Next generation of miniaturised receivers with new GNSS signals

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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 more robust 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 performance expected in future ESA satellites. The key architectural building blocks of future GNSS space receivers are presented, with special 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, will bring a significant improvement with respect to their predecessors (e.g. AGGA-2) and also represent an important step towards miniaturisation of the next generation of GNSS space instruments.

1. 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 the most precise POD receivers, but, due to the very low signal to noise (SNR) received, 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 2 presents more in detail the kind of requirements, mainly for POD applications, that will be needed in future ESA missions. Section 3 introduces the architecture of future GNSS space receivers, prior to the presentation in section 4 of 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 5 briefly presents the main issues that future GNSS receivers face in the RF area. Section 6 shows the impact that the availability of new and more robust GNSS signals from new constellations like Galileo or modernized GPS will have on GNSS space receivers. Finally, section 7 presents the conclusions.

2. 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 1, 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 can be retrieved several days after 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 archs of the LEO orbit are considered in the reduced dynamic solution [Ref. 3].

- the most stringent 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 Sentinel-3 (2 cm rms in the radial dimension). The GOCE performance has been demonstrated in flight [Ref. 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 later in the architectural section 3 what key system parameters (e.g. number of bands) can be relaxed in future GNSS receivers for lower accuracy requirements.

Mission	Real Time (RT)	Non RT (1-3h)	Slow Time Critical STC, (1-2 days)	Non Time Critical (1 month)
GOCE		< 50 cm rms (requirement)	< 10 cm rms (achieved ~ 4 cm)	< 2cm rms (achieved, [Ref. 4])
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)		0.1 mm/s (velocity. along)		

Table 1 Example of requirements in orbit determination for ESA missions.

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 ground post-processing. For more details, please consult the post-EPS MRD (Mission Requirement Document) [Ref. 5].

3. Future GNSS receivers architecture overview

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

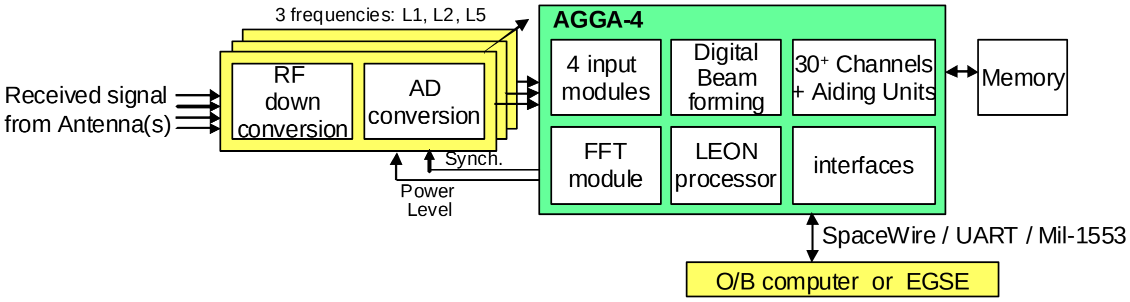

Figure 1 Architecture of the next generation of GNSS receivers

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 most new GNSS

constellation offer signals at these frequencies that can be processed with the same hardware. Three GNSS frequencies so close to each other will not bring benefits for ionospheric corrections.
- carrier and code measurements or only code measurements: carrier measurements is crucial to to sub-meter accuracies, but it also requires higher performance of the different building blocks than the simpler code measurements alone for the intended applications.
- 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.
- In RO, as shown in some assessments (e.g. [Ref. 6]), given the very low SNR, all kind of optimisations 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, though accuracies around 10 cm can be achieved with just single-frequency techniques like GRAPHIC [Ref. 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) paves the way for the rest. The Sentinels 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.

4. Baseband GNSS processor: AGGA-4

The development of the first AGGA (Advanced GPS/GLONASS 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. The AGGA-2 is a space-qualified digital integrated circuit providing all the high-speed digital signal processing functionality for GNSS EO applications including 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. BOC, secondary codes) in the signal processing.
- advances in space ASIC technology that allow on-chip integration of much more functionality

Table 2 shows the most interesting features that AGGA-4 offers with respect to AGGA-2.

The Channel Matrix 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 (see Figure 2) 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 the memory-based E1bc. In addition, secondary code and 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), as indicated in Table 3.

