Next generation of ESA's GNSS receivers for Earth Observation satellites

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Abstract— **This paper presents the key elements of the next generation of miniaturised GNSS space receivers in the European Space Agency (ESA) compatible with the new and more robust GNSS signals from Galileo, modernized GPS, Glonass and Compass-Beidou. A quick review of applications like Precise Orbit Determination (POD) and Radio Occultation (RO) is provided together with the performance achieved in current satellites like MetOp or GOCE and expected in future ESA satellites. The key architectural building blocks of future GNSS space receivers are presented, with focus on components like the AGGA-4 baseband GNSS processor and also, but to a less extent, on programmable RF ASICs. These components, in combination with the more robust features from the new GNSS signals, bring a significant improvement with respect to their predecessors (e.g. AGGA-2 based) and also represent an important step towards miniaturisation of the next generation of GNSS space instruments.**

Keywords: GNSS; receiver; AGGA-4; multi-constellation; RO; Radio Occultation; POD; miniaturisation; Earth Observation; LEO; Galileo; Glonass; Compass-Beidou.

I. INTRODUCTION

In the mid 1980's, Global Navigation Satellite System (GNSS) techniques became available also for satellites in the domains of orbit determination and Earth science applications. The success of GNSS space receivers for orbit determination does not come as a surprise since it complements and outperforms ground-based-only orbit determination techniques by providing continuous on-board availability of ranging measurements at very high accuracy with small hardware mass and power budgets. Precise Orbit Determination (POD) with GNSS from Low Earth Orbit (LEO) satellites is possible at a few centimetres level in order to support Earth science applications like altimetry, global geodesy, relative positioning between multi-satellites, Radio Occultation (RO) or GNSS-Reflectometry (GNSS-R). RO applications require not only POD support, but also some specific GNSS instrumentation, which provides on-board carrier phase measurements, like in the most precise POD receivers, but, due to the very low signal to noise (SNR) received after the atmospheric attenuation, they also require some additional support (e.g. directive antennas, open-loop tracking techniques, etc.). GNSS-R has even more specific processing requirements for the elaboration of delay-Doppler maps, which implies that a very different type of receiver is required compared to RO or POD, and for this reason we will not elaborate more in this paper on GNSS-R space receivers.

Section II presents more in detail the kind of requirements, mainly for POD applications, that are needed in future ESA missions. Section III introduces the architecture of future GNSS space receivers. Section IV shows the AGGA-4 GNSS baseband processor, which has a large number of GNSS channels and a micro-processor (LEON-2 FT) embedded on-chip. Section V briefly presents the main issues that future GNSS receivers face in the RF area. Section VI shows the impact that the availability of new and more robust GNSS signals from new constellations like Galileo, Glonass, Compass-Beidou or modernized GPS will have on GNSS space receivers. Specific issues on RO on-board processing are discussed in section VII. Finally, section VIII provides the conclusions.

II. APPLICATIONS USING GNSS SPACE RECEIVERS

POD in support to scientific applications is the main usage of GNSS receivers. It is important to note the following points from the numbers of TABLE I. :

- POD is less accurate in on-board real-time (RT) than when the data is post-processed over a few minutes, hours or days on-ground, where the clock errors of the GNSS transmitters can be corrected (e.g. using data from the International GNSS Service –IGS- networks) or longer archs of the LEO orbit can be considered in the reduced dynamic solution [3].
- the most stringent absolute positioning requirement in RT comes from missions like GMES Sentinel-3. Altimetry requires real-time knowledge of the radial position (to < 3 m rms in RT) in order to know the ideal time when the measurement echo or the radar altimeter should be sampled.
- In non-real time, the most stringent requirement comes from GOCE (2 cm rms) and again from the altimetry of Sentinel-3 (2 cm rms in the radial dimension). The POD performance in the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission has been demonstrated in flight [5].

- Radio Occultation in Metop-GRAS has the most stringent requirement in velocity accuracy (0.1 mm/s) in the along direction and has been demonstrated in flight since 2007 [4]. Given the results, the requirement for MetOp-SG (second generation, to be launched in 2019), is 0.05 mm/s [8],
- other missions not reported here may require POD with accuracies well above 10 cm. We will see in section III what key system parameters (e.g. number of bands) can be relaxed in future GNSS receivers for lower accuracy (> 10 cm) requirements.

