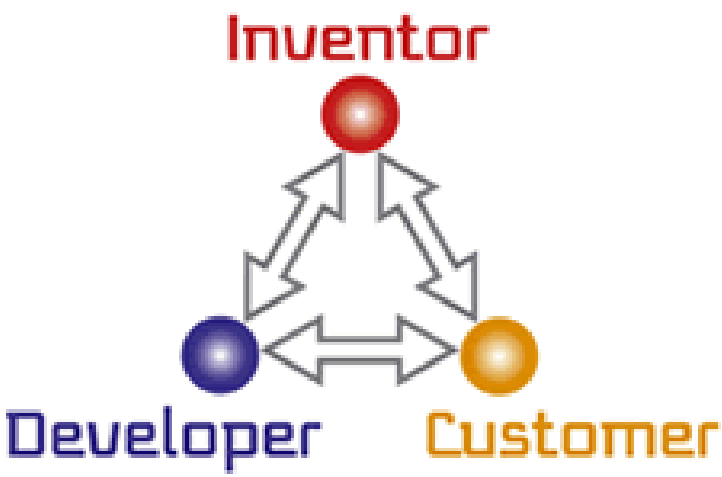
Wireless Passive Sensors for Temperature Monitoring Systems

ITI - type B activity



Final Presentation

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Subject of the activity

➢ Problem to be addressed

- Reduce AIT costs for temperature monitoring on space platforms during on-ground environmental tests
- Improve installation flexibility and reduce payload mass

– Huge quantity of temperature sensors installed in a medium size satellite, more than 500 copper-constantan thermocouples

– All sensors wired to the acquisition system via hermetic feed through (TVAC facility limit)

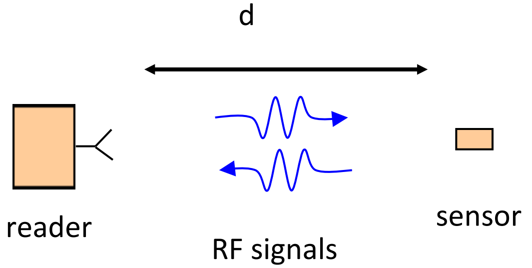
– Complexity of harnesses and assembly process

➢ Solution proposed

- Replace part of conventional wired thermocouples with wireless instrumentation
- Use of RF based systems relying on SAW passive sensors for temperature remote monitoring

<u>*Principle of operation*</u>

- *The reader/interrogator launches a RF signal to the sensor*
- *An echo is received back with temperature information (back scatter from the sensor)*
- *Very similar to radar operation*



Origin of the technology

- Spin-in from terrestrial wireless systems
  - Technology of SAW passive devices as remotely readable passive sensors
  - Initial studies appeared more than 20 years ago
  - Only in recent years practical systems have been designed and developed for use in terrestrial commercial markets

→**Basic idea**: apply the above technique for mapping the temperature within a spacecraft

Innovation content

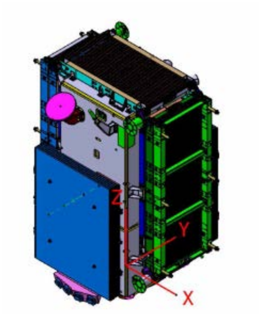
➢ Novelty of the proposed solution

- Temperature remote sensing based on radio frequency signals

with

- SAW passive sensor devices

in the frame of



Satellite in stowed configuration

- Shielded compartments with multipath fading and LOS/NLOS conditions of a satellite structure

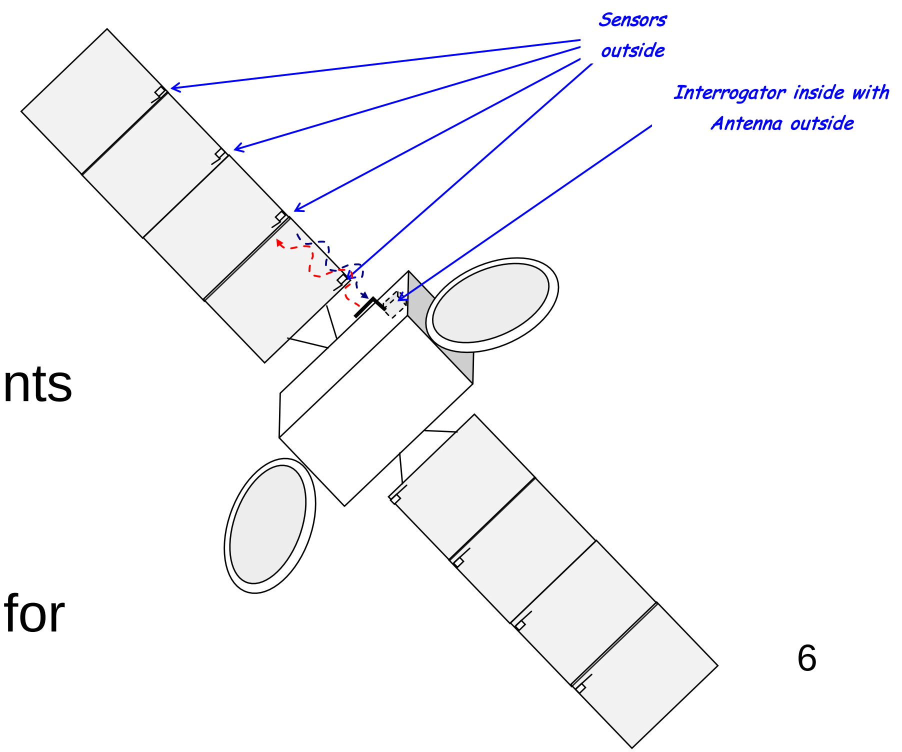
Innovation content

➢ Targeted space application

- On-ground test campaigns for space platforms, with particular regard to thermal vacuum tests

→ Then perspective for extension to space flight applications:

- Structural health monitoring during launch phase
- In flight temperature telemetry inside spacecraft compartments
- In flight temperature telemetry outside spacecraft structure, for instance on solar panels



Innovation content

➢ Benefits

- No wires → reduction of harnesses complexity, leading to shorter integration times and reduced payload mass
- No batteries and no active circuits, simple piezoelectric device, no maintenance, robustness and reliability
- Wide temperature range and insensitivity to ionising radiation
- Flexibility in modifying an already installed configuration (adding of a sensor)
- Ideally suited where access is limited or restricted and where providing power supply to sensors is difficult (with respect to active sensors)
- Removal of wire bundles and slip-rings of rotating joints

