Calibration of the ALTAI temperature sensor for the HEPD tracker on board CSES-02

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Summary. — The second China Seismo-Electromagnetic Satellite (CSES-02)is a space mission that aims to deepen our understanding of the Earth magnetosphere and explore the time correlation between variations in the electron flux in the Inner Van Allen belts and geophysical phenomena like earthquake shocks. For this purpose, the high energy particle detector (HEPD-02) on board CSES-02 is the first space experiment to feature a MAPS-based tracker that is implemented by using ALTAI chips developed in the framework of the ALICE (A Large Ion Collider Experiment) Inner Tracking System at CERN.
In this contribution, the assembly and quality test procedure of the tracker modules will be presented together with the calibration of the ALTAI in-chip temperature sensor performed by using a temperature reference placed on the flexible printed circuit to readout the chip.

1. – Introduction

The second China Seismo-Electromagnetic Satellite (CSES-02) is a satellite that will investigate the near-Earth electromagnetic environment and some phenomena of solar–terrestrial interactions, along with confirming the existence of possible temporal correlations between the occurrence of earthquakes of medium and strong magnitude and the observation in space of electromagnetic perturbations, plasma variations and burst of charged particles from the inner Van Allen belt.
CSES-02 is designed to take advantage of a multi-instrument payload composed of nine detectors for the measurement of electromagnetic field components, plasma parameters, and energetic particles as well as X-ray flux [1]. CSES-02 launch is scheduled for December 2024.
This project is a joint effort between the Chinese National Space Administration and the Italian Space Agency: the Italian collaboration is called Limadou, and contributes to

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the CSES missions by designing and operating two detectors: the Electric Field Detector (EFD) that will register the electric field components and the High-Energy Particle Detector (HEPD) devoted to the detection of electrons and protons or light nuclei respectively in the energy range 3-100 MeV and 30-200 MeV/Z [2].

This work is focused on the High Energy Particle Detector (HEPD-02), which will be launched on board CSES-02.
HEPD-02, shown in fig. 1, is composed by:

- a trigger system made by nine plastic scintillators: the first layer consists of five detectors and covers the HEPD top side while the second layer is placed under the direction detector and is made by four plastic scintillators;
- a direction detector composed by five modules (turrets), each of them composed by three planes (staves) that feature ten ALTAI sensors, a Monolithic Active Pixel Sensors (MAPS) based detector, each (fig. 2);
- a range detector which is implemented by twelve plastic scintillators;
- an energy detector composed by six bars of LYSO scintillators, placed on two layers perpendicular to each other;
- a containment detector that covers the sides of the range detector and the bottom of the energy detector, based on plastic scintillators.

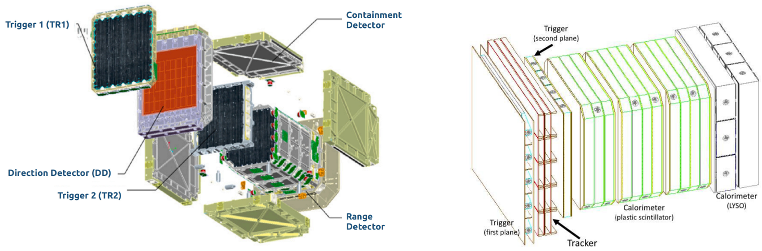


Fig. 1.: HEPD-02 on board CSES-02.

The innovation of HEPD-02 tracker is the use of MAPSs never used so far in space applications [3].

ALTAI sensors are MAPSs developed by the ALICE (A Large Ion Collider Experiment) collaboration inside the ITS (Inner Tracking System) sensor studies but classified as non dual-use [3].
The ALTAI sensor is composed by a 1024×512 pixel matrix each of size 29.24×26.88 μm^2 for a total area of 1.5×3 mm^2. Each pixel output is a digital signal, so each cell contains a sensing diode, an amplifier, a shaping stage and a discriminator as well as a multi-hit buffer. The chip is organized in double columns, readout by a priority encoder; a zero suppression logic is also implemented on each chip. The sensor has a spatial resolution as low as $5\,\mu m$ and a fake-hit rate much below 10^{-7} hits/pixel/event [4]. Moreover, in the peripheral electronics, there is a temperature sensor that reads out the ALTAI temperature in ADC units and that must be calibrated.

