DEVINS

Besoins de développement des détecteurs UVC Herzberg (200-240 nm) DEVINS (oxide de gallium ß-Ga_2O_3) pour l'observation de la Terre et du climat

L. Damé [a], M. Meftah [a],
C. De Santi [b], M. Meneghini [b], A. Caria [b], M. Buffolo [b],
P. Maso [c], E. Sandana [d] and F. Teherani [d]

[a] LATMOS, IPSL, CNRS, University Paris-Saclay, Guyancourt, FRANCE
[b] Dipartimento di Ingegneria dell'Informazione, University Padova, Padova, ITALY
[c] PIT, OVSQ, Guyancourt, FRANCE
[d] Nanovation, Châteaufort, FRANCE

Introduction – Paradigms

P1 – Ambitious science goal to measure with accuracy the Solar Spectral Irradiance in the Herzberg continuum:

monitoring the Solar Spectral Irradiance (SSI) at 215/220 nm (Herzberg solar continuum: **200 – 242 nm**) with an accuracy better than 0.5% @ 1**σ**

P2 – Ambitious technology goal through the **innovative development project of DEVINS** photodetectors (a LATMOS/CNRS ANR program 2018-2022):

disruptive ultra wide band gap (≥ 4.9 eV) solar blind (λ > 250 nm) UVC photo-detectors in ß-**Ga_2O_3** with max sensitivity at 215/220 nm -> DEVINS Payload

P3 – Ambitious programmatic New Space goal:

Realization and spatialization (first Space-based) of ß-Ga_2O_3 solar blind UVC "Herzberg" detectors to **TRL 9** ("flight proven") on Inspire-Sat 7

Motivation for UWBG ß-Ga_2O_3 Detectors

- β-Ga_2O_3 is one of the most promising candidates for **solar-blind UV detectors** due to its **ultra-wide bandgap (UWBG)**, economic efficiency, high radiation resistance and excellent chemical and thermal stability
- **PMTs** often call for a high voltage of more than 100 V and are bulky due to their large size and high weight
- **Thermal detectors** are absolute radiometric standards, often used for UV light calibration. However, their response is not wavelength-dependent
- **Narrow bandgap semiconductor** photodiodes and CCDs require only moderate voltages. However, the system's effective area is significantly decreased because of the costly optical filters
- **Ultrawide-bandgap semiconductors** are considered the most effective semiconductors for **solar-blind** light detection since their band gaps are larger than 3.4 eV (> 4.9 eV for β-Ga_2O_3):
  - **solar blind:** not sensitive to λ > 250 nm => no filter needed for Herzberg continuum: **factor 10 in flux**
  - **radiation hard:** limited degradation => long duty cycle
  - **working at ambient temperature** (no need for cooling => power advantage)

Accordingly, in this presentation:

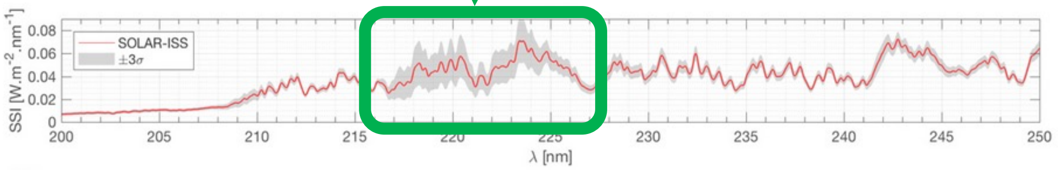
- we present the interest of the **first realized Space Qualified to TRL 9 ß-Ga_2O_3-based solar-blind DUV photodetectors** successfully flown on the INSPIRE-SAT 7 nanosatellite ("2U") April 15, 2023
- **we summarize development process:** material growth method, lithography and device manufacturing/packaging and present their **remarkable sensitivity and dynamical performances**
- **Main fields of application:** Deep UV and UVC (200 – 300 nm) space observations in the context of the exponential development of "New Space" possibilities (constellations…), UV lamps control, plume and "flame" detection…

Why the Herzberg Continuum?

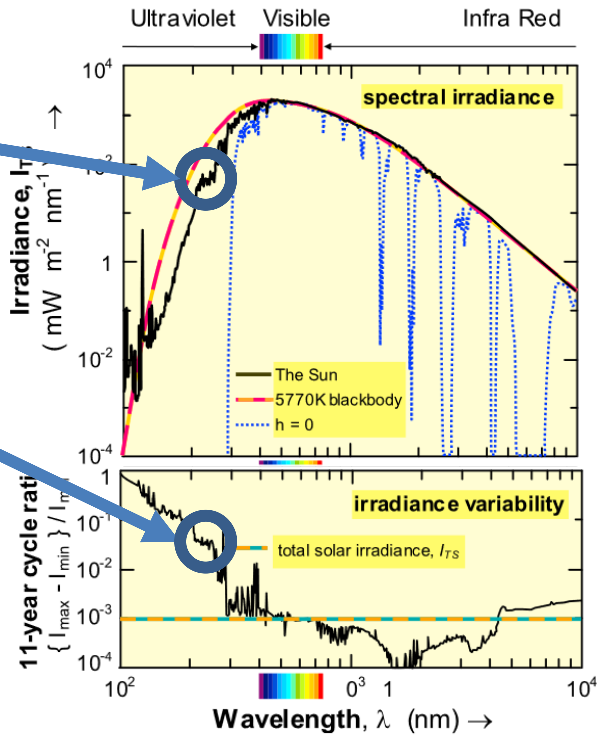
The **Herzberg continuum** is the solar irradiance spectrum between 200 and 242nm
Only observable in Space

High variability over a solar cycle
and significant energy to affect climate

High 3σ uncertainty between 217 and 227nm



SOLAR-ISS spectral irradiance from 200 to 2500 nm at a distance of one astronomical unit
[Meftah, Damé et al. (2018) *Astronomy & Astrophysics*]



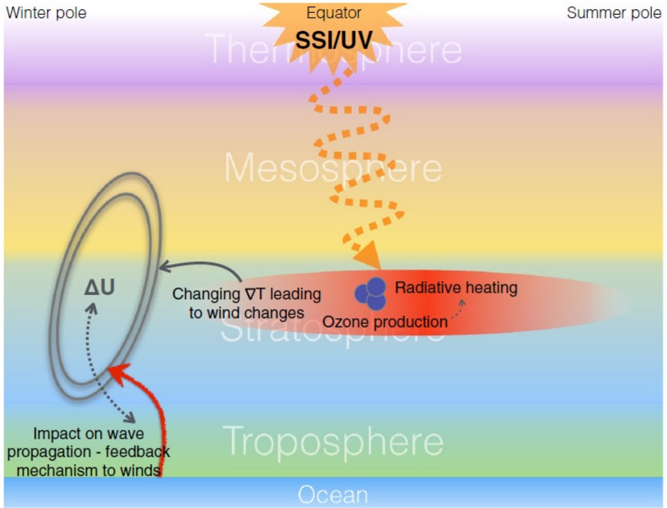
(top) Spectrum of solar irradiance, I.
(bottom) Spectral variability of the irradiance
[L. J. Gray et al. (2010) *Reviews of Geophysics*]

Herzberg Continuum and Climate

Herzberg continuum is responsible for the creation of the ozone O_3 layer by photolysis of molecular oxygen O_2 in lower stratosphere

By its **variability (~5%)** it creates a relative **warming of the upper stratosphere**: temperature and velocities anomalies that affect local climate

Monitoring the Herzberg Continuum and its variability is essential for Solar Physics and Chemistry Climate Modeling



Top-down mechanism for solar spectral irradiance (SSI) [A. Seppälä et al. (2014)]

Solar-blind: limited to UWBG ß-Ga_2O_3?

