

Keynote presentation at
Workshop on “Wireless Sensor Node Circuit and System Design”,
WiSe Design 2015

7-8 December, 2015, Thessaloniki (Greece)



***Energy Harvesting For Wireless Sensors In
Aeronautics Applications: From Dream To Reality***

Marise BAFLEUR, Jean-Marie DILHAC, Vincent BOITIER

LAAS-CNRS, TOULOUSE (France)

- **Abstract :** New applications of embedded systems are envisioned in the context of aeronautics. However, the increasing burden of on-board cabling requires wireless solutions. Moreover, concerns such as safety or system lifetime often preclude the use of electrochemical energy storage. Ambient energy capture, storage and management are therefore key topics. In this paper we illustrate these concepts by describing three actual implementations in an Airbus aircraft. The first application is energy harvesting for wireless in flight-testing. The main objectives are autonomous, battery-free power supply of a wireless system including pressure sensing glove, signal processing and RF communication. The system should be able to start-up with initial empty storage. The second application is dedicated to the autonomous power supply for aeronautical health monitoring sensors in the engine harsh environment of an Airbus A380 using thermogeneration as energy source. The third and last example is a more prospective study on the potentialities of aeroacoustic energy harvesting that was successfully validated in a wind tunnel.




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

Energy Harvesting For Wireless Sensors In Aeronautics Applications: *From Dream To Reality*

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Laboratoire conventionné avec l'Université de Toulouse

WiseDesign 2015, December 7-8, 2015





OUTLINE

- **Introduction**
 - Wireless sensor history
 - The energy roadblock
- **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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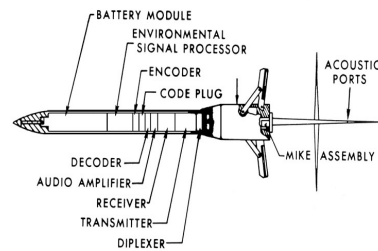
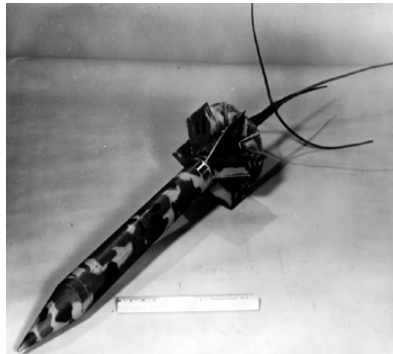
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Wireless Sensor History

- **Wireless sensors are not so new...**
- **1968-1973: Vietnam war – Operation Igloo White**



Cost: \$1-\$1.7 billion (design & fabrication) + \$1 billion/year (operation over 5 years)!

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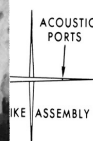


Wireless Sensor History

- **Wireless sensors are not so new...**
- **1968-1973: Vietnam war – Operation Igloo White**



20 000 sensors deployed
80% operational




Cost: \$1-\$1.7 billion (design & fabrication) + \$1 billion/year (operation over 5 years)!


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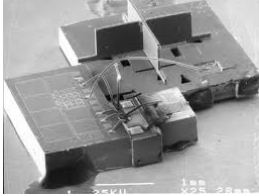

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Smart Dust







- **Smart Dust:** DARPA-funded research proposal of the [University of California, Berkeley](#), in 1998.
- **Objective:** build wireless sensor nodes with a volume of one cubic millimeter.
- **Results:** Autonomous 16mm³ solar-powered [mote](#), and larger "COTS Dust" devices kicked off the [TinyOS](#) effort at Berkeley.

©The University of Berkeley

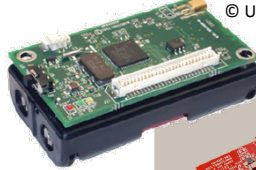
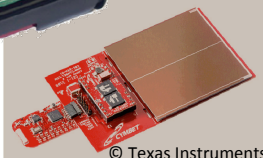


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The energy autonomy roadblock

- **Energy generation and storage devices are generally bulky**
- **Batteries have a limited lifetime**
 - Prohibitive maintenance cost
 - Environmental issue
- **Batteries can have safety issues**
- **Application dependent**
- **MAIN CHALLENGES:**
 - Smart energy management
 - Low-power communication
 - Increasing energy density
 - Efficient energy harvesting
 - Green storage

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Aeronautic Context & Applications

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Towards Wireless

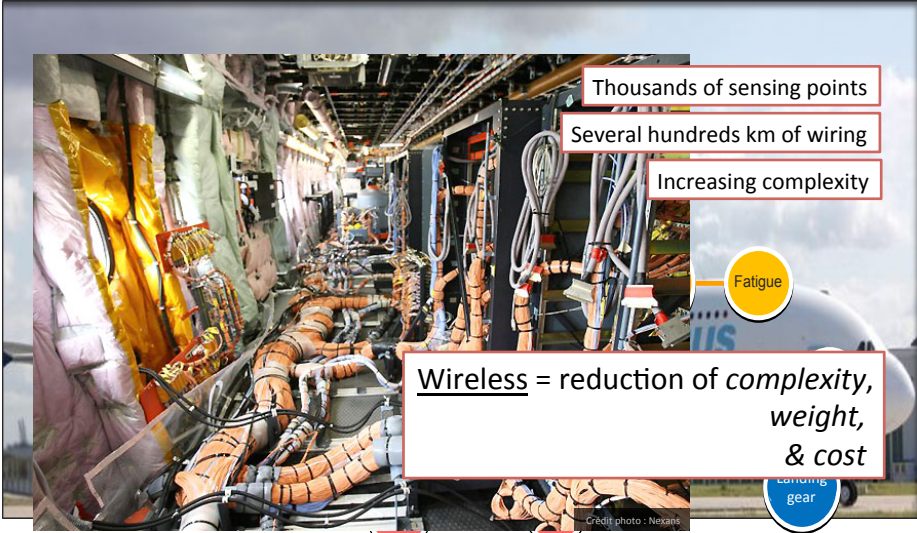
The diagram shows an Airbus A380 aircraft with several colored circles representing different sensor locations and data points. The circles are connected by lines, indicating a network of sensors. The circles are labeled: Temp (green), Wing (green), Humidity (green), Vibration (green), Engine (red), Vibration (red), Temp (red), Acoustic waves (yellow), Structure (orange), Fatigue (orange), Pressure (blue), Temp (blue), and Landing gear (blue). Three text boxes are overlaid on the image: 'Thousands of sensing points', 'Several hundreds km of wiring', and 'Increasing complexity'.

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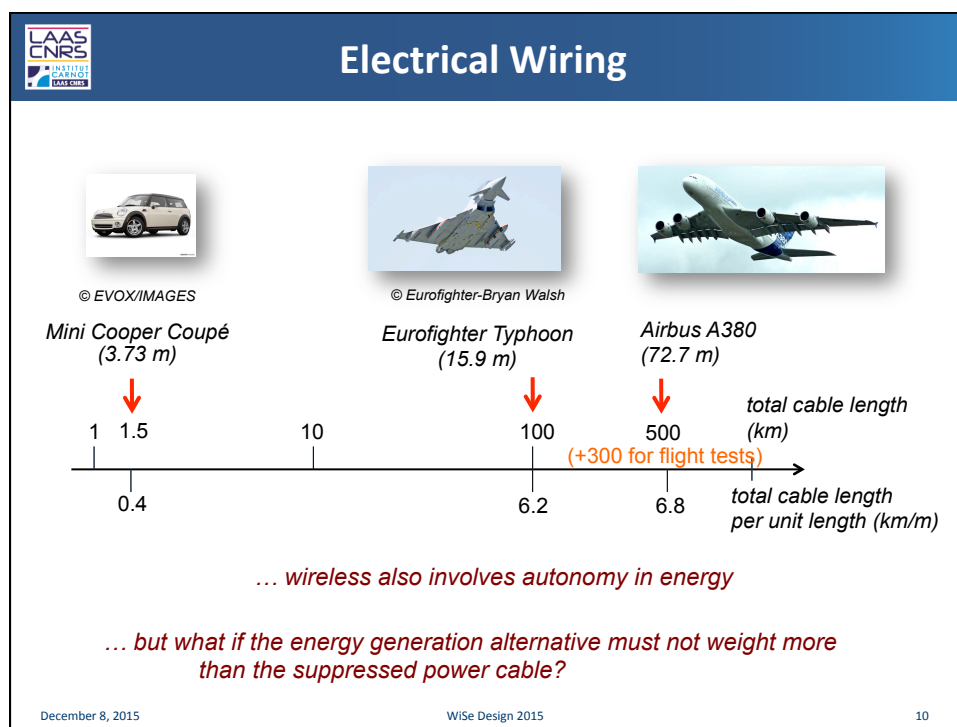
Towards Wireless



