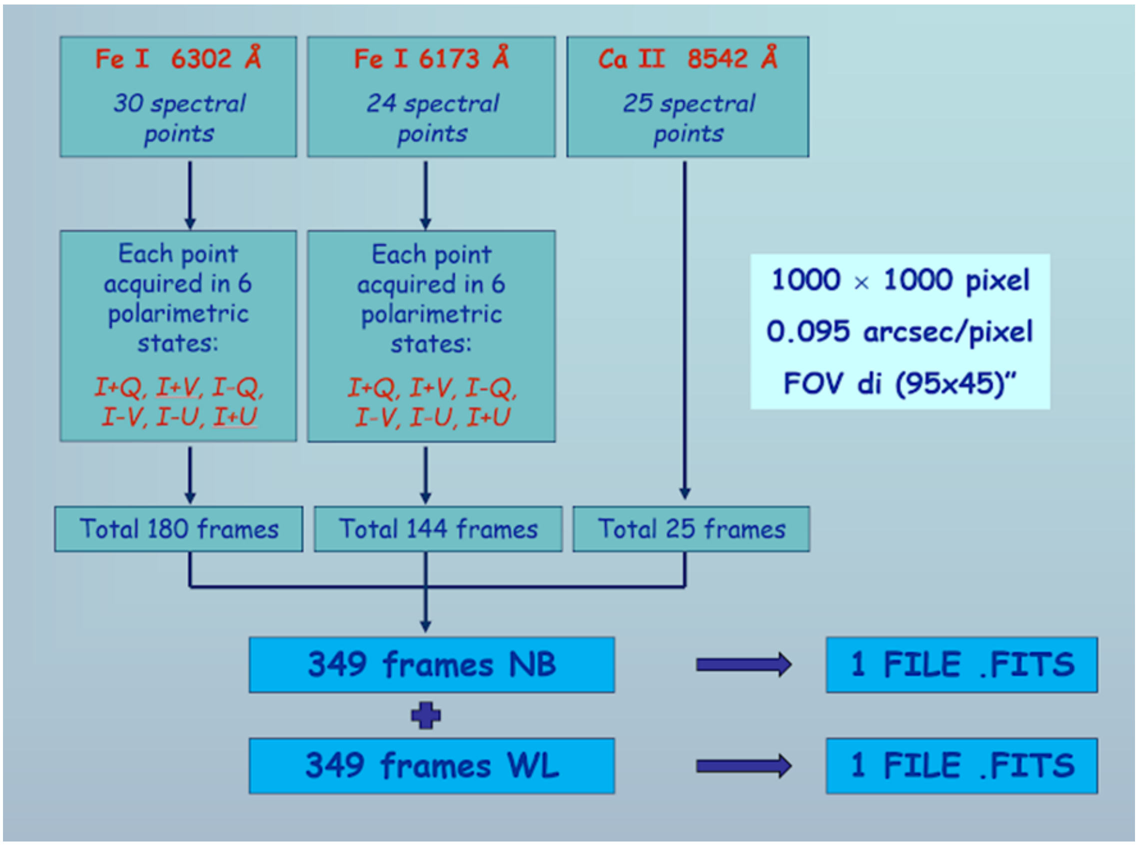

Figure 49: Structure of standard scan acquired with IBIS.

6.3 Software Reduction Package properties

The IBIS reduction software package is written in IDL and allows the user to calibrate one spectral line at a time following the steps shown below.

6.3.1 Dark calibrations

Calibrations based on measurements that allow determining the detector background noise and false light contributions. Dark measurements do typically not depend on wavelength, but on exposure time (non-linear or quasi-linear) and temperature. Mean dark calibrations for the BB channel are generated by averaging in time over the images acquired, while for the NB channel are generated by averaging in time over the images acquired per wavelength position and modulation state. Standard dark calibrations are obtained at the same wavelength positions as the science observations.

6.3.2 Flat-Field (Gain) calibrations

Calibrations based on measurements that allow determining the pixel-to-pixel transmission irregularities of the detector sensor (so-called flat-fields) and depend on wavelength and exposure time. Gain measurements are obtained by moving the image of the Sun continuously across the detector in circular way and by deforming the wave-front using the deformable mirror of the adaptive optics system, in order to obtain a uniform illumination on the detector. Mean flat-field calibrations for the BB channel are generated by averaging in time over the images acquired, while, for the NB channel, are generated by averaging in time over the images acquired per wavelength position and modulation state. Standard flat-field calibrations are obtained at the same wavelength positions as the science observations. The gain calibration for the NB channel is generated by taking into account the systematic wavelength shift across the FoV (see section 6.3.4).