Wide band gap materials:

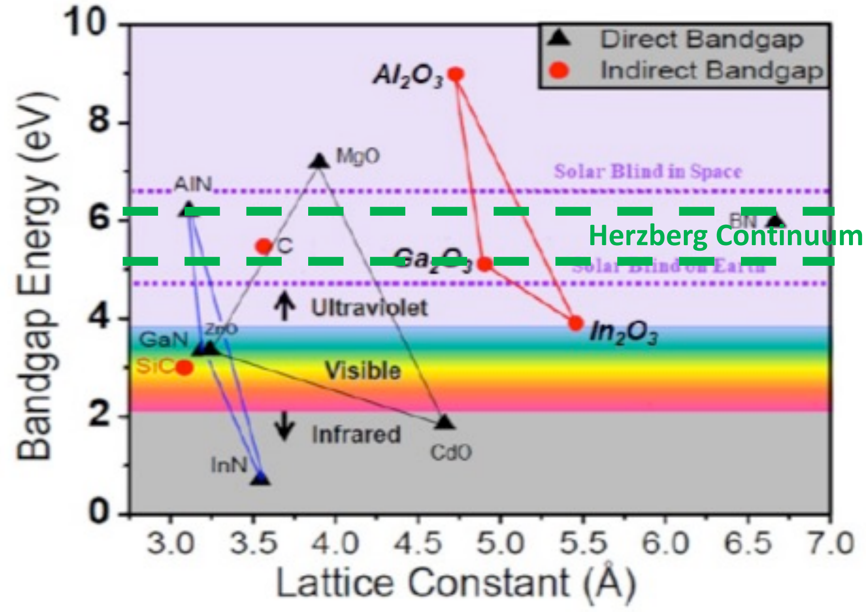
AlGaN:

- Performance drop-off approaching 250 nm (McClintock et al., 2004, Kalra et a., 2022)

MgZnO:

- Phases problem not suitable for device applications (Rogers et al., 2013)

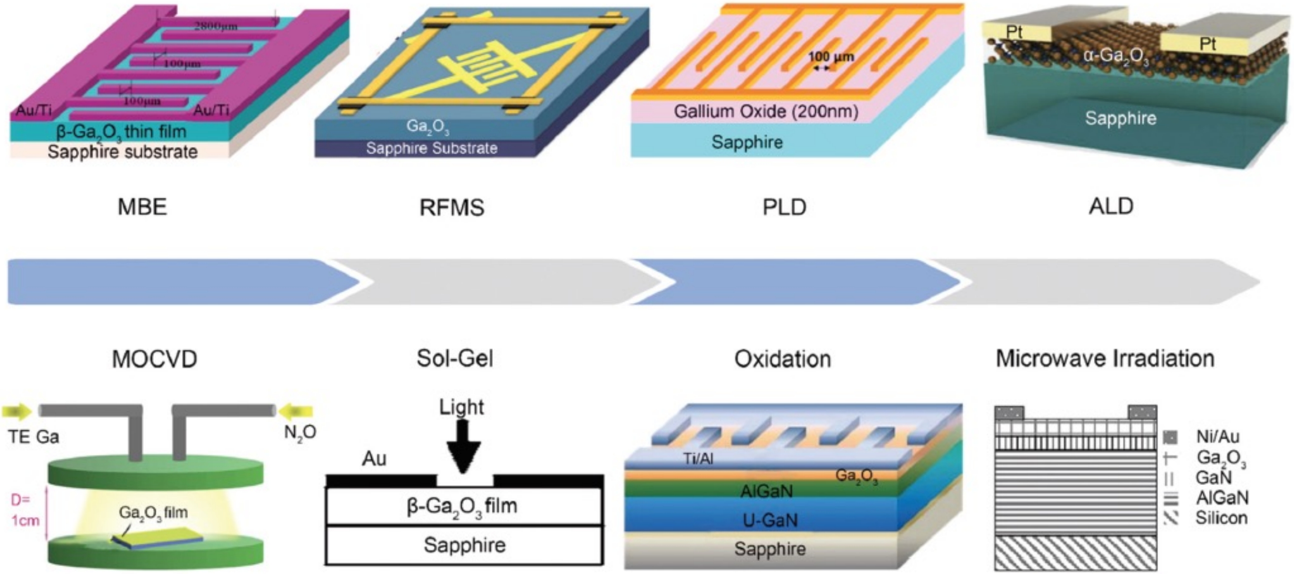
ß-Ga_2O_3: no show stopper



Bandgap engineering possibilities with the most common wide bandgap optosemiconductors (Rogers et al., 2021)

Material and Technique

β-phase aluminum−gallium oxide (β-$AlGa_2O_3$) can be continuously tuned from **4.8 to 6.6 eV**



PLD more suitable for **multi-component film growth** when compared with the other methods, and the **atomic-layer thickness can be controlled by adjusting the laser frequency**.

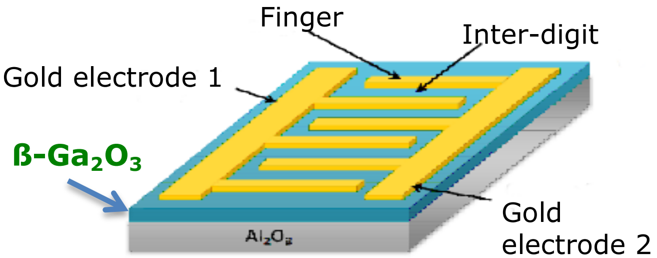
Meanwhile, the **high energy of the source particles** generated from the pulsed lasers **enhances the surface mobility of the atoms.**

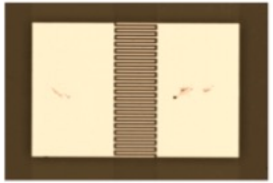
http://dx.doi.org/10.1021/acsami.9b04354
10.1039/c9tc02055a

