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MTG INFRARED SOUNDER DETECTION CHAIN: FIRST RADIOMETRIC TEST RESULTS

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ABSTRACT

Europe's next fleet of geostationary meteorological satellites, MeteoSat Third Generation, will introduce new functions in addition to continuity of high-resolution meteorological data. The atmosphere Infrared Sounder (IRS), as high-end instrument, is part of this challenging program.

IRS principle is a Fourier Transform Interferometer, which allows recomposing atmospheric spectrum after infrared photons detection. Transmission spectrums will be used to support numerical weather prediction. IRS instrument is able to offer full disk coverage in one hour, an on-ground resolution of 4 by 4 km, in two spectral bands (MWIR: 1600 to 2175cm⁻¹ and LWIR: 700 to 1210cm⁻¹) with a spectral resolution of 0.6cm⁻¹.

Among critical technologies and processes, IRS detection chain shall offer outstanding characteristics in terms of radiometric performance like Signal to Noise Ratio (SNR), dynamic range and linearity. Selected detectors are HgCdTe two-dimensions arrays, cooled at 55 Kelvins, hybridized on snapshot silicon read-out circuit at 160x160 format. Video electronics present 16 bits resolution, and the whole detection chain (Detectors and electronics) permits to reach SNR between 2 000 and 10 000 as requested by the application. Radiometric on-ground test results performed on design representative detection chains are presented and are confirming the challenging phase A design choices.

I. INTRODUCTION

Infrared Sounder (IRS) [1] is composed of four sub-assemblies [2]. A Front Telescope and the scanning entrance system, the interferometer itself (Michelson type), one back-Telescope and the Detector / Electronics Assembly, which includes cold lenses and Detection Chain.

The Detection Chain uses two Mercury Cadmium Telluride (MCT) staring arrays hybridized on silicon Read-Out Integrated Circuit (ROIC), linked to the Video Chain Unit, includes drivers boards and Analogue to Digital Converters.

The detection chain requested performances are driven by mission objectives and instrument design choices [3]

The following items are considered as performance drivers at space instrument level:

- Spectral bands of interest: MWIR: 1600 to 2250cm⁻¹ and LWIR: 680 to 1210cm⁻¹ (in wave-length, MWIR: [4.44, 6.25μm], LWIR: [8.26, 14.70μm])
- Full disk coverage in one hour
- On-ground resolution of 4 km²
- Radiometric measurement ranges between 180K and 313K (equivalent black-body temperature in Kelvin)
- Spectral radiometric noise (excluding spectral calibration) at 280K blackbody: between 170 and 900mK depending on the considered wave-number inside the band of interest.

Considering these performance drivers at instrument level, the following design choices and associated performance budget have been flown-down and proposed for the Detection Chain:

- Two 160x160 staring arrays at 90μm pitch in cooled at 55K,
- 16 bits resolution video chain, operated at 2 Gbits per second
- Number of useful loads (or electrons) to be stored: 30 Mega-electrons in MWIR, 440 Mega-electrons in LWIR, in the useful bandwidth, considering 395μs integration period,
- Signal to Noise ratio at 280 Kelvins at instrument input: 8800 for LWIR band
- Residual Non-linearity after correction: 0.05%

These figures are very challenging and cannot rely on existing space heritage in Europe. By this way, a representative detection chain breadboard has been developed and tested to secure the design choices and these high-end performance budgets. After detection chain hardware and test tools description, this paper is reporting SNR and linearity test results and de-selection / operability figures.

II. DESCRIPTION OF THE INFRARED SOUNDER DETECTION CHAIN

IRS detection chain receives the optical signal from cold optical chain and delivers digitized information to the processing chain of the instrument. The Detection Chain main sub-assemblies are the IR detectors, developed and validated by SOFRADIR and the Video Chain Unit (VCU), developed and validated by THALES ALENIA SPACE - ESPANA

The MWIR and LWIR detectors are hybridized on dedicated CMOS silicon Read Out Integrated Circuit (ROIC). This ROIC works on Snapshot integration mode, Integration While Read function is implemented to optimize the frame rate. It takes benefit of a high performance mixed CMOS technology, proposing 5V as analogue voltage, and the use of Metal-Inter-Metal capacitance as analogue devices. Thanks to these technological parameters, the maximum handling capacitance requested by the application in LWIR band can be reached. Pixel integration capacitance are 2.7pF (MWIR) and 31.3pF (LWIR) for about 2.3V of useful voltage swing.