TABLE I. REQUIREMENT FOR GNSS RECEIVERS

Mission	Real Time (RT)	Non RT (1-3h)	Slow Time Critical, (1-2 days)	Non Time Critical (1 month)
GOCE (launched 2009)		< 50 cm rms (req.)	< 10 cm rms (achieved ~ 4 cm)	< 2cm rms (achieved)
Swarm		< 10 cm rms		
Sentinel-1 (SAR interferometry)	10 m. 3s xyz	5 cm rms xyz		
Sentinel-3 (Altimetry)	3 m. rms (radial)	8 cm rms (radial)	3 cm rms (radial)	2 cm rms (radial)
MetOp-GRAS (Occultations) (launched 2006)		0.1 mm/s (vel. along)		
MetOp-SG (Occultations)		0.05 mm/s (vel. along)		

It is outside the scope of this paper to go in detail in the definition of a GNSS Radio Occultation and related parameters like observations per day, maximum impact height, or bending angle accuracy, which depend very much on the performance of the receiver but also on the atmospheric conditions and on the ground post-processing [5].

III. FUTURE GNSS RECEIVERS ARCHITECTURE OVERVIEW

The envisaged future GNSS space receivers for POD and RO is summarized in Figure 1. It shows a very modular architecture, with three (one per antenna) key blocks in the GNSS receiver, each of them with an RF module and a digital module based on AGGA-4.

Key architectural trade-offs to be made when designing a GNSS space receiver, that have a substantial impact on performance and complexity, are:

- number of frequency bands: two bands allow for compensation of ionospheric delays and results in sub-decimeter accuracy at the expense of adding RF chains and complexity on the software to be implemented. Currently, the preferred bands are L1 and L2, but in the future it is expected that L1/E1bc and L5 / E5a will be chosen bands because all new GNSS constellations will offer open signals at these two frequencies before 2020 and can be processed with the same hardware. Three GNSS frequencies so close to each other (specially L2/L5) will not bring benefits for ionospheric corrections in space receivers.
- carrier and code measurements or only code measurements: carrier measurements is crucial to sub-meter accuracies, but it also requires higher performance of the different building blocks than the simpler code measurements alone. Practically all modern space receivers require carrier measurements.
- acquisition timing: cold start, warm start or hot start differ in the a priori knowledge of several parameters like the almanac, PVT solution, etc. and result in slower or faster acquisition, at the expense of software complexity.
- given the very low SNR in RO, as shown in some assessments [6], all kind of optimizations are needed at the expense of higher complexity, such as
    - High performance of the RF Front End with short term stability of the receiver through the use of ultra stable oscillators (USO) with additionally very low phase noise and clock coherency.
    - High gain directive antennas
    - use of open loop tracking processing techniques when closed loop is no more possible, resulting in for example more acquisitions or longer measurements in lower troposphere heights

The choice of the number of bands is crucial. Accuracies around 10 cm can be achieved with just single-frequency techniques like GRAPHIC that combine code and carrier measurement to eliminate the ionospheric perturbations, thanks to the opposite change of group and phase velocity in an ionized medium [7].

Besides technical aspects, programmatic aspects like the common procurement policy adopted for the GMES Sentinels (1, 2 and 3) play a role. In this particular case, it implies that the highest required performance (i.e. Sentinel-3) paves the way for the rest. The Sentinels GNSS receivers are based on dual-frequency, carrier measurements and warm start up even if for example Sentinel-2 could do with just single frequency.

IV. BASEBAND GNSS PROCESSOR: AGGA-4

The development of the first AGGA (Advanced GPS/GLONASS and Galileo ASIC) device was initiated within ESA's Earth Observation Preparatory Programme (EOPP) in order to support the Earth observation applications of navigation signals. After prototyping iterations, the flight component known as AGGA-2 was manufactured as the Atmel product code T7905E [2]. The AGGA-2 is a space-qualified digital integrated circuit providing all the high-speed digital signal processing functionality for GNSS EO applications. AGGA-2 is available to all European space industries and is flying or will fly in a large number of ESA missions (e.g.

Metop-GRAS for RO, GOCE, Swarm, EarthCare, GMES Sentinels 1, 2, 3 for POD) and non-ESA missions (e.g. Radarsat-2, Cosmo-Skymed for POD, Oceansat2-ROSA, SAC-D, MegaTropiques for RO).

The need for a new generation of AGGA (AGGA-4) was driven by:

- the understanding of the processing functionality, in particular for RO through the development and exploitation of the GRAS instrument in MetOp [8] as well as new requirements for geodetic-quality receivers (e.g. for GMES Sentinel of second generation).
- enhanced GNSS signals from a larger number of GNSS systems (GPS / Galileo / Glonass, Compass-Beidou) calling for extra functionality (e.g. BOC, secondary codes) in the signal processing.
- advances in space ASIC technology that allow on-chip integration of much more functionality

The most interesting features that AGGA-4 offers with respect to AGGA-2 are shown in TABLE III.