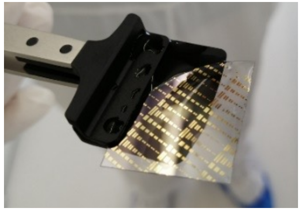
DEVINS Process Approach

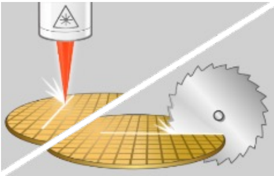
- **DEVINS are Metal-Semiconductor-Metal photodetectors in β-Ga_2O_3encapsulated in a standard TO-39 cap**

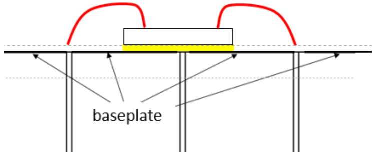
- MSM Device = 2 “back-to-back” Schottky Diodes (interdigitated fingers' sets, 2 µm)
- ß-Ga_2O_3 deposited by Pulsed Laser Deposition on 2" sapphire wafers
- Components' process (hundreds of them)
  - Mask and lithography
  - Back metallisation
  - Dicing
- Encapsulation/Packaging in TO-39
  - Soldered on base-plate
  - Hermetic cap with sapphire window

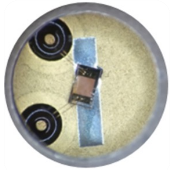



Lithography









DEVINS Realization Process

Substrate

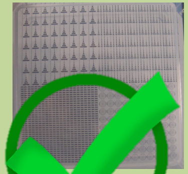
Sapphire

Front-end Level 0 - Epitaxy

- Nucleation layer
- Active layer

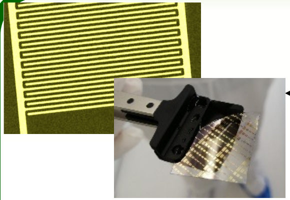
1. Nanovation MSM

Photo-mask



Front-end Level 1 - lithography

- Inspection/Caracterization
- Etching
- Metalization/Contacts

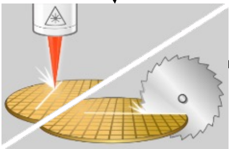


3. Lafayette

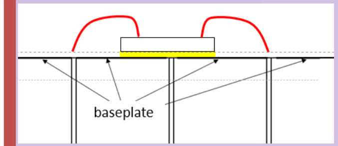
Back-end Level 0 - Packaging

- Device separation
- Die singulation
- Tests
- Binning

4. SERMA



Back-end Level 1 - Packaging



- Wire bonding
- Encapsulation (hermetic cap with sapphire window)
- Tests

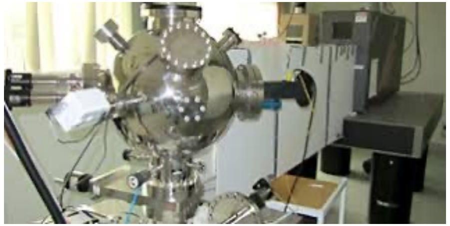
5. SERMA

Selection tests & Qualification

6. LATMOS

DEVINS

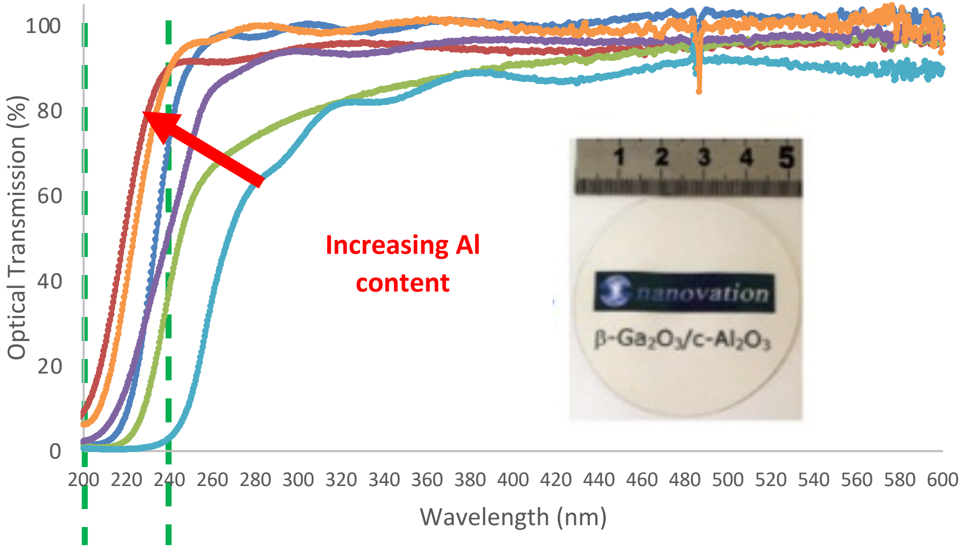
Photodetectors Realization: Epitaxy



PLD set up
(Nanovation)

ß-(Al)Ga_2O_3 Epiwafers (Nanovation) can be engineered to give in theory any optical transmission cut-offs between 200 and 240/280 nm

Several wafers realized with different thicknesses, **50 to 330 nm**, and doping, covering a large spectrum of characteristics



Herzberg Continuum

(Rogers et al., 2021)

LATMOS

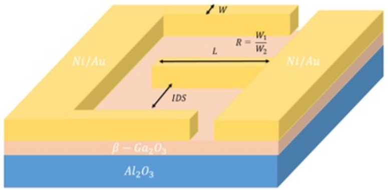
DEVINS

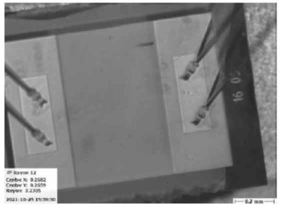
Photodetector Realization: Photo-Lithography

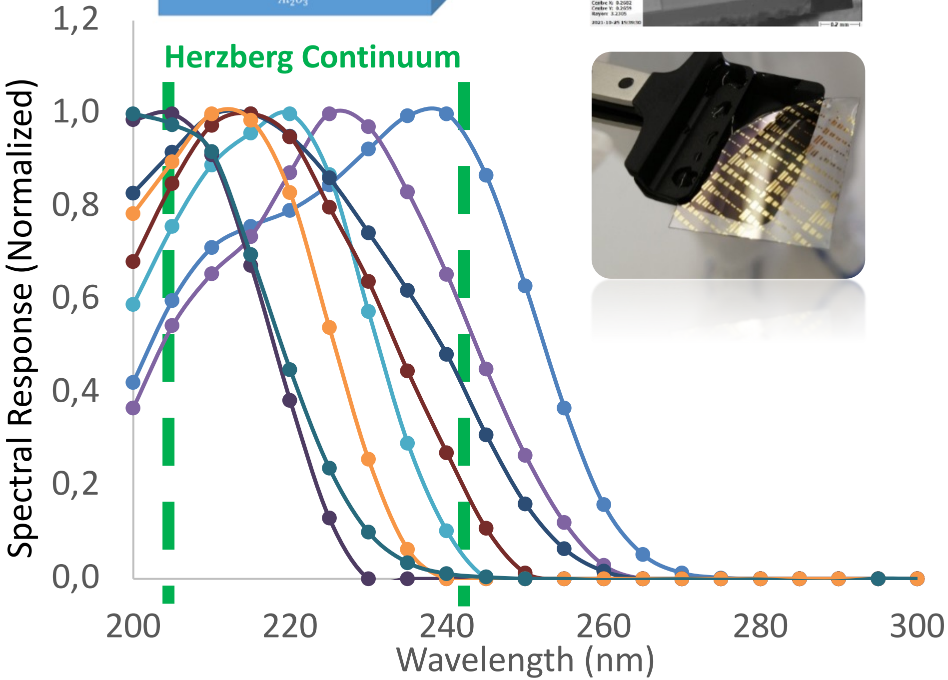
More than 5 000 MSM components were made using **various device geometries** (length of fingers, spacing, etc…) @Lafayette Institute (Metz), optimizing also contacts for soldering/packaging (4 layers Ti-Al-Ni-Au)

