CESAR: Cryogenic Electronics for Space Application and Research

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in the name of the (late) CESAR team

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Konkoly Observatory

• One of the four institution in the Research Centre for Astronomy and Earth Sciences (three "geo" institutions)
• Largest astronomy institution in Hungary (~100 employees)
• Main topics: variable and active starts, stellar pulsations, star- and planet formation, solar system (esp. small bodies), extragalactic astronomy (quasars, gamma-ray bursts, supernovae), etc.
• Largest telescopes in Hungary (Piszkéstető Mountain Station)
• Active participation in space missions: ISO, Herschel, Plato, Cheops, Corot, Ariel, Kepler, TESS...
• Hardver development: "Fly's eye" system: all-sky monitoring down to ~15-16mag w/ a 19-camera system
• Hosting several ERC, H2020, ESA, ... projects
Background: Applied science and astronomy

- Astronomy (as many other fields of physics) may have goals that cannot be reached by nowaday’s instrumentation —> development of new technologies
- CCDs: originally developed for astronomy, now in all smart phones and personal cameras (BTW, it was worth of a Nobel price… )
- Wifi technology originally was developed by radio astronomers (CSIRO)
- General Motors, AT&T, Texaco, BP… uses computer programs originally developed for astronomy to analyse data from car crashes, computer systems and solid-state physics graphics, core samples, etc… (IDL, Interactive Data Language)
- Computer tomography was developed from the work on reconstructing the Solar Corona from its projections
- X-ray observatory technology is used in current X-ray luggage belts in airports
- In airports, a gas chromatograph designed for a Mars mission is used to survey baggage for drugs and explosives
- A gamma-ray spectrometer originally used to analyse lunar soil is now used as a non-invasive way to probe structural weakening of historical buildings or to look behind fragile mosaics
Background: PACS camera testing and calibration in Konkoly Observatory

- Herschel Space Observatory: one of the cornerstone missions of the ESA in the early 2010-s (2009-2013)
- The largest mirror in space with scientific purpose so far (3.5m diameter)
- Far-infrared and submm (60-600um) / (PACS, SPIRE and HIFI)
- PACS: Photometer Array Camera and Spectrometer
PACS bolometers ("blue" and "red") working at sub-K temperatures

- To reduce thermal noise and allow the detection of very few photons the operational temperature had to be very low
- $^3$He sorption cooler (vibration free system with no moving parts)
- Far-infrared and submm (60-600um) / (PACS, SPIRE and HIFI)
- PACS: Photometer Array Camera and Spectrometer -- operational temperature below $\sim 0.3K$
PACS bolometers ("blue" and "red") working at sub-K temperatures

- Cooler developed in CEA-SAp/Saclay — test measurements were performed here and later with the flight module in MPE/Garching
  - Among our tasks:
    - Evaluation of PACS test measurements, including the cooler and detector noise behaviour
    - Performance characterisation
    - Monitoring of long-term behaviour during the mission

![Dependence of the calibration block signal level on the recycling time (Moör et al., 2014)](image-url)
CESAR: Motivation and main goals

- European Space Agency has scheduled programs in X-ray and far-infrared astronomy with improved cryogenic detector arrays (number of pixels and signal sensitivity).
- Restricted amount of available power, at low temperature, in space conditions.
- Power is mainly consumed by the ever-growing number of wires that link the cooled detectors to the distant (~10 m) warm electronics.
- Possible solution: development of the signal processing functions at the heart, or close to the detectors themselves.
- The development of such cryogenic and complex electronics —> CESAR.
- CESAR:
  - cryogenic front-end electronics with intrinsic properties as good as the detectors
  - complex electronics circuits (amplifiers, filters, multiplexers, DACs and ADCs) working at or below 4 K
  - combination of both developments and end-to-end tests on large 2D arrays (multiplexed X-ray microcalorimeters, far-infrared bolometers and magnetometers)
The CESAR Consortium
(EU-FP7, 2011-2014)

- **Coordinator:** COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (SAp/Saclay, France)

- **Participants:**
  - MTA KONKOLY OBSERVATORY (Hungary)
  - INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM (IMEC, Belgium)
  - CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (CNRS, France)
  - UNIVERSITA DEGLI STUDI DI PALERMO (Italy)
  - IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE (United Kingdom)
CESAR workpackages

**WP2: Elementary components**

**Goal:** Design, fabricate and supply various cryogenic Ge, SiGe and AsGa based transistors for front end readout electronics at $T \leq 4.2$ K and to push their performance better than that of the current Si JFETs at $T > 100$ K in terms of the low frequency noise, input capacitance and power consumption.