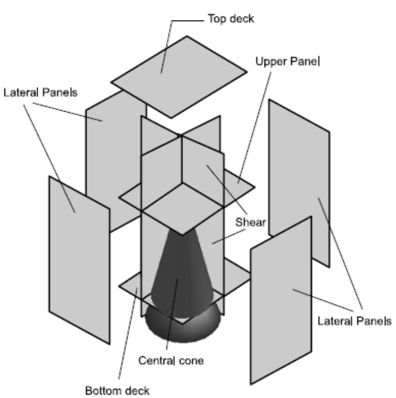
Work performed

- Objective
  - Demonstrate feasibility of wireless temperature monitoring on board of space platforms
- Activity steps
  - definition of operational and functional requirements
  - review of RF interrogation techniques applicable to SAW passive sensors
  - selection of a COTS wireless system to be used
  - design and implementation of a test bed, duly scaled
  - test verification over temperature and vacuum conditions, EMC included

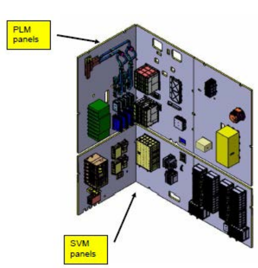
Work performed

➢ Operational constraints

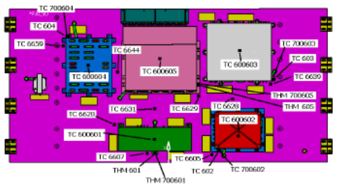
- Typical intra satellite structure composed of multiple cavities
- Single cavity with metal boundaries (panels), size of 1 meter order of magnitude, avionic equipment internally mounted (metal boxes) and MLI cover when needed
- RF propagation according to LOS/NLOS and multipath fading due to multiple reflections → quasi-mode stirred cavity
- EMC limits, RE and RS, versus existing satellite electronic systems



Satellite structure with basic compartments



C shaped panels (half deployed)



Single panel

Work performed

➢ Functional requirements

- Functional requirements on temperature measurement are derived from typical space requirements

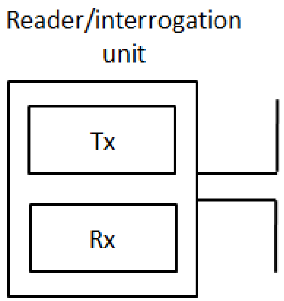
Temperature range	-40 ÷ +90 °C
Temperature accuracy	±2 °C
Resolution	0.1 °C
Sampling time	1÷30 s
Real-time availability	1 s

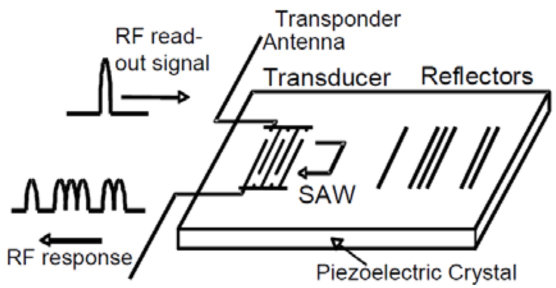
- The most common temperature range has been determined as -40 ÷ +90 ° C
- T-type Cu-Co thermocouples used as reference temperature sensors
- Sampling time is the rate the measurement is performed (temperature is a slowly varying parameter)
- Real-time availability refers to the maximum delay allowed between measurement time and delivery time to the acquisition system

Work performed

➢ Interrogation techniques with SAW sensors

- System composed of a reader and a number of sensors
- Completely passive sensors: a substrate of piezoelectric material (Quartz or LiNbO3)
- Technical complexity moved to the reader unit: very peculiar RF interrogation signal
- Two functions: identification and sensing → SAW tagged-sensor
- Anti-collision function: capability to identify and distinguish the sensors responses
- Multiple access techniques for anti-collision: FDMA, TDMA, CDMA and combinations
- Spectral efficiency intended as number of sensors per unit bandwidth ≈ 1÷3 MHz per sensor
- From commercial market: systems developed only with FDMA like approach, other types seem to be still at laboratory level prototypes

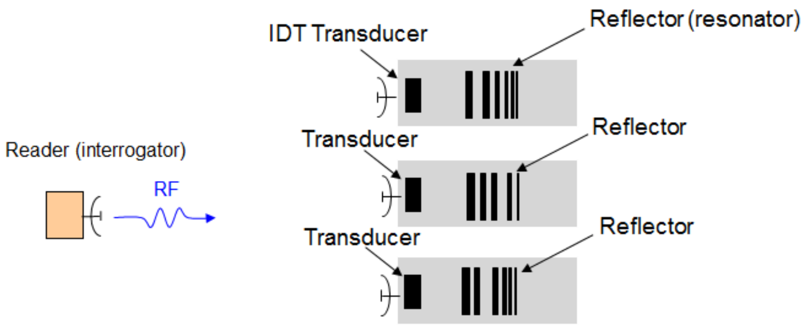


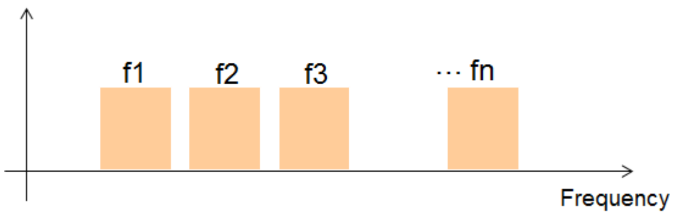


Work performed

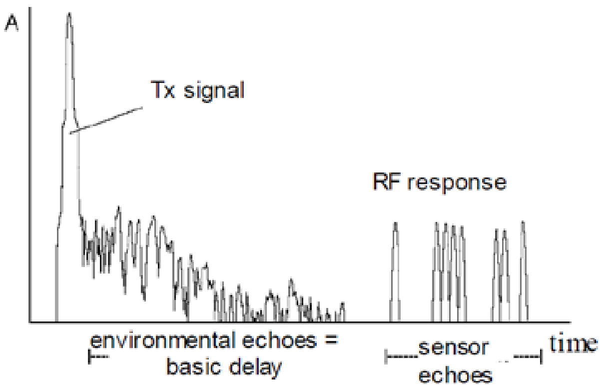
➢ FDMA like interrogation

- Sensor Identification
  - SAW device as a narrow band high Q resonator
  - Orthogonal to each other in frequency, i.e. different frequency bands for each sensor
  - SAW storage time (delay) longer than the duration of the decay of the environmental electromagnetic RF request echoes, 10 µs versus 10 ns over short distances (a few meters)





- Temperature Detection
  - shift of the centre frequency of the resonator with a typical temperature coefficient of ≈ 10 kHz/° C at 430 MHz



Work performed

- Selected system kits

  - SENSeOR (France) selected as main system for pass/fail criteria, deployed within the primary cavity of the test bed

  - Sengenuity (Germany, part of Vectron International) selected as auxiliary system, deployed within the secondary cavity of the test bed

	Frequency Range (MHz)	N° of sensors	Temp. range (°C)	Temp. accuracy (°C)
SENSeOR	430÷445	6	-40/ +90	±2
Sengenuity	429÷438	6	-25/+120	±3