Components were realized **with peak responsivities between 200 and 240 nm** presenting a large dispersion and some inhomogeneity (>> 5% even with experienced PLD method of Nanovation)

Binning was conducted based on spectral response in order to isolate the best components (cutoff @250) for subsequent packaging







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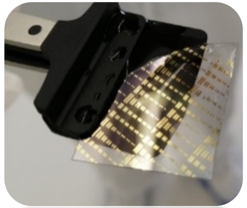
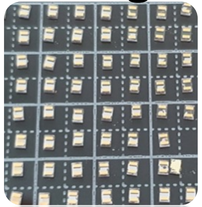
Photodetector Realization: Packaging

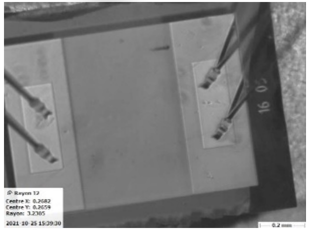
- **Die singulation with saw** using 150 µm thick sapphire blades
- **Wire bonding** (25 µm) **characterization** by pull tests: 10.26 gF (in agreement with MIL-STD-883)
- Encapsulation realized in TO-39 cans (with **sapphire windows**) under **nitrogen** (hermeticity certified)
  (Clear aperture of window is 6 mm, well compatible with the Ø4 mm aperture and Ø3 mm diaphragm)
- 80 successful detectors realized, **30 selected for flight and tested (SR, rejection, centering, absolute calibration, vibrations) for integration in INSPIRE-SAT 7**

Dicing & singulation

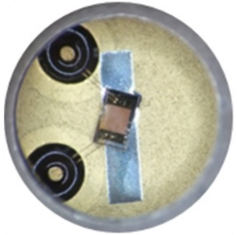




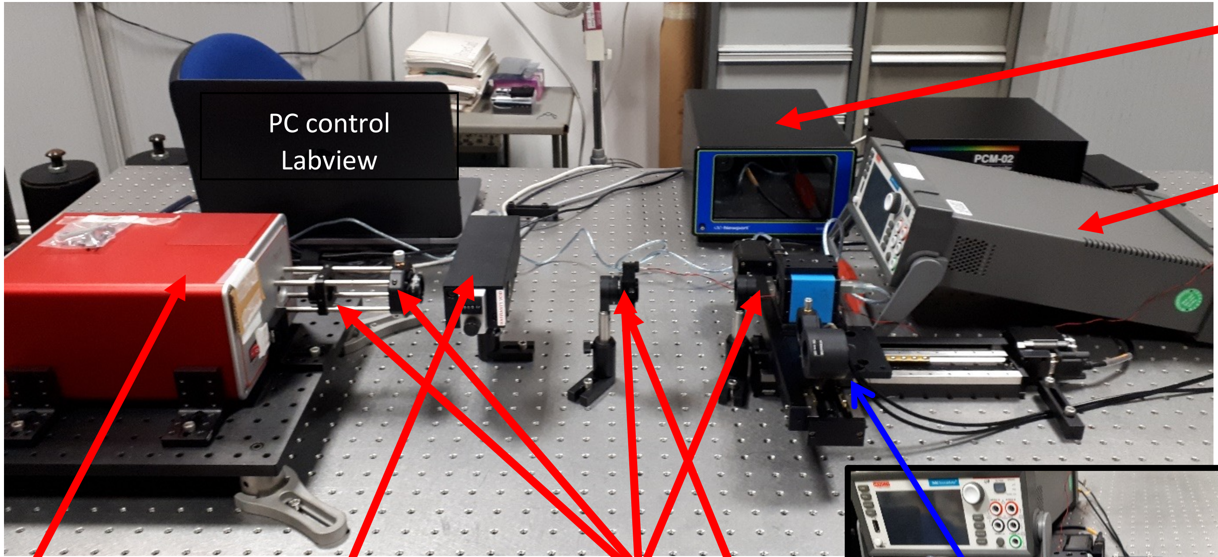
Packaging process



Die attach & wire bonding



Performance Measurement Setup



Powermeter
(Newport 1938-R)

Sourcemeter
(Keithley 2450)

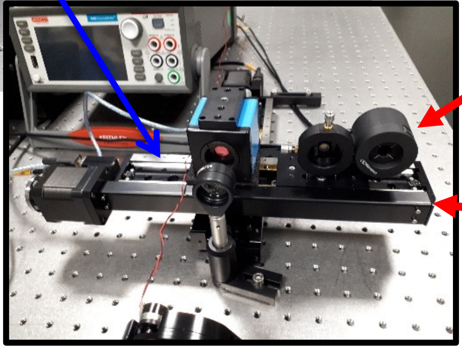
New CALIBRATED measurements
with automatic focusing and precise collimation

Deuterium Lamp
(Thorlabs SLS204)

Monochromator
(Optometrics SDMC1-02)
(Optometrics PCM-02)

Lens

Shutter

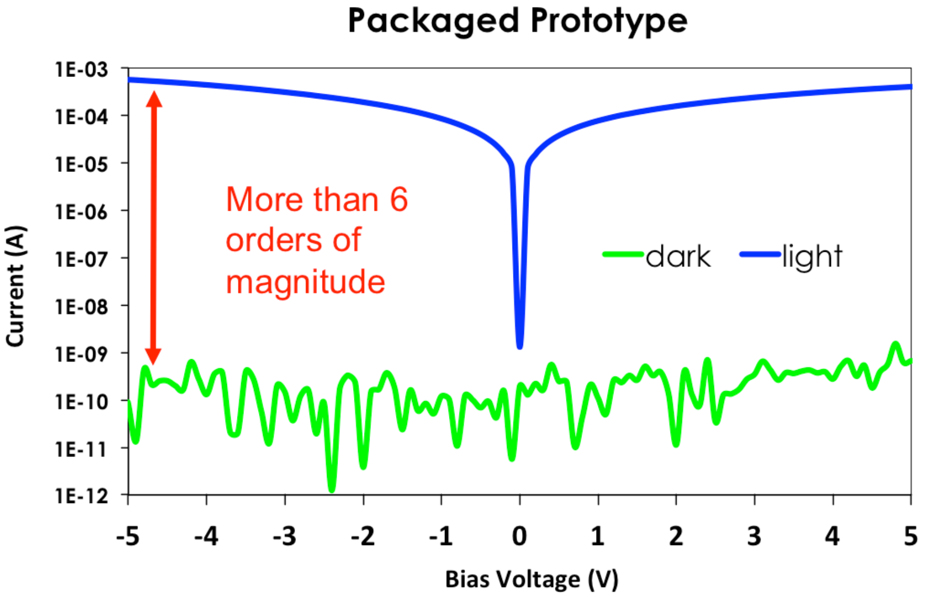


Calibrated Photodiode
(Newport 918D-UV-OD3R)

