Technical Note

LN_2 versus TE cooling for BRDD sensors

Noise is a fundamental characteristic within all detectors and how it is handled, with a view to reducing its effects, is key to enhancing the overall performance of any such device. An intrinsic source of noise within all CCD detectors is that associated with thermally generated 'dark' current. Cooling is clearly the means of reducing this particular noise source and there are a number of methods (incl. combinations) traditionally used, such as air, liquid coolant, Liquid Nitrogen (LN_2) and thermoelectric (TE). A widely made assumption is the 'cooler the better' when looking for the best performance out of a detector. This technical note looks at the basis of this assumption and considers the influence of temperature on two of the key parameters, namely the Quantum Efficiency (QE) and the dark current (DC), of a particular type of CCD sensor – the Back-Illuminated Deep-Depletion (BRDD) sensor.

Introduction

When cooling a CCD sensor it is important to remember two key factors:

a) it is dark current (DC) that counts and not necessarily the final temperature of the sensor,

b) the Quantum Efficiency (QE) is temperature-dependent.

In back-illuminated, deep-depletion sensors (BRDD types), which are designed to have particularly high QE in the NIR region (750 - 1,050 nm), the QE is found to have a particularly significant dependence on temperature. As a consequence of their design, these Non-Inverted-Mode-Operation (NIMO) devices also tend to have significantly larger dark currents compared with traditional Asymmetric-Inverted-Mode-Operation (AIMO) type sensors, so cooling is critical in improving their performance.

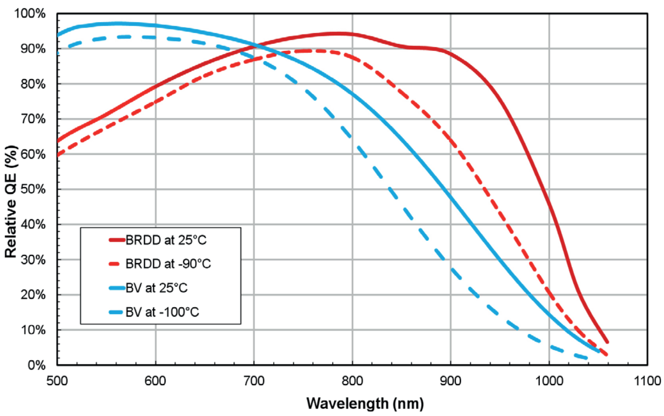

Figure 1: Characteristics showing QE dependence on temperature for Back-illuminated, deep-depletion BRDD and Back-Thinned BV sensors – based on manufacturers official supplied data.

Pairs of QE curves are presented in Fig. 1 for two different types of back-illuminated sensors. The QE curves are based on measurements taken at room temperature and with deep-cooling (<-80°C) for each sensor. A 'BV' sensor is a back-illuminated device with an antireflection (AR) coating optimized to provide the highest QE in the visible region. The BRDD sensor is optimized to provide the highest QE in the NIR region. What is clearly evident in both cases is the pronounced drop in QE within the NIR region with drop in temperature. It should also be noted that there is some temperature dependence in the QE even down into the visible and UV regions, though this is somewhat less significant than in the NIR region. When one considers the sensitivity, and particularly the signal/noise ratio (S/N) for taking measurements, it is of clear benefit to have as high of QE as possible.

This gives rise to several key questions:

- Is there some point in cooling beyond which further cooling may be detrimental to the overall performance in terms of S/N, i.e. is there a point where the reduction in QE is more influential than further reduction in the dark current?
- What is the trade-off between the influences of the reduction in QE and the reduction in dark current noise, with cooling of a given sensor?

1) Temperature dependence of QE

It is worth considering the quantitative change that occurs in QE with cooling between the given temperatures.

