CARMENES. V: Non-cryogenic solutions for *YJH*-band NIR instruments

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ABSTRACT

Currently, every single instrument using NIR detectors is cooled down to cryogenic temperatures to minimize the thermal flux emitted by a warm instrument. Cryogenization, meaning reaching very low operating temperatures, is a must when the *K* band is needed for the science case. This results in more complex and more expensive instruments.

However, science cases that do not benefit from observing in the *K* band, like the detection of exoplanets around M dwarfs through the radial velocity technique, can make use of non-cryogenic instruments. The CARMENES instrument is implementing a cooling system which could allow such a solution. It is being built by a consortium of eleven Spanish and German institutions and will conduct an exoplanet survey around M dwarfs. Its concept includes two spectrographs, one equipped with a CCD for the range 550-950 nm, and one with HgCdTe detectors for the range from 950-1700 nm, covering therefore the *YJH* bands.

In this contribution, different possibilities are studied to reach the final cooling solution to be used in CARMENES, all of them demonstrated to be feasible, within the requirements of the SNR requested by the science case.

Keywords: Planet finder, M-dwarf stars, exoplanets, Near-infrared spectroscopy, High-resolution spectroscopy

1. INTRODUCTION

1.1 Scientific programs benefiting from *YJH*-band observations

Several science programs can benefit from observing solely in the *YJH*-band region of the infrared spectrum, which means leaving out the *K* band and the regions beyond.

Stars less massive than M = 0.3 $M_{\odot}$ (i.e., later than M4) have temperatures lower than T~3000 K and emit the bulk of their flux at wavelengths beyond 1000 nm. Although a number of planets around early-M dwarfs have been found with visible spectrographs, mid- and late-M dwarfs are normally far too faint at this wavelength range to reach the data quality required for the detection of planets. Redward of ~1000 nm, the flux emitted by these stars is several factors higher than in the visible so that at near-IR wavelengths, many low-mass stars are in principle bright enough to be observed at very high precision. [1,2] carried out detailed simulations of the achievable precision in radial velocity (RV) determinations in the NIR region and found that the *Y* band is the optimum range, followed by the *JH* bands, when observing very low mass stars. While the *Y* band delivers the best precision, the *J* and *H* bands are also extremely useful to allow for proper estimate of activity effects and to increase the RV precision.

Magnetic activity is believed to be one of the most challenging problems mimicking RV variations or making RV signals much more difficult to detect. However, the dependence of activity variability amplitude with wavelength makes of the use of the *YJH* bands a very useful tool to distinguish this variation from a pure RV signal. The wavelength dependence

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of activity-induced RV signals will result in at least a factor of 2-3 different amplitude in the range 500-1700 nm with respect to the visible region, and thus provide an efficient and safe way to discard spurious signals.

Stellar pulsations in low mass stars have been theorised by [3] but are still to be observationally found. The discovery of these pulsations will allow the use of the full potential of asteroseismic techniques for the study of the structure and evolution of these stars. Asteroseismology benefits from the individual identification of the pulsation modes distorting the surface of the star and this can be achieved by the study of those pulsations in different spectral ranges. *YJH*-band RV or line profile observations in comparison with visible observations can provide the identification needed for asteroseismology to probe the interior of the stars.

Solar-mass red giant stars have also their emitted flux peaking at NIR wavelengths. Therefore, all these research lines applied to giant stars also benefit from the information provided by the *YJH*-band wavelength range.

1.2 Instrumentation

The benefit provided by this wavelength range comes from the fact that, not needing the *K* band, the amount of thermal background from a warm, or better, a non-cooled instrument, which can reach a sensitive detector can be minimized, although not completely removed.

[4] investigated the possibility of using large astronomical spectrographs, which had been designed for use in the visible, in the NIR. These spectrographs maintain a good efficiency well beyond the long wave-length cut-off of CCD detectors. They argued that, if one takes into account the large cost and complexity of constructing Infrared (IR)-optimized high resolution or multi-object spectrographs, it would be just a responsible thing to do to investigate the performance of those visible spectrograph equipped with modern NIR detectors to exploit a specific range of scientific programs. They did so and used a NIR camera (NICMASS) in the Coude Feed Spectrograph on Kitt Peak for moderate and high resolution infrared spectroscopy in the 1000-1800 nm range finding that the main performance limitation was imposed by the thermal background originated in the ambient-temperature spectrograph beyond a wavelength of 1000 nm.

[5] have also discussed this issue for the pathfinder of the HZPF instrument. Both are high-resolution spectrographs designed specifically to cover all or some part of the *YJH* region for the detection of planets around low mass M stars. The pathfinder is working at ambient temperature with a Hawaii-1 detector sensitive to 2500 nm. They mitigate the thermal background in the *Y* band by using a combination of filters of different materials and different coatings kept at cryogenic temperatures within the detector cryostat to suppress the thermal background at 10^{-5} level from 1300-3000 nm. HZPF will be working at a temperature of ~190K kept stable by using resistive heating elements and closed-cycle coolers.

