RF-MEMS Onboard a Satellite:

MEMO Flight Experiment Delivered!

J.-L.Cazaux, O.Vendier, L.Mesthé (Thales Alena Space)  
F.Courtade (CNES)
Outline

- Introduction: why a Flight Demonstrator?
- MEMO: Mission / Experience Presentation
- RF-MEMS inside MEMO
- MEMO Design
- Manufacturing and Testing of MEMO
- Conclusion
Introduction: why a Flight Demonstrator?
RF-MEMS potentialities for Space application

RF MEMS for space payloads excluding antennas
- High performance filtering
  - High Q Micromachined Filters (Ka-Band, Q/V-Band, and higher)
  - High Q BAW/FBAR Filters (C-Band and lower)
- Reconfigurable filters for wide band receivers
  - Multi-frequency filter bank or reconfigurable filter
- Self-redundant Front-End or other modules
- Advanced Local Oscillators (flexible payloads)
  - High Q BAW/FBAR Resonators
  - Variable MEMS Capacitors (at longer term)
- RF routing in flexible payloads
  - High order switch matrix in Ku band and higher

RF MEMS for application to space telecom satellite antennas
- (High power) Phase-Shifter
- Redundancy switch matrix in integrated front-end
- Reconfigurable reflect array
TAS-F is not a manufacturer of RF-MEMS

- (TAS-I has a MEMS Fab line over LTCC in L’Aquila)

4 Axis of development:

- Design: extension of our capabilities and experience in advanced microwave (ex: MMIC Design Lab)
- Reliability: tools and first studies already in place
- Qualification: a long-time experience at device/component level
- Integration: a breakthrough technology for long term evolution of our products
Flight Demonstration, for what?

Develop an Heritage

Visibility of the new technology for future customers
- Internal -> in the company
- External -> outside world

Bring it up from mid to high TRL
- Refine design / test methodology applicable to flight models
- Documentation
- Industrialisation approach

Enhance know-how for this new technology
- Use into industrial environment
- Integrate this Technology with Flight Proven Technologies
- Make Risk Assessment

Qualification of the available technology prior to flight demonstration
Decision to design and build a RF-MEMS Demonstrator

- To demonstrate In-Orbit Reliability
- To cumulate flying hours with RF-MEMS Switches
- To be embedded on a telecom satellite as a piggy bag

⇒ Ready and Low cost (both in development and in production)
⇒ Easily integrable, limited interfaces, very low consumption, small mass, no impact at payload level
⇒ Compliant with FM requirement
⇒ Absolutely immune, 0-risk, for the host satellite mission

MEMO: RF-MEMS Reliability Demonstrator

- Program launched in 2004
- Initially targetting a Technological Satellite
MEMO: Mission / Experience Presentation
Base for a Demonstrator definition

Observed failure modes for RF-MEMS Switches

- **Contact**:  
  - Contact degradation  
  - Stiction metal-metal  
  - *Electromigration (seen at high signal level)*

- **Membrane**:  
  - Residual stress, stress gradient, thermal stress  
  - *Creep (in case of metallic membrane)*

- **Electrostatic activation**:  
  - Dielectric charging

>20 Volts over 0.2 μm  
Charge injection + trapping is the main failure mode for RF-MEMS capacitive and ohmic switches
Experiment Definition

Based on DC parameters

- Fundamental solicitation modes
  - Address all kind of applications (redundancy, fast switching)

- Direct link with RF intrinsic characteristics:
  - $R_c$ (On) => Insertion Loss
  - $V_p$ => Isolation

- No need for RF parameters direct monitoring

$$R_s = 2R_c + 2R_{sl} + R_l$$

$$\text{losses} = \frac{4R_s Z_0}{|Z_s + 2Z_0|^2}$$

$$V_p = \frac{8k}{\sqrt{27\varepsilon_0 Ww}} g^{3/2}$$

Membrane spring constant

$$k = 4Ew \left(\frac{t}{l}\right)^3$$
RF-MEMS inside MEMO
MEMO: RF-MEMS Source

First RF-MEMS technology:

- Ohmic switch technology from CEA LETI, dielectric membrane, electrostatic actuator, non hermetic packaging at wafer level, Ruthenium contacts
Switch Performance: Ohmic switch (CEA-LETI technology)

a) Membrane UP

b) Membrane DOWN
Second RF-MEMS technology

- Ohmic switch technology from XLIM, metallic membrane, electrostatic actuator, no packaging, Au Alloy contact
F = 3 GHz

**MEMS XLIM " MEMO"**
Caractéristique S21=f(V)

Tension d'actuation (V)

-50 -40 -30 -20 -10 0 10 20 30 40 5

<table>
<thead>
<tr>
<th>Vpout= 32 V</th>
<th>Vpout= 32 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vpout= -32 V</td>
<td>Vpout= 32 V</td>
</tr>
<tr>
<td>Vpin= -33 V</td>
<td>Vpin= 33 V</td>
</tr>
</tbody>
</table>

Tension croissante

Tension décroissante

Vpout = 32 V, Vpin = -33 V, Vact = 40 V

Vpout = -32 V, Vpin = 33 V, Vact = 0 V

F = 3 GHz

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Basic Functions of MEMO Demonstrator

- Mode INIT: all the MEMS are switched On/Off 5 times, launched by TC
- Mode(1): MEMS aging due to On/Off cycling, launched by TC
  - 1 Cycle On/Off per second: 4 MEMS
  - 1 Cycle On/Off per day: 4 MEMS
  - 1 Cycle On/Off per year: 4 MEMS
- Mode(2): MEMS aging with sollicitation close to redundancy application
  - TC launched switch: 4 MEMS
- Mode(3) (not implemented): Monitoring of Rcontact
- Mode(4): Monitoring of Pull-in/Pull-out voltages
  - TC launched sequence: 4 MEMS
- Temperature monitoring

MEMO includes 20 RF-MEMS Switches
✓ Lot Qualification performed by CNES for the MEMS
✓ Packaged into an Hermetic Hybrid Space Qualified Micro-Package
✓ MEMS bonding: glued, wired
MEMO Demonstrator Block Diagram

- **POWER Bus**
  - TC ON
  - TC OFF

- **DC/DC board**
  - (same as FMs)

- **TMTC Board**
  - Std FM RUBI
  - Hybrid and Interfaces

- **OBDH Bus**

- **MEMS Hybrids**

- **MEMO Experiment**

- **Bias Regulators**
Demonstrator is composed of 2 Boards (PCB):
1 DC/DC et 1 TM/TC + MEMS Hybrid

- Aluminium Mono-structure with 2 covers.
- Interfaces to satellite platform by Sub-D Connectors
Main functions realized by TM/TC Board:

- Interface with SB4000 bus OBDH 485 (*including a Space Qualified RUBI hybrid as for regular TAS satellites*)
- Regulated Bias Voltages provided by DC/DC supply
- Generation of Clocks and Test signals
- Acquisition, management and processing of MEMS commands and measurements
- Generation of TeleMetries
- Include a FM FPGA to receive, decode and validate data coming from the RUBI and to manage ADC and Charge Pumps
- Including 5 Charge Pumps to operate the MEMS

This card is able to drive and monitor up to 5 Hybrids containing up to 20 RF-MEMS.
Charge Pump: ASIC Architecture

- Analog ASIC: 7.5 mm², 25 I/O, 5 K components, CMOS 0.8 µm HV
- Based on 5V & 8 MHz clock
- Deliver from **27 V to 40 V** programable bias to up to 4 MEMS
- Pd=8 mW

- Robust design, compliant with space constraints
- ASIC Process from XFAB (Ger.), High Voltage capability
- Packaged in hermetic ceramic package
- Qualified by L.A.T.
STANDARD MECHANICAL ENVIRONMENT: Specs for Vibrations

Quasi static load: Qualification level for quasi-static loads acting separately on each axis: ±10 g for out-of-plane axis, ±12 g for in-plane axes

Shocks
The equipment has to withstand a S4 severity shock test.
The applicable shock spectrum corresponds to:

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Qualification Shock Response (g) / Q = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>3000</td>
<td>2000</td>
</tr>
<tr>
<td>10000</td>
<td>2000</td>
</tr>
</tbody>
</table>