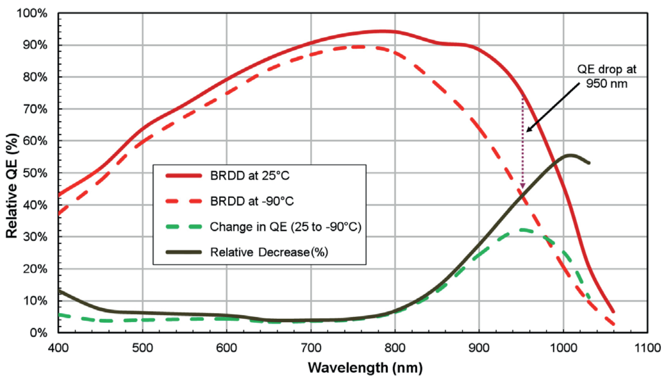

Figure 2: Relative change in QE for the BRDD sensor between 25˚C and -90˚C

The difference in QE and the relative change in QE (change relative to starting QE at ambient temperature) for the BRDD sensor are shown in Fig 2. At an illustrative wavelength of 950 nm, the relative QE is found to have dropped by ~40%. Towards the limits of the relevant NIR region at 750 nm and 1,000 nm, the relative QE is observed to fall by ~5% and ~50% respectively.

2) System Noise

System noise and consideration of detection-limits are discussed first before looking at the overall signal-to-noise performance, where the variation of QE with temperature will be taken into account.

The main contributing sources of noise in the detection of a signal are the **shot noise** of the signal itself, the **dark current** of the sensor, **spurious charge** such as clock induced charge (CIC), and the **readout noise** from the output electronics (preamp and A/D). Shot noise within the photon signal is an intrinsic contribution related to fundamental quantum physics, and will always be part of any signal. It represents a fundamental limit for any noise reduction.

The other sources of noise combine to form what we refer to as the system (or camera) noise, and a range of innovative techniques are used to minimize or eliminate their contributions. The detection limit refers to the collective system noise, and represents a limit for the smallest detectable signal level (minimum level of signal which can be distinguished from the background noise level or noise floor).

Denoting the dark current noise by N_{DN}, spurious or CIC noise by N_{CIC} and readout noise by N_{RN}, the total camera or system noise is given by:

$$System\_Noise = \sqrt{N_{RN}^{2} + N_{DN}^{2} + N_{CIC}^{2}} \quad [1]$$

The dark noise, N_{DN}, is related to the dark current, DC, by $N_{DN} = \sqrt{DC.t}$. The build up of dark current is linearly proportional to the exposure time. It therefore becomes more important to cool the sensor with increased exposures in order to minimise the dark noise. It is usual for the sensor to be cooled depending on the exposure times required, such that the system becomes readout noise limited, i.e. an operating regime where it is the read out noise that determines the ultimate limit of detection.

Fig. 3 - 6 present the detection limit as a function of exposure time for a BRDD sensor under different operating modes.

Clearly the dark noise will increase with increase in exposure times, such that for long exposures the overall system noise (and consequently the detection limit) will become dominated by the dark noise contribution. With cooling, the dark noise contribution is reduced significantly and with sufficient cooling can be reduced to an insignificant level.

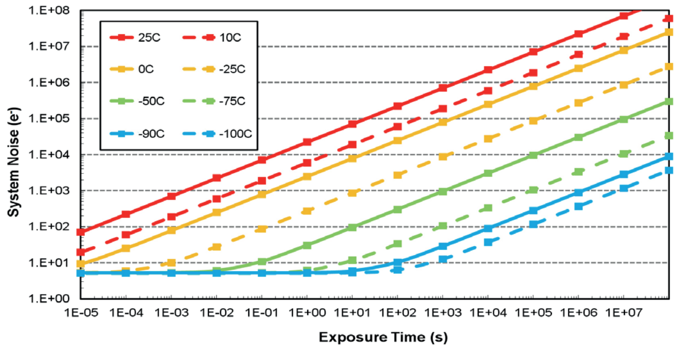

Figure 3: Detection limit as a function of exposure time for single pixels ***(image mode)*** *of a BRDD sensor at a* ***readout rate of 100 kHz (RN=16.2 e$^-$)****.*

