Reliability assessment of optoelectronic and photonic devices in severe environments: architecture and applications of the OpERaS consortium

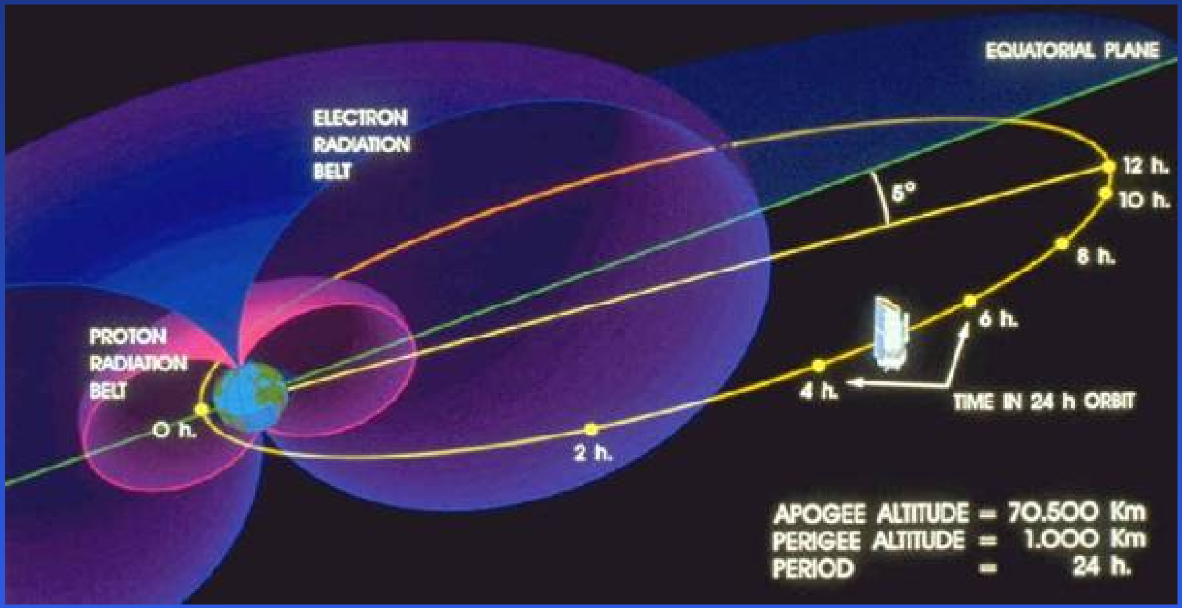
OpERaS : **Op**to-**E**lectronic **R**eliability **a**pplied to **S**evere environments

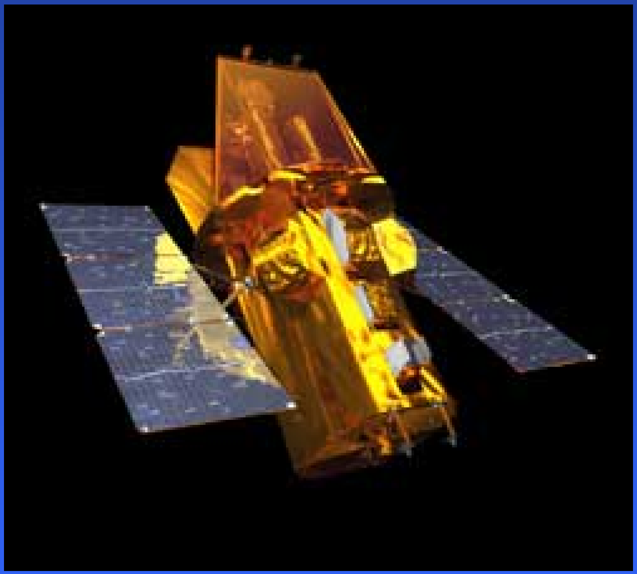
L. BECHOU, P. SPEZZIGU
Laboratoire IMS
University of Bordeaux 1
CNRS UMR 5218

phone : *+33 5 4000 2767*
laurent.bechou@ims-bordeaux.fr
piero.spezzigu@ims-bordeaux.fr

Space : an example of severe environments

RADIATIONS





+ HIGH THERMAL CYCLING : -160° C/+150°C
+ VACUUM (10^{-9} torr)
+ VIBRATIONS (± 10g)
+ ELECTROSTATIC DISCHARGE

Optoelectronic in space applications

Technologies :

- **Solid-State Lasers:** LIDAR, metrology, interferometer, atomic clocks…
- **Detectors** (X -> IR) **and fiber sensors:** T, P, mechanical stress
- **Optical links and interconnects:** Intra-&Inter-satellite, Inter-chip
- **Photonic Signal Processing, Non-linear optics:** optical data storage, µwave generation, MOEMS.

Source : Courtesy of Lumics GmbH, Berlin

Applications :

- **Astronomy / Planetary Exploration, Fundamental Science**
- **Earth Observation, Remote Sensing**
- **Telecom - Navigation**
- **Space Transportation**
- **ISS**

Source : E. Armandillo, Space Optoelectronic Day, Cork, 2006

Evaluation/Qualification strategy and feed-backs (1/3)

- **General strategy**
  - tests according to MIL, Telcordia or electronic-related ESCC standards

- **Huge constraints**
  - **Cost reduction**
    - small number of device per test groups
    - few characterisation steps and few number of electro-optical parameters measured
  - **Tight time schedule**
    - not enough time between reference selection and FM procurement
    - evaluation phase are more and more avoided
  - **Small procurement volume** (i.e. few tens of devices)
    - Insufficiently attractive for COTs manufacturers
  - **Specific environments** (i.e. radiation, vacuum, high temperature range)
  - **Few amount of reliability data** (especially true for custom devices or low volume productions)

Evaluation/Qualification strategy and feed-backs (2/3)

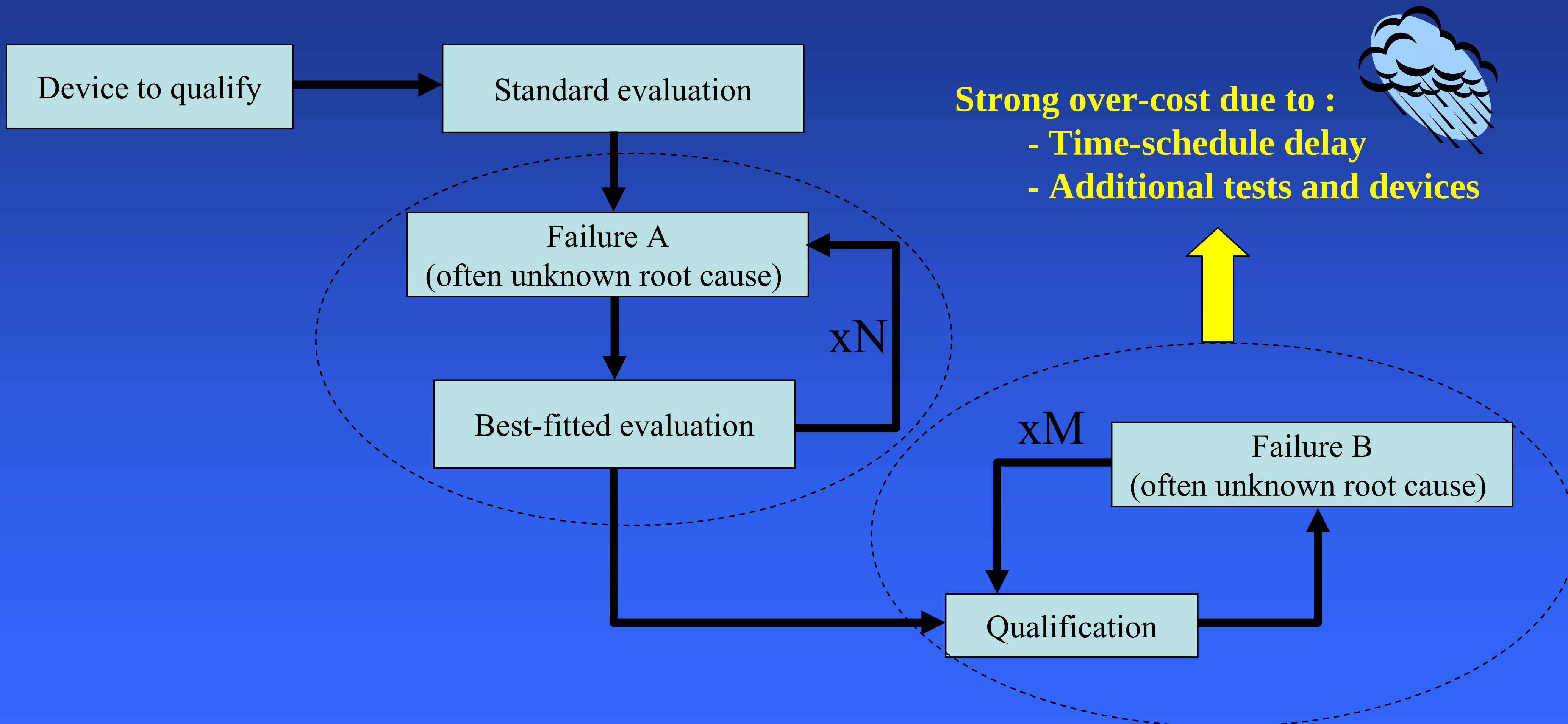
- **Feed-backs**
  - Standard tests are generally not well-fitted for the devices
  - Due to the small number of devices the objectives of the evaluation/qualification phases are not obvious

    (Could we rely on these tests to guarantee the reliability of the device during the space mission ? How could we prove it ?)
  - Difficulty to find companies that could take in charge evaluation/qualification tests

    (The manufacturers are not always interested due to the low procurement volume)
  - Many anomalies during evaluation or qualification phases
  - Difficulties to identify physical root causes and prediction of operating lifetime is traditionally extracted from empirical laws using classical methodologies ($t_{50\%}$, *MTTF…)*

Evaluation/Qualification strategy and feed-backs (3/3)

THE "VICIOUS" CIRCLE FOR COTs DEVICES RELIABILITY !



