ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

Overview of space activity at Sofradir and new trends for future detector for science applications

Bruno Fieque

Philippe Chorier

Nicolas Jamin

Cédric Leroy

et al.

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 105623Z · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296086

OVERVIEW OF SPACE ACTIVITY AT SOFRADIR AND NEW TRENDS FOR FUTURE DETECTOR FOR SCIENCE APPLICATIONS

FIEQUE Bruno(1), CHORIER Philippe(1), JAMIN Nicolas(1), LEROY Cédric(1), PIDANCIER Patricia(1), BOULADE Olivier(2) , GRAVRAND Olivier(3)
(1)SOFRADIR, France, (2)CEA-IRFU, France ; (3)CEA-LETI, France

I. INTRODUCTION

SOFRADIR is a leading companies involved in the development and manufacturing of infrared detectors for space applications leading to many space studies and programs from visible up to VLWIR spectral ranges. These studies and programs concern operational missions for earth imagery, meteorology and also scientific missions for universe exploration.

In parallel of this mission activity, studies have been performed concerning development of very large HgCdTe detector for science application. CEA and SOFRADIR have been manufacturing and characterizing near infrared detectors in the frame of ESA studies with the aim to develop a 2Kx2K large format low flux low noise device for space applications such as astrophysics. That types of detector requests a high level of mastering, and an appropriate manufacturing and process chain compatible with such a size

This paper will first describe the overview of Space activity at Sofradir in terms of programs and missions. Then a focus will be done on very large detector development studies for science. In addition to that, perspectives of such detector applications and impact at industrial level will be highlighted.

II. SPACE ACTIVITY AT SOFRADIR

A General overview

SOFRADIR has now a heritage of more than 25 years in space activity by working in close cooperation with national space agencies and companies worldwide. It concerns the following fields:

- Earth observation for military applications,
- Earth observation for commercial applications (agriculture, atmosphere chemistry, meteorology, environment and disaster monitoring),
- Science, deep space and scientific applications (astronomy).

Manufacturing of flight models is based not only on a state-of-the-art qualified process but also on military quality level production of several thousands of detectors per year that provides a high level of reproducibility and reliability. It also provides a permanent performance data base that allows commitment on future detectors specifications with a high level of confidence.

Due to the flexibility of MCT technology and the high reliability of the hybridization process, SOFRADIR is able to offer space qualified detectors that cover a wide spectral range from the visible spectrum up to very long wavelength (>15 µm), with linear or array formats, with long-life coolers or without coolers for passive cooling. All these contributors have enabled SOFRADIR to deliver more than 70 flight models over the past decade.

In total today, more than 20 second generation infrared detectors among delivered flight models have been or are currently operating in various spacecraft. One of the last significant results could be illustrated by the successful S2A satellite operation including 12 detectors on-board. The next figures illustrate a picture of S2A satellite in IR waveband and recall Sentinel-2 focal plane array and package at detector level (See Figure 1 for more details).

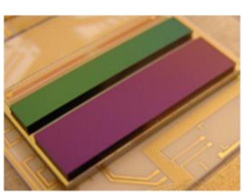
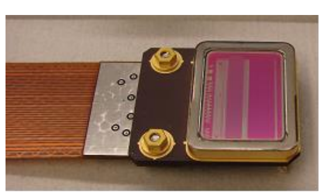


Figure 1: Sentinel-2 Focal Plane Array, Detector Package and image of French Riviera with Sentinel-2A satellite in IR waveband using SOFRADIR detectors (courtesy of ESA)

B Space programs at SOFRADIR

A major space development program for SOFRADIR concerned the IR detector of Helios II, a French military satellite. The detectors developed by SOFRADIR are operational on-board the two satellites and demonstrate the capability of SOFRADIR for the development of second and third generation infrared detectors for space applications.

