Developments for the next generation of Radio Occultation instruments in ESA

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- **Successful story**
  - AGGA-2 device in many missions
  - GRAS RO instrument in MetOp

- **Future RO instruments in ESA**
  - Technology under development (AGGA-4, other components, receivers)
  - New GNSS signals (e.g. Galileo)
  - MetOp-SG, Jason-CS and others

- **Conclusions**
AGGA-2:
✓ Started in ~1995 and manufactured by Atmel [T7905E standard component] in 2000
✓ Targeted to EO applications: POD, Radio Occultation (RO), attitude determination.
✓ Used successfully in many missions (RO in bold):
  - ESA: e.g. **MetOp-Gras a/b/c** for RO, GOCE, Sentinels 1/2/3, Swarm, EarthCARE, etc.
  - Non-ESA: e.g. **ROSA** in Oceansat, MeghaTropiques, Radarsat-2, Cosmo-Skymed, ...

AGGA-4: Reasons for a new generation
✓ new scientific requirements and experience from instruments like MetOp GRAS
✓ new enhanced GNSS signals (GPS / Galileo / Compass-Beidou / Glonass)
✓ ASIC (electronics) technology allows more on-chip integration
METOP GRAS: GNSS Receiver for Atmospheric Sounding
(developed by RUAG Space for ESA and operated by Eumetsat)

- GRAS: GPS based Atmospheric Sounder
- Electronics and antennas
- Receiver (GEU) Mass: 6 kg
  - GEU = GRAS Electronics Unit
- Power ~40 W
- ~20 MB per orbit / ~280 MB per day
- 650 – 700 occultations / per day
- Setting & Rising Occultations
- GPS dual frequ., semi-codeless tracking
- AGGA-2 based (only three chips, each processing four dual-frequ. channels)


**MetOp-B to be launched mid 2012** (same HW as MetOp-A) :  > 1200 occultations/ day soon!

**MetOp-C will follow, launch in 2017**
EQM model
(example with AGGA-2 for Swarm, POD only)
<table>
<thead>
<tr>
<th>Feature</th>
<th>AGGA-4</th>
<th>AGGA-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># of channels</strong></td>
<td>36 Single Freq. or 18 Dual Freq (target)</td>
<td>12 SF or 4 DF</td>
</tr>
<tr>
<td><strong>Compatible signals</strong></td>
<td>Galileo Open Service: E1bc, E5a, E5b</td>
<td>GPS L1 C/A</td>
</tr>
<tr>
<td></td>
<td>Modernized GPS: L1 C/A, L1C, L2C, L5</td>
<td>Semi-codeless L1/L2</td>
</tr>
<tr>
<td></td>
<td>Existing FDMA Glonass</td>
<td>Existing FDMA Glonass</td>
</tr>
<tr>
<td></td>
<td>Potentially: Beidou-Compass, modernized Glonass</td>
<td></td>
</tr>
<tr>
<td><strong>Semi-codeless P(Y)code</strong></td>
<td>No, (priority given to new signals and larger nb. Channels)</td>
<td>Yes (4 P-code units) – ESA patent</td>
</tr>
<tr>
<td><strong>Code Generators</strong></td>
<td>(2 code generators per channel for Pilot and Data)</td>
<td>1 code generator per channel</td>
</tr>
<tr>
<td></td>
<td>Primary: LFSR and memory based</td>
<td>Fixed LFSR for certain primary codes only</td>
</tr>
<tr>
<td></td>
<td>Secondary codes and BOC(m,n) subcarriers</td>
<td>No secondary code and no BOC.</td>
</tr>
<tr>
<td><strong>Correlators per channel</strong></td>
<td>5 complex (I/Q) with EE, E, P, L, LL (E=Early; P=Punctual) and autonomous NAV data bit collection in HW</td>
<td>3 complex (I/Q), with E, P, L (L=Late)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NAV data bit collection requires software interaction</td>
</tr>
<tr>
<td><strong>Channel Slaving</strong></td>
<td>Hardware and software slaving</td>
<td>Hardware slaving</td>
</tr>
<tr>
<td><strong>Aiding Unit per channel</strong></td>
<td>Yes: Code and Carrier aiding</td>
<td>No. Done in software</td>
</tr>
<tr>
<td><strong>Observables</strong></td>
<td>16 Integration Epoch (IE) observables - DMA capable</td>
<td>6 IE observables (no DMA – interrupt based)</td>
</tr>
<tr>
<td></td>
<td>5 Measurement Epochs (ME) observables – DMA capable</td>
<td>2 ME observables (no DMA – interrupt based)</td>
</tr>
<tr>
<td><strong>Common to all channels</strong></td>
<td>Antenna Switch Controller (ASC)</td>
<td>ASC</td>
</tr>
<tr>
<td></td>
<td>Time Base Generator (TBG)</td>
<td>TBG</td>
</tr>
<tr>
<td><strong>MICRO-PROCESSOR</strong></td>
<td>LEON-2 FT on-chip with IEEE-754 compl. GRFPU Floating Point Unit</td>
<td>Off-chip (typically ERC-32, ADSP 21020)</td>
</tr>
<tr>
<td><strong>INPUT FORMAT</strong></td>
<td>3 bit (0.17 dB loss)</td>
<td>2 bit (~0.55 dB loss)</td>
</tr>
<tr>
<td></td>
<td>(I/Q, real sampling and interface for IF ~ 250 MHz)</td>
<td>(I/Q and real sampling)</td>
</tr>
<tr>
<td><strong>CRC MODULE</strong></td>
<td>Check Redundancy Code in hardware On-chip</td>
<td>No</td>
</tr>
<tr>
<td><strong>FFT MODULE</strong></td>
<td>128 point FFT in hardware on-chip</td>
<td>No</td>
</tr>
<tr>
<td><strong>INTERFACES</strong></td>
<td>Two DMA capable UART, Mil-Std-1553, 4 SpaceWire SE, SPI I/F, DSU, S-GPO, 32 GPIO, SRAM I/F</td>
<td>Microprocessor I/F, Interrupt controller and I/O ports</td>
</tr>
<tr>
<td><strong>BEAMFORMING</strong></td>
<td>Yes (2 Digital Beam Forming)</td>
<td>No</td>
</tr>
<tr>
<td><strong>TECHNOLOGY</strong></td>
<td>0.18 Micron ATC18RHA process from ATMEL, 352 pins MQFP GNSS clock up to 50 MHz (target) ~ LEON clock target 80 MHz</td>
<td>0.5 micron from ATMEL, 160 pins GNSS clock up to 30 MHz</td>
</tr>
</tbody>
</table>
AGGA4 ASIC