Focal Plane topology is presenting a 160 x 160 pixel structure at 90µm pitch, each pixel being composed of 9 sub-pixels of 30µm pitch with independent integration capacitance. Each sub-pixels can be integrated and read-out independently (Imager or high resolution mode) or can be read by averaging all or a part of the 9 sub-pixels (Normal or Interferogram mode). Acquisitions in high resolution mode at 480x480 format will be used by the system for mission purposes but also to determine defective sub-pixels location. Each sub-pixel of each super-pixel can be deselected independently in order to increase the performance of the super-pixel and to minimize the number of defective super pixels.

The detector ROIC presents 16 analogue video outputs. The array is divided into 16 sub-array of 160 lines per 10 column, which leads to have 1600 super-pixels per outputs. Each output can be operated in parallel at 4 Mega-pixel per second.

The Video Chain Unit contains two Front End Electronics (FEE) located close to the detector cryostat and one Video Acquisition Electronic (VAE) located on the platform. The FEEs integrate the following functions: first stage of analogue amplification, detector signal conversion from pseudo-differential to full differential, detector management items and very low noise detector analogue voltage reference for detector biasing. Those biases are able to supply up to 50mA peak-current with a white noise about 15µVrms. The VAE integrates the following functions: second stage amplification, the 16 bits – 4MHz analogue to digital conversion using VASP ASIC. This VASP has been developed by TAS under ESA contract (1987/06/NK/JA) on HIVAC / VASP digitizer, confirming a better performance than the state of the art devices [4]

Detector images are continuously acquired by the VCU with a fixed rate of 2.4kHz, managing 32 active 16 bits acquisition chains in parallel for both MWIR and LWIR synchronized bands.

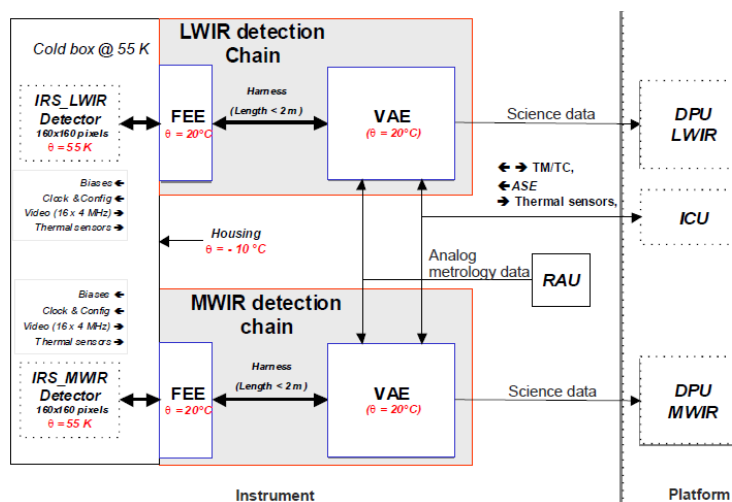


Fig. 1. Block diagram illustrating the detection chain main parts of IRS Instrument

Science digital data are then transmitted to the Digital Processing Unit (DPU) through a High Speed Serial Link (HSSL), space validated above 1.936 Gbits/s. The VAE also manages the metrology data which record the Interferometer mirrors locations. Detection Chain management and operating modes are insured by a 1553 serial link.

III. DETECTION CHAIN BREADBOARDS DESCRIPTION

Representative Detection Chain Breadboards have been developed and tested in order to secure the IRS instrument development. The main objectives are to verify the outstanding expected performance in terms of radiometric noise and linearity, by taking into account the accommodation constraints such limited power dissipation and impedance to be driven by the detectors analogue outputs.

MWIR and LWIR hybridized retina are fully representative of the flight model design. The only potential adjustments for flight models will be a second path design of the silicon ROIC (possibility to softly adjust the integration capacitance size) and a slight adjustment of the MCT layer cut-off wavelength.