2. – Assembly procedure and qualification tests

The whole tracker is divided in five modules (turrets), and each turret is made of three layers (called staves). Every stave is made of two parts: a carbon fiber support (cold plate) that allows to better dissipate the heat, and the HIC (Hybrid Integrated Circuit) that is composed by a Flexible Printed Circuit (FPC) and by ten ALTAI chips wire bonded to the FPC.
In the next lines, the alignment procedure will be outlined, a more detailed description can be found in [4]; ten ALTAI sensors are aligned in their final position using a CMM (Coordinate Measuring Machine), then the FPC is glued on top of the ALTAI chips. Subsequently the sensors are wire bonded to the FPC and the first electrical test can be performed.
The electrical qualification tests consist of a check for hot-spots performed by a thermal camera, the current measurements with clock disabled and with the clock enabled, read and write on memory registers and the injection of an increasing amount of charge to determine the average discriminator threshold on each ALTAI chip. These tests will be performed at every step of the assembly procedure.
If the electrical test gives acceptable results, the lateral wings and the tab of the FPC are cut, and another electrical test is performed. Then the HIC is glued to the cold plate and becomes a stave, that is again tested. Now electrical cables to bring power and readout commands to the stave are soldered to the FPC. The power and the controls are controlled by a Tracker Splitting Board (TSP) mounted inside a closed box. Then five turrets are assembled together in the final mechanics.

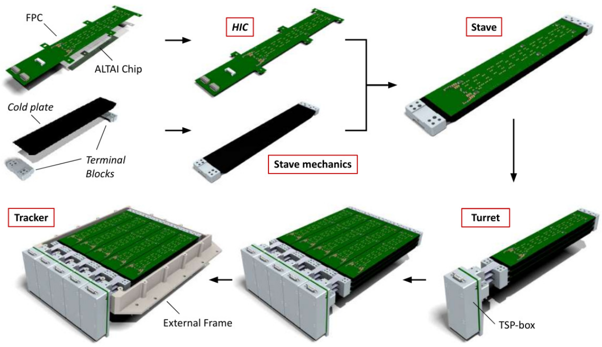
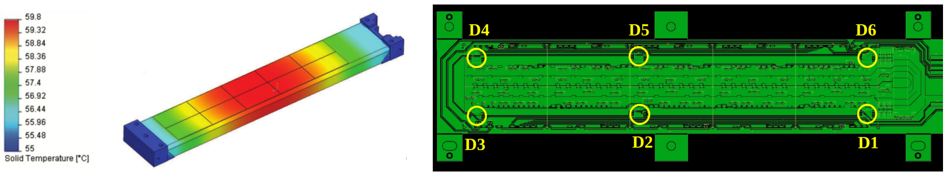


Fig. 2.: HEPD-02 tracker assembly steps.

3. – ALTAI temperature calibration

Temperature is a critical factor for the use of ALTAI in space applications because the satellite will operate outside the atmosphere where the temperature can range between $-30\,^{\circ}$C and $50\,^{\circ}$C [4]. The heat dissipation properties of the carbon fiber support structure had to be carefully studied to assure the thermal uniformity along the stave length: by simulation (reported in fig. 3 (a)), the temperature gradient was expected to be less than 5° C.
However, to test this temperature difference, six Dallas sensors (DS18B20U) were placed at different position along the FPC, see fig. 3 (b).



(a) *Temperature gradient simulation along the stave.*

(b) *Dallas positions along FPC.*

Fig. 3.: Simulation of the temperature gradient along the stave (a) and Dallas position along the FPC (b).

