

Coupling Ultracapacitors and Energy Harvesting for Autonomous Battery-Free Wireless Sensing in Aeronautics Applications

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Over the last few years, wireless sensor networks (WSN) have been considered for various aeronautical applications, including Structural Health Monitoring and flight tests [1]. Isolated from the onboard electrical network, each sensor node needs to be self-powered. Environmental concerns, together with economical and safety-related issues, often prohibit the use of electrochemical batteries. However, energy may be harvested in the sensor's environment, providing a reliable and sustainable electrical power source. Nevertheless, storage is needed both to accommodate for transient power surges and to maintain the energetic autonomy in case of intermittent environmental source. Ultracapacitors (UCs) are good candidates for doing the job. Although being affected by extreme ambient temperatures similarly to batteries, they are safe, provide an infinite lifetime and are environment friendly.

In this talk, we will present different case studies of energy harvesting coupled to ultracapacitors for autonomous battery-free wireless sensing in aeronautics applications. In this work carried out in cooperation with AIRBUS, we will highlight the main challenges that arise in such battery-free systems in two types of applications : flight-testing (Fig1) and aircraft health monitoring (AHM).

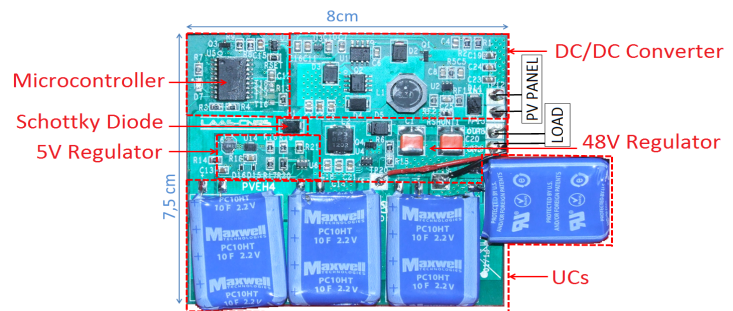



Fig1. Battery-free wireless system used for flight-testing implemented on an aircraft wing (left view). It is composed of a self-starting energy management system (right view), a thin-film photovoltaic energy source coupled to ultracapacitors (UCs) powering a matrix of pressure sensors and real-time data wireless communication.

The main challenges of flight-testing application are that, on the one hand, the wireless sensing system should not disturb the aerodynamics of the aircraft and that, on the other hand, it will be submitted to an environment, which is not pressurized and not regulated in temperature. Moreover, data rate and then power consumption is relatively high since real-time sensing is required. Fortunately, flight-tests are generally performed during daylight and photovoltaic energy harvesting can be used. In AHM applications, the main issues is that the locations that need for monitoring are submitted to very severe conditions in terms of temperature, vibrations, lightning and corrosion. An example of energy harvesting based on thermogeneration will be presented for health monitoring of the aircraft engine [2].

We will end this talk with some perspectives of such battery-free wireless sensing systems.

1. J.-M. Dilhac and M. Bafleur, "Energy harvesting in aeronautics for battery-free wireless sensor networks," *IEEE Aerospace and Electronic Systems Magazine*, vol. 29, pp. 18–22, Aug. 2014.
2. M. Bafleur, J.-M. Dilhac, V. Boitier, Energy Harvesting For Wireless Sensors In Aeronautics Applications: *From Dream To Reality*, Workshop on "Wireless Sensor Node Circuit and System Design" (WiSe Design 2015), Thessalonique (Greece), December 7-8, 2015.

Presentation Method: Invited Oral 30minutes





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Laboratoire d'analyse et d'architecture des systèmes du CNRS

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OUTLINE

- **Aeronautic context & applications**
- **Energy Harvesting for Wireless in Flight Testing**
 - Photovoltaic energy harvesting
- **Energy Harvesting for Aircraft Health Monitoring**
 - Thermal gradient energy harvesting
 - Aeroacoustic energy harvesting
- **Conclusion and perspectives**

