

CARMENES-NIR channel spectrograph – Cooling system AIV: Thermo-mechanical performance of the instrument

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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 is the Instituto de Astrofísica de Andalucía (IAA-CSIC). It has been manufactured, assembled, integrated and verified in the last two years, delivered in fall 2015 and commissioned in December 2015.

One of the most challenging systems in this cryogenic channel involves the Cooling System. Due to the highly demanding requirements applicable in terms of stability, this system arises as one of the core systems to provide outstanding stability to the channel. Really at the edge of the state-of-the-art, the Cooling System is able to provide to the cold mass (~1 Ton) better thermal stability than few hundredths of degree within 24 hours (goal: 0.01K/day).

The present paper describes the Assembly, Integration and Verification phase (AIV) of the CARMENES-NIR channel Cooling System implemented at IAA-CSIC and later installation at CAHA 3.5m Telescope, thus the most relevant highlights being shown in terms of thermal performance.

The CARMENES NIR-channel Cooling System has been implemented by the IAA-CSIC through very fruitful collaboration and involvement of the ESO (European Southern Observatory) cryo-vacuum department with Jean-Louis Lizon as its head and main collaborator. The present work sets an important trend in terms of cryogenic systems for future E-ELT (European Extremely Large Telescope) large-dimensioned instrumentation in astrophysics.

Keywords: thermal stability, cryogenics, thermal performance, AIV, large instrument, near-infrared instrumentation

INTRODUCTION

The present paper describes the performance of the CARMENES-NIR cooling system (CS) during the AIV stage at system level as well as in operation conditions at CAHA. The AIV at system level started with a couple of cryo-vacuum cycles (CVCs) to set the cooling system tunings. At this point, no optical components were integrated in the instrument so the main purpose was to check the performance of the CS with no risk for sensitive, critical components.

In the first cryo-vacuum cycle (CVC1), not all the mechanical mounts were available to be integrated on the optical bench (OB) so just the collimator mount was integrated (with a dummy) in order to check the temperature gradients and rates during the cycle, as well as its steady-state. In addition, the start-up procedure of the instrument was set for the first time and required further improvements and tunings, which were implemented in CVC2, as well as having most temperature points monitored on mechanical mounts.

After CVC2, the CS setpoints were mainly frozen because the aims of those cycles were focused on the optical performance at working conditions so the CS should work upon known, reliable parameters. Therefore, those parameters applied during the rest of the AIV stage at system level developed at IAA and the first installation of the instrument at CAHA. It was later on –with the instrument already in operation at CAHA- that was decided to further tune these parameters in order to reduce the oscillations on the OB. This is explained more in detail in section “Real performance of CARMENES-NIR Cooling System”.

In order to understand the reason of a so low amount of CVCs for setting the CS in proper operation, please see reference [1], which describes the real framework and context that has constrained the CARMENES instrument development. In that sense, the temperature stability requirement was –by the time of the AIV phase start-up at system level- by far the most worrying and critical one.

REQUIREMENTS

Next, Table 1 lists the main requirements applicable to the cooling system. CVC1 was used to ensure that the cool-down rate was consistent with what optical components typically need. The absolute working temperature was not so much a concern. Indeed, the final working temperature depends on the pre-cooling procedure so it is something that could be adjusted. Even in the case that the steady-state temperature did not fit the requirement, it could be tuned by adjusting the temperature of the radiation shield (RadSh).

Table 1. Main requirements applicable to CARMENES-NIR CS.

Requirement	Value
Working temperature	138±0.4K
Temperature stability	±0.07 K/day (goal: ±0.01 K/day)
Cool-down and warm-up rate	<10 K/h
Vacuum level	10 ⁻⁶ mbar
Liquid nitrogen consumption	<90 l/day

COOLING SYSTEM CONCEPT AND LAYOUTS

The CARMENES-NIR CS concept (see Figure 1) is based on a radiation shield (RadSh) –which is wrapped with MLI (multi-layer insulation) blankets- that is actively cooled in operation. The optical bench (OB), which supports all the optics and opto-mechanics, is completely confined by the RadSh. Therefore, in working conditions the OB is kept at 138±0.4K by keeping the RadSh at its steady-state temperature. Thus, the OB is passively cooled down, which, together with its high mass –cold mass is about 1000 kg (envelope: 2.7 m x 0.85 m x 0.1 m)- makes it extremely stable. Both the cold mass (OB + opto-mechanics) and the RadSh are inside a vacuum vessel (VV). The coolant (LN2, liquid nitrogen) is fed by a 350-l dewar and goes directly to a device –N2GPU (nitrogen gas preparation unit)- which evaporates the flow and carries the coolant to its working temperature by means of two PID control loops. The coolant coming out from the

N2GPU goes into the VV and cools down the RadSh by means of 19 heat exchangers distributed in 10 cooling lines. This configuration's layout is shown in Figure 2 and Table 2.