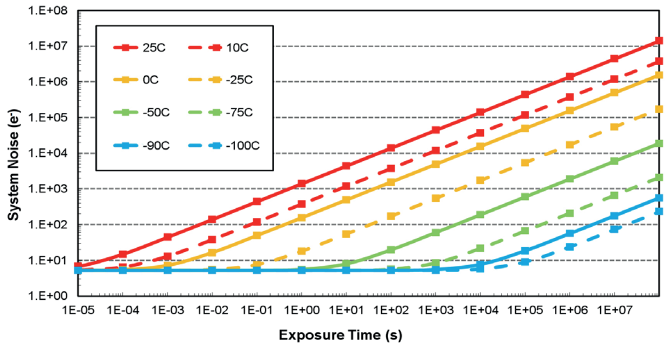

Figure 4: Detection limit as a function of exposure time for single pixels ***(image mode)*** *which are read out at a slower* ***rate of 33 kHz (RN=4.6 e$^-$)****.*

This shows up as the flat plateau region where the system noise is now read-noise limited. The data used to generate these characteristics was taken for a typical iDus DU420A-BRDD camera, which had readout noises of 16.2 e$^-$, and 4.6 e$^-$ at the A/D readout rates of 100 kHz and 33 kHz respectively; with relatively long exposure times (>10 s) speed is less critical and the slower readout rate with its lower noise can be used. The dark current was taken from its measured dark current characteristic; the spurious noise was intrinsically included within these measured parameters.

The advantage of cooling is evident when extremely long exposure times (>10's, if not 100's of seconds) are required in a given experiment. However, if short exposure times are being used, then it is clear that there is little benefit in deep cooling the sensor. There is little or no advantage cooling the sensor below -75°C, where the system is operating on the low plateau corresponding to the read-out noise limited regime. Similarly, if exposures less than 10 s are being used, there is little or no benefit to be gained by cooling below -50°C.

When moving to longer exposures the read out speed is of less importance and one can access the benefit of the lower read-out noise with slower read-out. This is illustrated in Fig. 4 for the same camera where the read-out noise limited detection has been lowered to just below 5 e$^-$. The corresponding characteristics for AIMO type sensors, e.g. back-thinned types, are even more favourable to limited cooling as there is significantly less dark current produced in them.

Much of spectroscopy work can utilize binning in order to improve the S/N. Similar characteristics have been generated when using full vertical binning (FVB) of the sensor before reading it out. As to be expected the characteristic elbow of the S/N versus exposure time moves to shorter exposure times, as for each readout (with associated read out noise) the dark current (with associated dark noise) corresponds to that summed or binned from multiple pixels.

There are a number of ways of interpreting the characteristics of Fig. 5 and 6. Considering uniform illumination of the pixels to be binned, if one wants to achieve a similar S/N ratio as for the single pixel case then the exposure time can be significantly decreased; this pushes the acquisition conditions further into the readout noise limited regime. Or alternatively if the exposure time is to remain the same then for the same S/N ratio more dark current noise can be tolerated; in this case the signal is being increased by a factor corresponding to the number of binned pixels. However way it is viewed, vertical binning does offer enhanced S/N for taking spectral measurements.

