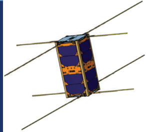
SPIE. PHOTONICS WEST



Performances and calibrations of new disruptive UVC ß-Ga_2O_3 sensors for new space applications

L. Damé[1], H. Ghorbel[1], M. Meftah[1], C. Dias[1], P. Gilbert[1], P. Maso[2], D. Bolsée[3], N. Pereira[3], D. Rogers[4], P. Bove[4], V. Sandana[4] and F. Teherani[4]

[1] LATMOS, IPSL, CNRS, University Versailles Saint-Quentin en Yvelines, University Paris-Saclay, 11 boulevard d'Alembert, 78280 Guyancourt, FRANCE

[2] PIT, OVSQ, 11 boulevard d'Alembert, 78280 Guyancourt, FRANCE

[3] BIRA-IASB, Brussels, BELGIUM

[4] Nanovation, 8 route de Chevreuse, 78117 Châteaufort, FRANCE

Introduction

DEVINS (a LATMOS/CNRS ANR financed program over the 3 last years) is an innovative development project with an ambitious **science goal**:

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

To measure with accuracy Solar Spectral Irradiance in the Herzberg continuum, we use disruptive new large band gap (~4.9 ev) solar blind UVC detectors in β-Ga_2O_3 -> DEVINS Payload with new generation UVC disruptive detectors

DEVINS, accordingly, has an ambitious **technology goal**:

> validation of the new/first Space β-Ga_2O_3 solar blind UVC "Herzberg" detectors to TRL 9 ("flight proven")

Rationale for Using ß-Ga_2O_3 Detectors

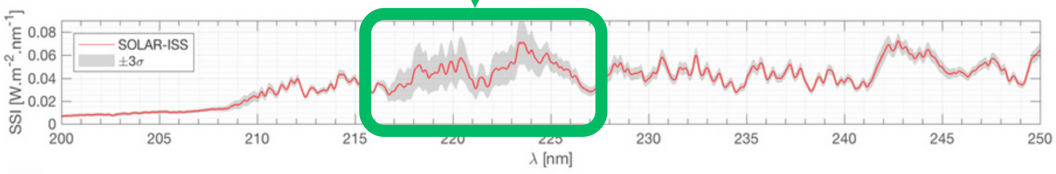
- β-Ga_2O_3 is considered to be one of the most promising candidates for solar-blind UV detectors due to its ultra-wide band gap (~4.9 eV), economic efficiency, high radiation resistance and excellent chemical and thermal stability. Herein, we provide a comprehensive review on the **first realized Space Qualified ß-Ga_2O_3-based solar-blind DUV photodetectors**. We detail the developmental process: material growth method, lithography and device manufacturing/packaging. Flight scheduled early 2023 in the INSPIRE-SAT 7 nanosatellite ("2U")
- Main field of application: Deep UV and UVC (200 – 300 nm) space observations in the context of the exponential development of "New Space" possibilities (constellations…)
- ß-Ga_2O_3 photodetectors are interesting for Space UV observations since:
  - solar blind: not sensitive to wavelengths > 250 nm => no filter needed: **factor 10 in flux**
  - radiation hard: limited degradation => long duty cycle
  - Working at ambient temperature (no need for cooling => power advantage)

What is the Herzberg Continuum?

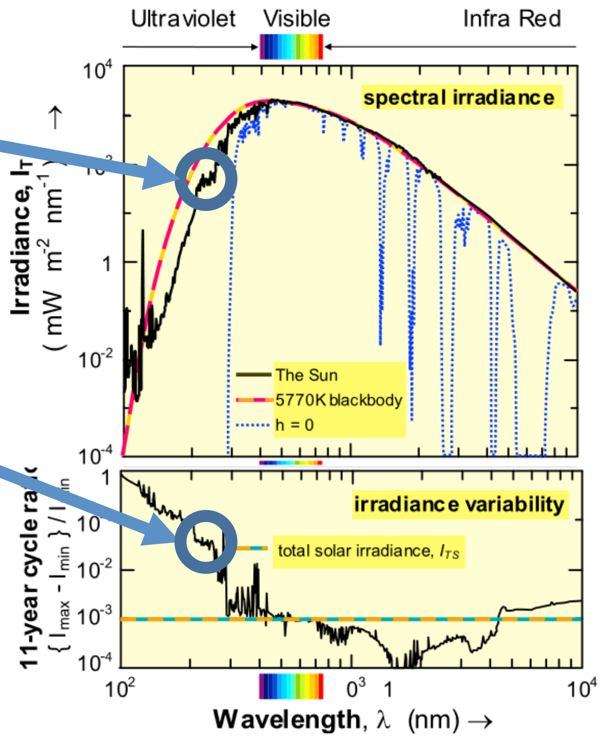
The Herzberg continuum is the solar irradiance spectrum between 200 and 242nm

High variability over a solar cycle

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*]



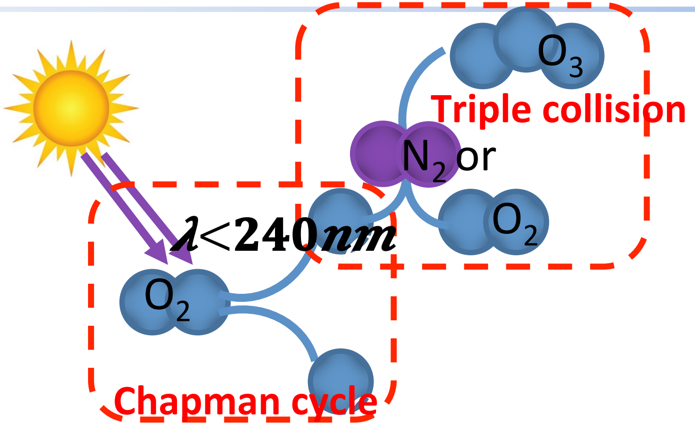
(top) Spectrum of solar irradiance, I.
(bottom) Spectral variability of the irradiance
[L. J. Gray et al. (2010) *Reviews of Geophysics*]

Why monitoring the Herzberg Continuum?