6.3.3 Channel alignment calibrations

Calibrations based on measurements that allow determining image scale (magnification or demagnification), offset and rotation between the NB and the BB channel. These measures, or targets, include: dots, line grids and also a pinhole. Target measurements depend on wavelength but not on exposure time.

Note that, under default setup conditions, the BB images are rotated and flipped with respect to the narrowband ones (see Figure 50). The alignment is performed through a cross-correlation of the line-grid images (stored in the GridImages sub-directory). Then a BB Gridline Target image is shown, on which the user is requested to select, by clicking, four points in clockwise direction. The points need to be chosen at the intersection of the grid lines in the following order: top-left corner, top-right corner, bottom-right corner, bottom-left corner (see Figure 50). The user is then requested to select the exact same points and follow the same procedure for a NB Gridline Target image. To finish, the user is asked to enter the distance between the 1st-2nd and 2nd-3rd points in mm (the distance between the grid lines is 1 mm). These points are used for the alignment. Currently only the cross correlation method is implemented.

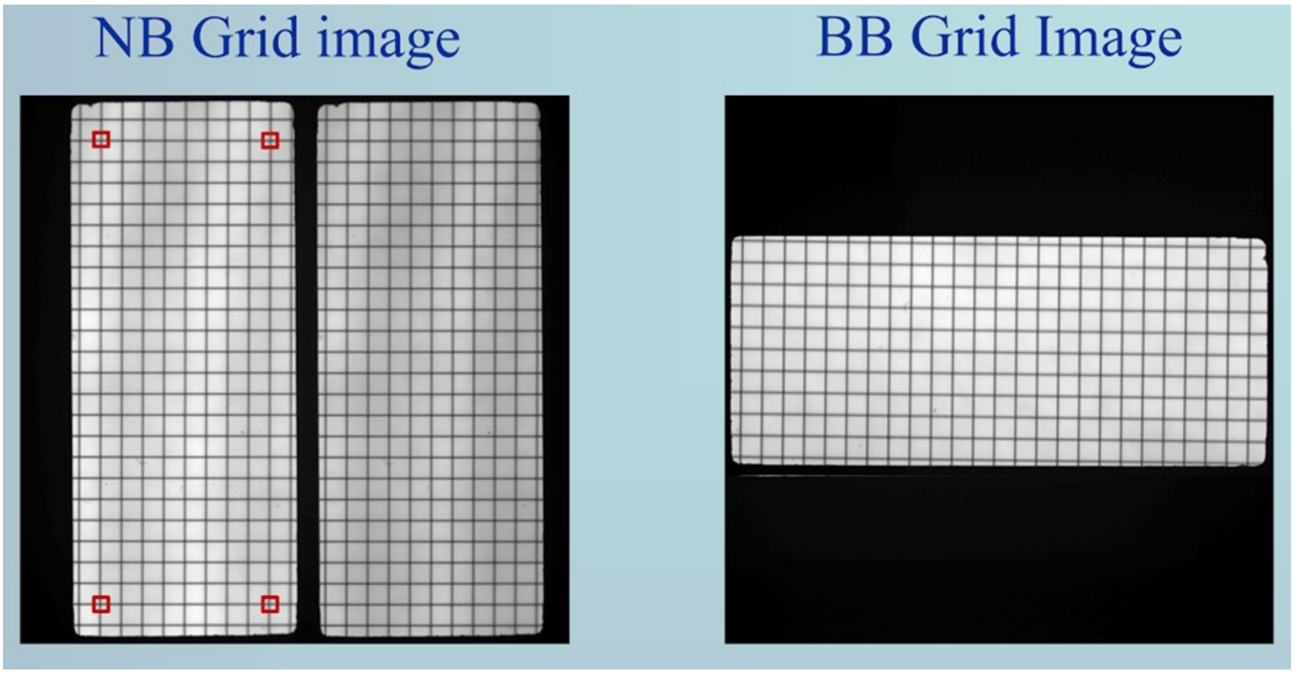

Figure 50: Example of Gridline Target image for the NB channel (left panel) and BB channel (right panel). The selected points are marked with red boxes.