Even if instrument temperatures can be raised to avoid the complications of cryogenics, those of the detectors still have to be sufficiently low to improve dark-current and noise characteristics. New technologies are being tested to avoid current cryogenic cooling system technologies, which make them costly, heavy and limit their applicability, for eventually being able to operate these detectors at temperatures that could be reached with thermoelectric coolers, which could lead to lighter and more compact systems [6], or even at ambient temperatures [7].

Currently there are few instruments which are or will be working in the *YJH* range of the NIR spectrum at non-cryogenic, non-Liquid Nitrogen (LN), temperatures. One of them is CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs), a next-generation instrument to be built for the 3.5m telescope at the Calar Alto Observatory by a consortium of eleven Spanish and German institutions [8].

1.3 CARMENES

CARMENES will be conducting a five-year exoplanet survey in search for very low-mass planets (i.e. "super-Earths") around ~300 late and moderately active M-type stars. In order to fulfil our science requirements and to be internationally competitive the proposed instrument consists of two independent high-resolution echelle spectrographs, working in parallel mode using a dichroic beam splitter to distribute the light. The two spectrographs are:

a. a near infrared (near-IR) spectrograph (operational wavelength 950–1700 nm)

b. a visual spectrograph (operational wavelength 550–950 nm)

The two spectrographs will cover their respective wavelength ranges at a spectral resolution of R = 82,000, fed by fibres from the Cassegrain focus of the telescope. The spectrographs are housed in vacuum tanks providing the temperature-stabilized environments necessary to enable a 1m/s radial velocity precision employing a simultaneous calibration with an emission-line lamp. Below, the CARMENES cooling system will be briefly discussed.

The simultaneous combination of optical and near-IR spectrographs make CARMENES an internationally unique instrument with the capability to disentangle radial velocity (RV) variations due to spots and other stellar activity effects from the presence of planetary companions and to characterize stellar pulsations when they are eventually detected in these stars. Furthermore, because of the comparable velocity accuracy achieved in the visible and near-IR for early and mid M spectral types, the RV precision will be increased thanks to the broad wavelength coverage.

2. GENERAL PROBLEM: BACKGROUND THERMAL RADIATION

One of the main complications in a near-infrared (NIR) instrument, resulting in higher total cost, is the need for cooling it down sufficiently as to avoid that the thermal background flux at the wavelength range of interest reaches the detector.

The radiation emitted by a black body at a certain temperature is given by the Stefan-Boltzmann law, which is just the result of the integration of Planck's distribution

The number of thermal photons per time unit that are received at a detector (individual pixel) is computed in the following way:

The approximation that each pixel, with area A, sees a warm instrument at the working temperature is made. This translates to assuming that the detector is at the centre of a hemisphere (radius unity) with an inner surface at instrument temperature and emissivity ε=1.0. The thermal emission from the hemisphere is given by the Planck function

$$B(\lambda, T) = \frac{2\mathrm{h}c^2}{\lambda^5}\frac{1}{e^{\frac{\mathrm{h}c}{\lambda kT}} - 1}\ \mathrm{W\,m^{-2}\,m^{-1}\,sr^{-1}}$$

where *h, k*, and *c* are Planck's constant, Boltzmann's constant, and the speed of light respectively.

The number of thermal photons per pixel expected in a time unit is then:

$$N_{\mathrm{ph}} = A\epsilon\frac{\int_{\lambda_1}^{\lambda_2} B(\lambda, T)d\lambda}{\mathrm{h}c/\lambda}\int d\Omega\ \mathrm{photon\ pix^{-1}\ s^{-1}}$$

Because black bodies are Lambertian (i.e. they obey Lambert's cosine law), the intensity observed along the sphere will be the actual intensity times the cosine of the zenith angle φ, and given by dΩ = sin(φ) dφ dθ in spherical coordinates. Therefore, for a hemisphere:

$$\int d\Omega = \int_0^{2\pi} d\theta \int_0^{\pi/2} \sin\varphi\cos\varphi d\varphi = \pi$$

and for a generic angle *φ,* the resulting solid angle is $\Omega=\pi\sin^2(\varphi)$. When this integral is performed for the whole wavelength range, i.e., when the total energy radiated per unit surface area of a black body per unit time (also known as the black-body irradiance or emissive power), is considered, this energy is directly proportional to the fourth power of the black body's thermodynamic temperature *T* (Stefan–Boltzmann law).

3. OPTIONS FOR A NON-CRYOGENIC INSTRUMENT

As mentioned above, a NIR instrument has to efficiently cut-off sufficient background thermal flux as to be able to run the scientific program in a photon-noise dominated regime.

In CARMENES, for instance, the noise requirement is such that the spectrograph will be photon-noise limited at a SNR=70, i.e., other sources of noise will be much smaller. This is quantified by the condition that each of these other sources will not increase the total noise by more than 10%. Noise sources such as detector read-out (RON), dark current (DC) or thermal background should therefore be smaller than 0.04 electrons/s/pix each. The first two are fixed by the detector characteristics whereas the third one is reduced by lowering the temperature of any radiant surface whose photons could reach the detector.

Three ways to reduce the thermal background onto the detector have been foreseen:

1. Equipping the instrument with a sufficiently blue cut-off detector. This may not be a real option as it will be seeing below.
2. Reducing the solid angle of warm instrument seen by each pixel by using a cryogenic baffling.
3. To place a cut-off filter just in front of the detector.

