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Development of critical technologies for the COSMO/SkyMed Hyperspectral Camera

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Summary

COSMO/SkyMed is a spaceborn program primarily dedicated to Earth observation, remote sensing and data exploitation for risks management, defence and intelligence applications and coastal zone monitoring. This program is going on under a contract of Agenzia Spaziale Italiana (ASI) that foresees also the development of critical technologies.

In the frame of this program, Officine Galileo is involved in some technological studies devoted to finalise the design of a hyperspectral camera (HYC) that will be part of the mission payload.

An instrument with state-of-art performance but with reduced mass, volume and power budgets is the challenging aim of these studies.

The major tasks performed are:

- manufacturing of very light mirrors with special emphasis on Silicon Carbide (SiC) material technology.
- development of electronics blocks at high integration level with the necessary speed for the acquisition and processing of the large amount of hyperspectral data
- testing of high quantum efficiency array detectors

The developed or under test subsystems are all parts of the HYC.

This paper presents just an overview of the camera design and it will focus on these subsystems development studies.

Introduction

Hyperspectral space imagery is an emerging technology but it has already proven it can support many scientific, civil and operational applications.

As technology of more sensitive detectors is rapidly evolving, the design of state-of-the-art hyperspectral imagers is getting more and more a challenge for sensor builders.

Officine Galileo is actively involved in this field [1] and in the development of relevant critical technologies.

In particular, at the moment Officine Galileo is developing a Hyperspectral Camera that will be part of the optical payload of the COSMO/SkyMed mission.

To improve the know-how background in the specific field , Officine Galileo has recently set up a program of technological development This program, currently going on, was defined with the support of ASI.

Many issues have been dealt with during the study, but the major efforts have been devoted to:

- Review and implementation of state-of-the-art manufacturing techniques for light components (SiC or lightweighted Zerodur mirrors, carbon fiber structures).
- High velocity electronics components at high integration level (including digital and analog ASICs).
- Performance testing and verification of detectors with high quantum efficiency (CCD Backside illuminated and Hybrid CMOS). This an essential requirement to get high SNR levels from a hyperspectral instrument with small spatial and spectral resolution.

At the moment all these studies are in the final phase of testing of the manufactured or purchased components.

The results obtained in terms of innovative design, improvements in manufacturing technique and breadboarding activity are presented in the next paragraphs following a short description of HYC.

Paper presented at the RTO SET Symposium on "Space-Based Observation Technology", held on the Island of Samos, Greece, 16-18 October 2000, and published in RTO MP-61.

Hyperspectral Camera Overview

The HYC is an instrument that utilises a pushbroom technique to get strip spectral images over the VNIR (0.4 ÷ 1.0μm) and SWIR (1.0 ÷ 2.5 μm) regions.

The camera includes also a complementary Panchromatic Channel (PAN) (0.4 ÷ 0.75 μm).

Fig.1 shows a block scheme of the instrument, while Table 1 summarises its main characteristics.

The design of the HYC camera utilises a TMA (Three Mirrors Anastigmat) Telescope, common to all three channels, composed of three lightweight aspherical mirrors, with entrance aperture of 150 mm.

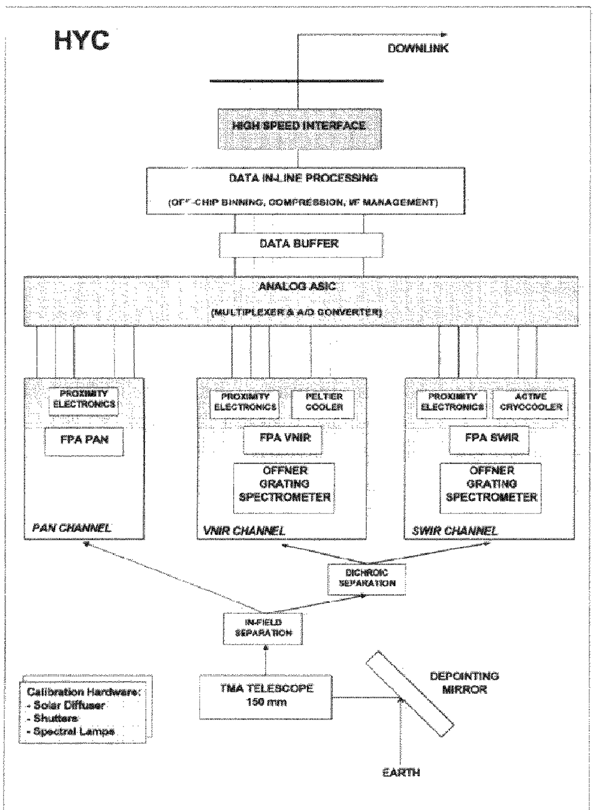

Fig. 1 - HYC Block Diagram

The telescope images a 20 km wide ground swath onto a beam slitting element that performs two different operations:

