Optical and Infrared Detectors Tests and Monitoring Plan at the LPO

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CONTENTS

1. INTRODUCTION

This document describes the requirements and specifications for the testing of the detectors which are being used onboard scientific instruments and relevant auxiliary systems (e.g. wave-front sensors) at the La Silla Paranal Observatory (LPO). Understanding the performance limits and the calibration requirements of an instrument is fundamental in the operational scheme followed at the observatory and crucially depends on our knowledge of the nature of the detector arrays, their key performance parameters and the way these are defined and measured.

This document is primarily intended as a guide for the establishment of a **monitoring plan** for IR and optical detectors at the Observatory and it does not supersede the characterization and testing plans devised in Garching by the infrared and optical detector teams (IDG and ODT): as such, it is limited at considering those parameters that can be measured at the telescope by means of daytime and nighttime calibrations. All other parameters should have been characterized before and during requisition (including the manufacturers' specs documents), integration and commissioning and will not be mentioned here. Nonetheless, in the interest of economy of effort and of ESO-wide standardization, we selected the relevant test procedures devised in the labs in Garching and included them in this document whenever relevant.

Secondarily, this document also provides a higher level **implementation roadmap** to serve as guide for:

1. the pipeline developers who have the task of providing the data reduction recipes;
2. the instrument scientists and the engineers who are interested in monitoring the health of their instruments and need quantitative measurements to plan for interventions.

The document thus describes only the outline of the implementation of the monitoring plan, leaving the specifics to other documents. However, for the sake of completeness, it will point to the relevant in-depth documentation supporting the detailed implementation of data-taking templates and data-reduction recipes (see Appendix 1).

In this way, it interests an additional audience:

- the support astronomer, who operates the instruments at night and is interested in optimizing their scientific output.
- The day astronomer who needs guidelines to validate the calibration data.
- The user support astronomer, who needs the nitty-gritty specifics of the detectors to advise the users when setting their observational tactics and techniques.
- The quality control scientist, who is in charge of the back-end instrument health checks.
- The astronomer (user), who is interested in planning a strategy for his observations and achieving specific scientific goals.

With the exception of the astronomers belonging to the ESO's scientific community at large, all the interested parties listed above have been involved in the production of this document, with the intent of reaching a wide consensus on the plan and insure ESO-wide implementation. In particular, the instrument operation teams (IOTs) have been the authors' primary contact to collect requirements, comments and questions. Moreover, we have polled members of both the IDG and the ODT to verify the soundness of our testing methods and procedures and their compatibility with the analogue work done in Garching on detectors.
A list of persons in charge and their assigned tasks is outlined under "RESPONSIBILITIES" in Section 2.

This document is meant to achieve the following **broad goals**:

- Standardize the test procedures whenever applicable (e.g. define a unique way to measure linearity).
- Unify test procedures for IR and Optical detectors whenever applicable and describe the differences in all the other cases (e.g. define unique ways to acquire data sets)
- Unify the measurement procedures and the use of data reduction recipe and algorithms
- Utilize available resources, such as data taking OBs, pipeline recipes, existing reporting tools (e.g. QC web pages, AUTREP).

Given the broad audience intended to use this document and their vested interests in the monitoring plan, the implementation map or the consolidated specs guide, we set some additional **specific goals**:

- List of all the detector systems in use at the LPO, their format (Single or Mosaic), the pixel size and the wavelength range. (Section 3).
- List of data types that have to be acquired for the tests (Section 4).
- The monitoring plan, which includes:
    - A list all the parameters, the required accuracy and their measurement frequencies (Section 5.1).
    - A description of each parameter, its impact on science and its dependencies on operating conditions, as provided at the observatory(sections 5.4.x, x=1-20).
    - Set of requirements for data acquisition and the conditions for measurements (Section 6)
    - Description of the algorithms for measuring a parameter and the methods for data analysis. (Section 6)
    - Description of the graphical outputs and plots for data comparisons. (Section 6)
    - Definition of the format for the publishing of the results. (Section 6)
- Appendixes: list of templates, acronyms, etc.

2. RESPONSIBILITIES

The following responsibilities are defined:

- definition of the Detectors Monitoring Plan: Calibration and Stability group/Detector with inputs from La Silla Paranal/Garching Instrument Scientists;
- preparation, implementation and maintenance of the Detectors monitoring plan: Instruments Scientists with the help of Paranal Software Group;
- execution of the monitoring plan: Science Operation Team;
- development and maintenance of the pipeline recipes: DMD Garching and DHA Paranal;
- analysis: DMD Garching and Science Operation Team;
- monitoring of the results: Instrument Scientists;

3. DETECTORS IN USE AT THE LA SILLA PARANAL OBSERVATORY

Table 1. Optical and infrared detectors datasheet for present and (near) future instruments at the LPO Observatory

OPTICAL DETECTORS

Instrument	Detector	Size	Pixel [μm]	Format	Wavelength range [nm]
FORS1	Tek 2048EB4-1	2048x2046	24	S	330-1100
FORS2	MIT/LL CCID-20	2x2048x4096	15	M of 2	330-1100
FLAMES (Giraffe)	E2V 44-82	2048x4102	15	S	370-950

UVES Blue	E2V 44-82	2048x4102	15	S	300-500
UVES Red	E2V 44-82 MIT/LL CCID-20	2048x4102	15	M of 2	420-1100
VIMOS	E2V 44-82	2048x2440	15	M of 4	360-1100
NAOS OPT	E2V CCD50	128x128	24	S	450-1100
SUSI2	E2V 44-82	2048X4096	15	M of 2	300-1000
EMMI blue	Tektronix 1024 AB	1024x1024	24	S	300-500
EMMi red	MIT/LL CID-20	2048x4096	15	M of 2	400-1000
WFI	E2V 44-82	2046x4098	15	M of 4x2	350-1100
FEROS	E2V 44-82	2048x4102	15	S	350-920
HARPS	E2V 44-82	2x2048x4096	15	M of 2	380-530 530-690
EFOSC2	Loral/Lesser MPP Thin	2048x2048	15	S	300-1100
CES	E2V 44-82	2048x2048	15	S	350-1000
OMEGACAM	E2V 44-82	2048x4096	15	M of 32	330-1000
GALACSI/GRAAL	E2V L3 CCD220	240x240		M of 5	450-950
MAD	E2V CCD 39	80x80	24	S	450-950
VISTA OPT	E2V CCD 42-40	2048x2048		M of 4	850-1100
X-Shooter OPT Blue	E2V 44-82	4096x2048	15	S	320-500
X-Shooter OPT Red	MIT/LL CID-20	4096x2048	15	S	500-1100

INFRARED DETECTORS

Instrument	**Detector**	**Size**	**Pixel [μm]**	**Format**	**Wavelength range [μm]**
ISAAC	Rockwell Hawaii HgCdTe	1024x1024	18	S	0.9-2.5
	SBRC Aladdin	1024x1024	27	S	1-5
VISIR	DRS BIB Si:As	256x256	50	M of 2	5-25
CONICA	SBRC Aladdin 3 InSb	1024x1024	27	S	1-5
NAOS	Rockwell Hawaii HgCdTe	1024x1024	18	S	0.9-2.5
SPIFFI	Rockwell Hawaii HgCdTe	2040x2048	18	S	0.9-2.5
MIDI	Raytheon IBC SI:As	320x240	50	S	5.0-25
AMBER	Rockwell Hawaii HgCdTe	1024x1024	18	S	0.9-2.5
SOFI	Rockwell Hawaii HgCdTe	1024x1024	18	S	0.9-2.5
TIMMI2	Raytheon Si:As	320x240	50	S	5.0-25
X-Shooter	Rockwell Hawaii 2RG	2048x2048	18	S	1.1-2.4
CRIRES science	Raytheon Aladdin III	4x1024x1024	27	M	0.95-5.2
CRIRES SV	Raytheon Aladdin III	1024x1024	27	S	1-2.2 (5)

NOTES: Format: S - single detector, M – Mosaic

4. DATA TYPES

We list here the type of frames that can be acquired and used for detector testing at the telescope site (e.g. we do not include special frames such as MTF pattern frames). Three types of data frames can be acquired for optical detectors (OPT) and two types for IR arrays (IR, NIR/MIR):

4.1. Bias frames (opt only)

Bias frames or 0-sec exposure time dark images can only be obtained for an optical detector. The careful examination of a bias frame may reveal a lot of features. The perfect bias frame is a featureless noise image, with the amplitude of the noise equal to the read-out noise of the detector. If there are features in the image, it means that other sources of noise are present and the instrument or the detector may have a problem.
Bias frames can be used to measure:

- Read-out noise
- Coherent and Incoherent pick up noise
- Burst noise
- Stability of the bias injection
- Hot pixels and hot regions
- Salt and pepper noise – i.e. neighboring pairs of high and low pixels

4.2. Dark frames

Dark frames of variable integration time. Long darks can be used to measure the dark current, although with most modern detectors, the dark current is so low that even the smallest light leaks can cause problems and cosmic rays must be carefully removed. Small variations in bias level can also compromise the data and overscan regions should normally be used.

4.3. Flat (illuminated) frames

Uniformly illuminated frames can be used for a variety of tests. Depending on the quantities being measured, one may need to acquire low or high count level flats. Flats can be used to build bad pixels maps, find traps, measure linearity, saturation level, shutter patterns, transfer efficiency, etc.

4.4. Data cubes

Some instrument in Paranal can now produce data cubes: ISAAC, NaCo and VISIR are regularly producing data cubes. Data cubes are not usually needed to take calibrations, but they are a potential powerful tool to analyze some problems. For instance, dark frames taken in cube mode can be analyzed to measure the temporal variation of electronic noise. With NaCo, it is possible to measure the residual jitter in closed loop using science data (or calibrations, such as a standard star) and also to get an idea of the variation of AO loop performance over time. At the moment of writing, ESO has no official tool to deal with data cubes (with NaCo the CubeFitsView by T. Ott is used informally) and the pipelines are not yet set up to handle data cubes. It is hoped that this may change in the future to allow those additional tests.

5. Monitoring Plan

Many parameters described above depend on operating conditions, such as temperature, applied voltages, clocking rates and illumination conditions. Unless these conditions are well defined, the device performance can vary. Moreover, building test sets that explore some well defined range for these conditions helps optimizing the performance of the device. For these reasons there is an important need for frequent calibration of devices when flux and wavelength accuracy are required.

