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A NEW FAMILY OF LOW COST INFRARED EARTH SENSORS

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RESUME - SODERN développe une nouvelle ligne de Senseurs de Terre Statiques (STS) infrarouges à faible coût pour le contrôle d'attitude des plateformes de satellites couvrant toutes les missions possibles en LEO, MEO, HEO et GEO. La conception de ce senseur repose sur un détecteur thermique non refroidi constitué de barrettes de thermopiles réalisées sur une puce silicium montée dans un module hybride ou sur plusieurs plan focaux mono-barrette en fonction de l'altitude de la mission. Le but de cet article est de présenter les principales analyses et choix qui ont conduit à la définition du détecteur à travers une revue rapide des concepts de détecteur possibles et une revue de l'optimisation du détecteur pour les différentes missions. Le traitement du signal et les algorithmes utilisés pour le calcul des transitions Terre/Espace puis du calcul Roulis et Tangage sont présentés préalablement à une description du capteur. Enfin une présentation de la façon dont le concept du STS est adapté aux différentes missions est effectuée avec la revue de ses principales caractéristiques pour des missions typiques.

ABSTRACT - SODERN is developing a new line of low cost infrared and static Earth Sensors (STS) for the attitude control of spacecraft platforms covering the whole possible missions in LEO, MEO, HEO and GEO. The sensor design is based on a silicon micromachining uncooled thermal detector made of 1D thermopile arrays arranged in a single multi-chips module (MCM) or several focal planes with a single 1D array according to the altitude of the missions. The aim of this paper is to present the main analyses and trade-offs which have led to the detector design through a brief review of possible detector concepts and a review of the detector optimization for the various missions. The signal processing and algorithm on which are based Earth/Space transition determination and Roll and Pitch calculation are described preliminary to the sensor hardware description. Then a presentation of how the STS concept is adapted to the various expected missions is made with the review of the sensor main features for typical missions

1. - INTRODUCTION

The evolution of commercial telecommunication market as well as the emerging market for small, micro and nano-satellites have led SODERN to develop a new concept of Earth Sensor, which allows an easy tailoring to the whole geostationary and non geostationary Earth Orbits. This concept relies on a common sensor architecture including the detector (with two possible options of detector

assembly according to the orbit) and the electronic. This common architecture can be adapted to the mission through a specific mechanical architecture of the detection unit which allows to adjust the field of view to the required operating range and accuracy.

The main advantages of this product line, with respect to the existing products, is not only the flexibility of the concept but the improvements which have been incorporated in the design compared to the previous generation of STD12/STD15/STD16 (ref.1) such as :

- a lower mass (reduced by a factor of 3).
- a lower power consumption (reduced by a factor of 2).
- a better reliability thanks to a static concept.
- an improved lifetime : up to 20 years in GEO.
- a reduced recurrent cost.
- a greater autonomy.

The improved sensor characteristics and modularity relies mainly on the detector concept. Thermopile detectors is an old concept, since SODERN has already manufactured Static Earth Sensors (STA 01/03/04) in the late 70's. These sensors were using single element devices but had only a reduced operational depointing range. For this reason, the following sensor generation (STD) was still using a single element detector (bolometer) with a scanning system to extend its capabilities, but the drawbacks of this concept with respect to a static concept is the cost, reliability, consumption and mass. Now the emergence of modern uncooled thermopile detector arrays allows the development of static sensors with extended capabilities.

2. - DETECTOR DESIGN

The detector choice was reduced to thermal detectors, mainly around the well known 15 μm infrared wavelength. Other detectors were eliminated mainly for cost reason (other infrared detectors) or for performance reason (visible detectors). Three families of thermal detectors have been identified and are available in 1D or 2D arrays (see table 1).

