CARMENES-NIR channel spectrograph: how to achieve the full AIV at system level of a cryo-instrument in nine months

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ABSTRACT

CARMENES is the new high-resolution high-stability spectrograph built for the 3.5m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions. This instrument is composed by two separated spectrographs: VIS channel (550-1050 nm) and NIR channel (950-1700 nm). The NIR-channel spectrograph's responsible institution is the Instituto de Astrofísica de Andalucía, IAA-CSIC.

The contouring conditions have led CARMENES-NIR to be a schedule-driven project with a extremely tight plan. The operation start-up was mandatory to be before the end of 2015. This plays in contradiction to the very complex, calm-requiring tasks and development phases faced during the AIV, which has been fully designed and implemented at IAA through a very ambitious, zero-contingency plan.

As a large cryogenic instrument, this plan includes necessarily a certain number cryo-vacuum cycles, this factor being the most important for the overall AIV duration. Indeed, each cryo-vacuum cycle of the NIR channel runs during 3 weeks. This plan has therefore been driven to minimize the amount of cryo-vacuum cycles.

Such huge effort has led the AIV at system level at IAA lab to be executed in 9 months from start to end -an astonishingly short duration for a large cryogenic, complex instrument like CARMENES NIR- which has been fully compliant with the final deadline of the installation of the NIR channel at CAHA 3.5m telescope. The detailed description of this planning, as well as the way how it was actually performed, is the main aim of the present paper.

Keywords: AIV, verification, system level, systems engineering, cryogenics, large instrument, near-infrared instrumentation

1. SCOPE AND SHORT OVERVIEW OF CARMENES-NIR

The present paper describes the AIV (Assembly, Integration and Verification) stage at system level of the CARMENES-NIR spectrograph carried out at the IAA (Instituto de Astrofísica de Andalucía) laboratory. Such a description includes both the previous plan foreseen for that stage and the deviations occurred from the plan to the real implementation, as well as the main problems and unforeseen facts that produced those deviations.

The time line here comprehended goes from the beginning of this AIV phase until the last task before the start of the preparation for the transportation of the instrument to the CAHA observatory.

CARMENES-NIR (see layout in Figure 1) consists on a spectrograph working in the wavelength range 950 to 1700 nm and a resolution of >80000. Due to the extremely high accuracy needed for the measurements of the shifts of the spectra on the detector, a special, on-purpose calibration unit (CU) is mandatory. Thus, both the calibration light and the object's light reach the spectrograph by means of two fibers (A (science); B (calibration)).

All the spectrograph's hardware is supported on an optical bench (OB) inside a vacuum vessel (VV). Furthermore, the NIR detector is housed inside a smaller, double-headed cryostat which interfaces, on one hand, the camera barrel (CB) – attached to the OB- and, on the other hand, the VV. The working temperature of the NIR spectrograph is 138K except for the detector, which works at ~84K.

The OB –together with all the hardware attached on- is enclosed in a radiation shield (RadSh) wrapped with MLI (multi-layer insulation) blankets. In addition, all this assembly –composed by the OB, the RadSh and the MLI- is mounted by means of three thermal-insulating feet to an extraction table. Thus, the assembly can be removed from the VV for any AIV and major maintenance task.

Concerning the cooling system, there are two main lots of hardware:

- In-vacuum cooling hardware (IVCH), which is mounted inside the VV: It is composed by cooling lines, heat exchangers and hoses that provide cooling to the RS in operation conditions and pre-cooling to the OB from room temperature to working temperature.
- External hardware, which is mounted outside the VV: Special mention has to be done about the N2GPU (nitrogen gas preparation unit) which has been custom-designed according to the tight CARMENES-NIR thermal requirements. Apart from that unit, the rest of this hardware consists on more generic items: external cooling lines, manifolds and LN2 dewars, the main feature being its vacuum-insulation for thermal losses minimization.

Finally, the spectrograph is placed in the Coudé Room of the CAHA 3.5m telescope building (see Figure 11 and Figure 12) and supported by 6 active pneumatic anti-vibration stages. Thus, it is insulated from any environment's vibration source. In order to maximize its stability, any mechanism or moving part was discarded to be integrated inside the VV. The same reason applies from thermal standpoint so CARMENES-NIR is inside a dedicated, thermal-conditioned room at 12ºC stable within ±0.5K.

2. CARMENES-NIR LAYOUT AND MAIN WORK PACKAGES DESCRIPTION

The main workpackages composing CARMENES-NIR are shown in Figure 1. Next, a short description of each one is done:

- **Vacuum Vessel (VV)** (Figure 6): This is the container of the NIR spectrograph and consists of a chamber whose dimensions are roughly 4m (length) x 1.4m (diameter). This vessel provides the vacuum enclosure and all the interfaces for feedthrough purposes of the fibers, cabling and cooling hardware. It works at 12±0.5ºC, which is the temperature given by the air-conditioned room where CARMENES-NIR is placed.

  This work package also included the rolling frame (OB support frame) where the entire in-vacuum assembly is attached to. This rolling frame allows for easy removal of the entire in-vacuum assembly from the VV for major maintenance and AIV tasks. Finally, when the in-vacuum assembly is out of the VV, it rests on a extraction table, which is also included in the present work package.

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- **Vacuum system (VacSys)**: It includes all the hardware necessary to provide and measure the vacuum level required for the spectrograph (~10^{-6} mbar) inside the VV. It is composed by a Roots-type roughing pump, an electromagnetic turbo-pump and a sorption pump (SP) –which was delivered by ESO- apart from minor standard hardware.

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- **Optical bench (OB) and mechanical link (MLK)**: It consists of a simple, massive piece (2.71m long x 0.85m wide x 0.1m thick; 640 kg) that supports all the opto-mechanical subsystems. This component's shape is like a bi-dimensional block, which allows for easy position shifts of some optical components from warm-AIV to warm positions (see section 3 for further description about alignment guidelines). Both the OB and all the opto-mechanical subsystems have to work at an extremely stabilized temperature of 138K. As a whole, they reach more than 1T of mass (cold mass) to be thermally conditioned and stabilized.

  The MLK is composed by three mechanical assemblies that support the cold mass. Those assemblies also provide the attachment of the cold mass and the IVCH to the rolling frame as well as appropriate thermal insulation.