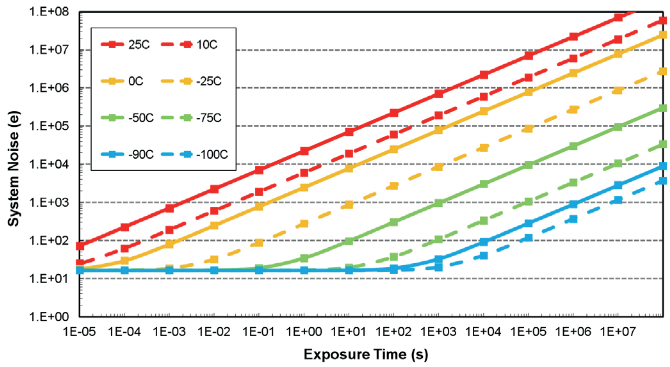

*Figure 5: Detection limit as a function of exposure time for vertically binned pixels (**FVB mode**) which are read out at the faster **rate of 100 kHz (RN=16.2 e-).***

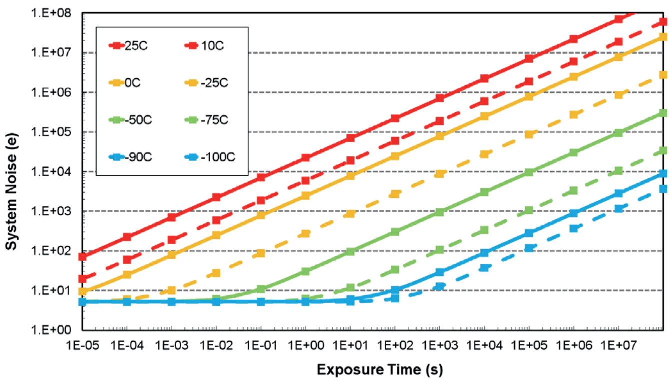

*Figure 6: Detection limit as a function of exposure time for vertically binned pixels (**FVB mode**) which are read out at the slower **rate of 33 kHz (RN=4.6 e-).***

3) Signal to Noise (S/N): Assessment of system performance

Ultimately when assessing the performance of any detector system in terms of its sensitivity, it is the achievable signal-to-noise (S/N) which is of key importance. As the S/N ratio will depend on QE among other factors, then any variation in the QE will impact on S/N. As already indicated, the shot noise associated with the signal itself must be taken into account along with the system noise in calculating the S/N ratio.

If we consider a photon flux of I photons per second incident on a pixel, then with an exposure time of t seconds this will give rise to a photon signal of P=I.t photons. In turn, if we take the quantum efficiency as QE, this will produce an electron signal, S, of electrons given by:

$$S = QE.P = QE.I.t \quad [2]$$

The shot noise (N_{SN}) intrinsic to the resultant signal is given in terms of the signal 'S' by:

$$Shot\_Noise(N_{SN}) = \sqrt{S} = \sqrt{QE.I.t} \quad [3]$$

For the BRDD sensor, it is possible to express the S/N by the following equation:

$$S/N = \frac{S}{\sqrt{N_{RN}^{2} + N_{DN}^{2} + N_{CIC}^{2} + N_{SN}^{2}}} \quad [4]$$

Or expressing in terms of the photon flux (I), exposure time (t) and dark current (DC):

$$S/N = \frac{QE.I.t}{\sqrt{N_{RN}^{2} + DC.t + N_{CIC}^{2} + QE.I.t}} \quad [5]$$

The above expression can be used to model S/N characteristics for a range of exposure conditions. The following figures show data modelled for a DU420A-BRDD camera which had a readout noise of 16.2 e^-. The selected photon energy was 1.31 eV corresponding to 950 nm wavelength. The dark current measurements were made at a limited number of temperatures, so an exponential fit to the measured data was used to estimate the dark current noise at other intermediate temperatures.

Clock induced charge (or CIC) is spurious charge that arises when carrying out the clocking processes to shift charge to the output node and eventually to reading the signal out. In general it is dominated by the parallel vertical shifts of pixel rows when charge is shunted down the sensor to the readout register. It has weak temperature dependence in conventional CCD sensors and will always make a contribution to the noise but is generally small when compared with the other noise sources. It should be noted that the measured readout noise will have this small contribution convolved within it, so the CIC noise (and associated term in equation 5) need not be treated explicitly here.