Innovation Triangle Initiative

Work performed

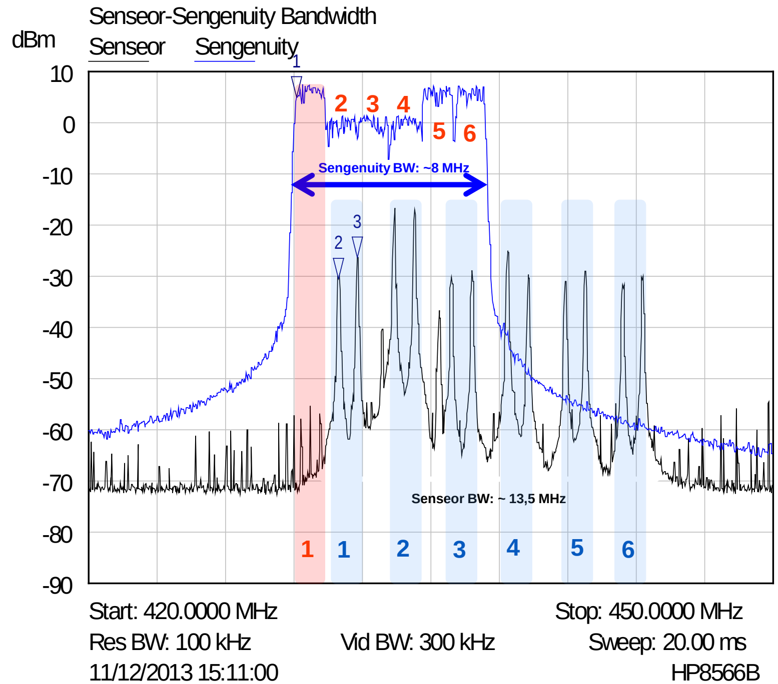
esa

➢ Spectrum of interrogation signals

Sengenuity Frequencies:

Sensor 1: 429 MHz
Sensor 2: 431 MHz
Sensor 3: 432,2 MHz
Sensor 4: 433,7 MHz
Sensor 5: 435,1 MHz
Sensor 6: 436,5 MHz

Almost the whole Sengenuity bandwidth is covered by Senseor frequencies



Mkr	Trace	X-Axis	Value	Notes
1 ▽	Sengenuity	429.1200 MHz	5.00 dBm	
2 ▽	Senseor	430.9500 MHz	-30.50 dBm	
3 ▽	Senseor	431.7900 MHz	-26.40 dBm	

Senseor Frequencies:

Sensor 1: 430,9 MHz – 431,8 MHz
Sensor 2: 433,4 MHz – 434,3 MHz
Sensor 3: 435,9 MHz – 436,8 MHz
Sensor 4: 438,9 MHz – 439,3 MHz
Sensor 5: 440,9 MHz – 441,8 MHz
Sensor 6: 443,4 MHz – 444,3 MHz

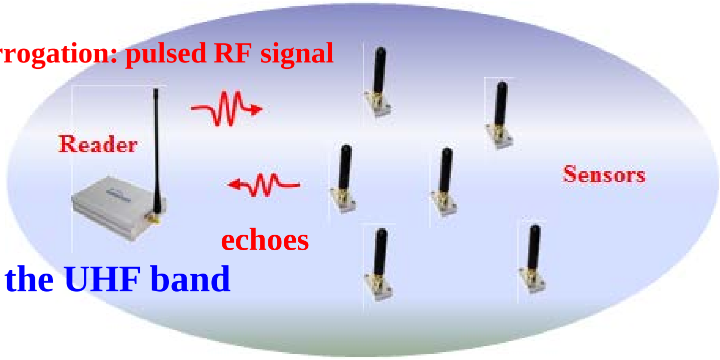
Only a few frequencies overlap with Sengenuity bandwith

Work performed

➢ Main wireless system (SENSeOR)

- Based on Frequency Domain Sampling (FDS), pulsed interrogation signal
- Interrogation mechanism very similar to RF Vector Network Analyzer swept frequency measurement: sweep of a frequency source with a spectral response narrower than that of the resonator and measure the signal amplitude
- Sensitive to saturation effects in the receiver
- ALC (Automatic Level Control) mode, the transmitted power level is adjusted over 31 dB dynamic range in order to maintain a fixed and optimal level at receiver input
- Dual resonator: differential design with opposite temperature coefficients for improved accuracy but two times the frequency bandwidth required
- Dual interrogating antennas for more robustness to multiple reflections, but may also work with a single antenna

SAW sensor within the package
(5 x 5 mm, without antenna)



Operation frequency in the UHF band

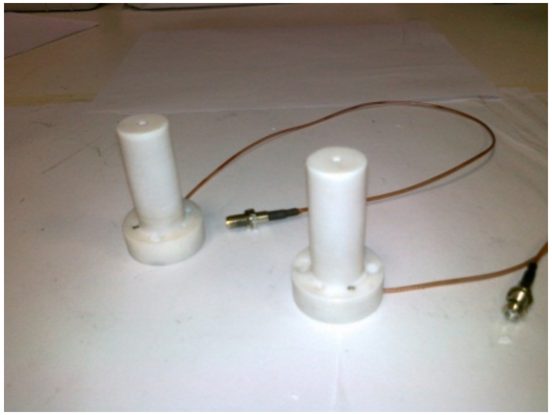
Work performed

➢ Main wireless system (SENSeOR)

Reader

Interrogation antennas

Wireless Sensors



Work performed

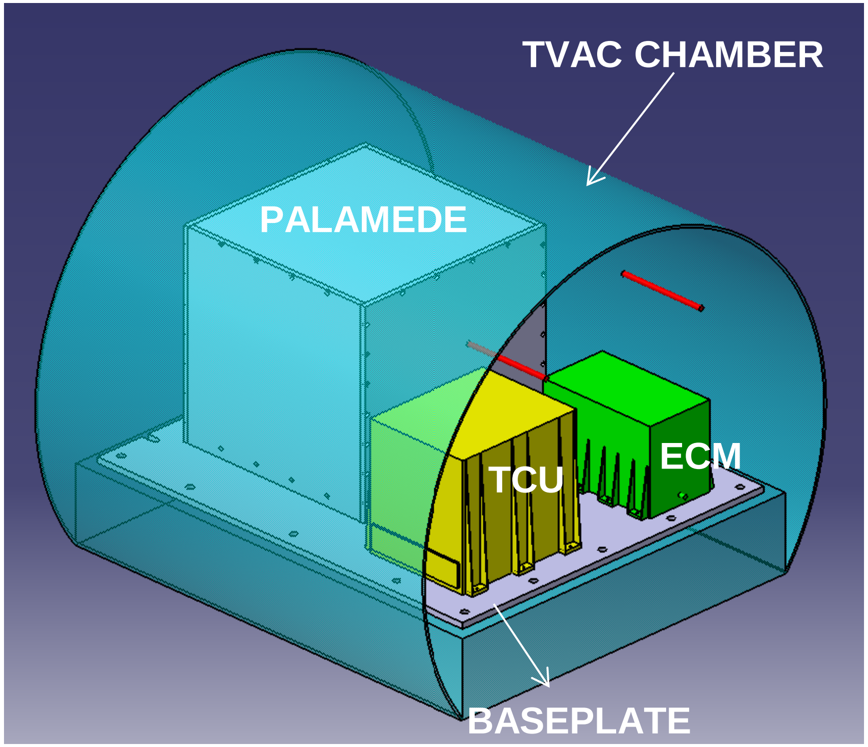
➢ Auxiliary wireless system (Sengenuity)