Maximum mass = 0.754 kg
Thermal analysis:

<table>
<thead>
<tr>
<th>MODULES</th>
<th>PUISSANCE (W)</th>
<th>Power dissipation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carte TM/TC</td>
<td>2,544</td>
<td></td>
</tr>
<tr>
<td>Carte DC/DC</td>
<td>0,795</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>3,339 W</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>Tmin (°C)</th>
<th>T max (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualification</td>
<td>-35</td>
<td>65</td>
</tr>
<tr>
<td>Acceptance</td>
<td>-30</td>
<td>60</td>
</tr>
</tbody>
</table>

Conclusion:
Thermal analysis shows that all component junction temperature remains below the value specified in internal reliability data base.
Thermal flux are also shown compliant with SB4000 requirements.
EMC & Radiation Analysis

EMC analysis:

<table>
<thead>
<tr>
<th>Ref. para.</th>
<th>Titre</th>
<th>Conformité</th>
<th>Commentaires</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Emission conduite sur les lignes de puissance (CE) – Domaine fréquentiel</td>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Emission conduite sur le bus OBDH</td>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>CS sinus sur les lignes d’alimentation</td>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Transitoire sur les lignes d’alimentation</td>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>Transitoire sur les lignes de télécopie</td>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>Emission rayonnée (RE)</td>
<td>C.</td>
<td>A confirmer pour les notches bande L et S</td>
</tr>
<tr>
<td>7.3</td>
<td>Champ magnétique continu</td>
<td>C.</td>
<td>Par analyse. Pas de mesure prévue.</td>
</tr>
<tr>
<td>7.4</td>
<td>Susceptibilité en champ électrique</td>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>Susceptibilité en champ magnétique</td>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Décharge électrostatique (ESD)</td>
<td>C.</td>
<td>A confirmer par un test ESD sur une maquette représentative</td>
</tr>
</tbody>
</table>

Radiation analysis:

Compliance to all environmental constraints has been demonstrated
Manufacturing and Testing of MEMO
## Test Plan

<table>
<thead>
<tr>
<th>Tests</th>
<th>Conditions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Initial inspection</td>
<td>X</td>
</tr>
<tr>
<td>T2-T3</td>
<td>Initial performance tests [IPT]</td>
<td>AP - TE + TC + TR</td>
</tr>
<tr>
<td>T4</td>
<td>Low level Sine survey</td>
<td>X</td>
</tr>
<tr>
<td>T5</td>
<td>Random vibration</td>
<td>A -TE</td>
</tr>
<tr>
<td>T6</td>
<td>Low level Sine survey Post vibration tests</td>
<td>X</td>
</tr>
<tr>
<td>T7</td>
<td>Functional tests @ 25°C [AFT 1]</td>
<td>AP - TE + TR</td>
</tr>
<tr>
<td>T8</td>
<td>OFF cycling</td>
<td>AP / A / (1)</td>
</tr>
<tr>
<td>T9</td>
<td>ON cycling</td>
<td>AP / A / (3)</td>
</tr>
<tr>
<td>T10</td>
<td>Functional tests @ 25°C [AFT 2]</td>
<td>AP</td>
</tr>
<tr>
<td>T11</td>
<td>Hot functional tests [HFT]</td>
<td>AP/ TE+TC</td>
</tr>
<tr>
<td>T12</td>
<td>Cold start [CST]</td>
<td>AP/ TE+TC</td>
</tr>
<tr>
<td>T13</td>
<td>Cold functional tests [CFT]</td>
<td>AP/ TE+TC</td>
</tr>
<tr>
<td>T14</td>
<td>Ambient functional test [ARFT]</td>
<td>AP/ TE+TC</td>
</tr>
<tr>
<td>T15</td>
<td>Functional tests @ 25°C [AFT 3]</td>
<td>AP - TE + TR</td>
</tr>
<tr>
<td>T16</td>
<td>Bounding / Grounding &amp; Isolation</td>
<td>X</td>
</tr>
<tr>
<td>T17</td>
<td>CE On Power Line</td>
<td>X</td>
</tr>
<tr>
<td>T18</td>
<td>CE on OBDH</td>
<td>TR</td>
</tr>
<tr>
<td>T19</td>
<td>CS (CW)</td>
<td>TR</td>
</tr>
<tr>
<td>T20</td>
<td>CS (Discrete)</td>
<td>TR</td>
</tr>
<tr>
<td>T21</td>
<td>Radiated Susceptibility</td>
<td>TR</td>
</tr>
<tr>
<td>T22-T23</td>
<td>Final Functional tests @ 25°C [FFT]</td>
<td>AP - TE + TC + TR</td>
</tr>
<tr>
<td>T24</td>
<td>Final inspection, mass properties</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Package for delivery</td>
<td>X</td>
</tr>
</tbody>
</table>