- 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 immediately after a new navigation solution has become available, either at each Measurement Epoch (ME) or at each Pulse Per Second (PPS) event.
- optimized raw sampling or retrieval of observables via DMA at the output of the correlators, which is useful for example for Radio Occultation applications in open loop tracking
- 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), which is important for the processing of BOC (Binary Offset Code) signals.
- ten (5I, 5Q) 29 bit integration accumulators.

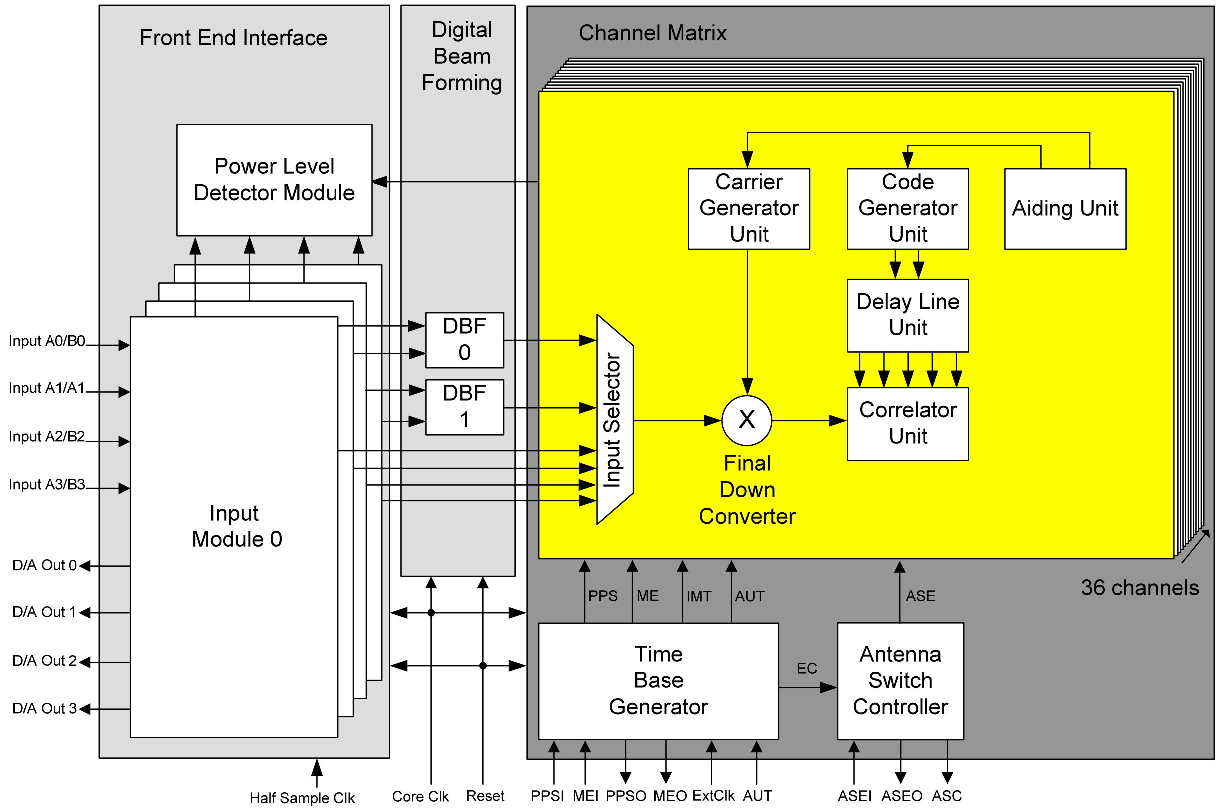

Figure 2 AGGA-4 GNSS Core (extract from a draft version of AGGA-4 Datasheet)

In order to reduce the gate count per channel, hence maximising 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 in spacecrafts. 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 we have at least two frequencies available in Open Service (OS) per constellation, as it is the case in Galileo.
- 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 in baseband (complex format) and intermediate frequency (real format) at sampling frequencies up to 250 MHz (target). 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.

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 four antennas, as shown in Figure 1.