- Based on Time Domain Sampling (TDS), pulsed interrogation signal
- Double heterodyne down-conversion is employed in reception with in-phase and quadrature sample streams at baseband
- Low sensitivity to saturation effects in the receiver
- Fixed transmitted power level, adjustable by software interface
- Single resonator design for the sensors
- Single interrogating antenna

Work performed

➢ Test bed design

- The Test Bed simulates the operational constraints related to RF propagation: 1 meter size cavity with metal walls and with metal boxes (equipment) internally mounted, vacuum conditions over temperature range
- Palamede microsatellite has been employed (by courtesy of Politecnico di Milano)
- The TVAC chamber boundaries represent the primary satellite cavity with SENSeOR system deployed
- Palamede is the secondary cavity with Sengenuity system installed

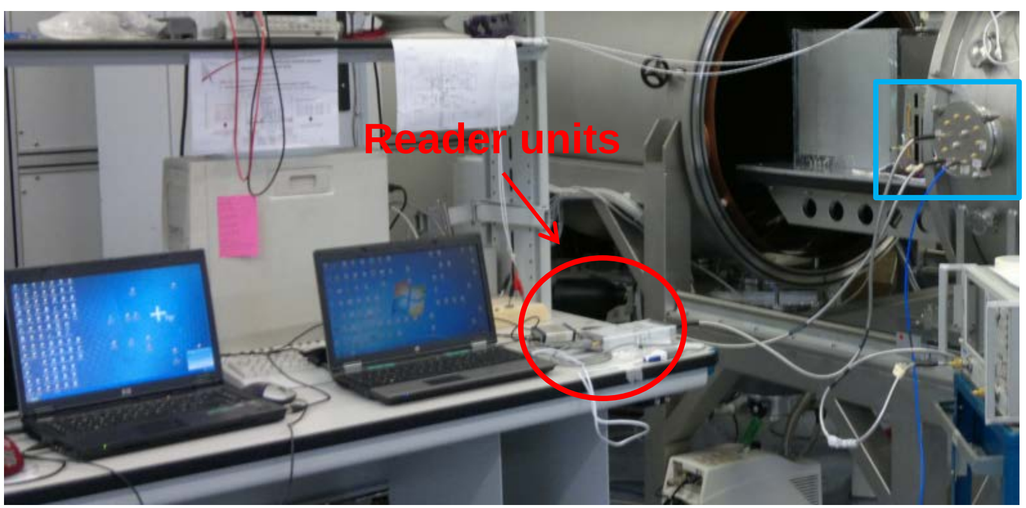


- The dual cavity allows verification of Space Division Multiple Access (SDMA), main and auxiliary systems share common frequencies → frequency reuse
- MLI cover sheets are not used

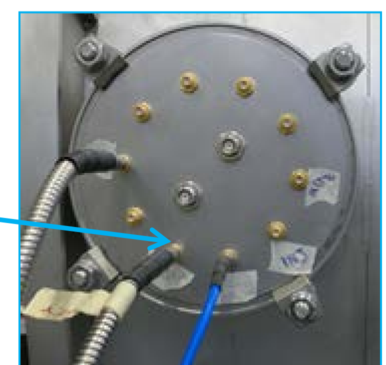
Work performed

➢ Test bed implementation

- Selex ES thermal vacuum chambers test facility
- The reader units of the wireless systems are placed outside the chamber and connected to the internal interrogation antennas via hermetic coaxial feed through
- PC's are used for interfacing the readers



Hermetic coaxial feed through



Work performed

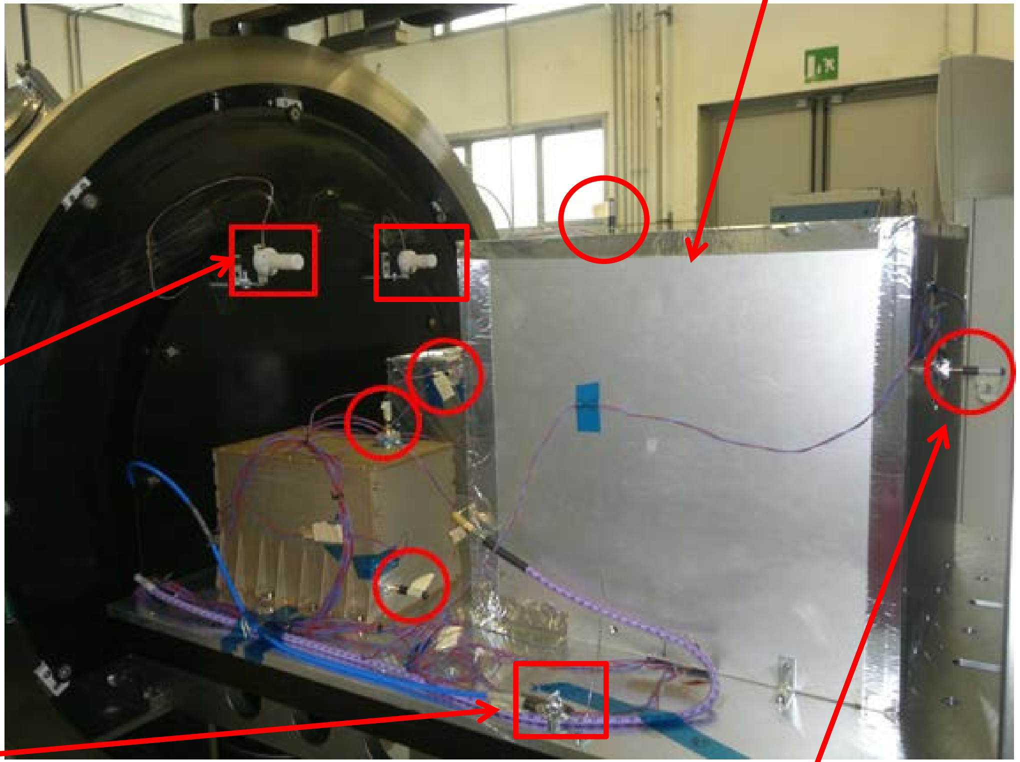
➢ Test bed implementation - primary cavity

- SENSeOR: main wireless system with 6 sensors
- Injection antenna used to test system susceptibility against interference RF noise (as verification of EMC tests in anechoic chamber)

View of open chamber

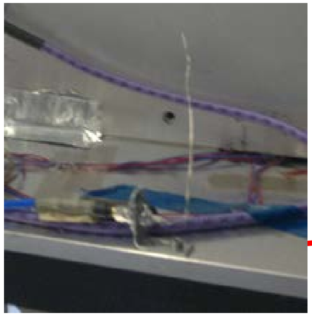
Palamede case (secondary cavity)