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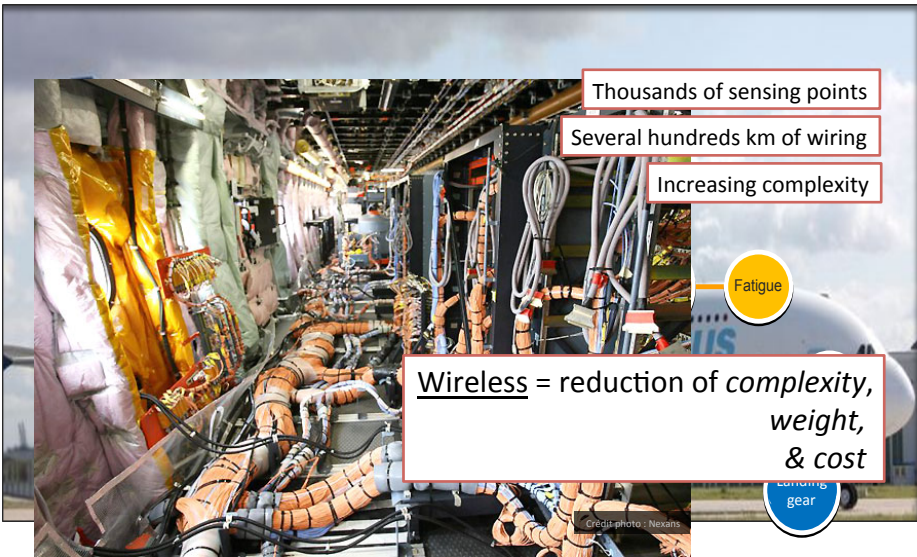
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Aeronautic Context & Applications

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Towards Wireless



Thousands of sensing points
Several hundreds km of wiring
Increasing complexity

Fatigue

Wireless = reduction of *complexity, weight, & cost*


gear

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Flight Tests

- 800 sensors for A380
- 300 km of additional wiring

wireless is of great interest



Pressure sensors are implemented on:

- wings
- flaps
- top of fuselage
- horizontal tail plane...

so are the energy generation modules

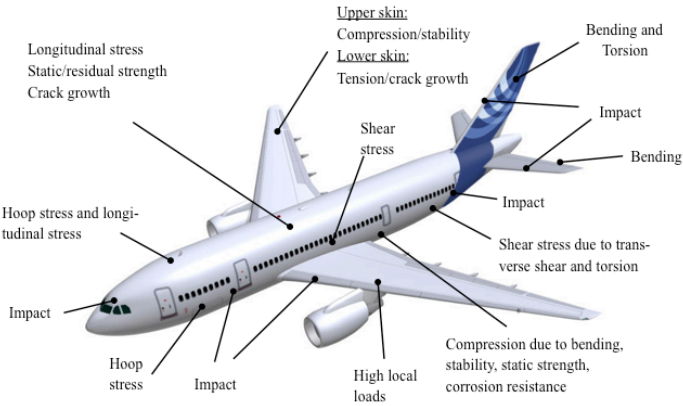
- curvy profiles
- aerodynamic constraints
- low temperatures