Another example of SOFRADIR high quality product for space applications is the Venus Express mission. For this mission, SOFRADIR made the infrared detector (320 x 256 MW / 30 µm pitch staring array cooled with a Stirling micro-cooler). This detector operated on board the spacecraft which was in orbit around Venus planet for 8 years after a trip from the earth of about 6 months.

Additionally, a new Neptune detector (with an adapted cut-off wavelength) was launched early December 2014 onboard HAYABUSA-2 probe of the Japanese Space Agency (JAXA) that aims to study an asteroid “1999 JU3” after a 3-years space journey. SOFRADIR’s Neptune SW-MW detector is implemented into the MicrOmega IR microscope developed by IAS (Institut d'Astrophysique Spatiale at Orsay, France) with the support of CNES (Centre National d’Etudes Spatiales, the French space agency).

For the Sentinel-2 mission (part of the Copernicus program), SOFRADIR has been selected beginning of 2008 by AIRBUS Defense & Space and ESA for the development of infrared detectors. The detectors have been designed and screened to operate for the in-orbit lifetime of Sentinel-2 satellites (over 7 years). They include three SWIR linear arrays of 1298 pixels at 15 micron pitch, incorporated in two different MCT detection circuits which are hybridized on the same readout circuit, see Figure 1 for retina and associated package. A significant flight models production phase have been performed for this program leading to the delivery of 27 flight models in total for the completion of the program in early 2014.

Finally, three detectors have been recently launched in March 2016 in the scope of EXOMARS TGO mission. Therefore, 3 new SOFRADIR detectors are flying to MARS including two MARS MW detectors ([2.2;4.3µm]) and one SCORPIO MW ([2.6;4.2µm]) detector. These detectors are respectively integrated in NOMAD (Nadir and Occultation for Mars Discovery) and ACS (Atmospheric Chemistry Suite) instruments.

Figure 2: MARS MW IDDCA integrated in NOMAD instrument

However, many of flight models furnished by SOFRADIR have not been launched at this time. A substantial part of completed space programs at SOFRADIR are based on SATURN and NEPTUNE products, respectively 1000x256 and 500x256 30 µm pitch SWIR detectors (See [2] for more details), mainly used for space hyperspectral and spectroscopy applications. To meet the needs of the different missions, SOFRADIR developed several versions of these products, either for the packaging (passive or active cooling configuration), either for the retina with a visible version of this detector (called VISIR) sensitive from 0.4 µm up to 2.5 µm, thanks to a removal technique of the CZT substrate, or with adaptation of the cut-off wavelength. The next table describes the missions using SATURN or NEPTUNE detectors, and their progress status.

Table 1 : Main programs using SATURN and NEPTUNE detectors

Product	Bandwidth	Mission/Instrument	Program status (at Sofradir stage)
SATURN SW - active cooling	0.9 – 2.5µm	APEX (airborne)	Completed
SATURN SW and VISIR - passive cooling	0.9 – 2.5µm and 0.4 – 2.5µm	PRISMA hyperspectral mission (space)	Completed
SATURN SW - passive cooling	0.9 – 2.5µm	Hyperspectral instrument HISUI (space)	Completed
SATURN SW - passive cooling	0.9 – 2.5µm	TROPOMI instrument - Sentinel-5 precursor satellite (space)	Completed
NEPTUNE SW-MW	confidential	SPIRALE mission – Early warning preparation (space)	Completed
NEPTUNE SW-MW	0.9 – 3.8µm	Russian PHOBOS GRUNT mission (space)	Completed
NEPTUNE SW-MW	0.9 – 3.8µm	Japanese HAYABUSA 2 mission (space)	Completed
NEPTUNE VISIR – TEC	0.4 – 2.2µm	EXOMARS – MAMISS Instrument (space)	In progress
NEPTUNE SW - passive cooling	0.9 – 2.2µm	3-MI (space)	In progress
NEPTUNE SW/MW - active cooling	0.9 – 5µm	CHANDRAYAAN-2 (space)	In progress
SATURN SW - active cooling	0.9 – 2.5µm	GISAT Mission (space)	In progress

Based on NEPTUNE FPA heritage, SOFRADIR has been selected to supply the infrared detector in the scope of EXOMARS mission for the MAMISS instrument. For this program, SOFRADIR is in charge to adapt the NEPTUNE VISIR with a cut-off wavelength of 2.2 µm and with a Dewar including a cooling system based on a Thermo-Electrical Cooler (see Figure 3). For this program, two flight models are planned to be delivered in 2017.