6.3.4 Wavelength-shift calibration (blue-shift)

Calibrations based on measurements that allow determining the systematic wavelength shift across the FoV introduced by the collimated mounting of the FP interferometers. This field dependent wavelength shift is determined utilizing the temporally averaged NB flat-field frames (mean flat-field scan) to calculate the position of the line core at each pixel position with respect to a reference. The wavelength-shift is calculated using two methods that attempt to provide a measure of the line position or the line core across the FoV. The first method is based on a Center-of-Gravity (COG) method, the second approach is based on a second order polynomial fit over a number of points specified by the user. In a subsequent step the two raw wavelength-shift maps generated are fitted with a second order surface fit. Hence, four wavelength-shift maps are calculated in total. Each method is applied to only those profiles with pixel positions that fall within the clear FoV. In order to define the clear FoV a masking procedure is used that attempts to identify the border of the field aperture. To this end the user will be asked to use the keystrokes “a” for an increase and “d” for a decrease of the the intensity threshold value. When hitting those strokes the user will see that the displayed information changes accordingly. The result of this process should show a connected and coherent outlining of the edge of the field mask with no more point inside the FoV.

6.3.5 Destretch calibration

Calibrations based on measurements that allow determining the residual effects of seeing on the images obtained within the same pre-filter scan in a first-order approximation. The destretch module is based on the Wiborg-Rimmele destretch algorithm (see [RD10]) with a wrapper that has been written by F. Woger.

In practice, all the BB images in a scan are compared against a BB reference image, with the hypothesis that the real object on the Sun is not changing during the spectral scan. The 'stretching parameters' needed for each BB image to match the reference are computed and stored, to be later applied to each NB counterpart (with the hypothesis that the NB and BB pairs are affected by the same aberrations, i.e. same exposure time, common optic path and close-by wavelength). As BB reference image, we can use a time average of the BB images in the scan or a reconstructed image, obtained beforehand by using an image reconstruction technique, like the MOMFBD (Multi-Object Multi-Frame Blind Deconvolution) or Speckle, on the BB images.

At this point we have performed the standard spectroscopic calibration of the data, as summarized in the scheme in Figure 51.

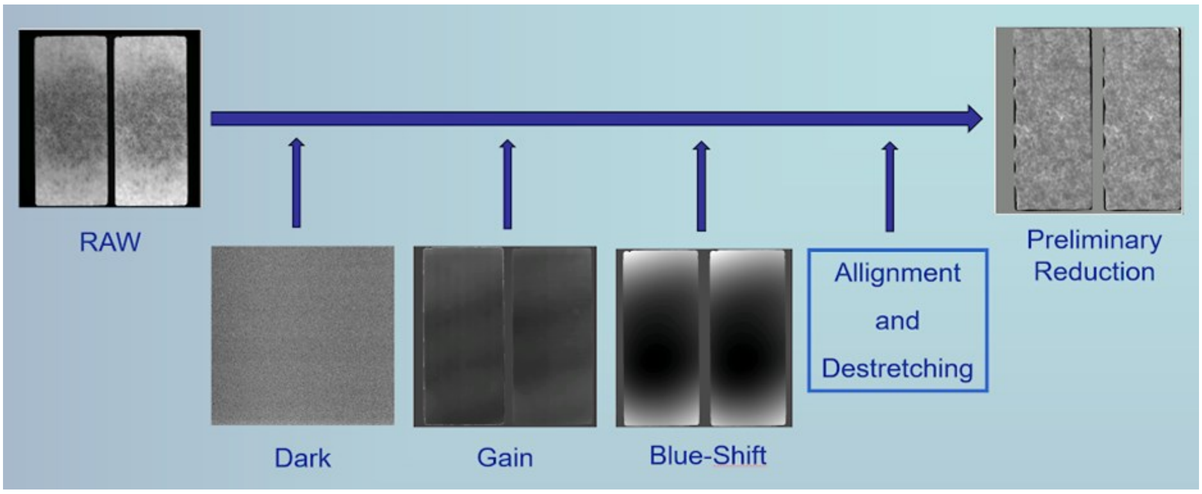

Figure 51: Steps for the standard spectroscopic calibration of IBIS data.

Now the user can go on with the calibration performing the spectropolarimetric calibration of the data, following the steps shown below.

6.3.6 Polarization calibrations

Calibrations based on measurements that allow determining the artificial polarization introduced by the instrumentation (X-matrices), excluding the telescope (T-matrix). Polarization measurements depend on wavelength.