5.1. Parameters

Not all parameters described are relevant for the different detectors operated at the VLT and La Silla. In addition they typically show variations on different scales. Therefore, a specific plan must be set to monitor the critical parameters of each detector with the suitable frequency. Table

2 lists in alphabetical order the detector parameters that we want to test and monitor at the LPO. Included in the lists, are the pertinent wavelength domains (optical (OPT) and InfraRed, divided into Near-Infrared (NIR) and Mid-InfraRed (MIR)), the required accuracy for the measurement and the units, the method of measurement (M), the Frequency (F) and the Priority set for the remainder of the program, which includes, preparation of pipeline recipes, preparation of observing templates (when needed), preparation of database tools (AUTREP) and of publication tools (web/AUTREP).

Table 2: Detector Parameters in alphabetical order and IR/OPT compatibility table. Green entries have been already implemented at the time of the last revision. Priorities list has also been modified.

PARAMETERS	OPT	NIR	MIR	ACCURACY [UNITS]	M	F	P
Amplifier Glow	X	X	X	Signal (ADU)	Statistics on Bias/Dark	N	14
Bias Level	X			<1 (1 digit [ADUs])	Bias Frames Statistics	D	1
Bad pixels, Cosmetic Quality	X	X	X	N/A	Bias Frames (OPT) Dark Frames (IR) Flat frames (ALL) analysis	Y	2
Contamination	X				UV Flats analysis	Y	16
Conversion Factor	X	X	X	2 digits [e-/ADU]	Transfer Curve TDI images	BA M	3
Cosmic Ray Sensitivity	X				Long darks statistics	N	17
Crosstalk (multiple ports)	X	X	X	1/300,000	Bright star sequence	Y	8
CTE (V/H)	X			10^{-6}	EPER (overscan); Signal variance;	O	6
Dark Current	X	X	X	2 digits [e-/px/s]–[e-/px/hr]	Dark Frames Statistics	D	1
Dark Signal Nonuniformity variable and fixed (DSNU +FPN)	X			<10%		BA	7
Full Well Capacity	X			1%	Linearity curve	BA	4
Linearity	X	X	X	<1%	Transfer Function	BA	3
Persistance (Remanence)	X	X	X		Dark current measurements after illumination	Y	11
Readout Noise (RON)	X	X	X	2 digits [e- RMS]	Bias Frames Statistics (OPT) Dark frames Statistics (IR)	D	1
50Hz Pick up Noise	X	X		2 digits (ADU)	FFT analysis	Y/ N	5
Microphonic Noise			X			BA	9
N-pixel correlated Noise			X			M	8
Odd-Even column effect		X				D	2
Shutter Pattern/Error	X				Linearity curve Shutter procedure	Y/ N	13
Spatial Uniformity, Photo Response non-Uniformity (PRNU) - Fringing	X	X	X	<2%	Analysis of flats	M/ N	10
Stability		X	X	N/A	Visual inspection, bias frames	D	15
Stray light	X				Flat frames(filters)	W	18
Temperature stabilization			X			Y	12

Notes:
M=Method (how it is calculated)
F= Frequency: D=daily, W=weekly, M=monthly, BA= biannual, Y=yearly, O=once, N=when needed, etc
P=Priority

Not all of the parameters listed in Table 2 affect performance at a system level. Therefore another table is provided (Table 3), which list the parameter, its importance at a system level and its dependencies on operating conditions. It is important to understand the dependencies on operating conditions in order to set test frequencies and to use predictive tools

Table 3: detectors parameters and their importance at system level.

Parameter	Importance	Operating conditions
Amplifier Glow	Low – it is becoming rarer as array design improves for Optical detectors. It can be large for IR (e.g. CRIRES).	Independent of temperature Proportional to integration time Non-uniform (apparent only for those pixels close to the output amplifier).
Conversion Factor (Gain, amplifier response)	High – affects absolute photometric measurements	Amplifier gain and offsets can be affected by temperature and applied voltages.
Cosmic ray effects	Low- important for long exposure, therefore affects observing strategies	Location (altitude) and surrounding materials. Both cannot be changed. Usually stable.
Crosstalk	Medium – affects spatial resolution	Important at design level but usually stable. Independent of pixel location, usually scales with signal.
Charge Transfer Efficiency in CCDs	Medium – Photometric accuracy can be affected of CTE is poor	Important at design level, but usually stable. Modern CCDs exceed “5 9s”.
Dark current and DSNU	High – affects photometric accuracy	Varies strongly with temperature Can change in time Changes with exposure time (IR)
Non-linearity	High – affects photometric accuracy	Usually stable, but needs to be characterized accurately.
Pick-up noise	Low	Depends on DITs, time, readout speed
Pixel Response Non-Uniformity, Fringing	Medium – affects photometry and can affect wavelength calibration accuracy in spectrometers	Varies with wavelength (fringing) and can depend on illumination conditions.
Quantum efficiency	High – affects absolute photometric accuracy	Depends on temperature (IR/OPT) Affected by contamination
Read out noise	High – affects all aspects of astronomical observations. Good indicator of instrument’s electronics problems	Can change with temperature, may be influenced by external electromagnetic interference.

5.2. ADDITIONAL NOTES FOR THE MONITORING PLAN OF OPT DETECTORS

The NAOS, MAD, GALACSI/GRAAL optical Wave-Front Sensor detectors are special cases, since they are not aimed at producing scientific data frames but to acquire data for the AO correction of the respective instruments.. For these reasons, the requirements for them are different. At present, only the simplest tests are foreseen to be carried out. See Table 4.

Although all optical instruments are listed in table 1, the initial implementation of the tests with the given priorities will be first implemented for the following instruments:
FORS1/2, UVES, VIMOS and FLAMES.

For the La Silla instruments detectors discussion is ongoing with the instrument scientists and a period of adjustment is foreseen to accommodate the transition form the current detector test procedures to the new ones.

The tests for new instruments (OmegaCam, X-Shooter, etc) will be implemented after “paranalization”.

5.3. ADDITIONAL NOTES FOR THE MONITORING PLAN OF IR DETECTORS

The NAOS IR Wave Front Sensor detector is a special case, it is not aimed at producing scientific data frames but to acquire data for the AO correction of CONICA and it does not share the operation mode with the other Hawaii detectors, in particular it is not operated by the IRACE system. For these reasons its requirements are different. The monitoring plan for the NAOS Hawaii is summarized below Table 3.

Table 4: Adaptive Optics Wavefront sensing detectors monitoring plan

Detector frequency	Test	Frequency
NAOS Hawaii NAOS OPT MAD GALACSI GRAAL	Read-out noise	Daily
	Dark current	Daily
	Cosmetic quality	Yearly

Priorities to implement the IR detector monitoring plan in the quality control daily health check are defined in Tab. 5.

Table 5: Priorities for the implementation of the IR detector monitoring plan with respect to the instruments. 1=Immediate. 2=Medium term, 6 months. 3=Long term, 1 year.

Priority	test	Instrument
1	dark	ISAAC-SW, ISAAC LW, CONICA, NAOS, SINFONI, AMBER, SOFI
1	ron	ISAAC-SW, ISAAC LW, CONICA, NAOS, SINFONI, AMBER, SOFI
2	Bad-pix	All
2	Odd-even	ISAAC-SW, SINFONI, AMBER, SOFI
2	Pick-up	ISAAC-SW, SINFONI, AMBER, SOFI
3	linearity	All (NAOS excluded)
3	gain	ISAAC-SW, ISAAC LW, CONICA, SINFONI, AMBER, SOFI

5.4. PARAMETERS DESCRIPTION

5.4.1. Amplifier Glow

It has been observed that the amplifiers of the multiplexer attached to the IR sensitive array are sources of glowing and generate a spurious signal, during the read-out process, with associated noise, see Fig. 1. This signal is detected by the array and can be a limit to the maximum useful DIT. The effect is most relevant in those read-out modes characterized by low RON.
Also, in some CCDs operated at low light levels, the biases applied to the output amplifiers can cause them to emit light. The effect is becoming rarer on CCDs and can be avoided altogether by applying the amplifier bias only during read-out.
The glow is:

- independent from temperature and integration time
- non-uniform (it appears only in areas close to the amplifier)

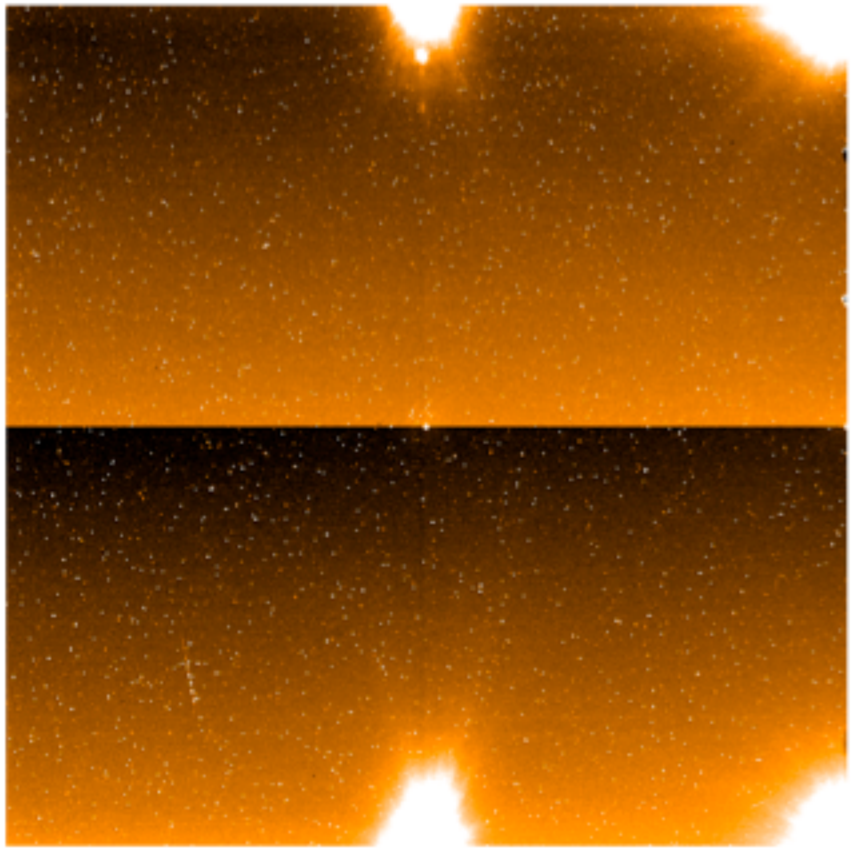


Fig. 1 - Multiplexer glowing and "hot" pixels in a dark frame of the Hawaii array.