...but flight tests are carried out during day

© AIRBUS MILITARY 2009 _ A400M First Flight - Photo by A.Doumenjou / Exm Company

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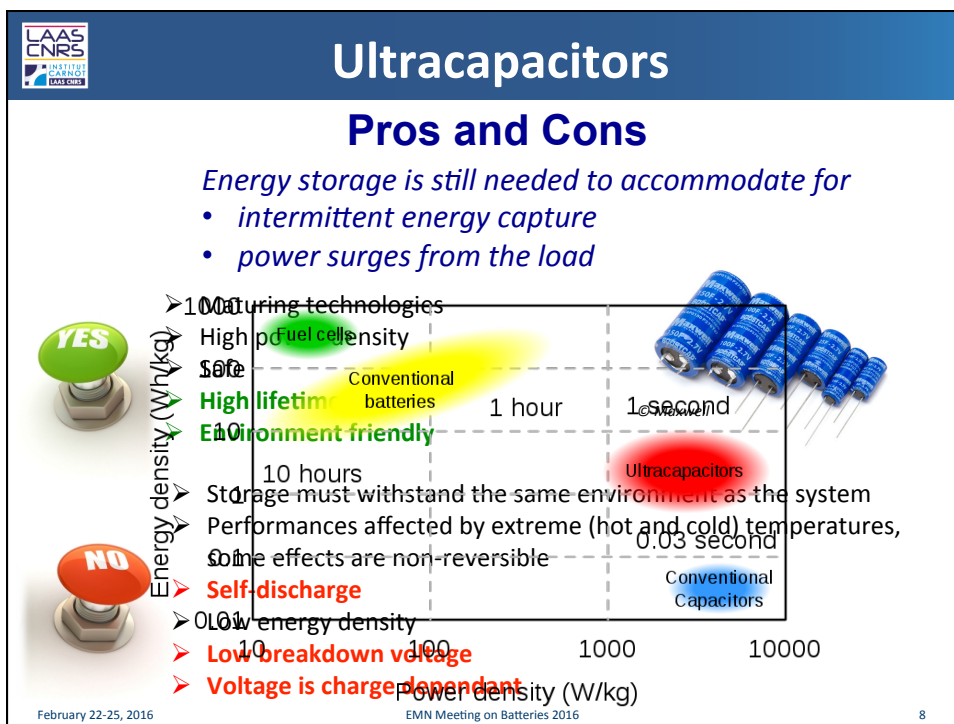
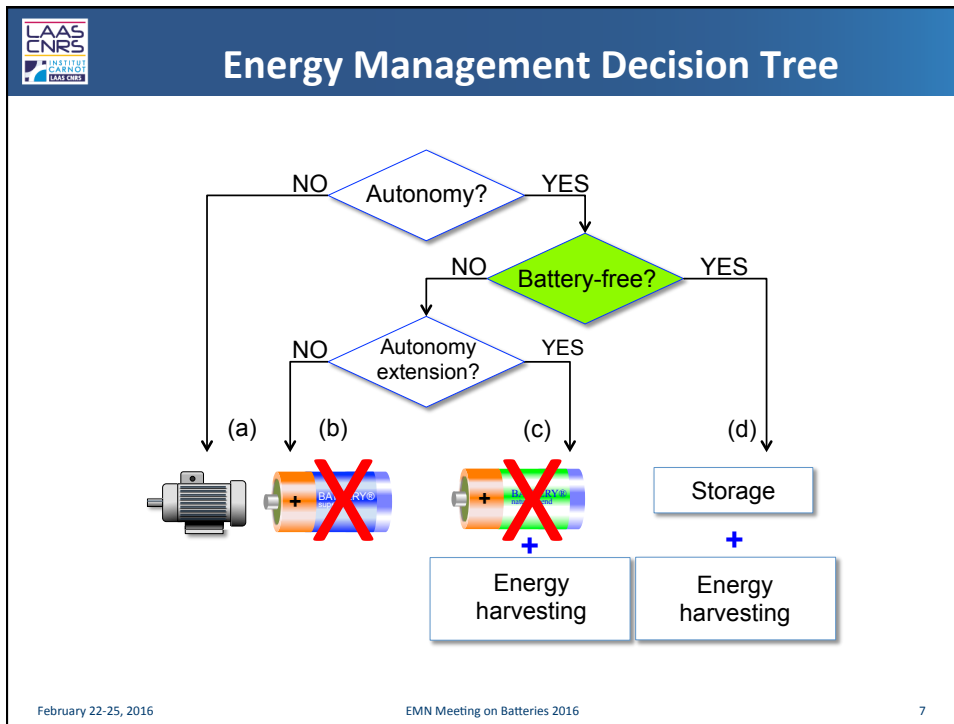
Aircraft Health Monitoring (AHM)