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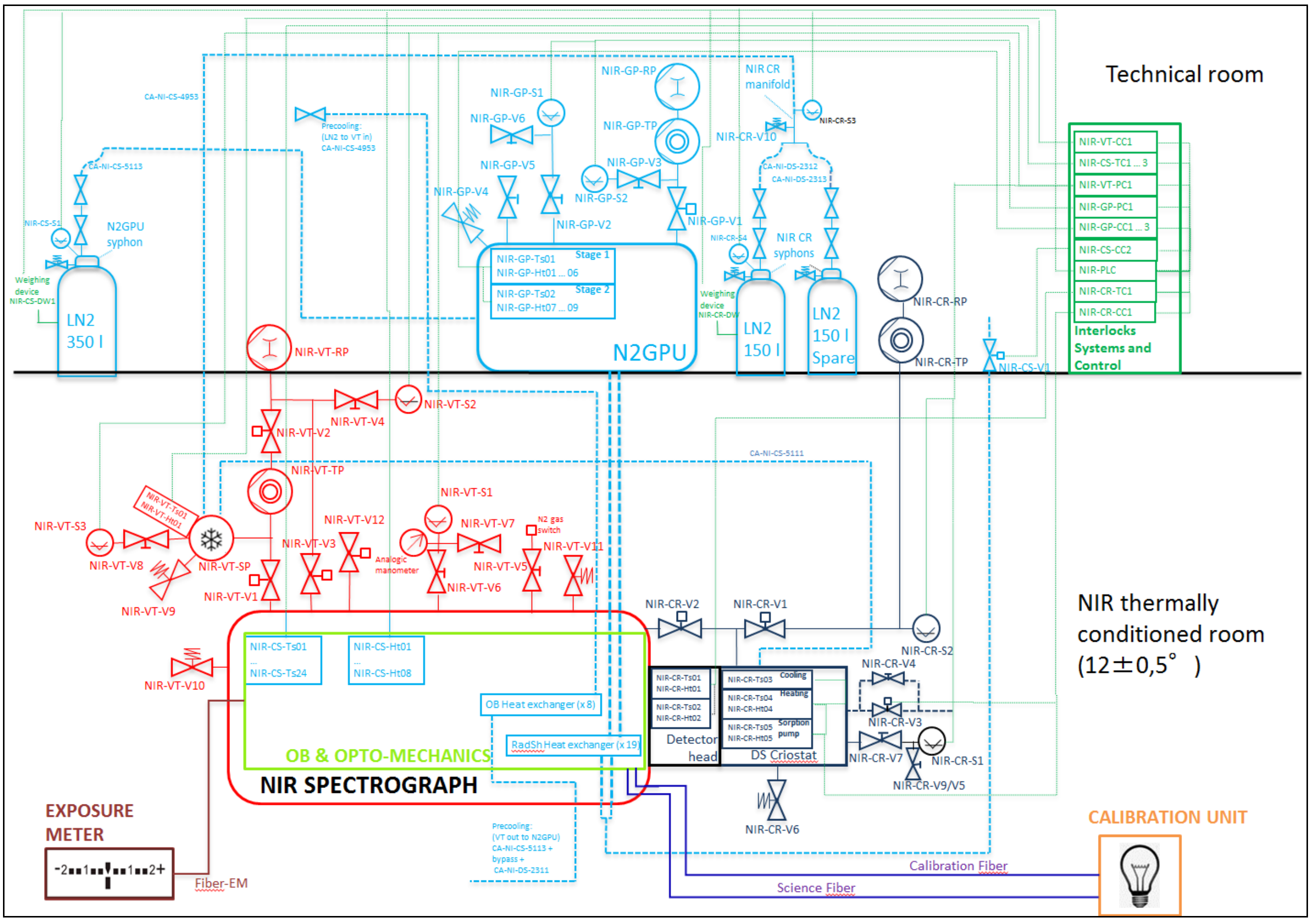

Figure 1. General layout of the CARMENES-NIR spectrograph. Note that the CARMENES instrument includes two channels: VIS and NIR. The NIR channel was entirely integrated at system level at IAA facilities, except for the Front End, whose purpose is to carry the light from the telescope to the spectrographs (VIS and NIR). The different subsystems here shown are: VV and VacSys (red), OB and opto-mechanics (light green), CS (light blue), DS (dark blue), EM (dark brown), fibers package (purple), CU (orange) and Interlocks System (dark green).

- **Main optics and optomechanics of the NIR spectrograph**: This very large workpackage includes all the optical components concerning the main optical layout (see Figure 2) and their respective mechanical mounts. These subsystems are the following:

- Fiber Exit Unit (FEU): This subsystem accommodates the end of the science and calibration fibers and places both ends appropriately w.r.t. each other. Besides that, it converts the #F coming from the fibers through a small lens barrel (Focal Adapter (FA)) and, finally houses and locates properly an Image Slicer (IS) w.r.t. the fibers. The mechanical mount of this complex subsystem allows for many degrees of freedom in order to provide high-accuracy and reliable relative position between the three different sub-packages (IS, FA and fibers). Of course, it also allows for position tuning of the whole FEU on the OB.
- Collimator and collimator mount: It is the biggest optical component at CARMENES-NIR (see Figure 4 and Figure 5). Light comes first from the FEU hitting this mirror, which collimates the beam to the Echelle. The beam hits the collimator two times more: after the dispersion on the Echelle and just before the beam comes to the cross disperser (CD).
- Folding mirror (FM): This slim, flat mirror allows the beam coming from the second hit on the collimator to be redirected to the latter again before its entrance to the camera axis.
- Cross disperser (CD): It provides cross dispersion to the collimated beam coming from the third hit to the collimator. Concerning the CD mount, it was IAC (Instituto de Astrofísica de Canarias) which was in charge of final design, manufacturing follow-up and first assembly at subsystem level.
- Camera barrel (CB): It receives the beam just after passing through the CD and focuses it on the detector.
- Baffles: This subsystem consists of two metal sheets attached to the OB. They are cleverly placed to discriminate the different beams that hit the collimator mirror such a way to avoid stray light coming into the detector.

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- **Exposure Meter (EM)**: This subsystem is in charge of getting the zero-order beam reflected from the Echelle and carries it to a fiber that transports the light up to a photon counter. The EM purpose is to give accurately the time for each exposure. This piece of hardware includes some electronic packages outside the VV and two opto-mechanical subsystems inside the VV:
  - Off-Axis Parabolic Mirror (OAP-EM): This slightly concave mirror stands over the upper part of the Echelle Mount and redirects the zero-order beam (coming from the Echelle) to the FIU–EM (Fiber Input Unit).
  - Fiber Input Unit (FIU-EM): This tiny opto-mechanical subsystem carries the Exposure Meter fiber that receives the beam from the OAP-EM and transports the light to the external electronic devices for photon counting.

  Concerning the mechanical mounts of the optics here involved, it was IAC (Instituto de Astrofísica de Canarias) which was in charge of final design, manufacturing follow-up and first assembly at subsystem level.

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- **NIR Detector System (DS)**: This subsystem is composed by the NIR detector frame and housing and the cryostat where it is enclosed, as well as all the in-vacuum cooling hardware to carry the detector to its working temperature (~84K). The detector's cryostat is a single stand-alone volume that can be independent from the VV volume. How both volumes are managed during the evacuation phase of the instrument is something that corresponds to the Interlocks System.