5.4.2. Bias Level (OPT only)

The bias level or offset represents the camera's output in ADU in total absence of signal electrons. Subtracting a precise offset is an important requirement in measuring signal levels. Offset can sometimes be determined from a dark exposure using pixels from the same array region where the signal is measured. However, the offset information on the array may be corrupted with dark current or other sources of charge (e.g. light leak). Whenever pre- and over-scan pixels (or extended pixel region of the horizontal register) are digitized for the system, then the offset level can be measured directly, averaged over several pixel values. If they are not digitized, then only the dark level, which is the bias level plus the dark signal, can be measured. This may not be important for the user, since it is the dark level that is ultimately of interest; but it is useful for predictive purposes to separate the two components. This parameter can be important for system-level performance but it is difficult to specify for an individual CCD since it is influenced by the shape of the readout clock waveforms and the temperature. Hence it is quoted by the manufacturers but has to be measured at system level. In some (rare) cases, temporal variations in clock waveforms can cause the offset level to vary across a line. It is usually subtracted from other images as a number, thus saving computing time. It is not necessary to subtract the bias level pixel by pixel (i.e. with a master bias frame), unless overall bias structures are present.

When using optical detectors, the overscan region is a convenient way to read off the bias level. The overscan region is a series of readouts of the CCD amplifier with no exposure, usually performed at the end of detector row readout. The main advantages, in using an overscan region for bias subtraction, are that no separate bias frames are needed and that the bias level obtained is closer in time to the actual observation than a separate frame can provide. Additionally, no physical defects (bad pixels, traps, etc) affect the statistical computation, making the computation easier and more accurate.

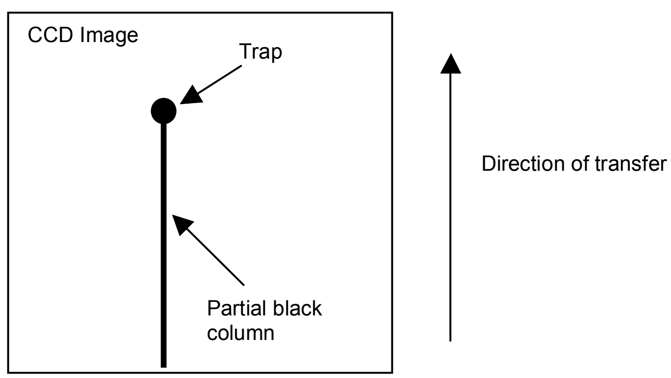
Fluctuation of bias level after multiple readouts has sometimes been observed and could be linked to many factors. Temperature values (of the detector and the electronics) and its stability should be monitored.

5.4.3. Bad Pixels – Cosmetic quality

Bad pixels are those elements of the detector that cannot be used for science because of a bad response or unpredictable behavior. They can be blind or have very low quantum efficiency (dead pixels), they can be all time saturated or close to saturation (hot pixels) or they can be significantly noisier than average (noisy pixels), as, for instance, those with highly variable dark level or quantum efficiency (see Fig. 1 for an example). Finally, they can be identified as bad pixels all those with other odd behaviors as, for instance, highly non-linear pixels and, in some IR arrays, pixels that produce electronics ghosts when saturated (not to be confused with cross talk, see below). This latter effect is particularly strong in the VISIR's DRS detectors.

The number of bad pixels is not constant, as it typically increases over the detector life time. In particular, because of thermal cycles in IR arrays, the contacts between the photosensitive elements of the array and the multiplexer can deteriorate or be completely lost. It is therefore important to monitor the number of bad pixels over time.

Traps (OPT only): dark pixels defects can be produced by charge traps. In a CCD charge is first transferred along columns and then along the read out register to the output node. If there is an obstruction in a column that impede charge transfer, then a partial dark column results (see figure).



Lesser obstructions lead to defects called traps. These can be caused by defects in the silicon used to fabricate the detector or by defects introduced during manufacturing. Traps can be classified as low-level or high-level. The former absorb a small amount of the charge that passes through the pixel. At low signal levels, not enough charge is transferred by each pixel to fill the trap, and the defect appears as a string of dark pixels following the trap. However, once the charge from several pixels has added up to fill the trap, then charge can pass through and the remainder of the column gives a good image. As the signal level increases, the number of pixels that are affected by the trap decreases, and at high levels many traps disappear. It can happen that a trap that gives a dark trail at low signal levels gives a bright one (rather that no trail at all) at high levels. The high –level trap shows the opposite behavior and only appears at high light levels. These traps are the equivalent of a constriction in the charge path through a pixel. Small amount of charge can pass through these traps unaffected, but signals above a certain level cannot be transferred. The visual effect is that a string of dark pixels occurs as for the low-level trap. At higher signal levels still, the trap can sometimes become filled and disappear.
Although trap defects are becoming rarer in high grade CCDs, large ones or lower grade devices may have some. Clearly, since the effect depends on the signal level, there is a signal-dependent

response non-uniformity, which can at times be difficult to detect.

5.4.4. Contamination

There are various effects of contamination:

1. Dust particles, solid contaminants (bits of paints) and other specimen (e.g. hair) in the dewar. They deposit on the detector and move in time, as a consequence of interventions which open the dewar, move or rotate the instrument. Such contaminants block the light from reaching the underlying areas of the detector, which therefore can be considered as much as dead pixels. This aspect is considered in section 5.4.19 (Spatial Uniformity).

2. Contamination due to materials either used for the construction of the system which outgas in vacuum conditions, or introduced in the dewar during integration in non clean-environment or by means or improper handling procedures. When the system is then cooled, most contaminants deposit on the coldest area of the dewar, i.e. on the detector. This type of contamination first shows up as a loss of transparency in the UV and blue wavelength bands. Later, layers become visible to the naked eye up to very ugly greasy deposits, which remain stable up to + 35 °C inside the vacuum. For more information on this type of contamination, see the *Ultraclean CCD Project* of the Optical Detector Team. Contamination of this type can only be measured on instruments that have UV capabilities (e.g. FORSx). The main effect of contamination is a non-uniform loss of QE, which typically increase over time, and the appearance of artifacts in the images.

5.4.5. Conversion Factor

The conversion factor (K) is measured in e-/ADU, its value defined by the electronics setup. Its inverse it is usually called system gain (G). It is usually determined by means of the photon transfer curve even though recently new fast measurement technique has been proposed for CCDs. It uses only 2 Time Delay Integration (TDI) images: the acquisition consists in collecting light and continuously reading out the detector. Under constant illumination the resulting image will have a saturated area, a signal ramp area and a no signal area. The photon transfer curve technique is then applied. At present it is unknown if it is possible to easily acquire TDI images with our instruments. The method allows computing the conversion factor, linearity and residual non-linearity with only two images, as opposed to minimum 20, as required by the photon transfer curve. It has been tested for the OmegaCam detectors in Garching. It requires stable illuminating source (1%) and narrow band filter to minimize the occurrence of photon response non-uniformities (otherwise flat fielding is required).
For more details See F. Christen et al. (ESO) "*Fast conversion factor measurement of a CCD using images with vertical gradient".* Scientific Detectors for Astronomy 2005, p 537, Kluwer

5.4.6. Cosmic rays

When a cosmic-ray particle hits a CCD pixel it causes an increase in charge which is indistinguishable from the arrival of photons. These spurious signals are usually (though not always) confined to a single pixel. Cosmic-ray hits appear as a set of pixels with intense values sparsely scattered over the CCD frame. Typically long exposures (~hour) might have hundreds cosmic-ray hits. The location of the hits within the chip is random. Also the distribution of event sizes is non Gaussian, and events two-three times the average value are usually possible If several frames of the same target object or flat field have been acquired (for example to avoid saturation, see above) then the cosmic-ray hits will occur at different positions in each frame and it is possible to detect and remove them by comparing corresponding pixels in the different images and rejecting those with aberrantly large values. The number of cosmic rays hitting a detector increases with altitude. The charge generated by a cosmic ray depends on the thickness of the detector: a cosmic ray passing through the device can generate a considerable amount of charge along its path. In addition, self-repulsion of this charge will produce enhanced lateral diffusion. As a result, charge deposited near the front of the device will have little opportunity to spread and will be confined to one or two pixels while charge deposited near the back of the device can be spread out over a region 5 to 10 pixels in diameter. This is a significantly different pattern than is observed in typical thinned CCDs. If the cosmic ray enters nearly perpendicular to the CCD surface the event may appear with a sharp core and a diffuse halo. If the cosmic ray enters at a sufficiently large angle, it may appear as a streak with a sharp end and a diffuse tail.

5.4.7. Crosstalk and electronic ghosts

In systems with more than one signal channel (either with more than one detector array or with an array with more than one output), crosstalk can occur not only in adjacent pixels, but also between the signal channels. For example, a bright image in one detector channel may give rise to a faint ghost image on another channel for those pixels that are read out at the same time. These crosstalk ghost images (not to be confused with optical ghosts) can be either positive (higher signal than average) or negative (lower signal than average), depending on the electronic crosstalk effect responsible.

In the Hawaii detectors, for instance, a stripe appears extending horizontally along the rows corresponding to the bright source and on the corresponding rows of the adjacent quadrants. This particular e inter-quadrant crosstalk and it is different from the effect described in section 5.4.3 for the VISIR's arrays, since it is common to all pixels of the array and not only to a few specific ones. Further details can be found at:
http://www.eso.org/~gfinger/hawaii_1Kx1K/crosstalk_rock/crosstalk.html

5.4.8. Charge Transfer Efficiency (OPT only)

The charge transfer efficiency (CTE) is a measure of the ability of the device to transfer charge from one potential well to the next. The CTE of a CCD is usually defined as the ratio of charge that is transferred from one pixel to the next, so that after N pixels the fraction that is correctly transferred (and not trapped or deferred into trailing pixels) is $(1\text{-CTE})^N$. CTE can be defined for horizontal (serial) transfer (HCTE) and for vertical (parallel) transfers (VCTE). The measurement, by means of the EPER method (Extended Pixel Edge Response), is limited to those detectors which have overscan areas. An alternative measurement method uses signal variance in flat field images: it is based on the decrease of variance in CCD rows and columns when flat field images are read out and uses the fact that imperfect charge transfer during readout has a smoothing effect on the final image. The method has been used for testing the OmegaCam CCDs. It provides both vertical and horizontal CTEs.
For more details, see F. Christen et al. (ESO) "*CCD Charge Transfer Efficiency (CTE) derived from signal variance in flat field images".* Scientific Detectors for Astronomy 2005, p 543, Kluwer

5.4.9. Dark Current and Dark Current Non Uniformity

Dark signal is the output signal (bias subtracted for CCDs, including bias for IR arrays) in the absence of illumination under special conditions (temperature, integration time). The signal can arise from several causes: electronic offsets (a.k.a. fixed pattern noise), thermally generated dark current, white pixels or columns, clock-induced dark current, instrument thermal background, stray light, spurious electrons generated inside the detector. Fixed pattern noise is negligible in CCDs and will not be considered.
For silicon devices, the thermal dark signal D varies with the absolute temperature (T): for example, at room temperature the dark current doubles for every 8^{o}C increase in temperature, at -40 ^{o}C for every 5^{o}C increase. For IR detectors the change of dark signal with temperature can be even larger.