- In-field separation between PAN and VNIR+SWIR channels
- Spectral separation before spectrometer entrance slits between VNIR and SWIR

Each image taken during the acquisition time captures the spectrum of a line perpendicular to the satellite motion and a ground sample distance (GSD) at nadir of 20 m for VNIR, 40 m for SWIR.

The light spectral dispersion is obtained by two Offner grating spectrometers with nominal spectral resolution of 10 nm for both channels.

Therefore the maximum number of available spectral channels of 210 (60 for VNIR, 150 for SWIR).

The detectors used are :

- VNIR: backside illuminated CCD-2D or Hybrid CMOS matrix array (1000 x 120 useful pixels);
- SWIR: CMT-2D focal plane (500 x 150 useful pixels) cooled by pulse tube Stirling cycle cryocooler.

For applications for which a better radiometric accuracy (e.g. sea measurements) is preferable respect to a high spatial resolution, it is possible to combine up to 4 pixels in VNIR band and up to 2 pixels in SWIR. In this case a lower spatial resolution of 80 m in both bands is obtained. Moreover, better SNR performances can be obtained also by means of spectral bands combination (spectral binning) so that larger spectral resolutions can be selected.

The PAN channel, that produce images at about 7 m GSD, utilises a 4000 pixel long linear array placed into the telescope focal plane.

A pointing mirror, that can be pointed ± 22° in the across track direction, allows the extension of the viewed area up to ± 250 km (with the assumption of an altitude of 619 km). The quite large dimension of this mirror (quasi elliptical shape - 320 x 160 mm) makes mandatory the use of light material.

Two different operating modes are foreseen for the HYC (Fig. 2):

- Strip mode: the pointing mirror is kept in the selected angular position and a spectral image of a strip 20 km in width is provided.
- Mosaic mode: the mirror motor can be controlled in a predefined sequence of angular positions, so that the area of interest is covered with a mosaic image. The mirror needs just 3 sec to change its orientation and this allows quick switches in observed zone.

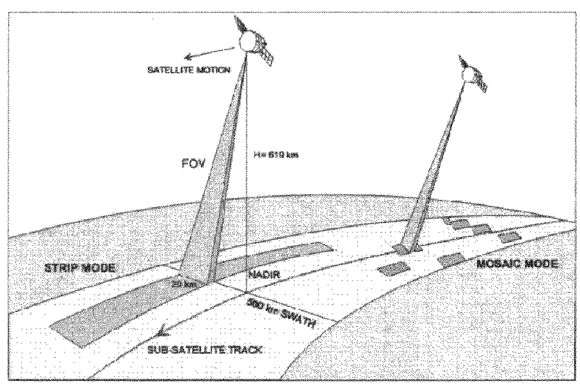

Fig. 2- HYC Operating Principle

HYC Parameters	*VNIR Channel*	*SWIR Channel*	*PAN Channel*
Scanning Mode	Pushbroom		
Spectral Range [nm]	400-1000	1000-2500	400-750
Spectral Resolution [nm]	10-20	10-20	NA
Swath Width [km] / FOV	20 / 1.85°		
GSD [m]	20-80	40-80	7.7
Covered Area [km]	500		
Spectral Bands	60	150	1
Aperture Diameter [mm]	150		
Focal Length [mm]	557		
F#	3.7		
Detector Pixel Size [μm]	18	18	7
Array Dimension (useful pixel)	1000 x 120	500 x 150	4000 x 1
FPA Type	Si CCD Backside	Cooled CMT	Si CCD
Quantization [bit]	12	12	12

Table 1 - HYC Main Specifications

The manufacturing of the pointing mirror and of the telescope (aspherical mirrors and structure) with lightweight materials was one of the main subject of the technological developments.