Nevertheless, the latter is not valid for pre-cooling purposes. Indeed, the OB needs to be actively cooled down from room temperature to working conditions so that this phase does not take extremely long time. Therefore, the pre-cooling phase needs an appropriate configuration whose layout is shown in Figure 3 and Table 3. The 350-l feeds directly the OB since it is the most massive component to be cooled down from room temperature (285K). The OB cooldown is done through 8 heat exchangers distributed in two different cooling lines (4 per line). The exhaust coolant at the exit from the VV is re-directed to the N2GPU and, from this unit to the RadSh. Finally, the coolant goes out through the on/off valve, which is permanently open in this phase.

All the external cooling hardware (hoses, lines, manifolds, by-pass extensions, siphons, etc) are vacuum-insulated in order to minimize the thermal loads from the environment to the flow.

Finally, the active cooling of the RadSh in operation is kept by setting a target temperature (set-point) to a specific, appropriate temperature sensor attached to the shield. This sensor controls the action of an on/off valve (#14 in Figure 2) at the end of the coolant circuit. The open/close regime of that valve keeps the temperature sensor value within a deadband under the set-point introduced.

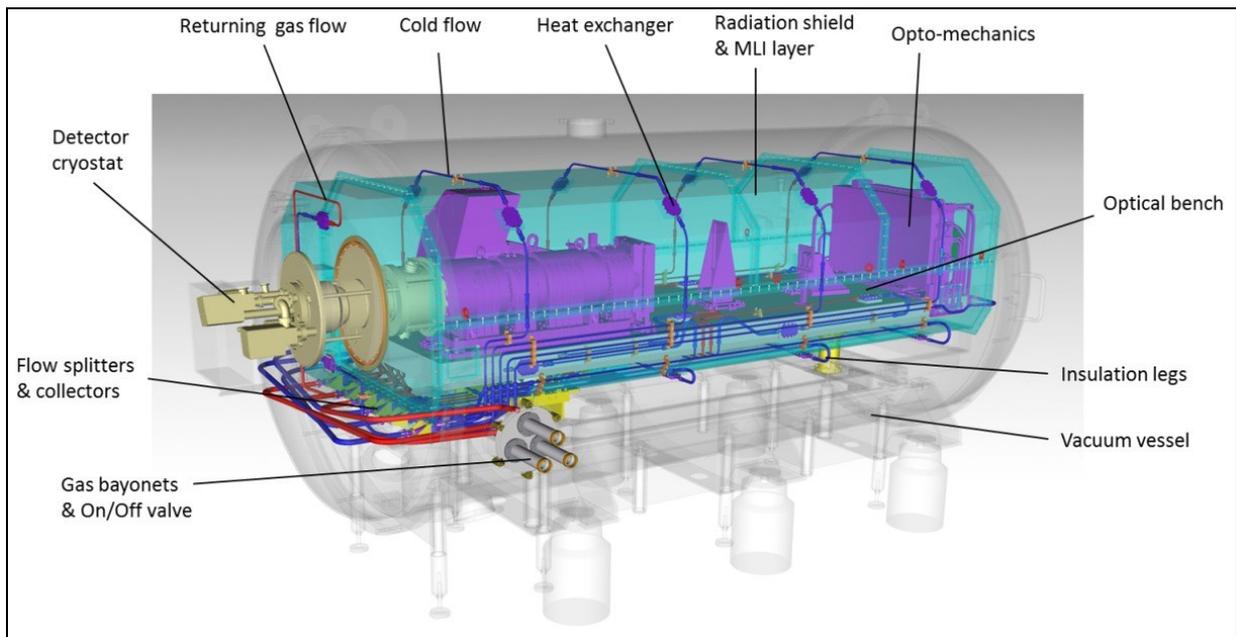


Figure 1. Overall view of the CARMENES-NIR CS final design.

Table 2. List of components applicable to the operation configuration.

1	LN2 Dewar 350L	7	LN2 NIR Manifold	13	Gas transfer exit line
2	LN2 Dewar 150L	8	LN2 NIR Feed line	14	On/Off Valve
3	Long siphon	9	LN2 NIR Feed line	15	Exhaust gas line
4	Short siphon	10	Gas transfer lines	16	LN2 NIR Feed line
5	LN2 NIR Feed line	11	Gas extension lines	17	Gas bayonet lid
6	LN2 NIR Feed line	12	Gas exit manifold	18	Relief valve