The calibration polarization curves necessary to estimate the X-matrices are calculated from the data stored in "AutomaticInstrumentPolarization" directory. Polarization calibration measurements consist of a set of 28 individual measurements that are repeated at four different table rotation angles. For each of these optical configurations, IBIS scans the selected pre-filter passband on a wavelength grid with a reduced number of wavelength points, typically 5-7 points extracted from the wavelength file that is used during the actual science observations. In a subsequent step, these measurements are spatially averaged over the IBIS FoV and also averaged over the tuned wavelength points for each of the two beams separately to generate what is called the polarization calibration curves (see Figure 52). Before the demodulation there are in total 6 curves, one for each of the measured 6 modulation states. After demodulation there are 4 curves, representative for the 4 Stokes parameters (I, Q, U, V).

As for gain calibrations (flat fields), it is important that during the acquisition of polarization calibration measurements the light level remains as constant as possible. The light level is extracted from the FITS header and displayed. If the light level is not constant the best solution is to use observations acquired on a different day during the campaign. The curves are corrected for the light level and plotted before and after the demodulation. An example of demodulated calibration curves is shown in Figure 52.

Using the results obtained during the previous step, the X-matrices are computed using a fitting procedure. The X-matrices for the two orthogonal beams are saved separately in two files: 01.ta.YYYYMMDD.lll.X.idl and 01.tb.YYYYMMDD.lll.X.idl, where "YYYY" is the year, "MM" the month, "DD" the day and "lll" the pre-filter wavelength in Å. These files also contain information about the fit, as well as the dichroism, the retardance of the retarder and the offset angle of the retarder.

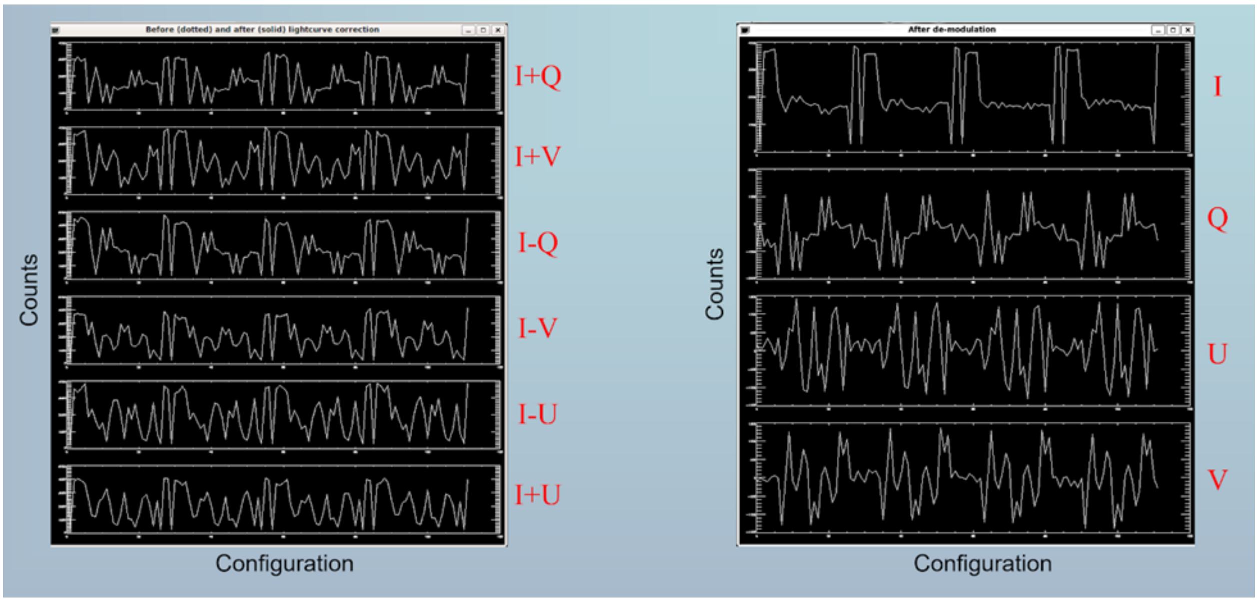

Figure 52: Typical polarization calibration curves obtained at 630,2 nm, before the demodulation (left panel) and after the demodulation (right panel), corrected for the light level.