Feature	AGGA-4	AGGA-2
GNSS CHANNELS		
# of channels	36 Single Freq. or 18 DF (target)	12 SF or 4 DF
Compatible signals	Galileo OS: E1bc, E5a, E5b GPS: L1 C/A, L1C, L2C, L5 Potentially: Beidou, modernized Glonass	GPS L1 C/A 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.
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
Common to all channels	Antenna Switch Controller (ASC) Time Base Generator (TBG)	ASC TBG
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 (I/Q, real sampling and interface for Intermediate Freq. ~ 250 MHz)	2 bit (I/Q and real sampling)
CRC MODULE	On-chip	No
FFT MODULE	on-chip	No
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	Yes (2 Digital BF)	No
TECHNOLOGY	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

Table 2 Short comparison AGGA-2 / AGGA-4

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).

In AGGA-4, frequency estimation during acquisition is supported by a 128 point hardware FFT module (see Figure 1). 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 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 extednded reset detection section. In addition, it is supported by a Floating Point Unit (FPU) that is IEEE-754 compliant 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 are implemented in the AGGA-4
- 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

Extensive functional validation, through the use of an FPGA prototype, by two independent teams (Ruag Aeropace Austria and Deimos Engenharia) is almost complete. This FPGA uses the same VHDL that will be used to manufacture the final AGGA-4 ASIC under Atmel ATC18RHA 0.18 μm technology. The assumed package is an Atmel MQFP package with 352 pins. ASIC components are expected to become available for the whole European space industry in 3Q-2011.

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	

Table 3 Modernized GPS and Galileo signals and possible AGGA-4 configuration

5. RF chain and Antennas in GNSS receivers

The RF chain performance is very important part of the overall performance of the GNSS receiver. Specifically, in Radio Occultation (RO) applications, parameters like phase noise, local oscillator stability and clock coherency and noise figure are crucial to increase 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 payload). Performance requirements also apply to POD applications, although the requirements are less stringent.

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. NJ10x7 for RF down-conversion and NJ10x8 for ADC, see Figure 1) 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 is very complex given the low number of components that can be used in the space business.

Quantisation losses are expected to 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. In case two frequencies are processed, normally L1 and L2 in the coming 5 years, and later on L1/E1bc and L5/E5a, good frequency plans based on integer factor relationships between the different domains (e.g. digital, intermediate frequency, carrier) to ensure clock coherency are very important.

Antenna gain is not critical for POD applications in a LEO geometry. Antenna gain is more important for RO applications, however, the rather large wavelength (around 25 cm in 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 with a 45 degree azimuth angle) that can hardly be improved with new technology.

In addition to the receiver improvements, the GNSS transmitted signals will be improved. GALILEO and modernized GPS signals will provide slightly higher transmit power compared to current GPS satellites. Pilot signals will allow for longer integration times. All these improvement together could enable for example relaxing the required antenna gain and size and therefore enabling embarking smaller RO instruments into a larger number of satellites that will lead to an increasing number of RO observations.

6. Implications of having 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 is unlikely that much better accuracy can be achieved, for POD applications 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 a RO.)
- Pilot components in 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 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 will bring robustness regarding interference, "lengthen" the spreading code and autocorrelation function peak while still allowing a fast acquisition.
- BOC modulations, together with higher chip rates and bandwidths provide higher robustness against multipath, but this is not the most severe problem in spacecraft. Nevertheless, it 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 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 are implemented in each GNSS channel
- 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 and also to the possible need to synchronise different constellations.

7. 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 [Ref. 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. These very high performance (< 10 cm rms) POD receivers in ESA missions are dual-frequency receivers. Accuracies above the decimetre accuracy can be achieved with techniques like GRAPHIC that combine code and carrier measurement to eliminate the ionospheric perturbations.

Radio Occultation is also an emerging technique for the elaboration of vertical profiles of temperature, pressure as well as humidity in the lower troposphere. The high performance of the Metop-GRAS instrument over compared to 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 use of 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, and this in itself will bring significant improvements in robustness (e.g. less loss of track) by the many more signals available and also thanks to some of its features, with pilot carriers probably the greatest performance enhancer for 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 in 3Q-2011 under equal basis. The RF chain is also on-going upgrades with better performance (e.g. higher bandwidth, less noise) and miniaturisation though programmable and more integrated RF devices like the Saphyrion chipset. .

8. Acknowledgements

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