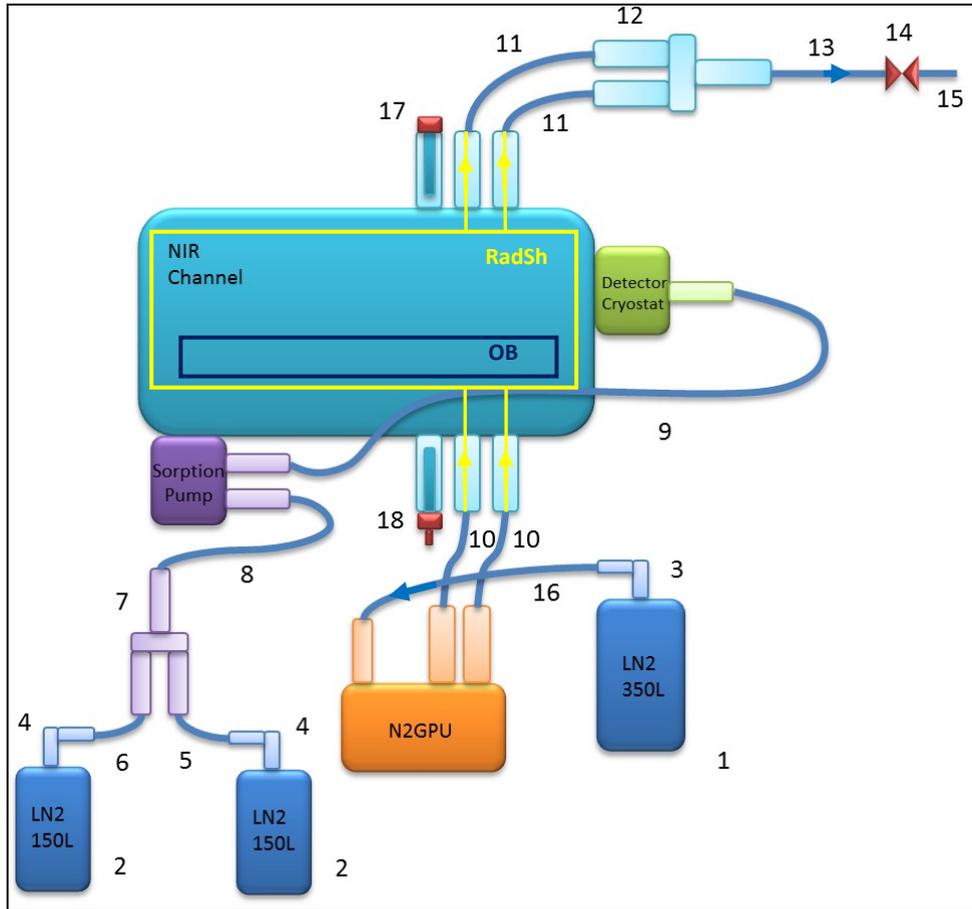


Figure 2. Operation configuration layout: In the present figure the cooling layout feeding the detector system (DS) is also shown. Note that the DS is fed in series with the sorption pump (SP). On the other hand, from the 350-l dewar the coolant goes to the N2GPU, which evaporates and carries the flow to its working temperature. Afterwards, the coolant goes into the VV and cools the RadSh. There is no active cooling on the OB.

Table 3. List of components applicable to the pre-cooling configuration.

1	LN2 Dewar 350L	8	LN2 NIR Feed line	15	Exhaust gas line
2	LN2 Dewar 150L	9	LN2 NIR Feed line	16	LN2 NIR Feed line
3	Long siphon	10	Gas transfer lines	17	LN2 NIR Feed Line
4	Short siphon	11	Gas extension lines	18	LN2 Bypass
5	LN2 NIR Feed line	12	Gas exit manifold	19	LN2 NIR Feed Line
6	LN2 NIR Feed line	13	Gas transfer exit line	20	LN2 to N2 adapter
7	LN2 NIR Manifold	14	On/Off Valve		