ASIC Manufactured in February 2012; available in April 2012; 1st mission with launch in 2015

Floorplan Picture taken in Nov. 2011

36 Channels + 4 Input Modules

LEON2FT Processor
PLLs
LEON2FT & Memories
FFT Module

GNSS core: 2.7 M gates
Clocks + I/F + Back End: 1.9 M gates
Design: 4.6 M gates
Pads+others: 1.4 M gates
Total: 6 M gates

European Space Agency
Overview of AGGA-4

- GNSS module
- FFT module
- LEON μ-processor
- external I/F
- AMBA I/F
- DMA I/F

Legend:
GIC: GNSS Interrupt Controller
CIC: Communication Interrupt Controller
PIC: Primary Interrupt Controller
AGGA-4  GNSS Core

Front End Interface

- Power Level Detector Module

Digital Beam Forming

- DBF 0
- DBF 1

Input Module 0

Input A0/B0, A1/A1, A2/B2, A3/B3

D/A Out 0, 1, 2, 3

Half Sample Ckl, Core Ckl, Reset

Channel Matrix

- Carrier Generator Unit
- Code Generator Unit
- Delay Line Unit
- Aiding Unit

Correlator Unit

Final Down Converter

5I / 5Q

36 channels

I/Q scheme and IF scheme

Digital Beam Forming

- Input Selector

PPS, ME, IMT, AUT

EC, ASE, ASEI, ASEO, ASC

Time Base Generator

Antenna Switch Controller

Developments for the next generation of RO instruments in ESA – Estes Park – 29 March 2012
AGGA-4 Channel matrix

* **36 single-frequency / double-code channels**

* Very flexible primary **code generator** units:
  - a LFSR (Linear Feedback Shift Register) for L2CL
  - memory-based codes for Galileo E1b/c

* Support of Binary Offset Carrier – **BOC(m,n)** and **secondary codes** for modernized GPS & Galileo signals (and Beidou, Glonass as known today)

* **5 complex (I/Q) code correlators**, to allow the EE, E, Punctual, L, LL for BOC signals.

