

AGGA-4: core device for GNSS space receivers of this decade

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Abstract—This paper presents the key elements of the next generation of miniaturised GNSS space receivers compatible with the new and improved GNSS signals from Galileo and modernized GPS. 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 and GOCE and that expected in future ESA satellites. The key architectural building blocks of future GNSS space receivers are presented, with special focus on the AGGA-4 (Advanced GPS / Galileo ASIC) baseband GNSS processor and, to a lesser extent, on programmable RF ASICs. These components, in combination with new features of the new GNSS signals, will bring a significant improvement with respect to their predecessors (e.g. AGGA-2) not only in terms of system robustness but also regarding miniaturization, which eventually could enable to have more GNSS space instruments in a larger number of EO satellites.

Keywords: AGGA-4, GNSS space receivers, POD, Radio Occultation, Earth Observation, Galileo, Modernized GPS

I. INTRODUCTION

In the 1980's, Global Navigation Satellite System (GNSS) techniques were demonstrated also for satellites in support to orbit determination and Earth science applications. The success of GNSS space receivers for orbit determination did not come as a surprise since GNSS complements and outperforms ground-based orbit determination techniques thanks to continuous on-board availability of ranging measurements of very high accuracy with small hardware mass and power budgets. Precise Orbit Determination (POD) of Low Earth Orbit (LEO) satellites is possible at a few centimetres level and supports Earth science applications like altimetry, global geodesy, relative positioning between satellites, Radio Occultation (RO) or GNSS-Reflectometry (GNSS-R). RO applications require not only POD support, but also some specific GNSS instrumentation. On-board carrier phase measurements, like for the most precise POD receivers, are required, but due to the very low signal to noise (SNR), also some additional support (e.g. directive antennas, open-loop tracking techniques, etc.) is needed for RO. GNSS-R has even more specific processing requirements for the elaboration of

delay-Doppler maps, which implies that a very specific type of receiver is required, which is out of the scope of this paper.

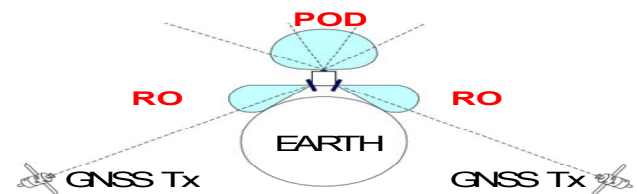


Figure 1. Geometry of GNSS space receivers

Section II presents more in detail the kind of requirements, mainly for POD applications, that will apply to future ESA missions. Section III introduces the architecture of future GNSS space receivers, prior to the presentation in section IV of the AGGA-4 GNSS baseband processor, which features 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 improved GNSS signals from new constellations like Galileo or modernized GPS will have on GNSS space receivers for Earth Observation. Finally, section VII presents the conclusions.

II. EO APPLICATIONS USING GNSS SPACE RECEIVERS

As anticipated above, POD in support to scientific applications is the main usage of GNSS receivers. From the numbers of TABLE I., it is important to note the following points:

- POD is less accurate in real-time (RT) than if data is processed over a few hours or days. The most accurate POD solution can be retrieved after several days because in on-ground post processing for example the clock errors of the GNSS transmitters can be corrected (e.g. using data from the International GNSS Service – IGS- networks) or longer arcs of the LEO orbit are considered in the (reduced) dynamic solution [3].
- the most stringent RT positioning requirement comes from missions like GMES Sentinel-3. Radar altimetry

requires real-time knowledge of the radial position (to < 3 m rms in Real Time) in order to adjust the timing when the measurement echo should be sampled.

- In non-real time, the most stringent requirement comes from GOCE (2 cm rms) and again from the Sentinel-3 (2 cm rms in the radial direction). The GOCE performance has been demonstrated in flight at very low altitude (255 km) [4].
- Radio Occultation in Metop-GRAS has the most stringent requirement in velocity accuracy (0.1 mm/s) in the along direction.
- other missions not reported above may require POD with accuracies well above 10 cm. We will see in section III which key system parameters (e.g. number of bands) can be relaxed in future GNSS receivers at the expense of, for example, accuracy requirements.