European space industry needs expression (2/2)

Round table "Main issues to be solved" - 12 may 2006
Workshop "Laser Diodes for Space Applications" (CNES Toulouse-France)

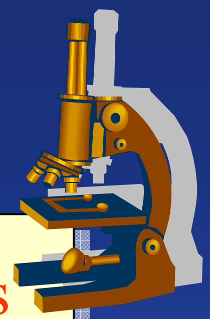
CHARACTERISATION

- Qualifiation procedures and characterisation methods should be outlined,
- Where can we characterise\qualify our components?
- Failure analysis: where and which methods?
- Tests of hermeticity how to perform it and does it change our qualification?
- Database with history of failure analysis!
- Database for qualified (including radiations) products (COTs especially)
- COTs and procedure changes (lot)
- How to compute MTTF : guidelines needed
- Same for upscreening

General objectives of OpERaS

- Scientific and technical Consortium between IMS Laboratory (University Bordeaux 1), AdvEOTec (French SME) and THALES Information Security System set up in 2007
- High synergy between industrial and academic expertises
- Establish a network of knowledge and experience (at European level)
- Data capitalization (AdvEOTec – Eurelnet/IMS) depending on cooperative agreement level & NDA (respect to industrial or R&D benefits)
- Driving force for implementation of new characterization techniques
- Implementation of new approaches for reliability prediction in space environments (mixing physical failure analysis and statistical approaches)

OpERaS added-value proposition



First design

Failure Modes and Effects Analysis

Technological weakness points identification
(semiconductor, assembling processes)

Evaluation
"Safe" qualification area assessment

Qualification test conditions

Customized qualification

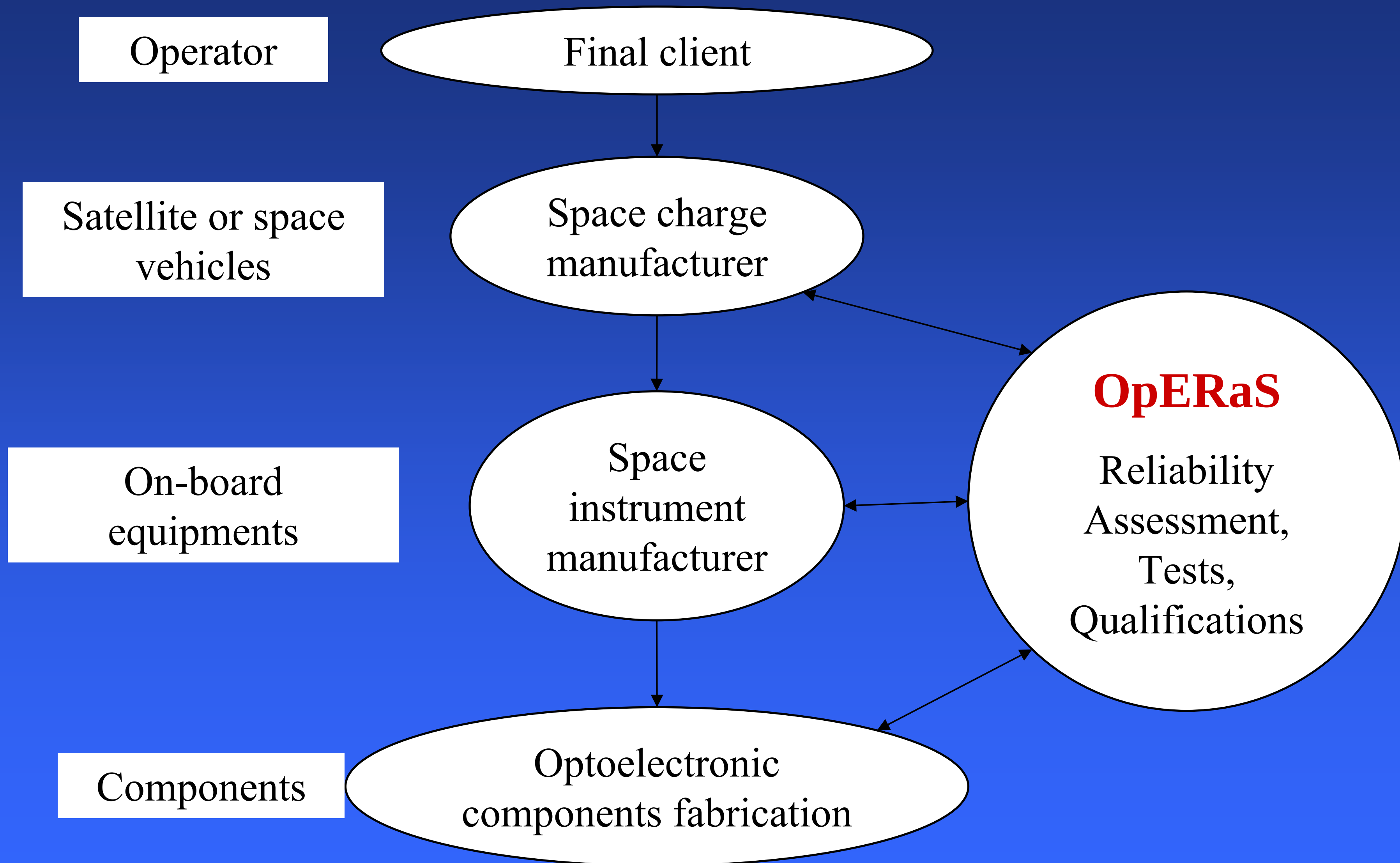
Reliability prediction

ims BORDEAUX

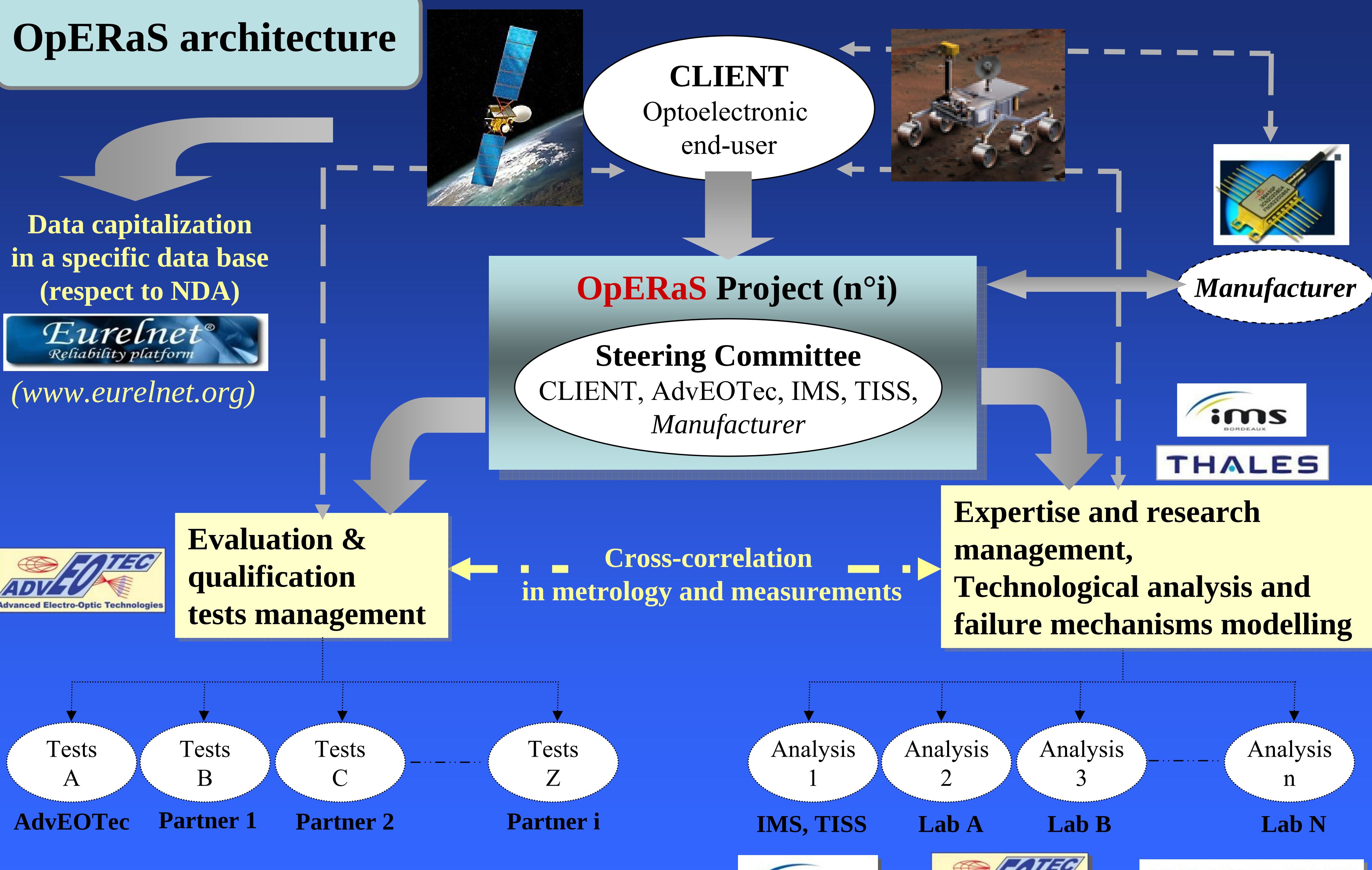
ADVEOTEC Advanced Electro-Optic Technologies