The HYC is essentially composed of the following units:

- Optomechanical head (HO) which includes:
  - Scanning Mirror and motor/encoder assembly
  - Telescope
  - Spectrometers (VNIR and SWIR)
  - FPAs (VNIR, SWIR, PAN)
  - Calibration Hardware
  - Baffles
  - Thermal control components (radiator, coolers, thermal blankets)
- Three FPA proximity electronics boxes (one for each detector)
- Main electronics box for:
  - Digital electronics
  - PDU & Mirror control

Fig. 3 and Fig. 4 show respectively the optical system layout and the optomechanical structure of the HO.

The optical systems and the proximity electronics elements are housed in a mechanical structure realised with CFRP (carbon fiber) trusses and plates. The main optical elements, i.e. telescope and spectrometers mirrors, will be realised in light material as SiC or lightweight ceramic glasses (e.g. Zerodur™ Schott).

The overall dimension of the optical head is about 1080 x 550 x 590 mm.

The instrument mass, including all the electronics boxes (main and proximity electronics) is less than 100 kg.

The power consumption is:

- 115 W during acquisition mode
- 110 W in calibration mode
- 60 W in standby mode

The Signal-to-Noise ratio (SNR) of this instrument has been estimated at different radiance conditions using a radiometric model that accounts for the characteristics of the optical system, focal plane arrays and electronics, including digitization.

Table 2 reports some typical SNR values at nominal GSD and spectral resolution.

Channel	**SNR**
VNIR (055μm-0.70μm)	200
SWIR (1.0μm-1.05μm)	100
SWIR (1.20μm-1.25μm)	100
SWIR (1.55μm-1.60μm)	100
SWIR (2.10μm-2.15μm)	50
PAN	300

Table 2 – HYC SNR

Assumption: 30% Surface reflectance, 60° Solar Zenith, 45° Latitude Scene, Atmospheric Model: Mid Latitude Winter, Aerosol model: rural visibility 23 km.