Below, each of these options is studied to assess their effectiveness for lowering the thermal flux sufficiently to be able to raise the minimum operating temperature to allow for a non-cryogenic solution.

3.1 Detector choice

The main restriction to a non-cryogenic solution comes from the availability of a detector which does not see the exponential raise of background thermal flux at a non-cryogenic temperature. To date, Teledyne Imaging Sensors is the only manufacturer that develops and produces high performance infrared sensors. These IR sensors are hybrid CMOS arrays, with HgCdTe used for light detection and a silicon integrated circuit for signal readout. Currently, the most advanced sensors are based on the Hawaii-2RG (H2RG), 2K×2K array with 18 µm pixel pitch. The HgCdTe detector achieves those specifications listed in Table 1, and can be tuned to provide a wavelength cut-off at 1700 (hereafter H2RG17) and 2500 nm (H2RG25).

The thermal background is, in any case, negligible below a spectrograph temperature of about 130 K with respect to the lowest dark current, of 1e-/pix per 1000 s, expected in any of these two NIR detectors.

Table 1: Summary of specified and typical values for H2RG17 and H2RG25.

	Comments	Typical 1.75µm	Spec. 1.75µm	Typical 2.5µm	Spec 2.5µm
Mean QE	800 nm	58%	≥ 50 %	83%	>70%
	1000 nm	57%	≥ 50 %	81%	>70%
	1230 nm	73%	≥ 70 %	78%	>70%
	1500 nm /2000nm	86%	≥ 70 %	81%	>70%
	Variation of QE (RMS)	15%	…	5%	-…
Median Noise CDS		19e rms	<30e rms	10e rms	<18e rms
Fowler 16		8.2e rms		3.7e rms	
Median DC		0.001e/s	<0.05e/s	0.004e/s	<0.05e/s
Well depth		96000	>80000	98000	>80000
Power dissipation		0.3mW	<1mW	0.25mW	<1mW
Cross talk		0.90%	<2%	0.80%	<2%
Operability		98.30%	>95%	99.20%	>95%
Clustering		0.01%	<1%	0.02%	<1%

However, for the selection of the detector to be equipped in a spectrograph, the specifications of the rest of its parameters, not only its cut-off wavelength, are also important and need to be considered to evaluate their impact in the science to be achieved.

Below, a comparison of the various parameters for these two detectors is provided:

Quantum efficiency

The specified QE for both types of detector is significantly different for the shorter wavelength bands 800 nm and 1000 nm (>50% compared to >70%), while for larger wavelengths the specified values are identical (>70%).

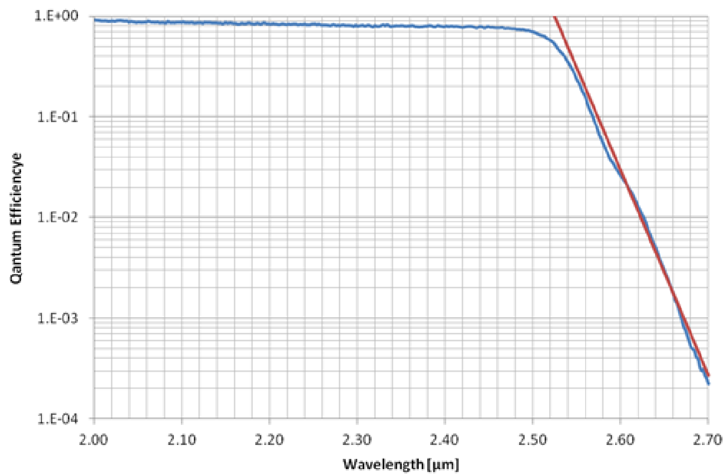

Figure 1: Measured and modeled quantum efficiency of Hawaii RG 2500 nm cut-off detector. Courtesy to Gert Finger.

Concerning the H2RG25 detector, the typical QE mean values can be expected to be beyond 80%. Concerning the H2RG17, the typical values that can be expected (but not guaranteed) were provided by Teledyne. The result is summarized in column 3 of Table 1: the typical QE values of the H2RG17 detector are significantly lower than those of the H2RG25.

The cut-off to wavelengths larger than about 2500 nm can be modelled by an exponential decrease in agreement with the theoretically expected behaviour (see Figure 1). Earlier detector arrays of type Hawaii2 have been observed to deliver non-zero quantum efficiency far beyond the cut-off wavelength (3200 nm) of 10^{-5} due to an extrinsic transition from impurity donors to the conduction band (see [9]). However, first: these values are well below the ones required; and second: they have been significantly improved since. Concerning the H2RG17 detector, no measured QE data are available beyond the cut-off wavelength.

In addition to the absolute value of the QE, there is a significant difference in homogeneity of the QE between these two detector types: The histogram of QE shows a tight peak at about 82% with a FWHM of about 5% points for H2RG25, while the corresponding histogram for H2RG17 is much broader (15% points FWHM). This variation is clearly displayed in the flat field, which shows scratches due to the polishing procedure. Obviously, the thinning procedure is much more difficult for the H2RG17 material. The same problem is revealed by the operability statistics.