Thousands of sensing points
Several hundreds km of wiring
Increasing complexity

Wireless = reduction of complexity, weight, & cost

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Flight tests



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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)

The diagram illustrates an aircraft with various stress and impact points labeled for health monitoring. The labels include:

- Longitudinal stress
- Static/residual strength
- Crack growth
- Upper skin: Compression/stability
- Lower skin: Tension/crack growth
- Bending and Torsion
- Impact
- Bending
- Shear stress
- Impact
- Shear stress due to transverse shear and torsion
- Impact
- Hoop stress and longitudinal stress
- Impact
- Hoop stress
- High local loads
- Compression due to bending, stability, static strength, corrosion resistance

© Holger Speckmann, Airbus Germany, IW/SHM 2007

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

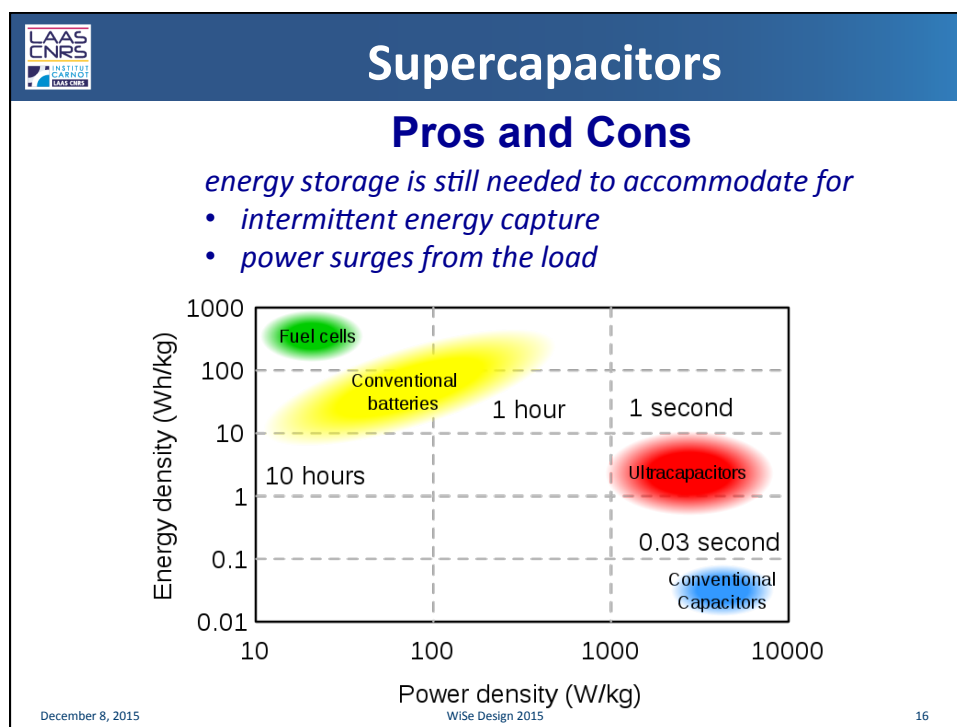
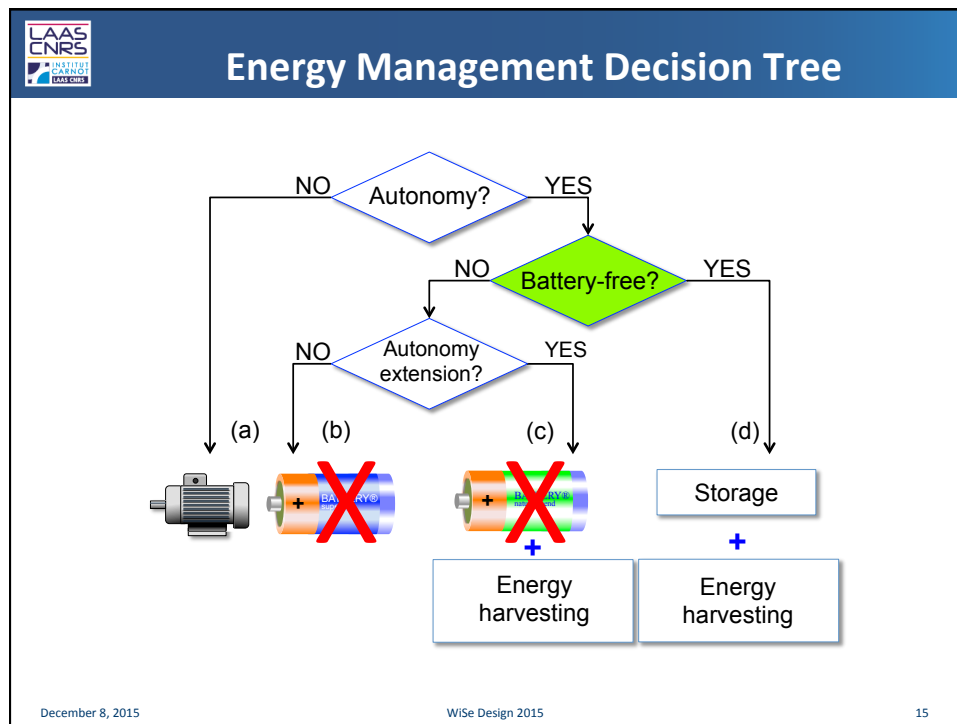
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DO-160G Test Standard

Environmental Conditions and Test Procedures for Airborne Equipment

- **Temperature and pressure conditions**
- Temperature variation
- Humidity
- **Operational Shocks and Crash Safety**
- **Vibration**
- Explosive Atmosphere
- **Waterproofness**
- Fluids Susceptibility
- Sand and Dust
- Fungus Resistance
- Salt Fog
- Magnetic Effect
- **Power Input**
- Voltage Spike
- Audio Frequency Conducted Susceptibility
- Induced Signal Susceptibility
- Radio Frequency Susceptibility (Radiated and Conducted)
- **Emission of Radio Frequency Energy**
- **Lightning Induced Transient Susceptibility**
- Lightning Direct Effects
- Icing
- **Electrostatic Discharge (ESD)**
- **Fire, Flammability**

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Supercapacitors

Pros and Cons


energy storage is still needed to accommodate for

- *intermittent energy capture*
- *power surges from the load*


- Maturing technologies
- High power density
- Safe
- **High lifetime**
- **Environment friendly**

- Storage must withstand the same environment as the system
- Performances affected by extreme (hot and cold) temperatures, some effects are non-reversible
- **Self-discharge**
- Low energy density
- Low breakdown voltage
- **Voltage is charge dependant**