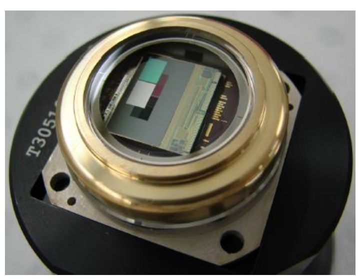

Figure 3: NEPTUNE VISIR – TEC (0.4 µm – 2.2 µm)

Besides, another program relying on NEPTUNE FPA has been started at SOFRADIR mid-2015 in order to deliver the SWIR detector for 3-MI instrument (METOP-SG mission). The selected detector design is derived from a NEPTUNE FPA with an adjusted cut-off wavelength (2.3µm at 185K) coupled with a SATURN package in its passive cooling version. The first flight model is expected to be delivered in 2017.

In addition, SOFRADIR has been selected by the Indian space agency (ISRO) in order to deliver a derivative of NEPTUNE detector in its active cooling version (RICOR K508 cryocooler). This program has started at the end of 2015 and consists in using a NEPTUNE detector ROIC coupled with a SWIR MWIR detection circuit. At package level, a specific filter is integrated between the FPA and the window in order to address the four requested bands. The delivery of the first flight model is expected to be in end of 2017.

Based on the previous developments and space heritage on SATURN and MARS detectors, SOFRADIR has started in 2013 two space programs with ISRO. For both programs, the main challenge is to develop a cooler and Dewar assembly compatible with space environment and offering a high reliability (see Figure 4).

Figure 4: SOFRADIR space Dewar and cooler assembly for MARS and SATURN detectors

Besides and in addition to the 27 delivered flight models in the frame of Sentinel-2 program for S2A and S2B instruments, SOFRADIR has been selected by AIRBUS DS & ESA in 2015 to provide 24 additional Sentinel-2 flight models in order to cover S2C and S2D instruments. The first flight models are planned to be delivered in 2017.

Moreover, SOFRADIR was selected in 2011 by Thales Alenia Space and ESA (European Space Agency) to develop and produce the infrared detectors for the European future meteorological program MTG (Meteosat Third Generation). For this program, SOFRADIR is developing the detectors for two different systems: Infrared detector assembly for the Flexible Combined Imager (FCI) and Infrared detector assembly for the InfraRed Sounder (IRS).

For the FCI satellite, four types of detectors (see Figure 5), covering wavebands from 1.3 µm up to 14 µm shared in 11 spectral channels, are developed for use around 60K. Each detector has the same overall definition. It is comprised of a retina (one ROIC on which one or two MCT arrays are hybridized), a sealed package with spectral filters and an entrance window associated to a space cryogenic flex cable with a space connector. The retinas of the different FCI detectors are linear arrays of pixels with pitches varying between 15 and 25 µm. Five flight models of each type of detectors (meaning 20 flight models in total) have to be manufactured and delivered in the frame of this program (See [3] for more details).

Figure 5: FCI detector (MTG FCI IR3) (top) and IRS detector (bottom)

Regarding the IRS satellite, two types of detectors covering two types of infrared wavebands ([4.4;6.3µm] and [8.3;14.7µm]) are developed for use around 55K. Each detector has the same overall definition. It is comprised of a large size retina with a format 160x160 and 90 µm pitch, a non-sealed package and a space cryogenic flex cable with a space connector. Three flight models of each type of detectors (meaning 6 flight models in total) have to be manufactured and delivered in the frame of this program.