Translation and controler
(Standa 8MT175-200-XY)
(Standa SMC5-USB-B9-2)

Performance Evaluation

- Probing tests on hundreds of MSM components realized to characterize detectors performance
- **Up to 6 order of magnitude between dark and light currents measured at only -5V bias voltage**
- **Dark current is very low (< 5 ± 1 pA); below the measurement capabilities of our equipment**



Spectral Response, Sensitivity & Rejection

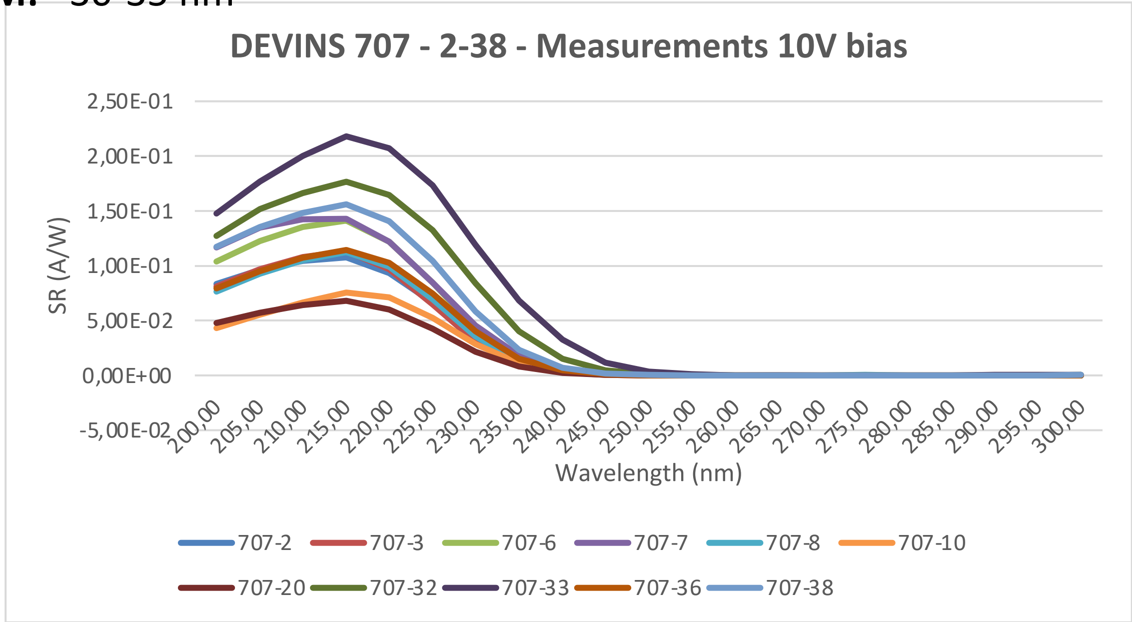
Example of the 707 series (164 nm thickness layer):

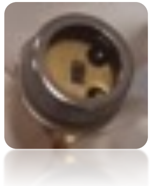
Sensitivity at peak: **≥ 100 mA/W** @10V bias (except 10 and 20)

Peak of sensitivity: 210-215 nm

Rejection efficiency @250 nm: ≥ 1000 (except 32 and 33)

FWHM: ~30-35 nm



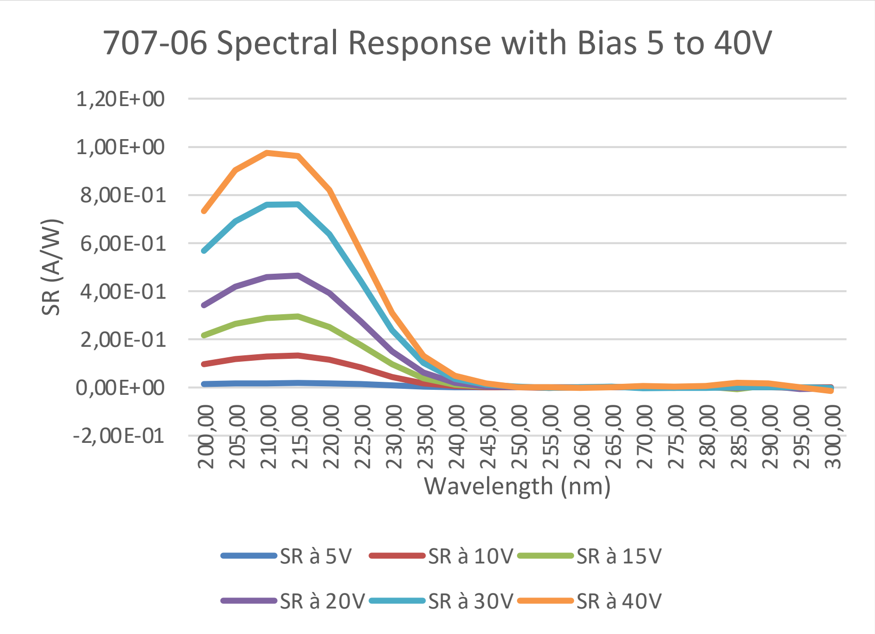


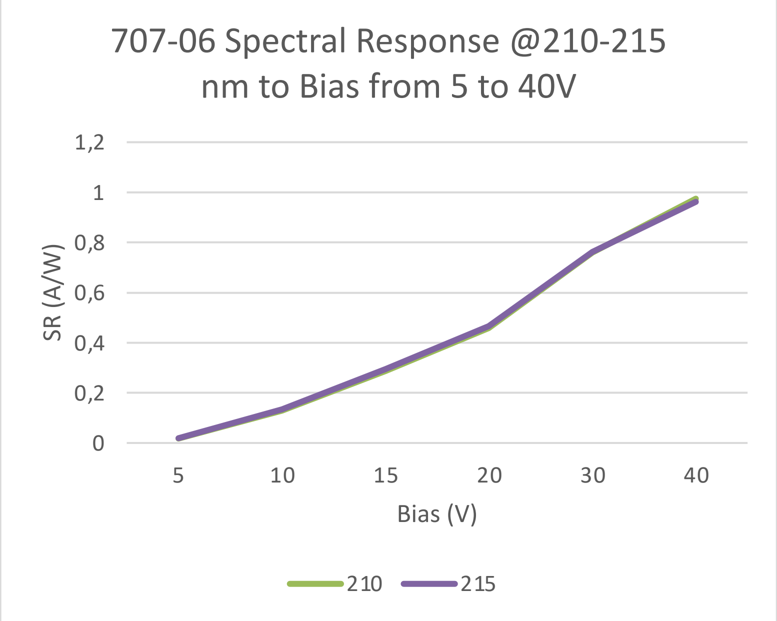
@10V bias (Nanosatellite)