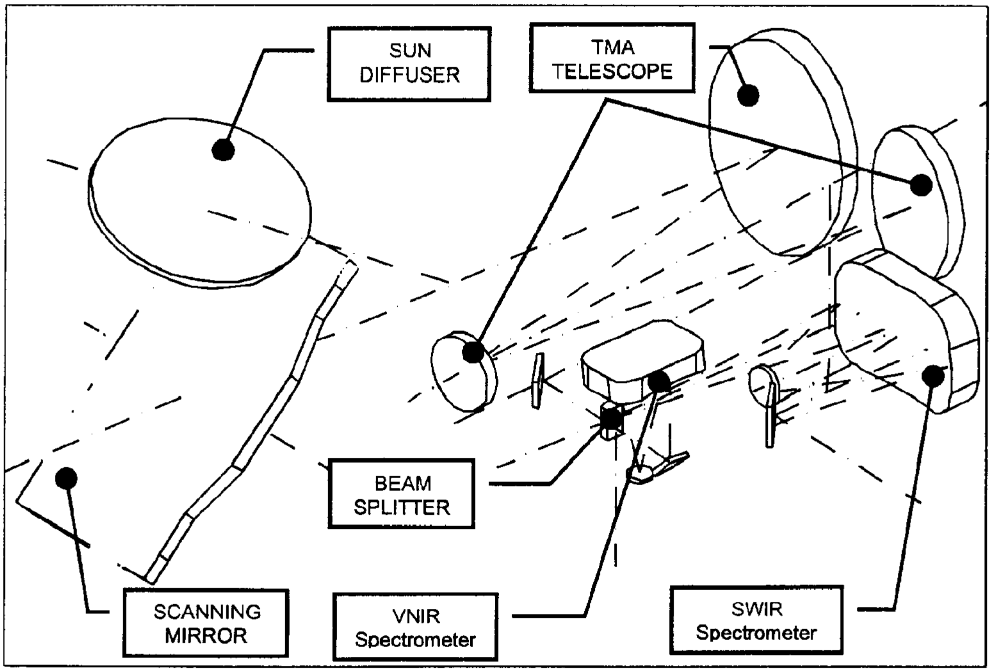

Fig. 3 – Optical System Layout

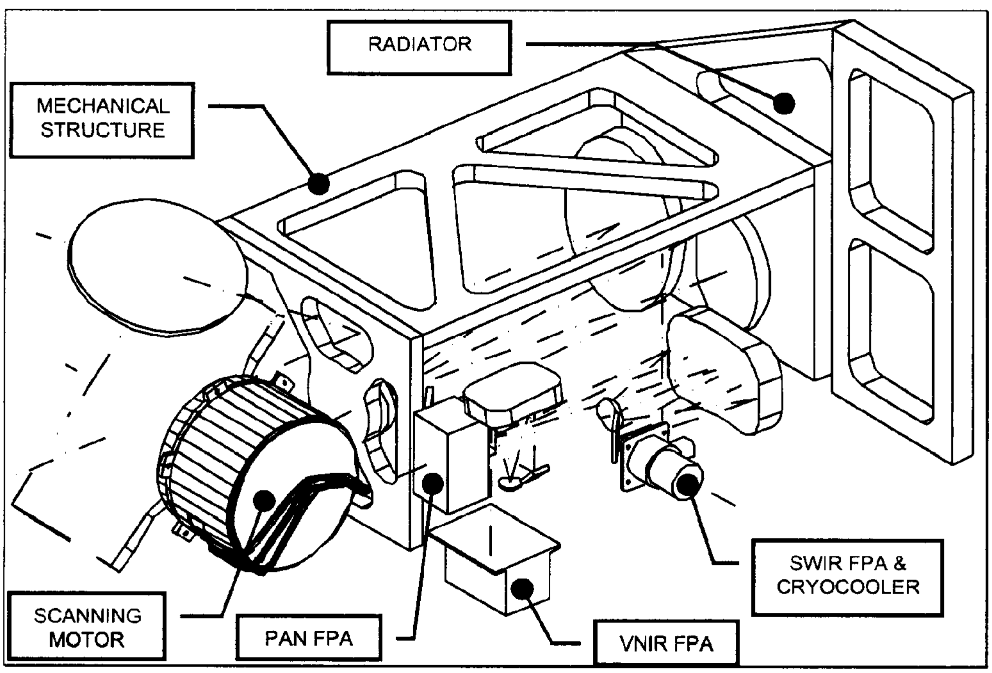

Fig. 4 – Optomechanical Layout

Lightweight Structures Development

An area of research and development has been dedicated to selection design solutions, materials and to development of processes for lightweight optomechanical structures.

A special emphasis was given to the use of SiC as substrate for reflective optics and for optics supports.

SiC offers a unique combination of critical properties, relative to other more traditional optical materials: high stiffness, high toughness, low thermal distortion, low toxicity and potential cost and schedule advantage.

There are several forms of SiC (i.e. Cold Pressed or Hot Pressed Sintered, Reaction Bonded, CVD-Chemical Vapour Deposited) corresponding to different manufacturing processes of the blanks.

The Cold Pressed-Sintered SiC has been selected as baseline process for the HYC pointing mirror (Fig. 5).

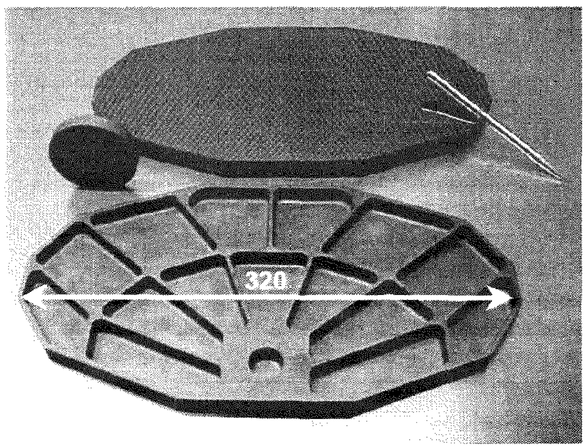

Fig. 5 - Prototypes of the SiC Pointing Mirror

This SiC can be bare polished up to the required specification of roughness. If necessary, it is also possible to further reduce the residual light scattering of the optical surface by coating the SiC substrate with the best polishable SiC-CVD layer that is without any CTEs (Coefficient Thermal Expansion) mismatch. Performance at cryogenic conditions of the mirror has been tested by interferometers placed in front of a vacuum chamber. In case of narrow operative temperature range, the expensive SIC-CVD layer can be substituted with electroless nickel plating, by using processes specially developed to deposit the nickel on SiC surfaces.