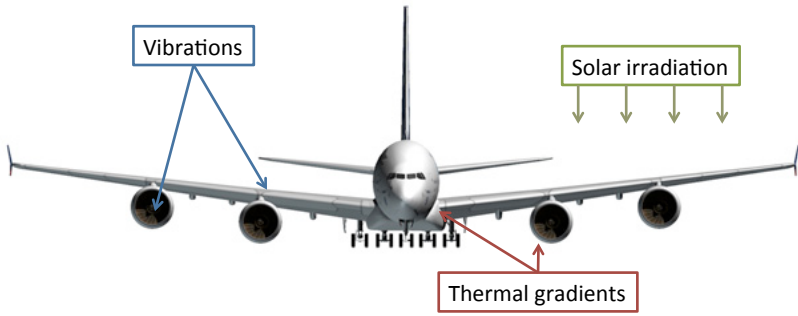
© Maxwell

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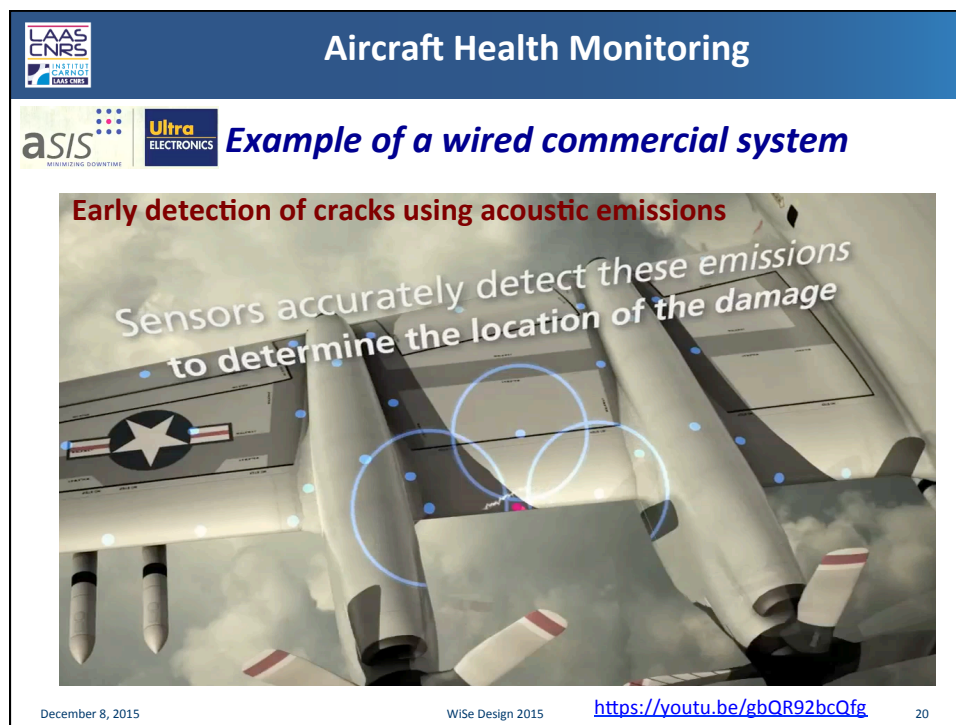
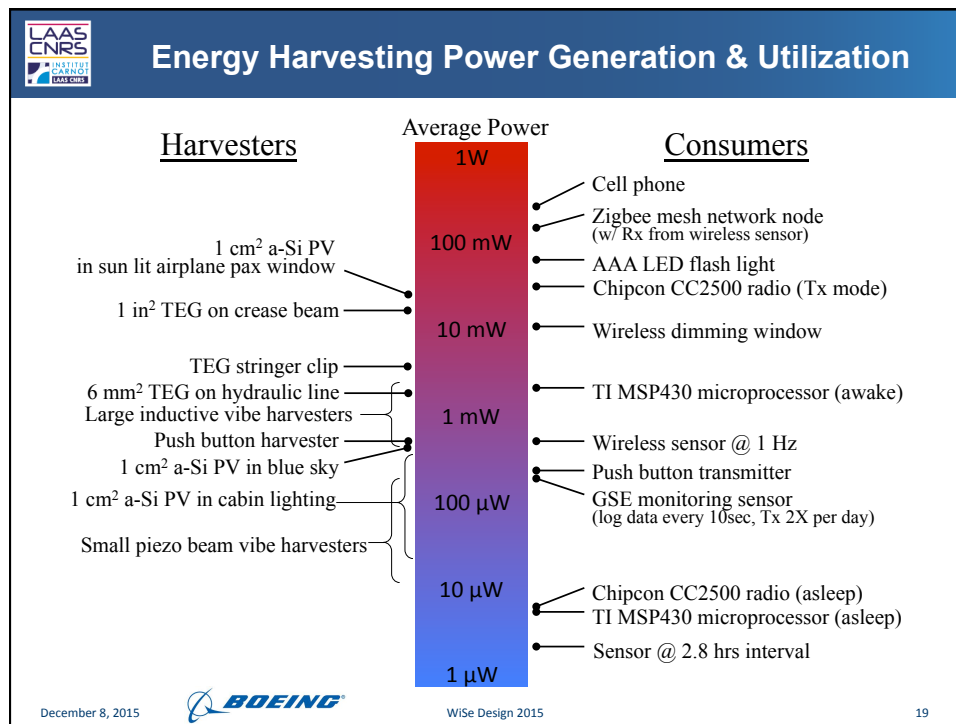
Energy Harvesting in Aeronautics


- **Various types of energy source...**




- **... but limited**
- **Energy storage generally required**


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Aircraft Health Monitoring

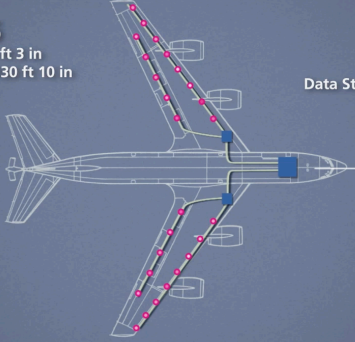




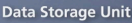
Example of a wired commercial system


KC-135

Length: 136 ft 3 in
Wingspan: 130 ft 10 in





Data Storage Unit






Small and lightweight - Easy to install






Remote Data Concentrator

Detect these emissions



Detect these emissions




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<https://youtu.be/gbQR92bcQfg>

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Some Wireless Sensor Implementations


Microstrain wireless sensor node on Bell 412 helicopter pitch link: strain & load sensing




PZT energy harvesters



Harvested energy 200-400µW





LORD MicroStrain®
SENSING SYSTEMS


S.W. Arms et al., "Energy Harvesting Wireless Sensors for Helicopter Damage Tracking", American Helicopter Society 62nd Annual Forum, Phoenix, AZ, May 2006.


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Thermoelectric stringer clip generates several mW from ΔT across insulation blanket in flight:

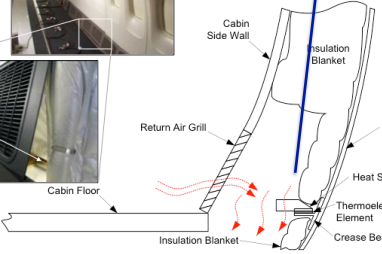
- Cold side: -30°C
- Hot side: +20°C

Harvested energy 30mW @ 160 Ohms










Cabin Side Wall
Insulation Blanket
Skin
Heat Sink
Thermoelectric Element
Crease Beam
Return Air Grill
Cabin Floor



BOEING®

<https://mentor.ieee.org/802.15/dcn/09/15-09-0074-00-004f-energy-harvesting-sensor-systems.ppt>

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Energy Harvesting for Wireless in Flight Testing

Photovoltaic energy harvesting

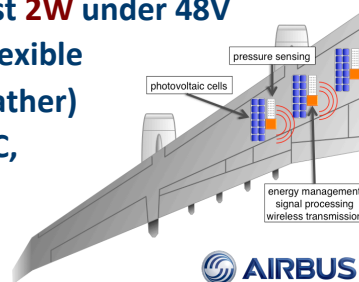
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Objectives and requirements