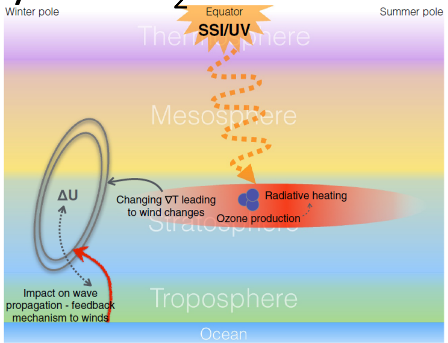
Herzberg continuum is responsible for the creation of the ozone layer by photolysis of molecular oxygen in lower stratosphere

Solar variability creates a relative warming of the upper stratosphere

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



Photolysis of O_2 and creation of O_3



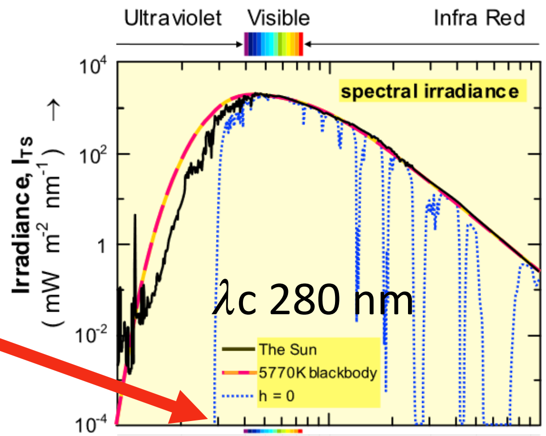
Top-down mechanism for solar spectral irradiance (SSI)
[A. Seppälä et al. (2014) *Progress in Earth and Planetary Science*]

Why do we monitor it from space?

Because it cannot be measured on earth since the atmosphere absorbs all λ < 280 nm

This implies space based observation of the Herzberg Continuum, a realization challenge for the photodetectors:

- Radiation Hardness
- Mechanical Robustness
- Compact Materials
- Low power
- Wavelength selection



Spectrum of solar irradiance

[L. J. Gray et al (2010). *Reviews of Geophysics*]

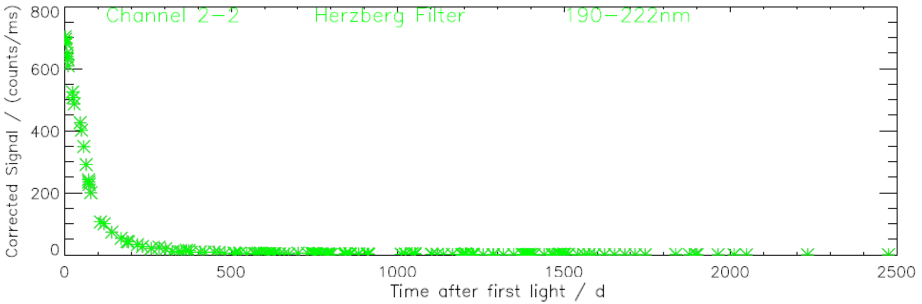
UVSQ-Sat (Inspire Sat 5) nanosatellite

No alternative

Si-based and broadband photodetectors:

- Not wavelength selective → Filter
- Fast on orbit degradation in time

Meftah et al. (2017)



Evolution in time of the collected signal of the Herzberg continuum channel of LYRA Meftah et al. (2017)

Wide band gap materials:

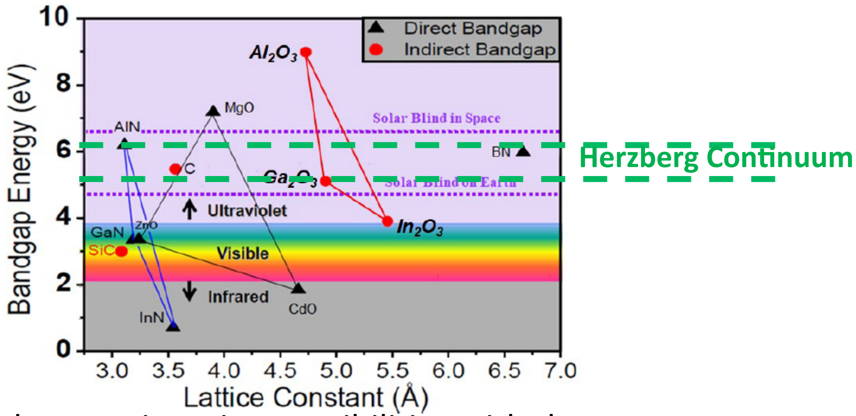
AlGaN:

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

MgZnO:

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

ß-Ga_2O_3: no show stopper

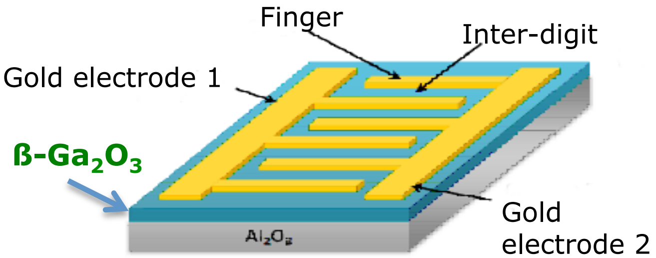


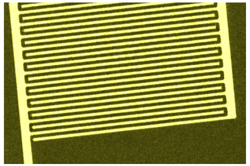
Bandgap engineering possibilities with the most common wide bandgap optosemiconductors (Rogers et al., 2021)