An alternative and more sophisticated technological solution has been considered also for mirror substrates, formed by a sandwich structure composed of two SiC face sheets deposited on a foam core of the same material (Fig. 6) [2]. Using this process to manufacture mirrors it is possible to reach even better performance in terms of weight and stiffness. The potentiality of this technology and its advantage respect to the traditional manufacturing techniques becomes accentuated as the size of the mirror blank increases. The realisation and test of prototypes of the pointing mirror with this solution are in progress also. The above mentioned solutions has been developed in collaboration with Italian manufacturers of ceramic products.

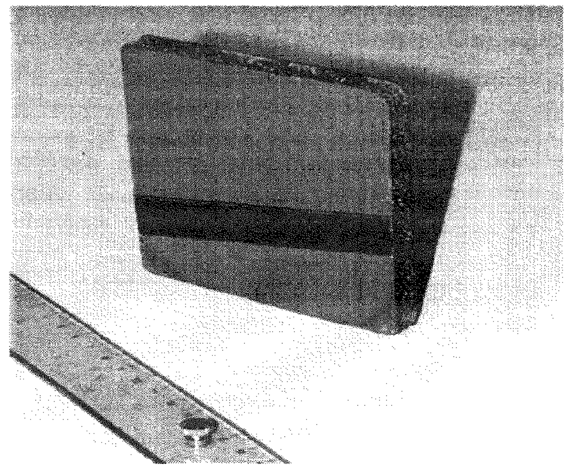

Fig. 6 - Mirror Substrate in SiC Foamed-core Sandwich

For what concerns the TMA Telescope of HYC, a more traditional solution has been adopted for the baseline, using mirrors in Zerodur™ and a metering structure in CFRP. Nevertheless, a dedicated investigation was carried out to get the highest lightening factors on the Zerodur mirror substrates. Several samples of the TMA telescope mirrors were realised to test the manufacturing capabilities and the achievable performance (Fig. 7).

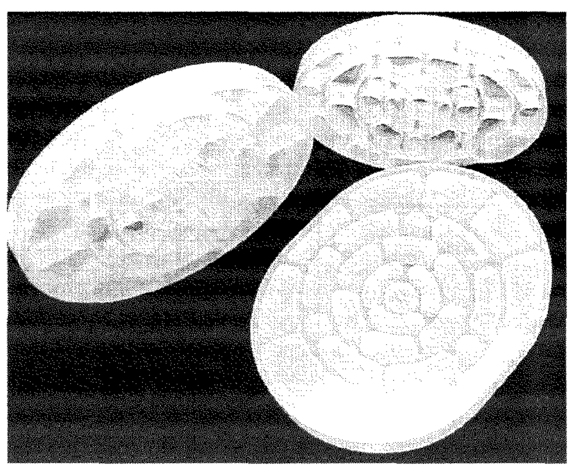

Fig. 7 - Lightweight substrates in Zerodur for TMA telescope mirrors

VNIR Electronics and Focal Plane Development

A very critical point of the design of hyperspectral instruments is the need to manage a great amount of data coming from the detectors.

For this reason particular effort was devoted to the development of the entire electronics chain. The study has started with the design of the VNIR channel, but many of the results of considerations presented here after can be applied also to the SWIR one.

The block diagram of the VNIR channel is reported in Fig. 8:

The electronics contains the following main parts:

- detector
- Proximity Electronics, formed by the front-end circuits to drive and bias the detector, the analog chain and signal processor up to the analog-to-digital conversion
- timing sequencer and acquisition control logic
- data and power supply interfaces

The task of the VNIR channel electronics is:

- to capture the image of the earth in its field of view
- to provide the downstream electronics with the amplitude of the pixels belonging to the addressed wavelengths [spectral editing] with the commanded grouping/binning

Considering the high data rate of the hyperspectral channels, the electronic architecture has been based on the possibility to put in parallel modules both for analog processing and for data in-line processing.

This approach allows increasing of N times the spatial resolution on ground of the instrument, where N is the number of modules in parallel. In fact it's impossible to begin a new readout of the detector before the end of the previous one, therefore the readout time represents a lower limit for the exposition time. To obtain the requested spatial resolution of 20 m, a maximum exposure time of about 2.9 msec is needed. The pixel acquisition rate of the analog processor is 3 MSPS. Hence, the complete readout of the maximum detector window of interest, formed by 120 lines with 1000 pixel per line, takes about 40 msec, giving a minimum spatial sampling interval of about 280 meters.