The retina are integrated into a laboratory cryostat (called CRYTER), using a cold finger-based hermetic structure, allowing to use a split-on stirling cooler, Thales Cryogenics LSF 9340.

Breadboard detection chain is presenting a flight representative electrical impedance between the detectors output amplifiers, the FEE analogue drivers and Analogue to Digital Converters. PCB boards have been implemented between the CRYTER and the Detector connector in order to characterize any signals close to the retina without degradation due to harness impedances. By this way, harness impedance impacts will be characterized and VCU accommodation will be validated.

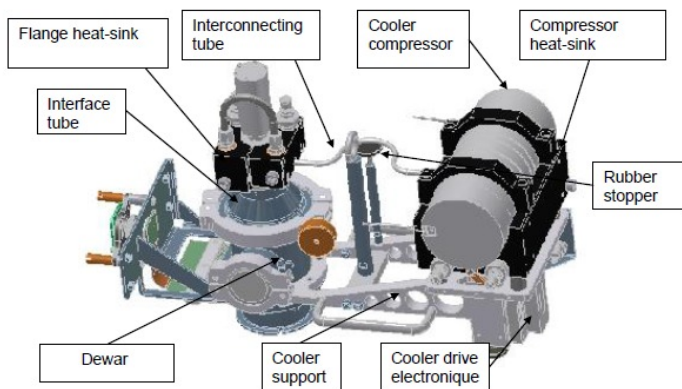


Fig. 2. IRS Detector Dewar and cooler assembly BBM

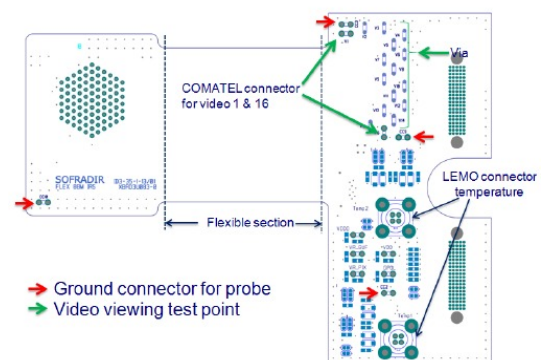


Fig. 3. Detector BBM PCB

The cooler assembly allows to cool-down the DA retina from ambient to 55K in less than 22 minutes, and ensure requested temperature stability during the tests, measured as better than ± 10 mK during one hour.

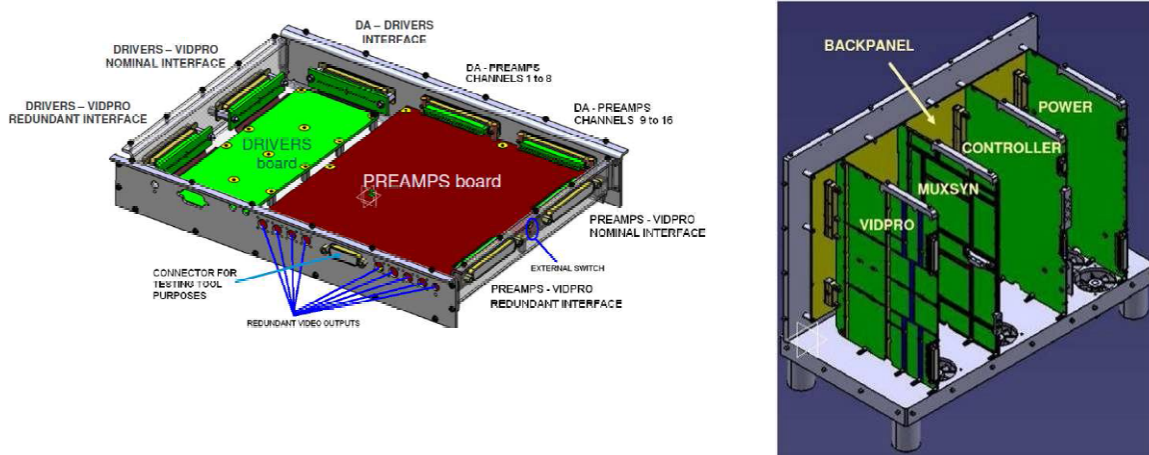


Fig. 4. Video Chain Unit (VCU) Bread-Board, composed of 2 parts: Front-End Electronics (FEE, on the left) and Video Acquisition Electronic (VAE, on the right)

IV. DESCRIPTION OF BREADBOARDS TEST SETUP

For MTG detection chain characterization, Thales Alenia Space have developed new dedicated test benches and have improved existing test bench thanks to long experience in the field of IR radiometric tests.