Between 2011 and 2013, SOFRADIR developed a new detector in a frame of an ESA R&T study (contract ref 4000101887/10/NL/RA). The objective of this ESA R&T program was to offer a new 1k x 1k detector with 15 µm pixel pitch able to combine detection in the near UV, Visible and SWIR ranges. (see [4])

Concerning the specification for the retina design, main objectives to achieve were : to enlarge the array size to 1024x1024 in order to provide more spectral channels, to reduce the pixel size to 15x15µm, to extend the spectral response of MCT into visible range down to UV, to provide a low noise and low consumption ROIC and to ensure good electro-optical performances such as Photo Response Non Uniformity (PRNU), Dark current and Dark Signal Non Uniformity (DSNU) at operating temperature.

In order to answer those needs, a specific Readout Integrated circuit has been designed, the detection circuit has been optimized to reach spectral bands of interest and standard hybridization technique has been used, based on

SOFRADIR hybridization process already demonstrated and industrialized for Jupiter 1280x1024, 15µm pitch detector.

NGP detector has been selected for Sentinel 5 mission. Sentinel-5 is a mission dedicated for monitoring the composition of the atmosphere for Copernicus Atmosphere Services. The Sentinel-5/UVNS instrument is a spectrometer for UV, Visible Near-Infrared and SWIR domain. In SWIR spectral range, this instrument is based on the use of two detectors named SWIR1 and SWIR3 which cover respectively [1.590-1.675µm] and [2.305-2.385 µm] spectral bands. In 2014, SOFRADIR was selected to develop and deliver SWIR detectors for AIRBUS DS, based on the use of the already existing NGP ROIC.

The detector package developed for the Sentinel-5 project is based on a material set used for years at Sofradir for both tactical and space programs. This material set has been used at different temperatures and associated to different mission profile providing good performances and behavior under harsh environment. A view of the complete SWIR detector package is given in Figure 6.

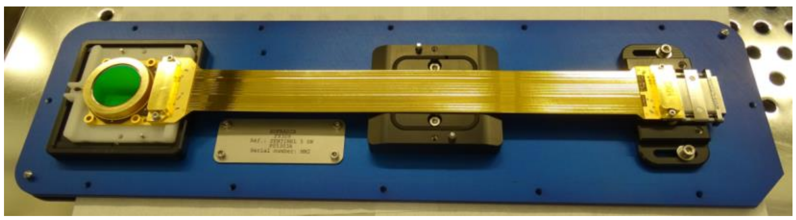

Figure 6: View of the complete detector package

II TOWARDS A 2Kx2K LOW FLUX LOW NOISE NIR DETECTOR

As described in [5], ESA started in 2009 the Near Infrared Large Format Sensor Array (NIRLFSA) program, in order to develop a low flux low noise near infrared (NIR) 2Kx2K detector for space astrophysics based on the use of MCT detection circuit and a readout circuit (ROIC) with a source follower per detector (SFD) as the input stage. The specifications for the main parameters and the results obtained during the 2 development phase are summarized in Table 1. A collaboration between the Commissariat à l'Energie Atomique (CEA) and Sofradir has been set up to participate to this roadmap. The detection layers of the detectors were developed at CEA-LETI in Grenoble, the ROICs were developed either at Sofradir (phase 1, 384x288 15µm pixels) thanks to CNES funding (contract reference: 92871/00) or CEA-LETI (phase 2, 640x512 15µm pixels), the hybridization took place at Sofradir and the electro-optical characterization of the detectors were performed at CEA-IRFU in Saclay.