- 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

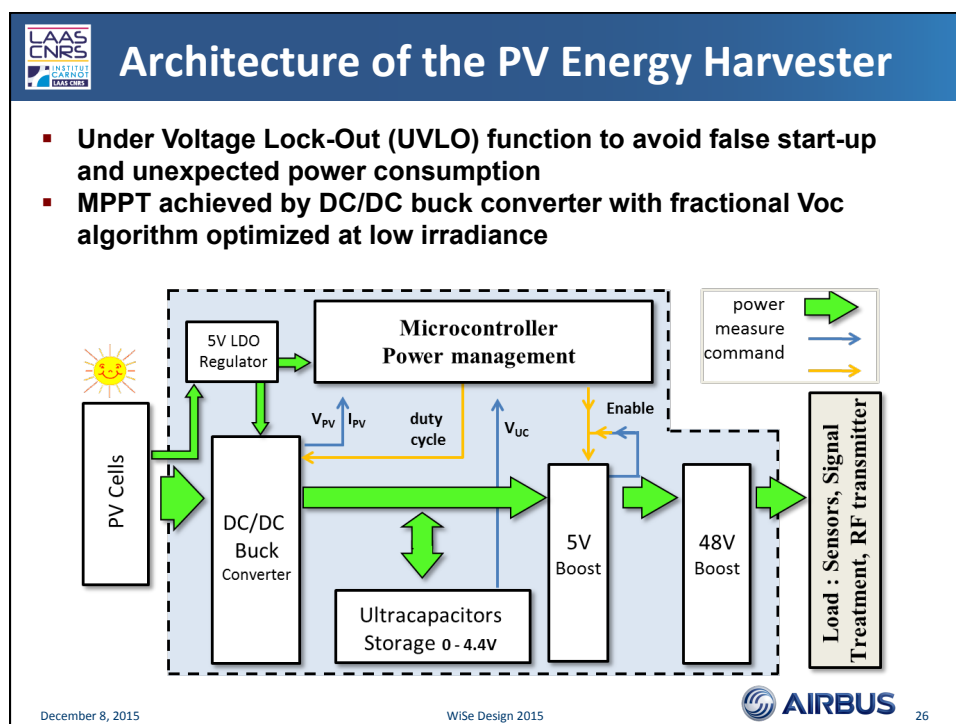
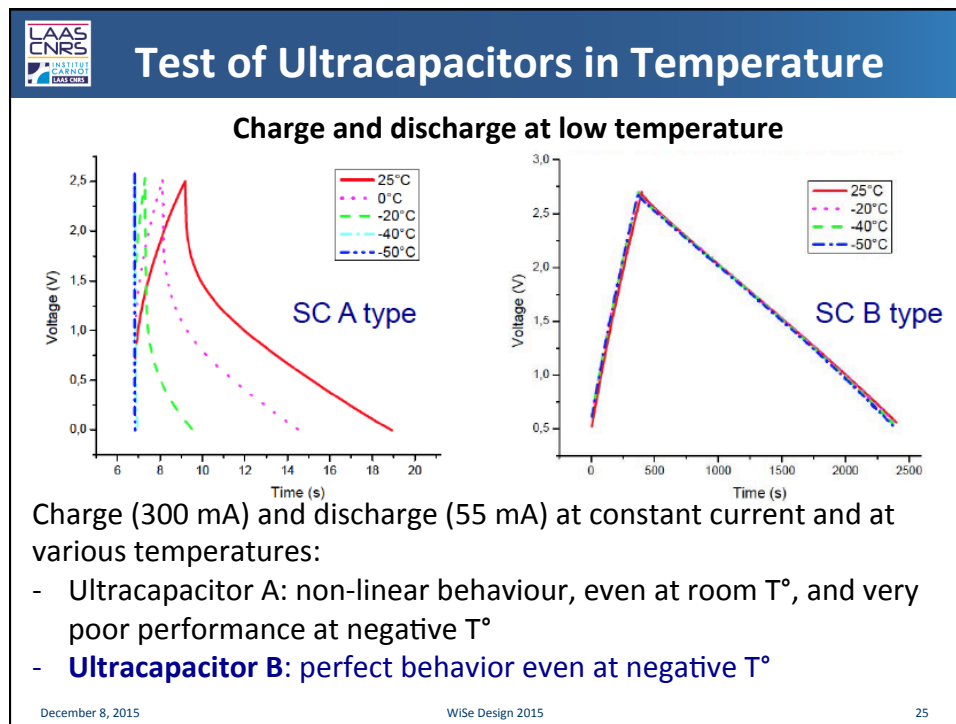


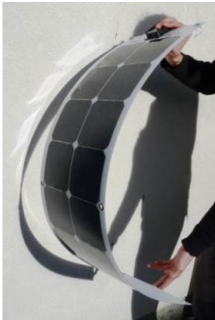
→ **PhotoVoltaic Energy Harvester and ultracapacitor-based storage**

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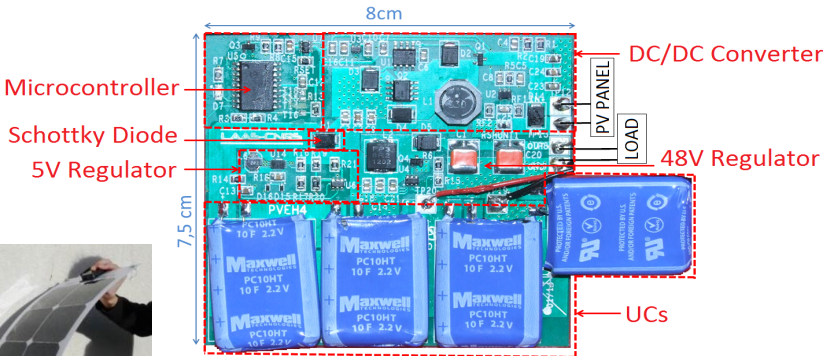
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Architecture of the PV Energy Harvester



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

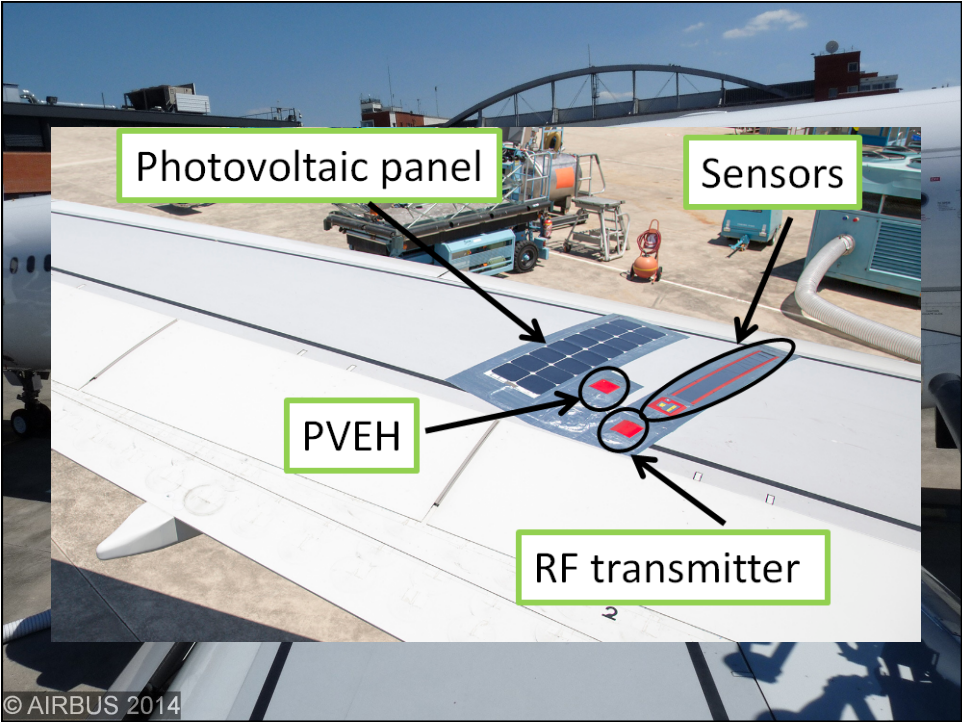
**50Wp thin film monocrystalline Si PV panel,
11% efficiency at 58 W/m²
17% for Standard Test Conditions**