DEVINS Instrument Definition

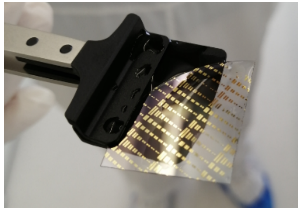
▪ DEVINS are Metal-Semiconductor-Metal photodetectors in β-Ga_2O_3 encapsulated in a standard TO-39 cap

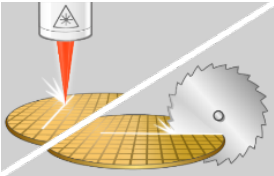
- MSM Device = 2 "back-to-back" Schottky Diodes (interdigited fingers' sets, 2 µm)
- ß-Ga_2O_3 deposited by Pulsed Laser Deposition on 2" sapphire wafers
- Components' process (hundreds of them)
  - Mask and lithography
  - Back metallisation
  - Dicing
- Encapsulation/Packaging in TO-39
  - Soldered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

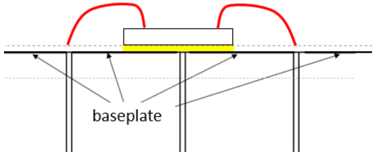




Lithography







DEVINS Realization Process

Substrat

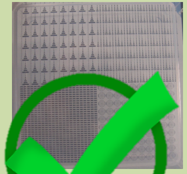
Sapphire

Front-end Level 0 - Epitaxy

- Nucleation layer
- Active layer

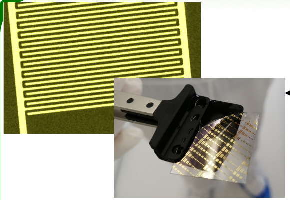
1. Nanovation MSM

Photo-mask



Front-end Level 1 - lithography

- Inspection/Caracterization
- Etching
- Metalization/Contacts

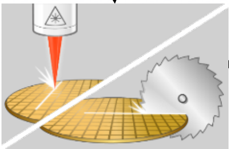


3. Lafayette

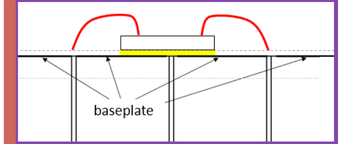
Back-end Level 0 - Packaging

- 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

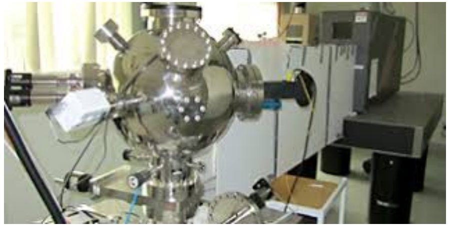
& Qualification

6. LATMOS

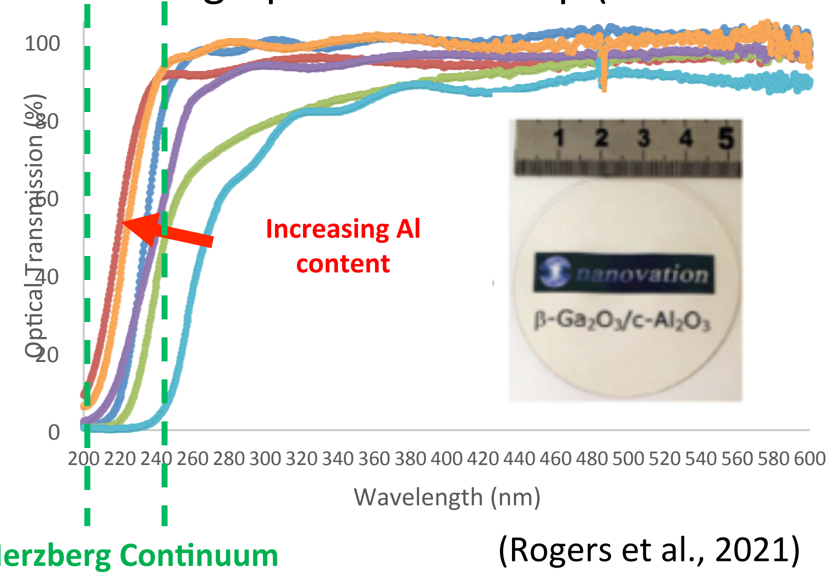
Photodetectors Realization: Epitaxy

(Al)ß-Ga_2O_3 Epiwafers (Nanovation) can be engineered to give in theory any optical transmission cut-offs between 200 and 240 nm
(Rogers et al., 2021)

Several wafers realized with different thickness, 50 to 320nm, and doping, covering a large spectrum of characteristics



Photograph of PLD set up (Nanovation)



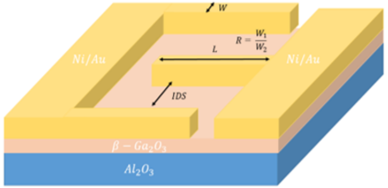
(Rogers et al., 2021)

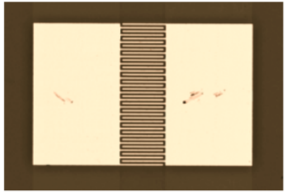
Photodetector Realization: Photo-Lithography