THALES

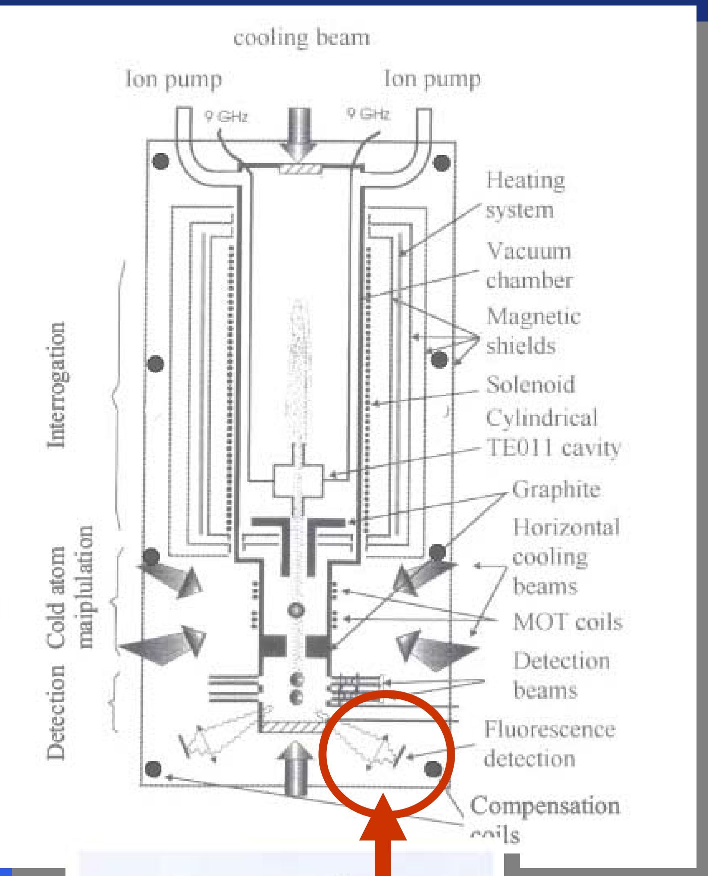
OpERaS value chain

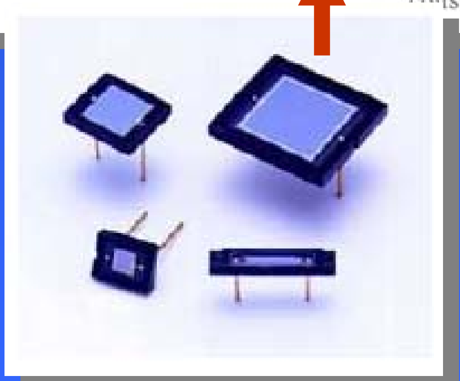


OpEPRaS architecture

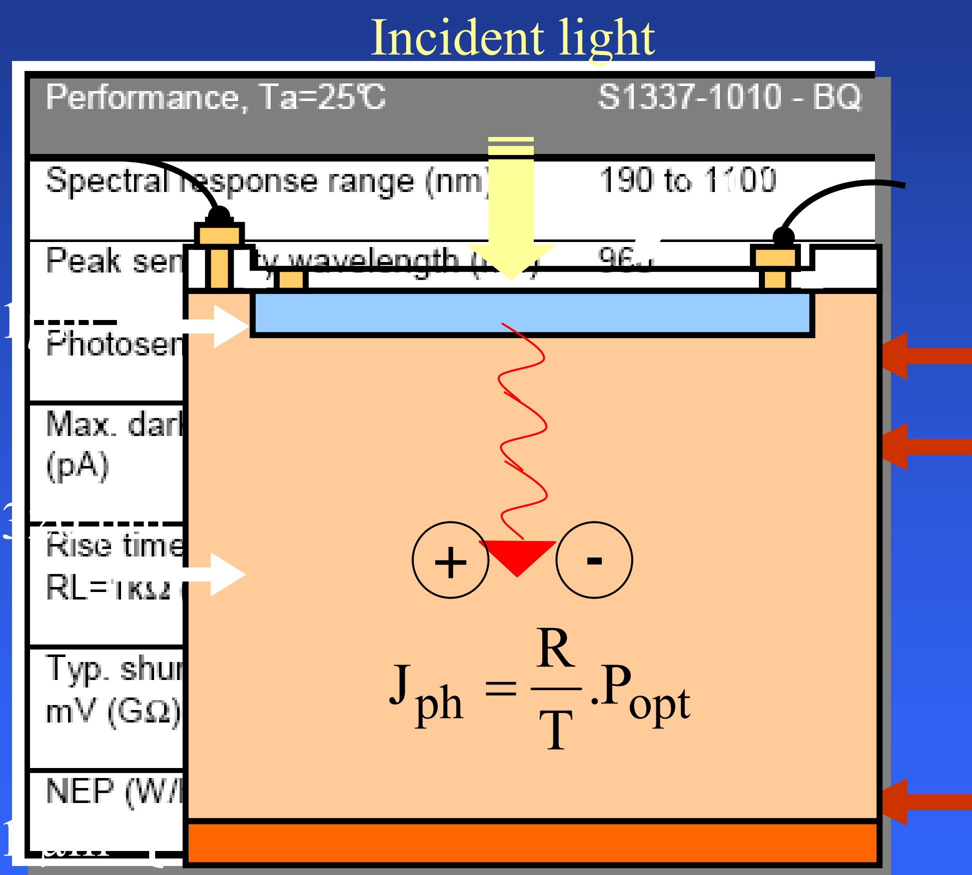


GALILEO Project : Study of 850nm silicon photodiodes degradation under radiation effects :
Gamma (ionizing dose), Protons (displacement dose)



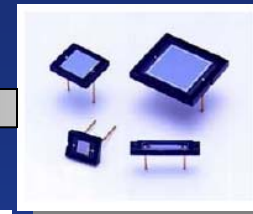


S1337 BQ/BR
Hamamatsu
(detection, dosimetry)



$$J_{ph} = \frac{R}{T}.P_{opt}$$

Project organization example (1/2)



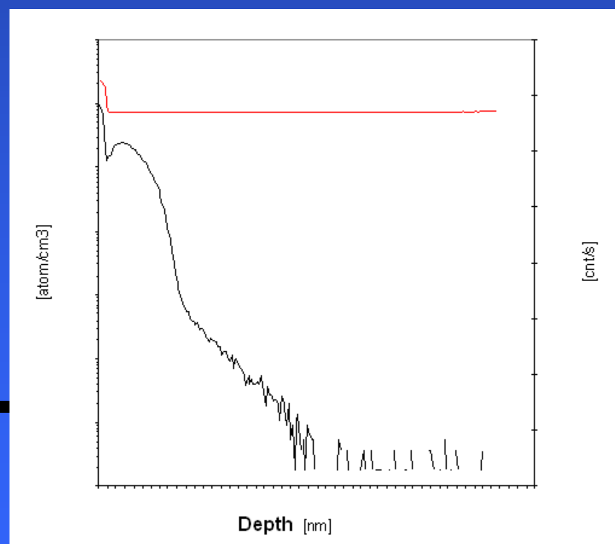
Client : CNES
Selected component:
PIN 850nm Si photodiode (COTs)
Application : Galileo (atomic clock)

Initial characterizations (I-V, S-λ, Linearity, NEP)

Pre-evaluation phase (radiation effects)

Modelling

Bibliography
Failure mechanisms
Operating lifetime



Ex. SIMS profile in P^+ zone
(extraction of dopants concentration)

Initial characterizations (I-V, S-λ, Linearity, NEP)

"Light" Pre-evaluation phase

Qualification phase

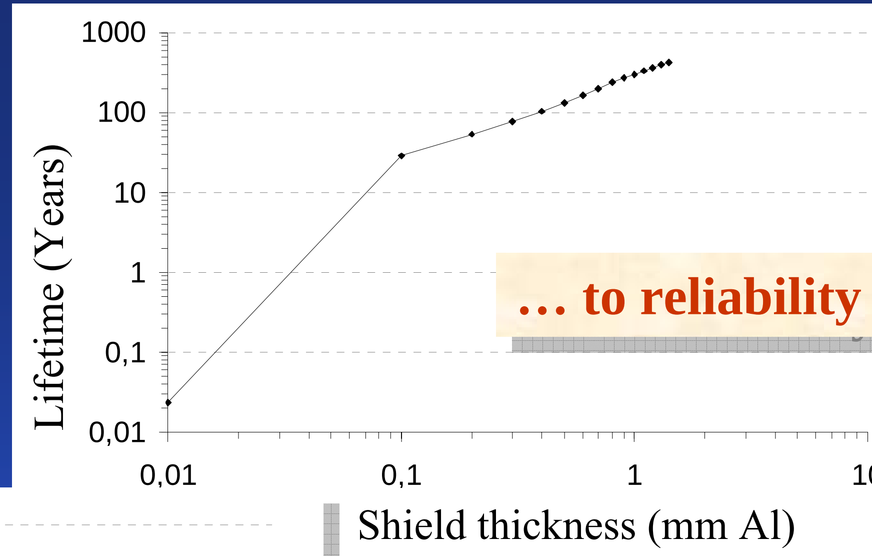
Project organization example (2/2)

$$L = \sqrt{D.\tau}$$

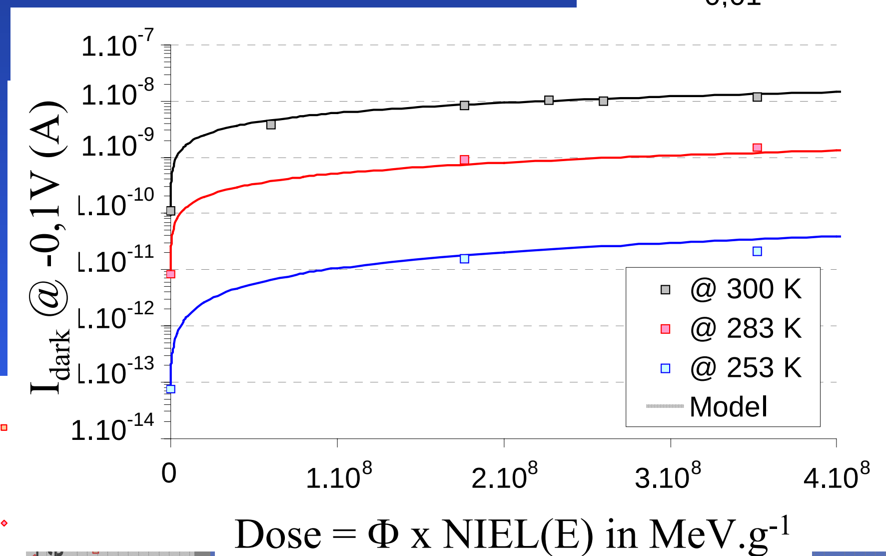
$$\frac{1}{\tau_{irrad}} = \frac{1}{\tau_{init}} + k_{g,d}.[D_d]$$

$$J_{dark(d)} \approx \frac{qn_i^2}{N_D} \cdot \frac{D_p}{\sqrt{D_p \tau_p}} \cdot \left(\exp\left(\frac{qV}{kT}\right) - 1 \right)$$

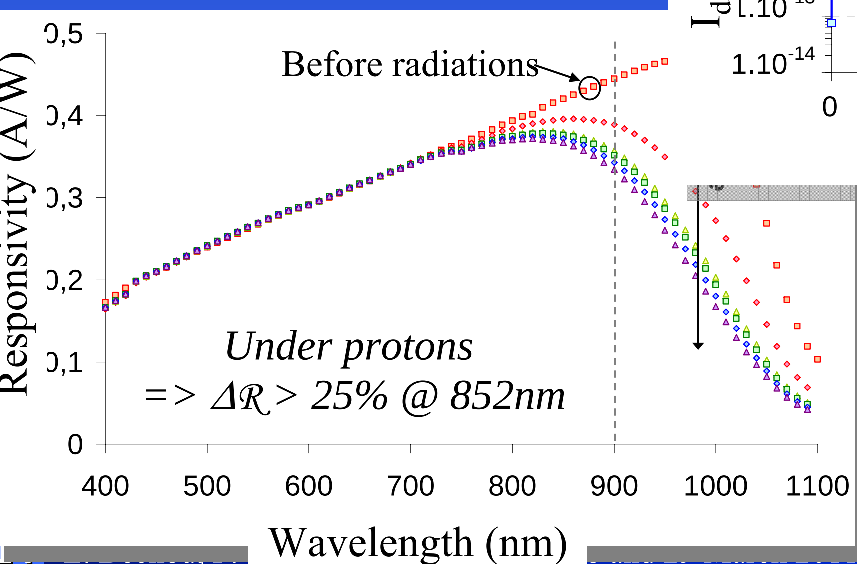
$$J_{dark(g)} \approx \frac{qn_i}{2\tau_g} \sqrt{\frac{2\varepsilon}{qN_D}(V_s - V)} \cdot \frac{\exp\left(\frac{qV}{kT}\right) - 1}{\exp\left(\frac{qV}{2kT}\right) + 1}$$



… to reliability



Results published at ESREF 2008 (Maastricht) and in JAP, Vol. 105, Issue 2, 2009



From physical failure mechanisms…

Other projects carried out or in progress in OpeRAs (1/2)

- CHEMCAM project (2006-2007): Reliability of FP 0.78µm Laser diode :
  CNES/AdvEOTec-IMS
- Reliability of Si phototransistors (2007-2010) : CNES/IMS-Univ. Cagliari (1 PhD defended)
- Evaluation of 0.98µm pump Laser diode for space applications (2008-mid 2010):
  CNES/AdvEOTec-IMS-TISS/3SPhotonics (1 PhD supported)

On-going projects :

- Evaluation of 1.55µm DFB Laser diode for space applications (2009-mid 2011)
  CNES-ASTRIUM-Thales Alenia Space/AdvEOTec/3SPhotonics
- Reliability assessment of commercial optocouplers (2009-2010)
  CNES/AdvEOTec-IMS/Micropac (USA)
- Failure analysis of 1.55µm Laser diodes under EOS/ESD tests (2009-mid 2011)
  CNES/AdvEOTec-IMS-TISS/3SPhotonics