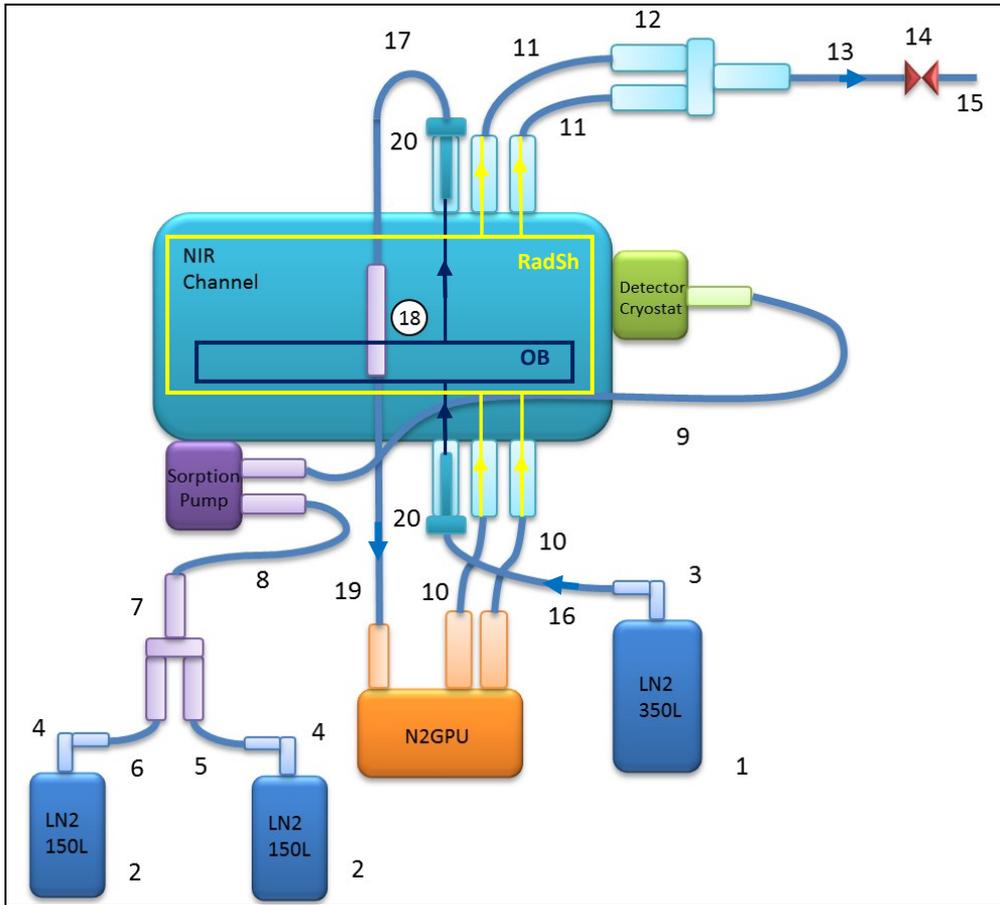


Figure 3. Pre-cooling configuration layout. In the present figure the cooling layout feeding the detector system (DS) is also shown. Note that the DS is fed in series with the sorption pump (SP). On the other hand, the pre-cooling configuration of the CS feeds the OB first directly from the 350-l dewar. Afterwards, the exit flow is taken to residually cool down the N2GPU and the RadSh later. Finally, the exhaust flow goes out.



Figure 4. View of the in-vacuum cooling hardware, mainly the RadSh, outside the VV.

REAL PERFORMANCE OF CARMENES-NIR COOLING SYSTEM

As already mentioned before, the aim of CVC1 and CVC2 was to ensure the fulfillment of the thermal requirements which might somehow compromise the optical components in later CVCs. Those requirements were the cooldown and warm-up rates, the LN2 consumption and the working temperature. Regarding to the latter, the fulfillment of this requirement depends strongly on the start-up procedure of the instrument from room to working conditions. Slight deviations – few degrees- from the required working temperature (138K) were not a huge problem in the first CVCs during the AIV at system level.

In addition, some hints about the temperature stability could be observed although the duration of the CVCs did not allow for monitoring long-term behaviour. Indeed, the typical length of a CVC was about 3 weeks: one for cooldown, one for working conditions and the last one for warm-up.

A typical start-up procedure was composed by the following phases:

1. *Pump-out phase*: This phase includes roughing pump and turbo-pump start-ups for the VV, the N2GPU and the DS cryostat.
2. *Cold mass pre-cooling phase*: Once the vacuum inside the VV is about $1 \cdot 10^{-4}$ mbar both in the DS cryostat and the VV, the pre-cooling phase can start both for the DS and the cold mass. Note that the VV sorption pump (SP) is in series with the DS cryostat (see Figure 2 and Figure 3) so during DS pre-cooling the cold trap capacity inside the VV will be enabled. Since the cold mass (1 Ton) takes much longer than the VV SP to be at cold-trapping temperatures, there is no risk to produce particles adsorption on surfaces of cold mass and optics. The applicable configuration here is shown in Figure 3.

The exhaust coolant coming out from the VV is re-directed to the N2GPU and later on to the RadSh. This is done to minimize LN2 consumption during the present phase. Therefore, during this phase the N2GPU and the RadSh are being pre-cooled by a relatively warm coolant. During this phase the on/off valve is permanently open (#14 in Figure 2 and Figure 3).

3. *RadSh cooldown transient phase*: Once the OB is at the proper temperature, this phase starts by changing the cooling configuration from pre-cooling layout (Figure 3) to operation layout (Figure 2). At the beginning of the present phase the temperature of the RadSh is typically about 200 – 210 K. Since the OB is not actively cooled anymore, the OB temperature will be passively increasing until the RadSh reaches its steady-state temperature. That's why at the end of the “cold mass pre-cooling phase” the OB must be 5 – 6 K cooler than its working temperature. Thus, the RadSh transient cannot be extended beyond 20 hours because, otherwise, the OB would deviate much from its working temperature.

The RadSh is carried to its steady-state temperature by successive decreasing steps. At this point, the on/off valve is fully operative. Therefore, those steps are implemented by providing several set-points to the temperature sensor controlling the on/off valve. Indeed, the sequence of set-points is approximately as follows: 200K (starting temperature of RadSh), 170K, 160K, 150K, 140K, 136K, 132K, 129.5K. The time lapse between consecutive set-points is about 1.5 – 2h (see Figure 6).

4. *Stability phase*: This phase starts when the temperature control sensor at the RadSh has the target of 129.5K as a set-point. At the beginning, therefore, there will be some time in which the system will tend to its natural steady-state. In other words, the OB and the RadSh will progressively approach its thermal equilibrium where the radiative exchange will be equal to the conductive losses of the OB. Indeed, the OB has very low –but existing- thermal losses though the pre-cooling circuitry hardware and its supporting pads. So the RadSh needs to be at slightly lower temperature as compared to the OB in order to drain these thermal loads out of the system.
5. *Warm-up phase*: During the AIV at system level, the warm-up procedure was used to finish a CVC in order to proceed with the plan. Some heaters on the OB were controlled by setting successive set-points. Once the temperature control sensor reached the set-point the heaters were switched off. Then the temperature decreased

down to the low limit of the deadband. At this point, the heaters were switched on. Once the entire OB was close to reach the set-point, a new, higher set-point was applied (see Figure 11).