The new test bench has been designed and manufactured for electrical interfaces validation and fast radiometric tests. It uses an off the shelf calibrated black body ($180 \times 180 \text{ mm}^2$ active surface). A cavity filled with dry air is placed between the black body and the cryostat. Its length can be adjusted to tune the distance between the focal plane and the black body active surface. Such configuration is compatible with a black body temperature between -21°C and $+135^\circ\text{C}$. Linearity values around 0.1% have been demonstrated with this simple configuration for several detectors (from SWIR to VLWIR). The standard configuration can be modified for remanence and time constant measurements. In this case the standard black body is replaced by a hot black body working at 1200°C and a fast shutter is placed in front of the detector.

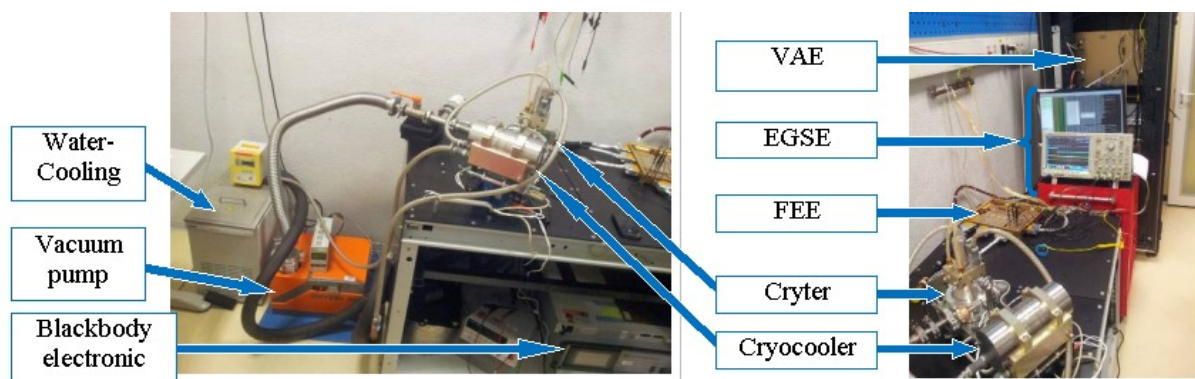


Fig. 5. Global view of the simplified radiometric test bench used for MTG breadboards characterization

For accurate radiometric characterization, a black body is placed inside a vacuum chamber and is cooled with a circuit of liquid Nitrogen. This circuit is cooling the diaphragms, implemented to adapt the field of view for minimizing the parasitic fluxes. The black body temperature is controlled by a tuneable heater, and its parameters are monitored by calibrated sensors and accurate multimeters. The spectral emissivity of the black body surface has been measured by a reference laboratory. Its diameter is about 300 mm. It could work between -120°C up to more than $+60^\circ\text{C}$. Lower values can be reached, but the uncooled cryostat window between the detector and the black body generates a background flux in the same order of magnitude than the useful black body flux (at -120°C). Thanks to a very good long term stability, this low radiance is generally used for $1/f$ noise measurements. In the vacuum configuration, the radiance absolute accuracy of the black body is about $\pm 2\%$ (at 1σ) in MWIR and the relative accuracy is about $5 \cdot 10^{-4}$ for a temperature range between -10 and $+50^\circ\text{C}$. In case of low temperatures, the cryostat window temperature shall be measured and taken into account in the flux calculation to keep a good relative accuracy. Linearity values around 0.05% have been demonstrated.