The AGGA-4 Channel Matrix includes 36 highly configurable single-frequency (SF) / double code GNSS channels. 36 SF channels correspond to 18 dual-frequency (DF) channels. Each SF channel includes (see Figure 3.):

- double code generators: the Linear Feedback Shift Register (LFSR) is needed to generate very long codes (e.g. for L2CL with 767,250 chips), whereas the memory-based generator is needed for very specific signals like the memory-based E1bc. In addition, secondary code and Binary Offset Code (BOC) modulation capabilities are included. This very flexible architecture allows the processing of all known GNSS open service signals in just one SF channel for both signal components (data/pilot) when in closed loop, as indicated in TABLE II. .
- code and carrier loop aiding support in each channel to support the high but predictable dynamics, experienced by Low Earth Orbit (LEO) satellites and launchers. Typically the aiding frequencies are computed at each Measurement Epoch (ME) or Pulse Per Second (PPS) event.
- optimized retrieval of observables (raw sampling) via DMA at the output of the correlators, which is useful for example for Radio Occultation applications in open loop tracking [8].
- a code delay line unit with two configurable delay lines, which allow the tracking of double-component (pilot/data) signals in one channel
- five complex (I/Q) code correlators (Early-Early, Early, Puctual, Late, Late-Late), for the processing of BOC signals.
- ten (5I, 5Q) 29 bit integration accumulators.

To reduce the ASIC gate-count and maximise the number of channels, AGGA-4 does not support:

- code generation of Multiplex BOC (MBOC) signal replicas in the form of Time MBOC (TMBOC) or Composite BOC (CBOC): MBOC signals can still be processed with the BOC codes generated by AGGA-4 at the expense of roughly only 1 dB loss in code phase tracking sensitivity.
- E5 AltBoc is not necessary given the rather reduced multipath present in spacecraft. Instead, AGGA-4 allows the processing of E5a and E5b in separate SF channels with negligible losses
- Galileo PRS (Public Regulated Service), Galileo CS (Commercial Service) and Galileo SoL (Safety of Life Service) are not important for EO applications as long as we have at least two frequencies available in Open Service (OS) per constellation, as it will be the case
- codeless processing capabilities (e.g. generation of P-code, or second integration stage). This restriction is largely compensated by the increasing number of new GNSS signals available.

Like in AGGA-2, all the channels in the AGGA-4 Channel Matrix share one Antenna Switch Controller (ASC) to support four antennas in attitude determination and a Time Base Generator (TBG). The TBG produces the Measurement Epoch (ME) strobe, the Pulse-per-Second (PPS) strobe for synchronising external equipment, and the Epoch Clock (EC). It also provides the Instrument Measurement Time (IMT) counter. It is possible to select between an internally generated ME signal and an external input.

AGGA-4 provides four input modules that support multiple input formats: Input Format Converter (IFC) in baseband (complex I/Q) format, Real to Complex (R2C), and the new Digital Down Converter (DDC) (real format) for intermediate frequency (IF) signals at sampling frequencies up to 250 MHz. Implementation losses are reduced through pre-processing (I/Q mixer, FIR decimation, and re-quantisation) which also converts all input formats into a common 3I/3Q bit output format. The front-end also provides Power Level Control (PLC) functionality to support Automatic Gain Control.

The GNSS baseband processor accesses memory by direct memory access (DMA) via the AMBA High-performance Bus (AHB). Data is shared through AHB and AMBA Peripheral Bus (APB).

AGGA-4 includes on-chip the LEON-2 FT processor based on the SPARC V8 standard. The LEON-2 processor and periphery consist of a cache sub-system, a memory controller, interrupt controller, four 32-bit timers, one 32-bit watchdog, bus status register, a write protection unit, a watch point registers, a 32-bit I/O-port and an extended reset detection section. In addition, it is supported by a Floating Point Unit (FPU) that is IEEE-754 compliant GRFPU from Gaisler Research. There is also an external SRAM memory interface for the LEON-2 FT.

AGGA-4 has many external Interfaces (I/F). In particular, it has four bidirectional SpaceWire interfaces implemented with single-ended IO's (no LVDS) at a rate per link related to the LEON-2 clock. The SpaceWire I/F are useful to transmit the Science (observables) data, where the Power and I/F module includes a SpaceWire router, as shown in Figure 1. Telemetry/Telecommands can make use of SpaceWire, Mil-Std-1553 or the two DMA capable UARTs available in AGGA-4

Extensive functional validation, was done on a Virtex-5 FPGA prototype, by two independent teams (RUAG Aeropace Austria and Deimos Engenharia).The FPGA used the same VHDL as the final AGGA-4 ASIC, except that only four of the 36 GNSS channels could be implemented in the FPGA. AGGA-4 ASIC prototypes, with 6 Mgates have been manufactured in 2012. AGGA-4 flight model ASICs will become available from ATMEL under equal conditions for the whole European space industry within 2013. The imminent availability of AGGA-4 has also allowed ESA to start the development of the next generation of GNSS receivers.