Dark current

The specified dark current is identical for both types of detectors (0.05 e^-/s). However, the typical values are somewhat lower for H2RG17 even at 120 K (0.001 e^-/s) than for H2RG25 at 77 K (0.004 e^-/s).

The H2RG25 detectors can be operated in CARMENES at 85 K, which means a DC of 0.007 e^-/s. All these values are negligible contributions to the noise.

Figure 2 shows the dark current versus detector temperature for different detector's cut-off wavelength.

Read-out noise

The H2RG17 read-noise is typically a factor two larger than that of H2RG25, both concerning specified values (30 e^- compared to 18 e^-) as measured values (19 e^- compared to 10 e^-). For CARMENES typical observation 900s individual integration times are planned, thus, the lowest available read noise (32Fowler) has to be compared with DC*900 s, which is typically 0.9 e^- for H2RG17 and 3.6 e^- for H2RG25@77K or 9 e^- for H2RG25@85K. Again, all these values for the noise due to the dark current are negligible contributions to the noise.

Operability

The specification of the operability is the same for both types of detectors, however, the typical values differ significantly (98.2% for H2RG17 and 99.3% for H2RG25). For some delivered H2RG25s even an operability of 99.9% has been found.

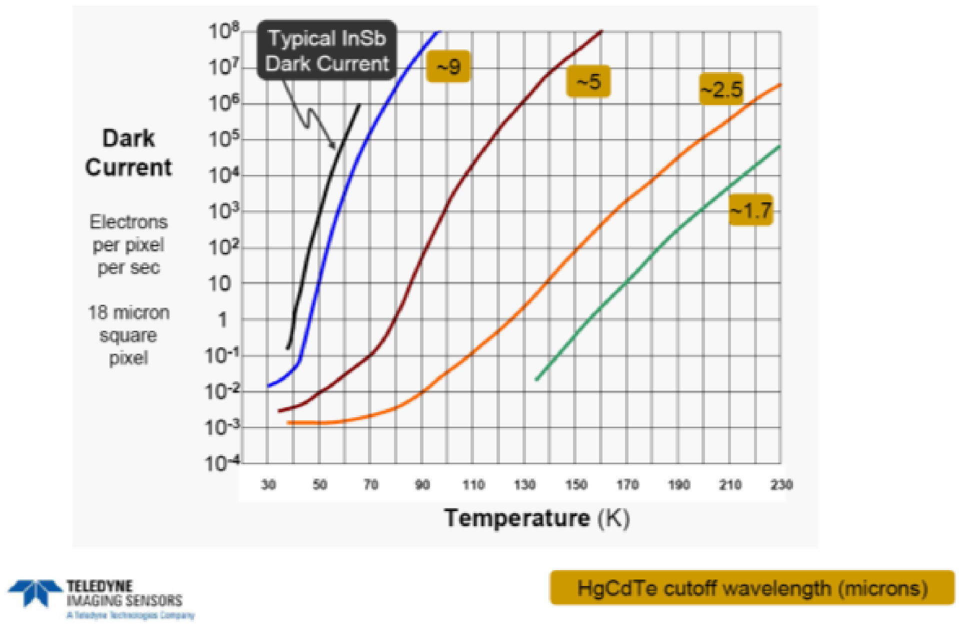

Figure 2: Dark Current vs. Temperature trade-off for the different detector's cut-off wavelengths. Courtesy of Teledyne Imaging Sensors.

Clustering

Again, the specification is identical for both types of array. The typical values are far below specification, 0.02% for H2RG25 and 0.01% for H2RG17. This difference is probably not significant, due to variations from chip to chip.

A final comment regarding these two detectors is that we find that Teledyne has not developed the H2RG17 sufficiently for scientific use. This is the reason why it is not in use yet in an astronomical instrument. It would be extremely interesting that they were further developed and reached sufficient maturity to provide specifications as good as the H2RG25.

For this reason, to date, this option is not estimated as a real one and hereafter all the computations and studies are made assuming the implementation of a H2RG25.

3.2 Filtering out the flux

The next possible solution to prevent thermal flux from reaching the detector is to block it out by using a filter. As mentioned above this is the solution used by the HZPF Pathfinder, which uses the *Y* band working at ambient temperature [5].

In principle, one could imagine that using blocking filters with a detector sensitive to 2500 nm should replicate the effect of the natural cut-off of the 1700nm detector. However, this is not the case.

There are only two materials that could provide the required cut-off at 1700 nm by absorption, which are Potassium Dideuterium Phosphate (DKDP) and Potassium Dihydrogen Phosphate (KDP). The former may not be available in sufficiently large dimensions depending on the surface needed to be blocked whereas the latter is under investigation in our laboratory. Large dimensions may be available and tests on KDP samples are currently been carried out, to determine parameters such as the transmittance as a function of the thickness (of the samples), vacuum and cryogenic survival temperatures and feasible coatings [10].

An alternative, not as good, solution would be to use PK50. The natural transmission of a 6 mm-thick glass together with the detector QE cut-off would help blocking out part of the thermal flux beyond 1700 nm (see Figure 3). This solution will allow raising the temperature of the instrument by only a few degrees (3 K). In any case, the use of such a blocking glass will assure that the thermal flux from 2700 up to 3500 nm will be blocked.