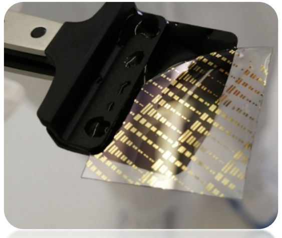
More than 5 000 MSM components were made using various device geometries (length of fingers, spacing, etc…) @Institut Lafayette, optimizind also contacts for soldering/ packaging

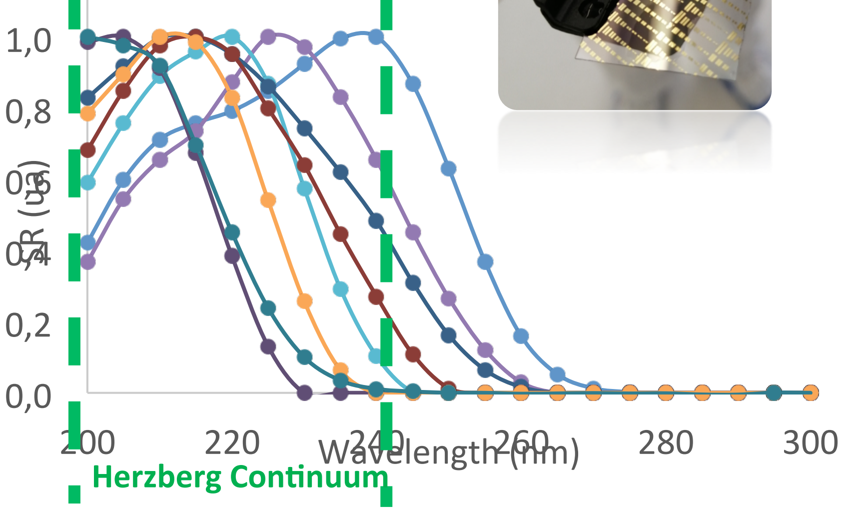
Components were realized with peak responsivities between 200 and 280nm presenting a large dispersion and inhomogeneity (>> 5% even with quality and experienced PLD method of Nanovation)

Binning was conducted based on spectral response in order to isolate the best components (cutoff @240) for subsequent packaging



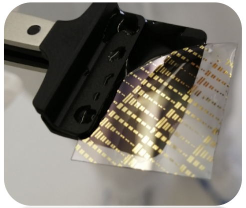




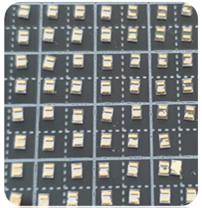


Photodetector Realization: Packaging

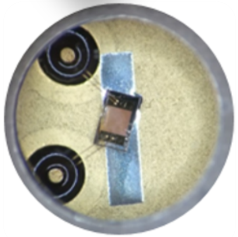
- Die singulation with saw using 150µm thick sapphire blades
- Wire bonding characterization by pull tests : 10.26 gF (in aggreement with MIL-STD-883)
- Encapsulation realized in TO-39 cans (with sapphire windows) under nitrogen



Dicing & singulation



Packaging process



Die attach & wire bonding

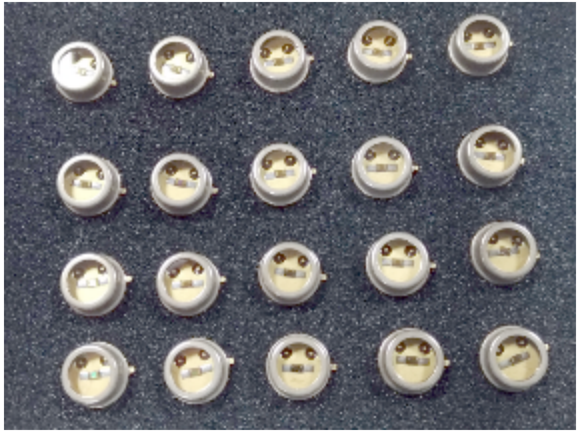
Encapsulation and Packaging

- **Encapsulation**
  - Caps with sapphire window

  Clear aperture of window is 6 mm, well compatible with the Ø4 mm aperture and Ø3 mm diaphragm.

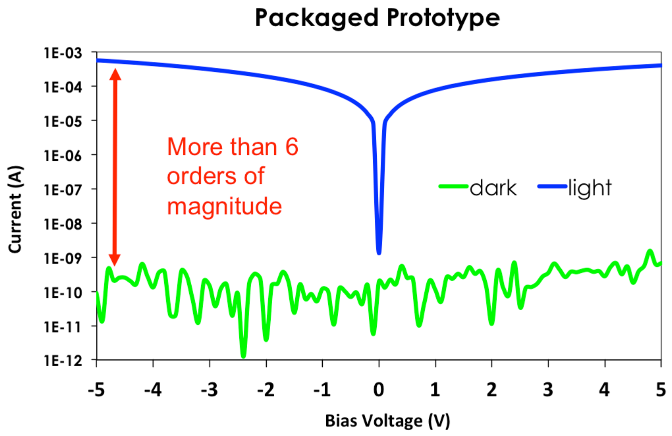
- **Packaging**
  - Hermetic nitrogen encapsulation (Hermeticity verified by SERMA).

  More than 80 successful detectors already made, 30 detectors selected for flight and a batch of the 10 best reserved for absolute calibration and integration in INSPIRE-SAT 7.