AGGA-4 is compatible with the GPS and Galileo signals shown in detail in TABLE II. It is also compatible with the BOC(2,2) in Beidou and BOC(4,4) in Glonass systems.

V. RF CHAIN AND ANTENNAS IN GNSS INSTRUMENTS

The RF chain performance is very important for the overall performance of the GNSS receiver. Specifically, in Radio Occultation (RO) applications, parameters like phase noise, noise figure, local oscillator stability or clock coherency between chains in different frequency bands (L1 / L5) are crucial to increase the quality of the carrier phase (science) measurements. Performance requirements in POD applications are less stringent than for RO, especially regarding phase noise. The frequency generation module (FGM) generates common digital, RF Local Oscillator (LO), and IF LO frequencies which need to be coherently combined for the L1/L5 signal chains within the RF and Digital modules shown in Figure 1.

New technology can be used to improve the receiver front-end. Specifically, very low noise amplifiers integrated close to the antenna can be used to improve the receiver system noise, which allows improving SNR. Requirements on signal quality and industrial reproducibility imply the replacement of earlier approaches based on a large number of discrete components by dedicated and more integrated devices like the Saphyrion (former Nemerix) chipset (i.e. SY1007 RF down-converter and NJ1017 ADC) developed under ESA Contracts. These devices are programmable and capable of processing all the relevant public GNSS bands (e.g. L1/E1bc, L2C, L5/E5a and E5b). Qualification of this kind of devices combining wideband analogue and digital capabilities has been very complex given the low number of components that can be used in the space business. Saphyrion already started developing under ESA Contract the next generation of RF ASICs to overcome the technical limitations (e.g. phase noise) seen in the first generation, in order to allow further simplification/ miniaturization of the FGM and RF modules.

Antenna gain is much more important for RO applications than for POD applications. The rather large wavelength (around 25 cm in L1) imposes a serious constraint on the RO antenna size (e.g. 86 cm x 46 cm in Metop-GRAS) required to achieve the expected gain (e.g. 9 dB with a 45 degree azimuth angle) that can only slightly be improved with new antenna technology. However, improvements in future GNSS signals (see section VI), and advanced open-loop processing techniques (section VII), will enable for example to relax the required antenna gain and associated size and therefore enable to embark smaller RO instruments into a larger number of satellites. In this respect, ESA is already studying the issues (e.g. accommodation, interference) required to embark a RO instrument with a reduced antenna size in Jason-CS, to be launched in 2019, and with a performance comparable to that of the reference mission: i.e. MetOp-SG.

VI. IMPLICATIONS OF HAVING NEW GNSS SIGNALS AND CONSTELLATIONS

In the present decade new GNSS signals are becoming available not only from an enlarged set of systems (i.e. modernized GPS, Galileo, Glonass, Compass-Beidou), but also with new characteristics that are making on-board processing better performing. Here below we provide a list of the most interesting features for future GNSS receivers.

- Higher number of available signals: more robustness with errors easier to detect and correct. It is unlikely that much better accuracy can be achieved due to the dominance of external errors.
- At least two open service frequencies available per constellation: no more need for semi-codeless processing which resulted in significant losses and loss-of-track. This allows a simplification of the receiver and improves the tracking limits with the two frequencies under unfavourable conditions (e.g. when observing the lowest layers of the troposphere in RO.)
- Pilot components in the new GNSS signals: this allows to extend the integration time (i.e. no need for navigation bit wiping) and brings robustness, less loss of track, faster acquisition and increase receiver sensitivity under lower SNR conditions. Given the interest in EO applications for carrier measurements, the availability of pilot components is very promising.
- Higher signal power levels (e.g. 1-2 dB) and higher bandwidths (e.g. 10 MHz), resulting in more accurate code measurements, but only slight improvements in carrier measurements.
- secondary codes bring robustness to interference, "lengthen" the spreading code and autocorrelation function peak while allowing a fast acquisition, which is good under low SNR.
- BOC modulations, together with higher chip rates and bandwidths provide higher robustness against multipath, but this is not the most severe problem in a spacecraft. Nevertheless, it may open new possibilities for example for GNSS-based attitude determination which is critically dependent on multipath errors .