TABLE I. EXAMPLE OF REQUIREMENTS IN ORBIT DETERMINATION FOR ESA MISSIONS.

Mission	Real Time (RT)	Non Real Time (1-3h)	Non Time Critical (1 month)
GOCE (launched in 2009)		< 50 cm rms (requirement)	< 2 cm rms (achieved, [4])
Swarm		< 10 cm rms	
Sentinel-1 SAR (interferometry)	10 m. 3σ xyz	5 cm rms	
Sentinel-3 (Altimetry)	3 m. rms (radial)	8 cm rms (radial)	2 cm rms (radial)
MetOp-GRAS (Radio Occultation) (launched in 2006)		0.1 mm/s (velocity along) (achieved)	

It is beyond the scope of this paper to detail the definition of a GNSS Radio Occultation and related parameters like observations per day, maximum impact height, or bending angle accuracy, which depend on the performance of the receiver but also on the ground post-processing. For this, see for example the MetOp Second Generation SRRD (Space Mission Requirements Document) [5].

III. FUTURE GNSS RECEIVERS ARCHITECTURE OVERVIEW

Our vision regarding future GNSS space receivers for POD and RO is summarised in Figure 2., which shows three key blocks in the GNSS receiver: the antenna, the RF chain and the baseband processing based on AGGA-4.

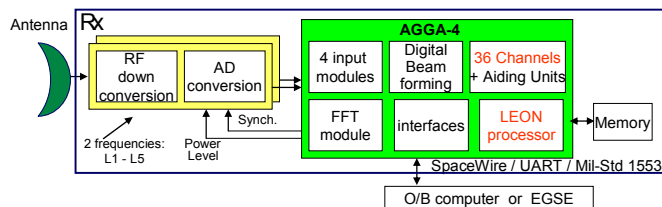


Figure 2. Module of the next generation of GNSS receivers (Rx)

Key architectural trade-offs in the design of 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 result in sub-decimeter accuracy at the expense of additional RF chains and complexity in 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 the chosen bands because most of the new GNSS constellations offer open signals at these frequencies that can be processed with the same hardware and because of the increased signal bandwidth on L5/E5a. Three GNSS frequencies close to each other will not bring benefits for ionospheric corrections.
- acquisition timing: cold start, warm start or hot start differ in the a priori knowledge of several parameters like almanac, PVT solution, etc. and result in slower or faster acquisition, at the expense of software complexity.
- In RO with very low SNR, as shown for example in [6]), all kind of optimizations are needed at the expense of higher complexity, such as
 - High gain directive antennas
 - use of open loop tracking processing techniques when closed loop is no more possible, resulting in for example more observations or longer measurements in lower troposphere heights
- Although not related to low SNR, in RO it is also important to have high performance of the RF Front End with short term stability of the receiver through the use of ultra stable oscillators (USO) with very low phase noise and clock drift.

The choice of the number of bands is crucial, although accuracies just below 10 cm can be achieved with just single-frequency techniques like GRAPHIC [7] 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.

Besides technical aspects, programmatic aspects like the common procurement policy adopted for all Sentinels 1, 2 and 3 play a role. In the particular case of the Sentinels, it implies that the highest required performance (i.e. Sentinel-3) defines the way for the rest. The Sentinel GNSS receivers will be 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

A. Building up from AGGA-2

The development of the first AGGA (Advanced GPS/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 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 and includes novel techniques for which international patents were assigned to the Agency. 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 for RO).

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

- the understanding of the processing functionality that is optimal for atmospheric sounding, in particular through the development and exploitation of the GRAS instrument in MetOp
- new requirements regarding 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) calling for extra functionality (e.g. memory codes, BOC modulation, secondary codes, pilot and data components) in the signal processing.
- advances in space ASIC technology that allow on-chip integration of much more functionality than for AGGA-2

TABLE III. lists the most interesting features that AGGA-4 offers with respect to AGGA-2. Figure 3. provides an overall view of the AGGA-4 functionality, where the AGGA-4 GNSS Core represents the most important block of the device.