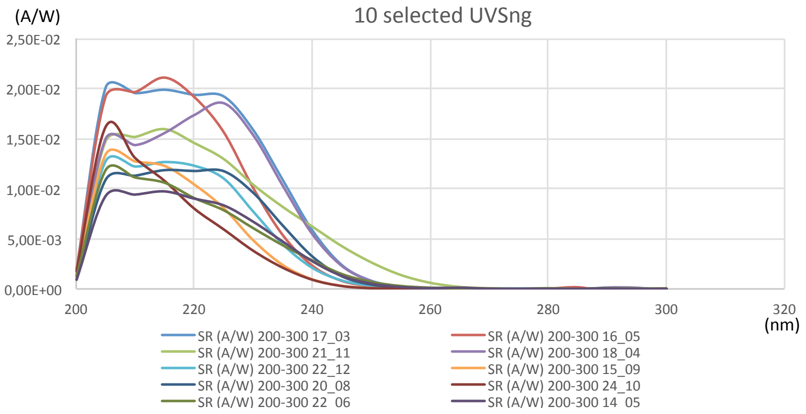


Performances Evaluation

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

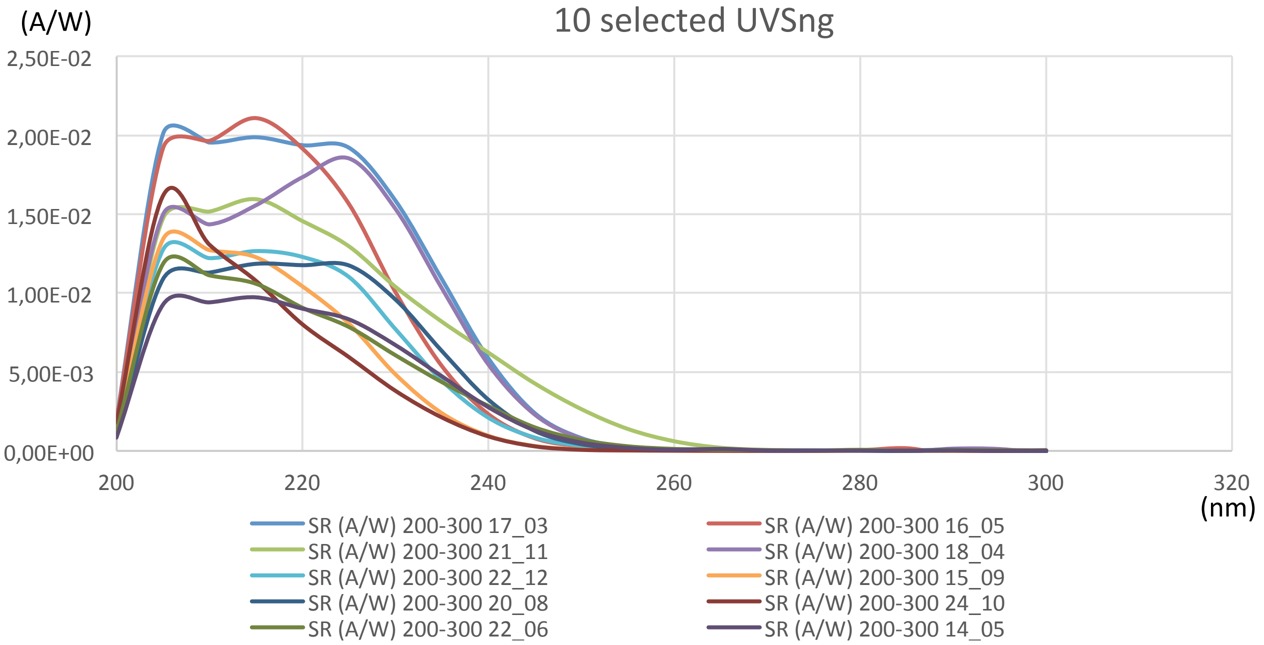


- **Responsivity** was measured and reaches **10 to 20 mA/W** on selected packaged detectors; **centering at 215-220 nm** was achieved with **FWHM of ~35 nm; rejection at λ > 250 nm ("solar blind") is excellent (> 1000)**



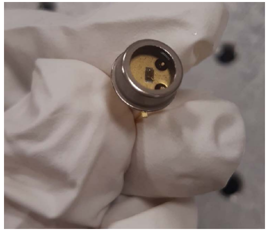
UVSng Detectors Selection

Sensitivity at peak: minimum 10 mA/W
Peak of sensitivity @210-215 nm
Rejection efficiency @250nm > 1000 (except one)
FWHM: ~30-35nm



DEVINS Detecteurs for INSPIRE-Sat 7

4 DEVINS detectors (UVSng: UltraViolet Sensor new generation) are foreseen on INSPIRE-Sat 7:



- 3 DEVINS-C: Classical version similar to UVS (packaging in TO-39) but without filter; nominal diaphragm Ø3 mm; nominal detector size 500x800 μm^2 (**0.4 mm^2**)
- 1 DEVINS-L: New optical concept **but** same detector packaging (TO-39), also without filter, with diaphragm Ø3 mm and with nominal detector size 500x800 μm^2. 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 11 for diaphragm of Ø3 mm => 7 mm^2 equivalent detector**)

DEVINS Scientific Requirements

Essential Variable for Solar Influence on Climate	Required Measurement Uncertainty @ 1σ	Stability (per Cycle/ Decade) @ 1σ
SSI @ 215/220 nm Herzberg Continuum 200-242 nm	± 0.5% (± 2 10^{-4} $Wm^{-2}nm^{-1}$)	± 0.1% per decade** (± 4 10^{-5} $Wm^{-2}nm^{-1}$)

**In practice ~3–4 years from launch (end of 2022/ Q1 2023) since of solar cycle length and shape

These define: - requirements on measurements
- limits on noise
- spectral rejection