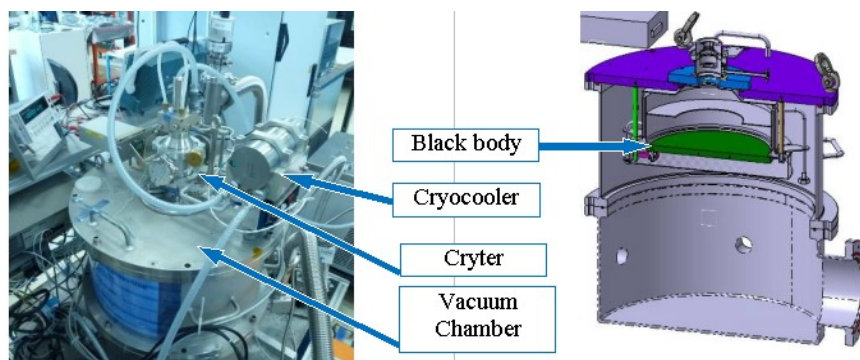


Fig. 6. Radiometric test bench used for accurate radiometric tests. The cryostat including the IR detector is fixed above the black body (in green), which is located in a vacuum chamber as illustrated on the right

V. TESTS RESULTS

A dedicated test plan has been applied on the detection chain breadboards, in order

- to validate the interfaces between the detectors and the video chain,
- to verify the functions
- to measure the radiometric noise, the linearity performance and the impact of sub-pixel deselection function which is integrated into the ROIC.

Interfaces and functions verification has been successfully tested on the simplified bench configuration. Accurate performance test have been made on the radiometric test bench.

A - Electrical floor Noise

Electrical floor noise of the video chain has been first measured by replacing the detector by a low noise voltage battery. Considering that the useful dynamic range is shared on 2.3V at the detector output, and considering the 16 bits resolution, the video chain noise has been measured between 2.0 and 2.2 LSB_{16} rms which lead to an effective noise between 73 and 80 μV rms for respectively the MWIR and the LWIR band, including the conversion noise.

Detector ROIC floor noise have also been measured by blocking the charge injection at the detector photodiodes level, and by knowing the noise of the video chain. This noise has been measured around 75 μV rms for the MWIR and 80 μV rms for the LWIR.

Thus, electrical floor noise of the detection chain has been measured as being the quadratic summation of these two electrical noises: the detector ROIC floor noise and the Video Chain Unit floor noise.

B - Radiometric Noise and Signal to Noise Ratio (SNR) results

Signal to Noise Ratio versus detection chain incident photon flux have been measured by using the radiometric test bench black body as the photon source. Only useful incident photonic signal is considered for Signal computation. Besides, all noise contributors are considered for Noise computation: electrical floor noise (ROIC + VCU), photonic shot-noise, parasitic flux shot-noise, dark-current noise. The following figures present the SNR histogram of all the pixels for each band, and the associated normalized spectral response. Test conditions are the following:

- Optical F-number: MWIR : F/4.5 , LWIR : F/ 5.04;
- Retina temperature: 55K;
- Integration time: 395 μs .