Interrogating Antennas



Injection antenna

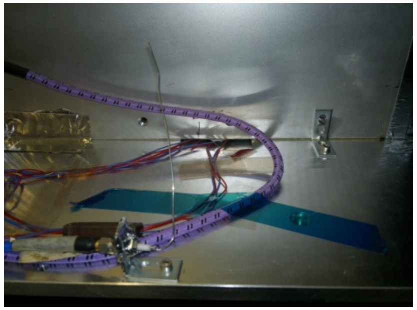
(ground-plane wire antenna)



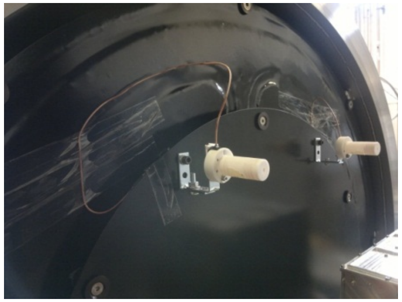
Wireless Sensor

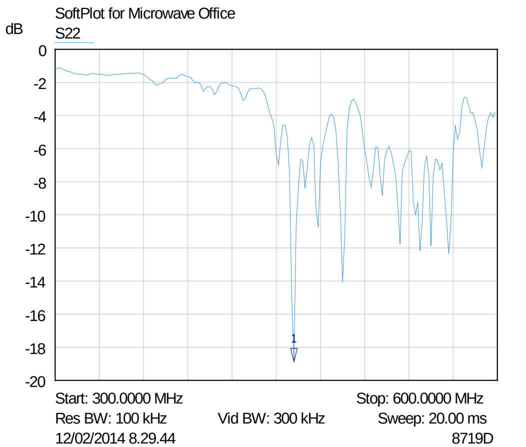
Work performed

- Test bed implementation - primary cavity
  - Antennas return loss, measured with closed chamber



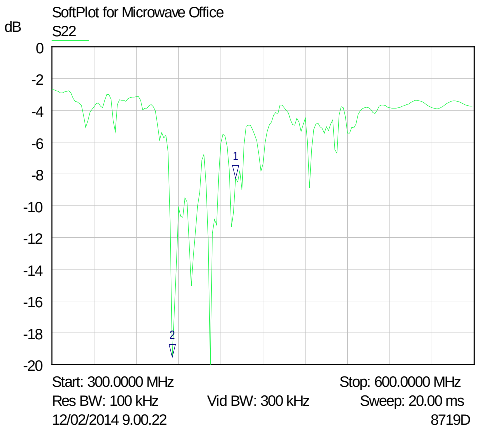
The antenna operates as a probe, gain and directivity are not relevant, but only coupling to the cavity



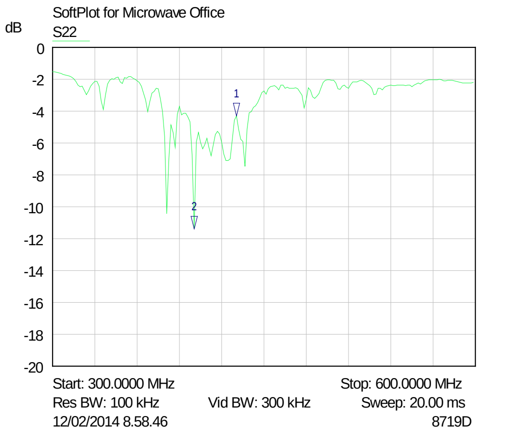


Mkr	Trace	X-Axis	Value	Notes
1 ▽	S22	462.0000 MHz	-18.88 dB	

Injection antenna
(tuned at a slightly higher frequency)



Mkr	Trace	X-Axis	Value	Notes
1 ▽	S22	430.5000 MHz	-8.26 dB	
2 ▽	S22	385.5000 MHz	-19.54 dB	



Mkr	Trace	X-Axis	Value	Notes
1 ▽	S22	430.5000 MHz	-4.29 dB	
2 ▽	S22	400.5000 MHz	-11.39 dB	

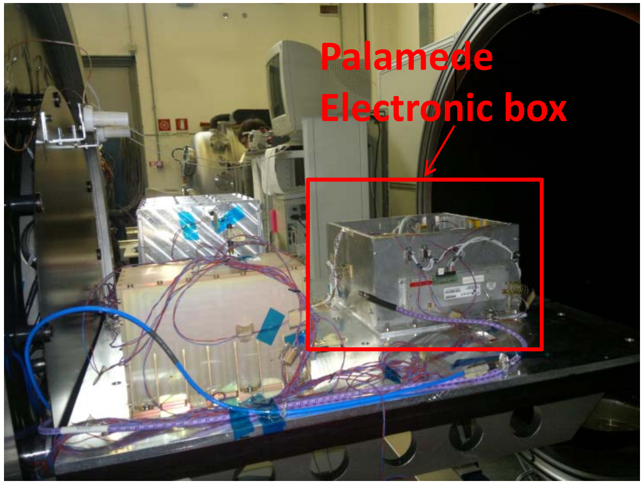
Senseor system antennas

Work performed

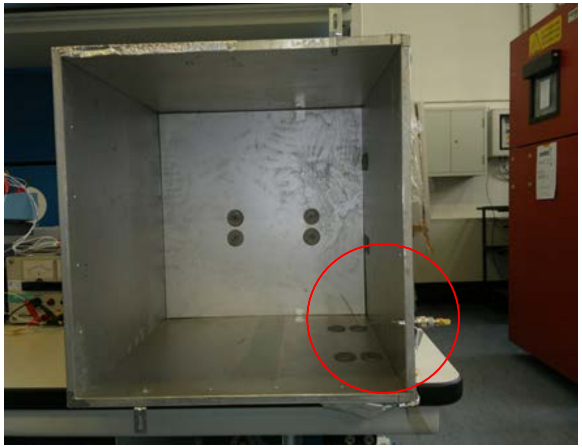
➢ Test bed implementation - secondary cavity

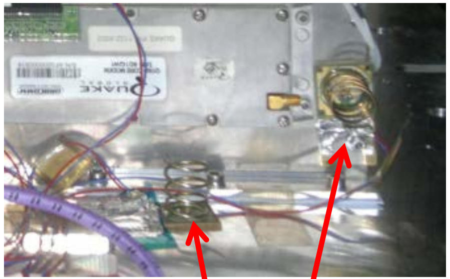
- Sengenuity: auxiliary wireless system with 6 sensors