TYPES	1D ARRAY	2D ARRAY
Thermopile	2 x 16, 128 pixels (Dexter, Honeywell)	32 x 32, 128 x 128 pixels (UM, Defense Japan)
Pyroelectric	<32 pixels (Servo, Eltec)	100 x 100, 240 x 320 pixels (GEC, Thomson, TI-SAT)
Bolometer	2 x 16 pixels (DSTO)	16 x 64, 128 x 128, 240 x 320 pixels (DSTO, Honeywell-Loral, Infravision LSI)

Table 1 - Available thermal Detectors

DSTO : *Defence Science and Technology Organization (Australia)*
 UM : *University of Michigan (US)*
 TI : *Texas Instrument (US)*
 SAT : *Société Anonyme de Télécommunication (SAGEM holding - France)*

For a space application these detectors present both advantages and drawbacks with respect to their detection principle and their application in an Earth Sensor :

- pyroelectrics deliver a high signal but the incident flux needs to be modulated, and in the 15 μm infrared band, only mechanical choppers can fulfil this function without unacceptable degradation.
- bolometers need a polarization circuit and a thermal reference (shutter or thermal stabilization) to compensate the offset voltages resulting from thermal drifts.
- thermopiles deliver continuous low signals and it is necessary to reduce as far as possible any disturbing signals coming from the near thermal environment and the electrical connections.

The choice of thermopiles was determined by the will to eliminate any mechanism. One dimension arrays were preferred to two dimension arrays to reduce the sensor complexity and cost and to allow an easy tailoring of the sensor to the specified altitude range. The number of pixels per array, the number of arrays and their position in the focal plane were chosen to optimize the accuracy and the availability of the sensor with sun or moon within the field of view. The basic detector configuration resulting from these trade-offs is a set of four cross positioned arrays at 45° of Roll and Pitch axes of the sensor. A simplified configuration can be implemented with only two arrays along Roll and Pitch axes for low accuracy missions (in LEO).

The large altitude range between LEO mission and GEO mission (including transfer orbit) involved to have two different detection unit architectures :

- for GEO and some MEO missions, the Earth equivalent angle remains small enough to have a single lens which allows a geocentric tracking of the Earth at very high altitudes (up to 140 000 Km) during supersynchronous transfer orbit.
- for LEO, HEO or some MEO missions, the FOV is split in four elementary ones to take into account the large Earth equivalent angle of these missions (see Ref.2)

The basic detector architecture remains the same in both cases with a linear array of two rows of staggered pixels, but the two detection unit configurations are achieved with two different detector assemblies. The first one, specially suited for GEO or MEO mission, in order to reduce mass and cost, is a Multi Chip Module including a single detector chip composed of four cross positioned 1 D arrays (see figure 1) and four multiplexer chips (one per array). The other, specially suited for LEO, HEO or MEO mission, is a Multi Chip Module including a single detector chip composed of only one array and one multiplexer chip : the detection unit in this case is made with a combination of two or four of these detectors, depending on the operating range and accuracy required.

The detailed definition of the array was optimized to detect the Space/Earth Transition on each array with the best possible accuracy according to the technological limits :

- The pixel sizing and pixel arrangement was a trade-off between the required signal level, the required pixel overlapping due to image blur and technological constraints.
- The pixel resistance was minimized in order to reduce the noise.
- The pixel sensitivity was optimized through the choice of the pixel blackening technology.

Figure 1 : Focal Plane Array (FPA) for "single head" concept

The main measured characteristics on engineering models are mentioned in table 2.

Pixel dimensions	440 x 495 μm^2
Pixel number	32
Responsivity	$\geq 60 \text{ V/W}$
TC of responsivity	$\leq 0.2\%/K$
Pixel resistance	$\leq 25 \text{ K}\Omega$
Time constant	$\leq 16 \text{ ms}$
Cross-talk (adjacent pixels)	$\leq 1\%$

Table 2 - Thermopile array characteristics

The central membrane resulting of the silicon micromachining process in the detector chip assembly is very sensitive to the mechanical stress which could result from thermal variation. For the « single head » concept detector, which is the most critical according to the size of the chip (20.5x20.5 mm^2), the design was optimized such that the detector can withstand a temperature range larger than -55°C to +125°C (see figure 2).

Figure 2 : « Single head » concept detector

3. - SIGNAL PROCESSING AND ALGORITHM

The Roll and Pitch calculation principle with the detector and detection unit architectures defined above remains very similar to the scanning sensors like STD15. Two, three or four Earth/Space transition positions are measured along the detector arrays, according to Earth, moon and sun positions and are used to compute Roll and Pitch angles with respect to a reference position. To achieve this calculation with a good accuracy and confidence, the following steps are necessary :

- pixel signal pre-processing.
- determination of a transition along the arrays.
- research of sun or moon presence.
- calculation of Roll and Pitch angles.
- validity verification of calculated angles.