6.3.7 Telescope calibrations

Calibrations based on measurements that allow determining the artificial polarization introduced by the telescope. These measurements depend on wavelength and time and are very infrequent (only once per year). The software package contains the most recent telescope polarization measurements available, stored in the directory "Tmatrices".

6.3.8 Residual cross-talk

At this step the software estimates the residual I → Q,U,V crosstalk and corrects for it. The user has the option of either using and correcting for a known cross talk or to calculate the cross-talk based on each individual scan.

In case the percentage of the cross-talk is known, the file path and name where the cross-talk percentages are stored must be defined by the user. This file must be an IDL save file containing a three dimensional vector which entries store the percentages of cross-talk from Stokes I to U, Q and V, respectively.

Alternatively, the cross-talk is calculated either by predefining a quiet area in the FOV in form of a rectangle or by generation of a mask based on the total polarization signal. In the former case, the rectangle is defined by the user setting the lower-left and upper-right pixels of the region. In the latter case, the user interactively generates a mask (by using the same keyboard inputs as described in 6.3.4) based on thresholding the total polarization map.

The calibrated data is saved with the naming convention llll_nbsss.pc.sav (where “llll” is the wavelength in Å, and “sss” is the scan number) and stored in the directories defined by the user.

The standard spectropolarimetric calibration of the data is summarized in Figure 53. At this point the data are ready to be analyzed.

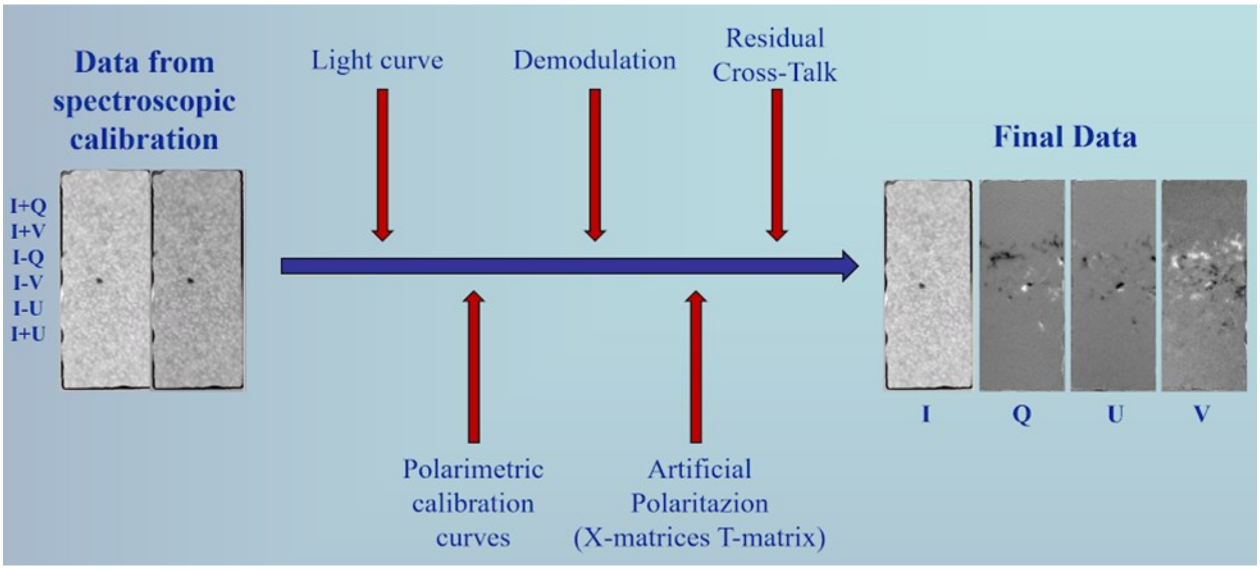

Figure 53: Steps for the spectropolarimetric calibration of IBIS data.

6.3.9 More calibrations

Certain calibrations are not performed. As the most important ones, we need to mention:

Calibration of any fringe pattern that still may exist after the main gain calibration.

Calibration of residual polarization cross-talk that may still exist after the main polarization calibration.

As minor, we mention the following:

Calibrations for distortions between the NB and BB channel.

Calibrations for distortions between the two orthogonal images when IBIS is operated in standard spectro-polarimetric mode.

Calibrations for non-linearities of the detector system.

Also, the standard reduction pipeline does not include any routines or procedures that perform an overall (temporal) alignment of all reduced scans in all filters.

Appendix A: Scientific Bibliography

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