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- **Cooling System (CS)**: This workpackage includes a large amount of components whose purpose is to provide the working temperature to the cold mass with the stability required (0.7K within 24 hours). Those components can be grouped in the following sub-packages:

- Radiation Shield (RadShield): It is the aluminum-made enclosure where the cold mass (OB + opto-mechanical subsystems) is confined. This is actively cooled down and provides the working temperature and stability to the cold mass.
- In-vacuum cooling hardware (IVCH): It includes cooling components inside the VV in direct contact with the coolant flow as flow splitters, heat exchangers and circuitry components to carry the coolant (N2 gas) to the spots of the Radiation Shield that need to be actively cooled. They also carry the coolant flow to the OB but just for pre-cooling purposes.
- External cooling hardware: This group includes cooling hardware in direct contact with the coolant flow that is mounted outside the VV. Some of these components are external hoses, manifolds, dewars , etc… External circuitry components are vacuum-insulated in order to minimize thermal loads.
- Nitrogen gas Prepation Unit (N2GPU): It is a device that receives the LN2 flow and produces its evaporation as well as increasing and stabilizing its temperature at the exit before the flow comes into the VV. This device has been developed by ESO according to requirements needed for CARMENES-NIR. It is based on a small vacuum chamber that houses all the cooling hardware (customized heat exchangers, cooling pipes, heaters, temperatures sensors,…) necessary to carry the coolant to the appropriate conditions at the exit.
- Multi-layer insulation (MLI): It is a set of blankets that wraps entirely the RadSh outer surfaces and maximizes the radiative insulation from the inner surfaces of the VV and the RadSh itself.
- Warm-up heaters: This set of components has the purpose of warming the instrument from workingconditions to room temperature whenever the operation has to be aborted for major maintenance tasks.

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- **Calibration Unit (CU)**: This external module is in charge of providing very stable and wavelength-defined light to the spectrograph through the calibration fiber that reaches the FEU inside the VV. It consists on a range of lamps that can be selected for calibration purposes as well as a small optics and opto-mechanical setup that allows for re-directing the beam to the corresponding fibers.

  Responsible institution: Thüringer Landessternwarte Tautenburg (TLS, Tautenburg, Germany)

- **Fibers package**: This package includes all the fibers of the instrument as well as all the interfaces and feedthroughs required along their entire tracks. It includes fibers for science and for calibrations. They have also to cope with vacuum requirements wherever is necessary and provide transitions and connections in a reliable way. This package includes also an image scrambler in order to homogenize the light across the fiber section. The image scrambler was not involved in the CARMENES-NIR AIV stage at system level.
- **Interlocks and control systems**: This work-package includes all the electronics and software needed for the entire instrument monitoring, process control and safety actions to minimize hazard in case of failures such as vacuum leaks, exhaust of coolant, temperatures and pressure overranged, etc…

  Responsible institution: Centro Astronómico Hispano-Alemán, (Calar Alto (Almería), Spain) (co-directed and funded by Germany and Spain)

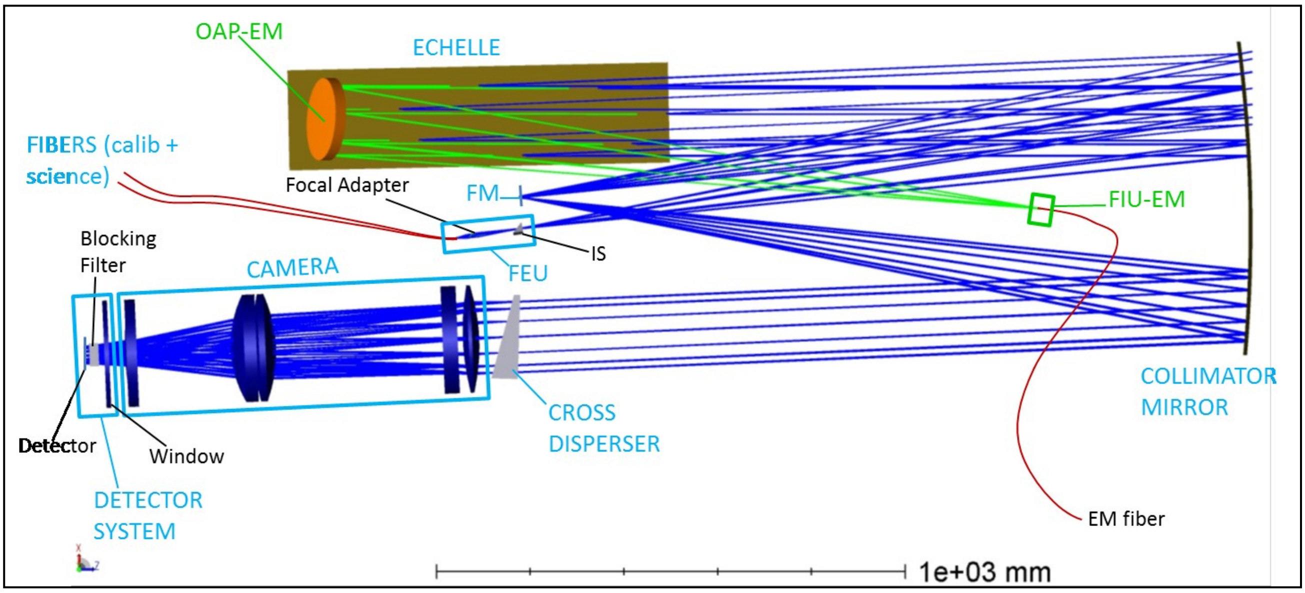

Figure 2. Optical layout of CARMENES-NIR. Note two different beam paths: the zero-order beam (green-coloured labels and rays), which goes from the Echelle to the OAP-EM and finally to the FIU-EM; and the main layout (blue-coloured labels and rays).

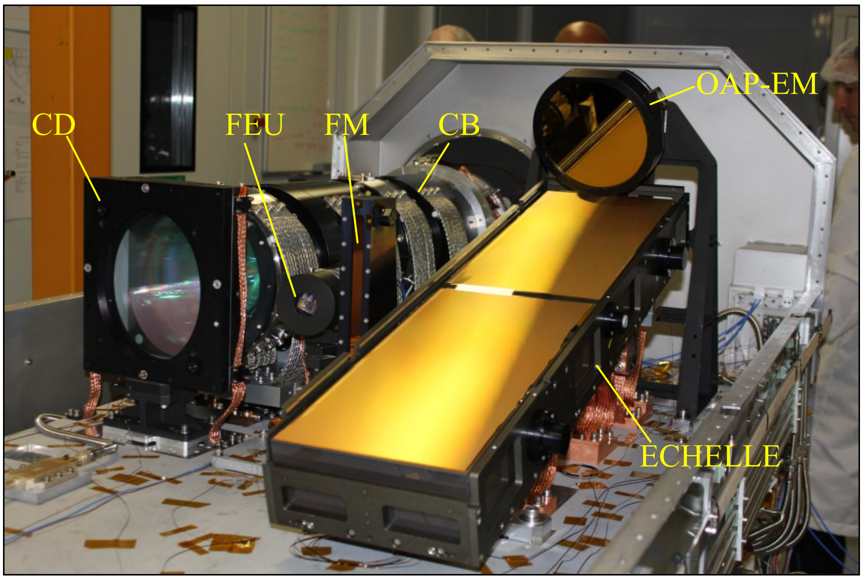

Figure 3. Overview of the front part of the optical assembly: CD, FEU, FM, Echelle, OAP-EM and CB are shown completely integrated in their mounts.