Because of the large change with temperature it is important to check the dark signal for each set of measurements, particularly as the thermal dark signal varies from pixel to pixel. The same integration time should be used for dark images as for those under illumination.

The dark signal non-uniformity, expressed ad a percentage of the average value, is highest for low dark current silicon devices.

Since 0-sec exposures cannot be taken with IR detectors, the dark and the bias signal cannot be separated. It has been observed in some cases a dependency of the dark on the average signal, the Hawaii detector is an example of such a case. As for the RON a variation of the dark level is an indicator of instrumental problems.

5.4.10. Full Well Capacity

It is defined as the point where the linearity error (see above 2.6) exceeds a defined limit (e.g. 5%) and it is measured as a by-product of linearity measurements.
For a CCD, the full well capacity can be defined for the image region, the readout register and the output amplifier, the latter two quantities being important when pixel binning is used.

5.4.11. Linearity

IR Array Detectors are intrinsically non linear. Within a limited dynamic range the effect of non linearity is small and the detectors can be used as they were virtually linear; outside this dynamic range a linearity correction must be applied. It has been observed in some cases a dependency of the linearity on the flux intensity, different illuminating fluxes can produce different responses even if the average number of counts generated is in the same range.

In CCDs non-linearity effects can be present both at low and high signal levels. The linearity error is defined as the difference between the measured output signal and the ideal (straight line) behavior. The maximum allowed linearity error will usually also define the useful saturation level or full well capacity, since the largest departure from linearity will occur at saturation. A problem with the linearity error is that it can be specified either as a percentage of the signal at full well or as a percentage of the signal level at which it is measured. In the latter case, which is the most accurate definition, the linearity error will of course be higher at low signal levels.

5.4.12. Persistence or Remanence

Latent charge, or "persistence," is the remaining signal apparent in a series of dark exposures, after the array has been exposed to a bright radiation source. Any process which, after some delay, releases charge into the conduction band, can contribute to latent charge. Latent charge is a function of fluence during a previous exposure and the time elapsed since the previous exposure. Usually, for fluence levels below the saturation persistence is negligible. As soon as the fluence exceeds the saturation level, persistence can be observed. This threshold effect may indicate that traps in the surface passivation layer are filled when the p-n junction moves from reverse bias toward forward bias. If the Hawaii-2RG array is used in a high-resolution spectrometer, latent images can be observed in subsequent dark exposures for several hours.
(For more details see G. Finger's paper,
http://www.eso.org/~gfinger/taormina/gert_finger_Hawaii-2RG_corrected_29_July_2005.pdf).

The ghost generated by this effect disappears only after the detector has been read-out several times or after some time has passed since the illumination. The resulting effect resembles an increase of dark current, especially at temperatures lower than 180 K.
In CCDs, the mechanism producing persistence has to do with charge being trapped within the dielectric surface layer. The length of the time that persistence lasts depends strongly on temperature.

Remanence effects may also occur if a flat field (Mean>10000e-) is taken prior to the dark frame. The resulting effect resembles an increase of dark current, especially at temperatures lower than 180K. The figure below shows the apparent value of the dark current for a set of 24 consecutive dark frames exposed each one-hour. This set was taken after the CCD was exposed to the ambient light. It requires four 1 hour darks frames to eliminate the remanence and to reach the actual dark current value.

When the illumination level is sufficient to generate more charge than can be stored in a pixel and the excess charge spreads to adjacent pixels is called blooming. Strong blooming may generate persistence effect.

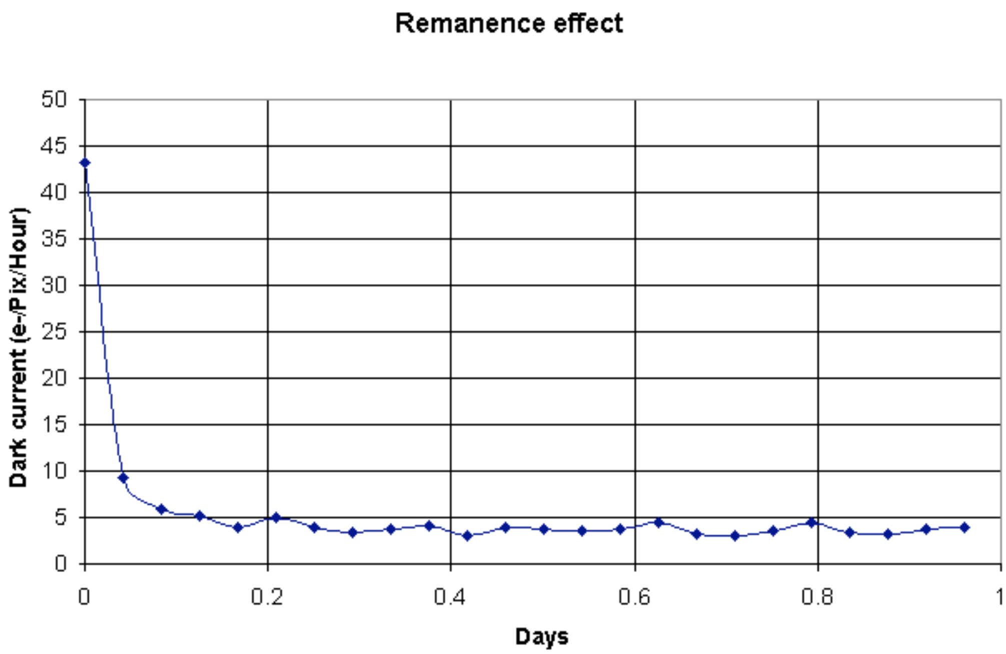


Figure 8a : 2048 x 512 pixels subframe, one hour exposure dark frame, just after a flat field, the dark current is 43 e⁻/pixel/hour and the "dark current" is related to the "blue diamond" pattern.

Figure 8b : Same frame as figure 8a, 2nd one hour exposure dark frame, the diamond pattern is fainter, 10 e⁻/pixel/hour of dark current. Overscan- / prescan area is visible.

Figure 8c : Same frame as figure 8b, 28th one hour exposure dark frame, dark current has reached its minimum value (4 e⁻/pixel/hour).

Fig.2 Persistance plot as a function of time and persistence as seen in dark images taken after illuminating the detector.

5.4.13. Read Out Noise

The noise parameter usually refers to temporal noise in the image data. If samples of the output of a given pixel are repeatedly measured over a period of time and the rms is calculated, then this is the noise. The temporal noise arises from the following sources:

- Noise associated with the output amplifier
- Reset (kTC) noise associated with the resetting of the output stage
- Shot noise on any signal (arising either from illumination, spurious charge injection or thermal dark current).
- Noise due to external (off-chip) electronics.

There is a temporal noise component that varies as the square root of the signal (Poisson Noise), but for pixels that have no signal (like in Bias frames) the noise comes solely from the readout process. Therefore, in 0-sec exposures the contribution of the shot noise component is practically 0. The last effect is considered separately in sections 5.3, 5.4, 5.5 and 5.6.

The RON depends on the read-out mode employed and on the temperature. It is measured in electrons. Beside its intrinsic relevance monitoring the RON is important also because it can be a good indicator of different instrumental problems.
This readout noise is normally stable, but it can vary if the CCD temperature changes significantly or if there is a change in the bias voltage applied to the output amplifier. The read out noise will also be influenced by any electromagnetic interference (see section on 50Hz pick-up noise).

The readout noise has an effect o the minimum detectable signal and hence on the dynamic range. In particular, IR instruments will perform better when operated in background limited conditions (BLIP), for this reason it is important to make sure that this condition is verified as much as possible during the observations. In order to operate a detector in BLIP, the RON must be known.

Although not a form of temporal noise, another contribution to the total value of the noise is the quantization noise introduced when the pixel value is digitally encoded by the analog to digital converter (ADC). Quantization Noise (QN) is found by calculating the rms value of the staircase response about a perfect ramp. It is important to note that the quantizing noise is constant with the camera gain when expressed in ADUs.
The total noise (in electrons) becomes:

$$Noise = \sqrt{RON^2 + (K \cdot QN)^2}$$

Where RON is the read-out noise and K is the conversion factor of the camera.
Note that in most systems, the contribution of the quantization noise to the total noise is minimized by properly setting the inverse gain of the system to equal the read-out noise.

5.4.14. 50 Hz pick-up noise

The pick-up of the 50 Hz frequency manifests in the form of stripes crossing the detector (Fig. 3). These strips are typically inclined with respect to the rows and the columns. The pick-up noise depends on the read-out speed, changes with time and it is strongest for some DITs.

There are two types of pick-up noise:

1. Coherent pickup noise - interference noise which is the same for every image and which may be removed from science data by subtraction of a mean or median bias image.
2. Incoherent pickup noise - interference noise, which is different for every exposure and therefore cannot be removed from science data.

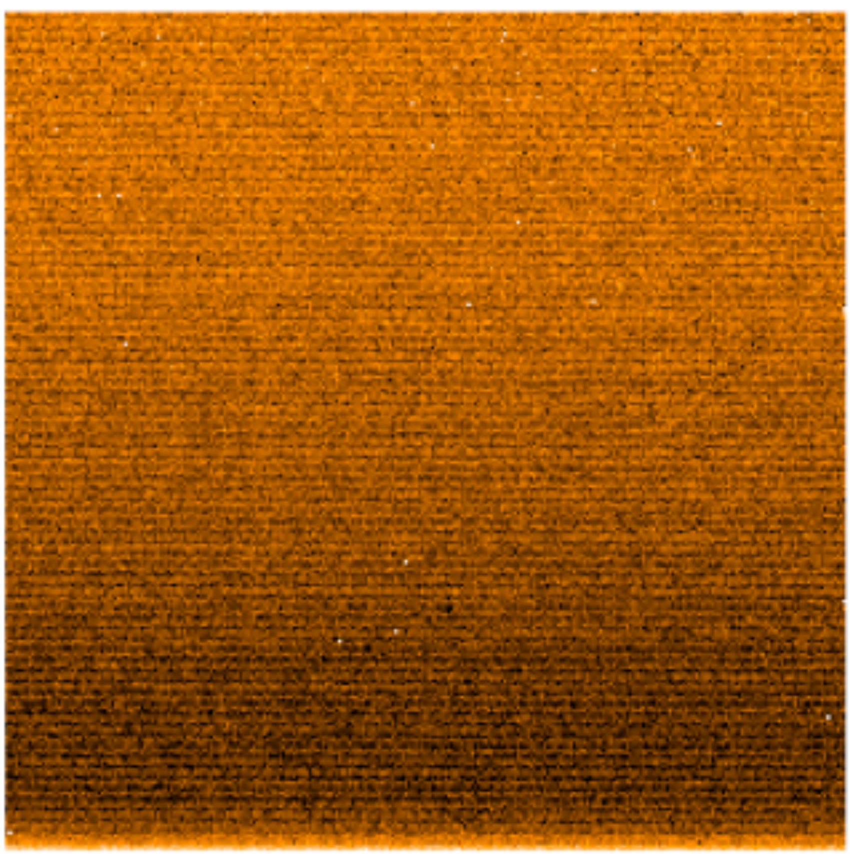


Fig. 3 50 Hz pick-up noise in one quadrant of the Hawaii array.