DEVINS

Response vs Bias Polarization Voltage

A bias voltage of **10 V** instead of **5 V** (as initially envisaged on the Nanosatellite) multiply the response by a **factor of ~7** owing to the non-linearity of the response





707-06 response rises by a factor 7 from 19 mA/W at 5 V to 133 mA/W at 10 V
and by a factor 50 to ~1 A/W at 40 V
Peak sensitivity stays centered at 210/215 nm

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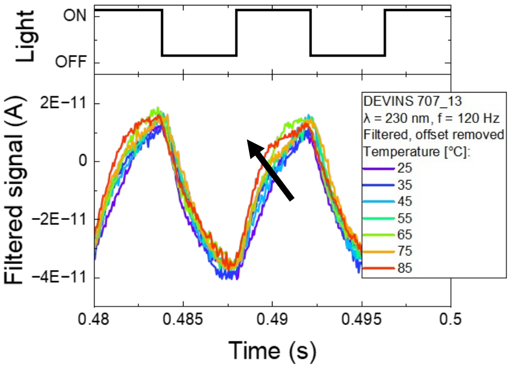
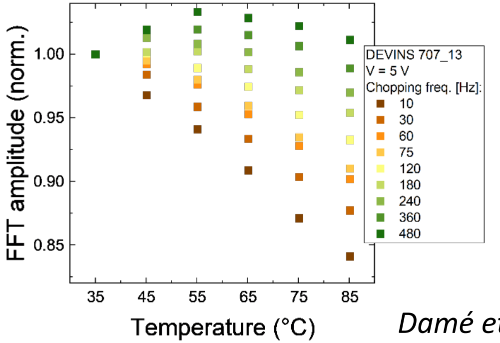
Response vs Temperature

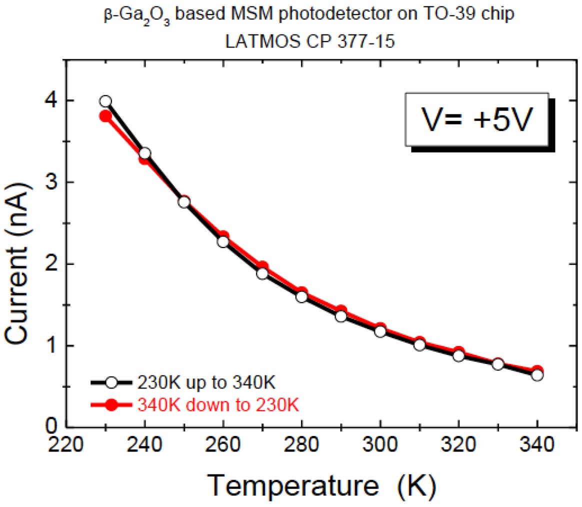
Response is temperature sensitive => need monitoring of temperature at detector level (Nanosatellite integration concern):

- ➢ DEVINS-L (inside) near sensor -> OK (± 5 ° C)
- ➢ DEVINS-C near solar panels -> affected (control?)





Damé et al. (2023)

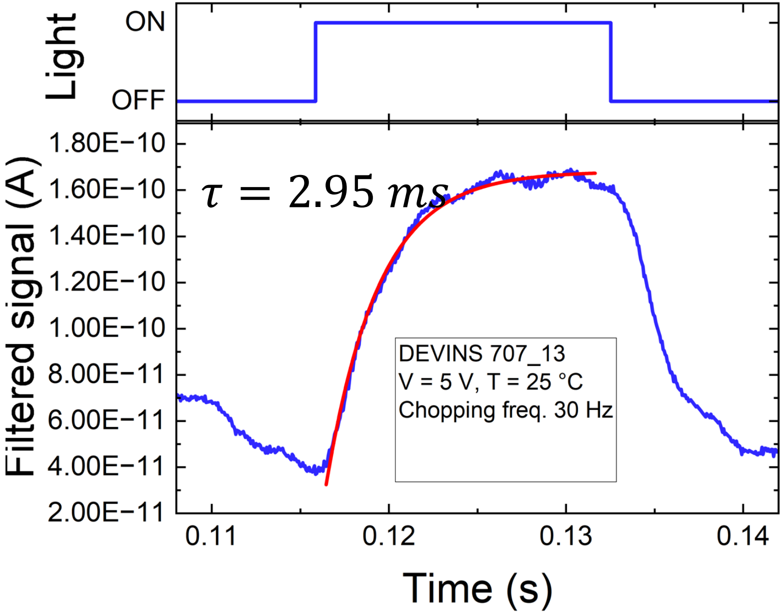


Ghorbel, Damé et al. (2021)

Temperature has a significant impact on the speed and amplitude of the response

This behaviour can be caused by various effects, including the variation in leakage level with temperature and the change in defect capture and emission rate

Dynamic Performance



Damé et al. (2023)

Detector response under chopped light (frequency = 30 Hz)

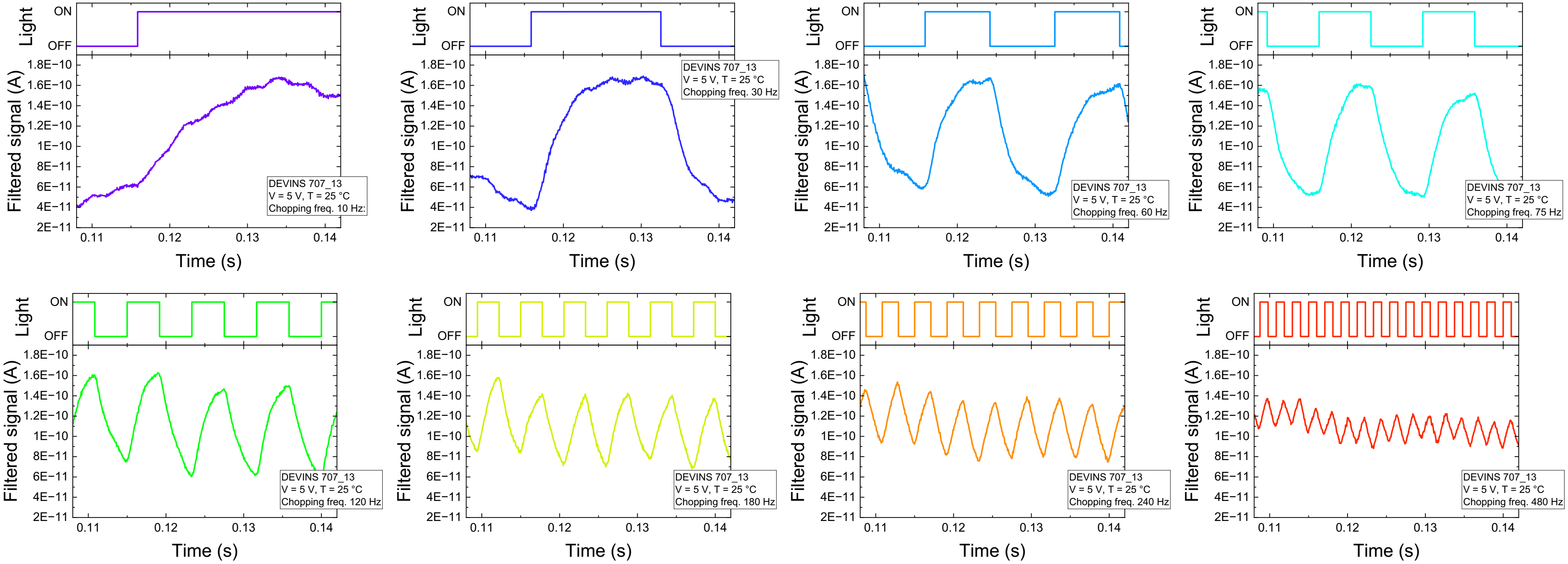
Detectors show an exponential response, with a time constant $\tau = 2.95\ ms$ (shorter than [1-5])