The full thermal performance achieved in the CARMENES-NIR CS is shown from Figure 5 to Figure 11.

Concerning the cooldown rate of the OB and the opto-mechanical mounts, Figure 5 shows the thermal behavior of the cold mass during the cooldown phase from 293K to working temperature at CVC1 (March 2016). According to Table 1, this rate must not be higher than 10K/h. As shown in Figure 5, the actual rate in CVC1 was always lower than 2K/h. Therefore, the requirement was fulfilled by far. Certainly, CVC1 was the first cryo-cycle of the instrument and the approach taken was a bit conservative. Anyway, for further CVCs and start-up at CAHA the aim was to reach and keep a cooldown rates between 2 and 3K/h, which gave a full length of the cool-down phase around 2.5 – 3 days.

Likewise, the warm-up rate requirement was respected (see Figure 11). The mean rate was lower than 2K/h, very conservative as compared to the value required.

Concerning thermal stability, CVC1 was not appropriate to check such a requirement in the long term. Nevertheless, good hints about its compliance could be extracted already during this CVC. Indeed, Figure 7 shows that the entire OB was within 0.1 K variation during 96 hours. The temperature stability requirement (0.07 K/h) was fulfilled at each one of those 4 days, the goal (0.01 K/h) being achieved during one of the days. Besides that, the steady-state temperature gradient across the OB is 0.3 K, which gives a notion of the temperature homogeneity of the bench.

Already in operation, the typical temperature stability easily reached at the OB is shown in Figure 9. During the 3 weeks shown in the figure, the OB never moved further than 0.17 K (between 138.1 and 138.27 K), the stability requirement being fulfilled every single day of that period. Likewise, the goal was very often reached (0.01 K/day).

In order to keep the OB at 138.1 K around, the RadSh must stay about 135 K. Note that the gradient across the RadSh is wider as compared to the OB because of its active cooling. The temperature of 135 K applies to the large areas of the shield away from the cold spots (heat exchangers). The RadSh is kept at this temperature by the active cooling implemented through 19 heat exchangers. The heat exchange is driven by the on/off valve (#14 in Figure 2), which, in turn, is controlled by a specific temperature sensor located on the shield. Once this sensor reaches the set-point of 129.5K, the valve opens the temperature starts decreasing. When it reaches the low limit of the deadband associated to the temperature control sensor, the valve closes. This behavior is clearly shown in Figure 10. Note that relatively high frequency in the oscillating behavior of the heat exchangers on the RadSh. These quite repetitive, regular oscillations do not disturb the cold mass because of its high mass and its passive thermal conditioning inside the shielding enclosure.

Regarding the working temperature, during the first CVCs at AIV where the CS was tuned, this requirement was not very critical since no optical nor sensitive components were inside the VV. That's why, even if this requirement was not fulfilled at CVC1 (see Figure 7), this was not a problem by that time. Indeed, once the instrument has been installed and started up at CAHA, the cold mass working temperature requirement has been respected (see Figure 9).

Eventually, the LN2 consumption requirement is also fulfilled as shown in Figure 8. This graph belongs to CVC1 stability phase, where the LN2 consumption was 89.5 l/day. Mention has to be done that the fulfillment of such a requirement depends strongly on the good insulation of the external cooling hoses and tubes. Indeed, these components are vacuum-insulated in order to minimize thermal load from environment. Nevertheless, if the vacuum level degrades inside these hoses and tubes, the LN2 consumption will increase importantly.