The aim of this measurement was to test whether there was a difference in the Dallas measurements depending on their position along the FPC and to calibrate the temperature sensor inside the ALTAI by using the temperature measured by Dallas sensors as reference. Another parameter that influences the ALTAI temperature sensor readout values is the digital and analogue voltages that feed each chips: the nominal value is 1.8 V, and it was varied between 1.65 V and 1.9 V to perform the ADC calibration as function of the applied power supply voltage.

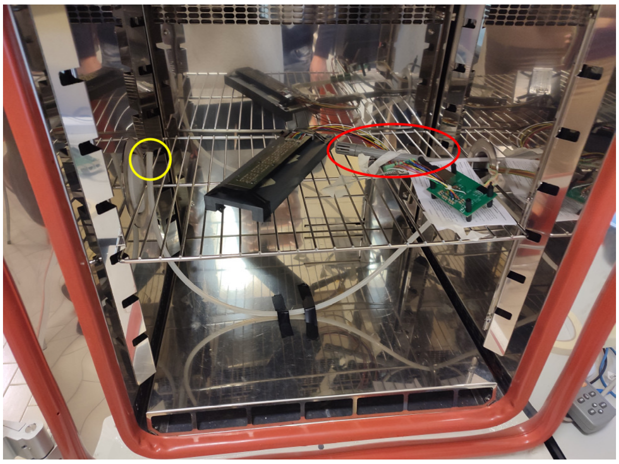
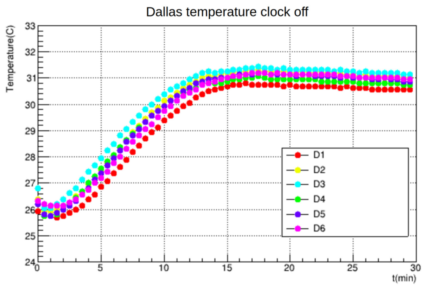


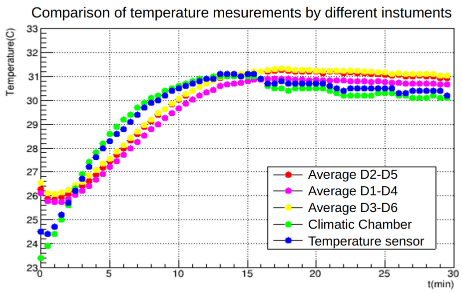
Fig. 4.: Stave placed inside the climatic chamber for temperature measurements. The dry air tube is evidenced by a yellow circle while the temperature sensor is enhanced by a red oval.

To perform these measurements, a stave was placed inside a climatic chamber and a dry air pump was used to control the chamber humidity (yellow circle in fig. 4), moreover a temperature sensor (red oval in fig. 4) was used to check the climatic chamber temperature. The stave was connected to the power supply and to a Field Programmable Gate Array, placed outside the climatic chamber, to readout the data and send them on a computer.

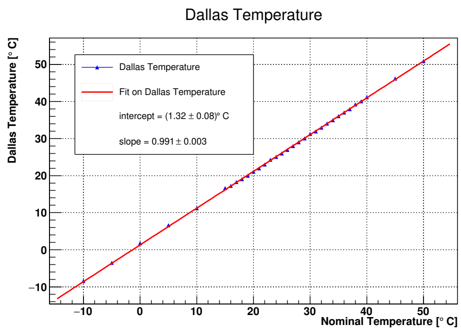
Dependence of temperature on Dallas position. The first measurement was performed by bringing the climatic chamber to a nominal temperature of 30° C and 50° C while measuring the Dallas recorded temperature. The data at 30° C will be used as reference. From the data plotted in fig. 5 (a) and fig. 5 (b), it is possible to see that no significant differences were observed along the FPC length and a difference of around 1° C was observed with respect to the thermometer and the climatic chamber measured temperature. Temperature uniformity along the stave length, not expected from simulations (see fig. 3 (a)), can be explained by the different heat dissipation process: simulation were made to check the thermal gradient by using the carbon fiber as thermal conduction material (this is the method used in the final system, where no atmosphere will be present), while in the climatic chamber, the atmosphere is still present and contributes to the thermal equilibrium. To better estimate the temperature offset between the set climatic chamber temperature and the temperature measured by Dallas sensors, a fit reported in fig. 5 (c) was made. The fit intercept is a good estimation of the offset and is equal to $(1.32 \pm 0.08)°$ C. Another observation is that the climatic chamber takes around 20 minutes to reach thermal equilibrium, this is the time that will be waited before acquiring each measurements.