This is compatible with the satellite acquisition time (1 s, required for satellite pointing drift)

Oxygen vacancies form trap states in the bandgap, increasing the transit and rise time constants [6]

[1] /10.1021/acsphotonics.9b01727?ref=pdf
[2] /10.1021/acsami.8b14380
[3] /10.1021/acsphotonics.7b00359
[4] /10.1002/adfm.201906040
[5] /10.1021/acsphotonics.7b01054
[6] 10.1021/acsphotonics.7b01054

Dynamic Performance



Response to a square-wave excitation of different frequency; the low pass behavior is highlighted, rise time and fall time measured are better than expected: ≤ 20 ms

Performance Summary

Parameter	Requirements	Compliance (10V bias)
DEVINS signal range	0 - 2.1 Wm^{-2} (200-242 nm) Target value: 1.4 Wm^{-2}	Yes
DEVINS peak wavelength	215 ± 5 nm	Yes
DEVINS FWHM	20 +10/-5 nm	30 ± 5 nm achieved
DEVINS rejection	10^4 from 250 to 3000 nm	Better than 1000 peak to 250 nm
DEVINS sensitivity	> 10 mA/W	**> 100 mA/W** on selected detectors
DEVINS noise detection	< 30 pA for DEVINS-C <0.1 nA for DEVINS-L	< 5 pA in laboratory but challenge for electronics on board nanosatellite…
DEVINS time response	< 0.1 s	**Rise & Fall Time < 20 ms**
DEVINS acquisition time (sampling)	Better than 10 seconds	Yes, **1s** (but pointing drift dependant of sat rotation: less may be required…)

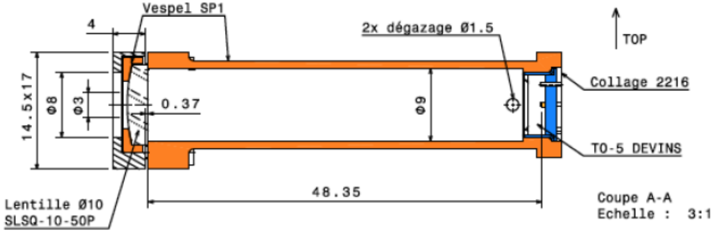
DEVINS-L & -C for INSPIRE-Sat 7

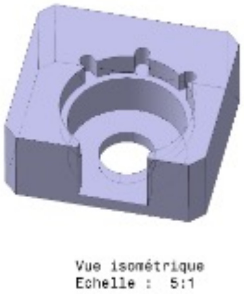
The DEVINS detectors onboard INSPIRE-SAT 7

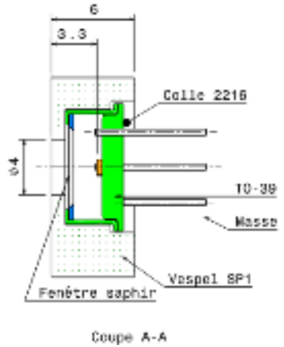
- **4 DEVINS**

- **2 configurations:**
  - 1 DEVINS-L (Long): focusing lens, large equivalent surface (7 mm^2 —flux increased x 17.6) but small field of view (1°)

  - 3 DEVINS-C (Classic): small (0.4 mm^2) but wide field of view (40°)







LATMOS

Applications & Developments

- **Deep UV and UVC (200 – 300 nm) space observations in the context of the exponential development of "New Space" possibilities (constellations…)**:
  - DEVINS detectors were spatialized (TRL 9) on the LATMOS “2U” nanosatellite INSPIRE-SAT 7 with excellent performance (although limited by onboard electronics and rapid satellite rotation….)
  - DEVINS could be part of several climate/Space Weather constellations since of the small resources required. In order to reach ultimate measurement uncertainty (± 0.1% @215-220 nm) we need:
    - a larger collecting area: 2x2 mm^2 (4 mm^2), or a quad cell possibility: 4 x 1 mm^2 (centering control)
    - improved packaging (scattered light, centering); would help with focusing devices (like DEVINS-L)
  - Production process is mastered but still delicate (wafers homogeneity and reproducibility will have to be improved) for a commercial production stage (>1% success wafer to detector?). PLD advantageous for development but MBE or HVPE probably more suitable for industrial series.

- **Other potential & promising applications and developments:**
  - Laboratory UV lamps control
  - Plume and "flame" detection
  - Spectroscopy with a 256 pixels linear detectors (useful for LATMOS Nanosat Program on Solar Spectral Irradiance Monitoring: SOLSIM instrument, etc.)

Thank you for your attention!
Questions?