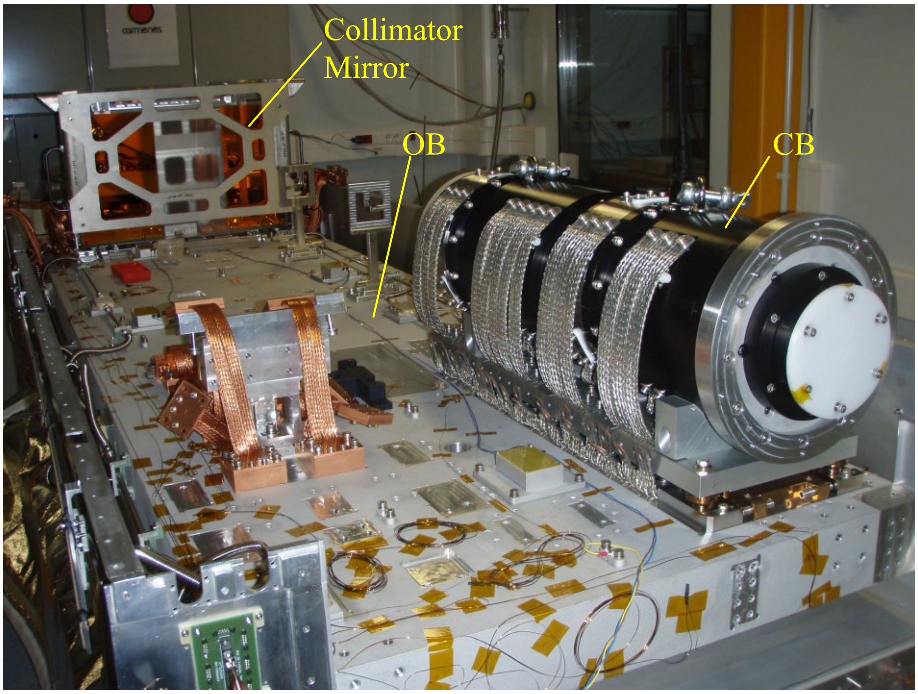

Figure 4. General view of the OB at an early phase of the AIV. CB and collimator are shown completely integrated in their mounts.

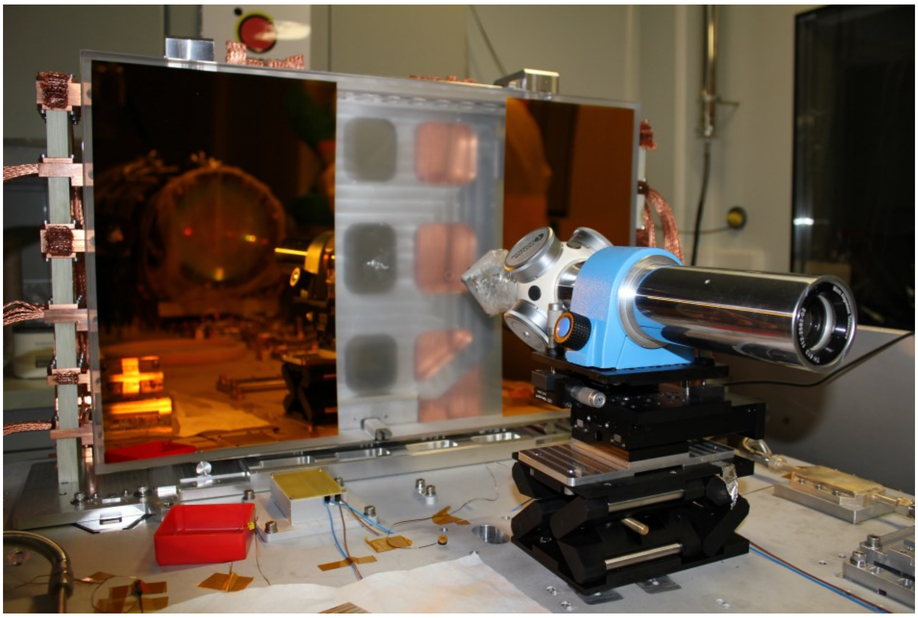

Figure 5. View of the collimator mirror on its mount.

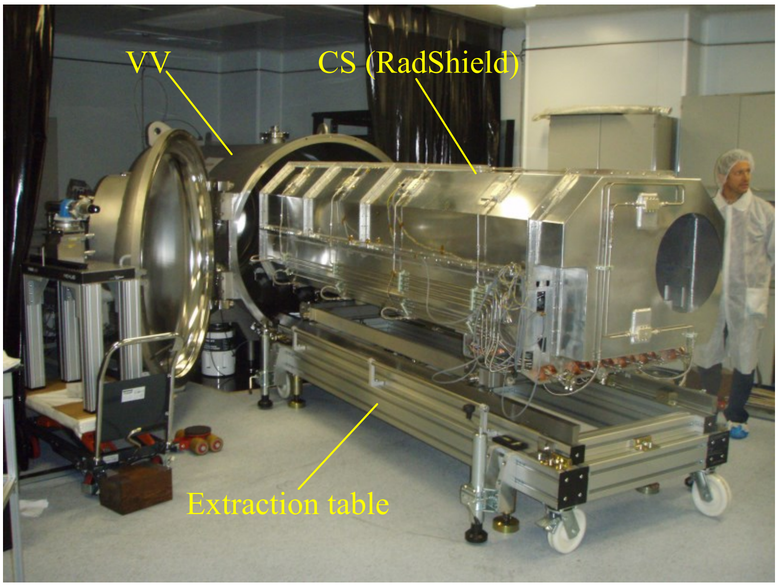

Figure 6. General view of CARMENES-NIR during the extraction from the VV of most part of the hardware that goes inside the chamber.

3. MAIN AIV GUIDELINES AND CONTOURING CONSTRAINTS

The tightest constraint driving the overall schedule of the project has been the date for the operation start-up of the instrument at Calar Alto. The development of this instrument has taken place in a very complex, uncertain age in Spain from economic point of view, where the resources for science and research have been dramatically cut off. In such a context, the CAHA observatory survival had been very seriously compromised, the CARMENES instrument being of capital importance to ensure its continuity within next lustra whenever it came to operation before end of 2015. This mandatory milestone led us to design the CARMENES-NIR AIV plan according to very aggressive approaches and guidelines:

1. High flexibility in the AIV at system level by very frequent and regular reviews –upon weekly basis- of the plan and subsequent updates and arrangements to fulfill the operation start-up milestone. This feature of the CARMENES-NIR AIV plan reached not just low-level tasks but also its main approaches.

2. Minimization of cryo-vacuum cycles (CVC) of the instrument: Indeed, this is typically one of the most time-demanding tasks in a large cryogenic instrument like CARMENES-NIR. In this case, each CVC took about 3 weeks including pumping-out, pre-cooling and warm-up phases. So if, in addition, a verification task or measurement had to be implemented in working conditions, each CVC could take up to 4 weeks.

3. Optical alignment involving most of opto-mechanical sub-systems done in warm (room temperature conditions) according to very accurate, updated optical models: This way the amount of CVCs could be reduced. Once the optical alignment had been implemented in warm, the entire system was carried to working operations. There were no intermediate checks in cold with partial integration of the opto-mechanical subsystems, which would have led to a higher amount of CVCs. Just fine tunings required additional CVCs once the detector came into play within the AIV plan.