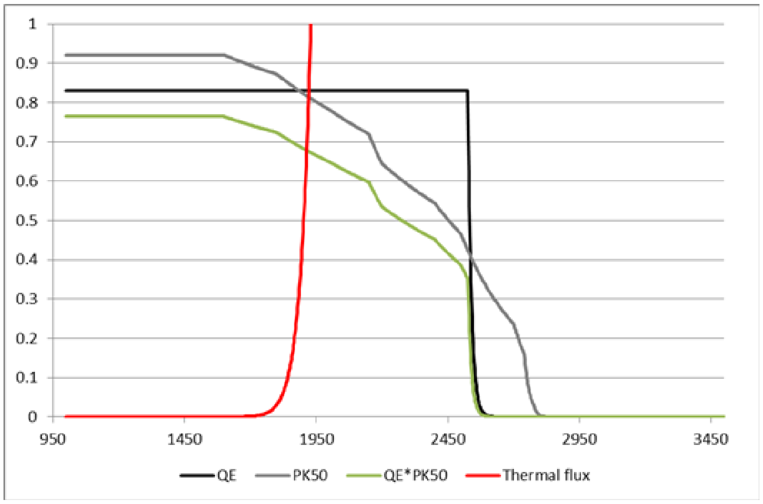

Figure 3: Realistic approximation of the H2RG2.5 QE curve (black), transmission curve of the PK50 6 mm-thick glass (grey), combined curve (green) and thermal flux (red)

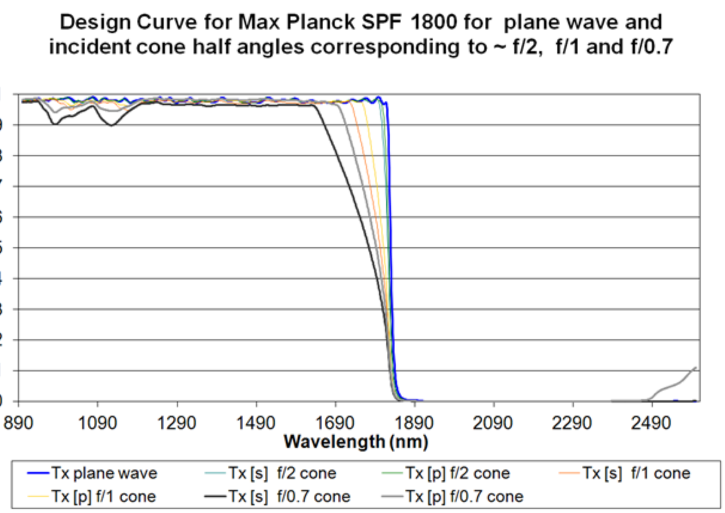

Figure 4: Optimized Cut-off filter to suppress photons beyond 1.8µm up to the detector cut-off at 2.5 µm for different cone angles. Courtesy to Peter Hook, IRIDIAN.

The next possibility to obtain such a filter is based on a multi-layer solution. This filter must be positioned just in front of the detector array. However, this filter will be efficient only if the offered solid angle seen by each pixel is smaller than 0.59 (corresponding to an f-ratio of 1, see Figure 4). Therefore, the incoming beam should nonetheless need to be baffled up to avoid noise gradients in the image. The cryo-mechanical consequences are described below.

Cryo-mechanical design aspects of this option

In case the thermal radiation between 1700 nm and 2500 nm should be blocked by a filter, this filter has to be mounted light-tight to the detector mount and cooled down to a temperature below 130 K. There is no material that provides such blocking effectively (the increase of absorption for DKDP is not steep enough and the KDP is still under study [10]), thus, such filter has to be realized as a multilayer dichroic filter. Unfortunately, the behaviour of such filters depends on the angle of incidence as mentioned above. If no cold baffling in front of the filter is provided, the detector is hit by the full half sphere of thermal background. Photons reaching the detector with large angles of incidence (outside the cone of about f/0.7) are able to pass the filter (see Figure 4). Thus, completely un-baffled reduction of thermal background by a filter does not seem to be feasible to date. A cut-off filter may only be used in combination with baffling and/or temperature reduction.

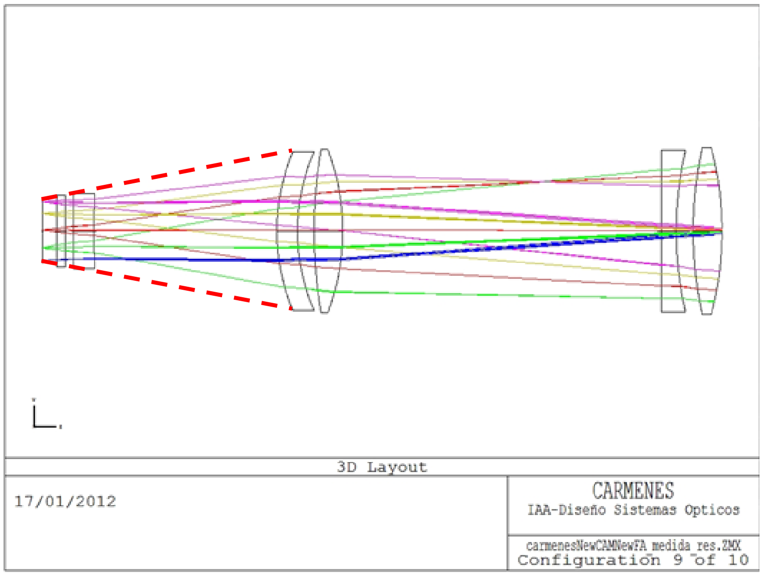

Figure 5: Schematic view of the CARMENES camera and the possible baffling (in red dashed line).