The pixel signal pre-processing consists in a correction of the digitized signals delivered by the A/D converter (after amplification by the analog chain) taking into account the pixel response non-uniformities. This pre-processing is performed according to a predefined pixel response model with

calibration parameters which have been determined on ground for each pixel and stored in the PROM of the sensor.

After this first step, an Earth/Space transition is searched on each array and its position is calculated from the position of the center of the pixel on which is the transition, at which is added an additional analog term. Two cases can occur for the calculation of this term, whether the Earth/Space transition is sharp (high altitude) or not (low altitude) :

a) For GEO and MEO, the transition width is smaller than the pixel size, and the analog term can be calculated from the immersion factor (η) of the pixel on which is the transition :

$$\eta = \frac{I_T - I_N}{I_T - I_S} \quad x_1 = x_T + \left(\eta - \frac{1}{2}\right) \cdot h$$

With :

x_1 : transition position along the array
 x_T : pixel center position along the array
 η : immersion factor
 h : pixel height along the array
 V_T, V_S, V_E : pre-processed pixel signals for pixels looking at the transition at Space and at the Earth

b) For LEO, the transition width is larger than the pixel size and the analog term is calculated from a modulation factor of the three pixels on which is spread the transition.

The Earth/Space transition angle $\delta\phi_i$ (see figure 3) is then calculated from these positions along the arrays with a third order polynomial correction law to take into account the distortion of the optical system.

Figure 3 - Earth/Space transition angles

After sun or moon presence determination, the Roll and Pitch angles are calculated from the four transition angles according to the following simplified formulas (in fact the applied formulas include additional correction factors to take into account the staggered geometry of pixels) :

$$R = \frac{(\delta\phi_2 - \delta\phi_4) + (\delta\phi_1 - \delta\phi_3)}{2\sqrt{2}} \quad P = \frac{(\delta\phi_2 - \delta\phi_1) - (\delta\phi_4 - \delta\phi_3)}{2\sqrt{2}}$$

When only three or two adjacent transition angles have been determined, the same formula is applied but the missing transition angle is then replaced by the transition of the opposite array with an opposite sign. The final operation is a checking of the validity of the calculated Roll and Pitch angles (only when four transition angles are available) by a comparison of the values obtained with four and only three transition angles.

4. - SENSOR DESCRIPTION

a) Detection unit

The detection unit is made of three main parts : the focal plane, the optical system and the mechanical housing of the optical head. This part of the sensor is specific to each version of the STS.

Focal plane and proximity electronic

The signal delivered by the detector (for the « single head » concept as well as for the « several heads » concept described above) is pre-amplified as close as possible from the detector output with a specially developed analog ASIC. This proximity electronic is fixed at the rear of the detector packaging.

Optical system

The optical system for the "single head" configuration is a telecentric one made of two antireflective coated germanium lenses, with a total circular field of view of 40°. This system is optimized to ensure a good image quality and thermal stability in the whole field of view.

The optical system for the "several heads" configuration is a single aspherical lens with a total circular field of view of 22°. Two or four such optical systems are placed in the detection unit along with their associated focal plane.

Mechanical structure of the optical head

The mechanical structure of the optical head is based on the following concepts :

- an outer thermally conductive body (in aluminum) with a low solar absorption external coating.
- lenses fixed in a special alloy mechanical mount, screwed in the aluminum body.
- an inner thermal baffle in aluminum reducing thermal exchanges between the focal plane and the outside.
- all elements in the focal plane and in the optical head are coated to minimize the parasitic fluxes and the straylight impacts.

b) Electronic processing

The electronic processing is organized around the main following functions (figure 4)

- analog processing

- time multiplexing (on proximity electronics).
- preamplification (on proximity electronics).
- signal processing (suppression of voltage spikes due to multiplexer switching).
- offset correction.
- postamplification.
- filtering (integrator type).
- digital conversion on 14 bits

- digital chain

The numerical architecture is organized around a sequencer which monitors a 16 bits processor, the program memories (PROM), the storage memories (RAM) and the communication interface.