DEVINS Scientific to Technical Requirements

Requirement for ± 0.5% uncertainty goal (± 2 10^{-4} $Wm^{-2}nm^{-1}$)

Noise Equivalent Flux (NEF): **2 10^{-5}** W m^{-2} nm^{-1}

Detector surface (S): **0.4 10^{-6}** m^2 for DEVINS-C but **7 10^{-6} m^2 for DEVINS-L** (focused Ø3mm)

Responsivity average 200-242 nm (R): ~**10** mA/W (limited by the -5V polarization)

Noise $= \mathrm{NEF} * \mathrm{S} * \Delta\lambda * \mathrm{R} \approx$ **30** pA (**~0.5 nA for DEVINS-L**)

Note that detector surface foreseen is only 500x800 µm^2 (DEVINS-C response would increase with larger surface) and that the responsivity of 10 mA/W of the detectors (around 215 nm) is the minimum expected (responses at 15 and 20 mA/W measured).

Noise of components is very low (≤ 1 pA) and, accordingly, electronics' noise is the potential limit of detection (**0.1 nA expected but TBC**).

Solar flux on DEVINS-L (200-240 nm band) is around 10 µW and, accordingly, current expected is **100 nA**. Variations at 1% level (not full cycle to account since launch in 2023) around this average are therefore **1 nA**. Situation is just acceptable for DEVINS-L but probably critical for DEVINS-C with average of < 6 nA and variations < 60 pA…

Response Time

Photo-response Time

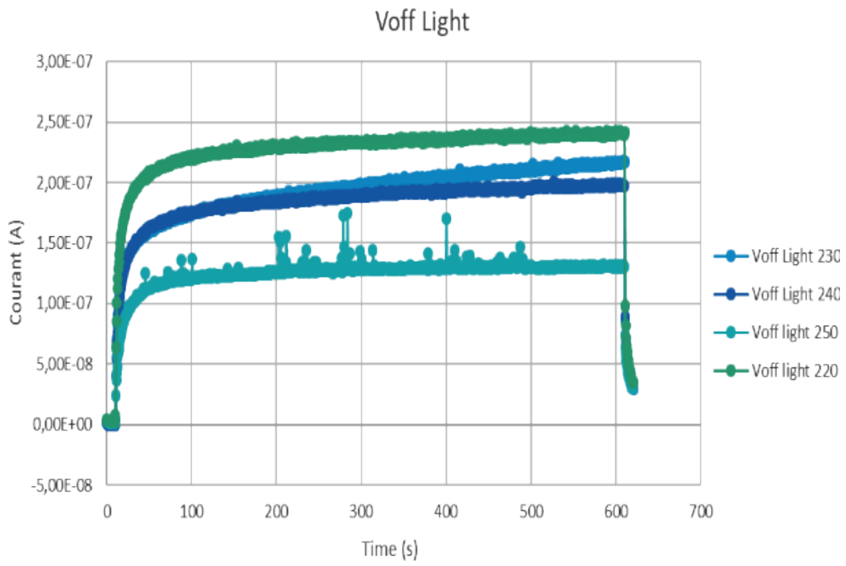
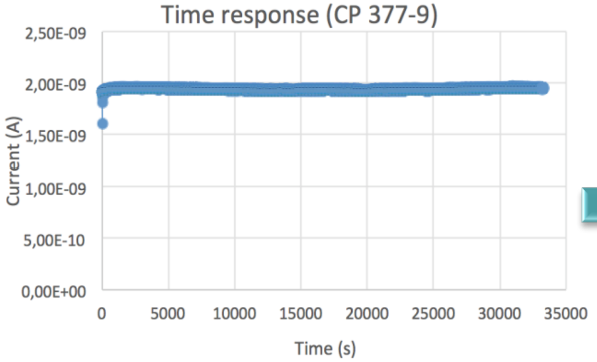
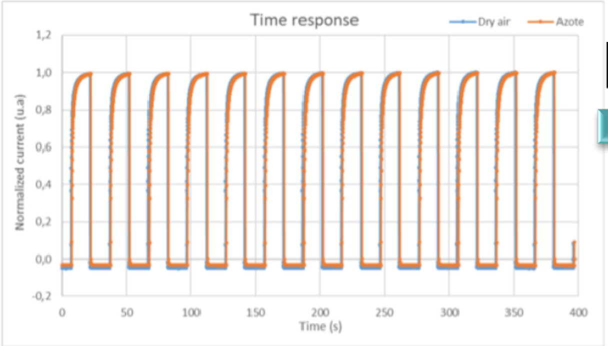


Photo-response time of a MSM photodetector (CP730C).