Using a N-ports (taps or outs) detector, the analogue processor throughput can be increased by N and the spatial sampling interval can be decreased approximately by N. For a detector with 4 outputs, the equivalent pixel rate becomes 12 MSPS with a readout time of 10 msec and a SSI of 70 meters. Consequently, as shown in Table 3, a 16 outputs detector is needed to obtain the requested spatial resolution of 20 m.

N° of Detector Outputs	*Readout Time*	*Maximum Spatial Resolution*
1	40 msec	280 m
4	10 msec	70 m
8	5 msec	35 m
16	2.5 msec	17.5 m

Table 3 – Resolution vs. detector number outputs

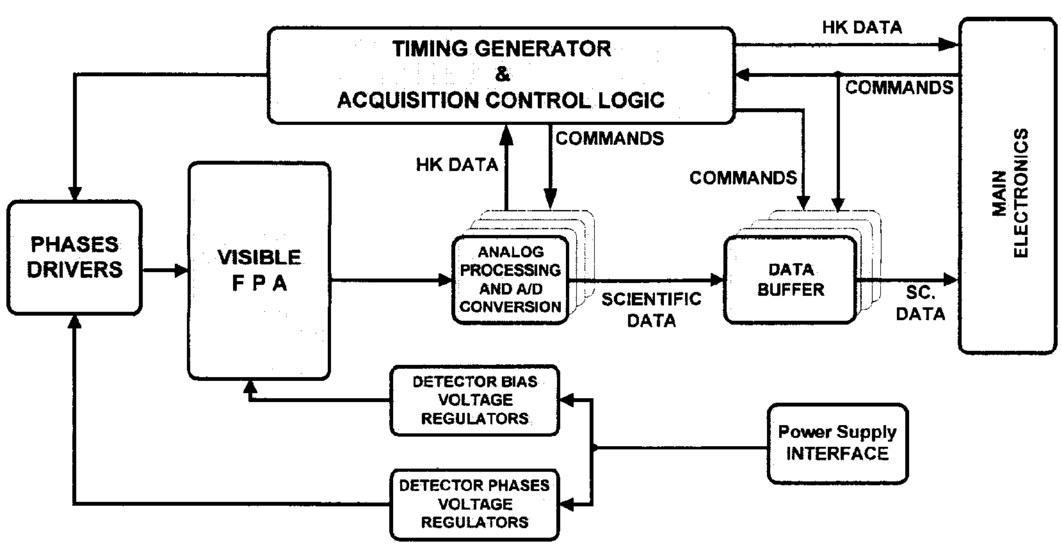

Fig. 8 – VNIR Focal Plane Electrical Architecture

Analog processing

The design of the analog processing electronics is essentially formed by modules already used and qualified in previous programs, with the addition of a new developed analog ASIC for detector signal conditioning, sampling and digitalisation.

The use of this ASIC is in line with the trend to reduce the size, weight and power consumption of digital imaging sensors and electronics for spaceborne systems. This trend is emerging in the market, due to the improvement in the micro-electronics technology and to the introduction of the 3D technology. The goal of this approach is to produce a 10x reduction in imaging sensor size, weight and power over the today's focal plane units.

As it can be seen from the block diagram (Fig. 9), the new analog ASIC contains all the main functions necessary to process a signal outgoing a photodetector. A CDS channel is provided to be used with CCD detectors, while 7 High Speed Sample and Hold channels are provided to be used with CMOS detectors. These channels can also be used to process and convert housekeeping (HK) signals. All the channels are equipped with a Programmable Gain Amplifier (x1 – x4). A multiplexer stage selects one of the 8 channels to be converted with 12 bits resolution. A 6 bits control code (Hamming) is provided together with the output. In the ASIC is also integrated a D/A converter, that can be useful for many practical applications. The component is realised in DMILL technology, it's latchup free, and it can withstand a total dose of about 1Mrad(Si).

The main characteristics of the new analog ASIC, are listed below:

- 12-Bit 3 MSPS A/D Converter
- 12-Bit 200 nS D/A Converter
- 1 integrated CDS with programmable gain amplifier (PGA, x1 – x4)
- 7 High Speed S/H channels with programmable gain amplifier (PGA, x1 - x4)
- 8:1 Multiplexer
- 12 bit output with 6 bit Hamming code
- Low power consumption: 400/500 mW max.
- RH Device: DMILL Technology.
  SEU tolerance≥70MeV/mg/cm^2.
  Total Dose≥1Mrad(Si).
  Latchup free.