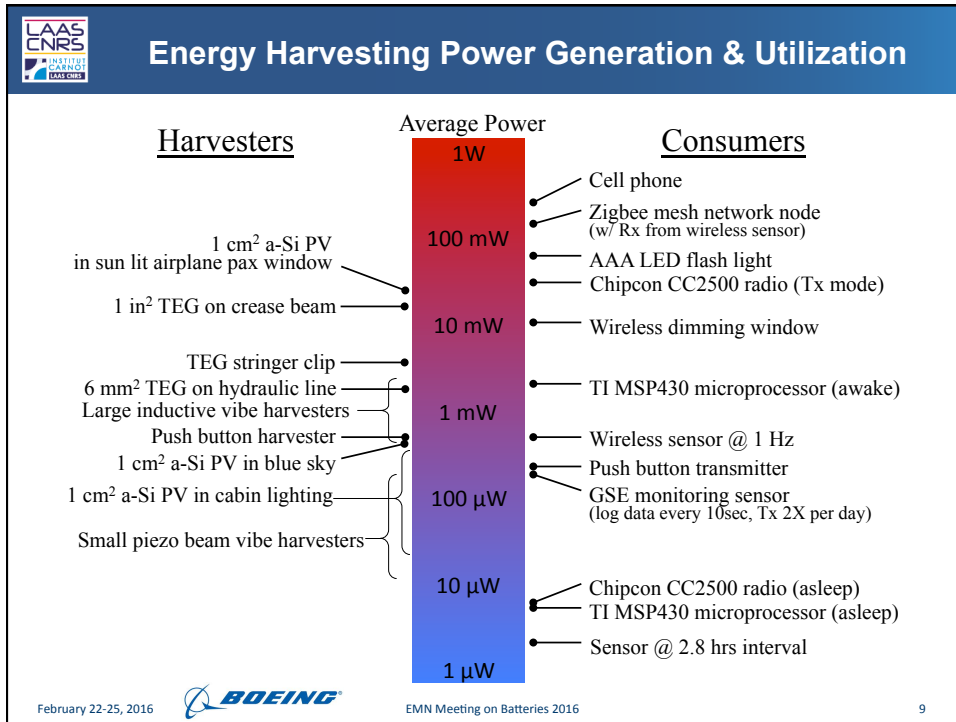


- **Predictive maintenance** – major challenge
- Installation in a non pressurized and non controlled temperature zone
- Night and day operation
- Embedded fitment (no more test rig) => energy generation mature method
- **DO-160G compliant**

© Holger Speckmann, Airbus Germany, IW/SHM 2007

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Energy Harvesting for Wireless in Flight Testing

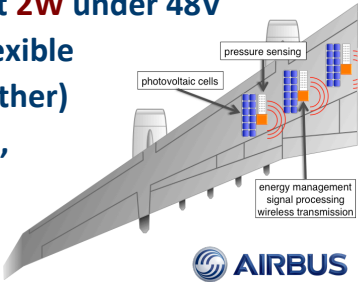
Photovoltaic energy harvesting

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Objectives and requirements

- **Autonomous, battery-free power supply** of a wireless system including pressure sensing glove, signal processing and RF communication
- Autonomous start-up with initial empty storage
- Average electrical power of at least **2W** under 48V
- Few millimeters in thickness and flexible
- Operation at low light (cloudy weather)
- Operation between **-50°C and 85°C**,
- Reduced pressure down to **200hPa**
- Daylight tests




photovoltaic cells
 pressure sensing
 energy management
 signal processing
 wireless transmission



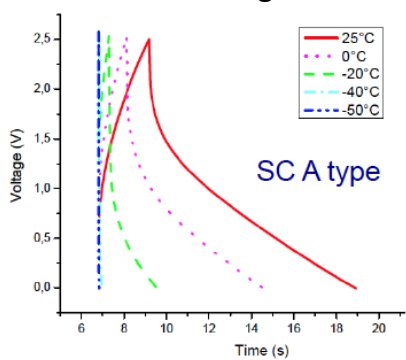
→ PhotoVoltaic Energy Harvester and ultracapacitor-based storage

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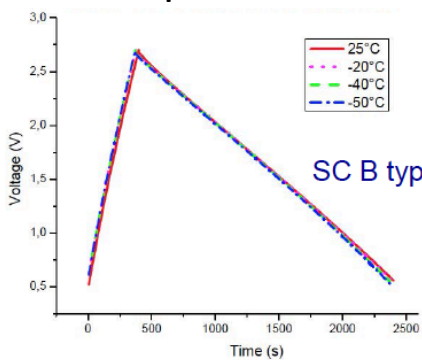


Test of Ultracapacitors in Temperature

Charge and discharge at low temperature



SC A type



SC B type

Charge (300 mA) and discharge (55 mA) at constant current and at various temperatures:

- Ultracapacitor A: non-linear behaviour, even at room T°, and very poor performance at negative T°
- **Ultracapacitor B: perfect behavior even at negative T°**

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Architecture of the PV Energy Harvester

- **MPPT** achieved by DC/DC buck converter with fractional Voc algorithm optimized at low irradiance
- **Under Voltage Lock-Out (UVLO)** function to avoid false start-up and unexpected power consumption