Luc.Dame@latmos.ipsl.fr

anr agence nationale de la recherche AU SERVICE DE LA SCIENCE

INSTITUT LAFAYETTE

SERMA MICROELECTRONICS

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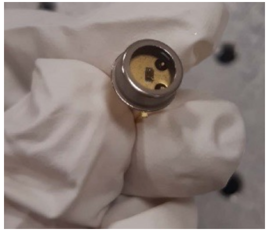
DEVINS Detectors on INSPIRE-Sat 7

4 DEVINS detectors are integrated on INSPIRE-Sat 7:

- 3 DEVINS-C: **C**lassical version packaged in a TO-39) with a nominal diaphragm of Ø3 mm for a detector size of 500x800 µm^2 (**0.4 mm^2**)



- 1 DEVINS-L: New optical concept "**l**ong" using the same detector packaging (TO-39) with diaphragm Ø3 mm and nominal detector size of 500x800 µm^2

  Specific: the TO-39 photodetector package (with a sapphire window for UV), is in the nanosatellite behind (@50 mm) a **plano-convex lens** (fused silica) that focuses the full Sun on 465 µm => Flux collection largely improved (**factor 17.6 for diaphragm of Ø3 mm => 7 mm^2 equivalent detector**)

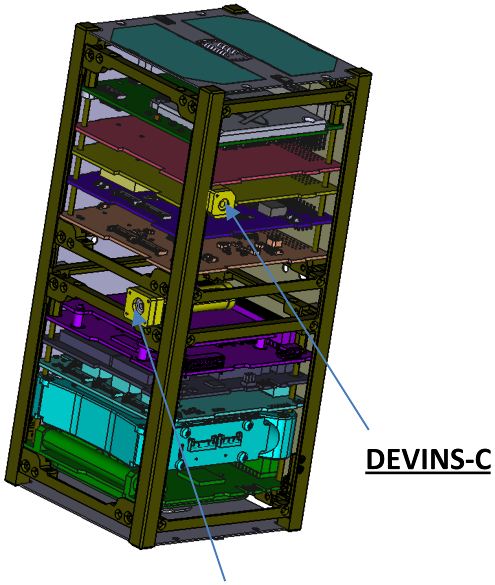
Nanosatellite Program

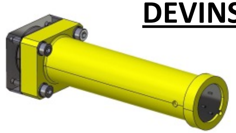
INSPIRE-Sat 7 "2U"CubeSat

INSPIRE-Sat 7 is an evolution of the "1U" UVSQ-SAT CubeSat, which was launched in January 2021 (Meftah, Damé, Keckhut, et al., 2020)
This new CubeSat was launched: SpaceX **April 15 2023**

Three main objectives

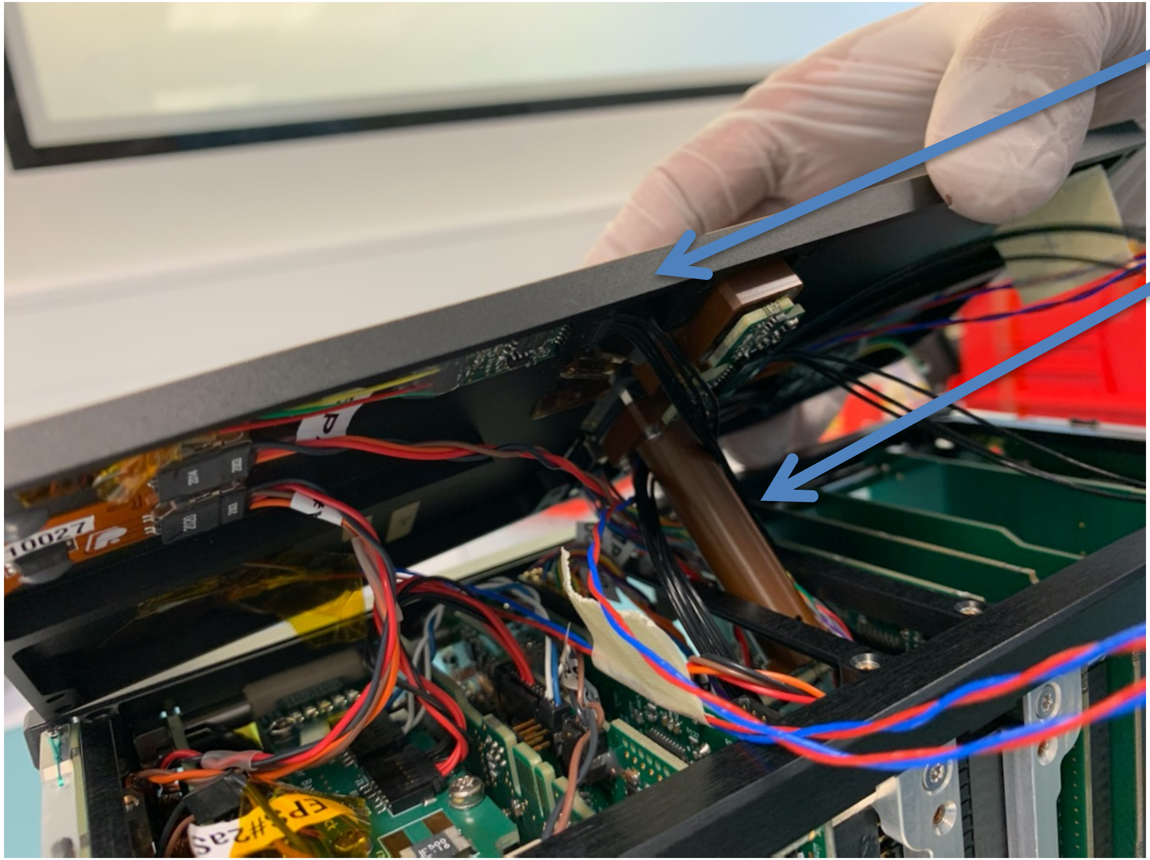
- **Science**: Earth observation, Solar physics
- **Technology demonstration**: Instruments miniaturization for solar physics (**DEVINS to TRL 9**) & validation of ultraviolet solar variability measurements, Instruments & satellites constellation validation for Earth observations, Validation of an inertial measurements unit, Validation of the Totem electronic board, Validation of a LiFI system
- **Education & outreach**: Satellite development, Payload development, Software development, Training material





Credit LATMOS

Integration on INSPIRE-SAT 7



Closing Satellite Panel

DEVINS-L

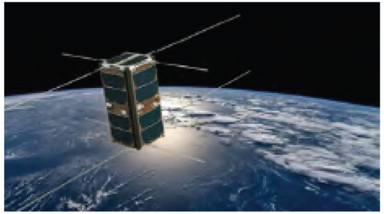
LATMOS

LATMOS Nanosatellite Program

UVSQ-SAT (Inspire-sat 5)

2018 — Etudes (1) + Réalisations, Tests (2) — **24/01/2021** (launch) — Exploitation (3) 13/03/2021 — Fin de vie 24/01/2024 ? — Utilisation des données (4)

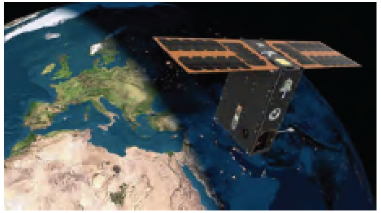
UVSQSAT



INSPIRE-SAT 7

2020 — Etudes (1) + Réalisations, Tests (2) — **15/04/2023** (launch) — Exploitation (3) 15/05/2023 — Fin de vie 15/04/2026 ? — Utilisation des données (4)

inspire.sat 7 MONITORING THE EARTH



UVSQ-SAT NG (Inspire-sat X)

2022 — Etudes (1) + Réalisations, Tests (2) — **11/03/2025** (launch) — Exploitation — Fin de vie — Utilisation des données (4)