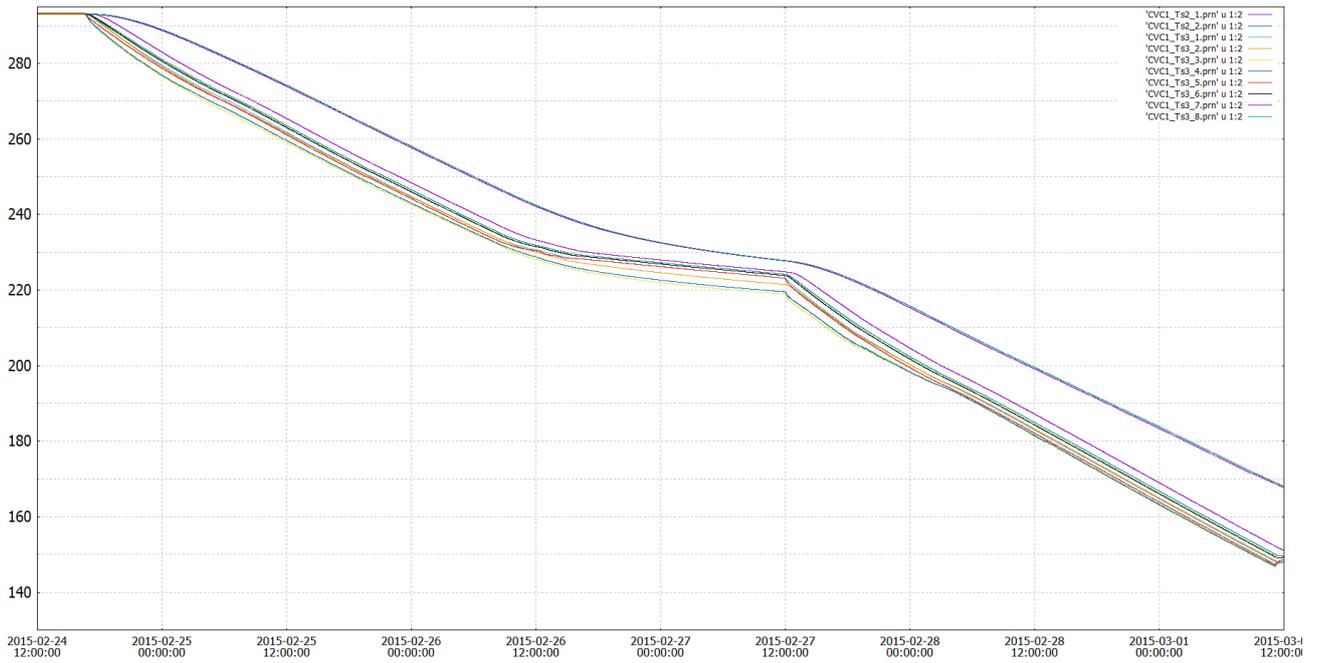


Figure 5. OB cooldown during CVC1. The maximal cooldown rate was around 2K/h.

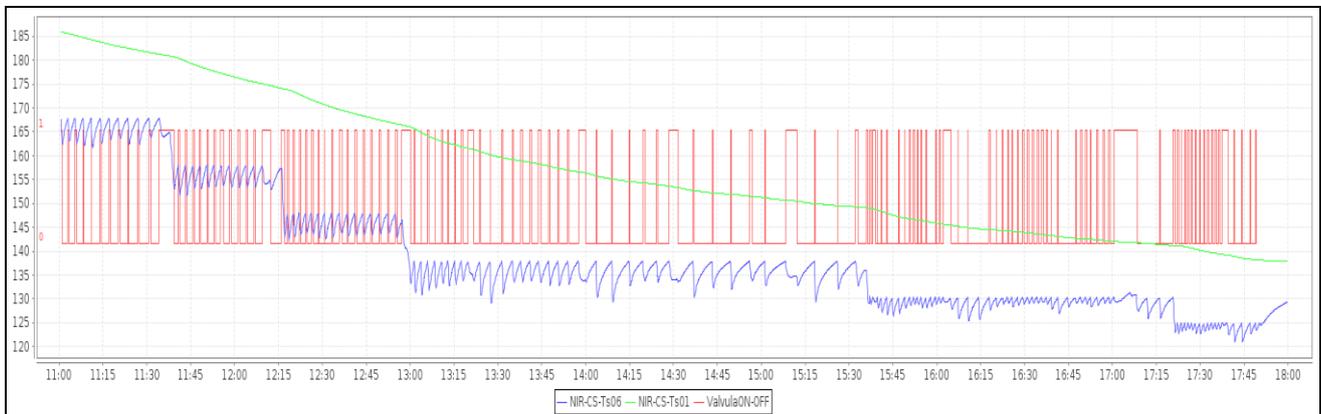


Figure 6. Typical transient cooldown of the RadSh. Note the different temperature steps provided to the heat exchanger associated to the temperature control sensor by giving successive set-points. The behaviour of that heat exchanger is coupled to the open/close regime of the on/off valve. Note how the temperature teeth in the heat exchanger are perfectly aligned with the open/close states of the on-off valve.