   More in detail, there were three different optical layouts:

   - Warm-AIV model: This layout provided appropriate distance between the opto-mechanical subsystems to have optical consistency at room temperature.

   - Warm model. From the Warm-AIV model, this layout included displacements of few opto-mechanical subsystems to provide the distances in warm for the optical components to have appropriate relative distances at working conditions (in cold). This model is not optically consistent at room temperature.

- Cold model: From the Warm model (at 293K), this model results from the mechanical contraction of the OB and opto-mechanical systems. Thus, relative distances between optical components are optically consistent at working conditions (138K).

4. Continuous update of the optical model according to the results from the meausrements at each step of the optical AIV: This guideline allowed for having more accurate and consistent models according to real conditions, thus the error probability being reduced at further AIV steps.
5. Information and know-how transfer between human resources: As a result of a very close and fruitful interaction with the project management, human resources were managed such a way to minimize time gaps in the work flow due to holidays breaks and any other personnel absence. In this line, such absences were foreseen in advance, know-how and information transfer being done in order to cover the absence in question. Thus, tasks compromised by the absence could be implemented by keeping the work quality required for those.
6. Concerning the workpackages, IAA responsibility included the whole optics and opto-mechanics (except for the DS), the OB (MLK included), the EM, the CS and the full AIV at system level of CARMENES-NIR. AIV at subsystem level was also in charge of IAA regarding those systems whose responsibility lied on this institution. Therefore, the external packages integrated in the system by IAA were the following: DS (MPIA, Heidleberg), VV and vacuum system (IAG, Göttingen), the CU (TLS, Tautenburg) and the interlock system (CAHA). The reception and acceptance of the external packages were obviously included in the CARMENES-NIR plan, those being important contouring conditions to be into account.

4. AIV PLAN AT SYSTEM LEVEL

The plan was supposed to work with the starting conditions shown in Table 1 (left column). Nevertheless the real conditions existing at the beginning of the CARMENES-NIR AIV at system level were quite different as shown in Table 1 (right column) as well.

On the other hand, Table 2 lists the different phases (and their purposes) of the CARMENES-NIR AIV plan at system level as well as the schedule that was implemented in reality. Note that some tasks concerning AIV at subsystem level had to be realized in between the AIV tasks at system level. In red colour the tasks defining the critical path of the AIV at system level are highlighted. For each phase the duration in weeks is also shown (in brackets).

Next, a list is shown of the main problems and incidences occurred during this nine-month AIV at system level:

1. *[Main integration – Phase I]* Important mismatch in some parts of MLK dimensions: Those components were mountable without centering pins. We decided to go ahead and, meanwhile, evaluate whether we could keep them so or we needed to order new ones.
2. *[First Vacuum Cycle]* No bake-out was feasible since only a small amount of heaters were integrated: This was finally skipped according to the pressure value that was required. Another reason that led to that decision is that the low working temperature of the NIR spectrograph, together with the presence of a sorption pump provided the ability to have cold trap inside the VV, this being advantageous for having low pressure values.
3. *[Main integration – Phase II]* SP received but slight changes inside were necessary concerning electronics. SP feeding lines received but did not fit in: Decision taken was to postpone the SP full integration to the step "Integration phase for CVC-2". In the meantime, the SP was returned to ESO for fixing.
4. *[Main integration – Phase II]* CS external lines received but some interfaces did not fit perfectly: Feeding lines, which were essential, had no showstopping defects so the decision was to go ahead by integrating them in this phase. Although external exhaust lines were less critical from integration point of view, they had more important mistakes so decision was to return them to manufacturer for fixing.
5. *[Main integration – Phase II]* Not all the mounts and dummies were available so decision was to mount just the collimator mount (with an aluminum-made dummy). This mount was the most significant from thermal standpoint so it was not criticall at all if the rest of mounts were not there.
6. *[Main integration – Phase II]* Slightly different configuration of temperature sensors cabling was implemented at this point cabling for schedule reasons: Final configuration was done at CVC-2.

7. *[Main integration – Phase II]* Warm-up heaters boxes manufacturing took quite longer than expected: Decision was made to split the production into different very flexible, quick-reaction companies in order to minimize the delay.
8. *[Main integration – Phase II]* No pressure transmitters were implemented on the LN2 dewars: This task was postponed to "Integration phase for CVC-2". Meanwhile, the overpressure read-out was done through analogic manometers.
9. *[Main integration – Phase II]* Opto-mechanical targets were not on time: These components had the purpose to enable the measurement of the OB deformation. They were used just in the AIV phase. These measurements were postponed to CVC-2.
10. *[CVC-1]* Heaters did not work: Warm-up phase to finish CVC-1 could not be forced so the system was naturally left to reach the room temperature. This led to a delay of few days. A comprehensive inspection of the heaters was done after CVC-1 in order to find this problem's source.
11. *[CVC-1]* Vacuum leak in the N2GPU: This problem was fixed during the CVC. This also led to the decision of purchasing urgently a new leak tester since the existing one was very old and not sufficiently sensitive.
12. *[CVC-1]* Vacuum level inside the VV was not good enough. Certain dependency with the CS is seen so the leak was in the IVCH: Decision made was to go ahead with the CVC since the poor vacuum was not a hazard because the optics was not inside the VV at this point. Comprehensive leak detection was done after CVC-1.
13. *[CVC-1]* Due to the leak occurred inside the VT, this info was taken to implement the interlocks process in case of a small vacuum leak.
14. *[CVC-1]* MLI was shifted down due to bad fastening: This was fixed in following integration steps.
15. *[CVC-2]* Fastening of opto-mechanical targets got released during the cycle so measurements were not reliable: The task of finding the OB deformation from warm to cold was suppressed since no specific requirement was applicable to it. Otherwise, the plan could have been seriously compromised in terms of schedule. In the end, the key structural point here was the stability of the OB shape at working conditions, not how much it deformed from warm to cold.
16. *[DS Acceptance at IAA]* Support and handling tools were missing: These absolutely essential tools for DS integration in the system were decided to be designed and manufactured with the highest priority and with MPIA support since resources at IAA were completely overloaded due to the AIV tasks in the lab.
17. *[CVC-3]* This CVC was suppressed for schedule reasons and because its purpose was not completely critical and had been already marginally checked due to the leak produced during CVC-1.
18. *[CVC-4]* This CVC was suppressed for schedule reasons: Its as-planned purposes were not so imperative. On one hand, CB survival was ensured according to the very low cooling rates observed during the previous CVCs. On the other hand, the CB alignment in cold was a strong design requirement that had been very closely tracked through different reviews at subsystem level.
19. *[Optical AIV in warm]* Alignment of EM optics was not done on time: This task was postponed to "Integration phase for CVC-5".
20. *[Optical AIV in warm]* Baffles not on time: Its integration was postponed to "Integration phase for CVC-5".
21. *[CVC-4]* Slow evacuation rate was observed during the rough pump-out phase of the N2GPU: Water vapour condensation came into the roughing pump. The system was left being pumped out in the overnight so humidity was evacuated and the cycle could follow on as usual.
22. *[CVC-4]* VacSys roughing pump broke down: Order was done of urgent replacement of this pump by an identical pump –from the VIS channel- that was not being used by that time. This was done in the range of several hours so no great impact was applied to CVC-4 schedule.
23. *[CVC-4]* One of the detector arrays was off (Figure 7): Indeed, the detector is composed by two arrays. During CVC-4 both were switched on but only one worked. Full comprehensive inspection was scheduled to be done in "Integration phase for CVC-5".
24. *[CVC-4]* Flat spectra on the other detector were not filling the entire chip (Figure 8): There was water vapor absorption through some fibers specially integrated for AIV purposes (not in final operating configuration). Those fibers turned to be high-OH content. Order was done to urgently purchase low-OH content fibers so they could be integrated during "Integration phase for CVC-5".
25. *[CVC-4]* Spectra produced by arc lines shown "ghosts" on the detector (Figure 9): This was produced by the lack of a cut-on filter at 950nm so some visible light was entering in the second order of the NIR wavelength range. Order was done to urgently purchase a cut-on filter to be placed in the CU at "Integration phase for CVC-5".