3.3 Internal cold baffling

The other possible solution to prevent thermal flux from reaching the detector is to block it out by using a cold baffling surrounding the detector (see Figure 5).

A cold baffle from the detector cryostat to the camera of the instrument will reduce the solid angle seen by the detector. Therefore the smaller thermal flux reaching the detector would allow increasing the temperature of the instrument. For CARMENES, however, this increase is small, being between 5 and 10 K. A larger, more complicated, baffle, enclosing the whole camera, would be needed to substantially reduce the background.

Cryo-mechanical design aspects of this option

This option can allow a higher instrument's temperature. However, the camera barrel gets more complex since an internal, cooled baffle should be included. This may complicate matters for thermally stabilised instruments, as this implies that a temperature stability requirement has to be set for this subsystem.

Furthermore, this baffling must be compatible with the interface with the detector head. The baffle would need to be shielded outwards by means of Multi-layer Insulation (MLI) and the rear part of the barrel would, therefore, become wider due to the baffle+MLI envelope.

Finally, inlets and outlets (and feedthroughs in the vacuum tank) will need to be foreseen to allow for the cooling lines for the baffle.

4. CARMENES SOLUTION

While earlier in the CARMENES development (at the time of Preliminary Design Review; PDR) an H2RG17 was chosen as the base line concept, after PDR and already during preparation of the Final Design Review (FDR), the CARMENES detector work package group identified possible risks in the H2RG17 detectors and suggested a change in configuration by equipping the NIR channel with the better known H2RG25. The decision was documented and discussed since, even if both detectors had specifications that were within the requirements of our science, it turned out that in terms of QE, noise properties and operability, the H2RG25 is a significantly better choice than the H2RG17. The new detector cut-off wavelength required, however, stronger constraints on thermal background reduction efficiency. Therefore, the previous options were studied to optimize the solution for CARMENES.

As mentioned above, the previous solution presented at PDR considered equipping the H2RG17 detector. The instrument operating temperature needed to reduce the thermal background to the required levels with those detectors was 210 K

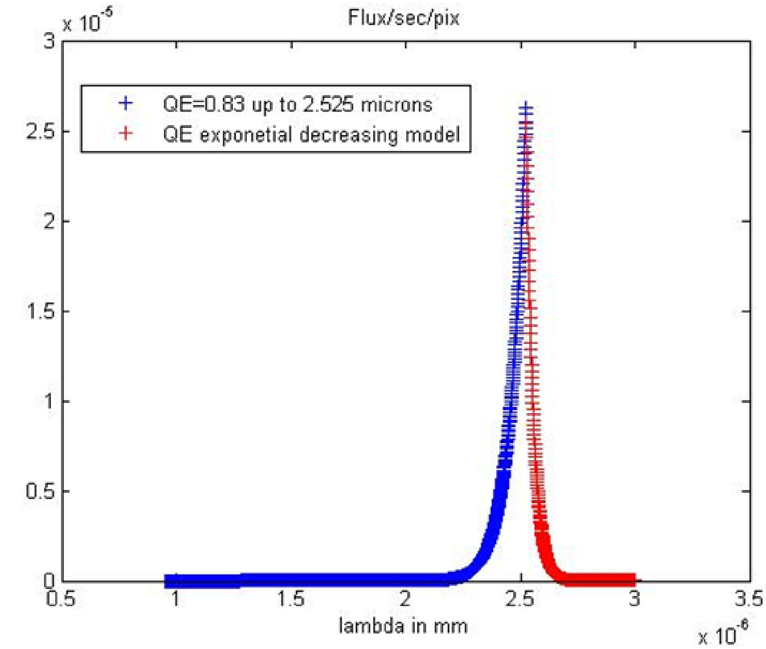

Figure 6: Background thermal flux (blue crosses) and assumed QE cut-off (red crosses) as a function of wavelength.

(−60ºC). A working temperature of 190 K (−80ºC), easily achievable by the CARMENES cooling solution at no extra-cost with respect to the 210K temperature, was chosen in order to keep a good safety margin.

Now the instrument will be equipped with the H2RG25 detectors, and, as has been shown above, the only feasible option to reduce the thermal flux to the required level is to set a new, cooler, operating temperature. The flux "seen" by these detectors has been computed assuming a constant detector QE of 83% up to λ_{cut}=2.525 μm and an exponentially decreasing QE of 0.83*exp(-47(λ- λ_{cut})) for longer wavelengths (see Figure 6).

Under these considerations, a working temperature of 140 K (−130ºC) is needed to reduce the thermal background thermal down to a value of 0.006 e^-/s/pix, which yields a flux of 6.0 e^-/pix for 1000 s. This means a 2.4 e^-/pix noise contribution in comparison with 3.7 e^-/pix Fowler16 RON and 2 e^-/pix DC noise.