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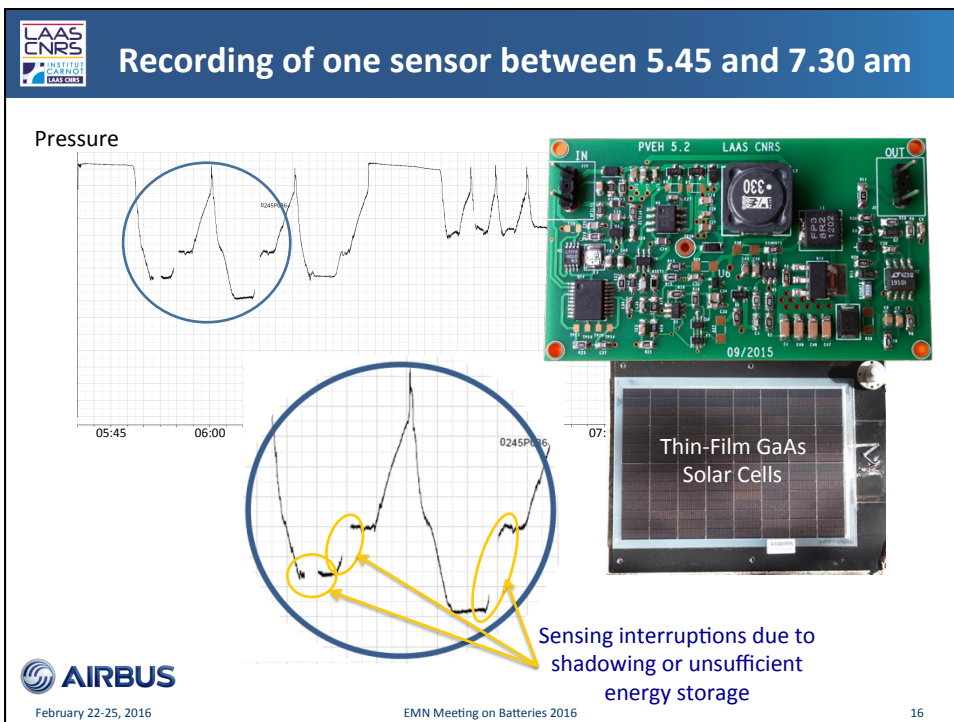
Architecture of the PV Energy Harvester

Total storage: 10F (4 UCs mounted in 2S2P)

**50Wp thin film monocrystalline Si PV panel,
11% efficiency at 58 W/m²
17% for Standard Test Conditions**

P. Durand Estèbe, *Energy Harvesting for Wireless in Flight Testing on A321 Aircraft, More Electrical Aircraft (MEA2015)*, Toulouse (France), 3-5 February 2015.



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Energy Harvesting for Aircraft Health Monitoring

Thermal gradient energy harvesting

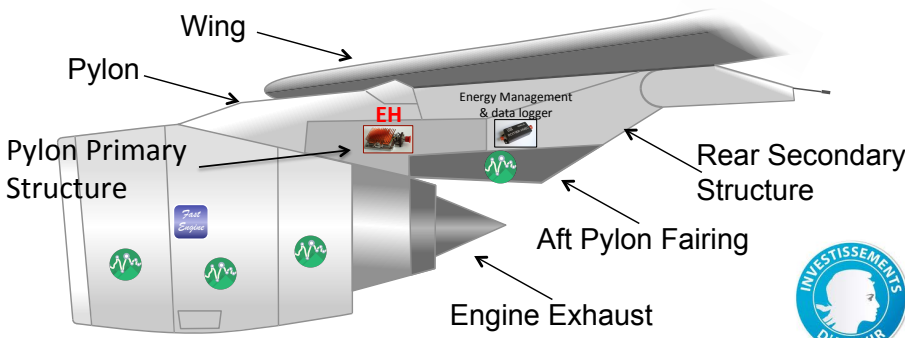



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CORALIE Project

Instrumentation of the Aft Pylon Fairing (APF) for over-temperature and/or crack detection



Very harsh environment in terms of temperatures, pressure, vibrations, fluids and lightning

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Energy autonomous AHM system

Crack wire sensors
Crack location #1
Main Crack wire #1
Reference Crack wire #1

Thermocouples
CNRS-LAAS Energy harvester
Module TEG #1
Energy Accumulator

Data logger #3 AGI

Data Concentrator 28V DC

US Patent n°005969260

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Thermal Gradient Energy Harvesting

Cold side
KOMATSU

Efficiency (%)
Power (W)

Hot Side Temperature, °C

ca. 1W/cm²

Power (mW)
Voltage (V)

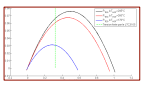
$T_{COLD} = 70^{\circ}C$

Hot Day
Medium Hot Day
Standard Day

DO-160G compliant

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Energy Harvester of the AHM system