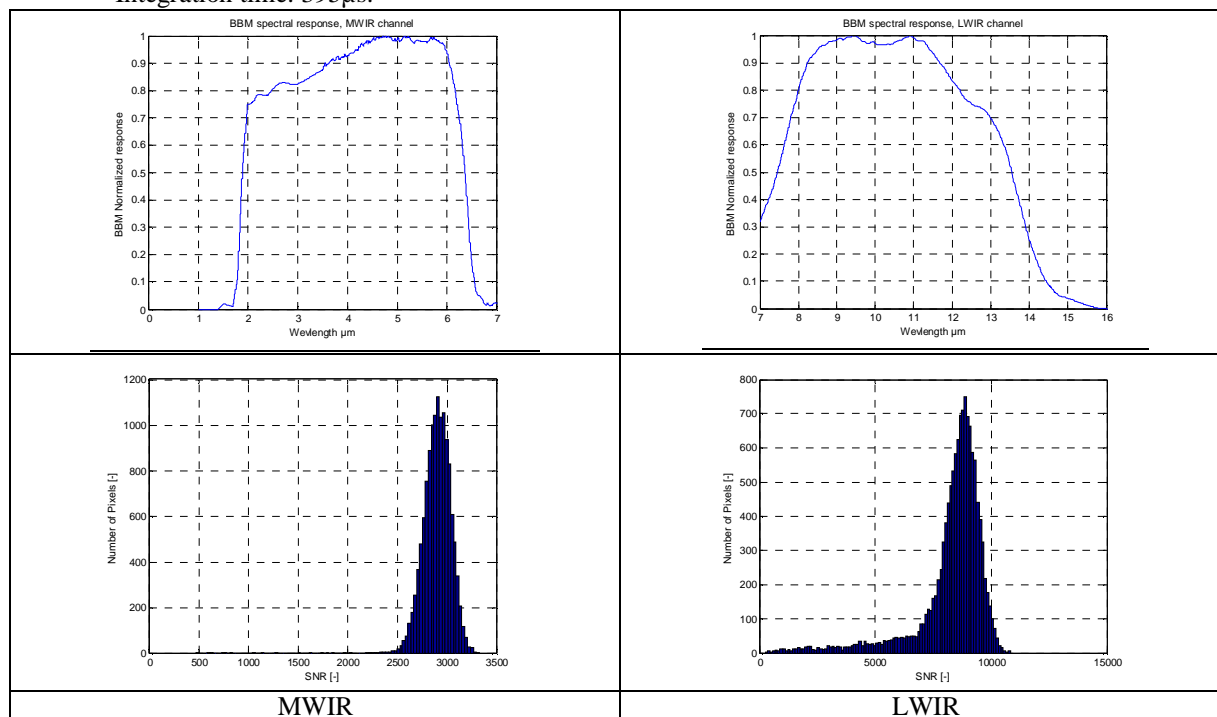


Fig. 7. Radiometric MWIR and LWIR Normalized Spectral Response and SNR histograms, for flux corresponding to 280 K at instrument input
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These results are not corrected by any algorithm, as gain / offset uniformity, dead pixel deselection or field of view correction.

MWIR SNR is driven by the incident flux only (“back-ground limited”). For LWIR band, main noise contributors are electrical noises (see above, ROIC and VCU noises) and in a lower contribution the dark current. Nevertheless, the average LWIR SNR among all pixels for flux equivalent to 280K at instrument input is 8816, with a standard deviation of 7%. These figures are in accordance with the targeted results, as presented in the introduction.

SNR have been measured for the full input photonic range as expected during the flight mission. The following figures presents the fit between theoretical radiometric model SNR output and the test results. It appears that SNR test results are fitting the model outputs with accuracy better than 5%. Considering radiometric test bench uncertainties in these wavelength domains, the radiometric models are considered as validated by these measurements.

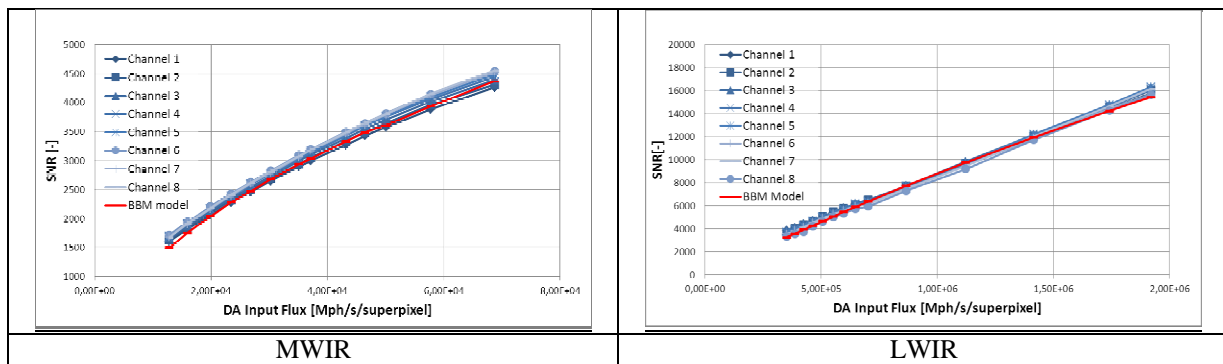


Fig. 8. SNR measurement results (averaged SNR per ROIC outputs # 1 to 8) compared to radiometric model outputs: Validation of the fit better than 95%

C - Detection chain linearity performance

Linearity performance is defined as the delta between the detection chain answer to the incident flux and a linear regression, after a fit of the detector signal by a 4th order polynomial for each pixel. This corresponds to the in-flight algorithm strategy for the instrument.