* **hardware Aiding Unit**, allowing autonomous CODE and CARRIER aiding (for high orbit dynamics)
### Signals processed with AGGA-4

- relying on public signals (not encrypted) and compatible with GLONASS and Beidou (as known today)
- two component (pilot/data) signals in one channel (thanks to double code generator)
- 36 SF channels = 9 occultations (dual-frequency; open and closed-loop tracking simultaneously)

<table>
<thead>
<tr>
<th>Band</th>
<th>Freq. (MHz)</th>
<th>Component</th>
<th>Code Rate (Mcps)</th>
<th>Primary code length (chips)</th>
<th>Secondary code length (chips)</th>
<th>Symbol/Data Rate (sps / bps)</th>
<th>Replicas in AGGA-4</th>
<th>LFSR/ Memory (config. AGGA4)</th>
<th>AGGA4 Nb. Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>1575.42</td>
<td>E1 B</td>
<td>1.023</td>
<td>4,092</td>
<td>No</td>
<td>250/125</td>
<td>BOC(1,1)</td>
<td>Memory</td>
<td>1 SF (Sing. Freq.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E1 C</td>
<td>1.023</td>
<td>4,092</td>
<td>25</td>
<td>Pilot</td>
<td>BOC(1,1)</td>
<td>Memory</td>
<td>1 SF (idem)</td>
</tr>
<tr>
<td>E5a</td>
<td>1176.45</td>
<td>E5a-I</td>
<td>10.23 (idem)</td>
<td>10,230</td>
<td>20</td>
<td>50/25 (250/125)</td>
<td>BPSK(10) (idem)</td>
<td>LFSR (idem)</td>
<td>1 SF (idem)</td>
</tr>
<tr>
<td></td>
<td>(E5b)</td>
<td>E5a-Q</td>
<td>10.23 (idem)</td>
<td>10,230</td>
<td>100</td>
<td>Pilot</td>
<td>BPSK(10) (idem)</td>
<td>Memory</td>
<td>1 SF (idem)</td>
</tr>
<tr>
<td></td>
<td>(1207.14)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1c</td>
<td>1575.42</td>
<td>L1Cd</td>
<td>1.023</td>
<td>10,230</td>
<td>No</td>
<td>100/50</td>
<td>BOC(1,1)</td>
<td>Memory</td>
<td>1 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L1Cp</td>
<td>1.023</td>
<td>10,230</td>
<td>1800</td>
<td>Pilot</td>
<td>BOC(1,1)</td>
<td>Memory</td>
<td>1 SF</td>
</tr>
<tr>
<td>L1</td>
<td>1575.42</td>
<td>L1 C/A</td>
<td>1.023</td>
<td>1,023</td>
<td>No</td>
<td>50</td>
<td>BPSK(1)</td>
<td>LFSR</td>
<td>1 SF</td>
</tr>
<tr>
<td>L2C</td>
<td>1227.6</td>
<td>L2CM</td>
<td>10.23</td>
<td>10,230</td>
<td>No</td>
<td>50/25</td>
<td>BPSK(0.5)</td>
<td>Memory</td>
<td>1 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L2CL</td>
<td>10.23</td>
<td>767,250</td>
<td>No</td>
<td>Pilot</td>
<td>BPSK(0.5)</td>
<td>LFSR</td>
<td>1 SF</td>
</tr>
<tr>
<td>L5</td>
<td>1176.45</td>
<td>L5-I</td>
<td>10.23</td>
<td>10,230</td>
<td>10</td>
<td>100/50</td>
<td>BPSK(10)</td>
<td>LFSR</td>
<td>1 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L5-Q</td>
<td>10.23</td>
<td>10,230</td>
<td>20</td>
<td>Pilot</td>
<td>BPSK(10)</td>
<td>Memory</td>
<td>1 SF</td>
</tr>
</tbody>
</table>

Developments for the next generation of RO instruments in ESA – Estes Park – 29 March 2012
AGGA-4 design and validation

- AGGA-4 developed by Astrium GmbH (Germany) under ESA guidance and Contracts.
- Extensive independent validation (block testing, and also acquisition & tracking) with FPGA version (same as ASIC but with only 4 GNSS channels) at ESTEC in Aug-2010 by RUAG Space Austria
- The FPGA already allowed substantial SW development for future receivers
As modular as possible (reproducibility and re-use, adapting to e.g. small carriers)
Difference between POD and RO limited to software and antenna

Two developments of POD receiver with AGGA-4 under negotiation
Development of GRAS-2 instrument prototype expected to start in 2Q / 3Q 2012
RF Module & Antennas

✓ Saphyrion (CH) chips (down-converter SY1007; ADC SY1017): highly integrated
- used in a high number of satellites (Swarm, 6 Sentinels, ...) for POD
- however, phase noise requirements for RO are more stringent than for POD

✓ RF chain in future RO instruments:
- innovative architecture for coherent clocks with existing components under study
- new devices with improved phase noise also under development

✓ Scalable antenna design
- more radiating elements (for high performance reference – e.g. MetOp-SG)
- less radiating elements if antenna to be accommodated in smaller satellites
Innovative processing