**HEMT (high electron mobility transistor) development:**

- Replacement of silicon JFETs
- Noise increase from 1.7K to 77K: $<3x$ in white noise and $\sim 4x$ at low frequencies (100 Hz)
- Record low frequency noise performance (much better than the record of JFETs)

**Ge-JFET development:**

- method development to clean germanium substrates before epitaxial growth of the JFET channel
- Ultra-high vacuum chemical vapor deposition (UHV-CVD) homoepitaxial growth of doped germanium,
- superficial gas immersion laser doping (GILD)
- formation of ohmic contacts on n and p types doped germanium

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*Graphs and charts showing performance metrics of various transistor types across different temperatures and frequencies. Additional images of test results.*
CESAR workpackages

• WP3: Complex circuits
  
  • Phase 1:
    • Complex circuits developed from standard CMOS technology (TSMC 0.18um)
    • Single transistors, input buffer, DAC, ADC
    • Final design of Ultralow power cryogenic ADC and DAC developed by IMEC and tested/characterised in Konkoly Obs. (ASIC T10)
    • Good performance at 4 and 20K, successful performance characterisation at 4K
  
  • Phase 2:
    • SiGe ASICs CryoCom1 and CryoCanal1 (0.35um SiGe BiCMOS technology)
    • Development of test electronic boards
    • Functional tests of the ASICs
    • Tests of control registers (internal clocks)
    • Tests of controls (e.g. baseline equalizer and test signal output driver)
CESAR workpackages

- WP4: X-ray microcalorimeters (SAp/ Saclay and Palermo)
  - Upgrade of testing facilities in Saclay and Palermo (UNIPA, new ADR cryostat)
  - Faraday cage for testing the cryoelectronics and the monopixel microcalorimeter
  - New cold electronics (Cryotrans0) developed for UNIPA
  - Cryotrans0 integration
CESAR workpackages

• WP5: Far-infrared and magnetometry

  • Goal: Realization of a complete electronic chain equivalent to the PACS (Photodetector Array Camera and Spectrometer) bolometer array electronics aboard the Herschel space observatory, but with all signal processing made at cryogenic temperatures.

  • Herschel-PACS project: new detector arrays with thousands of pixels (FIR/submm). Before that the largest bolometer arrays were only made with few tenths to few hundreds detectors.

  • For sensitivity reasons these detectors are located at the heart of a cryostat at very low temperature (~0.3K) and surrounded by different temperature stages: 2 K (superfluid Helium), 4K (normal Helium), 20-40K (pulse tubes) and 150K (shields).

  • Tough power requirements cannot be fulfilled in a spacecraft at cryogenic temperatures — too much power dissipated by analogue electronics.

  • PACS multiplexing was done at 300mK and 2K, to avoid signal degradation on the high impedance side of the circuit. First step in cryogenic electronics / relatively high signal level of the targets.
CESAR workpackages

• WP5: Far-infrared and magnetometry

  • Perturbations were experienced: induced all along the ~10 m wires. Source of noise: solar panels and communication between the satellite and ground stations.

  • Next generation space observatories: this will not be sufficient. — E.g. the B-modes of the Cosmologic Microwave Background (CMB) is few orders of magnitude below the thermal fluctuations measured by Planck or WMAP —> all the signal processing must be done at cold level, in order to communicate only through robust digital links.

  • New test rig development in Saclay: cryogenic “full-chain” for “PACS-like” test, including new cryostats — tested and operational

  • Successful testing of the “PACS chain” with most components under cryogenic conditions, providing improved noise properties
Test measurements in Konkoly Observatory

- Major help from the Institute of Nuclear Physics in the assembly of our cryogenic equipment
- Refurbishing of the electronic lab to meet the requirements
- Cryostat “borrowed” from Saclay (AirLiquid)
  - Outer Nitrogen vessel (4.6l) — 0.15 l/h evaporation at 4.2K
  - Inner Helium vessel (4.0l) — 0.05 l/h evaporation at 4.2K
  - 1.5 K – 350 K temperature range
  - Manual temperature control
- Measurements equipment purchased on the CESAR budget (National Instruments)
  - PCI eXtensions for Instrumentation (PXI)
  - Digital multimeters, digitizers, data acquisition modules, digital I/O cards, labview graphical programming language (PXI 4130, 4132, 4071, 6551)
- TE7C: general-purpose, flexible, high-channel-count test platform with accurate power sources for analog and digital measurements (developed in Konkoly Obs., by L. Döbrentei)
Test measurements in Konkoly Observatory

- Measurements performed mainly by S. Király
- Example: nMOS and pMOS samples in DIP28 package
- $I_D - V_{DS}$ and $I_D - V_{GS}$ characteristics (drain current, drain-source and gate-source voltages)
- Nb.1 and Nb.2 families measured at 3, 3.7, 120K and at 4.1, 150, 300K
- Checking the freeze-out effect of nMOS at 25K
Connection between fundamental and applied science in CESAR