Overall, the implication of the new GNSS signals for the receiver are:

- a possible slight relaxation of antenna gain requirements, but there are more bands to be received
- more and newer frequency plans for the RF part with the introduction of the new L5 frequencies and with higher bandwidths, asking for more flexibility in the components
- more digital processing, as shown above with AGGA-4, with many more channels and more digital functions (e.g. new sampling schemes at IF, carrier and code aiding, etc). Flexibility to ensure compatibility with a larger number of GNSS signals also implies large complexity: e.g. in AGGA-4, LFSR and memory-based code generators in each of the 36 GNSS channels
- different software, simpler because no codeless processing or bit wiping will be needed, but also more complex due to the larger amount of available signals.

VII. RO SPECIFIC PROCESSING

The next generation of RO instruments will benefit from Open Loop (OL) processing techniques, already demonstrated in MetOp since 2007, from which more accurate range and Doppler models could be refined [8]. For MetOp-SG, better OL with the new GNSS signals described in section VI (e.g. no codeless in the second frequency) should enable to have lower altitude tropospheric measurements down to almost Earth surface.

Coverage will also increase (from 650 to some 2600 observation per satellite and day) in 2020 thanks to the availability of new L1/L5 open CDMA signals from four constellations (GPS, Galileo, Glonass, Compass-Beidou) and of the large number of GNSS channels in AGGA-4. This will open new scientific possibilities already with MetOp-SG (first pair of satellites to be launched in 2019, third pair to be operated until 2040). The PVT solution in the POD receiver will only be needed from one or two GNSS constellation, but the almanac shall be retrieved for the four constellations in order to plan/schedule the upcoming occultations.

VIII. CONCLUSIONS

POD with post-processing on-ground, in support of scientific applications like altimetry, global geodesy, relative positioning of satellites or Radio Occultation is well consolidated. Accuracies around 2 cm rms have been proven in the first ESA Earth Explorer: GOCE [5]. The radar altimeter of Sentinel-3 has the most demanding performance requirements of the near future ESA satellites and is expected to impose a standard for all other ESA missions. The very high performance (< 10 cm rms) POD receivers in ESA missions are dual-frequency receivers. Accuracies still well sub-meter lelvel can be achieved with single frequency receivers and techniques like GRAPHIC that combine code and carrier measurement to eliminate the ionospheric perturbations.

Radio Occultation is also a well-established technique for the retrieval of vertical profiles of temperature, pressure as well as humidity in the lower troposphere. The high performance of the Metop-GRAS [6],[8]. instrument compared to other RO instruments proves the importance of low noise instrumentation, large antenna gains and high quality ultra stable oscillators (USO) in combination with innovative processing techniques (e.g. open loop model).

The use of the baseband processor AGGA-2 was instrumental for these achievements in both ESA and non-ESA missions. The next generation, AGGA-4, will be compatible with the new GNSS signals, and this in itself will bring significant improvements in robustness (e.g. less loss of track) thanks to the larger number of available GNSS signals and also to some the features present in those signals such as for example the pilot carriers that will well benefit Earth Observation applications requiring carrier phase measurements like high accuracy POD or RO. AGGA-4 supports many more GNSS channels (target 36) and includes much more functionality on-chip (e.g. aiding unit per channel, LEON2-FT micro-processor on-chip, etc). AGGA-4, as with AGGA-2, will be made available to all European space industry within 2013 on an equal basis. The RF chain is also on-going upgrades with better performance (e.g. higher bandwidth, less noise) and miniaturization though programmable and more integrated RF devices like the Saphyrion chipset. The development of new GNSS receivers based on these components has already started.

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REFERENCES

[1] P. Silvestrin et al, Spaceborne GNSS Radio Occultation Instrumentation for Operational Applications, ION 2000 conference

[2] T7905E [AGGA-2], Rad Tolerant GPS/GLONASS ASIC User's Manual http://microelectronics.esa.int/vhdl/doc/T7905E.pdf

[3] O. Montenbruck, T. van Helleputte, R. Kroes, E. Gil., "Reduced Dynamic Orbit Determination Using GPS Code and Carrier Measurements", Aerospace Science and Technology 9/3, 261-271 (2005).