Other projects carried out or in progress in OpeRAs (2/2)

Funded projects for 2011:

- New generation of spectral-resolved cathodoluminescence imaging system for failure analysis investigations on photonic devices (2011-2013) : CNES/IMS-INSA
- New architecture of rad-hard optocoupler using VCSEL technologies (2011-2012) : CNES/IMS-IES
- ESD effects on low-frequency noise of 980nm pump Laser diode (2011) : IMS-IES/3SPhotonics

In submission projects :

- Embedded passive devices in multilayer PCBs for high-frequency applications: innovative materials and in-situ thermomechanical stresses optical monitoring (IMS/AdvEOTec/Polyrise - EDA Projects and Programmes – ITP SIMCLAIRS in evaluation)

ims BORDEAUX ADVEOTEC Advanced Electro-Optic Technologies THALES

Electrical and optical characterization test benches at IMS

Emitters

Cryogenic bench
L-λ, P-I,
Far-field
(chip on submount)

Photodetectors

CW & pulse I-V, P-I
t_r, t_f, C-V

Δλ, RIN, Chirp,
frequency
modulation
measurement
(Fiber Laser diode)

Spectral sensitivity,
CTR, linearity and
Gummel-plot

OpeRAs partners

Companies and agencies

- cnes
- ThalesAlenia Space
- ASTRIUM – AN EADS COMPANY

Consulting experts

- 3S PHOTONICS
- Quantel laser diodes

SMEs

- Optoi Group
- TRAD Tests & radiations
- POLYRISE
- GESEC R&D Inc. Semiconductor Materials Engineering

Academic

- Xlim
- Université de Nantes
- INSA Toulouse
- Dee
- McMaster University

Core partners

- ims Bordeaux
- ADVEOTEC Advanced Electro-Optic Technologies
- THALES

COD in 0.98µm Laser diode under vacuum

Long term in-vacuum ageing of 980 nm laser diode pump modules for space applications

G. Pedroza[1], L.S. How[1], L. Bechou[2], O. Gilard[3], J.-L. Goudard[4], C. Nissim[4]
+33 (0)1 60 86 43 61 - gpedroza@adveotec.com

[1]AdvEOTec, Lisses, France
[2]IMS Laboratory, University of Bordeaux I-ENSEIRB-CNRS UMR 5218, Talence, France
[3]Centre National d'Etudes Spatiales, Toulouse, France
[4]3S Photonics, Nozay, France

ISROS 2010, Cagliari (Italy)

- Experimental procedure -

8 components : 4 sealed and 4 punctured
→ accelerate long high vacuum exposition

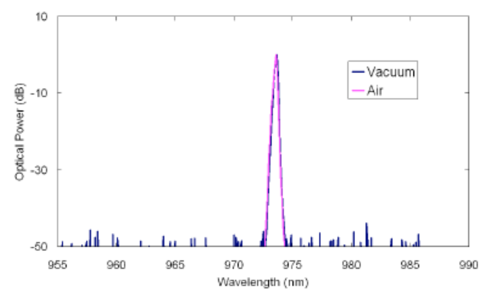
New dedicated bench : AdvEOVac

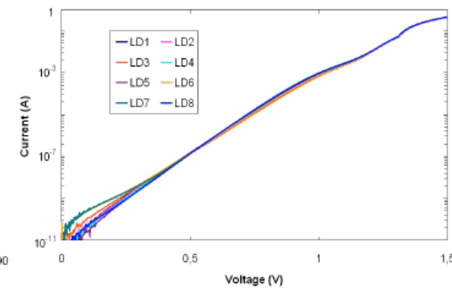
- Temperature, pressure, current, voltage, optical power and monitoring photodiode current in-situ, real time measurements
- Mass spectrometry control
- Residual pressure : 10^{-9} torr

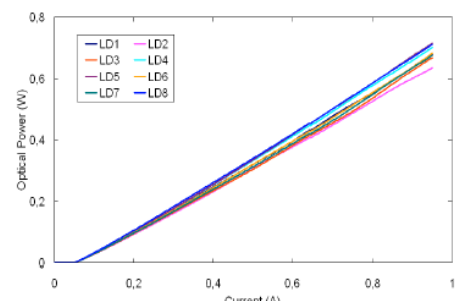
L-I, Q-I, V-I and low-level I-V characterisations in air and in vacuum (initial, intermediate, final)

Ageing conditions : 10^{-7} torr, 60°C and 800 mA (→500 mW/device) during 5000 h deduced from step-stress analysis

- Initial electro-optical characteristics -



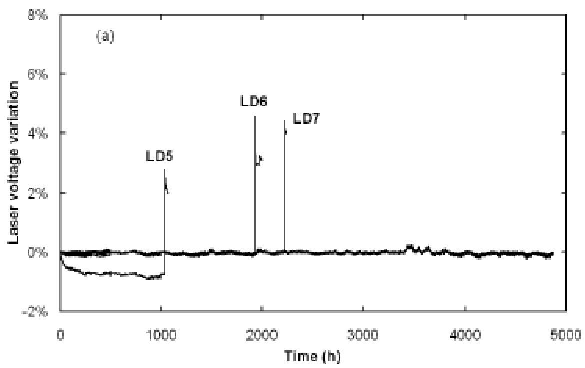


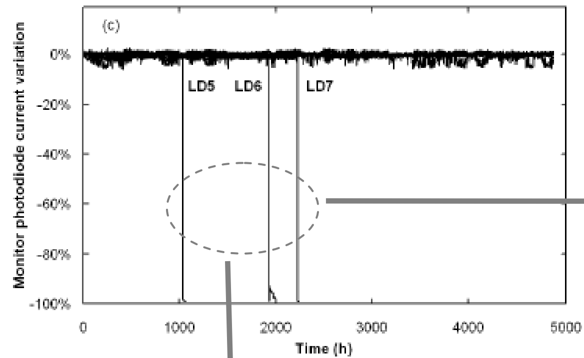


At -8°C, 25°C and 65°C in air and vacuum
No difference found

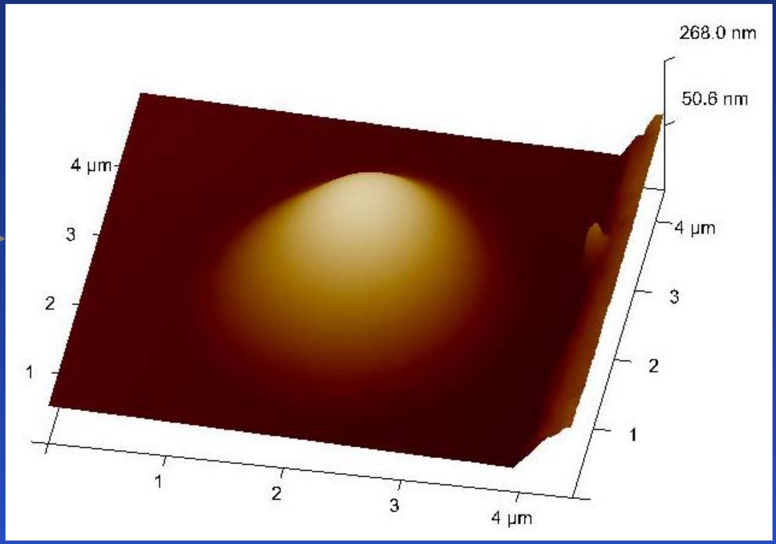
ims BORDEAUX ADVEOTEC Advanced Electro-Optic Technologies THALES

- In-situ tracking -

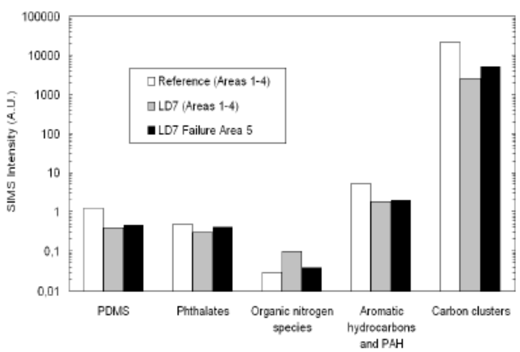




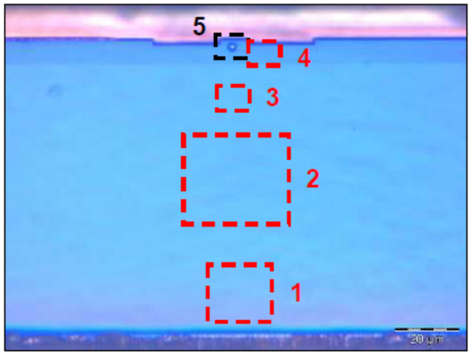
AFM imaging on COD (CRPP, Bx)



- ToF-SIMS analysis -



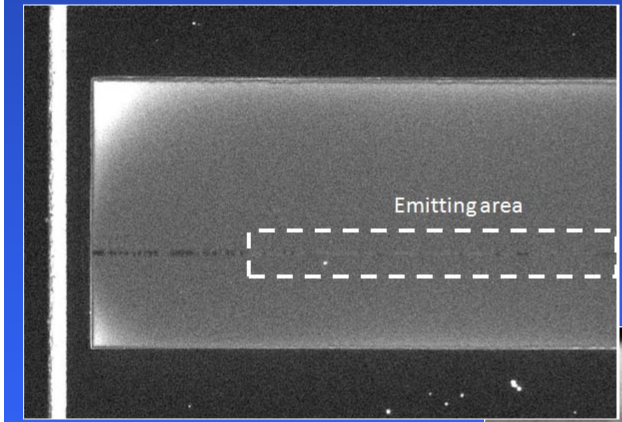
Areas analyzed



No contamination evidence
No package-induced failure

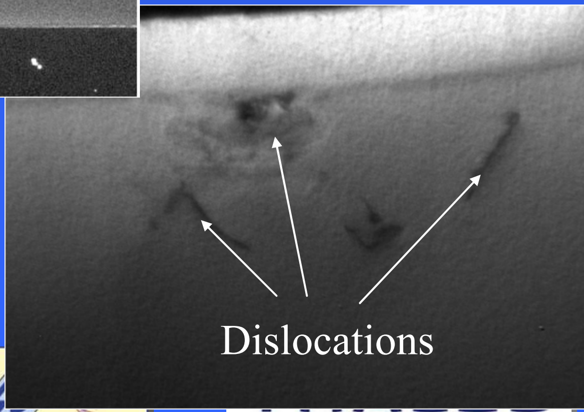
➡ **Failure mechanism specific to vacuum operation**

No failure observed on sealed components : **package hermeticity is critical**

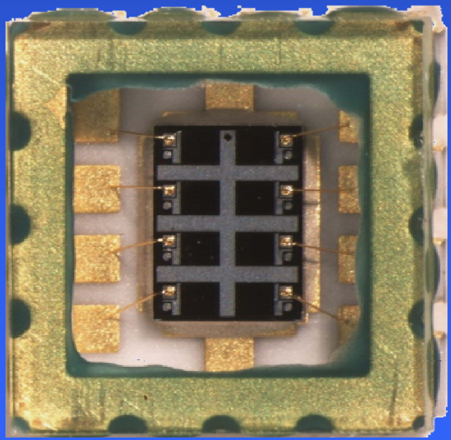


CL imaging (THALES ISS)