Parameter	**Requirement**	**Measured value**
Operating wavelength	0.9 – 2.0µm	0.8- 2.1µm
Cutoff wavelength	<2.3µm	2.1µm
Quantum efficiency	≥70%	74% mean value
Operating temperature	≥100K	100K
Dark current (at 100K)	≤0.1 e-/pix/s	<0.5e-/s
Linear well capacity	≥60ke-	60ke-
Non-Linearity	≤3%	3.2% and 2.5%
Cross talk (inter pixel capacitance)	≤2%	0.6% to 1.1%
Readout noise (single CDS)	≤18e- rms	11.4 to 11.5e-
Readout speed	≥100kHz	100kHz

Table 2 : requirement and results obtained during the ESA development phase

The ultimate goal of the ESA study is to develop a full size detector product (2048x2048, 15µm pixel pitch) and finally to have one European IR detector manufacturer ready to propose this NIR/SWIR LFA at production level with the requested level of TRL. This section presents Sofradir strategy to reach this challenging objective. Beginning by the technology to provide a ROIC compliant with requirements (especially low noise) and HgCdTe technology to provide utmost electro-optical performances (especially low dark current), the next step deals with hybridization technique compatible with the size of the detector. Once all the technologies are available, it is necessary to demonstrate that this detector is ready to be produced in large quantities in order to fulfill the astronomy needs (space and ground telescopes).

A Available technologies

ROIC performances obtained by CEA/Sofradir prototypes in the previous ESA development phases are in line with the requests. Readout noise is lower than 12 e-, non-linearity mean value is 3% and capacitance of the CMOS pixel in the ROIC is very low (typically 5fF) in order to minimize the readout noise. The pixel design of the SFD input stage used both on 384x288 15µm and 640x480 15µm are thus compatible with the final need. This building block will thus be used to design the full scale 2K² detector.

Concerning HgCdTe technology, it has been demonstrated in this paper that the very low dark current requested for science and astronomy application is closely reached by CEA technology. The dark current is lower than 0.5 e-/s/pixel and the QE is higher than 70%. As for ROIC design, PV diode p/n building block will be used to design the large 2048x2048 size NIR/SWIR detector.

Once ROIC and detection circuit are available, hybridization is a high challenge for this detector size and this low pitch (15µm). In order to verify Sofradir capacity to produce such hybridized circuit, a mock-up was manufactured at Sofradir.

B Hybridization challenge

At the beginning of the years 2000's, Sofradir developed a new technology for 15µm pitch. This new pitch means a new definition of each technological block and design linked. For this new small pitch, Sofradir developed new faster and reliable processes and designs, in particular design of indium interconnection, Under Bump Metallization and indium process coating, hybridization process (Sofradir proprietary process), underfilling structure process. A first design was launched in 2003, a 640x512 VGA format leading to a product called "Scorpio" operates in the MWIR spectral range.

The last phase of development in 15µm pitch was the introduction of a megapixel format: the Jupiter megapixel (1280x1024, 15µm MWIR) was introduced in the market in 2010.

The 2048x2048 array will benefit from continuous improvements in the 15µm pitch production and new know-how from the 10µm pitch development.

C 2k² - 15µm pitch – feasibility demonstration

Sofradir has decided to launch an internal study in 2015 in order to demonstrate that our process can be applied to manufacture MCT IR detectors with 2K² class size. Therefore, the objective of this study was to manufacture a first mechanical breadboard representative of the final NIR/SWIR large focal plan array to be developed in the expected ESA study.

The test vehicle which has been manufactured represents a pre-validation of hybridization process and device architecture. It has to demonstrate the robustness of the hybridization process which will be used for the 2k² development program. To simulate the closer configuration of 2048x2048 FPA, we chose to dice a block of 4 megapixel ROIC 15µm pitch from a NGP 1024x1024 ROIC complete wafer. A monolithic PV is hybridized on this alternative structure.

The hybridization surface contains the same number of indium interconnection bump, nevertheless the surface is 41 % larger than the expected 2048 x 2048 design because of the "dead zone cross". The test vehicle is equivalent to 2428x2428 FPA.