[4] O. Montenbruck, A. Hauschild, Y. Andres, A. von Engeln, C. Marquardt, (Near-)real-time orbit determination for GNSS radio occultation processing, GPS solutions, DOI 10.1007/s10291-012-0271-y, (2012)

[5] P. Visser et al., Rapid and Precise Orbit Determination for the GOCE Satellite, presented in June-2010 in the ESA Living Planet Symposium in Bergen, Norway

[6] C. Marquardt et al., Tropospheric GRAS data, IROWG-2 Workshop, March 2012,Estes Park, USA

[7] D. Svehla, D. Escobar, J. Dow, GPS Single Frequency Precise Orbit Determination of LEO Satellites with Cm-Level Accuracy, 38th COSPAR Scientific Assembly, July 2010, Bremen, Germany

[8] Final Report ESA contract 21995, GRAS Radio Occultation Performance Study, with RUAG Space AB, June 2012,

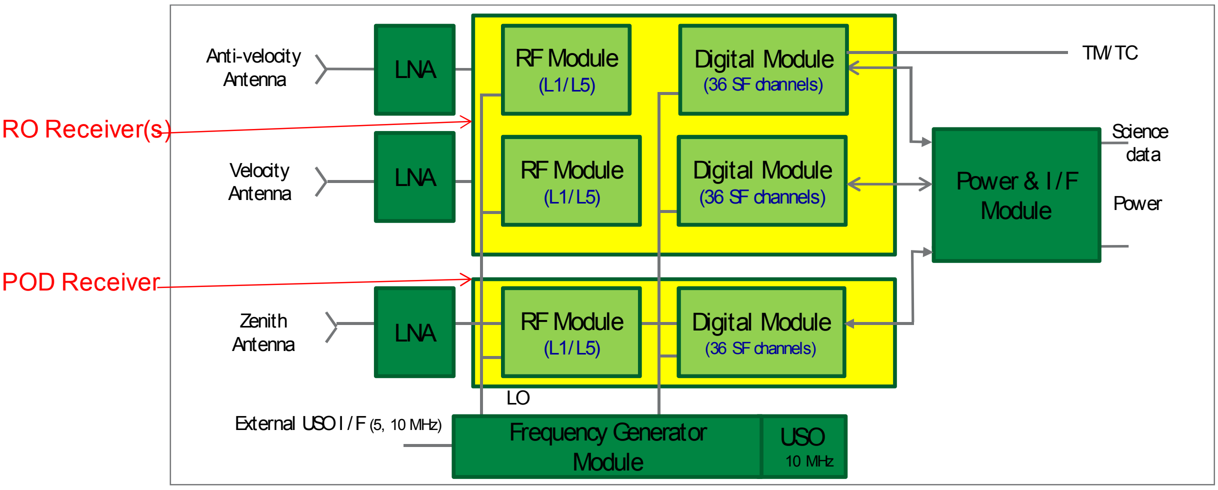

Figure 1. Modular architecture of the next generation of GNSS receivers

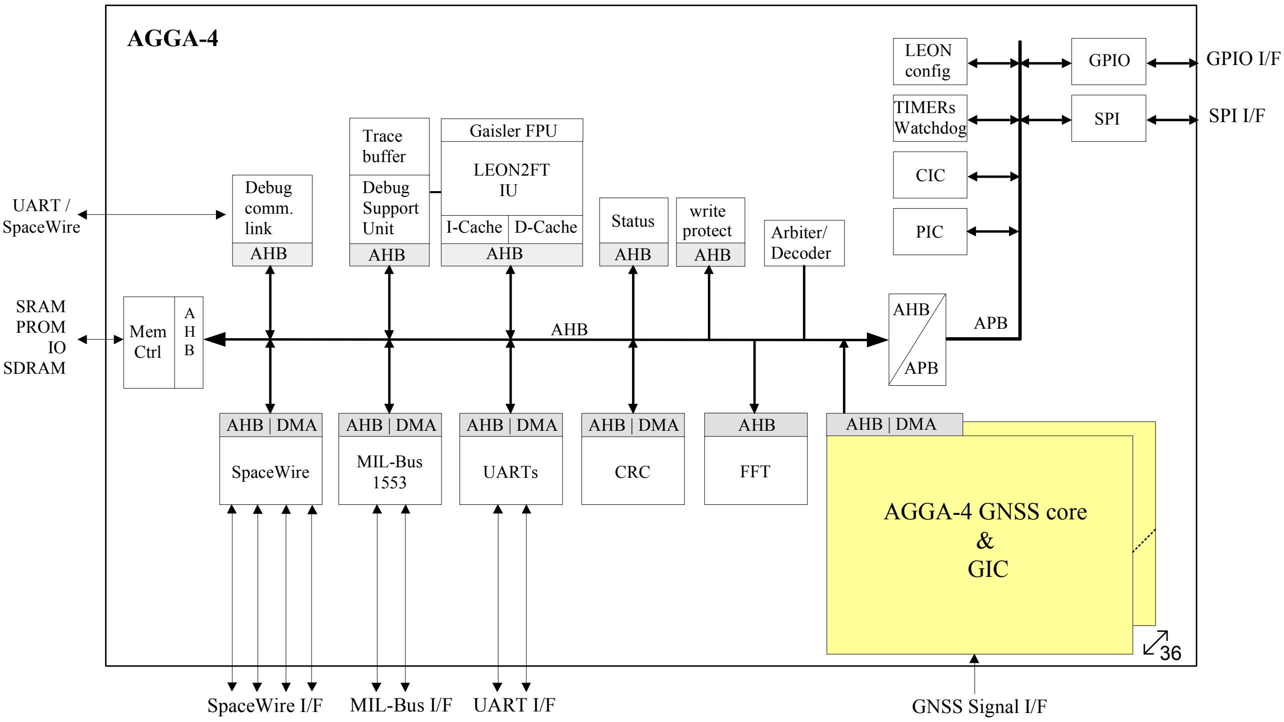

Figure 2. AGGA-4 System overview (extract from draft AGGA-4 Datasheet)

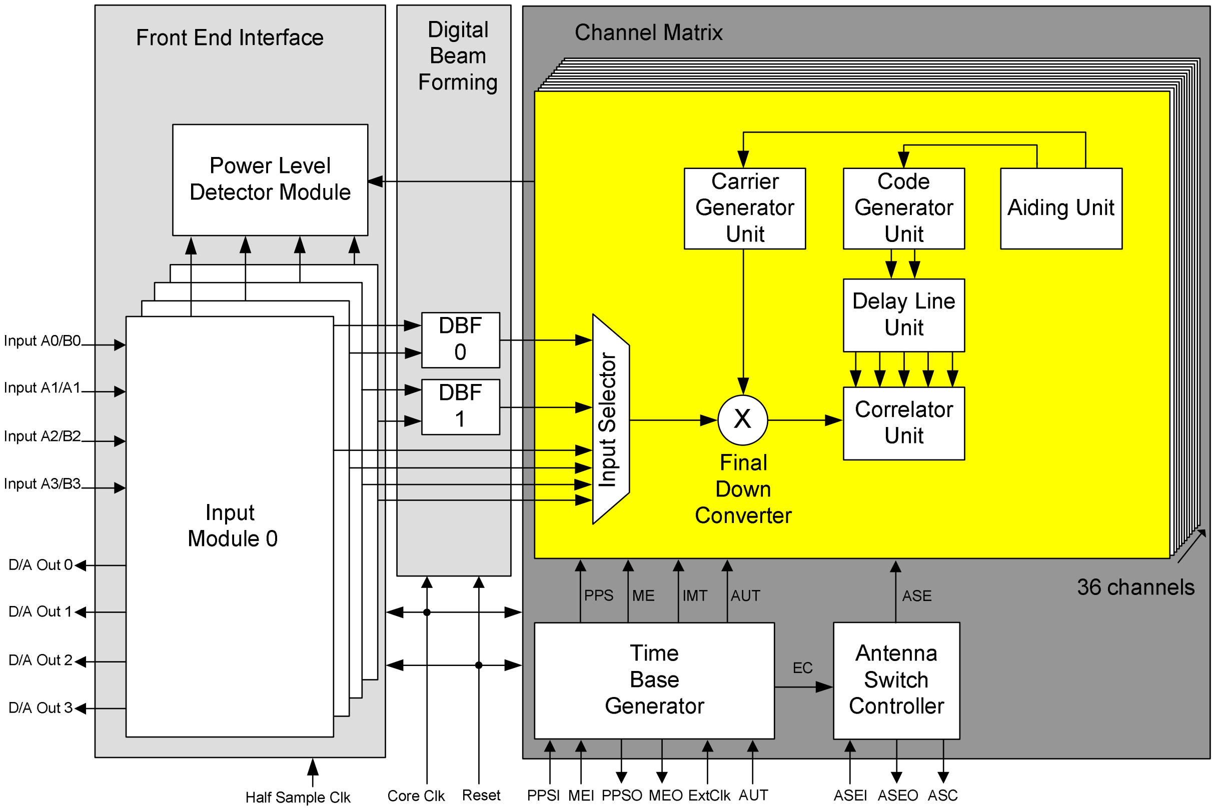

Figure 3. AGGA-4 GNSS Core (extract from a draft version of AGGA-4 Datasheet)