5.4.15. Microphonic Noise (IR only?) – Periodic Noise Interference

Phonon or acoustic noise is typically produced by mechanical vibrations as those generated by Closed Cycle Cooler systems. It produces a series of horizontal or vertical strips that moves on the detector from one integration to the other.

5.4.16. N pixel correlated noise (IR only)

Similar to the odd-even column effect, but occurring on an N pixel base. An 8 pixel correlated noise is observed in the CONICA's and CRIRES' Aladdin detectors.

5.4.17. Odd-Even Column Effect (IR only)

The odd-even column effect is observed in the Rockwell array detectors only and it is an offset between the signal of the odd and even columns of the array. It depends on the flux and it can be as large as few %. Beside the flux, the effect also depends on the quadrant, on the read-out speed and on time. In particular, the effect has shown random variations with time, in occasion of instrument interventions or detector warming up. For these reasons it is important to monitor the effect carefully

5.4.18. Shutter Pattern/Error (OPT only)

A mechanical shutter takes a finite time to travel from fully closed to fully open. In a short exposure this can have a significant effect, which is not uniform across the CCD (unless the shutter is in the parallel beam). The form of the shutter delay pattern can be deduced by comparing a long exposure flat field with an exposure in which the shutter has been opened and closed many times.
The counts in pixel x of the image where the shutter has been opened and closed once is:

$$I_{x,1}\ (ADU)=(DIT_1+S_x)F_x$$

Where DIT_1 is the reported exposure time, S_x is the total shutter delay at pixel x and F_x is the counts detected per second ad pixel x.
If the shutter is opened and closed n times before the CCD is read out, then the counts are:

$$I_{2,x}=(DIT_2+nS_x)F_x$$

Where DIT_2 is the reported exposure time for the second image and it has been assumed that the shutter delay is the same for every open-close cycle.
Since F_x is the same for both images, we can solve for the shutter delay

$$S_x=DIT_1 \times I_{2,x}-DIT_2 \times I_{1,x}/(n \times I_{1,x} - I_{2,x})$$

It is unclear at this point if it is possible to collect such data. A simplified analysis on how to determine the shutter error is described in the test procedure for the transfer curve.

5.4.19. Spatial Uniformity - PRNU – Fringing - SPRNU

The response of an Array Detector is not spatially uniform and shows pixel to pixel, low scale variations and larger scale structures. All are mostly corrected in the flat fielding process, however this is not always true and the correction is never perfect so that it is important to monitor the evolution of these structures with time to keep the science targets far from them.

Large deviations from uniformity can be produced in some pixels by spurious deposits formed during manufacture (stains or metallization deposits) or by dust either on the surface of the array or on the window. The effect of dust particles will depend on the cone angle of the illumination. A narrow cone angle gives a more pronounced shadow and greater contrast between the defect pixels and their neighbors. Adherence of dust to the outside window is more common and tends to give out-of focus, low-contrast regions of lower response (often in a form of a halo).

For a uniform illumination, the photo-response non-uniformity (PRNU) is the difference in percentage between the signal in each pixel and the average signal of the total photosensitive area (excluding the extreme edge pixels). PRNU is usually obtained from the whole chip area, but it can also be obtained from calculations on small groups of pixels (with the PRNU being taken as the maximum of the local PRNU values for all the pixel groups).

PRNU across the chip measures the amount of fringing, which is an issue for spectroscopic purposes and narrow band imaging applications. The near IR PRNU depends upon the fringing effect. This effect is related to the thinning of the CCD, and also to the aperture of the incoming beam, the more this beam is open, the less the fringing is visible (figure B). In the blue part of the spectrum the PRNU degrades also due to the backside p+ implementation laser annealing. The images show qualitatively these effects.

A quantity related to the PRNU is the spectral photo-response non-uniformity (SPRNU). This is related to the spectral variation in the responsivity and can be measured by taking the ratios of the PRNUs at selected wavelengths or narrow wavebands to the PRNU for broad waveband. The ratios can be weighted according to the spectral shape of the broadband illumination.

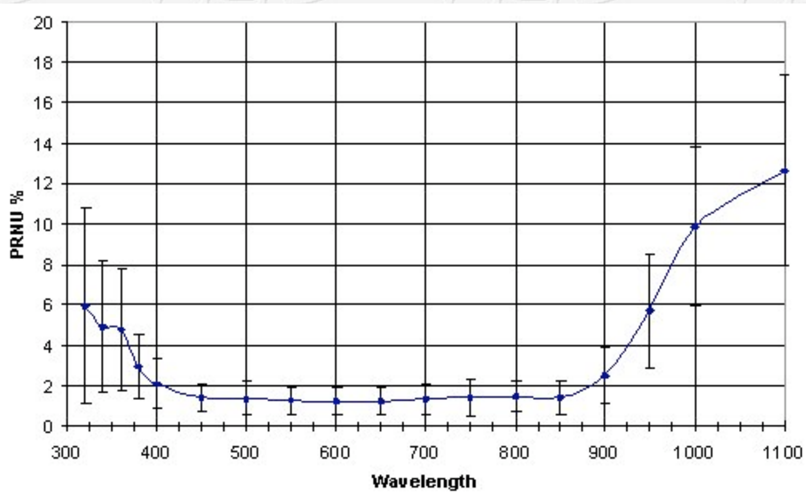


Fig. 4: Above - Flat fields from the same area at different wavelengths, 5nm bandwidth, parallel incoming beam, left 320nm, middle 650nm, right 950nm, F/2 beam. Below – Plot pf % of PRNU ad a function of wavelength.

5.4.20. Stability (IR only)

The purpose of the test is to give a quick flavor of the stability of the detector. The stability is then more accurately quantified by monitoring specific detector parameters, as ron, dark, linearity, bad pixels etc.

5.4.21. Stray light

Stray light is a general term used in spectrometry to describe the level of optical radiation measured at a given wavelength position that reaches the detector by other than the direct optical path or the light which is of a different wavelength to that being observed. Problems due to stray light can be diagnosed by means of detector tests. Stray light can be light reflected off the surface of the array being directed back to the detector by reflection off either the array window or nearby optical components. The effects tend to be more noticeable in back-illuminated CCDs since the refractive index of silicon is high. With front-illuminated CCDs the reflection from the electrodes on the front surface is usually less. The anti-reflection coating reduces reflection at the design wavelength, but for other wavelengths the reflection can be large. The effect on the measurement is most pronounced when the stray light is of a wavelength for which the detector responsivity is large and it falls on a part of the image (or spectrum) where the signal is normally low. For these reasons the measurement of stray light as a function of wavelength is an important part of the calibration procedure. Unfortunately an accurate measurement requires the use of monochromatic light, or edge filters (long-pass, short–pass) or notch filters (band-stop), which are not necessarily on-board the instrument.

5.4.22. Temperature Stabilization (IR only)

Despite the fact that the detectors are stabilized in temperature by an active control they can show some times instability mostly related to the level of illumination. As the illumination level increases, it also increases the current through the chip and the power dissipated. The operation points of the current sources and amplifiers are shifted and there is a temperature variation. If the temperature control is not fast enough the change of temperature can produce a significant variation of the response of the detector. This variation may take some time before stabilizing.

6. INDIVIDUAL TEST PROCEDURES

In this section we list the individual test procedures, the data requirements, the data analysis and the data outputs expected by the recipe. Note that, at difference to the previous chapters, the test entries are not listed in alphabetical order, but rather organized in logical order whenever needed.

Even if not mentioned in each single test procedure, the ASCII data produced are expected to be stored in the observatory's AUTREP database. Therefore, the data produced by the pipeline recipes should produce output in the form of log files identical to the quality control operational logs[1], which are in use at the observatory.
Although the format of these files corresponds to a normal ops-log, the data are organized in blocks of data products (group) and the timestamp corresponds to the reduction time and not to the time when the product was taken on the instrument.

hh:mm:ss>-START GROUP / Start [<instrument>]
..
..
hh:mm:ss>-STOP GROUP / Stop [<instrument>]

The ops-log log record format consists of maximum of 250 byte long terminated with a newline character and its format is like this:

hh:mm:ss> keyword / comments [<source mask>] or
hh:mm:ss/ comments [<source mask>]

The authoritative reference for the keyword specifications are the ESO Data Dictionaries. Additional information on AUTREP can be found in the AUTREP's User Manual (Doc.No. VLT-MAN-ESO-10200-1791).

6.1. BIAS FRAMES ANALYSIS (OPT ONLY)

Through the analysis of bias frames it is possible to characterize many parameters for CCDs. We list them below, as separate items, even though the analysis can be (and should be) performed as a unit. Depending on the detector system, the measurements on bias frames should be performed for each gain setting and binning setting (a.k.a. for a defined read-out mode), for each port/amplifier in use and for each device (Mosaics).

6.1.1. BIAS LEVEL

Applies: OPT

Frequency: D/BA

Purpose: Measure the bias offset/level for the system as the mean value of bias frames.

Data Acquisition: 3 0-sec integration time (bias) frames for all defined read-out modes and amplifier modes (e.g. 1x1, 4 amp readout, low gain, 2x2, 1 amp readout, high gain, etc).

Analysis:

[1] Pipeline data quality control writes the QC parameters in operational log-files. These logs provide highly valuable information to the observatory to monitor the performance of the instrument and, if necessary, to recover or improve its quality.

1) **Daily**
   a. Measure the mean value of overscan and pre-scan areas (if available).
2) **Biannual**
   a. Measure the mean of 20-100 100x100 pixels randomly selected regions in the illuminated area of the CCD for all frames and for all amplifiers in use Calculate the median value of the distribution for each amplifier/sector in use (i.e. a 4 quadrant frame will give 4 values). Alternatively, measure the mean of a region of each bias frame and sectors which are free from cosmetic defects (hot pixels, traps, etc).
   b. Measure the mean of the overscan and pre-scan areas (if available).
   c. Generate a median stacked frame (master bias): generate 1-d images of mean row and columns.