	2048x2048 (nominal)	block of 4 NGP matrix	relative difference (%)
length (µm)	30720	36880	20%
width (µm)	30720	35980	17%
surface (µm²)	943 718 400	1 326 942 400	41%

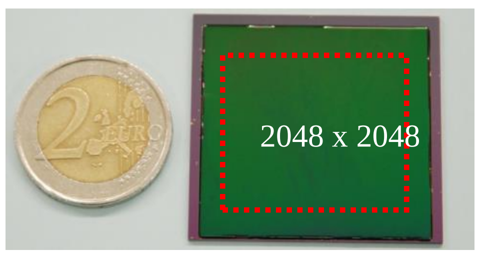

Figure 7 Sofradir test vehicle 2K² - comparison with 2 euros coin and size comparison between the test vehicle and the nominal size of 2048² detector

Electrical characterization of interconnections cannot be done with this test vehicle; a cross section is the only way to verify hybridization of indium bumps.

Two FPA have been diced, the first has been diced in the X axis and the second in the Y axis, each device is cut by four lines, an equal spacing is programmed. The 4 individual parts are mechanically polished and the gap of the FPA is analyzed directly in Scanning Electronic Microscope equipment.

Each area analyzed demonstrates creation of expected interconnections, no short or open defect was found.

FPA n°1	Cross section	Numbers of bumps analyzed	Rate of interconnections
X axis analysis	1	800	99,9999%
	2	1200	99,9999%
	3	1400	99,9999%
	4	300	99,9999%

FPA n°2	Cross section	Numbers of bumps analyzed	Rate of interconnections
Y axis analysis	1	1200	99,9999%
	2	1000	99,9999%
	3	800	99,9999%
	4	500	99,9999%

The FPA n°1 and FPA n2 show a fully interconnection done, height measurement give typical result whatever cross-section analyzed. Sofradir test vehicle demonstrate with success, capability of the design and the hybridization process to meet 2048x2048 requirements. The first FPA architecture contains the same number of interconnection that the aimed 2048x2048 FPA, whereas the surface is 40% bigger, these configurations was not optimal for hybridization and underfilling process, in spite of that results from the cross sections are fine. The weak variation of gap interconnection height gives a good level of confidence for the 2K² configurations.

This realization allows Sofradir to mitigate the risk for large detector hybridization and demonstrate that current hybridization process can be used to manufacture large NIR/SWIR LFA detector without complex adaptation.

D 2K² production

It is foreseen that a significant number of large NIR/SWIR detectors will be needed for ground based telescopes (eg E-ELT) and also for space telescopes in the next 10 years. In order to produce these detectors, adaptation of the manufacturing chain is mandatory. One of these adaptations is about the PV wafer size. Indeed, a way to increase the production capability is to increase the size of the CdZnTe substrate where the epilayer process is grown onto. The diameter of ingots will determine the maximum size of the CZT substrate before epilayer process. Since 2010, an important step was taken because the diameter of the ingot was increased by 40% from 2.5'' to 3.5'', partially funded by CNES and DGA programs (see [6]). Figure 8 presents different sizes of CZT ingots obtained at CEA-LETI (left) from the very first beginning of MCT technology in France to the very recent ingots realized (2015) at Sofradir facility with the illustration of the substrate wafer size to be sliced.

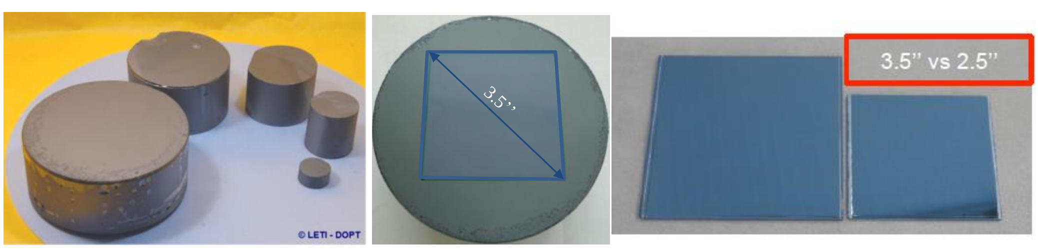

Figure 8 Ingot size evolution (left), wafer 3.5'' size illustration (right)

Such ingot manufacturing compatible with 3.5'' CZT substrate size is now under production at Sofradir. The quality of the ingots is a key parameter for the final performance of the detector especially for large array size detection circuit. Ingots produced by Sofradir are compatible with this expected cristal material quality.