The sequencer (ASIC) ensures the synchronous monitoring of the focal plane, the data update, the dedicated logical functions of the processor (watch dog, DMA, interrupt and clocks) and the communication interface. It is working with a sequence programmed in the PROMs, the focal plane sequence depending on the measurement mode :

- in coarse mode, all the pixels of the focal plane are addressed.
- in fine mode, only 8 pixels per array are addressed (7 active thermopiles and 1 electrical reference).

The microprocessor is the RTX2010 from Harris, which runs the sensor software and manage the sequencer and 1553 interface. The PROM contains the software and the calibration parameters. The RAM contains the numerical data, the intermediate data and calculation results.

The communication interface (compliant to the MIL STD 1553 B), is made of three parts :

- the bus management.
- the line drivers.
- line isolation transformers.

Figure 4 - Electronic block diagram (single head version)

Power converter

The power converter is used to generate secondary voltages (± 5 V and ± 15 V) for the sensor powering. The power supply converter works with a regulated or unregulated voltage bus in the 16 V to 55 V range. An option is also available in case of 100 V primary bus line.

The whole electronic is gathered on three boards linked together with flex circuits and folded up in order to have a compact subassembly.

c) Mechanical architecture

The mechanical housing supports the detection unit and the electronics. This structure is made of a frame of four lateral faces on which are fixed the mounting plane on one side and the conical structure of the detection unit at the other end. The walls of the structure protect the electronic from radiation and give a good overall mechanical stability. The boards are fixed on a central stiffener and lateral columns.

The interface with the detection unit has been specially designed to facilitate the adaptation to other detection units for other orbits (LEO, MEO and HEO missions) (see figure 5).

An optional Self-Inhibition device (SI) can be added to detect the sun presence within the sensor field of view. This device is mounted on the upper part of the structure along with the alignment cube.

For spinning transfer orbit an Horizon Crossing Indicator (HCI) can be optionally added. This device is embedded in the mechanical housing of the sensor and directly connected on the Z1 board. It may be mounted on any of the three free sides of the sensor, and oriented at 90° apart the sensor line of sight.

Figure 5 - Sensor exploded view

d) Software and dialogue interface

The Earth Sensor has four operating modes (without HCI option) :

- a coarse measurement mode
- a fine measurement mode
- a reading mode (to read any memory zone for in flight analysis).
- a writing mode (for in flight software or calibration parameter modification).

Each mode has to be activated by a specific command word generated by the AOCS, except at the switching on where the coarse mode is imposed. The two first modes are the main ones. They consist of delivering the transition variations and the Roll and Pitch operating angles with :

- a reduced accuracy over the whole field of view for the coarse mode.
- a good accuracy over a reduced operating range for the fine mode.

In each measurement mode, the sensor is able to work with one or two inhibited arrays. The inhibition configuration can be monitored by two different processes :

- an external selective command word generated by the AOCS.
- a self-inhibition device (option SI) able to automatically inhibit one detector array when the Sun impinges the useful pixels.

The associated software achieves the pixel signal pre-processing, the transition position calculation on each array, the Roll and Pitch and the Earth presence calculation.

The software design has taken into account both following principles :

- the Earth Sensor is autonomous with respect to the AOCS, that means it does not need specific data except the nominal commands.
- the Earth Sensor does not take any decision in case of identified anomaly, it delivers in its status words what is wrong and continues to deliver its nominal output data.

As it concerns the dialogue protocol, the data handling is performed through the 1553 communication interface bus, the Earth Sensor being considered as a simple subscriber. The command and output data words are coded on 16 bits.

5. - STS PRODUCT LINE

The various STS versions have been classified with respect to the mission orbits and are summarized on figure 6 (STS product line). They correspond to the following models :

a) STS 01/STS 03

These versions are intended to the LEO missions in the 300-1500 km altitude range. The STS01 is more specifically devoted to small satellites for which the performance requirements are not severe and covers a $0.1^{\circ}/0.2^{\circ}$ accuracy range. For higher accuracy it is preferable to use the STS03 which

presents a better accuracy ($0.05^{\circ}/0.1^{\circ}$) and a better autonomy with respect to the altitude and the Sun inhibition.