At this moment this ASIC is going to be delivered to Officine Galileo for the testing phase.

Detector

In the frame of the technological program, several kinds of detectors have been taken in consideration. A market survey has been performed on COTS components, and finally two detectors have been selected to be tested in OG: the Sarnoff VCCD512H (512 x 512 Back Side Illuminated CCD) and the Rockwell TCM6600 (640 X 480 Hybrid CMOS).

The Sarnoff VCCD512H is a multiport detector with split storage architecture, projected to work with very low noise levels and high readout frequencies. The architecture of the device is illustrated in Fig. 10.

Each of the two readout registers presents 8 outputs, for a total of 16 outputs, each provided with an integrate CDS amplifier, eventually by-passable to use an external CDS circuit. This type of architecture, together with an elevated charge transfer rate, allows obtaining an extremely high frame rate (up to 800 frames/sec with binning and grouping X2). The detector structure is of back side illuminated type, with a silicon thickness of about 10μm, and it allows to obtain a very high level of quantum efficiency in a spectral range from 350nm to 1000nm.

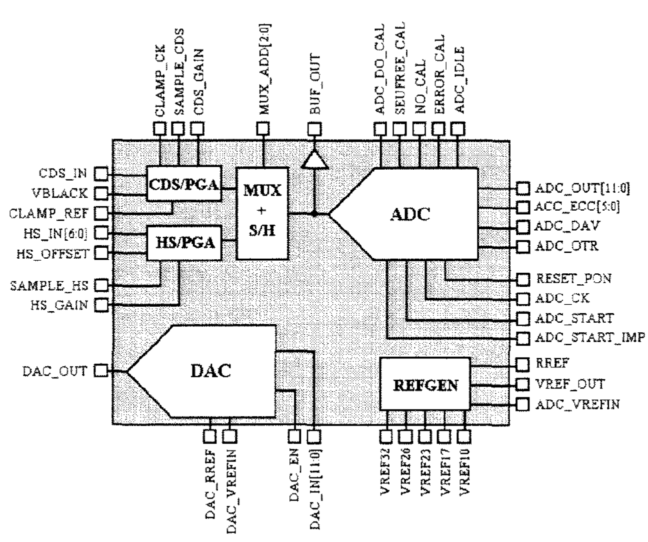

Fig. 9 – Analog ASIC functional block diagram

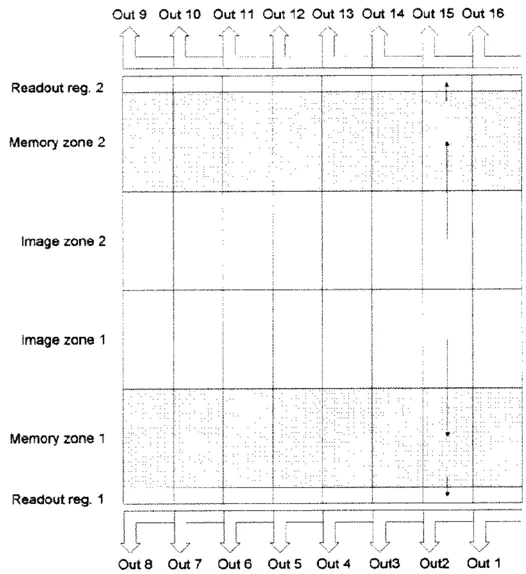

Figure 10 – VCCD512H architecture

The dimensions of the pixel are 18μm x 18μm, and the optic fill factor is about 100%. In the device a lateral anti-blooming drain is present on each pixel, that guarantees a good control on overexposure levels of up to 5000X. The manufacturing process used by Sarnoff guarantees a level of dark current in the order of 0.5 nA/cm^2 at ambient temperature without the use of MPP technology.

These technical characteristics match very well with those required for the VNIR channel, with the only difference in the number of pixels. In fact, the image zone has to be formed by at least 120 lines with sensitive 1000 pixels, but the technological step doesn't seem critical.