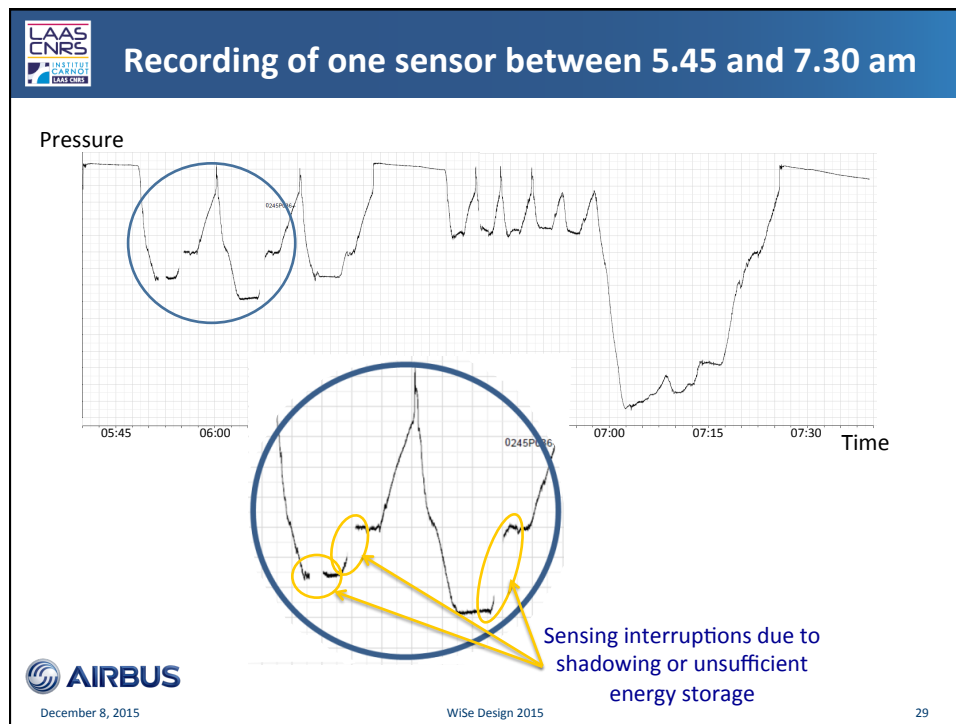
P. Durand Estèbe, *Energy Harvesting for Wireless in Flight Testing on A321 Aircraft, More Electrical Aircraft (MEA2015)*, Toulouse (France), 3-5 February 2015.

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Energy Harvesting for Aircraft Health Monitoring

Thermal gradient energy harvesting

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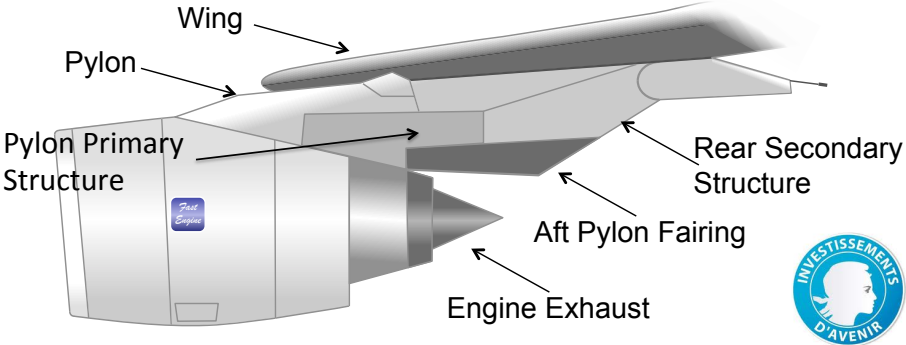
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CORALIE Project

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

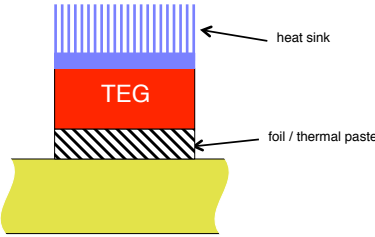
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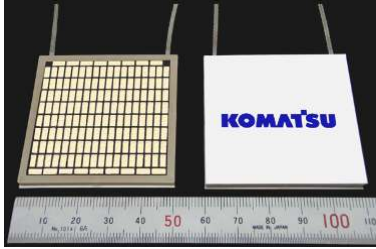
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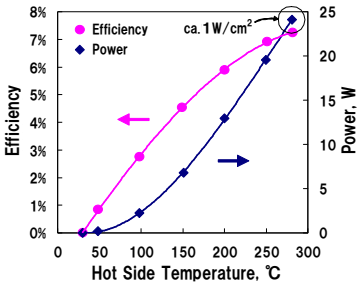
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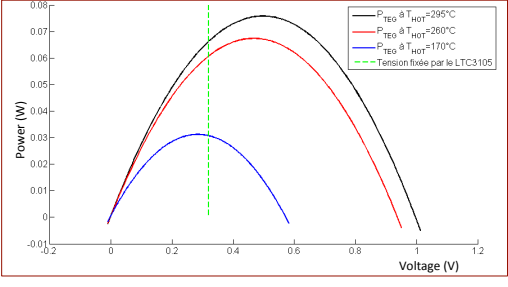
Thermal Gradient Energy Harvesting







Hot Side Temperature (°C)	Efficiency (%)	Power (W)
50	1.0	1.0
100	2.5	2.5
150	4.5	5.0
200	6.0	10.0
250	7.0	15.0
300	7.5	20.0

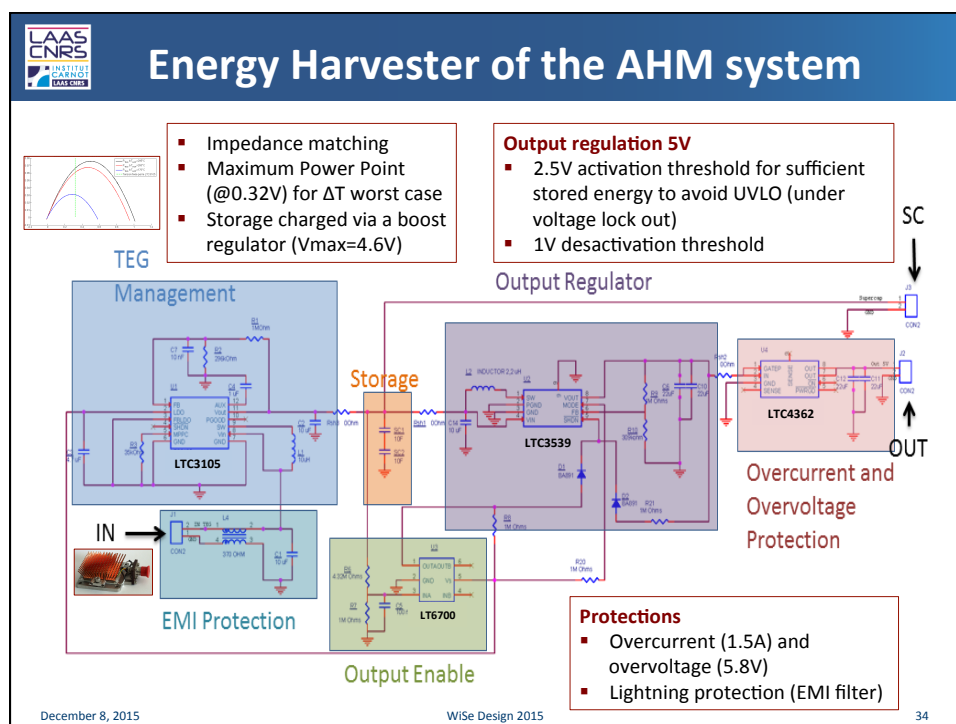
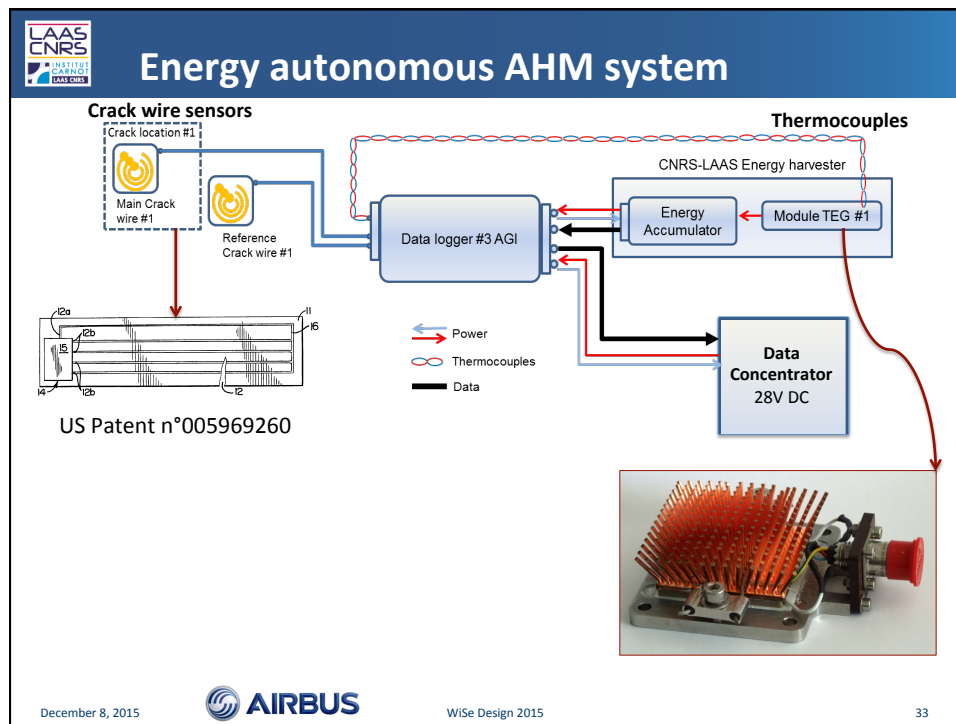