The graphs in Fig. 7 show the calculated S/N for different exposure times when different input photon fluxes are introduced. Fluxes here refer to the number of photons incident on a pixel per second (ph/s). The graphs show the generally expected trends – increase in S/N with increased exposure, increase in S/N with increased fluxes (intensity of signal), increase in S/N with reduction in sensor temperature – but interestingly it also shows a higher S/N is possible at -75°C compared with -100°C for the spectral region in the NIR. This is due to the influence of changes in QE.

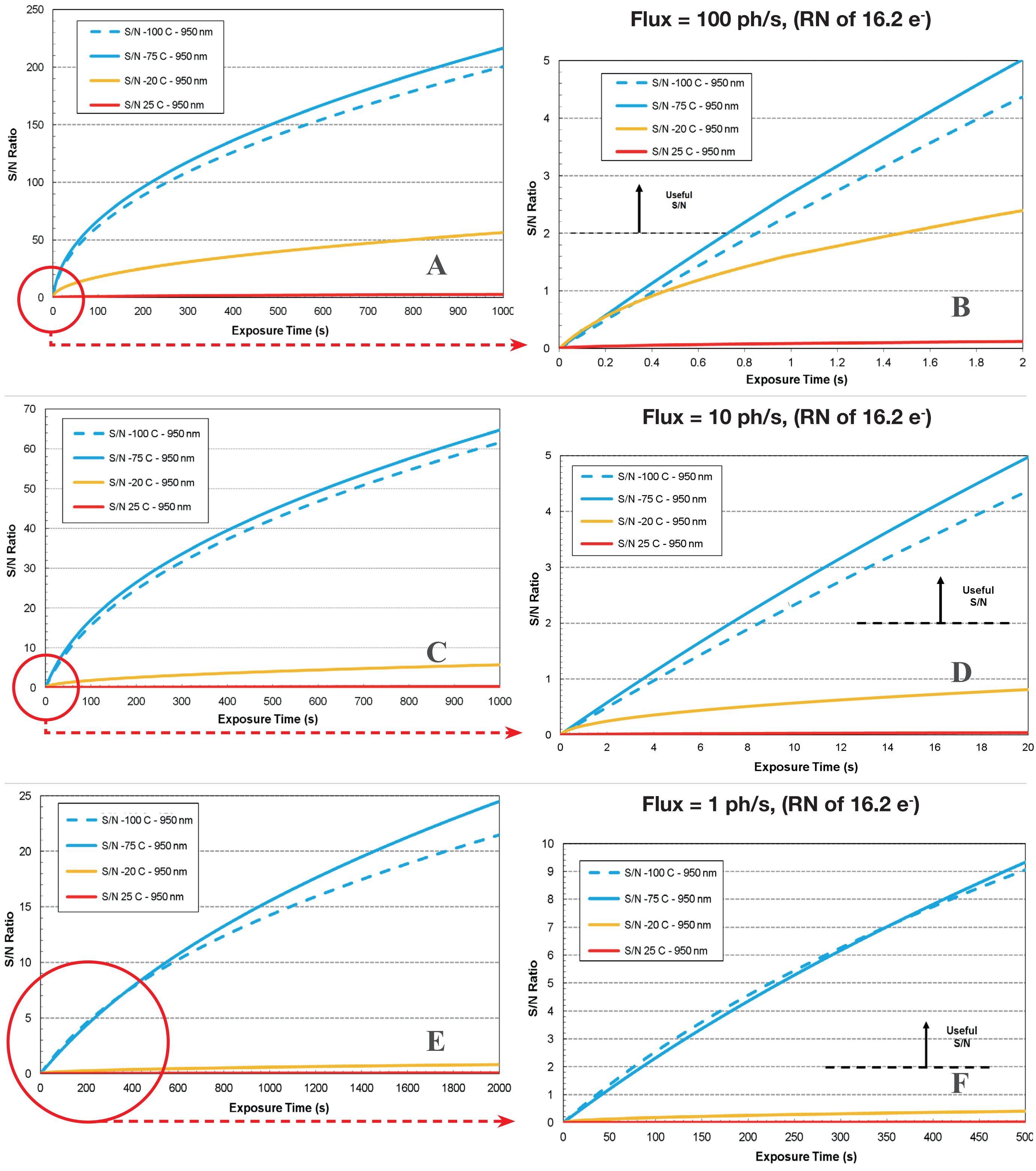

Figure 7: S/N versus exposure time for different input fluxes or signal intensities.