TABLE II. MODERNIZED GPS AND GALILEO SIGNALS AND POSSIBLE AGGA-4 CONFIGURATION

Band	**Freq. (MHz)**	**Compo nent**	**Code Rate (Mcps)**	**Primary code length (chips)**	**Secondary code length (chips)**	**Symbol/ Data Rate sps / (bps)**	**Modulation in AGGA-4**	**LFSR/ Memory (config. AGGA4)**	**AGGA4 nb. channels**
E1	1575.42	E1 B	1.023	4,092	No	250/125	BOC(1,1)	Memory	1 SF
		E1 C	1.023	4,092	25	Pilot	BOC(1,1)	Memory	
E5a (E5b)	1176.45 (1207.14)	E5a-I (E5b-I)	10.23 (idem)	10,230 (idem)	20 (4)	50/25 (250/125)	BPSK(10) (idem)	LFSR (idem)	1 SF (idem)
		E5a-Q (E5b-Q)	10.23 (idem)	10,230 (idem)	100 (idem)	Pilot	BPSK(10) (idem)	Memory (idem)	
L1c	1575.42	L1Cd	1.023	10,230	No	100/50	BOC(1,1)	Memory	1 SF
		L1Cp	1.023	10,230	1800	Pilot	BOC(1,1)	Memory	1 SF
L1	1575.42	L1 C/A	1.023	1,023	No	50	BPSK(1)	LFSR	1 SF
L2C	L2C	L2CM	10.23	10,230	No	50/25	BPSK(0.5)	Memory	1 SF
		L2CL	10.23	767,250	No	Pilot	BPSK(0.5)	LFSR	
L5	1176.45	L5-I	10.23	10,230	10	100/50	BPSK(10)	LFSR	1 SF
		L5-Q	10.23	10,230	20	Pilot	BPSK(10)	Memory	

TABLE III. SHORT COMPARISON AGGA-2 / AGGA-4

Feature	AGGA-4	AGGA-2
FRONT END I/F	4 Input Modules supporting: IFC, R2C, and **DDC** (Digital Down Conversion from IF) - **3 bit** => 0.17 dB implementation loss Enhanced Power Level Control (PLC)	4 Input Modules supporting: **IFC** (for I/Q), and **R2C** (real sampling) - **2 bit** => 0.55 dB imp. loss One PLC per Input Module
Digital Beam Forming (DBF)	2 DBF combining inputs from 2 antennas: Inputs from 4 antennas possible.	2 DBF – by digital phase shifting (same as in AGGA-4)
GNSS CHANNELS	(main changes in **bold** letters)	
# of channels	**36 Single Freq**. or 18 DF (target)	**12 SF** or 4 DF
Compatible signals	**Galileo** Open Serv.: **E1bc, E5a, E5b** GPS: L1 C/A, L1C, **L2C, L5** Existing FDMA Glonass Beidou, modernized Glonass (CDMA), (as known by the time of this paper)	GPS L1 C/A **Semi-Codeless** L1/L2 Existing FDMA Glonass
Code Generators	(2 code gener. per channel for **Pilot and Data**) Primary: Flexible **LFSR and memory based** **Secondary codes** and **BOC(m,n)** subcarriers	1 code generator per channel Fixed LFSR for certain primary codes No secondary code and no BOC.
Delay Line	Dual stage for pilot and data	Single stage
Correlators per channel	**5 complex (I/Q)** with EE, E, P, L, LL and autonomous NAV data bit collection	**3 complex (I/Q)**, with E, P, L where E=early, P=Punctual, L=Late) NAV data bit collection requires software interaction
Codeless P(Y) code	No	**Yes** (4 P-code units) – ESA patent
Channel Slaving	Hardware and software slaving	Hardware slaving
Aiding Unit per channel	Yes**: Code and Carrier aiding**	No. Done in software
Observables	16 Integration Epoch (IE) Observables (DMA capable) 5 Measurement Epochs (ME) Observables (DMA capable)	6 IE Observables (no DMA) 2 ME Observables (no DMA)
Common to all channels	Antenna Switch Controller (ASC) Time Base Generator (TBG) with ME, PPS, IMT counter, External Clock interface extended reset detection section	ASC TBG with ME and PPS
MICRO-PROCESSOR	**LEON-2 FT** on-chip with IEEE-754 compliant GRFPU (Floating Point) support	Off-chip (typically ERC-32, ADSP 21020)
CRC MODULE	On-chip	No – task done in software
FFT MODULE	**On-chip** (128 points , fixed format) **(**ideal for fast acquisition,)	No – task done in software
EXTERNAL INTERFACES	Four **SpaceWire** SE , Two DMA capable UART, **Mil-Std-1553**, SPI I/F, DSU, S-GPO, 32 GPIO, SRAM I/F	Microprocessor I/F, Interrupt controller and I/O ports
TECHNOLOGY	ATMEL ATC18RHA 0.18 µm, 352 pins ; 6 Mgates ; GNSS clock up to 50 MHz LEON clock up to 90 MHz	**0.5** micron from ATMEL, 160 pins ; 200 k gates GNSS clock up to 30 MHz