TEM imaging (THALES ISS)



An original DoE-based tool for silicon photodetectors EoL estimation in space environments



Statistical Design of Experiments (1)

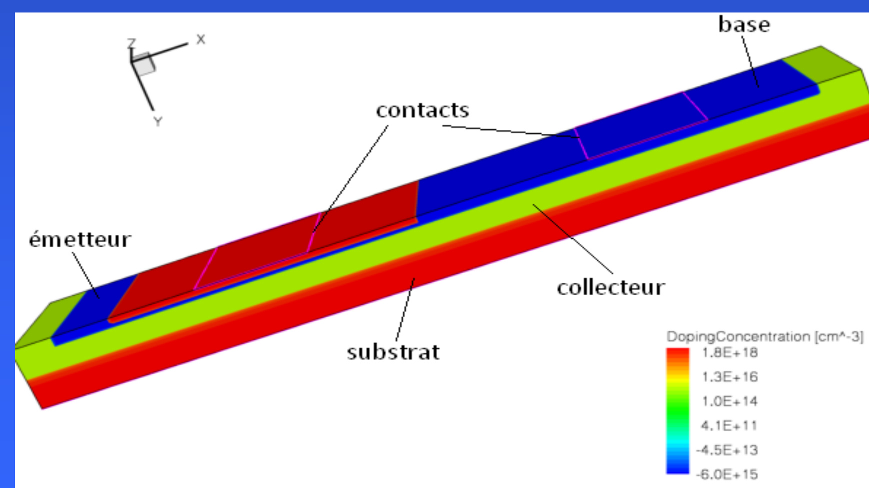
Issues in **phototransistors** degradations in space environment physical modeling approach:

- Needs high knowledge on devices and degradation physics
- Models will become very complex
- Technology dispersion is difficult to be taken into account
- In most of cases is not possible to extract all needed parameters
- Testing activity becomes onerous and may not cover all operating life conditions (i.e. space mission profiles)

$$I_{nE}(V_{BE}) := \frac{q \cdot A_{E.B} \cdot n_{i.lit}^{2} \cdot D_B \cdot \left(e^{\frac{V_{BE}}{V_T}}\right) \cdot \coth\left(\frac{W_B - W_{PB2}(V_{BE}) - x_{Bc}}{L_B}\right)}{L_B \cdot Na_B}$$

$$I_{nC\_hi}(V_{BE}) := \frac{q \cdot A_{E.B} \cdot n_{i.lit}^{2} \cdot D_B \cdot \left(e^{\frac{V_{BE}}{fid2(V_{BE}) \cdot V_T}}\right)}{L_B \cdot Na_B \cdot \sinh\left(\frac{W_B - W_{PB2}(V_{BE}) - x_{Bc}}{L_B}\right)}$$

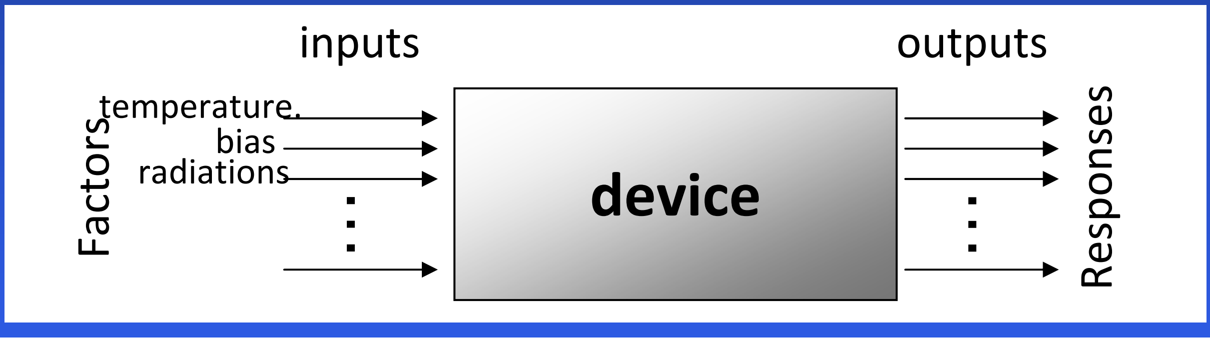
$$I_{nC}(V_{BE}) := \frac{q \cdot A_{E.B} \cdot n_{i.lit}^{2} \cdot D_B \cdot \left(e^{\frac{V_{BE}}{V_T}}\right)}{L_B \cdot Na_B \cdot \sinh\left(\frac{W_B - W_{PB2}(V_{BE}) - x_{Bc}}{L_B}\right)}$$



Statistical Design of Experiments (2)

Design of Experiment (DoE) could be used to foresee device degradations towards potential missions

Design of Experiments is a structured, organized method for determining the relationship between factors affecting a device characteristic and the characteristic itself



- Does not need knowledge in devices physics – *"black-box" approach*
- Basic knowledge in TID and DDD effects
- Models are based on a pre-defined polynomial function of degradation factors
- Technology dispersion could be taken into account
- Could be easily extended to other devices and technologies

Study Domain definition (1)

TID and **DDD**: the experimental damage factors

The study domain boundaries depend on test facilities capabilities:

$$0.1 \text{ krad} \leq TID \leq 100 \text{ krad}$$

$$10^{6} \text{ MeV/g} \leq DDD \leq 10^{9} \text{ MeV/g}$$

Proton energies: 184MeV and 30MeV

TID and DDD deposition with γ-rays and protons irradiation → TID is also deposited by proton irradiation

The Domain in which the couple (TID,DDD) could be deposited with **only proton** irradiation is defined by (using a logarithmic scale):

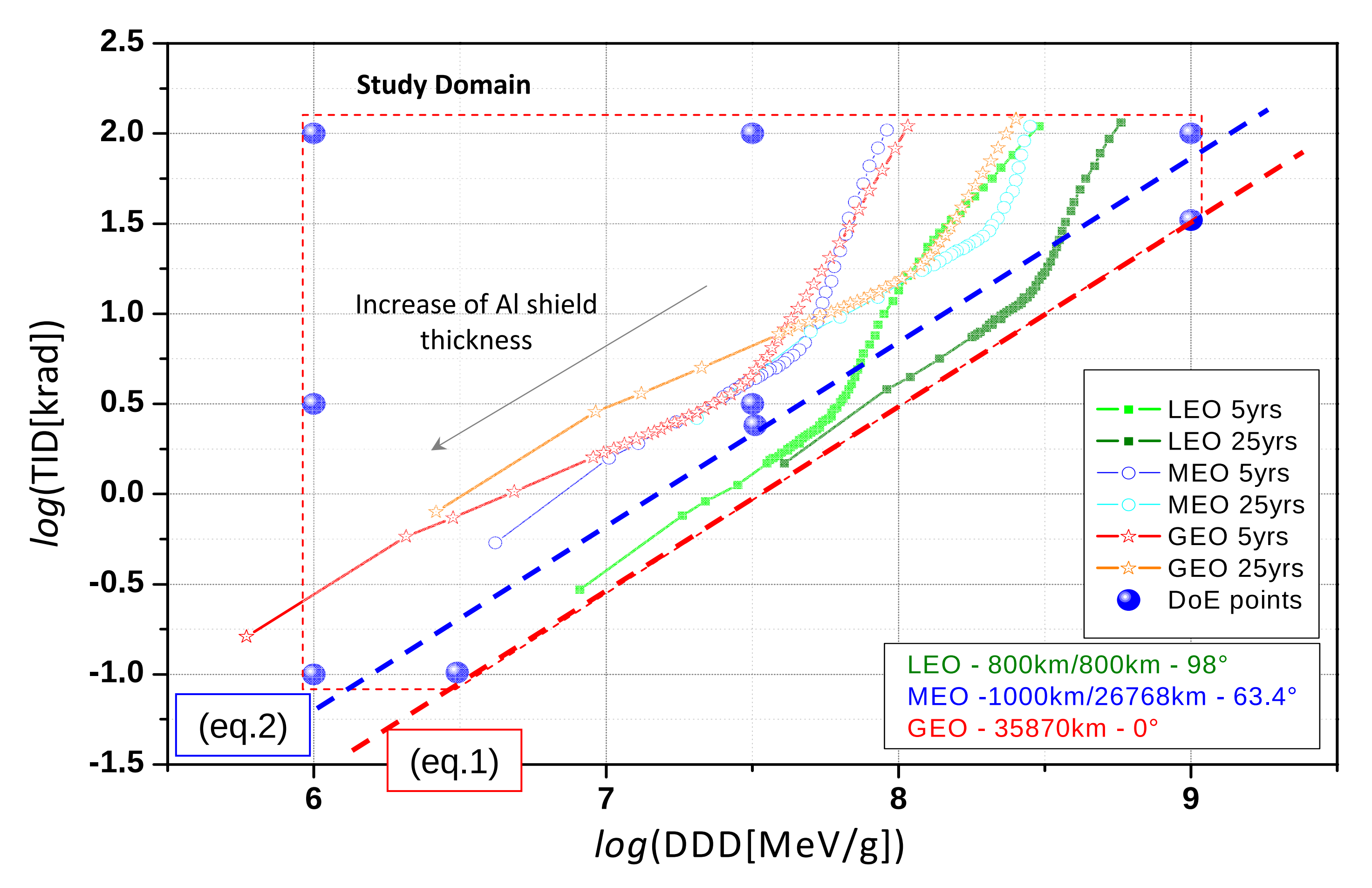
$$(1)\ \log(TID) \geq \log(LET(184)) + \log(1.6 \cdot 10^{-11}) - \log(NIEL(184)) + \log(DDD)$$

$$(2)\ \log(TID) \leq \log(LET(30)) + \log(1.6 \cdot 10^{-11}) - \log(NIEL(30)) + \log(DDD)$$

Study Domain definition (2)

Empirical explorative approach – Design of Experiments (4)

- **Study Domain**
- TID&DDD for different GEO/MEO/LEO mission profiles (OMERE)
- Experimental points given by a DoE software and based on a “optimality criterion”



ims BORDEAUX

ADVEOTEC Advanced Electro-Optic Technologies

THALES

Polynomial response definition

Pre-defined *Response* function :

$$R(x,y) = Z0 + A\cdot x + B\cdot y + C\cdot x^2 + D\cdot y^2 + F\cdot x\cdot y$$

where $x=\log(DDD)$ and $y=\log(TID)$.

$\boldsymbol{R(x,y)}$: response of interest *(i.e. photocurrent, darkness current, or Sp. Responsivity)*

B=Z0,A,B,C,D,F *:* the **unknown coefficients** of the polynomial.