TEG

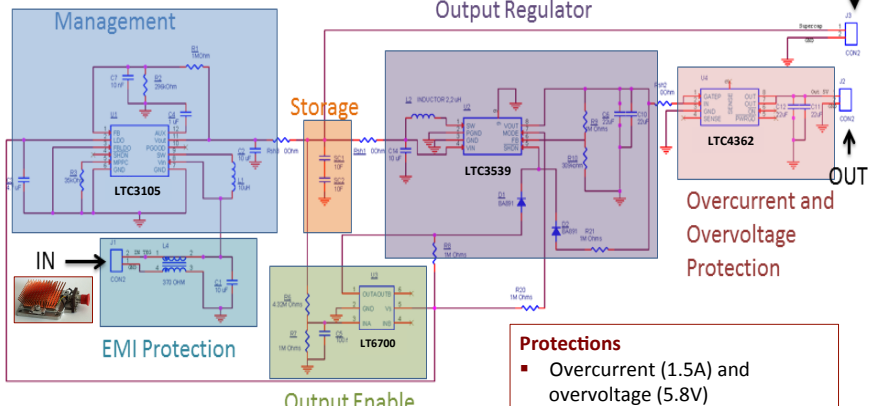
- Impedance matching
- Maximum Power Point (@0.32V) for ΔT worst case
- Storage charged via a boost regulator ($V_{max}=4.6V$)

Output regulation 5V

- 2.5V activation threshold for sufficient stored energy to avoid UVLO (under voltage lock out)
- 1V desactivation threshold

Protections

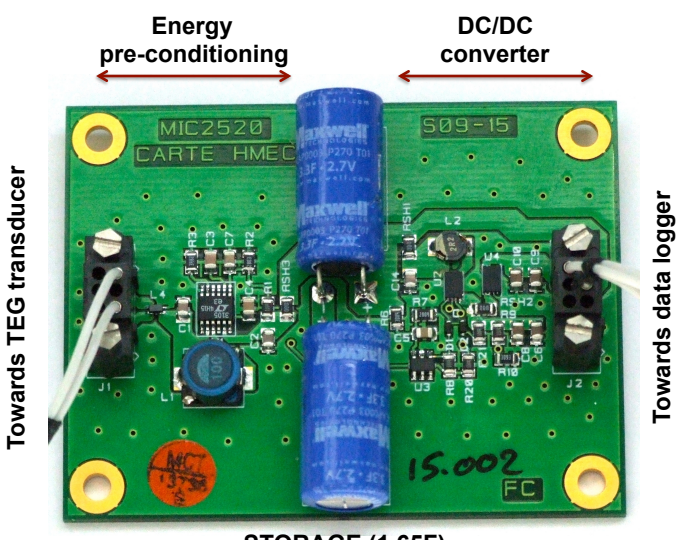
- Overcurrent (1.5A) and overvoltage (5.8V)
- Lightning protection (EMI filter)