Table 1. Starting conditions for both the previous AIV plan at system level (14/02/2014, left column) and the real implementation (right column).

Starting conditions as planned (at 14/02/2014)	***Real starting conditions (at 9/12/2014)***
VV + VacSys (including SP) integrated, tested and received	DONE except for the SP, which came later.
VV with the OB support frame inside and well positioned	DONE
Optics components fully received, accepted and verified	Only fulfilled by the Echelle, the Collimator and the CD
Opto-mechanical mounts accepted and integrated with its optical components	Not fulfilled by any opto-mechanical mount
IVCH accepted and leak-tested	DONE, in principle
OB and mechanical links accepted	Only received, not accepted.
CU integrated, tested and received	DONE
Fibers package tested and received	NOT RECEIVED

Table 2. Main phases of the AIV plan (left) as compared to the real implementation (right). For the different phases –both planned and implemented in reality- the duration in weeks is detailed (see number in brackets). Note that the red-coloured tasks define the critical path of the real AIV at system level.

Phases as planned (at 14/02/2014)	***Main purposes***	***Real implementation phases***	***Real purposes***
Main integration – Phase I *[1.5]*	+ In-vacuum cooling hardware + OB. + Mechanical Links integrated inside the VV.	**Main integration – Phase I** ***[1.5]***	+ Same as planned.
		First Vacuum Cycle ***[4]***	+ Check leakless assembly. + Vacuum level in warm (at 293K). + Check outgassing load. + Bake-out for materials outgassing inside the VV.
		FM acceptance at IAA *[0.5, in parallel to "First Vacuum Cycle"]*	
Main integration – Phase II *[3]*	+ All the optomechanical mounts with dummies on the OB. + Temperature sensors integration. + Warm-up heaters integration. + MLI integration. + Integration of all the external cooling hardware (including N2GPU). + SP integration. + Integration of Interlocks and monitoring systems. + Integration of Opto-mechanical targets.	**Main integration - Phase II** ***[5]***	+ Same as planned except for SP and some exhaust cooling hardware.
		EM-OAP Opto-mechanics acceptance and integration *[1, in parallel to "Main integration- Phase II"]*	
CVC-1 *[3]*	+ Check warm-up and pre-cooling rates. + Check thermal stability in 1-week term. + Set LN2 flow.	**CVC-1** ***[3.5]***	+ Same as planned except for measurement of OB mechanical deformation. + Set process in case of a small leak (this was not foreseen but an incidence occurred was used to do that).

	+ Measure temperature gradients across the OB. + Check steady-state temperature at OB and RadShield. + Check duration of pre-cooling. + Check vacuum refresh procedure through Interlocks system. + Measurement of OB mechanical deformation from warm to cold		
		Echelle Mount assembly + FM integration in the mount + CD integration in the mount. *[0.5, in parallel to CVC-1]*	
		Integration phase for CVC-2 ***[3]***	+ Comprehensive leak test of the IVCH and fixing of the leaks. + Inspection of warm-up cabling and fixing of the problems. + Integration of some opto-mechanical mounts with dummies (Collimator Mount, Echelle mount and FM Mount). + Integration of pressure transmitters on LN2 dewar syphons. + Final configuration of temperature sensors cabling. + Mount of opto-mechanical targets on OB. + Fixing MLI fastening. + Implement forced warm-up process.
CVC-2 *[3]*	+ Fine setting of pre-cooling and warm-up protocols to fulfill transient rates. + Fine setting of PID of the CS for thermal stability in the steady-state. + Check Interlocks protocols.	**CVC-2** ***[3]***	+ Measurement of OB mechanical deformation from warm to cold. + Confirm cooling and warm-up rates on the opto-mechanical mounts. + Check the steady-state temperature gradients and stability on the mounts.
		DS Acceptance at IAA *[1,in parallel to CVC-2]*	
CVC-3 *[3]*	+ Check the Interlocks protocol in case of leakage from the IVCH.	Suppressed.	Suppressed.
CVC-4 *[3]*	+ CB survival and alignment in cold.	Suppressed.	
Optical AIV in warm *[10]*	+ Provide the entire main optical layout aligned in warm (Warm-AIV position). + From the Warm-AIV position, provide appropriate offsets to FEU, FM and DS to reach the Warm position.	**Optical AIV in warm** ***[14.5]***	+ Full FEU AIV at subsystem level. + Provide the entire main optical layout aligned in warm (Warm-AIV position). + From the Warm-AIV position, provide appropriate offsets to FEU, FM and DS to reach the Warm position. + Same purpose for the EM optics layout with an auxiliary fiber bundle instead of real EM fiber. + Provide optimal Y tilt of Echelle in order to place the maximal efficiency peak as desired (trade-off between the throughput and spectral coverage top-level requirements). + Provide appropriate Y Tilt of CB+DS to include the desired spectral coverage on the detector (top-level requirement). + Integrate DS in the system. + Integrate fiber package in the system. + Integrate CU in the system.
		Reception of Fibers *[0.5, in parallel to "Optical AIV in warm"]*	
CVC-5 *[3]*	+Take images of the spectra on the detector for the first time. + Tracking of EM auxiliary fiber	**CVC-4** ***[2]***	+ Implement for the first time a comprehensive CVC with the NIR-DS integrated. + Check the evacuation protocol by Interlock

	bundle and measurements to correct the position of the EM spot on the bundle. + Measure tilt over Y correction of CB+DS.		Systems (including DS cryostat volume) + Check the proper working of the peripheral systems integrated (CU, fibers, DS ROE) + Tune the working parameters of the DS control according to the real environment of the DS integrated in the system. +Take images of the spectra on the detector for the first time.
		Integration phase for CVC-5 ***[3]***	+ Warm alignment of EM optics Integration of the Baffles. + Comprehensive inspection of DS electronics and corrective action: There was an in-vacuum connector not fully tightened!
CVC-6 *[3]*	+Take images of the spectra on the detector. + Check the position of the spectra on the detector. + Check the position of the EM spot on the bundle. + Measure the tilt and Z position of the detector w.r.t. the CB for focus optimization.	**CVC-5** ***[2.5]***	+ Take images of the spectra on the detector for the first time with the entire detector available. + Check that problem with the detector was fixed. + Check that problem with water vapour absorption lines was fixed. + Check that the problem VIS second-order "ghosts" was fixed. + Track the EM spot on the auxiliary fiber bundle.
CVC-7 *[3]*	+Take images of the spectra on the detector. + Check focus. + Check the FIU flux on the EM.	**PENDING FOR CARMENES-NIR INSTALLATION CAHA.**	+ Compute de-focus and tilt of detector. + Appropriately shim the interface between the DS and the CB for tilt and focus correction. + Adjustments of FIU-EM position. + Replacement of the auxiliary fiber bundle by the EM fiber. + Formal check of the Top Level Requirements with the whole instrument in operation.