Outputs:
Save mean value for the day.
Generate plot of mean value vs. time.
Check that results of a) and b) are within 1 ADU of each other.
Plot 1-d row and column images, check for gradients (rows) and slopes (columns) between the illuminated area and the overscan areas, check for patterns (Fixed Pattern Noise).

6.1.2. READ-OUT NOISE (OPTICAL)

Applies: OPT

Frequency: Daily/Biannual

Purpose: Measure the read-out noise in ADU/pixel of the system and its variation with time/temperature.

Data Acquisition: 3 0-sec integration time (bias) frames for all defined read-out modes and amplifier modes (e.g. 1x1, 4 amp readout, low gain, 2x2, 1 amp readout, high gain, etc)
Analysis:

1) **Daily**
   Measure the standard deviation (rms) of 20-100 100x100 pixels randomly selected regions in the illuminated area of the CCD for all frames and for all amplifiers in use. Calculate the median value of the distribution for each amplifier/sector in use (i.e. a 4 quadrant frame will give 4 values). Alternatively, measure the rms of a region of each bias frame and sectors which are free from cosmetic defects (hot pixels, traps, etc). Measure the rms of the overscan area.
2) **Biannual – Noise distribution**
   Make a histogram of a sub-region of at least one bias frame.

Outputs: Check that the rms in ADU/pixel is the same for each bias image. Compare the value of rms measured in the overscan area and those measured in the illuminated area of the frame. Save rms value for the day, save detector temperature. Generate plot of rms vs. time, generate plot of rms vs. temperature.

The histogram should be fitted by a Gaussian, indicating that the noise has normal distribution (check).

6.2. BAD PIXELS TEST

Applies: OPT/IR
Frequency: Yearly, after instrument interventions and warm-up of the detector

Purpose: The purpose of the test is to assess the cosmetic quality of the detector in terms of pixels with bad response (bad pixels), including hot, dead and noisy pixels. Pixels with different types of misbehavior are not treated here.

Data Acquisition: Bias, Darks and Flat frames (OPT: high and low level) obtained as part of the regular calibration plan. A minimum of 3 bias/dark/flat frames in sequence are needed for this test.
Analysis: construct a median or mean stack of the bias/dark/flat frames.
The **hot** pixels are identified as those exceeding by more than 5 σ the mean level of a master bias/dark. A master bias/dark is the average of 3 or more bias/dark frames obtained in the same read-out mode and with the same DIT and it is routinely generated by the pipeline.
Bad pixels are also identified as hot pixels those exceeding by more than 5 σ the mean level of a master flat. For IR arrays master flat is a gain map obtained through a linear fit, pixel by pixel of the single pixel value versus the median value of the frame, over a sequence of flat frames with different illuminations. For OPT arrays a master flat is a median stack of low or high level flat frames.
The **dead** pixels are identified as those below more than 5 σ the mean level of a master flat.
Finally the **noisy** pixels are identified as those deviating by more than $\pm$ 5 σ from the mean level of the map of a sequence of darks and a sequence of flats. A σ map is obtained as the σ, pixel per pixel, of the average combination of a number of frames.
The combination of hot, dead and noisy pixels gives the global number of bad pixels. The test is repeated for different read-out modes and DITs.

Output.
Number of bad pixels and their classification (hot, dead, etc) and bad pixel mask (map). The fraction of bad pixels as function of time.

6.3. DARK LEVEL AND READ OUT NOISE TEST (IR)

Applies: OPT/NIR/MIR
Frequency: The dark signal is monitored daily for all detectors, the RON is monitored daily for the Hawaii and Aladdin detectors.
Purpose: The purpose of this test is to measure the mean dark level of the detector and the RON for a particular read-out mode.
Data Acquisition: A set of darks (minimum 3) with suitable DIT is acquired daily in different read-out modes as part of the calibration plan. Beside few basic modes and DITs included by default in the daily calibrations, the details of the sequence acquired depend on the observations executed during the previous night. A sequence of darks can also be acquired independently of the daily calibrations using a specific OB.
Analysis: A master dark is created by the pipeline and the mean dark level is measured. A master dark is the average of 3 or more dark frames obtained with an identical setup and it is routinely generated by the pipeline. For daily monitoring the RON can be simply measured as the RMS, on defined areas, of the difference of two dark frames divided by the square root of 2. The RON must be measured independently for each quadrant or port. For a more accurate analysis a detector transfer curve must be obtained, see Section 4.5.
Outputs: The mean dark level in electrons per DIT and the RON in electrons. Plots with the evolution of the two parameters with time are available in the QC web-page.

6.4. DARK SIGNAL NON-UNIFORMITY AND FIXED PATTERN NOISE (DSNU+FPN)

Applies: OPT
Frequency: Bi-annual
Purpose: Measure the DSNU and FPN
Definition: The dark signal differs from one pixel to the other. The variable part of the signal, dependent on temperature and integration time, is defined as DSNU, as opposed to its fixed part

(Fixed Pattern Noise, FPN see below). It mainly arises from thermal dark current but also defective pixels, such as white spots or columns, contribute to it.
For pixel x,

$$DSNU(x)= (V(x)-Va)/Va$$

Where V(X)=píxel signal and Va=average signal on frame.
There are several ways to specify the DSNU

- peak-to-peak
- max and min
- standard deviation
- table of defect pixels below or above specified interval
- uniformity map and/or histogram of pixel values

DATA Acquisition:

- Dark images (min/max 3/9) at specific operating temperature and for a grid of integration times (instrument dependent).
-Non-binned, non-windowed images.

Algorithm/Analysis

is done by analysis of dark images. Averaging of several frames may be needed to remove effects of temporal noise or pick up noise.
For each DIT, build average frame of set of n frames and

1) Compute DSNU map for each pixel
2) Compute peak-to-peak and stdev in frame. Using stdev(DSNU) plot versus temperature and DITs

Output: DSNU map, plot of stdev vs. temperature and DITs

6.5. TRANSFER FUNCTION – CONVERSION FACTOR – NOISE

Applies: OPT/IR
Frequency: Biannual

Purpose: The purpose of the test is to generate the detector transfer function, measure the conversion factor and the read out noise accurately.

DATA Acquisition OPT: To generate a transfer curve the noise must be measured at each exposure level, independent of flat field variations. The illuminated frames should be taken by means of a stable source (e.g. stabilized LED, halogen lamp, arc lamps). Collect a sequence of pair of images with increasing exposure times, generating signal levels from just above the bias to near digital saturation (65535). The integration time sequence should be such as to cover the dynamic range of the detector, with particular emphasis on points for low and high level of illumination. Note that points at very low level are strongly affected by shutter non-linear response. Also the sequence of pairs of flat images should be obtained in two groups: the first with increasing and the second with decreasing exposure times. The exposure times of the two groups should be different and interleaved. (e.g. first sequence: 2x1sec, 2x3sec, 2x5sec…2x20, 2x40, 2x80, 2x90, 2x100., second sequence: 2x95, 2x85, 2x45…, 2x6sec, 2x4sec, 2x2sec,…). At least 10 pairs per sequence should be acquired. The sequence is instrument dependent and as such has to be defined by the instrument scientist. Also depending on the instrument the test can be performed for the different read-out modes available.

DATA Acquisition IR: A series of internal flats with average counts spanning the linear dynamic range of the detector is acquired. Different count levels can be obtained both varying the intensity of the test source or the DIT. At least two frames must be obtained for each level of counts. The stability of the test source must be checked.

Analysis OPT: take each pair of images (same integration time) and subtract one from the other. For each quadrant (port), select a region which is clear of non-linear defects (traps, hot pixels, etc). Compute the variance of this region in the difference image and **divide by two**. Also compute the mean signal in the same region for both pair of raw images. Perform the same calculation for all other pairs of flat field and for the pair of bias frames. When finished one should have a table with four columns (1=integration time of the pair, 2=mean counts in frame 1, 3=mean counts in frame 2, 4=one half of the variance of the difference frame).

1) Subtract the bias level from the data in columns 2 and 3, as calculated as mean value of the corresponding overscan areas. Alternatively, especially when there is a significant fixed pattern noise in the bias frame, a median stacked frame (master bias) must be subtracted from the flat images before the computations are made.
2) Generate the transfer curve as a plot of the variance (column 4) vs. column 2 (or 3). This plot should be a straight line up to count levels approaching saturation, when the noise turns over and may go to zero in a completely saturated image.
3) The transfer curve below saturation should be fitted by a straight line, Compute the reciprocal of the slope. This is the conversion factor of the CCD in e-/ADU.

Analysis IR: The mean and σ frames are calculated for those frames obtained at the same count level and a linear regression of σ^2 versus mean signal is produced over the sequence of flats. The σ^2 must be normalized to the number of frames used to derive it. Each quadrant or port is analyzed independently, the mean and can be calculated over the entire quadrant or on selected subsections. The slope of the linear regression gives the inverse of the conversion factor in electrons per ADU while the intercept gives the square of the RON in ADUs according to the relation:

$$\sigma^2 (ADU) = 1/K \times I(ADU) + 1/(K^2 \times RON(e^-)^2)$$

where K is the conversion factor in electrons per ADU. The conversion gain given by this technique must be corrected for a factor that takes into account the coupling of adjacent pixel's capacitance. This is described in:

http://www.eso.org/~gfinger/taormina_gert_finger_conversion_corrected_29_july_05.pdf

Output. RON and K. The RON must be consistent with the values derived on the daily monitoring described in Section X. Evolution of G with time.

6.6. CONVERSION FACTOR WITH TDI IMAGES (OPT ONLY)- FAST

Applies: OPT (requires stable illumination and availability of TDi mode)

Frequency: M

Purpose: Determine if the conversion factor.

Data Acquisition: Two TDI illuminated images, with a narrow band filter.

Analysis: Compute an average TDI image from the two available. For each row in the image area, calculate mean signal S and subtract bias level (as measured in the corresponding overscan pixels). Subtract one TDI image from the other. For each row of the image area calculate variance=$1/2\sigma_{row}$. Compute linear fit of (S,σ), compute slope

Outputs: Plot variance versus mean signal, print inverse of slope, which is the conversion factor. (K)

6.7. LINEARITY (+ OPT: SHUTTER ERROR, FULL WELL CAPACITY)

Applies: OPT/IR

Frequency: Biannual
Purpose: The purpose of the test is to evaluate the response of the detector in terms of linearity, define the linear dynamic range if possible, and define a linearity correction. In the case of CCDs the shutter error is also derived.