B. AGGA-4 GNSS core

As shown in Figure 4. , the Channel Matrix in the GNSS Core includes 36 (target) highly configurable single-frequency (SF) / double code GNSS channels. 36 SF channels correspond to 18 dual-frequency (DF) channels. Each SF channel includes:

- 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 E1bc. In addition, secondary code and BOC modulation capabilities are included. This very flexible architecture allows processing of any known GNSS open service signals in just one SF channel for both signal components (data/pilot), as indicated in TABLE II.
- code and carrier loop aiding in each channel to support the high but predictable range dynamics experienced by Low Earth Orbit (LEO) satellites and launchers. Typically the aiding frequencies are computed immediately after a new navigation solution has become available, either at each Measurement Epoch (ME) or at each Pulse Per Second (PPS) event.

- optimized signal raw sampling or retrieval of observables via Direct Memory Access (DMA) at the output of the correlators, which is useful for example for RO applications in open loop tracking
- a code delay 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, Punctual, Late, Late-Late), which is important for the processing of BOC (Binary Offset Code) signals.
- ten (5I, 5Q) 29 bit integration accumulators.

In order to reduce the gate count per channel, and maximise the number of channels, AGGA-4 does not support:

- code generation of Multiplex BOC (MBOC) signals 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 1dB loss in code phase tracking sensitivity, which is acceptable.
- E5 AltBoc is not necessary given the rather reduced multipath present on spacecraft. Instead, AGGA-4 allows the processing of E5a and E5b in separate SF channels with negligible performance loss
- 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 at least two frequencies are available in Open Service (OS) per constellation, as is the case for Galileo and modernized GPS.
- Semi-codeless processing capabilities (e.g. generation of P-code, or second integration stage). The removal of the semi-codeless processing, which is present in AGGA-2, is largely compensated by the increased number of new GNSS signals available in AGGA-4.

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, which allows slaving of multiple AGGA-4's, hence increasing the number of available channels if needed.

AGGA-4 provides four slaveable input modules that support multiple input formats at baseband (complex format) and intermediate frequency (real format) at sampling frequencies up to 250 MHz (target). Each input module contains two Digital DownConverters (DDC) chains allowing to process up to eight GNSS bands at a time. Implementation losses are reduced through pre-processing (I/Q mixer, FIR decimation, and re-quantisation) which also converts all input formats into a common 3-bit I and 3-bit Q output format. The

front-end also provides Power Level Control functionality, including Digital to Analogue (DAC) conversion to support Automatic Gain Control (AGC).

Each of the two digital beam-forming (DBF) modules performs digital phase shifting and combination of two antenna signals prior to the channel correlations. In total, the two DBF modules can process the inputs from up to four antennas.

C. Other modules and interfaces in AGGA-4

As shown in Figure 3, the GNSS Core and other AGGA-4 modules access memory by direct memory access (DMA) via the AMBA (Advanced Microcontroller Bus Architecture) High-performance Bus (AHB). Data is shared through AHB and AMBA Peripheral Bus (APB).

Frequency estimation during acquisition is supported by a 128 point hardware FFT module (see Figure 3). The FFT could be implemented in software, but the FFT results under high dynamic conditions may be outdated before they can be applied. Furthermore, if done in software, there is a risk of overloading the LEON-2 CPU for the 36 channels of AGGA-4.

AGGA-4 includes on-chip the LEON-2 FT (Fault Tolerant) processor based on the SPARC V8 standard. The LEON-2 processor and periphery consist of a cache sub-system, a memory controller, interrupt controller (see Figure 3. with GIC: GNSS Interrupt Controller; CIC: Communication Interrupt Controller and PIC: Primary Interrupt Controller), four 32-bit timers, one 32-bit watchdog, bus status register, a write protection unit, watch point registers, a 32-bit I/O-port and an extended reset detection section. In addition, it is supported by a IEEE-754 compliant Floating Point Unit (GRFPU) from Gaisler Research. Target frequency for the LEON-2 is at least 80 MHz.