a

Current is stable on time (<1%) 10 hours test

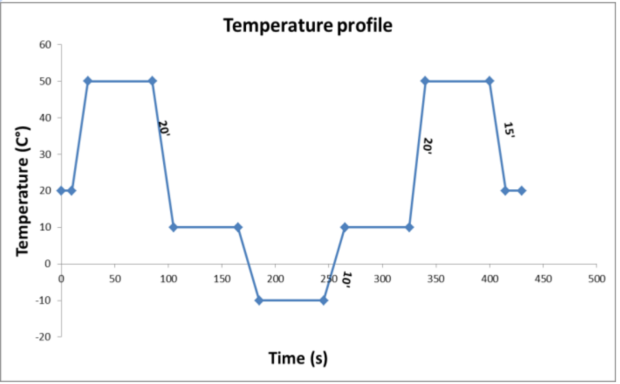


b

Response is reproducible
Rise time: < 1 s
Fall time: < 80 ms

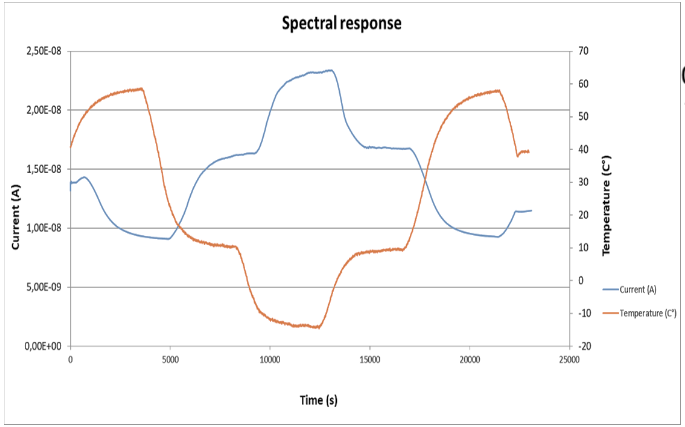
Illustrative photo-response time and dynamics of a MSM photodetector (CP377-9).

Thermal Tests

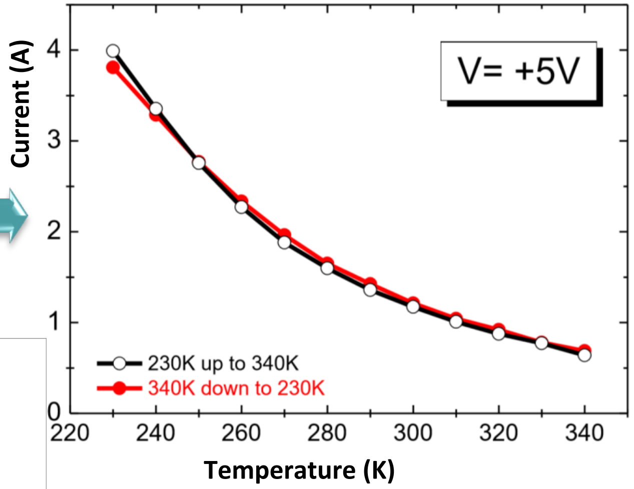


Temperature cycle applied on a MSM photodetector (CP 377-9).

No hysteresis phenomena observed



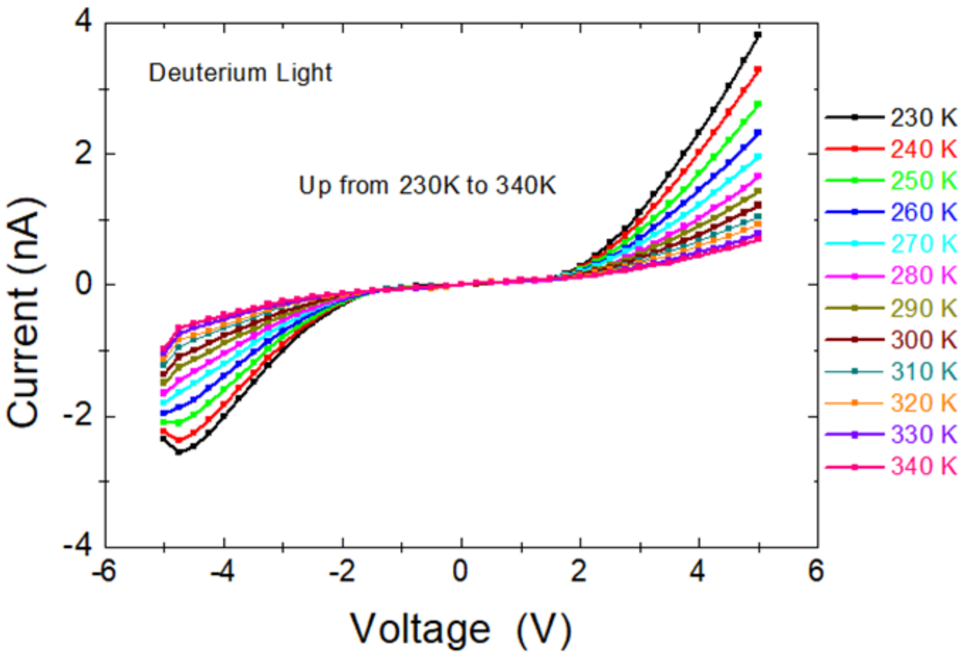
Temperature and current evolution as a function of the process time cycle.



Temperature changes are evolving in reverse to the current intensity.

Ghorbel, Damé et al. (2021)

Vacuum Tests

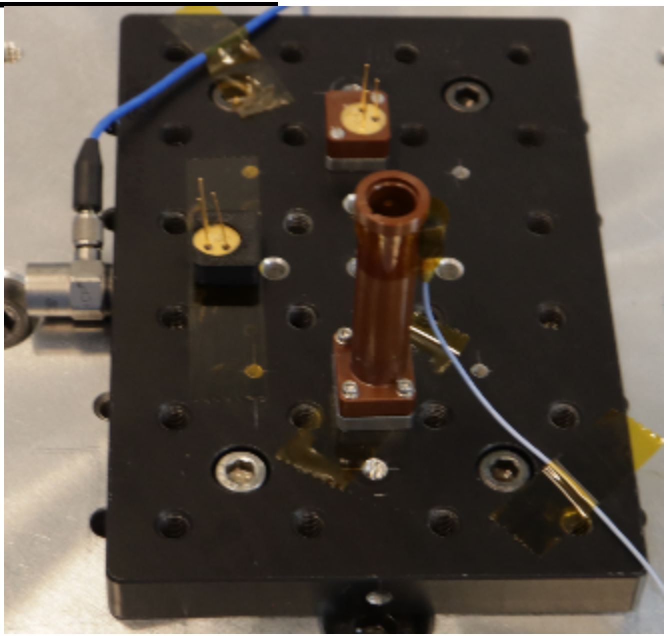


IV curves for different temperatures from 230 to 340k

Note that the photocurrent is largely reduced (3 V!) by a raise of the temperature