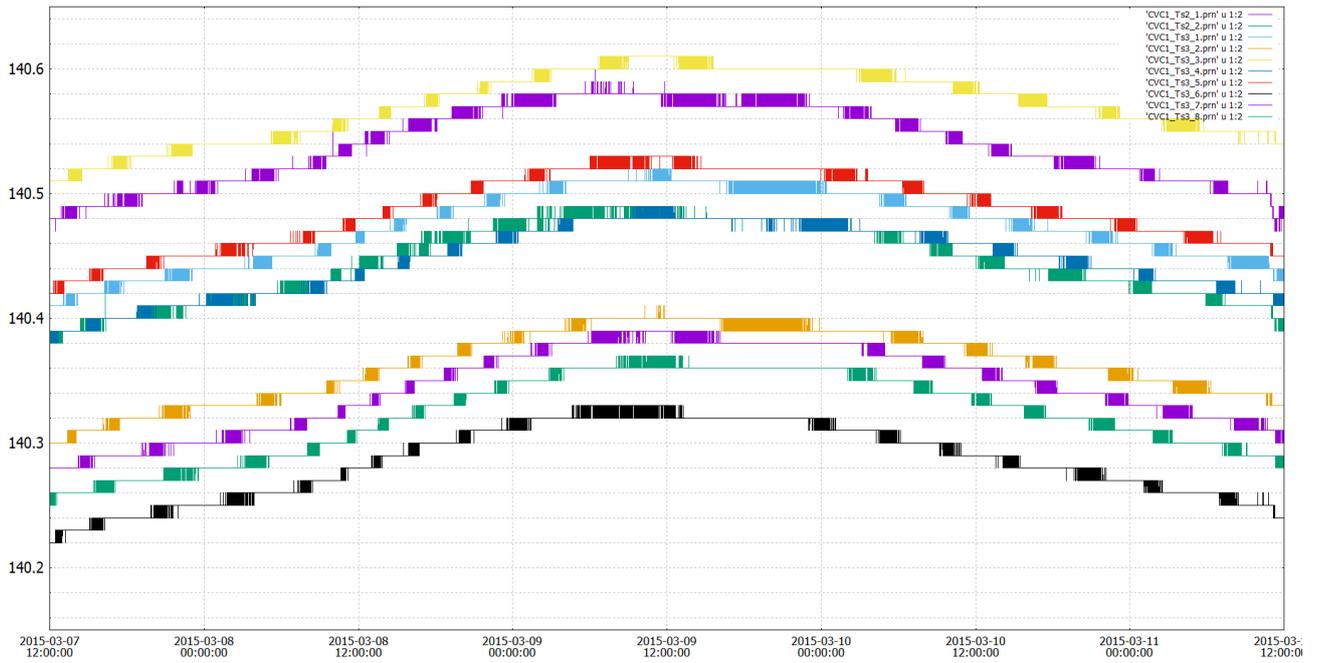


Figure 7. Thermal behaviour of the OB during the short stability phase at CVC1. Note the very narrow temperature gradient along and across the OB. For any time of this phase, all the ten sensors there monitored are within a range of 0.3K. Note, in addition, that all the sensors were within 0.1K variation during the 4 days this stability phase took long.

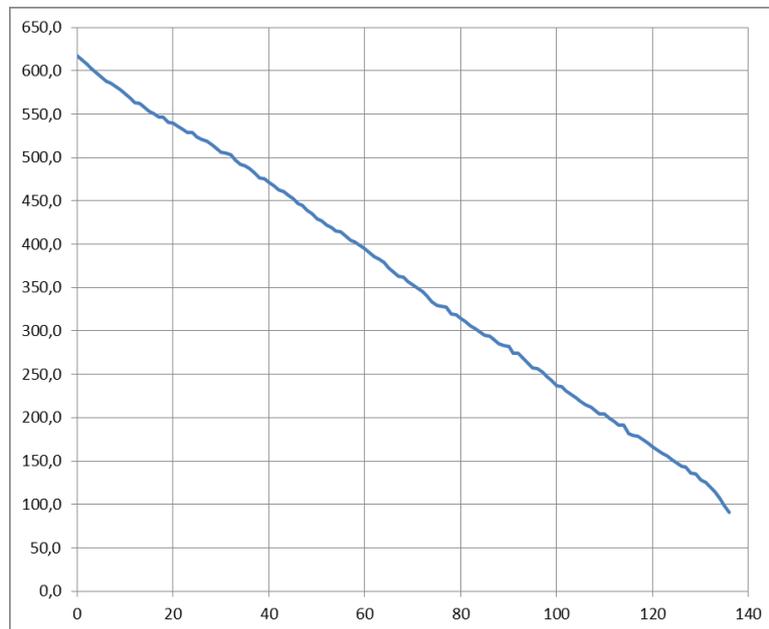


Figure 8. LN2 consumption (liters) versus time (hours) during CVC1 stability phase.

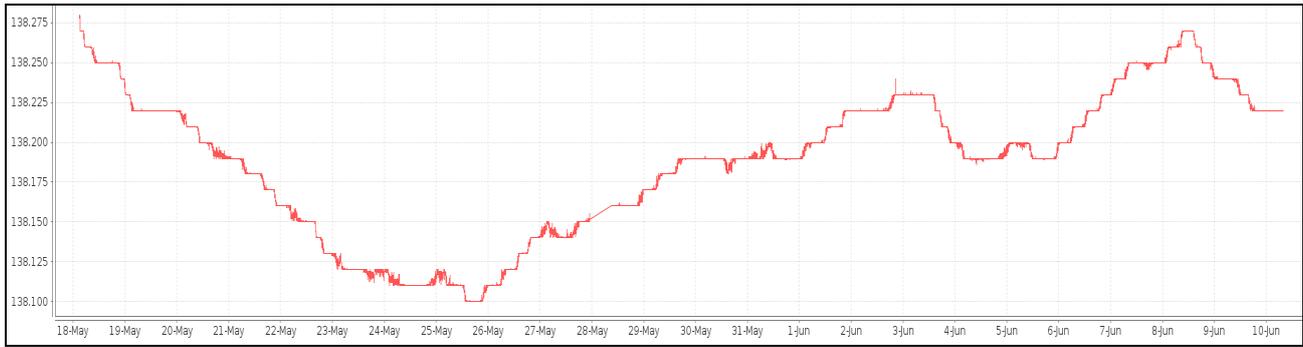


Figure 9. Temperature stability of the OB during 3 weeks (from May 18th to June the 10th 2016). Note that the working temperature requirement is fulfilled since it is within 138 ± 0.4 K.

