

Development of an Advanced GPS GLONASS ASIC

Peter Sinander

*Microelectronics section, Directorate of Technical and Operational Support
European Space Agency, PO. Box 299, NL-2200 AG, The Netherlands
phone: +31-71-565 3367, fax: +31-71-565 4295, e-mail: psi@ws.estec.esa.nl
http://www.estec.esa.nl/wsmwww/*

Pierluigi Silvestrin

*Low Orbit Systems section, Directorate of Application Programmes
European Space Agency, PO. Box 299, NL-2200 AG, The Netherlands
phone: +31-71-565 3689, fax: +31-71-565 4696, e-mail: psilvest@estec.esa.nl*

ABSTRACT

This paper presents the second generation of the Advanced GPS GLONASS ASIC, the AGGA-2, a chip covering a wide range of GPS and GLONASS space related applications, including Spacecraft Control (position, velocity, time and attitude determination in orbit), Precise Orbit Determination, Atmospheric Sounding and Reference Stations. The AGGA-2 has twelve channels, each channel supporting GPS or GLONASS operation with C/A-code, P-code or GPS Y-code. Its features include both single-frequency and dual-frequency operation, 36 complex correlators, support for the Hybrid Parallel-Multiplex attitude determination scheme, and high-performance adaptive semi-codeless tracking of GPS Y-code. The AGGA-2 will be manufactured in a radiation tolerant technology and will be available to European industry as an Application Specific Standard Product.

The paper first describes the principles of GPS and GLONASS operation and lists the main applications targeted by the AGGA-2. This is followed by an outline of two typical receivers and by an overview of the AGGA-2 functionality. Finally the design heritage, the development logic and the AGGA-2 availability and evaluation activities are presented.

1. PRINCIPLES OF OPERATION

The Global Positioning System (GPS) is a navigation system deployed by the United States Department of Defense. While the driving reasons behind the development were military, civilian usage was foreseen from the beginning and has rapidly expanded beyond any initial expectations. Today, it represents a large application area ranging from consumer equipment to spaceborne Spacecraft Control receivers and remote sensing instrumentation.

The GPS space segment consists of 24 satellites on accurately determined orbits, each carrying 10.23 MHz atomic oscillators, monitored to a few nanoseconds accuracy with respect to the GPS system time. Each satellite transmits unique Code Division Multiple Access (CDMA) signals by modulating the carrier with pseudo-random code sequences, namely with the 1.023 Mb/s Coarse/Acquisition (C/A) code, modulated on the 1575.42 MHz L1 carrier for standard applications, and with the 10.23 Mb/s Precision (P) code, modulated on the L1 and the 1227.6 MHz L2 carriers for precise applications. The P-code is currently encrypted by a code which is generally reserved to military users, and the resulting code modulated on the GPS signals is called the Y-code. Nevertheless, codeless and semi-codeless tracking techniques have been developed to circumvent this limitation for civilian applications. Semi-codeless techniques exploit the knowledge of the P-code prior to encryption to reduce the pre-correlation bandwidth to that of the encrypting code, improving the Signal-to-Noise Ratio (SNR) by approximately 13 dB.

The code sequences and the signal carriers are all coherently derived from the on-board atomic oscillators. The position of the GPS satellites and other useful parameters are transmitted on both the L1 and L2 signals at a rate of 50 b/s.

A receiver generates replicas of the pseudo-random code sequences and synchronizes them to the signals received from the satellites. Neglecting atmospheric propagation effects, each received signal has been delayed during its transmission by a propagation time corresponding to the distance between the satellite and the receiver. If signals from four satellites are received simultaneously and the related propagation times are accurately measured, the receiver can resolve for the three physical coordinates and the receiver time.

A different approach is used to determine attitude. The signal from a satellite is received via three or more separate antennas connected to a receiver capable of measuring precisely the difference in carrier phase between the antenna signals. The carrier phase differences allow the receiver to recover the angle between the antenna baseline and the incident signal direction. To fully determine the attitude at least two attitude measurements along different baselines are needed. The phase determination precision is typically 1 mm, so that with an antenna spacing of 1 meter an angular accuracy better than 0.1° can be obtained [1].