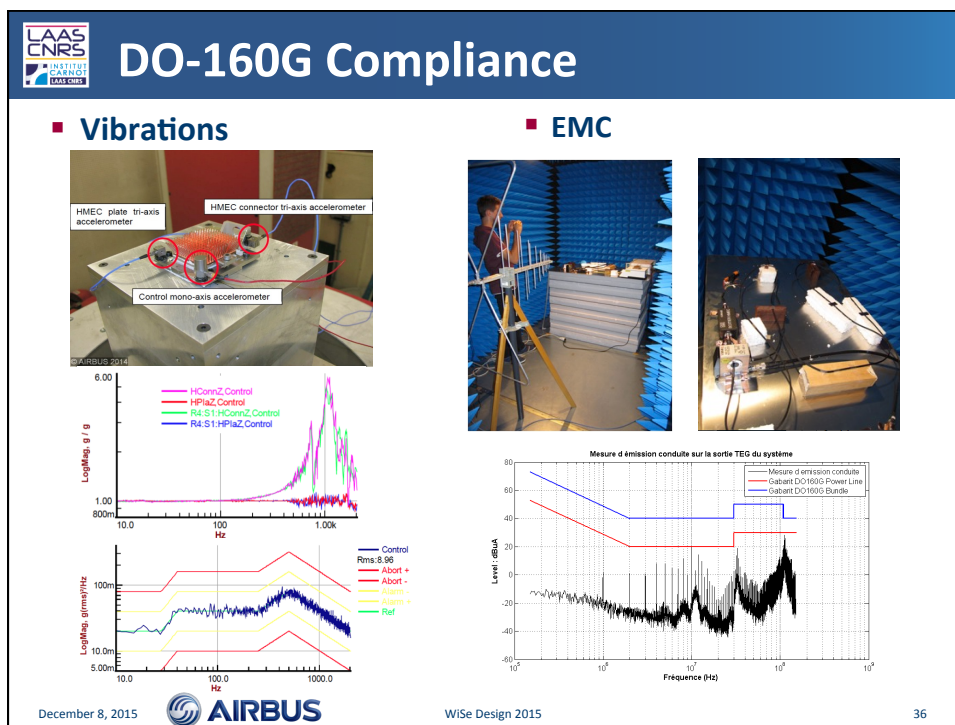
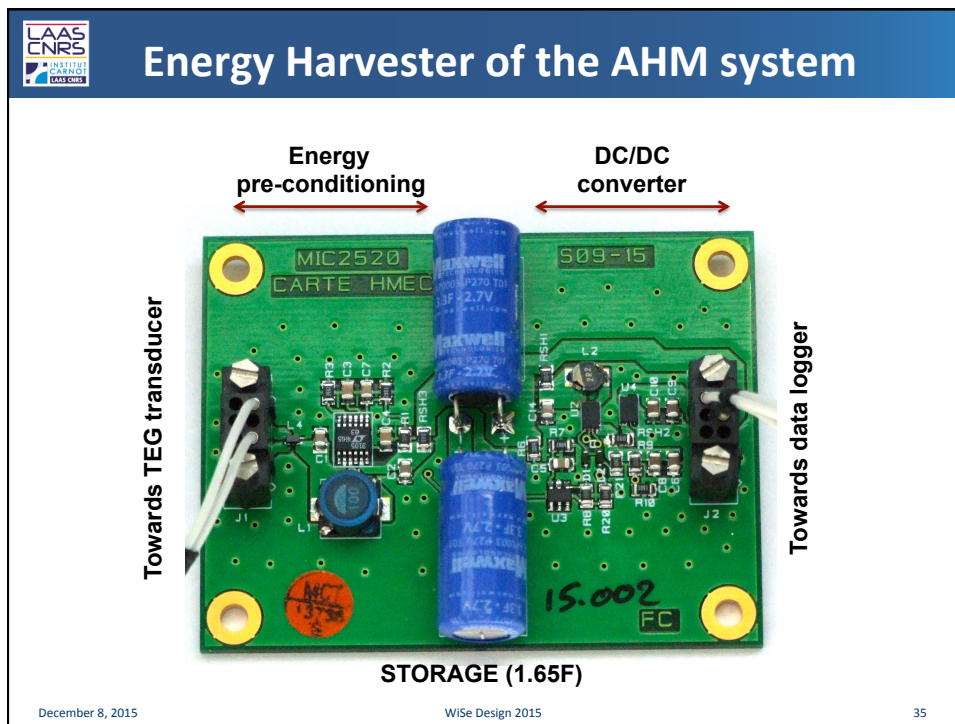
Voltage (V)	Power (W) at 295°C	Power (W) at 260°C	Power (W) at 170°C
0.0	0.00	0.00	0.00
0.2	0.04	0.03	0.02
0.4	0.07	0.06	0.03
0.6	0.07	0.06	0.03
0.8	0.04	0.03	0.02
1.0	0.00	0.00	0.00