Mechanical tests

- **Shaker on DEVINS-L system** **(free extension)**
- **Shaker on similar system to UVS used on UVSQ-Sat**
- **Shaker on DEVINS-C system demonstrator**



- Search and control for resonances 5-2000Hz
- Resistance test for system bonding:
  20g @33Hz
- Acceleration measurement instead of detectors for DEVINS-L

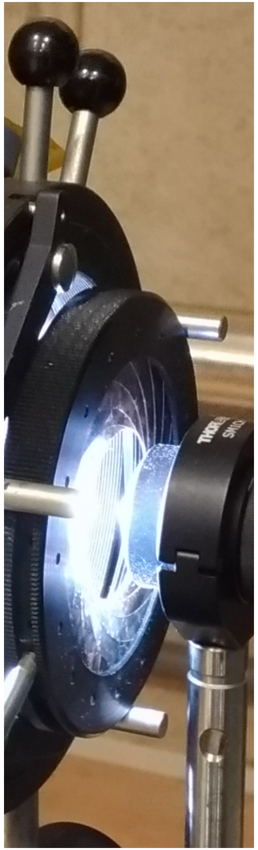
-> **successful**, no failure on detectors, same characteristics than before test.

Solar flux test and absolute calibration

Sensitivity of each sensor requires an absolute calibration.

The checking process on solar flux and other function checks require measurements in operation to prevent any failure and ensure compatibility with INSPIRE-SAT 7.

-> Tests to be done with IASB, Brussels, this Spring.



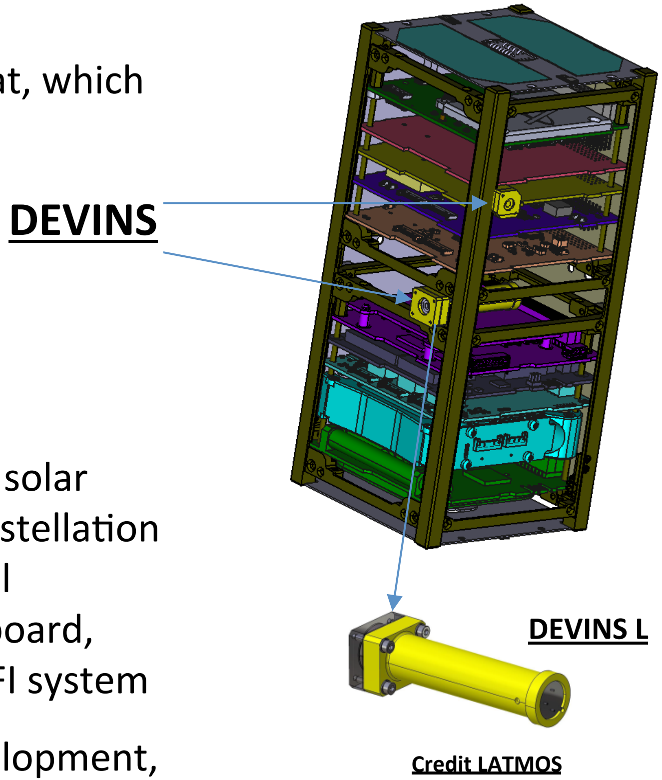
Compliance to Requirements

Parameter	Requirements	Compliance
DEVINS signal range	0 to 2.1 Wm^{-2} (200-242 nm) Target value: 1.4 Wm^{-2}	Yes
DEVINS peak wavelength	215 ± 5 nm	Yes on selected UVSng (9)
DEVINS FWHM	20 +10/-5 nm	30 ± 5 nm achieved
DEVINS rejection	10^{-4} 250 – 3000 nm	Better than 10^{-3} at 250 nm (dark not measurable)
DEVINS noise detection	< 30 pA for Devins-C <0.1 nA for Devins-L	< 5 pA but electronic challenge…
DEVINS time response	< 0.1 s	Rise time < **1 s** Fall time < 80 ms (further measurements expected)
Acquisition time	Better than 10 seconds	Yes (but pointing drift dependant: 1 s may be required for Devins-L)

Perspectives: the nanosatellite

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).
An application ranging from science to education.
This new CubeSat will be launched in 2023.



Three main objectives

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

Conclusions

- **DEVINS detectors are realized, spatialized, awaiting absolute calibration and integration in satellite but have established that scientific goal (±0.5% measurement uncertainty @1σ @215 nm) is potentially reachable for DEVINS-L detectors**
- **Process is still delicate mainly at the epitaxy level where PLD wafers lack homogeneity and reproductibility for a production stage (1% success?)**
- **Large improvements are expected from next generation of nanosatellites (3U & larger) or small satellites with stable & precise pointing and increased power (> 5V) => will achieve full potential of the DEVINS detectors: ±0.1% measurement uncertainty @215–220 nm**

LATMOS example study of a 3U Nanosatellite mission:
Solar **U**ltraviolet variability **P**ermanent monitoring of **E**arth Radiative **B**alance and **O**zone (**SUPERBO**) mission

Thank you for your attention

Questions?

Luc.dame@latmos.ipsl.fr