Electronic box without case

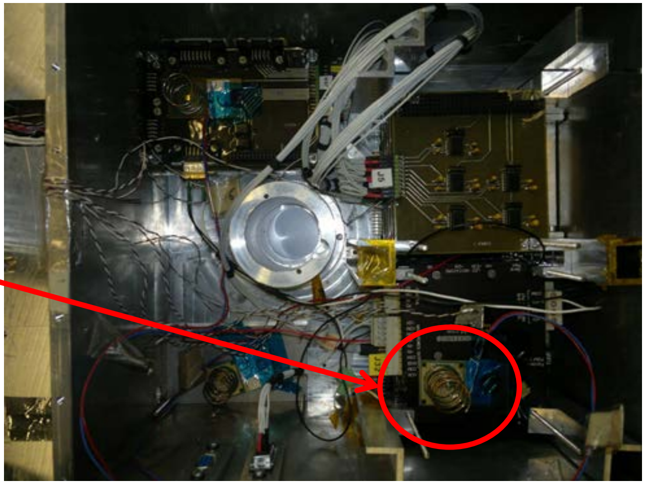


Interrogation antenna in Palamede case: ground plane wire antenna with SMA connector





Wireless Sensor



Electronic box top view

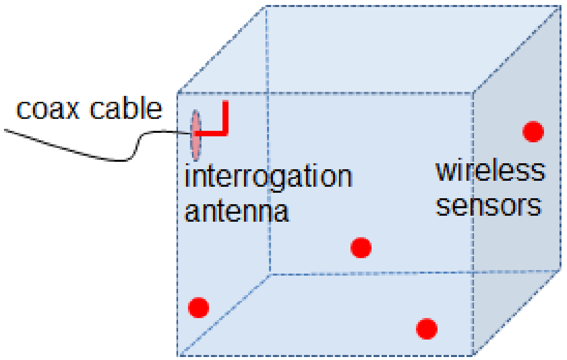
Work performed

- **Mode Stirred cavity**
  - Cavity size (1÷3 meters) > RF signal wavelength, λ ~ 70 cm at 430 MHz
  - Quasi-mode stirred behaviour
  - Field distribution as a result of multiple reverberation effects
  - About 10 dB Electric Field amplitude variation has been measured from point to point within the primary cavity
- **Isolation between cavities** (at 430 MHz)
  - 30 dB isolation measured with harness deployed between the two cavities
  - 50 dB isolation measured with harness removed
- **MLI**
  - 10 layers lay-up with double side aluminized, 6 μm polyester film interleaved with 10 layers polyester non-woven spacer. External Al layer with thickness of 250 Å
  - From laboratory tests, MLI sheets seem to heavily attenuate the RF signal at UHF frequencies despite the penetration depth is much higher than aluminium metal thickness (to be further verified)
  - Acceptable attenuation only with a single or dual Al layer
  - Not used in the test bed

Work performed

➢ Wireless sensing setup and calibration

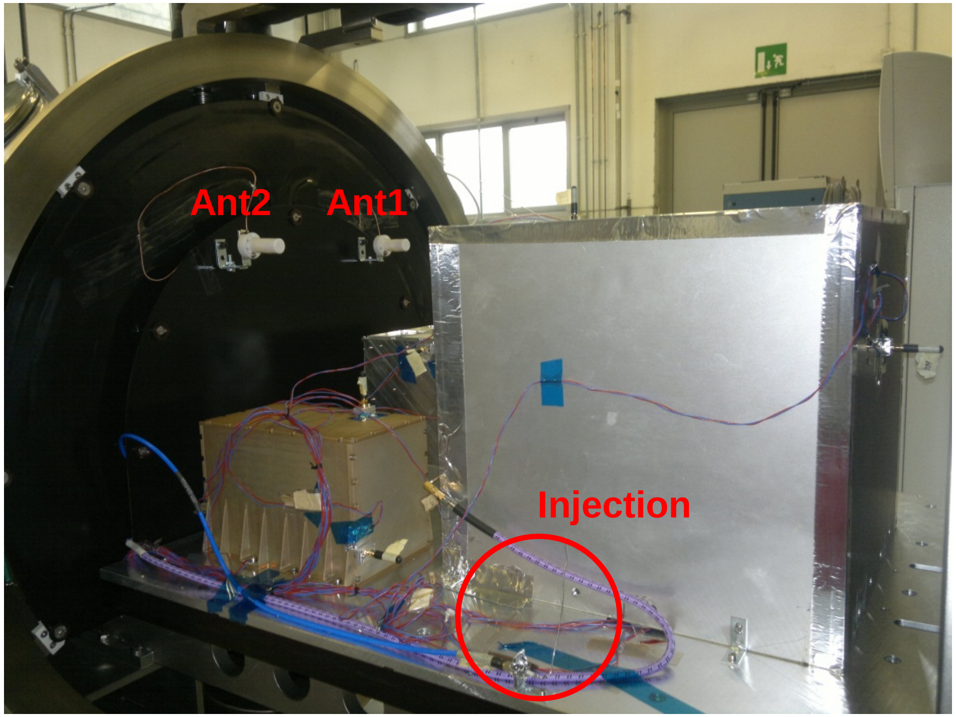
- Deployment of sensors within the compartment
- Interrogation antenna is integrated with the panel structure
- System calibration is performed at reference temperature, typically at ambient temperature
- Electromagnetic conditions have to remain stable after system calibration



Satellite compartment with integrated antenna

Work performed

- Link budget – SENSeOR system
  - **Implemented EM configurations for the interrogating antennas**
    - Dual antenna nominal (the two antennas from SENSeOR, Ant1 and Ant2)
    - Dual antenna modified (SENSeOR antenna 2 with a wire antenna, laboratory made, i.e injection antenna)
    - Single 1 (SENSeOR)
    - Single 2 (SENSeOR)

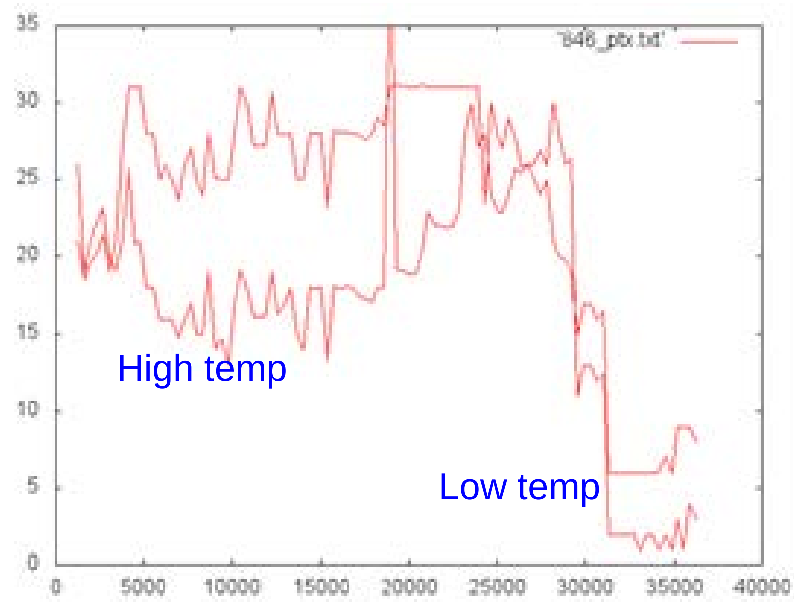


Work performed

➢ Link budget – SENSeOR system

- Tx power level during operation over a temperature cycle
- Each sensor has two resonators