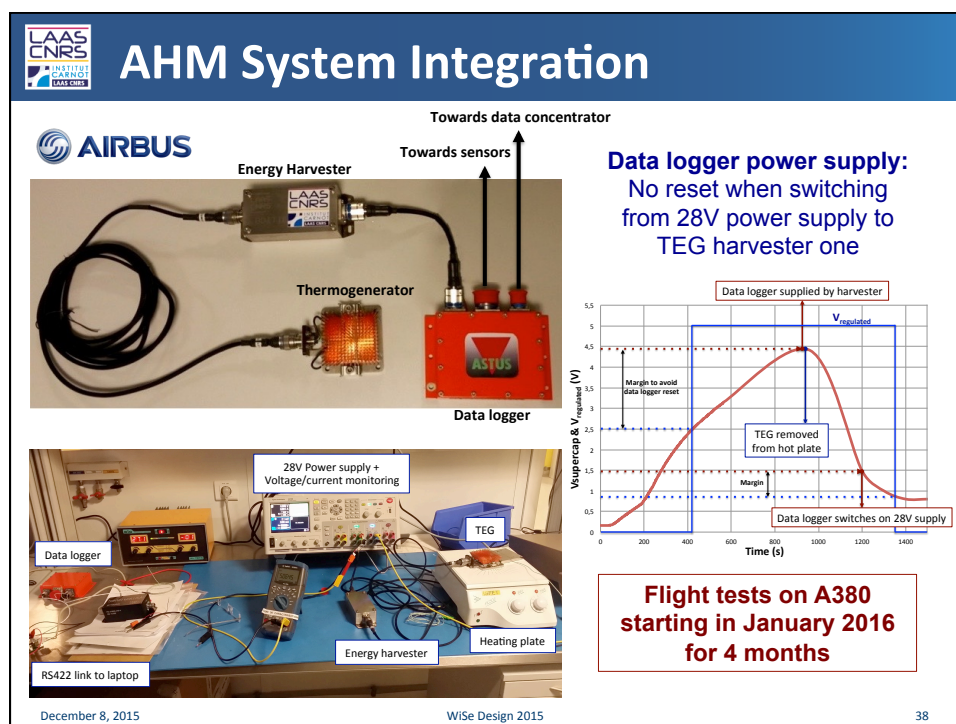
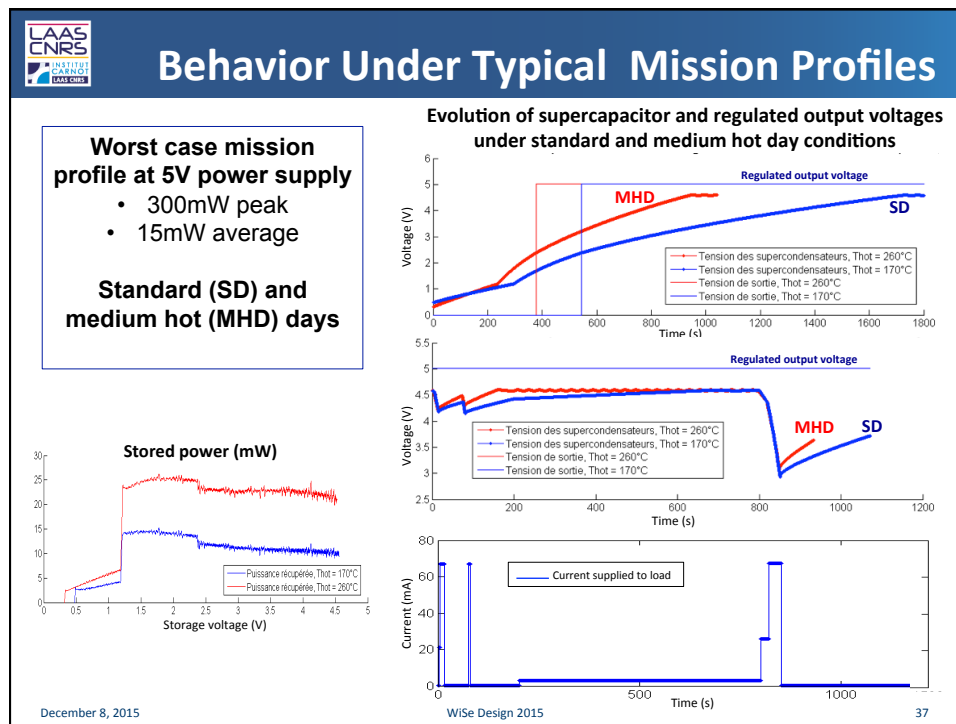
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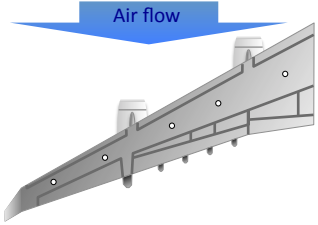
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Energy Harvesting for Aircraft Health Monitoring

Aeroacoustic energy harvesting

INVESTISSEMENTS D'AVENIR

ONERA
THE FRENCH AEROSPACE LAB

IMFT
INSTITUT DE MÉCANIQUE
DES FLUIDES DE TOULOUSE

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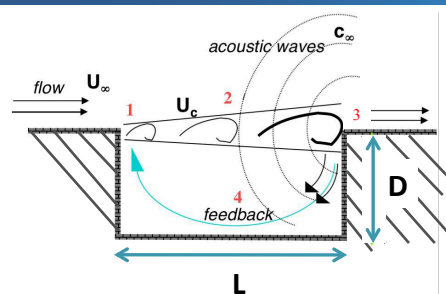
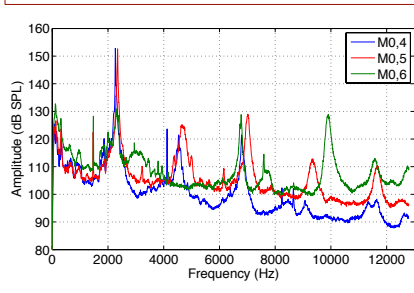
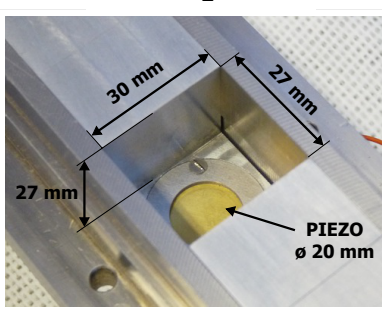
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Aeroacoustic Noise

■ Rossiter model for frequency peaks

$$f_n = \frac{U_\infty}{L} \frac{n - \alpha}{M + \frac{1}{\kappa}}$$

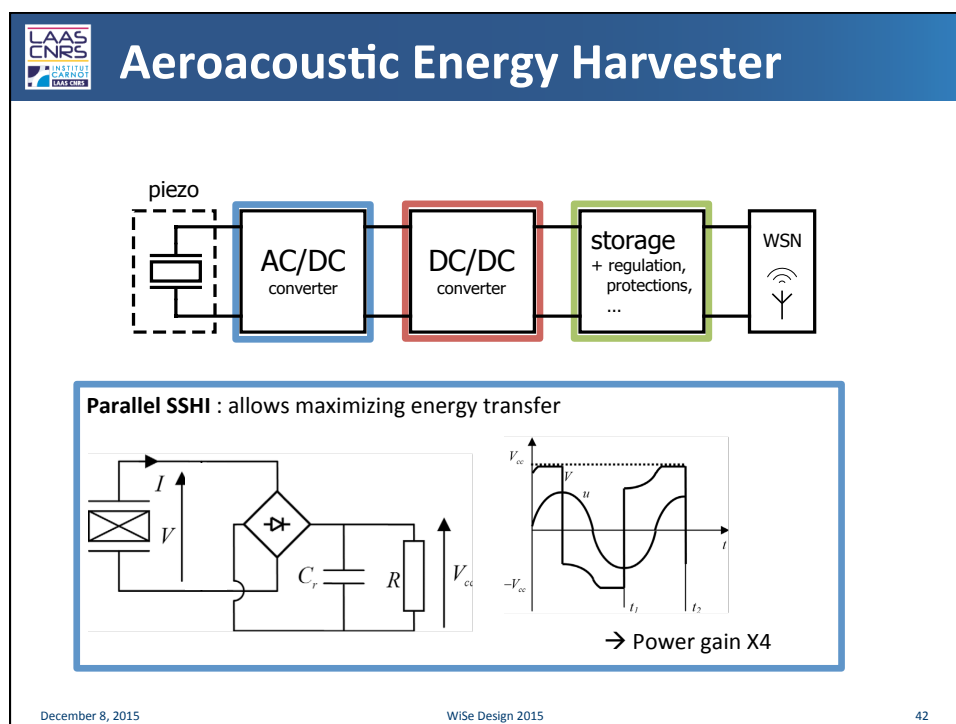
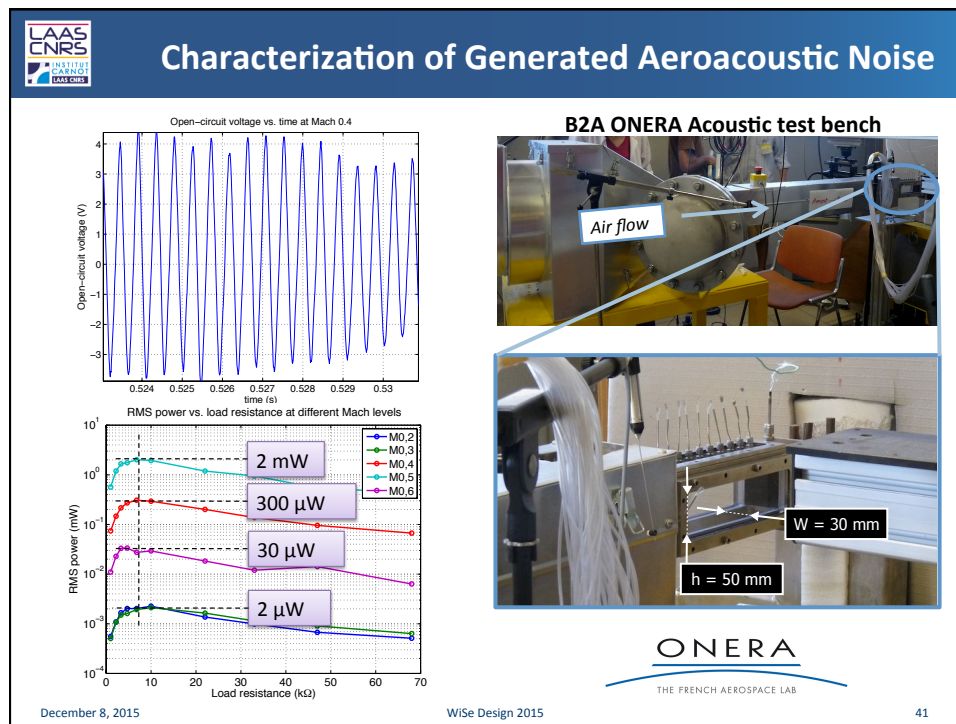
U_∞ : free airflow speed
 L & D : cavity length & depth, respectively
 Ma : number of Mach
 n : considered Rossiter mode
 α, κ : semi-empirical parameters depending on L/D