The process used at Sofradir is based upon HgCdTe liquid phase epitaxy (LPE). Large epilayer manufacturing is obtained thanks to dedicated ovens and associated tools. The increase of the size of the epilayer has an impact on the whole process. It is necessary to master all the environment conditions during the epilayer process.

HgCdTe material growth has been proven as well as the realization of large CdZnTe large format substrate. Epilayer growth feasibility and performances have been demonstrated. Photovoltaic technology implementation on large substrate and detector performances evaluations are under progress.

3.5" size epilayers have been characterized and from the first manufacturing batch the following major quality criteria are respected such as the uniformity of thickness, the crystallographic quality and uniformity and the expected lambda cut-off and its dispersion over the wafer

Industrial technology and capacity improvements at Sofradir are under progress to be in line with scientific and astronomy roadmaps for the production of large NIR/SWIR Focal Plan Arrays.

III. CONCLUSION

This paper demonstrates the capability of SOFRADIR to deliver flight models detectors over a wide spectral range which is increasing. MCT IRFPAs are now available for space applications from visible to VLWIR up to 16µm cut-off wavelength. Through all current programs and successful pre-developments, SOFRADIR confirms its position as a worldwide reference supplier for space IR detectors.

Concerning science and astronomy topic, this paper presents the status of the development of low flux low noise near infrared MCT detectors at CEA and Sofradir for applications in the astrophysics and space science domains. This work is part of technological development activities initiated at ESA in order to eventually have providers of such devices within Europe. The electro-optical performances of the current 640x512 15µm pitch devices are in line with the requirements set by ESA. The next step of the development is the manufacturing of a full size 2Kx2K 15µm pitch device. To achieve this goal and prepare future industrialization, CEA and Sofradir already started a number of technological activities to develop the different building blocks of such a product.

Results obtained with CEA technology coupled with Sofradir industrial experience and work on large dimension detector allow French actors to be confident to address this type of future missions.

IV ACKNOWLEDGMENTS

The authors thank all the SOFRADIR and CEA teams, dedicated to quality work and won challenges, which made SOFRADIR become a top-ranked key player in the infrared field for space applications. The authors would like to thank also the European Space Agency (ESA), the French space agency (CNES) and the French MoD for their support through the different programs where SOFRADIR is involved.

REFERENCES

[1] Dariel A., Chorier P., et al., "Development of a long wave infrared detector for SGLI instrument" Proc. SPIE 6744A 38, Florence (2007)

[2] Leroy C., Fieque B., et al., "SWIR space detectors and future developments at SOFRADIR" Proc. SPIE 8889 44, Dresden (2013)

[3] Pidancier P., et al., "SOFRADIR detectors for MTG FCI application" ICSO 66345, Tenerife (2014)

[4] B. Fieque, N. Jamin, P. Chorier, P. Pidancier, L. Baud and B. Terrier, "New Sofradir VISIR-SWIR large format detector for next generation space", *Proc. SPIE. 8533 Sensors, Systems, and Next-Generation Satellites* XVI, 853313, 2012

[5] Olivier Boulade, Vincent Moreau, Patrick Mulet, Olivier Gravrand, Cyril Cervera, Jean-Paul Zanatta, Pierre Castelein, Fabrice Guellec, Bruno Fièque, Philippe Chorier, Julien Roumegoux, « Development activities on NIR large format MCT detectors for astrophysics and space science at CEA and SOFRADIR" 9915-10 - SPIE Astronomical Telescope and Instrumentation – Edinburgh (2016)

[6] Brellier D., Gout E., Gaude G., Pelenc D., Ballet P., Miguet T. and Manzato M.C., "Bulk Growth of CdZnTe: Quality Improvement and Size Increase", J. Electron. Mater. 43, 2901 (2014).