The QE of any of these detectors has not been measured for wavelengths above 2700 nm. If, instead of the previous exponential drop in QE, a constant QE level of 1% is assumed for the wavelength range from 2600 to 3000 nm, then the integrated flux seen by the detector is of 0.009 e^-/s/pix at 140 K and 0.1 e^-/s/pix at 150 K. This flux is the same as the total integrated flux from 900 to 2600 nm. Therefore, it will be crucial to verify that the detector QE above 2600 nm is at the level of 0.1% or lower, or that this flux is blocked.

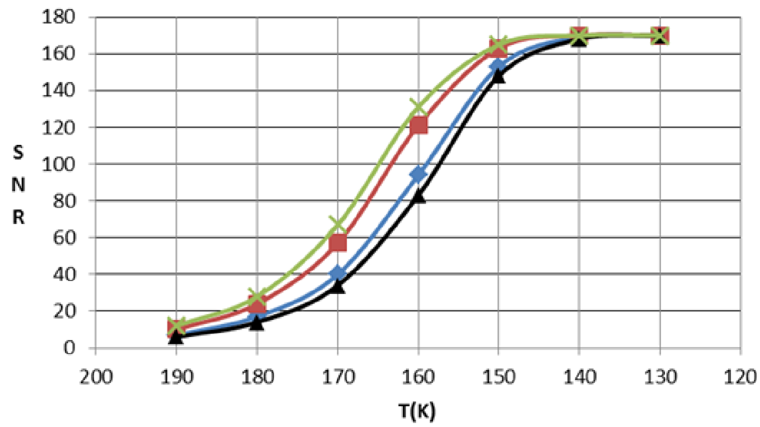

Figure 7: SNR for different temperatures of the un-baffled instrument. The worst case, given by the black triangles, considers a detector cut-off at 2700 nm and 100% detector QE, the best one (green crosses) considers a cut-off at 2600 nm and 70% detector QE.

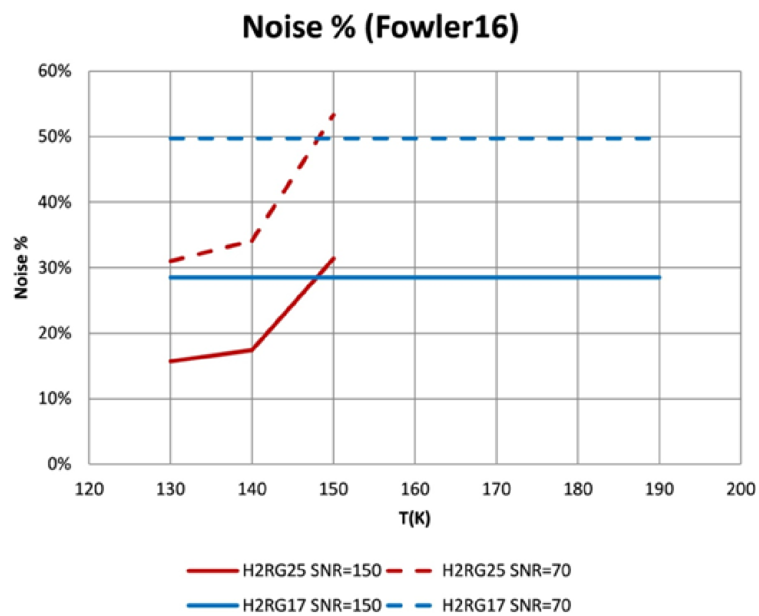

Figure 8: Other noise percentage to the total noise for the two detectors HG2RG25 (red) and H2RG17 (blue horizontal lines) working at the SNR=150 (solid) and SNR=70 (dashed lines) regimes.

4.1 SNR requirement

The computation of the stellar flux reaching the detector and of the noise contribution from different sources has been carried out by one of us (PJA). This work has been used within the CARMENES consortium to understand the flux requirements and noise-limit specifications to reach the RV precision requested by our science.

Those computations include, among other factors the spectral resolution for the NIR channel (R~82,000), the size of the resolution element (2.8 pix in the middle of the spectral orders) and the specifications for the QE of the detectors (see Table 1), which have been included in the total mean efficiency of the system [11].

From the SNR point of view, a comparison is made between the results using the H2RG17 detector, with cut-off at 1750 nm and an operating temperature for the instrument of T=190 K, and a H2RG25 detector, assuming cut-offs at 2500 nm and 2700 nm and operating temperatures of 150 K and 140 K.