  → two power curves
- Tx power decreases at low temperature
- It is expected that SAW insertion losses are lower at low temperature
- Link budget limits are respected over any of the four implemented configurations for the interrogating antennas



Data extracted from system internal monitors

31 dB Tx dynamic range (0-31)

0 → -21 dBm

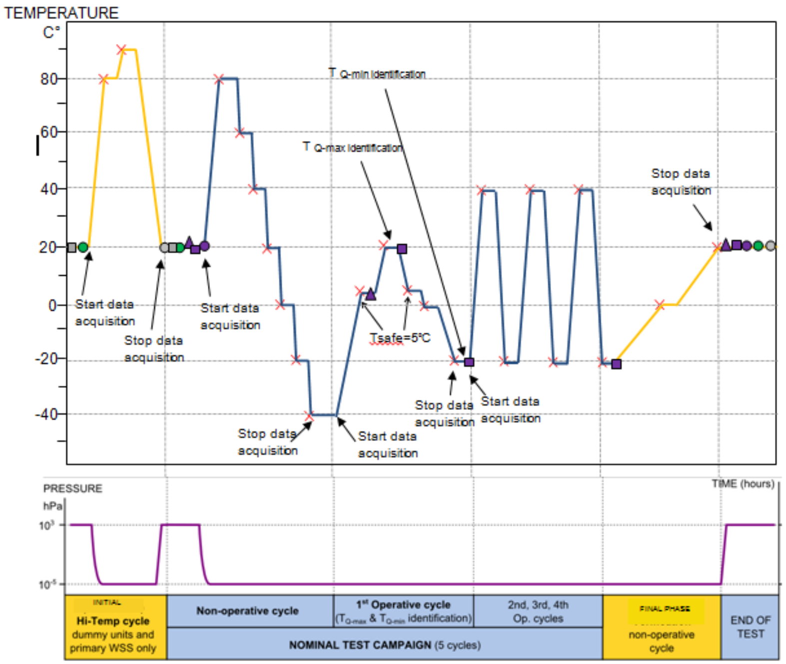
31 → +10 dBm

Results and tests

➢ Temperature tests under vacuum conditions

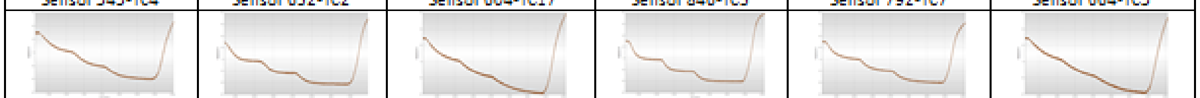
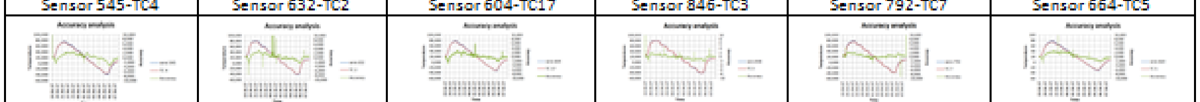
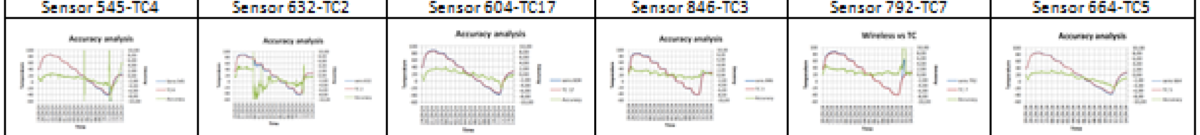
- Each wireless sensor is equipped with a reference thermocouple for comparison purpose, measurements done with 1 second sampling time
- Time synchronization between wireless systems and recorders of thermocouples

- Multiple Temperature cycles are performed
- +20/+90 deg C
- -40/+80 deg C
- -40/+90 deg C
- Under different EM conditions, depending upon the configuration of the interrogating antennas



Results and tests

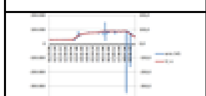
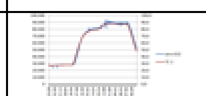
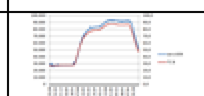
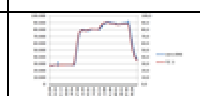
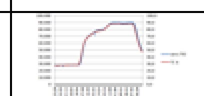
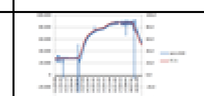
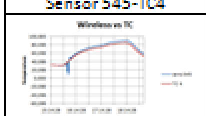
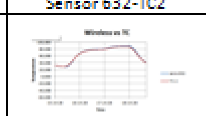
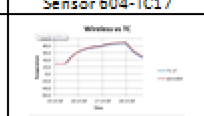
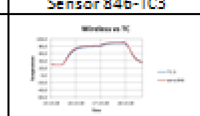
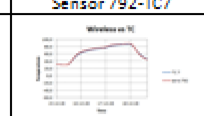
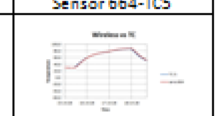
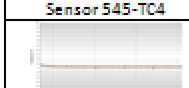
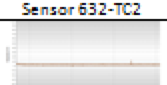
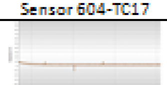
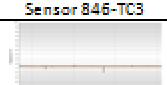
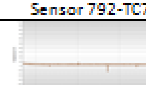
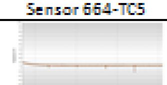
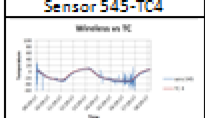
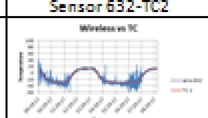
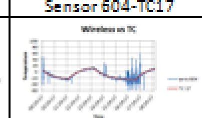
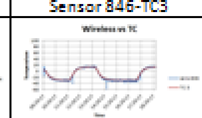
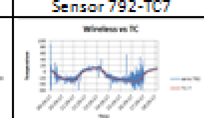
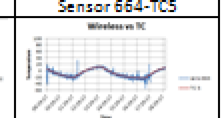
- Temperature cycles - SENSeOR

