Performance and technical commissioning of an ultra-stable cooling system for a mid-range cryogenic astrophysical instrument (CARMENES-NIR)

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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 of two separate spectrographs, VIS channel (550-1050 nm) and NIR channel (900-1700 nm). The Instituto de Astrofísica de Andalucía, IAA-CSIC was responsible for the NIR-channel spectrograph. This was installed at the telescope by the end of 2015, technical commissioning and final tuning of the instrument being extended up to fall 2016. In that sense, one of the most challenging systems in the instrument involves the cooling system of the NIR channel. It is a key system within the stability budget and was entirely under the control of the IAA-CSIC. That development has been possible thanks to a very fruitful collaboration with ESO (Jean-Louis Lizon). The present work describes the performance of the CARMENES-NIR cooling system, mainly focusing on the extremely high thermal stability –on the order of few cK- around the working temperature (138K), as well as the main events and upgrades achieved during commissioning. As a result of its performance, CARMENES-NIR is a cornerstone within the field of astrophysical instrumentation and, in particular, related to discovery of earth-like exoplanets.

1. Introduction and requirements

The present paper describes briefly the design of the CARMENES-NIR cooling system and its performance during commissioning (functional mode) and in operation (ultra-high stability mode) of the instrument at CAHA (Observatorio Astronómico Hispano-Alemán de Calar Alto).
During commissioning the cooling system parameters were first tuned in order to fulfill technical requirements. It was later on – with the instrument already in operation at CAHA- that further tunings were made to reach a higher degree of thermal-mechanical stability. The resulting configuration is the so-called “ultra-high stability mode", which minimizes the precision error of the instrument thus enhancing its capability for exoplanets hunting.

For a more detailed description of the cooling system design, see the companion paper by Lizon (ref [11]). The applicable requirements are:

- Working temperature: 138±0.4 K
- Temperature stability: ±0.07 K/day (goal: ±0.01 K/day)
- Cooldown and warm-up rate: <10 K/h
- Vacuum level: 10\(^{-6}\) mbar
- Liquid nitrogen consumption: <90 l/day

The requirement concerning the cooldown and warm-up rates was driven by preservation of the spectrograph’s optical components. Indeed, since optical materials have very poor thermal conductivity, large gradients throughout the component may arise in case of fast cooldown and warm-up. This may stress or damage the very delicate, sensitive optical components. Note that this requirement only applies to the transient stages of the instrument, not to the permanent, operational stage. Therefore, it is not necessary to maximize warm-up and cooldown speeds within the values specified.

2. Cooling system concept and layouts

The CARMENES-NIR cooling system concept (see Figure 1 and refs. [2], [3] and [5]) based on a radiation shield which is wrapped with multi-layer insulation. That shield is actively cooled in operation. On the other side, the optical bench, which supports all the optics and opto-mechanical components, is completely enclosed by the radiation shield. Therefore, in working conditions the optical bench is kept at 138±0.4 K by keeping the radiation shield at its steady-state temperature.

![Figure 1. Overall view of the CARMENES-NIR cooling system. All the opto-mechanical components are on the optical bench. The detector cryostat is also shown interfacing with both the opto-mechanical assembly and the radiation shield.](image)

Because the optical bench is passively cooled, its high mass (about 1000 kg) and thermal isolation make it extremely stable. Both the cold mass (optical bench + opto-mechanical components) and the radiation shield are inside a vacuum vessel.

The coolant (liquid nitrogen) is fed by a 350-l dewar and goes directly to an external device (nitrogen gas preparation unit) which evaporates the flow and carries it to the working temperature by means of several PID control loops. The coolant coming out from the nitrogen gas preparation unit
goes into the vacuum vessel and cools down the radiation shield through 19 heat exchangers distributed in 10 cooling lines. This configuration’s layout is shown in Figure 2.

![Figure 2. Operation configuration layout.](image)

This cooling process is not valid for pre-cooling purposes because the optical bench would need extremely long times to cool by radiation from room temperature. Therefore, an appropriate configuration for pre-cooling is necessary (Figure 3). 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.