→ 9 Equations (for 9 experiments) and 6 unknown system:

$$R_{exp} = X \cdot B \quad \Rightarrow \quad B = \left(X^T \cdot X\right)^{-1} \cdot X^T \cdot R_{exp}$$

Experimental Results (1)

Irradiation sessions: “OFF” and “ON”

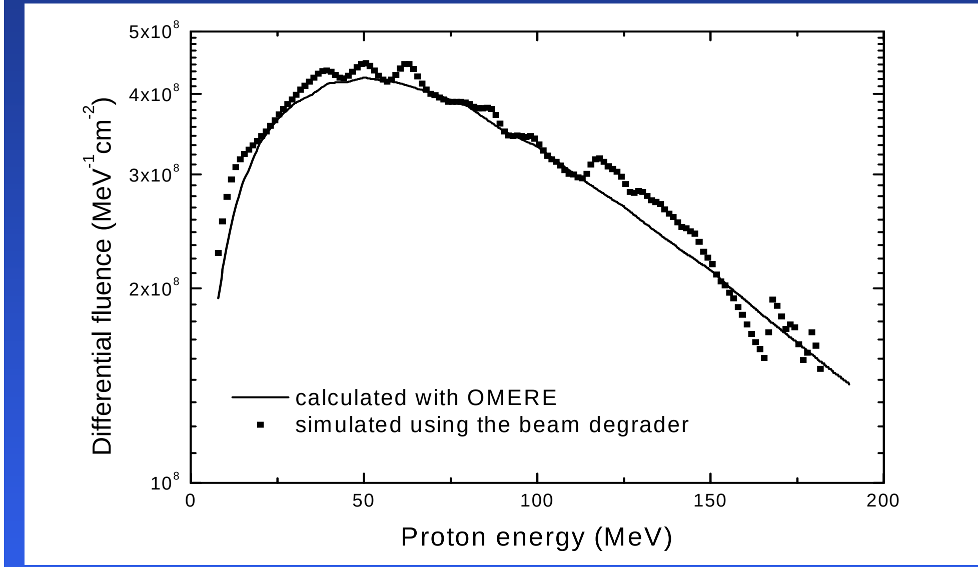
Responses:

- Photocurrent
- Darkness current
- Spectral Responsivity

Methodology validation:

Beam degrader **target** mission simulation

800km – LEO – inclination of 98° – 7mm-thick spherical Al shield. Duration: 18 years



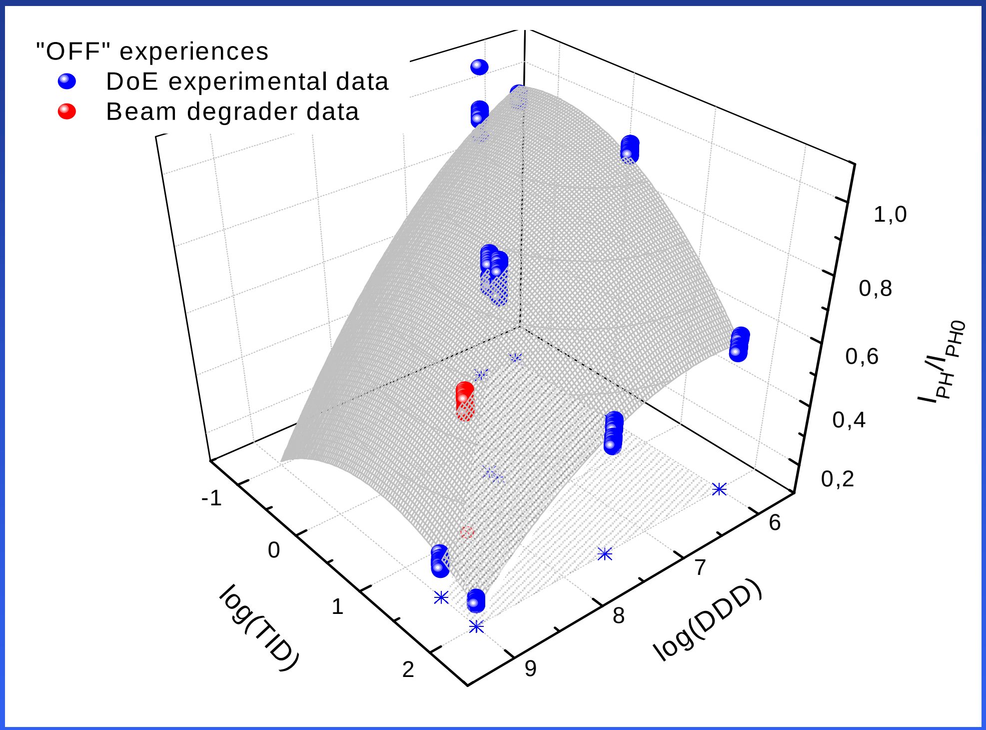
The target DDD and TID are: ***1.8•10^8*MeV/g** and ***9.32*krad(Si)**

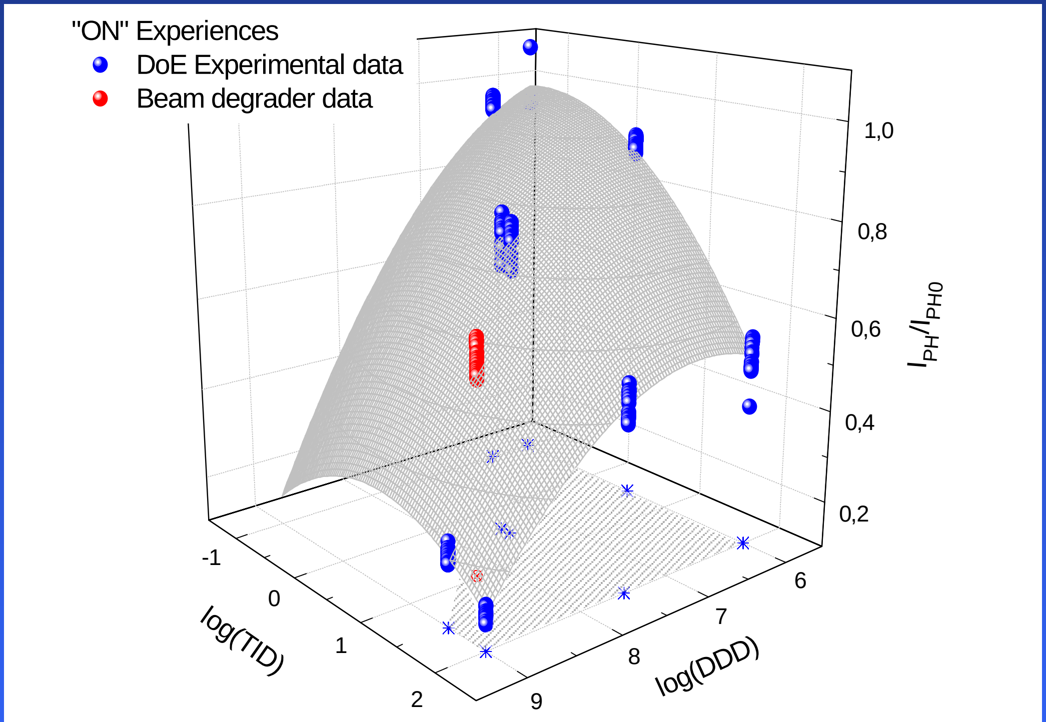
corresponding logarithm values: *8.2553* (log(DDD)) and *0.9694* (log(TID))

NB: Dose Rate Sensitivity evaluation: **not relevant**

Experimental Results (2)

Normalized photocurrent: I_{PH}/I_{PH0}





Predicted value:

$$I_{PH} / I_{PH0}(8.2553, 0.9694) = 0.531$$

Predicted value:

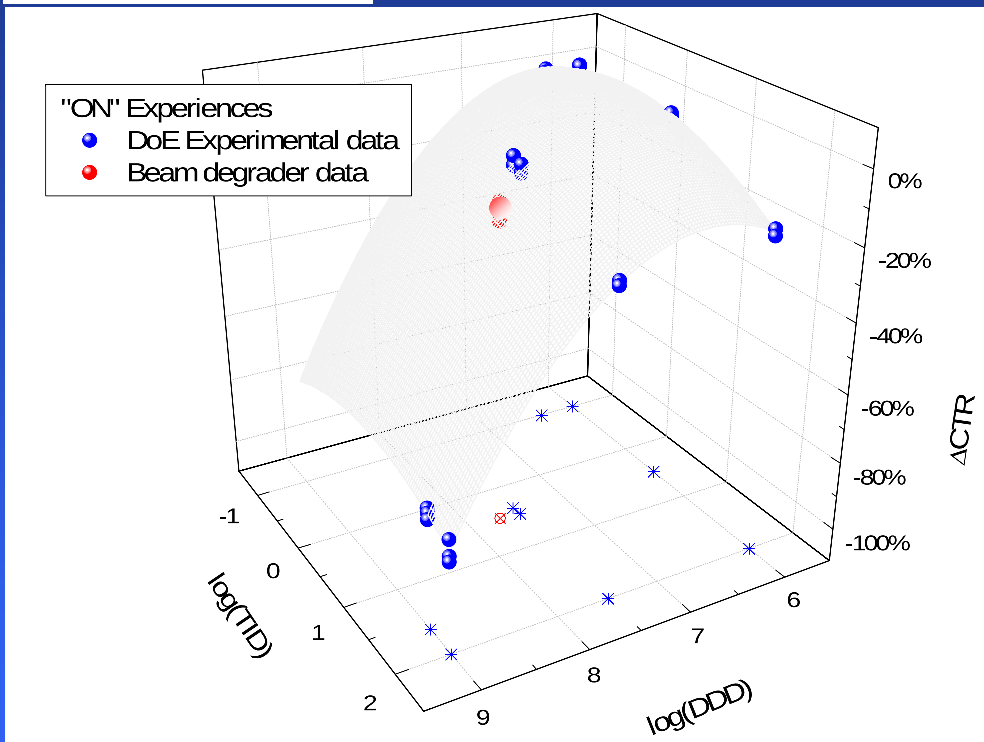
$$I_{PH} / I_{PH0}(8.2553, 0.9694) = 0.5219$$

Predicted values in agreement with Beam Degrader simulation

Experimental Results (3)

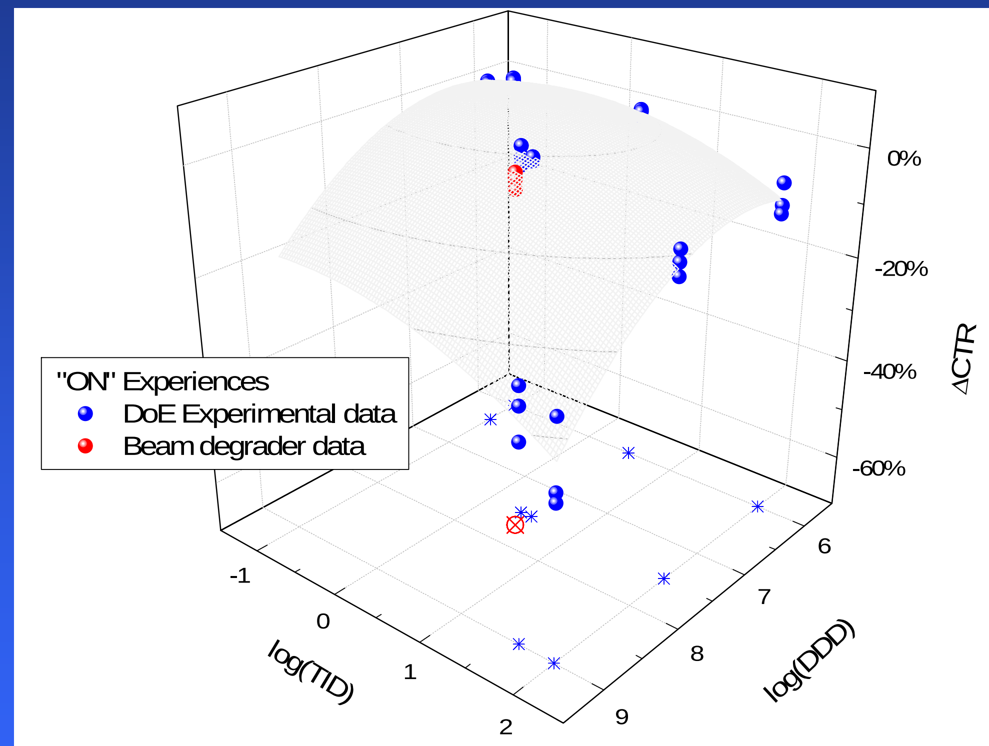
Optocoupler CTR degradation

Type 1 (non rad-hard)