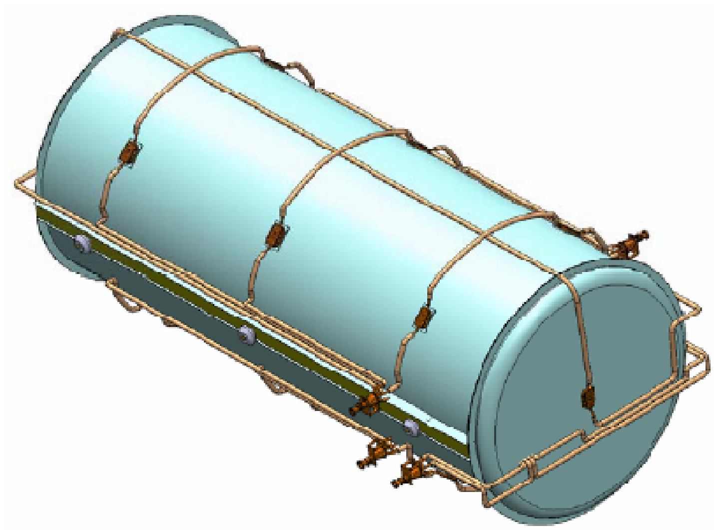

Figure 9: General view of the CARMENES-NIR radiation shield together with the circuit of pipes of the cooling system.

The result of this comparison is that the SNR is greater than 150, i.e. within the requirement established by the science for bright objects, for all the different options considered (see Figure 7. The SNR obtained with the H2RG17 detector (SNR=155) is limited by its lower QE, the thermal noise being negligible. On the other hand the higher SNR obtained with the H2RG25 detector (SNR=160-180) benefits from the higher QE but is affected by the selection of detector cut-off and working temperature.

CARMENES top-level scientific requirements also specify that “the spectrograph shall be photon-noise limited at SNR = 70”. Photon-noise-limited regime is defined as that in which “other sources of noise shall not be significant, and is translated as increase in the total noise by less than 10%”. This should be the most restrictive condition and a comparison of the two detectors working in that regime, together with the regime at SNR=150, is made in Figure 8. The comparison shows that the temperature at which both detectors reach the same level of noise for all contributors except photon noise is a little below 150K. Therefore, from the SNR point of view, the H2RG25 in an instrument at 150K, should show the same performance as the H2RG17 at 190K.

4.2 CARMENES cooling system

The CARMENES instrument cooling system is based on the Continuous Flow Cooling system of ESO. This system has been widely used in the instruments implemented by ESO so far. In fact, this is the core of the cryo-vacuum standards used at ESO. These standards have been successfully implemented in CRIRES, HAWK-I, XShooter and many other instruments.

The application of this system on the CARMENES-NIR spectrograph is based on the active cooling of the metal radiation shield inside the vacuum tank with stabilized Nitrogen (N2) gas delivered by a preparation unit (see Figure 9).

The definition of our cooling system as a non-cryogenic system derives from the facts that it works at non-cryogenic temperatures (almost cryogenic temperatures are also achievable though) and it does not directly use LN for the cooling as it circulates Nitrogen gas. In [12] more information on the CARMENES cooling system is provided.

Cryo-mechanical design aspects

According to the thermal studies related to the detector performance, the temperature “seen” by the H2RG25 detector should be less than or equal to 140 K. In this regard, the cooling system is clearly impacted by the change of detector and final operating temperature, since the change from 190 K to 140 K affects some of the parameters of its design. For instance, the decrease of temperature implies an increase of the radiative power affecting the radiation shielding.

The impact on the cooling system is currently under investigation with a prototype of the preparation unit that is being currently built. The flexibility of the system in several requirements, like LN consumption, number of cooling lines and minimum environmental temperature for having stable N2 gas, will, in theory, be able to assume the impact.

Preliminary estimates allow reaching a temperature in the optical bench of between 140 K and 150 K with small but, most important, stable gradients of the order of 0.01 K in the optical bench.

5. CONCLUSIONS

This contribution focuses on the studies made to provide information on the feasibility of different options which would allow reducing the thermal background reaching a sensitive NIR detector. Thermal and cryo-mechanical aspects have, therefore, been studied in the context of the CARMENES project to evaluate those different options that would allow using non-cryogenic cooling to reach the needed operating temperature for the instrument. This temperature requirement is finally imposed by the amount of noise contributed by the thermal background which is acceptable for the science objectives to be reached.

Currently no instrument working in the *YJHK* bands of the spectrum can work at non-cryogenic temperatures and none working in the *YHJ* bands has being built so far.

Three options were studied: 1) the use of detectors with bluer cut-off wavelengths like Teledyne's H2RG17 detectors, 2) the use of cut-off filters and 3) the use of internal cold baffling. The combination of these three options would allow operating temperature higher than ~190K (−80ºC), temperature reachable for cooling systems not using liquid Nitrogen.

However, it was found by the CARMENES detector working group that the H2RG17 is not mature enough to reach the science goals of the instrument and is therefore discarded as a real option. Therefore, the H2RG25 was considered as the best choice. The new detector, with redder wavelength cut-off, puts harder constraints on the cooling system and it was found that the only feasible solution to lower the thermal background was to decrease the operating temperature of the CARMENES NIR spectrograph from 190 K to 140 K. The other options (filters and baffles) were found to help, allowing for a few degrees larger temperature, but at the cost of extra mechanical complications, and were, therefore, rejected.

The CARMENES cooling system is a novel design based on ESO standards using thermally-stabilized nitrogen gas and allowing a broad range of operating temperatures for the instrument, from non- to quasi-cryogenic temperatures. This design could now work for instruments equipping detectors with the shorter (1700 nm) and longer (2500 nm) cut-offs.

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