The main AGGA-4 external interfaces are:

- two DMA capable UARTs
- SpaceWire interfaces: AGGA-4 has four bidirectional SpaceWire interfaces implemented with single-ended IO's (no LVDS) for general communication purposes (e.g. connection to EGSE, booting, extracting observables, etc), at a rate per link related to the LEON-2 clock
- Mil-Std-1553 bus
- External SRAM memory interface with the on-chip LEON-2 FT microprocessor
- Debug Support Unit (DSU) with debug Interface (UART and Spacewire)
- Serial Peripheral Interface (SPI) for communicating e.g. with RF Front End

D. FPGA verification and ASIC manufacturing

A very extensive functional validation through the use of an FPGA prototype has been carried out by RUAG Space Austria under ESA contract. This FPGA is based on the VHDL design provided by Astrium GmbH and includes exactly the functionality of the final ASIC with the sole exception of

implementing only 4 GNSS channels, as opposed to the 36 channels in the ASIC. This testing campaign has been carried out in different stages: e.g. block level testing using specific synthesized inputs, and also system testing during the 3rd quarter of 2010 using multiple Galileo and modernized GPS signals generated by the Spirent simulator at the ESA/ESTEC Navigation Laboratory. In addition, Deimos Engenharia (Portugal) has also performed a valuable, though reduced, independent verification campaign on the FPGA prototype.

This VHDL design will be used to manufacture the final AGGA-4 ASIC with approximately 4.5 M gates under Atmel ATC18RHA 0.18 μ m technology. The assumed package is an MQFP package with 352 pins. The first samples of the AGGA-4 ASIC components are expected to become available in 4Q-2011 for the whole European space industry under equal conditions, as it was the case in AGGA-2.

V. RF CHAIN AND ANTENNAS IN GNSS RECEIVERS

The RF chain performance is a very important part for the overall performance of the GNSS receiver. This is particularly true for Radio Occultation (RO) applications, where parameters like phase noise, local oscillator stability and clock coherency with multi-frequency plans based on integer ratios between the different domains (e.g. digital, intermediate frequency, carrier) and components serving the relevant bands (L1, L2 or L5), are crucial to the observation science. Stringent out-of-band filtering requirements are also required due to emitted signals close to the GNSS spectrum (e.g. Search and Rescue – S&R – on-board payload) or due to ground interference in the L-band. New technology can also be used to improve the receiver front-end. Specifically, very low noise amplifiers (LNA), integrated close to the antenna when no S&R payload is considered, can be used to improve the receiver system noise, which allows improving SNR. Quantization losses will also be lower in future receivers: e.g. from 0.55 dB with 2-bit ADCs for AGGA-2 to 0.17 dB with 3-bit ADCs for AGGA-4. Performance requirements are less stringent for POD applications than for RO, nevertheless improvements made for RO will also benefit POD.

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. NJ10x7 for RF down-conversion and NJ10x8 for ADC, as shown in Figure 2.), which were developed under ESA contracts. These devices are programmable and capable of processing all the relevant public GNSS bands (e.g. L1 and L2C in the coming 5 years, and later L1/E1bc and L5/E5a). Qualification of this kind of devices combining wideband analogue and digital capabilities is complex given the low number of components used in the space business. For these reasons, there is a strong need that the next generation of these RF ASICs can be used in as many EO GNSS applications as possible, namely POD, RO and GNSS-Reflectometry, with the expected performance of the most demanding of them (i.e. RO). If this objective is fulfilled, the same miniaturized hardware modules shown in Figure 2. could be used many more times, hence reducing costs, and enabling their possible use in a larger number of satellites.