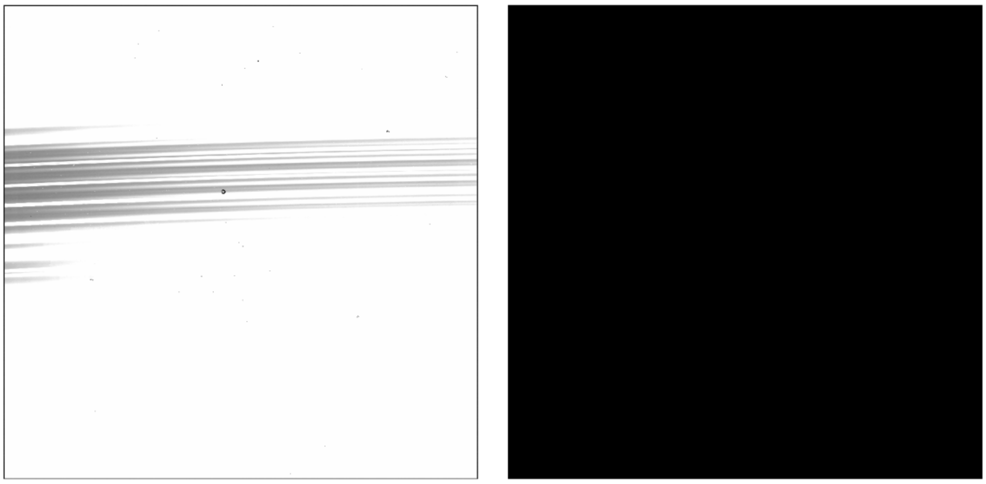

Figure 7. First image (highly saturated) taken from CARMENES-NIR. Note how one of the arrays was completely off.

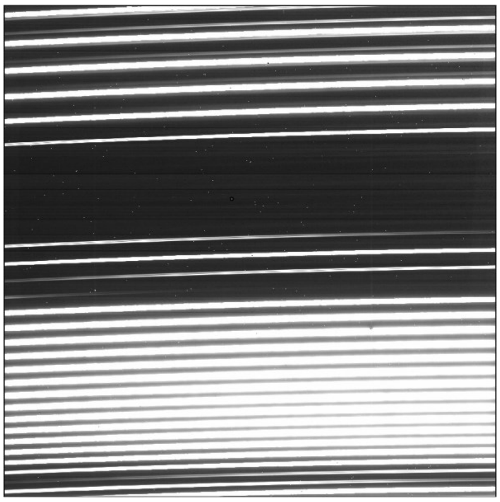

Figure 8. Spectrum taken on CARMENES-NIR produced by flat illumination (CVC-4).

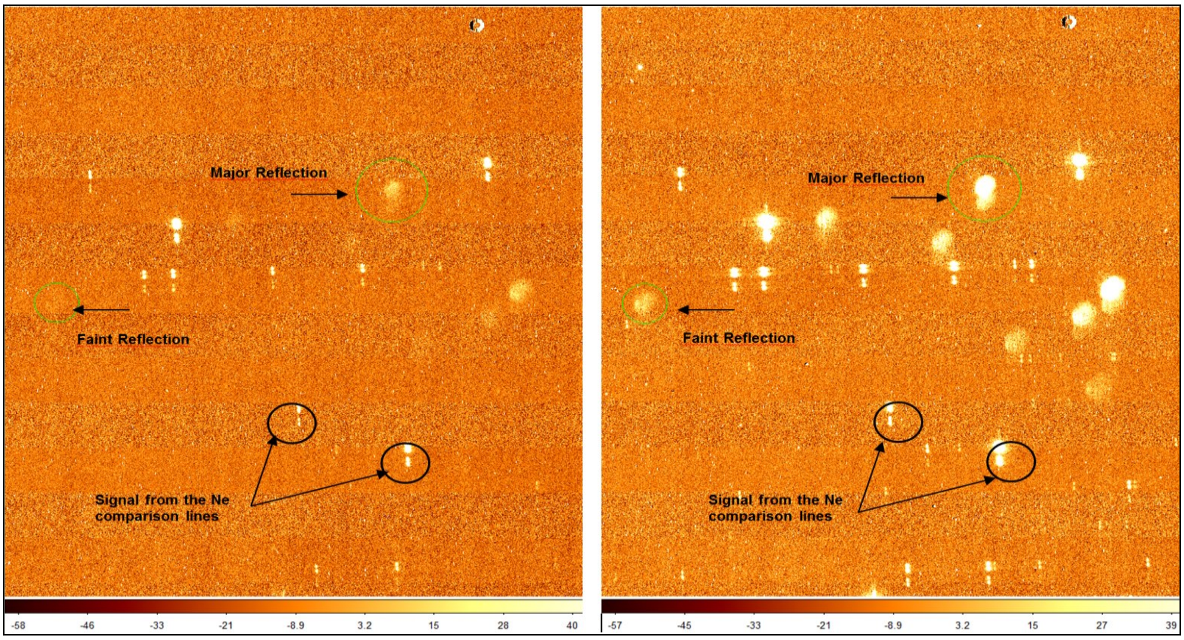

Figure 9. Spectrum taken on CARMENES-NIR produced by UNe arc lamp. The effect of the “ghost” spots is here shown.