Graphs A and B correspond to a flux of 100 ph/s, with B just showing more detail at the shorter exposure times. Graphs C and D are for a lower flux of 10 ph/s, with D expanded for lower exposure times. What both sets of graphs show is that the S/N is slightly better for the -75°C case for all exposure times. It is only when we get to extremely low fluxes that we see benefits at -100°C, as illustrated in graphs E and F. In this latter regime, extremely long exposures (>5 mins) are required to get reasonable measurements.

Discussion and Conclusion

When using a BRDD sensor for carrying out work in the NIR region, it is a key consideration to decide the best temperature to operate at for optimized S/N. It is the best achievable S/N that counts and whilst this is generally improved with cooling, it is important to remember that the QE of such sensors is also temperature dependent; the QE gets worse with fall in temperature. The conclusions may be summarized as:

- When the temperature dependence of the QE is factored in along with all the sources of noise, there is no advantage in using LN_2 cooling compared with deep TE-cooling for the vast majority of experimental working conditions in the NIR region of interest (750 - 1,000 nm).
- Depending on any given set of experimental conditions e.g. signal level, exposure time, photon energy, and sensor type, the optimum temperature will typically be anywhere in the region of -70°C to -90°C.
- There are implications for even deeper cooling to well below -100ºC - the influence of the reduced QE exceeds the benefit of lower dark noise and the S/N actually deteriorates. This accounts however for a very small number of very specific scenarios.
- In some liquid nitrogen (LN_2) cooled systems, this latter problem may be dealt with by actually supplying heat to the system and thereby raising the sensor temperature to where the S/N is optimized. This adds significant complexity to the system; generally it is more difficult to control such schemes in that both active cooling and heating are being applied, as opposed to TE-based schemes where one has only to control the degree of cooling applied.
- Of course, there are a number of secondary but very important issues to be considered when deciding between TE-cooling versus LN_2 cooling. These include:
  - ▷ the convenience factor
  - ▷ the day to day running costs
  - ▷ the handling issues (health and safety requirements incl hazards)

A scenario is outlined in Appendix A giving estimates for the costs involved in running a typical liquid nitrogen cooled system, which shows that substantive costs are involved over the lifetime of a camera.

Appendix A

Estimates for cost/time analysis with Liquid N_2 cooling.

LN_2 cooling does involve added overheads in terms of raw material and handling costs, as well as the inconvenience with handling and associated health and safety considerations. Outlined here is a simple estimate of the costs for supply of LN_2 to cool the CCD camera over a period of five years.

	Estimates
Liquid nitrogen volume to fill the detector	1 L
Volume requirements per week (incl evaporation wastage)	10 L
Volume requirements per year (over 10 months)	400 L
Nitrogen Dewar 25 litre – Monthly rental	€ 28
Cost per litre – small volumes (<50 L)	€ 2.90
Cost per litre – large volumes (>50 L)	€ 2.30
Cost for 25 litre liquid nitrogen Dewar refill + delivery cost	€ 120
Cost of liquid nitrogen per year based on 16 x 25 litre refill	**€ 1,920**
Costs of liquid nitrogen supply over 5 year period	**€ 9,600**
Initial capital expenditure on 25 litre Dewar, handling/protective tools	€ 1,500
Estimated cost of LN_2 over a period of 5 years	**€11,000**

As can be seen from the estimates in the table the costs of supply and handling of liquid nitrogen will be quite substantial over the working life of any LN_2 cooled camera.