- ESA study with RUAG, DMI, DLR, Graz, GFZ-Postdam and Eumetsat revealed:
  - better performance of MetOp-GRAS than initially specified
  - open loop models (both in **Range**, **Doppler**) validated
  - some issues can be improved (e.g. data gaps)

- New study to minimise data gaps in **MetOp-GRAS** with RUAG Sweden:
  - Development of a **receiver simulator** (based on L1, P1/P2 and AGGA-2 specifics)
  - Use of simulated data (derived from ECMWF profiles) from a Eumetsat study
  - corrected parameters to be patched in the on-board MetOp software

- New study to minimise/avoid data gaps in **MetOp-SG** initiating:
  - Development of a receiver simulator
    (based on L1/E1, L5/E5a and AGGA-4 specifics)
  - More flexibility in the operation of Open Loop (more channels)
  - Use of simulated data from a Eumetsat study
  - output relevant to tune MetOp-SG requirements
RO opportunities for future missions

- **Jason-CS** in 2018 first opportunity
- **MetOp SG** (is not GMES: not in this list)
A 66° inclination orbit as of Jason CS has the maximum number of events at mid latitudes with an increase of events in the tropical regions at the expense of the high latitude events.

Jason-CS alone
no. occ events: 1180 = 583 set + 597 rise
Tx: GPS + Gal

Jason CS & MetOp-2G A & B
no. occ events: 4044 = 2016 set + 2028 rise
Tx: GPS + Gal
More **robustness** thanks to **more and better signals in Open Service**

- error detection, correction and re-acquisition easier
- no semi-codeless needed: dual frequency available also with low SNR
- pilot components (no bit wiping) => very good for EO, needing robust carrier measurements
- secondary codes: ‘lengthen’ the spreading code, better autocorrelations while fast acquisition

**Some (small) improvement in accuracy** (better codes, but similar carrier measurement)

The new GNSS signals imply:

- **Components more flexible** (as AGGA-4) and **with more digital processing**
  - more channels + more functions (e.g. carrier and code aiding).
  - Flexibility (e.g. LFSR and memory-based code generators)
- Different software: no codeless processing or bit wiping, but more available signals; tracking in both open and closed-loop

**ESA preparing** the AGGA-4, RF ASICs and antenna **components** compatible with new GNSS.
Developing the new **receivers** (ASIC final pin layout known)
Active Limb Sounding Beyond Radio Frequencies in ESA

- investigated limb sounding using higher RF frequencies (~10, 22, 27 GHz) under ACE+, WATS,.. project concepts
- investigated limb sounding using SWIR lasers (ACCURATE concept)
  - suitable for vertical profiling of Greenhouse Gases using a differential absorption technique
  - 2-2.5 micron SWIR band allows probing of CO₂, CO, CH₄, H₂O, N₂O, O₃ and isotopes at high vertical resolution
  - Technique allows to measure line of sight wind as additional parameter
- Experiment to test concept implemented 2011:
  - 150 km baseline used to probe CO₂ (2.1 micron) and CH₄ (2.3 micron) between Tenerife and Gran Canaria
  - Concept successfully demonstrated
  - Final results from data analysis expected in Q2 2012
  - Ongoing projects to advance the processing
Active Limb Sounding Beyond Radio Frequencies

Institutions Involved: Wegener Centre Graz, University of Manchester, University of York, IAP Moscow, MPI Jena
Other ESA activities

OPS-GRAS Project with Wegener Center in Graz:
- Mostly new implementation of the Level 1b/2 processing chain
- Allows modernization and optimization of code
  - Immediate benefit: significant improvement of processing speed
- Harmonization of background information used
- Reduction to a baseband:
  - Potentially increases numerical stability
  - Potentially allows for more efficient filtering
  - New “clean” and improved system will be compared against the old one

Project with ECMWF
- Estimating the Optimal Number of GNSS Radio Occultation Measurements for Numerical Weather Prediction and Climate Reanalysis Applications
Conclusion

AGGA-2 baseband processors: widely used in ESA and non-ESA missions
- cm accuracy in POD demonstrated (GOCE,..)
- RO: excellent performance of MetOp GRAS; data used operationally

ESA preparing the next generation of RO instruments
- **AGGA-4**: compatible with Galileo, modernized GPS, Glonass, Beidou, and higher number of channels. ASIC samples in April 2012
- RF ASICs, antennas
- innovative processing
- New receivers

Generic developments aiming at MetOp-SG, Jason-CS, next generation of GMES Sentinels, and open to others

Collaboration with European partners (Eumetsat, others) working very well