Antenna gain is not critical for POD applications in a LEO geometry (see Figure 1.) although precautions have to be taken into account for example to minimize multipath. Antenna gain is much more important for RO applications, however the rather large wavelength (around 25 cm at L5) imposes a serious constraint on the antenna size (e.g. 86 x 46 cm in Metop-GRAS) required to achieve the expected gain (e.g. 9 dB at 45 degree azimuth angle) that can only be slightly improved with new technology.

VI. NEW GNSS SIGNALS AND CONSTELLATIONS

In the 2010 decade new GNSS signals will be available not only from an enlarged set of systems (e.g. modernized GPS, Galileo, Glonass, Beidou), but also with new characteristics that will make 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, as well as more science observations (e.g. in RO). It seems unlikely that much better accuracy can be achieved for POD applications with respect to the cm-level performance of today, due to the dominance of external errors.
- At least two open service frequencies available per constellation: no more need for semi-codeless processing at low SNR, 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 unfavorable conditions (e.g. when observing the lowest layers of the troposphere in a RO).
- Pilot components in new GNSS signals: this will allow to extend the integration time (i.e. no need for navigation bit wiping) and brings robustness, less loss of track and increased 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 dB) and higher bandwidths (e.g. 10 MHz), resulting in more accurate code measurements, but only slight improvements in carrier measurements. Under very low SNR in RO, carrier tracking is often lost, so having better code measurements will be beneficial to new retrieval algorithms.
- secondary codes will bring robustness regarding interference, "lengthen" the spreading code that will result in better autocorrelation function peak while still allowing a fast acquisition.
- BOC modulations, together with higher chip rates and bandwidths, will provide higher robustness against multipath, though this is not the most severe problem in spacecraft. Nevertheless, they may open new possibilities for example for GNSS-based attitude determination.

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

- a possible slight relaxation of antenna requirements.
- 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. sampling at intermediate frequency and digital final down conversion, 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 as well as code and carrier aiding are implemented in hardware in each GNSS channel.
- different software: simpler in one side because no codeless processing or bit wiping will be needed, but on the other side more complex due to the larger amount of available signals and also to the possible need to synchronise different constellations.

In short, it is expected that the new GNSS signals will bring higher robustness and similar accuracy in the next generation of GNSS space receivers for POD. Under very low SNR in RO, there is a potential accuracy improvement because the losses in semi-codeless processing will not be present and thanks to pilot signals. In addition, the higher code bandwidths could help when only code tracking is possible.

The Agency is preparing the field by developing new and more versatile components like AGGA-4 and programmable RF Front-End ASICs. Activities to develop Engineering Models of the next generation of GNSS space receivers will follow the near availability of those components.

VII. CONCLUSIONS

POD by 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, also for very low altitude (255 km) in the first ESA Earth Explorer: GOCE [4]. 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, also in terms of POD and real-time navigation.

Radio Occultation is a successful technique for the derivation of vertical profiles of temperature in the atmosphere as well as humidity in the lower troposphere. The high performance of the Metop-GRAS instrument over 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 models).

The baseband processor AGGA-2 was instrumental for these achievements. AGGA-2 is widely used not only on ESA missions. The next generation, AGGA-4, will be compatible

with the new GNSS signals, which in itself will bring significant improvements in robustness (e.g. less loss of track) thanks to the many more signals available and also to some of their features, pilot carriers being probably the greatest performance enhancer for applications requiring carrier phase measurements like RO. AGGA-4 supports many more GNSS channels (target 36) and includes more functionality on-chip (e.g. aiding unit per channel, LEON2-FT micro-processor on-chip, etc). As with AGGA-2, AGGA-4 will be made available to all European space industry in 4Q-2011 on equal basis. The RF chain is also undergoing upgrades with better performance (e.g. higher bandwidth, less noise and clock coherency) and miniaturization through programmable integrated RF devices like the Saphyrion chipset. The development of these devices (AGGA-4 and new RF ASICs) will be soon complemented with more development activities at GNSS space receiver level. Miniaturization of the devices and overall receiver should also enable the possibility to use more and cheaper GNSS space receivers, also for scientific applications, in a larger number of EO satellites.