Predicted value: -14%

Type 2 (rad-hard)



Predicted value: -2%

Predicted values in agreement with Beam Degrader simulation

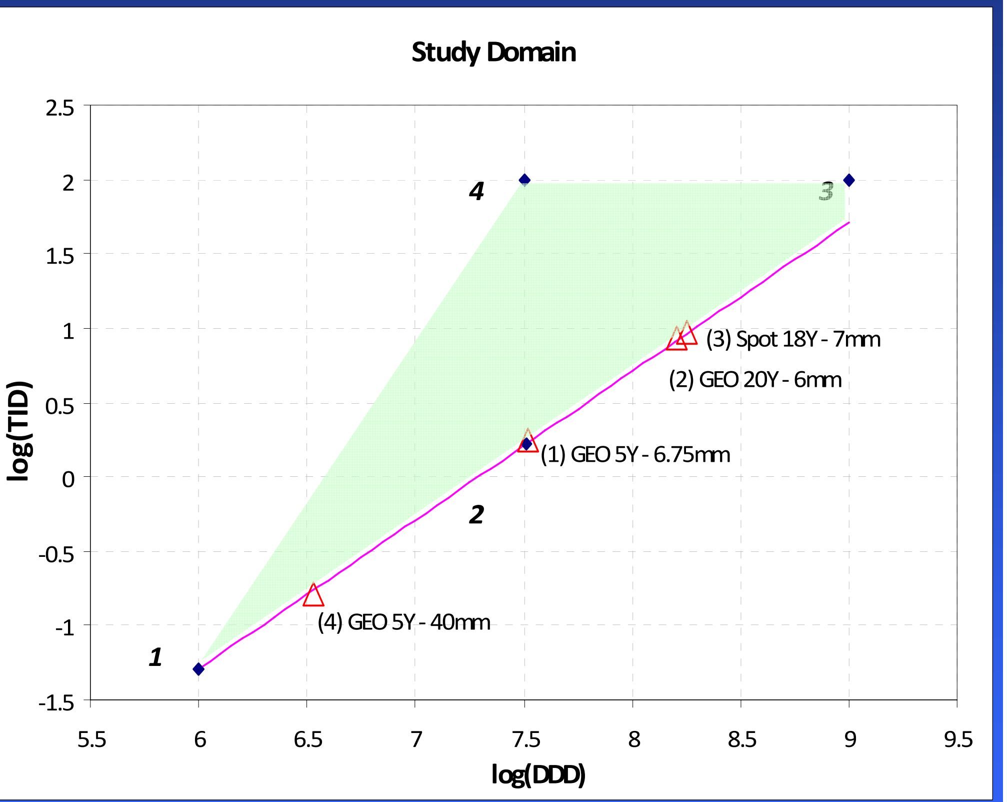
ims BORDEAUX

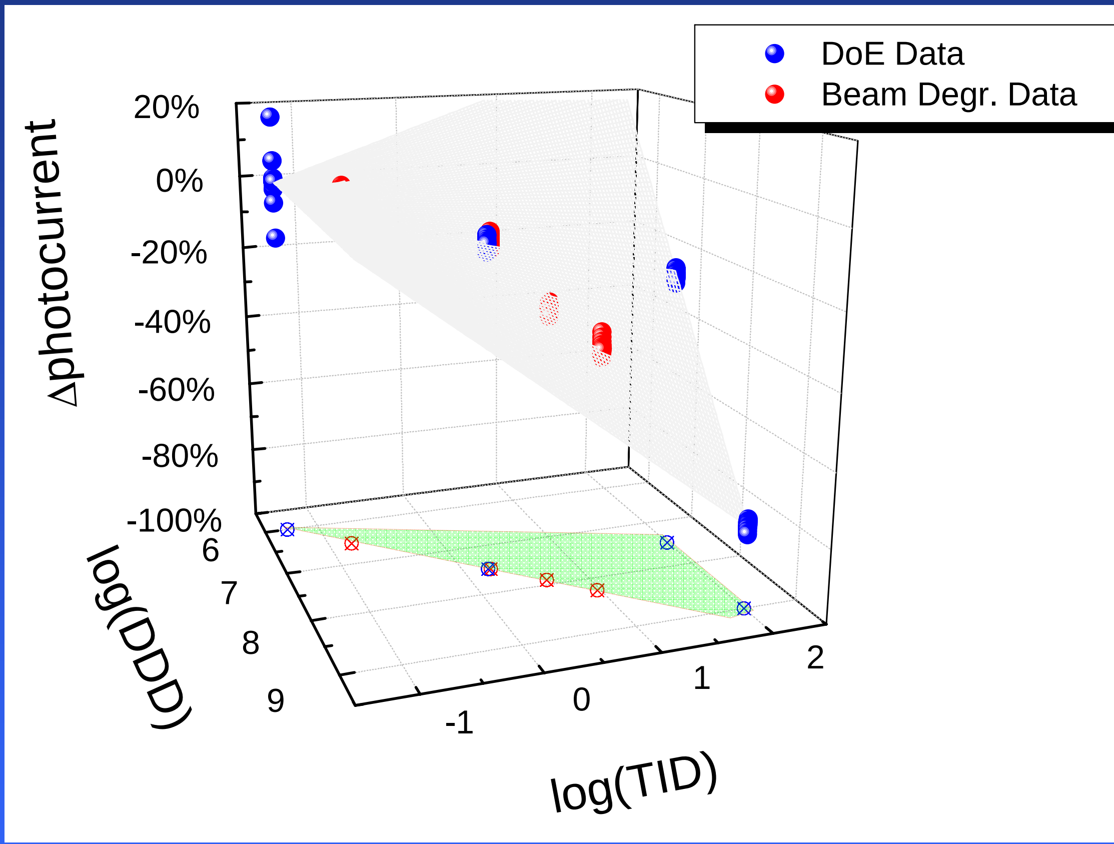
ADVEOTEC Advanced Electro-Optic Technologies

THALES

Experimental Results (4)

Reducing number of experiments



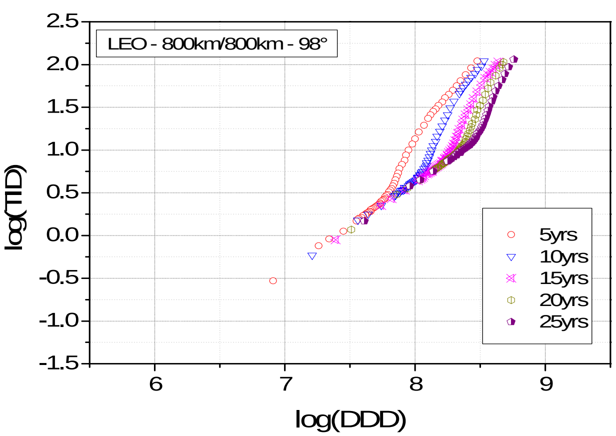


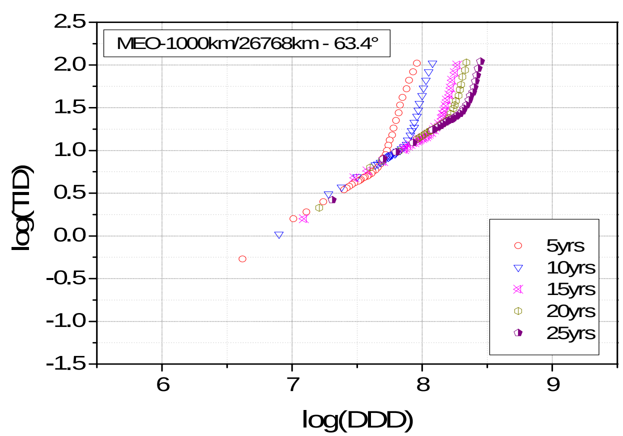
Predicted values in agreement with Beam Degrader simulation

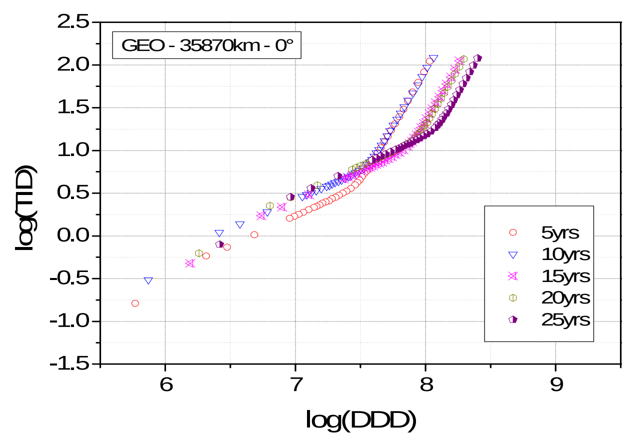
Exploiting DoE data (1)

From OMERE database: ionizing and displacement doses for different mission profiles

	Perigee	Apogee	Inclination	Period	# of orbits
LEO (Low Earth Orbit)	*800*km	*800*km	*98°*	*6043*s	*100*
MEO (Medium Earth Orbit)	*1000*km	*26768*km	*63.4°*	*28689*s	*300*
GEO (Geostationary Earth Orbit)	*35870*km	*35870*km	*0°*	*86400*s	*1*







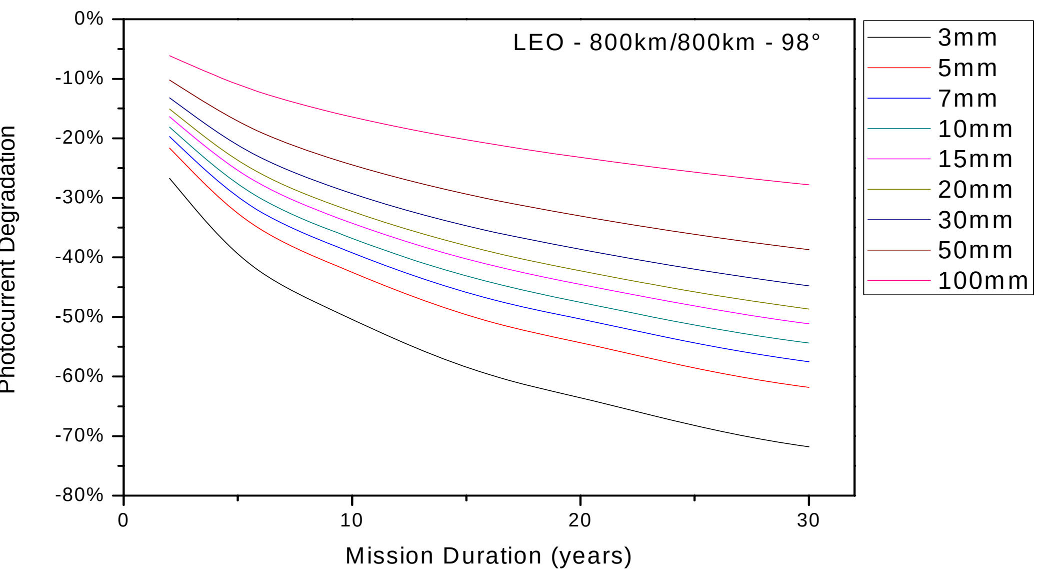
Extracted photocurrent polynomial from "ON" irradiations results:

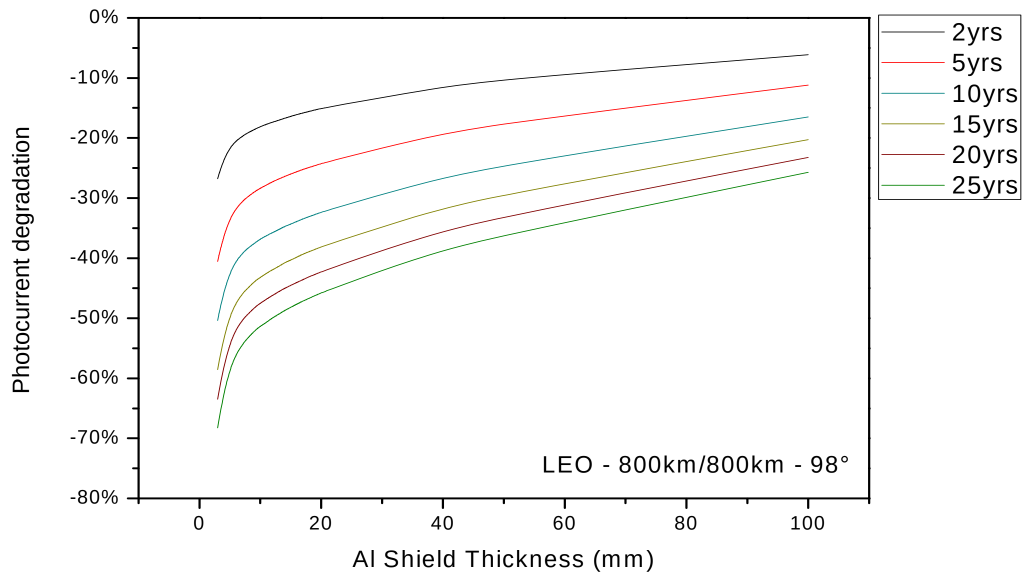
$$\frac{I_{PH}}{I_{PH\,0}}(x,y) = 0.636\cdot x - 0.385\cdot y - 0.059\cdot x^2 - 0.069\cdot y^2 + 0.052\cdot x\cdot y - 0.692$$

Exploiting DoE data (2)

Example: **LEO mission profile**

Photocurrent degradation vs. mission duration (for different shield thicknesses) or vs. the shield thickness (for different durations)

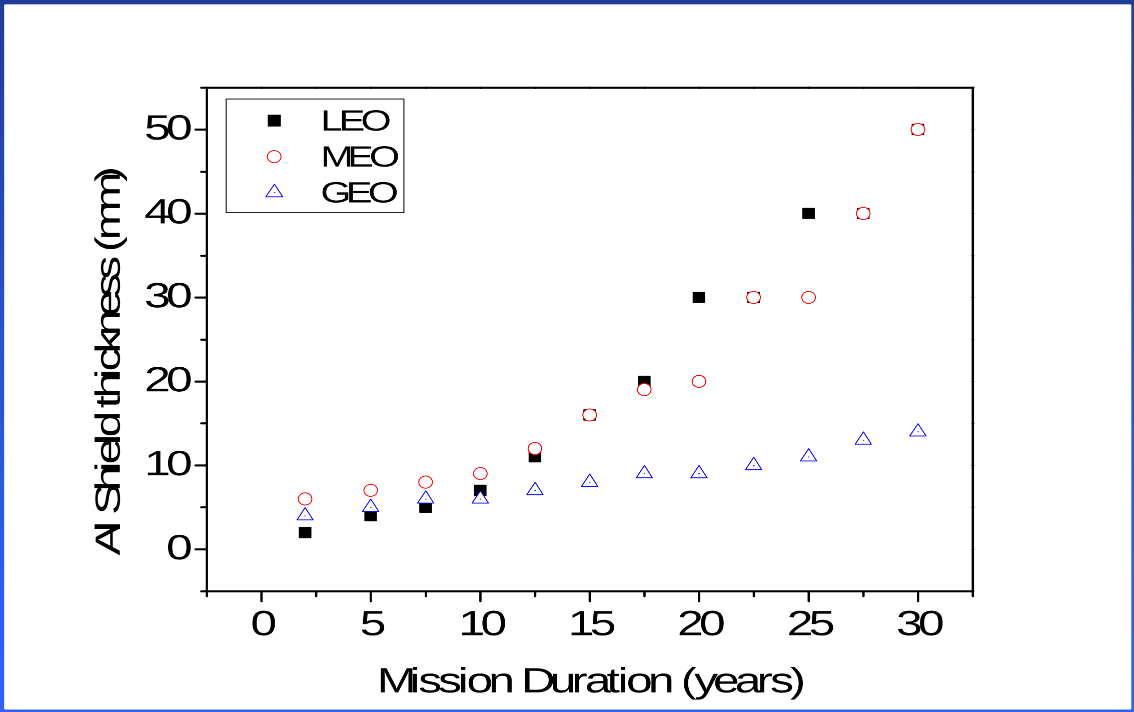




The same charts could be easily obtained for MEO or GEO mission profiles

Exploiting DoE data (3)

Failure criterion: **40% photocurrent degradation**

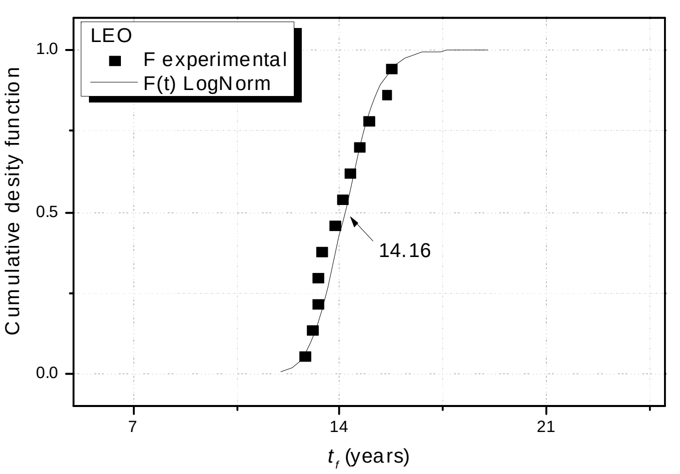


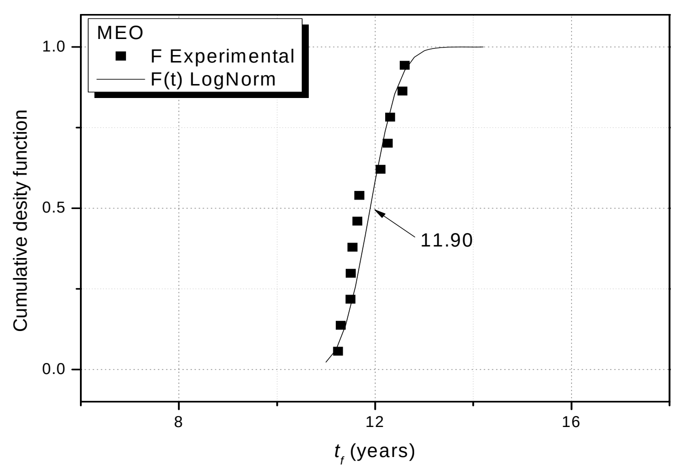
These charts provide a quick overview, for qualification purposes, of the amount of shielding needed for specific orbit and a fixed duration, for a fixed failure criterion.

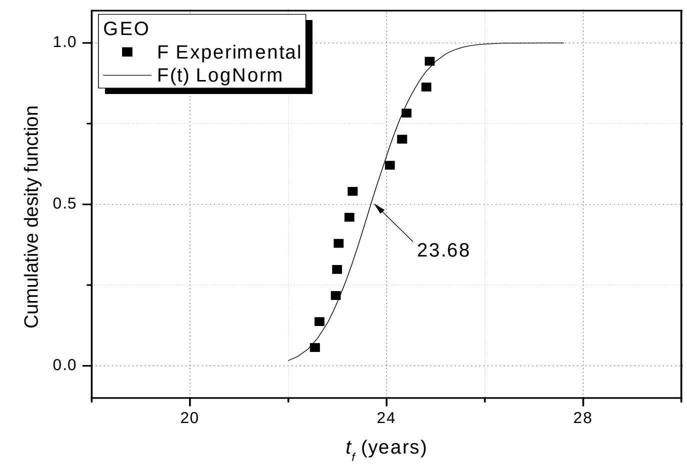
Exploiting DoE data (4)

Reliability data extraction

From DoE data, OMERE mission profiles data, and considering a **40% of photocurrent degradation**, using a lognormal distribution we obtain the cumulative function plots:







lognormal distribution CdF:

$$F_X(t_f;\mu,\sigma) = \frac{1}{2} + \frac{1}{2} erf\left[\frac{\ln t_f - \mu}{\sigma\sqrt{2}}\right]$$

lognormal distribution PdF:

$$f_X(x;\mu,\sigma) = \left(x\sigma\sqrt{2\pi}\right)^{-1} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}$$

devices mean time to failure $MTTF = t_m e^{\frac{\sigma^2}{2}}$

devices failure rate $\lambda(t) = \frac{f(t)}{1-F(t)} 10^9 FIT$

Conclusions

We have demonstrated that statistical **Design of Experiments** is a very useful tool to evaluate BSPA degradations in space environment

- It needs basic knowledge of device and device degradation physics
- As device is described with the "**black box**" approach, it could be extended to other families of components
- It provide a **tests plan** depending on test facilities capabilities
- With **only one tests session**, it gives the BSPA degradation previsions relative to a **wide range** of possible space mission profiles
- Could be optimized (reducing number of experiences)

Design of Experiments is suitable as a **rapid qualification method** for devices that are sensitive to both **ionizing** and **displacement doses**

OpERaS contacts

Win -Win partnership

✓ **AdvEOTec** – F. Rosala (CEO)
Expertise and experience in optolectronic qualification
+33 (0) 1 6086 4361
francoisrosala@adveotec.com
www.adveotec.com

✓ **IMS** – L. Bechou (Full Prof.)
Laboratory with expertise and experience in optoelectronic reliability for space and telecom applications*
+33 (0) 5 4000 2767
laurent.bechou@ims-bordeaux.fr
www.ims-bordeaux.fr

✓ **THALES ISS/CEL** – G. Guibaud (Failure Anlysis Expert)
Expertise on failure analysis, security, dependability of electronic components
+33 (0) 5 6128 1695
gerald.guibaud@cnes.fr
www.thalesgroup.com