The Global Orbiting Navigation Satellite System (GLONASS) is being deployed by the Russian Federation and is based on the same operating principles as GPS, although with some implementation differences, such as the use of Frequency Division Multiple Access (FDMA) instead of CDMA for satellite identification. GLONASS employs different carrier frequencies for each of the planned 24 satellites, although antipodal satellites reuse the same frequency, effectively halving the number of occupied frequency channels. Currently the GLONASS frequencies are $1602+9/16 \cdot i$ MHz for L1 and $1246+7/16 \cdot i$ MHz for L2, with i being the channel number ranging from -7 to +12 (-7 to +4 from 2005). Other differences include the lower code modulation rates (511 kb/s for C/A-code and 5.11 Mb/s for P-code) and the absence of encryption on the P-code.

From an application point of view, the combination of GPS and GLONASS offers increased precision, availability and reliability with respect to each system alone and is therefore very attractive, although it has been limited so far by difficulties in the GLONASS deployment. Detailed information on GPS and GLONASS can be found in [2].

2. AGGA-2 TARGET APPLICATIONS

The second generation Advanced GPS GLONASS ASIC (AGGA-2) implements all the high-speed digital signal processing required to acquire and track GPS and GLONASS signals. It is being developed to cover a majority of space related applications, including those listed below.

2.1 Spacecraft Control

Spacecraft Control applications include the determination of position, attitude and time, normally using only the C/A-code on the L1 frequency. The on-board Attitude and Orbit Control System (AOCS) computer can use the position and attitude information in real time for control purposes, while the time information can be used by the Data Handling System and the payload to precisely time-tag on-board

measurements or to synchronize satellites in a constellation.

The AGGA-2 supports several receiver architectures for attitude measurement, including the parallel architecture and the novel hybrid parallel-multiplex architecture [3] which requires 30% to 50% fewer channels than the parallel one. The position determination accuracy is typically a few tens of m, depending on the on-board software complexity and computational resources [4], while the accuracy for attitude determination is strongly dependent on the accommodation of the antennas, and in particular by the on-board multipath environment.

The AGGA-2 also fully supports tracking of signals provided by systems such as the European Geostationary Navigation Overlay System (EGNOS) and the equivalent US and Japanese systems (WAAS and MTSAT). These signals will be used for ranging, and for broadcasting of integrity information and differential corrections.

2.2 Precise Orbit Determination

In this application the spacecraft user position is obtained by combining the L1 and L2 carrier phase data with tracking information from a set of ground reference stations and using sophisticated models of the perturbations affecting the orbit, such as air drag, gravity anomalies, etc. These calculations are performed as post-processing on ground and can yield cm-level accuracy of the position relative to the reference obtained from the set of reference stations.

2.3 Atmospheric Sounding

Atmospheric Sounding is a limb sounding technique which takes advantage of the variations in refraction index when the signals pass through the earth's atmosphere so as to finally determine temperature and humidity up to heights of 50 km and 10 km, respectively. When signals from a rising or setting GPS or GLONASS satellite pass through the stratosphere and the troposphere before reaching the sensor, the propagation paths are subject to refraction. The refraction angle profile can be precisely determined from carrier phase measurements, allowing the vertical refractivity profile to be recovered. In the stratosphere and upper troposphere where the water vapor content is low, refraction is mainly determined by vertical temperature gradients and the temperature profile can be accurately retrieved. In the lower troposphere the water vapor effects are dominant and the humidity can be retrieved, provided the temperature is known with a modest accuracy.

From a Low Earth Orbit (LEO) satellite about a thousand measurements of temperature and humidity profiles can be performed per day using both GPS and