ACKNOWLEDGMENT

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

Band	Freq. (MHz)	Component	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	

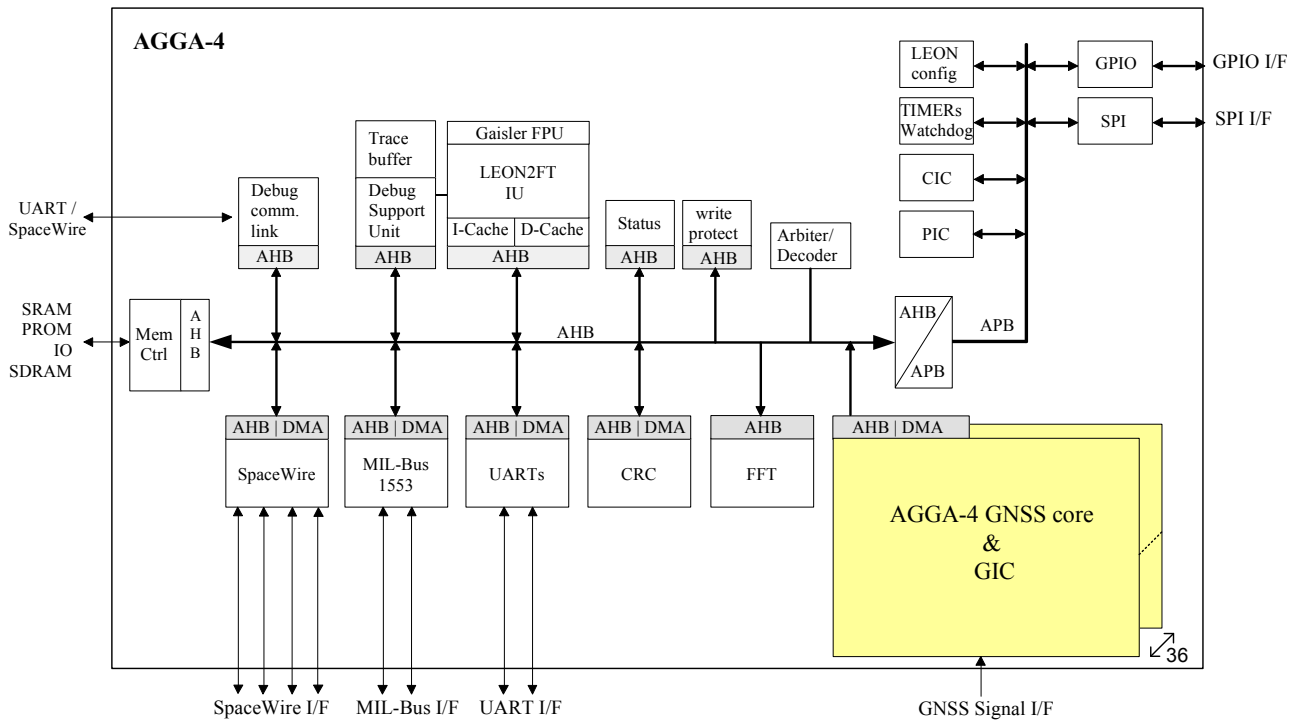


Figure 3. AGGA-4 System overview (extract from draft AGGA-4 Datasheet)