![Figure 3. Pre-cooling configuration layout.](image)

Finally, the active cooling of the radiation shield in operation is achieved by setting a target temperature (setpoint) to an 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 opening and closing of that valve keeps the temperature sensor value within a deadband under the set-point introduced. The design here described is based on continuous-flow cooling techniques developed at ESO (Jean-Louis Lizon).
3. Performance of the cooling system during the commissioning phase (functional mode)

The aim of the commissioning phase (see ref. [1]) was to ensure the fulfillment of thermal requirements. The tuning and settings here implemented to reach these requirements led to a configuration running the instrument in the so-called “functional mode”. Some of the requirements applicable to the cooling system concern how the instrument is carried from room to working conditions through a so-called “cryo-vacuum cycle”, which is composed of the following steps:

1. **Pump-out phase**: This phase includes roughing pump and turbo-pump start-ups for the vacuum vessel, the nitrogen gas preparation unit and the detector cryostat [ref. 6] to get the appropriate vacuum level.

2. **Cold mass pre-cooling phase** (see Figure 3): Once the vacuum inside the vacuum level is about 1·10⁻⁴ mbar both in the detector cryostat and the vacuum vessel, the pre-cooling phase can start both for the detector cryostat and the cold mass (inside the vacuum vessel). The exhaust coolant coming out from the vessel is re-directed to the nitrogen gas preparation unit and later on to the radiation shield. The on/off valve is permanently open (#14 in Figure 2). Figure 4 shows the thermal behavior of the cold mass during the cooldown phase from room temperature in the lab (293 K) to working temperature. Cooldown rate was around 2 K/h, which is compliant with the requirement. This conservative performance makes the pre-cooling phase quite longer than needed. Nevertheless, this was not a critical issue even if this stage could have been faster by increasing liquid nitrogen flow. Note that this requirement does not apply to the operation phase because the instrument is then kept at working conditions 24 h/day with the cooling system permanently on.

![Figure 4](image_url)

**Figure 4.** An example of optical bench cooldown during technical commissioning. The "plateau" in the central was produced because the inlet flow from the liquid nitrogen dewar was not enough to keep the cooldown at the previous rate. At 2015-02-27 12:00, the flow was increased and so the cooldown rate enhanced. Note that this did not happen during the operation phase.

3. **Radiation shield cooldown transient phase**: Once the optical bench 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 radiation shield is typically around 200 – 210 K. The temperature of the shield is decreased to its working temperature within less than 21 hours in order to keep the optical bench close to its operation temperature. At this point, the on/off valve is fully operative.

4. **Stability phase**: This phase starts when the temperature control sensor at the radiation shield reaches its working temperature (129.5K). The optical bench and the shield will progressively approach its thermal equilibrium where the radiative exchange will be equal
to the conductive losses of the optical bench. Indeed, the optical bench has very low thermal losses through the pre-cooling circuitry hardware and its supporting pads. So the radiation shield needs to be at slightly lower temperature as compared to the OB in order to drain these thermal loads out of the system. Figure 5 shows a time frame of 4 days and how the temperature stability requirement was fulfilled at each one of those 4 days. Another example is shown in Figure 6: During 3 weeks the optical bench never moved further than 0.17 K (between 138.1 and 138.27 K), the stability requirement being fulfilled (< 0.07 K/day) every single day. Likewise, the goal (0.01 K/day) was very often reached.

**Figure 5.** Thermal behaviour of the OB at a very early stage of the commissioning. Note that stability requirements are fulfilled even if the cooling system parameters were not yet fine-tuned. Indeed, thermal stability at its best performance needs time but performance here shown was during one of the cryo-vacuum cycles where the instrument was kept at its operational conditions just for few days.

**Figure 6.** Temperature stability of the OB during 3 weeks (from May 18th to June the 10th 2016).

5. **Warm-up phase:** This procedure was used during commissioning phase to finish any cryo-vacuum cycle in order to proceed with the plan. Some heaters on the optical bench are controlled by setting successive set-points on a specific sensor. Each set-point was held until the optical bench reached a nearby temperature. Then a new, higher set-point was applied. Warm-up requirement was fulfilled since its rate was around 4 K/h.