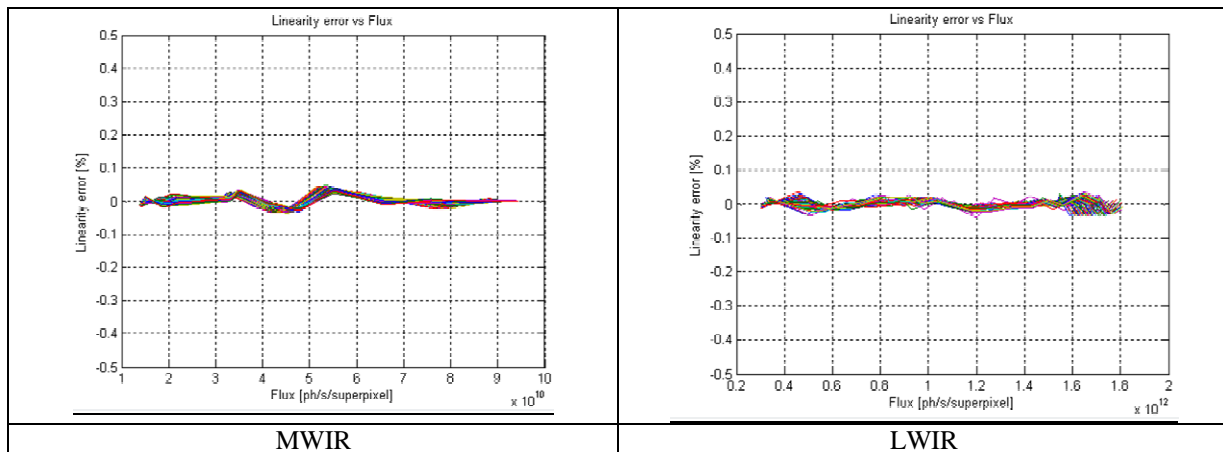


Fig. 9. Residual Non-Linearity after 4th order polynomial fit on the operating incident flux range

This test is quite tricky to lead: the expected performance level (< 0.05% of residual non linearity) in of the same order of magnitude than the test bench accuracy. That is why a specific attention has been paid on test bench parameters monitoring and stability during all the test sequence. These figures present the residual non-linearity of 80 typical pixels, selected as being representative in terms of photoresponse, gain and dark-current. The obtained results are showing a very low residual non-linearity, equal to the test bench accuracy. These very good results are confirmed by linearity measurements versus integration time, while the incident photon flux remains constant.

D - Sub-pixels deselection

Part of the 9 sub-pixels composing each super-pixel can be deselected at detector ROIC level in order to optimize the number of defective super pixels. The reason is that some photo-diodes crystal defects, smaller than the sub-pixel pitch (30 μ m) can be responsible of performance degradation at super pixels level (90 μ m pitch). Sub-pixels coordinates which shall be deselected are identified by frame acquisitions in imager mode. A processing simple algorithm has been developed to detect sub-pixels presenting too low SNR or Responsivity, and the coordinates of these sub-pixels are transmitted to the detection chain by the 1553 serial link.

Radiometric tests have been made with and without “mapping” application, the mapping being defined by defective sub-pixels coordinates. The following figures are presenting SNR histograms and cartographies with and without deselection, meaning with and without defective sub-pixel mapping application at ROIC level.