	Sensor 545-TC4	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Antennas Config	PC	Firmware	Remarks
11 Febbraio							Dual Nominal	Sicral 2	Old	• Palamede Off • Seng On
12 Febbraio	Sensor 545-TC4 	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Single 2	RF	Old	• Palamede Off • Seng On
12-13 Febbraio NOTTE	Sensor 545-TC4 	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Single 2	RF	Old	• Palamede Off • Seng On
13-14 Febbraio NOTTE	Sensor 545-TC4 	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Dual Invert	RF	Old	• Palamede Off • Seng On
14-15 Febbraio NOTTE	Sensor 545-TC4 	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Single 1	Sicral 2	Old	• Palamede Off • Seng On
18-19 Febbraio NOTTE	Sensor 545-TC4 	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Dual modified	Sicral 2	Old	• Palamede Off • Seng On
19-20 Febbraio NOTTE	Sensor 545-TC4 	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Dual modified	Sicral 2	NEW	• Palamede Off • Seng On • Moving average
20-21 Febbraio NOTTE	Sensor 545-TC4 	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Dual modified	Sicral 2	NEW	• Palamede Case • Tamb-Vacuum • Moving average • +90°C, -40°C

Results and tests

➢ Temperature cycles – SENSeOR

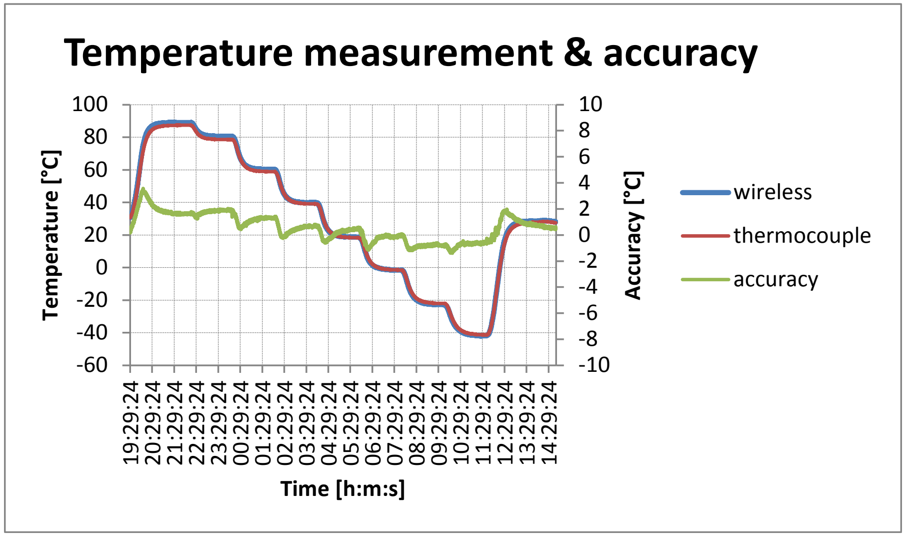
- Some bugs in the firmware of the reader were detected and fixed
- Firmware was upgraded during the test campaign
- During temperature cycle with Palamede in on condition, Palamede spurious emission has induced noise on temperature reading
- The spurious level was verified to be comparable with system susceptibility as observed during EMC test (a few mV/m Electric Field at 433 MHz, harmonic frequency of internal CPU clock)

	Sensor 545-TC4	Sensor 632-TC2	Sensor 604-TC17	Sensor 846-TC3	Sensor 792-TC7	Sensor 664-TC5	Antennas Config	PC	Firmware	Remarks
30 Gennaio							Dual Nominal	Sicral 2	Old	• Palamede Off • Seng On
20 Febbraio	Sensor 545-TC4 	Sensor 632-TC2 	Sensor 604-TC17 	Sensor 846-TC3 	Sensor 792-TC7 	Sensor 664-TC5 	Dual Nominal	Sicral 2	New	• Palamede case • Moving average
17-18 Febbraio NOTTE	Sensor 545-TC4 	Sensor 632-TC2 	Sensor 604-TC17 	Sensor 846-TC3 	Sensor 792-TC7 	Sensor 664-TC5 	Single 2	Sicral 2	Old	• TVAC • 5°C, Vacuum
18 Febbraio	Sensor 545-TC4 	Sensor 632-TC2 	Sensor 604-TC17 	Sensor 846-TC3 	Sensor 792-TC7 	Sensor 664-TC5 	Dual modified	Sicral 2 (CTRL)	Old	• Palamede Oncase • Seng On

Results and tests

➢ Temperature tests results: accuracy analysis

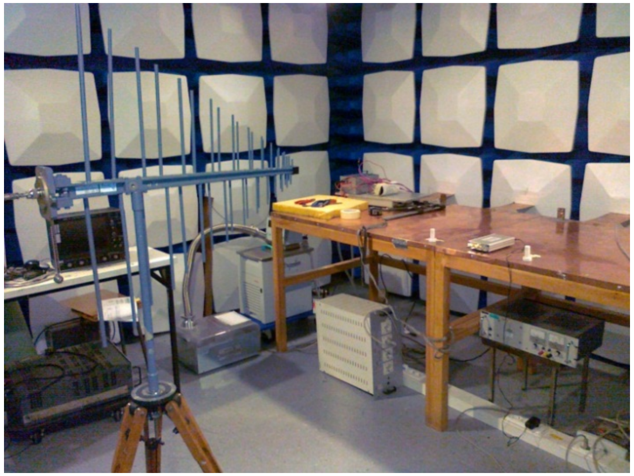
- Typical sensor measurement together with reference thermocouple as acquired over a temperature cycle
- Sensor and thermocouple overlap with the accuracy indicated by the green curve, accuracy being the difference between sensor and thermocouple temperatures
- It is clearly noted the effect of the thermal time constant of the commercial sensor package, observed as a delay versus thermocouple reading during thermal transitions
- The sensor outline has to be newly designed for the intended application
- Accuracy of ±2° C is generally achieved



Results and tests

➢ EMC test

- Radiated Emissions test



- Emissions measured at 1 meter distance from interrogation antennas, with +10 dBm RF output power
- No sensors installed → ALC forced to maximum power

- Radiated Susceptibility test

- Susceptibility verified with sensors deployed on copper test bench along with interrogation antennas, the latter at 1 meter distance from test facility antenna

Results and tests

EMC test results

RE	System emissions	Satellite susceptibility requirement (equipment level)	Remarks
	95 dBµV/m	126 dBµV/m (2 V/m)	OK
RS	System susceptibility threshold (20 dB margin)	Satellite emissions requirement (equipment level)	Remarks
	46 dBµV/m	60 dBµV/m	14 dB notching, seems feasible

- Emission levels at 430 MHz, 2^{nd} harmonic is 20 dB lower
- No concern for the system emissions with +10 dBm Tx RF power
- Regarding radiated susceptibility, 14 dB notching on the current requirement for satellite noise emissions is recommended in the wireless system operating frequency range, where 30 dBµV/m is typical measured emission

Further developments

- Recommended developments
  - Optimization of sensor packaging design and antennas, including the interrogation one for best fitting into the described space application, starting from existing commercial systems
- Applications
  - On-ground test campaigns for space platforms, in particular thermal vacuum tests
  - Health structural monitoring during the launch phase
  - Thermal mapping of spacecraft for in-flight operation
    - inside the spacecraft structure
    - outside it, for instance on photovoltaic assemblies
- Spin-offs
  - rotating parts of aircraft engines
  - rotary wings of helicopters

Developments roadmap