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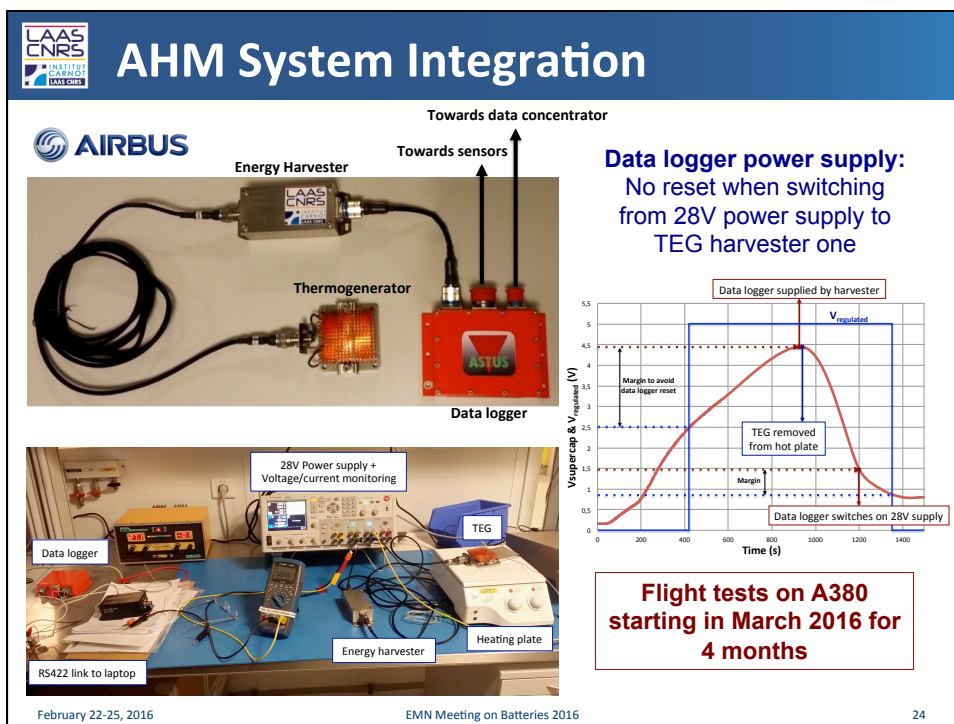
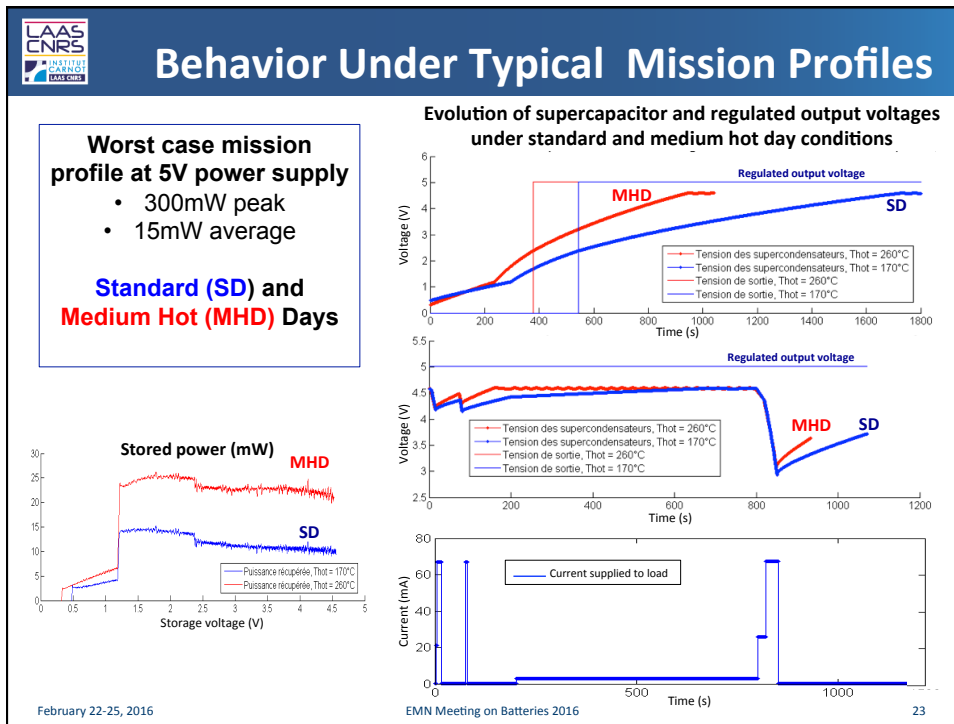
Energy Harvester of the AHM system

Energy pre-conditioning DC/DC converter

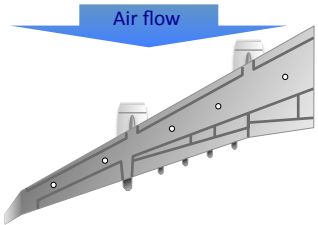


STORAGE (1.65F)

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Energy Harvesting for Aircraft Health Monitoring

Aeroacoustic energy harvesting

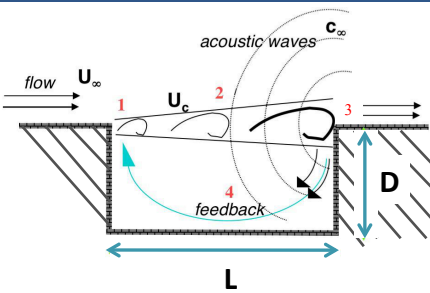
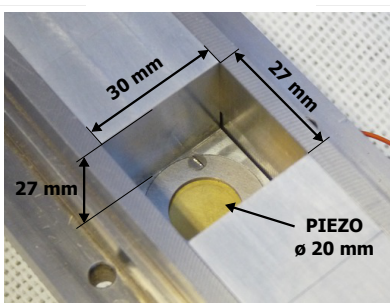


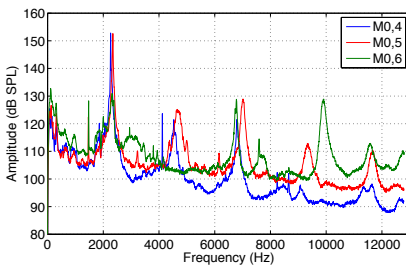
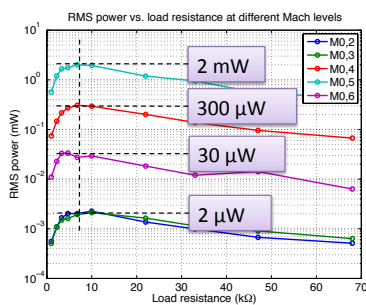


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Aeroacoustic Noise

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Aeroacoustic Energy Harvester

piezo **Parallel SSHI** AC/DC converter DC/DC converter storage + regulation, protections, ... WSN