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Aeroacoustic Energy Harvester

piezo

AC/DC converter

DC/DC converter

storage
+ regulation,
protections,
...

WSN

Buck-Boost in discontinuous conduction mode: provide impedance matching whatever load conditions

Input impedance: $Z_{in} = \frac{2Lf_s}{\delta^2}$

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Aeroacoustic Energy Harvester

piezo

AC/DC converter

DC/DC converter

storage
+ regulation,
protections,
...

WSN

Supercapacitors : 2x 0.5F in series ($V_{max}=5.5$ V)

conv. DC/DC

V_{scap}

bal

OVLO

UVLO

To load

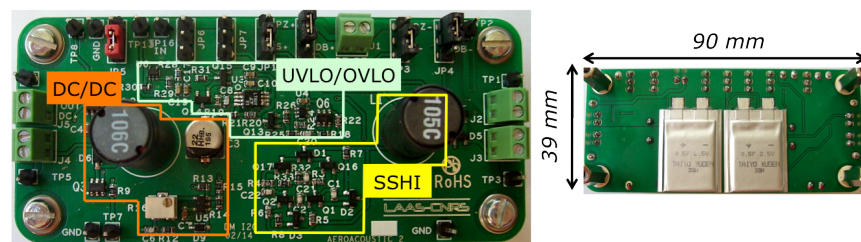
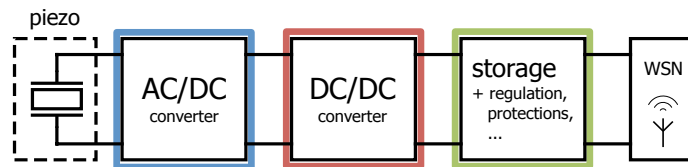
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Aeroacoustic Energy Harvester



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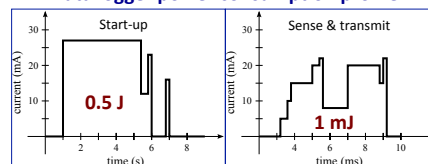
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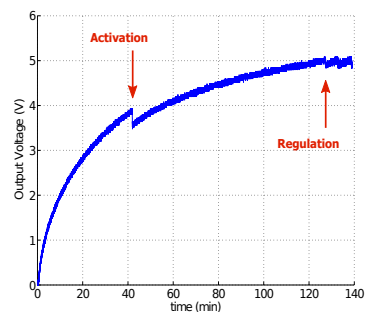


Powering a Jennic JN5148 Data Logger

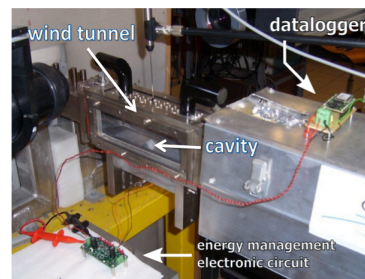
Data logger power consumption profile



Average
data logger
power
180 μ W



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

Air flow

charge

discharge

Charge

Discharge

DC-DC activation threshold

Almost instantaneous availability of energy

+13% autonomy

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On-chip micro-storage

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

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

Technologies investigated at LAAS-CNRS

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

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

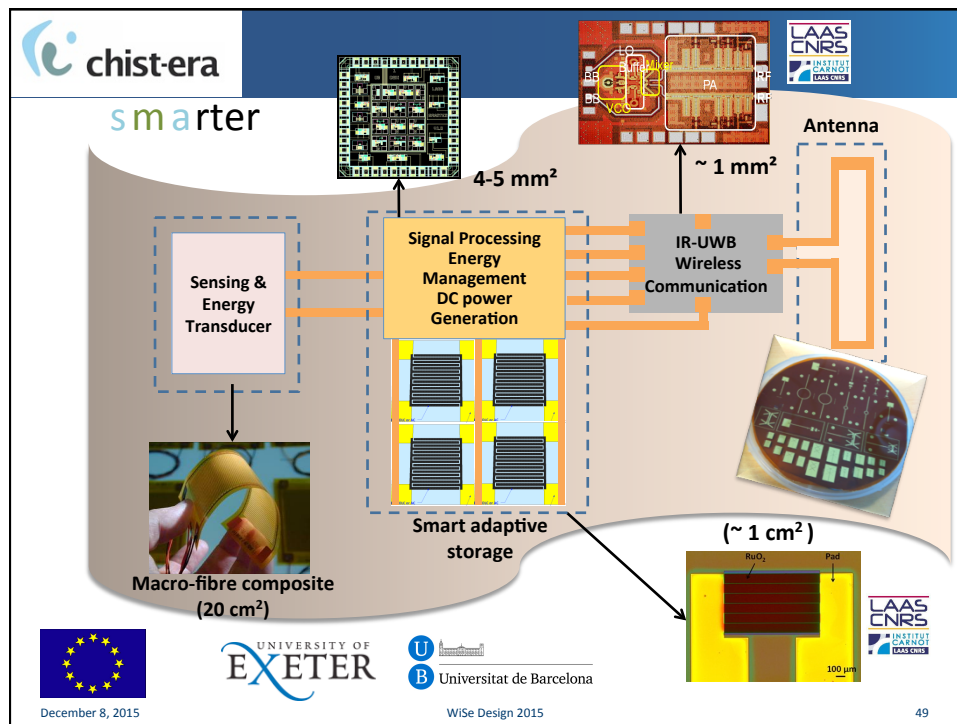
Electrolytic Deposition (RuO₂)
D. Pech et al., J. Power Sources 230 (2013) 230.

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

3F/cm²
450 mJ.cm⁻²

0.7 W.cm⁻²

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Conclusion

Aeronautics has a true need for wireless sensing

- 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
 - Dependability over aircraft lifetime has to be proven