DATA Acquisition OPT: The same data acquired for the transfer function can be used. Additional data taken for very shirt exposure times may be used to determine at what exposure time the shutter becomes unreliable (optional).

DATA Acquisition IR: A sequence of internal flats is acquired with fixed illumination and different DITs in such a way that the entire dynamic range of the detector is covered. The stability of the test source must be checked during the acquisition, for this reason frames acquired with a reference DIT are periodically taken during the sequence of exposures. A typical sequence of DITs could be, for instance: 0.5, 1, 1.5, 2, 2.5, 3, 0.5, 3.5, 4, 4.5, 5, 5.5, 0.5, 6, 6.5, 7, 7.5, 8, 0.5, 8.5, 9, 9.5, 10, 10.5 0.5 sec. A sequence of darks is taken with the same DITs. For those detectors that show a dependency of the linearity on the flux two sequences of measurements are taken with high and low illumination respectively.

Analysis OPT: We are using the same table prepared for the transfer function test: column 1 contains the integration times, column 2 and 3 the bias subtracted means counts in a defect free region of the detector for each if the pair of images. We use only columns 1 and 2 or 1 and 3, since they give identical results. (We do not use column 4). Plot the conventional linearity curve, mean counts versus exposure time and fit a straight line (quadratic) to the points that are not affected by saturation. Calculate the residuals to estimate the non-linearity or the variation in the illumination level during the test. Generate a 5^{th} column, containing the measured count rate: it is obtained by dividing column 2(3) by column 1 and by dividing these values by the mean of column 5. Plot column 5 versus column 2 (3). It should produce a straight line, which tends to small values for smaller count rates. The shutter error can be deduced by iteratively adjusting the exposure time (with guesses at his error), re-computing the mean counts (column 5) and fitting a straight line until the best fit is found. The input guess is then the shutter error, allowing for first order nonlinearity of the CCS. The amplitude of the points on the final curve is the amplitude of any non-linearity over the examined dynamic range, expressed as a fraction of the linear term in the response function.
If the light source varies during the test, it does so in a smooth fashion, typically at the level of 1% or less. Since the images used to construct the count rates are collected in two sequences, one in increasing and one in decreasing exposure times, the light variation, if present, should cause the count rate curve to present two distinct arms. In this case, the evaluation of the shutter error as described above might not be possible. Also non linearity can only be estimated as upper limits. In this case, the stability of the lamp should be corrected and a new dataset acquired.
In an intermediate case, CCDs non-linearity is of the same order of light source variations. In this case the analysis is more difficult. It may help to use a sky flat sequence on sky to measure non-linearity independently form light source variations. The procedure to take and analyze these data is TBD.

If a large number of exposures are taken at short exposure times, it may be possible to determine at what exposure time the shutter becomes unreliable, by measuring the scatter of the measurements at low light levels in the count rate plot.

The full well capacity can be defined as the point at which the linearity error exceeds a defined limit (5%) and is thus measured as a by products of linearity measurements

Analysis IR: Darks with the corresponding DITs are subtracted from the Flats. The stability of the lamp is checked using the frames taken with the reference DIT. The stability of the lamp must be within 1%. A plot of the average counts on selected areas versus DIT is produced.
A fit of the counts versus DIT is produced pixel by pixel in those cases where the linearity

significantly changes from one pixel to the other. A polynomial of order 3 is used. The test is repeated for different readout modes and DITs. The pixels that show high non-linearity are included in the number of bad pixels.

Outputs OPT:

a) Plot of the mean counts versus integration time. The exposure time intercept provides a first order measurement of the shutter delay (i.e. exposure time at zero counts). Plot the residuals as a function of exposure time to estimate.
b) Plot average count rate versus the average counts (column 5 vs. 2).
c) Plot the count rate curve corrected for the derived shutter error. Calculate amplitude of non-linearity.
d) If appropriate data-set available, measure the scatter of data points with respect to the measured fit and derive at which exposure time the scatter becomes comparable with the one measured at longer exposure times.
e) Measure the full well capacity at high signal levels.

Outputs IR: Plot of the average counts on selected areas versus DIT, linear dynamic range, coefficient frames, and linearity correction.

6.8. Shutter Delay Pattern

Applies: OPT

Frequency: N (Shutter interventions)

Purpose: measure the shutter delay pattern, which affects short time exposures.

DATA Acquisition: a single well exposed unsaturated image taken while cycling the shutter open-closed as many time as possible (pause/continue sequences?). Plus a single well-exposed image (e.g. one of those taken for the transfer function sequence).

Analysis: Apply equations listed in section 5.19 across the image

Outputs: Contour plot / shutter delay map.

6.9. Spatial Uniformity

Applies: All
Frequency: M/BY
Purpose: The purpose of the test is to monitor the spatial uniformity of the detectors, the possible appearance of large scale structures and features intrinsic to the detector or even produced by dust grains that could possibly escape the bad pixel monitoring because not contrasted enough as to be detected in a σ clipping process.

Data Acquisition: A series of sky or internal flats with low and high level of illumination

Analysis: Flats are compared with reference flats. Flats with high counts are divided by flats with low counts, the result is compared with a reference image ratio.

Outputs: On screen. Description of the detector's features in the suitable documentation.

6.10. Pixel response Non-Uniformity (PRNU)- Fringing

Applies: OPT

Frequency: N

Purpose: Quantify PRNU (due to e.g. fringing) for a detector as a function of wavelength

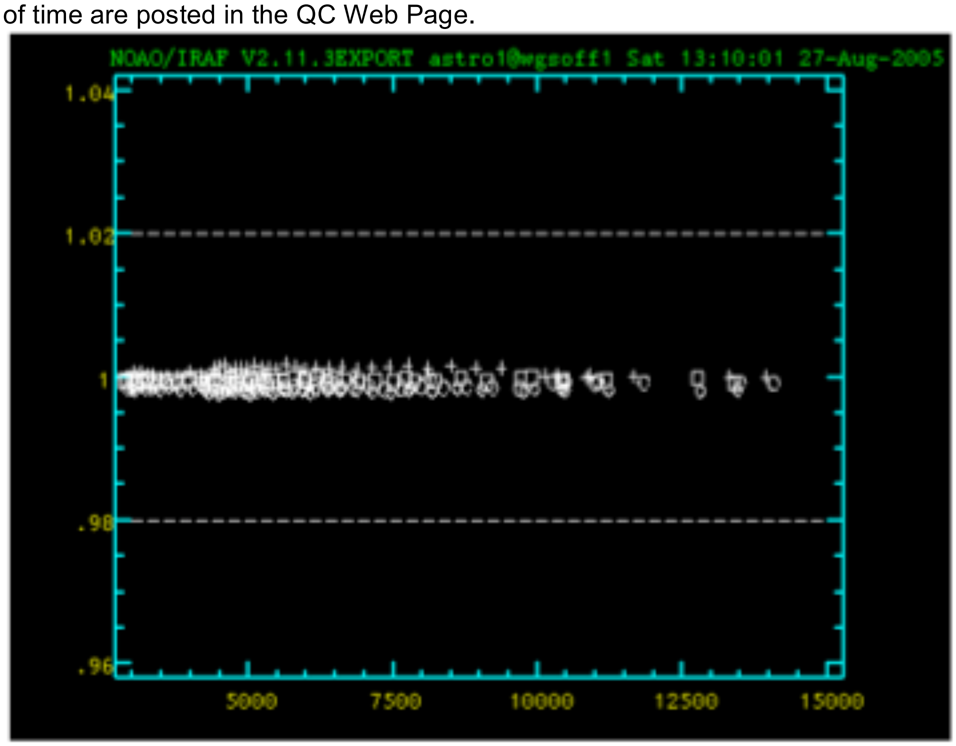
Data Acquisition: Flat field images with good signal at different wavelength, possibly with narrow band filters or in those filter that show fringing. Dark images with identical exposure time.

Analysis: Subtract the darks from the corresponding flat**,** mask out bad pixels. Calculate the difference in percentage between the signal in each pixel and the average signal of the area considered (depending on the case, the whole chip can be considered or small defect-free regions on the chip)

Outputs: Plot 2-d map of PRNU. Plot of PRNU [%] as a function of wavelength. Standard deviation of PRNU, min/max PRNU (when multiple windows are used).

6.11. ODD-EVEN TEST

Applies: NIR
Frequency: Daily on Hawaii detectors
Purpose: The purpose of the test is to quantify the odd-even column noise.
Data Acquisition: The test is executed using flat field frames. Sky or Internal Screen Flats are regularly acquired depending on the needs as part of the calibration plan.
Analysis: The analysis is based on the comparison of the signal averaged over the even and odd columns of the array, respectively. The analysis must be independent for each quadrant or port. The average ratio odd/even is compared with the average signal in counts, its evolution in time is monitored.
Outputs: Ratios of the average odd/even as function of the average signal (see Fig. 3) and as function of time are posted in the QC Web Page.



Odd-Even effect measured for the four quadrant of the Hawaii array as a function of the average signal.

6.12. Amplifier Glow

Applies: All

Frequency: N

Purpose: The purpose of the test is to monitor the glowing of the multiplexer in those cases where the effect is relevant.

DATA Acquisition: A sequence of darks in the different readout modes, typically those with the lowest RON, is taken with increasing exposure times.

Analysis: The glow signal is measured on the darks on selected areas of the array, close to the output amplifier. Measure the size of the affected area and the maximum and average levels of the glow signal as a function of exposure time

Outputs: plot of maximum and average level of glow signal as a function of exposure time. Measure of the size and location of the areas on the chip affected by the glow.

6.13. 50 Hz pick up noise

Applies: All

Frequency: Yearly, after instrument interventions.

Purpose: Evaluate the 50-Hz pick-up noise.

DATA Acquisition: A sequence of bias frames (OPT) and a sequence of dark frames with DIT=1 (OPT/IR) for different read-out speeds. Or any other sequence of different DITs, when it is know to suffer from the problem.

Analysis:
The bias/dark frames are visually inspected first to determine the orientation of the 50 Hz strips if present and to approximately evaluate their spatial frequency. Each image is sliced in the direction perpendicular to the strips in subsections few tens pixels wide. These subsections are block averaged to 1 x N images, where N is the dimension of the array in the direction perpendicular to the 50 Hz stripes. Since the 50 Hz stripes are typically slightly tilted with respect to the rows or columns it is important that the slices are not too wide not to smooth away the effect to be measured. A Fourier power transform is obtained for each 1D image, the power spectra are average combined in a single one. The analysis must be performed independently on each quadrant or port. Apply the calculation to both raw frame and the median stack of the frames (where the effect should not be seen).