During commissioning (functional mode) the shield setpoints and the nitrogen gas preparation unit PID's parameters were first tuned. At that time, the shield was kept around 135 K to induce having the optical bench at 138.1 K. Note that the gradient across the shield is wider as compared to the optical bench. The temperature of 135 K applies to the large areas of the shield away from the cold spots (heat
environment. Nevertheless, if the vacuum level degrades inside these hoses and tubes, the LN2 consumption will increase importantly.

Figure 7. Thermal performance of the RadSh during the stability phase (commissioning): The lower curve belongs to the controlling sensor of the RadSh –placed on one of its heat exchangers- submitted to the temperature setpoint driven by the on/off valve, whereas the upper curve belongs to the non-directly-controlled behavior of another sensor –also placed on a heat exchanger.

Figure 8. LN2 consumption (liters/h) reached during working conditions phase in a typical commissioning cryo-vacuum cycle.

4. Performance of the cooling system during operation (ultra-high stability mode)

Once the thermal requirements were fulfilled in its functional mode (commissioning phase) and the operational phase of the instrument was started, efforts were focused on further enhancing thermal stability. Indeed, the instrument’s thermal stability directly translates into its error.

Thus, the better the thermal stability is, the lower the instrument’s error. The resulting configuration defines its ultra-high stability mode, which is currently running and enhancing the outstanding science in the field of discovery of Earth-like exo-planets.

To reach this aim, further tunings were implemented to the nitrogen gas preparation unit PID parameters as well as the radiation shield set-points. A key upgrade consisted of modifying the location of the sensors driving the PID closed-loop controls of the several stages of the nitrogen gas preparation unit.

Indeed, the nitrogen preparation unit is based on a series of two conditioning stages of the flow. Liquid nitrogen flow is first evaporated (1st stage) and, once fully in gaseous phase, it is warmed up
(2nd phase) to its working temperature. Each of these two processes is managed by a single PID controller. In turn, each PID loop provides control action through a heater while the signal to be stabilized is the one of a temperature sensor located on the corresponding conditioning stage.

First location of those sensors was not the most appropriate because they were closer to the heater than to the coolant flow. This led to wrong action ordered by the PIDs and, therefore, bad control issues. New location was at the exit pipe of the each stage and so the temperature signal was much closest to the exit temperature of the flow. This provided much more stabilized flow at the exit of the nitrogen gas preparation unit.

As a consequence, thermal stability reached on the optical bench is as good as 0.07 K P-V in 1 month and 0.02 K P-V in 1 week (Figure 9 and Figure 10). Besides that, the steady-state temperature gradient across the optical bench is 0.24 K (Figure 9), which gives a notion of the temperature homogeneity of the bench. Stability on the radiation shield has also improved accordingly (Figure 11) up to 0.25 K P-V in 48 h.

Figure 9. Thermal behaviour during 1 month of the optical bench in the instrument’s ultra-high stability mode.

Figure 10. Detailed temperature evolution of a single sensor the optical bench (ultra-high stability mode). Time frame is the same as for the Figure 9.
performance thus reached is as follows:

\[ T(\text{K}) \]

\[ 135.4 \]
\[ 135.6 \]
\[ 135.8 \]

5. Conclusions

During the commissioning phase (functional mode), all the requirements applicable to the cooling system were fulfilled. More important, the most critical requirement of thermal stability was reached from the very beginning, which gives an idea about how good the thermal concept is.

Once the instrument was set into operation, an upgrading phase took place just focused on thermal stability performance since this parameter directly scales on lower precision errors. The main upgrade here implemented consisted on the re-location of the temperature sensors driving the N2GPU. The performance thus reached is as follows:

- OB stable within 0.07 K in one month (0.02 K in one week).
- RadSh stable within 0.25 K P-K in 48 h.

Eventually, the present state of the instrument gives a very advantageous starting point for further applications on ultra-high-accuracy next-generations instruments.

6. References

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