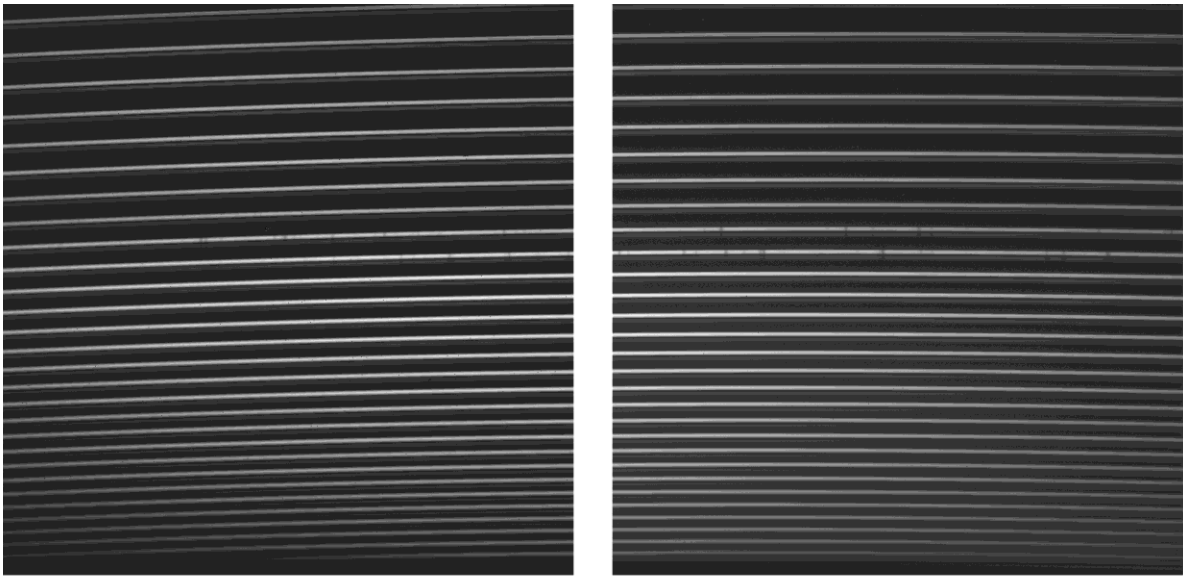

Figure 10. Spectrum taken on CARMENES-NIR produced by flat illumination (CVC-5).

5. MAIN TOP-LEVEL REQUIREMENTS AT CARMENES-NIR SYSTEM LEVEL

The final aim of the AIV phase reported here was the check of the CARMENES-NIR top-level requirements. All of them were checked during the AIV phase at IAA. Most of them were verified through the spectra taken at CVC-5. Nevertheless, some of them –marked with * in Table 3- were either pre-checked or not verified at IAA. The latter were fully verified at CAHA because the full verification at IAA would have meant the start-up milestone (by end 2015) to be seriously compromised. On the other hand, those requirements were much better to be verified with the whole instrument.

Eventually, note that some top-level requirements are linked to each other. In the case of those requirements that were not fully verified at IAA, there existed other ones that were indeed verified and provided a good clue about its compliance. For instance, the temperature stability requirement was verified and its goal fulfilled, which gives a clue about the compliance of relative stability and radial velocity requirements. So the instrument was in really good shape when AIV at IAA finished.

Table 3. Main requirements to be verified at system level.

Requirement	**Value**	**Verification status at the end of AIV at system level (end of CVC-5)**
Working temperature	140±2.5 K	VERIFIED AND FULFILLED
Detector working temperature	< 85 K	VERIFIED AND FULFILLED
Field of view	Fiber entrance shall collect >90% of the energy for the 80 percentile seeing at Calar Alto	BY DESIGN
Illumination of the fiber	The fibre exit should be homogeneously illuminated for maximum radial velocity stability (scrambling factor > 1000).	NOT FULLY APPLICABLE (since the Image Scrambler was not integrated at IAA)
Image quality	PSF < 1.5 pixel rms diameter over 80% of the detector PSF < 2 pixel rms diameter for the remaining 20%.	VERIFIED AT FIRST APPROXIMATION*

Pixel sampling	> 2.355 pixels per resolution element (dispersion direction)	VERIFIED AND FULFILLED
Spectral resolution	> 80000	VERIFIED AT FIRST APPROXIMATION
Relative stability	< 1/1300 pixel between the object and calibration spectrum in 24 hours.	NOT VERIFIED*
Absolute stability	< 2 pixels over years timescale	NOT VERIFIED*
Image slicing	2 symmetric slices for the object and the calibration fibers. Inter-slice separation: 1 pixel	VERIFIED AND FULFILLED
Inter-order separation	Shall leave sufficient pixels for background determination	VERIFIED AND FULFILLED
Spectral coverage	950 – 1700 nm Optimized within 950 – 1350 nm No gaps between orders up to 1110 nm	VERIFIED AND FULFILLED
Throughput	> 5% (goal 7%) Optimized within 950 – 1350 nm	BY ACCEPTANCE OF SINGLE COMPONENTS*
Signal-to –noise ratio (SNR)	< 70	VERIFIED AND FULFILLED
Detector cross-talk and persistence	$< 10^{-3}$ (goal: $< 5\cdot10^{-4}$)	VERIFIED AND FULFILLED
Radial velocity precision	5 m/s over 4 years (goal: 1 m/s over 10 years)	NOT VERIFIED*
Temperature stability	±0.07 K (±0.01 K goal) in the timescale of 1 day	VERIFIED AND FULFILLED
Vacuum level	~ 10-6mbar	VERIFIED AND FULFILLED

6. CONCLUSIONS

The complete AIV phase at system level of CARMENES-NIR took place at IAA facilities and started in December the 9th 2014. It took 9.8 months, which means a delay of 1.5 months with respect to the AIV plan that had been previously designed (plan designed and produced by IAA engineering group by February 2014). This length, which includes holiday periods, is astonishingly short for a large cryogenic instrument like CARMENES-NIR. Within this period, AIV phases at subsystem level -as well as reception and acceptance of some components and packages to be integrated in the instrument- were inserted in between the steps of the AIV at system level. This was done such a way to minimize the impact on the overall duration of the schedule. Four CVCs were implemented during the AIV at system level.

The AIV phase finished in September the 30th 2015. Right after that, the instrument was prepared for its transportation to CAHA, which took place in October 22nd 2015. Most of the top-level requirements were successfully verified prior to the transportation to CAHA. Only few were not checked but there existed strong hints about their compliance. There was, of course, a trade-off between the formal compliance of all the requirements and the fulfilment of the mandatory instrument start-up date at CAHA (before end of 2015). A formal, comprehensive verification of all the top-level requirements would have needed quite long time, which would have compromised the start-up date. On the other hand, since some requirements are related to each other, good hints were obtained through the different CVCs and tests performed at IAA to state that a formal check of those requirements not verified at IAA would be passed successfully at CAHA. This was demonstrated to have been a good decision within the constraints CARMENES-NIR. Indeed, for the time being the instrument is fully compliant with all the top-level requirements.

This huge, outstanding-quality work was done at IAA by a team of 10 people that provided 14000 hours during the whole length of the AIV at system level (9.8 months). From these 10 people, 5 engineers were full-time dedicated whereas other two engineers were half-time dedicated and the rest had a residual dedication.

Very important was the fact of having quick-response companies at our disposal for fast works during this phase. These companies offered a wide flexibility in the way of work, thus the time delivery being prioritized over other important issues. This was crucial in the case of CARMENES-NIR and was a key factor for the fulfillment of the schedule. In particular, IAA worked in very close and collaborative way with two companies specialized in mechanical engineering – for design, analyses and manufacturing- called ProActive R&D and INDICAM. Regarding optical engineering, an external senior optical engineer (Ernesto Sánchez-Blanco) was subcontracted on demand within a 50% of mean time of dedication. Besides that, CARMENES project management was in charge of a private company called Fractal that also supported the AIV of CARMENES-NIR.

Eventually, this multidisciplinary project has meant a real cornerstone for the engineering capacities at IAA. This important success and the know-how acquired may provide future opportunities for IAA to get involved in the development of large, cryogenic and extremely accurate instruments.

Figure 11. CARMENES-NIR inside the NIR thermally conditioned room at CAHA.

Figure 12. External systems of CARMENES-NIR running in the Coudé Room at CAHA.