Outputs: Frequency and intensity of the pickup noise in the spatial frequency domain. The analysis could also evidence other type of periodic structures in the array. Compare the intensity (ADU) with the corresponding system RON. Plot the frequency/intensity as a function of time.

6.14. Crosstalk

Applies: All system with more than one output port (crosstalk between video signals)

Frequency: N

Purpose: Evaluate the presence of crosstalk effects for pixels read out at the same time and electronic ghosts.

DATA Acquisition: Observe a bright star and collect a jitter sequence. Repeat for different signal level of the main star.

Analysis: Crosstalk is expressed as a fraction of the signal in a given pixel, since it usually scales with this signal. Calculate the ghosts' intensity as a fraction of the signal in the star image for all frames in sequence. Images should be visually inspected and the location of the electronic ghosts described

Outputs: Description of the ghosts and value of the signal as a function of the signal in the star image. Derive the maximum signal for which no effect is observed.

6.15. PHONON TEST

Applies: IR

Frequency: Y

Purpose: Evaluate the phonon noise

DATA Acquisition: A sequence of dark frames with NDIT=1

Analysis: The dark frames are visually inspected to detect the presence of phonon noise and to determine its orientation. At difference with other sources of noise, mechanical vibrations produce groups of stripes that change position from one frame to the other and that, therefore can be easily identified. Each image is collapsed in the direction perpendicular to the stripes, the resulting line is plotted and searched for picks of noise exceeding a threshold.

Outputs: Intensity of the noise

6.16. TEMPERATURE STABILIZATION TEST

Applies: IR

Frequency: Y

Purpose: Evaluate the effect of the illumination on the detector temperature and on its response.

DATA Acquisition: A sequence of internal flats is acquired with short DIT. The test source is initially OFF and it is switched ON during the acquisition sequence, the acquisition of frames continues for a suitable time, typically a few minutes. The test is repeated for different illumination levels

Analysis: The average counts on selected areas are plotted as function of time.

Outputs Temperature stabilization time of the detector.

6.17. STABILITY TEST

Applies: IR

Frequency: Daily

Purpose: The purpose of the test is to give a quick flavor of the stability of the detector. The stability is then more accurately quantified by monitoring specific detector parameters, as ron, dark, linearity, bad pixels etc.

Data Acquisition: Darks and Flats as part of the calibration plan.

Analysis: Darks and Flats are divided by reference frames that are updated on a monthly base. The frames are inspected and possible changes are quantified.

Outputs: On screen, evaluated in real time.

6.18. CONTAMINATION (OPT ONLY)

Applies: OPT, instrument with UV filters

Frequency: BA

Purpose: Determine if there is contamination on the CCD surface

Data Acquisition: One flat field in the U band, one reference flat taken after last baking of detector.

Analysis: Divide the recently acquired flat by the reference flat, normalize. Extract central row for each amplifier/region of the CCD.

Outputs: Plot of extracted rows, check that there are no significant (TBD) deviations from unity.

6.19. COSMIC RAYS SENSITIVITY

Applies: All

Frequency: N

Purpose: Determine the average number of cosmic rays hits per hour

Data Acquisition: One 1-hour dark exposure.

Analysis: Detect and count the total number of cosmic rays that hit the detector. Calculate the average charge measured per pixel.

Outputs: Print cosmic-rays event rate ($cm^{-2}s^{-1}$). Print average charge per pixel.

6.20. CHARGE TRANSFER EFFICIENCY (CTE) – EPER METHOD

Applies: OPT

Frequency: N

Purpose: Determine the CTE.

Data Acquisition: One well illuminated but not saturated flat image.

Analysis: Compute mean row (leaving out the overscan area). Compute I_N=counts above bias on the last pixel of the exposed area, I_{N+1}=counts above bias in the first pixel of the overscan area. N= number of transfers along the row that pixel N had to make before arriving at the output amplifier (including pre-scans). Compute CTE as:

$$CTE = 1 - \frac{I_{N+1}}{I_N \cdot N}$$

Note that this calculation produces an average value for the CTE across an image.

Outputs: Print CTE or 1-CTE.CTE versus time.

6.21. CHARGE TRANSFER EFFICIENCY (CTE) – VARIANCE METHOD

Applies: OPT

Frequency: N

Purpose: Determine the Vertical and horizontal CTE.

Data Acquisition: Two flat field images (as taken for the transfer curve) with identical exposure time, two bias images.

Analysis: Subtract bias from the flats, divide one flat by the other. Multiply by the mean value of one of the two images This generates an image free of fixed pattern noise. Apply sigma-clipping or masking to eliminate bad pixels from the image. Measure total noise and subtract readout noise (calculated as usual from the bias images). Calculate variance for each row (column) and plot as a function of row (column) number. Perform linear fit and derive slope (s) and constant term (k). 1-CTE=s/2k
Outputs: Value of CTE. Plot CTE versus time.

6.22. STRAY LIGHT

Applies: All

Frequency: N

Purpose: Determine amount of stray light in the system as a function of wavelength.

Data Acquisition: Pairs of flat field images (continuous source), one taken without filter and the other with an edge filter.

Analysis: Divide flat with filter by flat without filter. Measure amount of signal outside the filter transmission range.

Outputs: Plot % signal vs. wavelength.

6.23. PERSISTENCE

Applies: All

Frequency: Y

Purpose: Determine amount of stray light in the system as a function of wavelength.

Data Acquisition: Illuminate the detector uniformly with a bright source, possibly saturating. Take a sequence of 60-minutes dark exposures for 6 hours or longer

Analysis: Measure the dark signal in the bad-pixel corrected dark images.

Outputs: Plot dark current [e^-/pix/hr] as a function of time.

7. APPENDIX: OBS, RECIPES AND SCRIPTS

In this Appendix we summarize the templates used for data acquisition and the pipeline recipes or scripts used for data reduction. In addition to be executed in "stand-alone" mode when required, many of the templates listed are called by the OB CALOB.YYYY-MM-DD which is run daily to perform the daily calibrations.

Infrared Templates:

Instrument	Test	template	script	product
ISAAC SW	dark	ISAACSW_img_cal_Dark	isaacp_dark-avg (p)	master dark, QC Web
		ISAACSW_spec_cal_Dark	" "	master dark, QC Web
	int. flats	ISAACSW_img_tec_LampFlat		master flat
	tw. flats	ISAACSW_img_cal_TwFlats	isaacp_twflat (p)	master flat, QC Web
	ron		isaacp_dark-ron (p)	QC Web
	odd-even	ISAACSW_img_cal_TwFlats	isaac_twflat_oe (p)	QC Web
			ampl.cl (i)	wgoff1
	linearity	SW_lin_DCR	isaacp_dtlin (p)	lin. plot
		ISAACLW_img_tec_Linearity		coeff. frames
	bad-pix	use darks and flats		
ISAAC LW	dark	ISAACLW_all_cal_Dark		master dark, QC Web
	flat	ISAACLW_img_cal_TwFlats		master flat, QC Web
	linearity	LW_lin_LWI3_DCHB, DCHLB		coeff. frames, QC Web
		LW_lin_LWI4_UCHB		
	bad-pix	use darks and flats		
CONICA	dark	NACO_all_cal_Darks	conicap_dark (p)	QC Web
	int. flat	NACO_img_cal_LampFlat	conicap_lampflat (p)	master flat
	tw. flat	NACO_img_cal_TwFlats	conicap_twflat (p)	master flat
	ron			QC Web
	linearity	NACO_img_cal_Linearity	conicap_detlin (p)	coeff. frames, QC Web
	bad-pix	use darks and flat		QC Web
SINFONI	dark	SINFONI_ifu_cal_Dark	si_rec_mdark (p)	master dark, QC Web
	flats	SINFONI_ifu_cal_mflat	si_rec_mflat (p)	master flat, QC Web
	ron			QC Web
	linearity	SINFONI_ifu_cal_Detlin	si_rec_detlin (p)	coeff. frames, QC Web
	bad-pix	use darks and flats		QC Web
VISIR IMG	flat	VISIR_img_cal_ExtSrcFlats	visir_img_ff (p)	master flat
	linearity			coeff. frames, QC Web
	bad-pix	VISIR_img_tec_BadPixels	visir_img_ff (p)	QC Web
VISIR SPC	flat	VISIR_spc_cal_ExtSrcFlats	visir_spc_ff (p)	master flat
	linearity			
	bad-pix	VISIR_spc_tec_BadPixels	visir_spc_ff (p)	QC Web
MIDI	flats			master flat
	ron	MIDI_autotest_tec_detron		
	linearity	MIDI_autotest_tec_detlin		
AMBER	linearity	AMBER_gen_tec_nonLinearMap		
	bad-pix	AMBER_gen_tec_badPixelMap		
SOFI	dark	SOFI_img_cal_Dark		
	flat	SOFI_img_cal_SpecialDomeFlat	special_flat.cl (i)	master flat
	ron	SOFI_det_tec_Ron	SOFI_Ron.prg (m)	ron by quadrant
	conv. f.	SOFI_det_tec_Gain	SOFI_Gain.prg (m)	conv. factor
	linearity	SOFI_img_tec_Linearity	SOFI_Linearity.prg (m)	coeff. frames, lin. plot
	bad-pix	SOFI_img_tec_BadPixels	bad_pix.cl (m)	bad pixel mask
TIMMI				
NAOS				

Optical templates:

Instrument	Test	Template	Script	Products
FLAMES	Bias Dark Flats	?		
FORS1/2	Bias Dark Flats	FORS1/2_img_cal_bias FORS1/2_img_cal_dark FORS1/2_img_cal_scrflat		
UVES	Bias Dark Flats	UVES_mode_cal_bias UVES_mode_cal_dark UVES_mode_cal_??		
VIMOS	Bias Dark Flats	VIMOS_img_cal_bias ? VIMOS_img_cal_dark VIMOS_img_cal_flat ?		

8. APPENDIX: LIST OF ACRONYMS USED IN THIS DOCUMENT

ADU: Analog Digital Units
AUTREP: Automatic Report Generator
BIB: Blocked Impurity Bands.
BLIP: Background Limited Performance
CCD: Charged Coupled Device
DIT: Detector Integration Time
IRACE: InfraRed Array Control Electronics
EPER: Extended Pixel Edge Response
FPN: fixed pattern noise
LPO:La Silla Paranal Observatory
LW: Long Wavelength
MIR: Mid Infrared
NIR: Near Infrared
OPT: Optical (wavelength)
PRNU: Photo Response non-Uniformity
QC: Quality Control
QN: Quantization Noise
RON: Read Out Noise
SW: Short Wavelength
TDI: Time delay integration