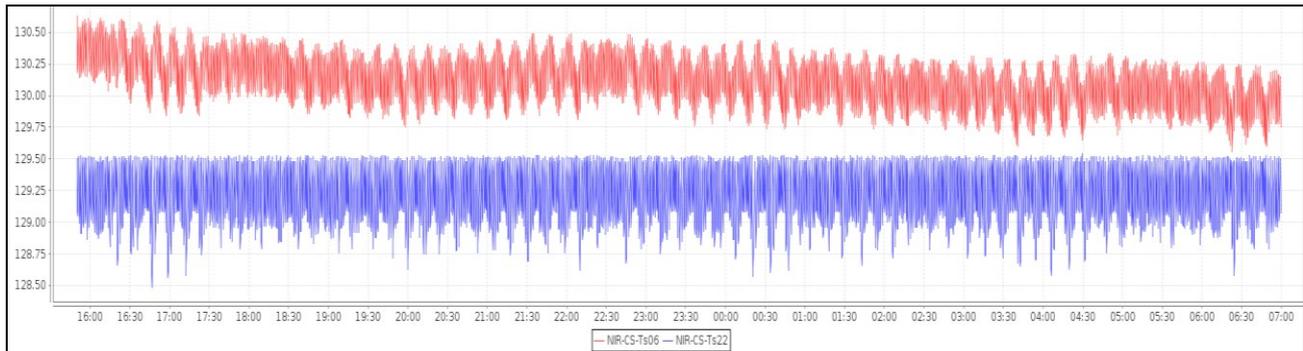


Figure 10. Thermal performance of the RadSh during the stability phase. The oscillations produced are intrinsic to the CS “modus operandi”. When the control sensor (blue) has reached its setpoint, the on/off valve opens and the coolant flow starts decreasing the temperature of the heat exchangers. Once the deadband’s low limit is reached, the valve closes and the heat exchangers see its temperature increasing. Red curve corresponds to a heat exchanger –also on the RadSh– whose sensor is not controlling the on/off valve, so this is the natural response of the heat exchanger to the control.

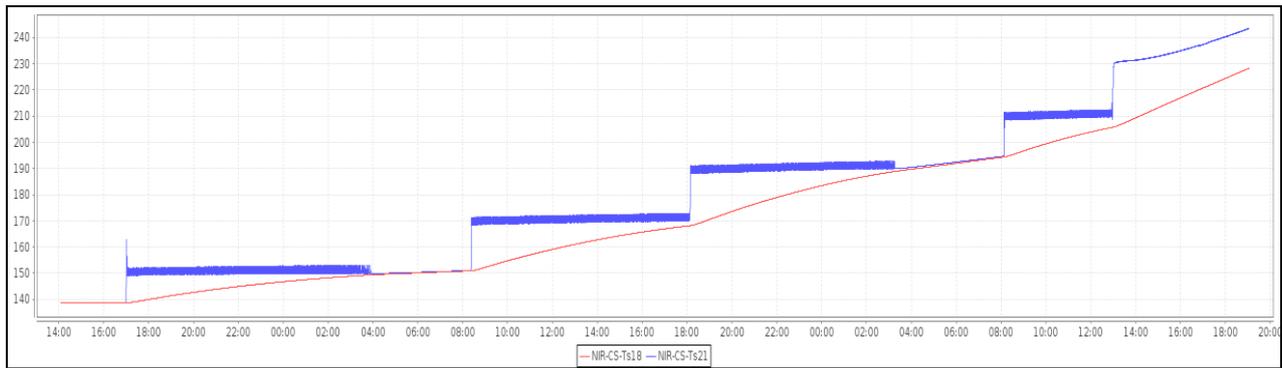


Figure 11. Thermal behaviour of the OB during the warm-up phase in CVC1.

CONCLUSIONS

As described in the previous section, all the technical requirements applicable to the CARMENES-NIR CS have been fulfilled. The most critical one concerns the temperature stability of the cold mass. Compliance with this requirement has been shown from the beginning of the AIV phase at system level. During the CVCs taken place at IAA just checks in the short term were done concerning the temperature stability. Nevertheless, very soon it was shown that the concept of the CS was very robust and very good prospective came up about its performance.

Indeed, the cold mass is almost as default thermally stable within the requirement (0.07K/day), very often the goal (0.01K/day) being fulfilled. This has been confirmed in the mid-term of several weeks during CARMENES-NIR operation at CAHA.

The most difficult requirement to be fulfilled is the LN2 daily consumption and is strongly dependent on the vacuum level of the external cooling hardware (hoses, tubes, extensions, etc...). Daily consumption was at the limit of the value required by the time where CVC1 took place. Later on during the AIV phase, this requirement has not been always fulfilled. This has led to set a regular maintenance on the vacuum level of the external cooling hardware.

Eventually from the start-up at CAHA on, the CARMENES team –together with the CAHA staff involved- has improved the behavior of the RadSh itself because of its influence on the radial velocities measured by the instrument. During the AIV phase, errors on radial velocities were not measured and main focus was put on the temperature stability of the OB, which was very easily reached regardless the temperature profiles on the RadSh –within a reasonable range, obviously.

The present performance of the CS has been a complete success and demonstrates how well the complex analyses done in previous design phases of the CS fit the real performance. The complete track of the design and analyses performed for this final success of the CARMENES-NIR CS are all published in the SPIE proceedings as referenced in [2], [3] and [4]. This states a very good starting point for future instruments requiring ultra-stable thermal conditions in cryogenics.

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