(a) *Temperature measured by Dallas sensor when the climatic chamber is reaching a temperature of* 30° *C.*



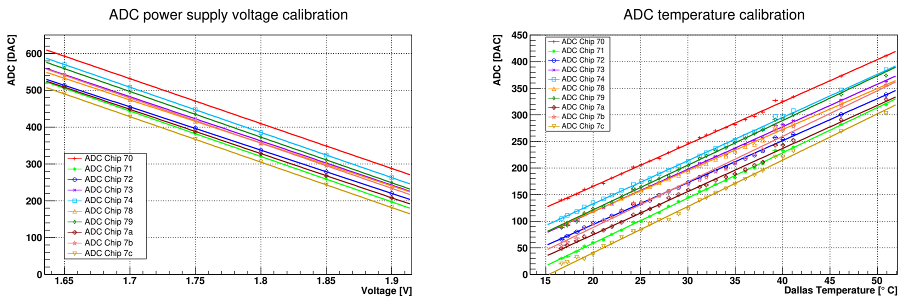
(b) *Comparison between Dallas sensors, temperature sensor, and thermal camera displayed temperature.*



(c) *Linear fit between the Dallas recorded temperature and the nominal climatic chamber temperature.*

Fig. 5.: Comparison between Dallas measured temperature, set temperature on the climatic chamber and temperature sensor placed inside the climatic chamber.

ADC calibration. The Dallas sensor reference allows to completely calibrate the temperature sensor on the ALTAI chip, both with respect to the power supply voltage and to the Dallas temperature.
Fig. 6 (a) reports the ADC calibration as function of the applied power supply voltages, when the climatic chamber temperature is kept at 50° C. A linear dependence can be observed and this calibration can be used to adjust the readout value if there are voltage drops along the FPC.
By doing a scan on different temperature values, it is possible to perform the ADC calibration as function of the temperature measured by the Dallas sensors, this is done on fig. 6 (b).



(a) *ADC calibration at* 50° *C as function of the power supply voltage.*

(b) *ADC calibration as function of the Dallas recorded temperature*

Fig. 6.: ADC calibration as function of the power supply voltage (a) and of the temperature (b).

The relation between temperature and ADC measured voltage is again linear and allows an easy calibration of the ALTAI in-chip temperature sensor. A difference between different ALTAI chips can be observed which can be due to the implantation process on different regions on the wafer, that can cause a slight difference in the ADC readout values without any effective change of the chip performance.

ALTAI performance. Another measurement to check the ALTAI performance at different temperatures was to estimate the threshold variation when changing the temperature of operation. From the acquired data, a variation of $1e^-/°C$ was found [3]. The expected temperature gradient is 5°C, as shown on fig. 3(a): however, the threshold standard deviation on each chip is $20e^-$ that is significantly greater than the $5e^-$ variation along the stave length expected by simulations so the ALTAI performance will not be affected by the temperature gradient.

4. – Conclusions

The tracker of the High Energy Detector is made of Monolithic Active Pixel Sensors, never used for space application so far. The assembly procedure together with the qualification test allowed to select the better modules to be mounted on the final detector. The temperature calibration of the in-chip temperature diode led to the complete calibration of the ALTAI temperature sensor as function of the analogue and digital voltages and of the temperature. This measurement campaign allows to state that the ALTAI performance won't be affected by the simulated thermal gradient along the stave length, to have a precise and multiple temperature reference on the whole tracker permitting to keep track of the on-line ALTAI temperature, and to use this information for in-orbit monitoring.

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