The Rockwell TCM6600 is a Hybrid detector, in which a matrix of revealing PIN is connected at pixel level to a CMOS readout multiplexer (ROIC) by means of Indium bumps. This allows the PIN diodes to inject the accumulated photocharges in the ROIC, where the input circuits, realised with a CTIA architecture (capacitive Trans-Impedance Amplifier), can convert them in a voltage signal. The pixel signals are then multiplexed and put out one at a time. The maximum frame rate is 100 frames/s, involving a pixel rate of about 5.5 MHz. The dimensions of the pixel are 27μm x 27μm. Also in the TCM6600 an anti-blooming structure is present. In Table 4 are summarised the main characteristics of the two detectors.

Test equipment

A complete equipment, that allows to obtain all the necessary measures in a totally automatic way, has been developed for both the detectors. In Fig. 11 a schematic block diagram of the test equipment 11 is depicted.

The system is based on the possibility to drive the focal plane electronics and to acquire the outgoing frames with a PC, using some appropriate I/O boards. In this way it is possible to program an appropriate sequence of acquisitions and to process the outgoing data in the PC.

It has been developed a dedicated software that allows to acquire the necessary images, with the requested operating conditions (window of interest, gain, offset, scan sequence), and to run the appropriate procedures on the outgoing data.

Thanks to the use of an optical bench, it is possible to obtain all the illumination conditions requested by the procedures. In this way, all the required measures can be obtained in a fully automatic way.

Parameter	***VCCD512H***	***TCM6600***
QE (600-800nm)	≥ 60%	≥ 80%
Full Well	≥ 700·10^3 el.	≥ 650·10^3 el.
PRNU	≤ 5%	≤ 5%
DSNU	≤ 10%	≤ 10%
Dark Current (293K)	≤ 500 pA/cm^2	≤ 1 nA/cm^2
Fixed Pattern Noise	None	≤ 5% of Qsat
CTE	≥ 96%	NA
Readout Noise	≤ 30 el.	≤ 100 el.
Pixel Pitch	18 μm	27μm
Output Taps	16	1

Table 4 – Main characteristics of the selected detectors

The test activities are currently in progress.

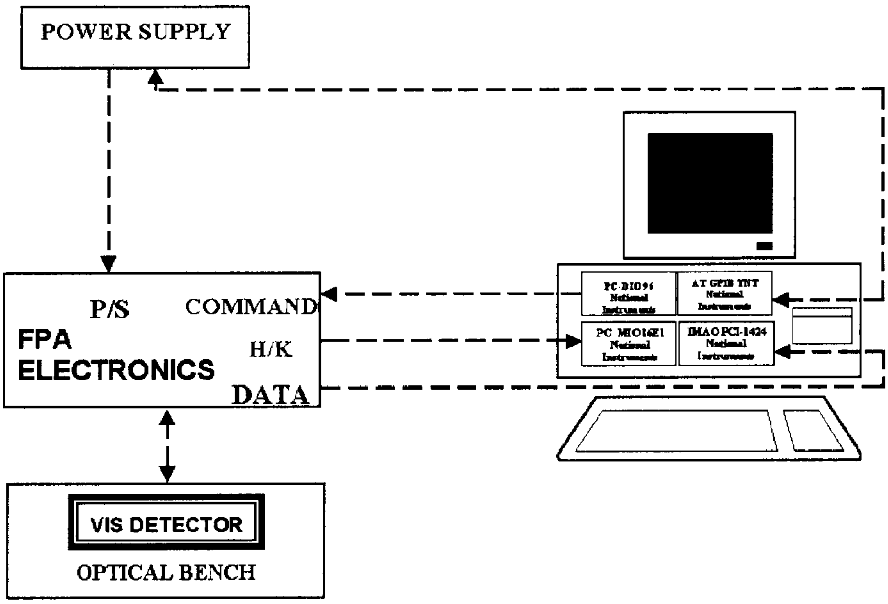

Figure 11 – Test equipment block diagram

Conclusion

The development currently going on will provide Officine Galileo with part of the technological background necessary to set up a challenging remote sensing mission.

The innovations coming from the study are enabling Officine Galileo to design and realise a flexible state-of-the-art instrument.

First use of this instrument will be the demonstration of the potentiality of the satellite hyperspectral technique that in a near future could satisfy different needs for a wide range of applications ranging from scientific studies of the Earth to civilian/military uses.

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The authors of this paper represent all the people involved in the technological developments and design of this instrument. This work virtually belongs to them.

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