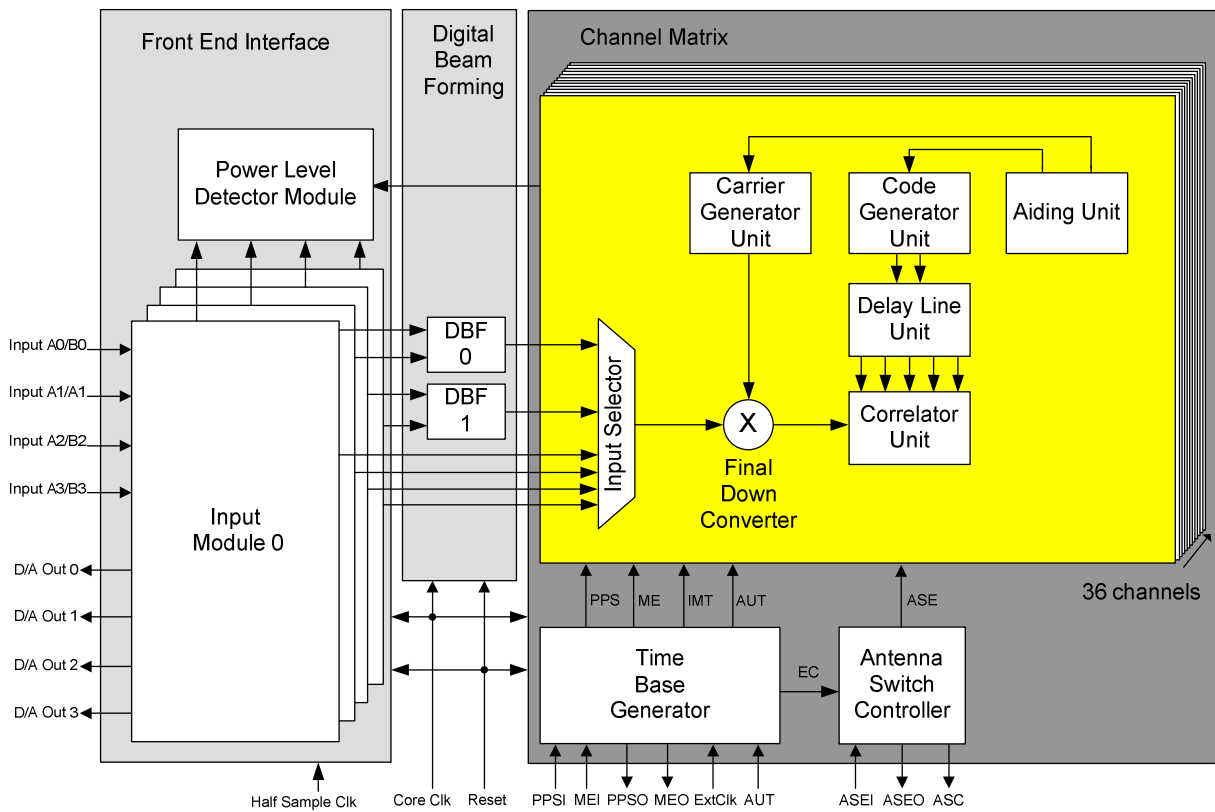


Figure 4. AGGA-4 GNSS Core (extract from draft AGGA-4 Datasheet)

TABLE III. SHORT COMPARISON AGGA-2 / AGGA-4 (MAIN FEATURES IN BOLD LETTERS)

Feature	AGGA-4	AGGA-2
GNSS CHANNELS		
# 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 Best effort: Beidou, modernized Glonass (CDMA)	GPS L1 C/A Semi-Codeless L1/L2 Existing FDMA Glonass
Code Generators	(2 code generators 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 only 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)	Off-chip (typically ERC-32, ADSP 21020)
INPUT FORMAT	3 bit => 0.17 dB implementation loss (I/Q, real sampling and interface for Intermediate Freq. ~ 250 MHz (target))	2 bit => 0.55 dB implementation loss (I/Q and real sampling)
CRC MODULE	On-chip	No – task done in software
FFT MODULE	On-chip (ideal for fast acquisition)	No – task done in software
INTERFACES	Two DMA capable UART, Mil-Std-1553 , 4 SpaceWire SE, SPI I/F, DSU, S-GPO, 32 GPIO, SRAM I/F	Microprocessor I/F, Interrupt controller and I/O ports
BEAMFORMING TECHNOLOGY	Yes (2 Digital BF)	No
	0.18 Micron from ATMEL, 352 pins GNSS clock up to 50 MHz (target)	0.5 micron from ATMEL, 160 pins GNSS clock up to 30 MHz