X : to be performed  A : Acceptance level  AP : Ambient Pressure  AT : Ambient Temperature
TE : Electrical Test  TC : Complete Functional MEMS Test  TR : Reduce Functional MEMS Test
Vibration Tests

Evaluation of RF-MEMS sensitivity in Vibration

Application of ECSS norm

- ECSS-Q-ST-70-08C « Space product assurance : Manual soldering of high reliability electrical connections ». §13.2 Vibration

Progressive Test Plan

- 50g RMS, 80 g RMS, 110 g RMS in Random

MEMS Measurement (Vact, RF Loss) after every accelerating step
Results:
- Limited on Vact drift
- Negligible impact on contact quality

Conclusion: No major risk for the mission
3 Temperatures Tests

<table>
<thead>
<tr>
<th>Températures</th>
<th>I max (mA)</th>
<th>C/NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10 °C</td>
<td>29.6</td>
<td>C</td>
</tr>
<tr>
<td>+25°C</td>
<td>29.6</td>
<td>C</td>
</tr>
<tr>
<td>+60 °C</td>
<td>29.3</td>
<td>C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NON OPERATING MODE</th>
<th>OPERATING MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>T min</td>
<td>T max</td>
</tr>
<tr>
<td>-30°C</td>
<td>+65°C</td>
</tr>
</tbody>
</table>

TNOH = T° Non Operating Hot (+65°C)
TNOC = T° Non Operating Cold (-30 °C)
TOAH = T° Operating Acceptance Hot (+60°C)
TOAC = T° Operating Acceptance Cold (-10°C)
End of the story
Major Milestones

- Program Kick-Off: 08/12/2004

- 1st MEMS Delivery (LETI): Prototypes 05/2005

- 2nd MEMS Delivery (LETI) 03/2006
  Evidence of Reliability problem on MEMS (dielectric charging, shifts on pull-in pull-out voltages)

- Functional Review with CNES: 10/2006
  Stand-by waiting for a new MEMS lot from LETI Wafer Fab 200mm

- 3rd MEMS Delivery (LETI) 07/2011

- Decision to evaluate XLIM as alternative source 10/2011

- MEMS Delivery (XLIM): 05/2012

- Delivery of MEMO PFM 01/2013
A new unit has been developed aiming at prove in-orbit MEMS reliability

- Autonomous and immune
- Flight proven interface, compatible with GEO telecom platforms SB4000 from Thales Alenia Space or E*3000 from Astrium

It passed the standard procedure applied to commercial satellite equipment (EMC, thermal vacuum, vibration/shocks)

MEMS are from CEA-LETI 200mm and XLIM wafer fabs

A strong background have been accumulated in implementing RF-MEMS into TAS RF Hybrid Manufacturing Line
Flight opportunity soon

- On-board a GEO satellite, platform SB4000
- Joint exploitation of data between TAS and CNES
L’équipe MEMO

- TAS : Equipe MEMO
  - QA : M. Perrel
  - IEP : B. Jacquet/V. Lavalette
  - IES : L. Mesthe
  - IDI : J. Bornet
  - Qualité Etude : F. Grojean
  - CPE : O. Vendier

- Support TAS Toulouse Payload :
  - S. Forestier

- Support TAS Cannes Satellite :
  - O. Brize

- CNES
  - F. Courtade, J. Dhenin
  - C. Zanchi, F. Pressec

- CEA LETI
  - B. Reig

- XLIM
  - P. Blondy