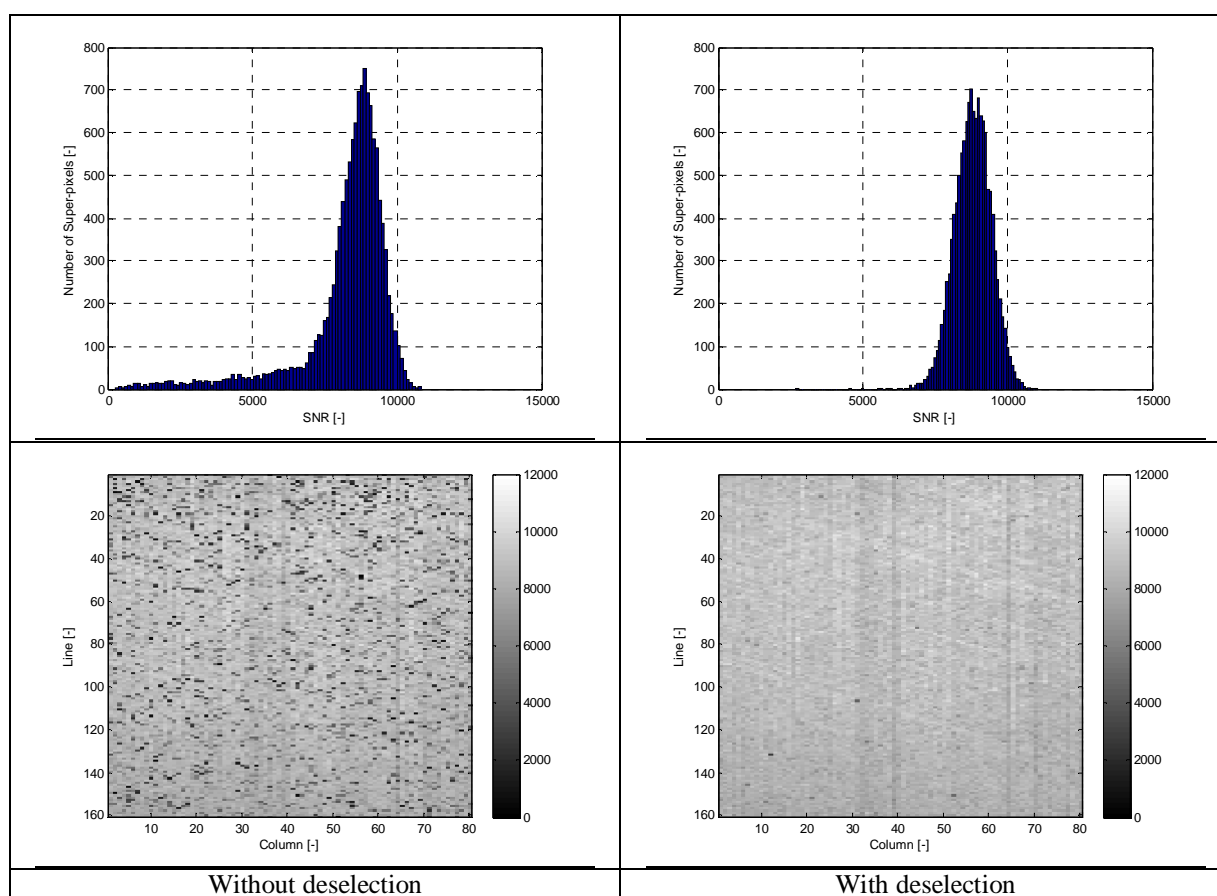


Fig. 10. LWIR SNR at 280K, histograms and cartography, with and without deselection at ROIC sub-pixel level

In the LWIR band, for the considered breadboard sample, the number of super-pixels which are degraded in terms of SNR (criteria: less than half of the measured SNR and Responsivity) switches from 4% without deselection to nearly zero when deselection mapping is applied.

These test results clearly demonstrate the efficiency of this sub-pixel deselection function to optimize the detection chain performance and operability.

VI. CONCLUSIONS

IRS detection chain shall offer outstanding characteristics in terms of radiometric performance, dynamic range and linearity. In order to validate detection chain design choices and to secure the instrument development plan, detection chain breadboards have been developed and tested, with representative cooled infrared detectors and representative Video Chain Unit. An extensive test campaign has demonstrated the following major points:

- ü Interfaces between detectors and video Chain electronics are validated,
- ü Expected radiometric performances have been reached: up to SNR of 8800 in LWIR band for input flux equivalent to 280K at IRS entrance
- ü Radiometric models are validated by the test results
- ü Instrument radiometric budgets are consolidated
- ü Linearity performance on the whole useful dynamic range have been measured as being at 0.05%
- ü Sub-pixel deselection function inside each pixel allows to offer a nearly zero defective pixels InfraRed staring arrays, even in the LWIR band.

Moreover, this breadboard campaign allows MTG teams to be well prepared for the next integration phase of the project, which consists in instrument Engineering Model integration and test.

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These representative breadboard test campaign has also been made possible thanks to the excellent work of SOFRADIR for the detector and THALES ALENIA SPACE ESPAÑA for the Video Chain Unit.

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