According to the required depointing during the nominal mission orbit (acquisition and fine pointing) the angle between the geocentric direction (yaw axis) and each optical head can be adjusted between 55° (for 1500 km) and 75° (for 300 km). So, a 64° angle (for 750 km) allows to cover the whole altitude range (300-1500 km) with a maximum depointing field obtained at an altitude of 750 km.

Obviously the present concept enables to cover altitude ranges higher than 1500 km up to 5500 km by decreasing the tilt of each optical heads of the STS03 with respect to the geocentric direction.

b) STS02

This model corresponds to the baseline hereabove described and is specifically suited to geostationary mission orbits with a 3-axis transfer capability in the altitude range from 15000 km up to 140000 km (for supersynchronous GTO).

It can also be used for about 20000 km circular orbits (MEO) depending on the depointing field requirements.

In order to improve the operating autonomy in GEO nominal mode an automatic Sun Inhibition device (SI) has been designed and can be easily added in option to the basic sensor : this is the STS02-SI.

Besides, for spinning transfer orbit missions, an horizon crossing indicator (HCI) can be optionally added : this is the STS02-HCI.

A combination of these two options is obviously possible.

c) STS 04

This model is more specifically suited to MEO (10000-20000 km) missions, but with a 3-axis transfer capability only from 5500 km to 23200 km.

However, below 5500 km, it is possible to measure the spacecraft attitude roll or pitch variations by applying at the spacecraft a known roll or pitch bias which value depends on the altitude. In this range the one axis attitude determination can be continuously achieved through a servo control loop performed from two adjacent array transitions. Obviously the attitude accuracy will depend on the accuracy of this applied bias and of the altitude knowledge.

The HCI option can also be added to this version for the spinned transfer.

d) STS 05

This model is suited to HEO missions and has been designed for a 3-axis stabilized nominal operating in the 8300-54800 km altitude range.

Besides it can also be used for MEO missions (10000-20000 km) according to the depointing field requirements.

Figure 6 - STS product line

6. - STS MAIN CHARACTERISTICS

- updating frequency : 8 Hz nominal (can be adjusted between 1 Hz and 10 Hz on ground)
- accuracy :

	Roll	Pitch	quantization	noise (3σ)
STS01	0.2°	0.2°	0.005°	0.05° (4Hz)
STS03	0.1°	0.1°	0.005°	0.035° (4Hz)
STS02-STS04-STS05	0.03°	0.035°	0.002°	0.015° 4Hz

- weight :
 - 1 kg for « single head » concept (STS02)
 - 1 kg for « several head » concept (STS01)
 - 3 kg for « several head » concept (STS03 to 05)

- Size : 145x125x140 mm³ (for « single head » concept STS02)
- power supply : 16-55 V (100 V optional)
- power consumption : 3.5 W
- turn on time : ≤ 5 s
- communication interface bus : 1553-B (RS422 optional)
- Lifetime : 20 years in GEO
minimum 5 years for other orbits.
- Reliability : 500 fit (MIL-HDBK-217F-N1 30°C)

7. - CONCLUSION

The new STS product line has been designed to cover the need for the attitude control of the whole possible missions through the development of two versions of a thermopile detector array. The STS02 was specially optimized for the GEO mission orbit, with its « single head » concept built around a single focal plane array (FPA). This version is a response to the evolution trend of GEO satellite towards a longer lifetime, a better autonomy level, a better robustness and a significant reduction of the recurrent cost. The other missions are covered with the « several head » concept using separated linear array detectors (ISA) which allow an easy tailoring to almost any kind of orbit. These versions are specially devoted to the merging market of small satellites (like for instance satellite constellations) with a lower mass and cost.

The development of this new product line is now on the way with the end of the detector prototyping phase and the realization of engineering models scheduled for the end of the year for both versions of the detector. A first step has also been successfully passed on the sensor itself with the test of a functional single head mock-up (Ref.3) which demonstrated the concept feasibility and the achievement of the main design goals. The further developments are now in progress, with the CNES support, in order to deliver a first STS02 model (for GEO orbit) by the end of 1998 to fly as a passenger on the STENTOR satellite. The production line for the STS02 is scheduled to be operational in early 1999, in parallel with the end of the detector qualification and sensor qualification.

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