Energy transfer maximization Impedance matching Protections: overvoltage, UVLO

90 mm
39 mm

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Powering a Jennic JN5148 Data Logger

Data logger power consumption profile

Start-up
0.5 J

Sense & transmit
1 mJ

Average data logger power 180 μW

Output Voltage (V)
time (min)

R. Monthéard, PhD thesis, Nov. 2014
R. Monthéard et al, POWERMEMS 2014

http://youtu.be/1kkq-5g9D_g

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Perspectives

- **Miniaturization of the system**
- **Aeroacoustic transducer**
 - Helmholtz resonator
- **Dynamic behavior**
 - Adaptive storage to allow earlier start-up & improved energy usage

charge

discharge

$C_{eq} = C_{tot} / 4^{N-1}$

$C_{eq} = C_{tot} / 4$

$C_{eq} = C_{tot}$

Charge

DC-DC activation threshold

Almost instantaneous availability of energy

Discharge

+13% autonomy

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On-chip micro-storage

Technologies investigated at LAAS-CNRS

Inkjet Printing
D. Pech et al., *J. Power Sources* 195(2010) 1266.

Screen Printing
H. Durou et al., *Microsys. Technol.* 18(2012) 467.

Electrolytic Deposition (RuO₂)
D. Pech et al., *J. Power Sources* 230 (2013) 230.

3F/cm²
450 mJ.cm⁻²

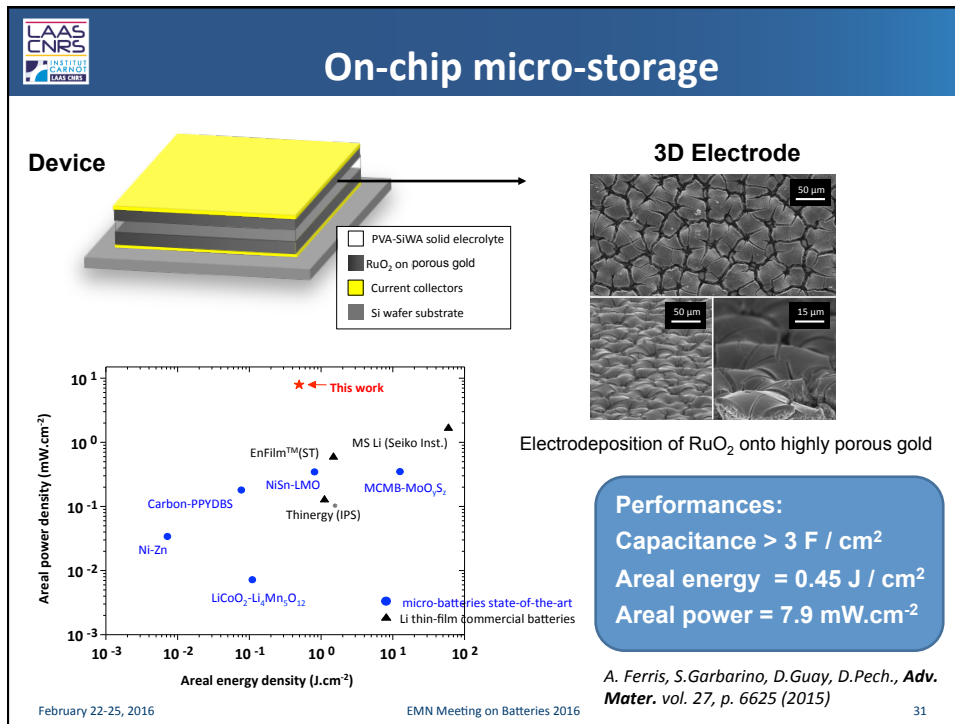
A. Ferris et al, *Advanced Materials*, 30 sept. 2015

Thin Films
P. Huang et al., *J. Power Sources* 225 (2013) 240.

Electrophoretic Deposition
P. Huang et al., *Electrochem. Commun.* 36 (2013) 53.

0.7 W.cm⁻²

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Conclusion

Aeronautics has a true need for wireless sensing

- **Ultracapacitor is a safe and efficient alternative to batteries**
- **Flight test is the most obvious killing application with great benefits in terms of:**
 - Ease of installation
 - Cost
 - Flexibility
- **Aircraft Health Monitoring:**
 - **Long-term goal:** conditional maintenance based on advanced diagnosis/prognostic
 - Various Proofs of Concept
 - Miniaturization limited by the harvester
 - Reliability over aircraft lifetime has to be proven

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