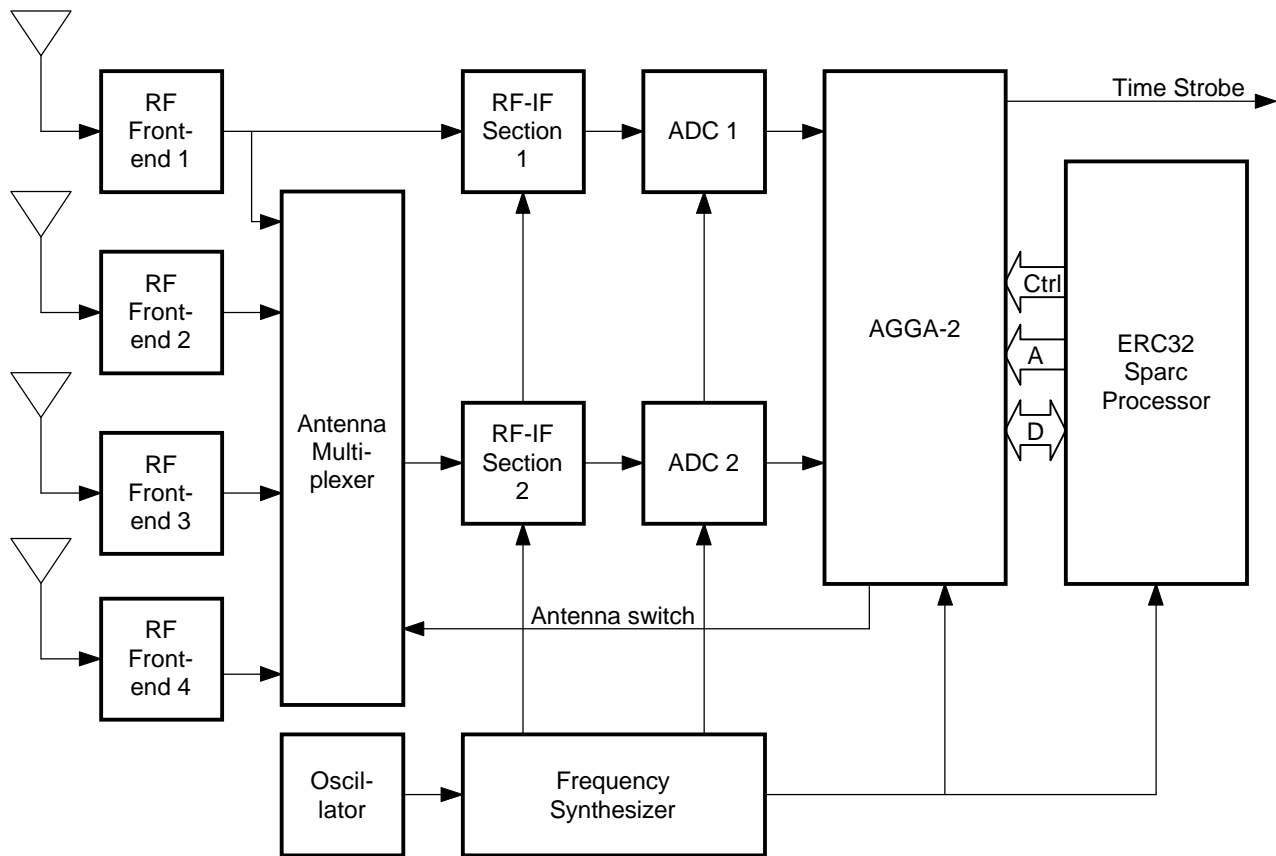


Figure 1: Receiver for Spacecraft Control using the Hybrid Parallel-Multiplex architecture

GLONASS signals. This is expected to have a substantial impact on operational meteorology and on climatology.

A similar technique can be applied for monitoring the electron density in the ionosphere up to the LEO orbital height.

2.4 Reference Stations

Reference Stations are used to compensate for the intentional and non-intentional errors in the GPS and GLONASS signals. A reference station is placed at a fixed well-determined location on the ground, and thus any change in the position calculated from the received signals can be used to identify errors in the same signals. Estimates of the errors can be transmitted to other receivers, allowing them to compensate for the errors using differential techniques. Reference stations require a receiver capable of receiving and decoding both the L1 and L2 frequencies to eliminate the effects of ionospheric propagation delays.

3. AGGA-2 GPS/GLONASS RECEIVERS

A typical receiver consists of Radio-Frequency (RF) circuitry, the AGGA-2 Digital Signal Processing chip

described in the following section, and a microprocessor.

For applications requiring only the GPS L1 signals, the GP2010 [5] or the STB5600 [6] bipolar single-chip RF front-ends could be used, depending on requirements on radiation and component quality level. In this type of receiver the AGGA-2 will typically operate at a core clock rate of 3 MHz.

Many applications will however use both GPS and GLONASS L1 signals in order to increase the availability, reliability and accuracy. Because of the GLONASS FDMA, the signal bandwidth is larger than for GPS and the AGGA-2 needs to operate at 15 MHz to allow digital removal of the GLONASS channelisation frequency. This higher processing frequency also allows higher precision and better multipath mitigation, although at the expense of increased power consumption. Until a suitable single-chip GPS/GLONASS RF front-end similar to the GP2010 becomes generally available, a single-stage down-conversion to Intermediate Frequency (IF) and discrete comparators for A/D conversion would typically be used. An example receiver for Spacecraft Control is outlined in Figure 1.

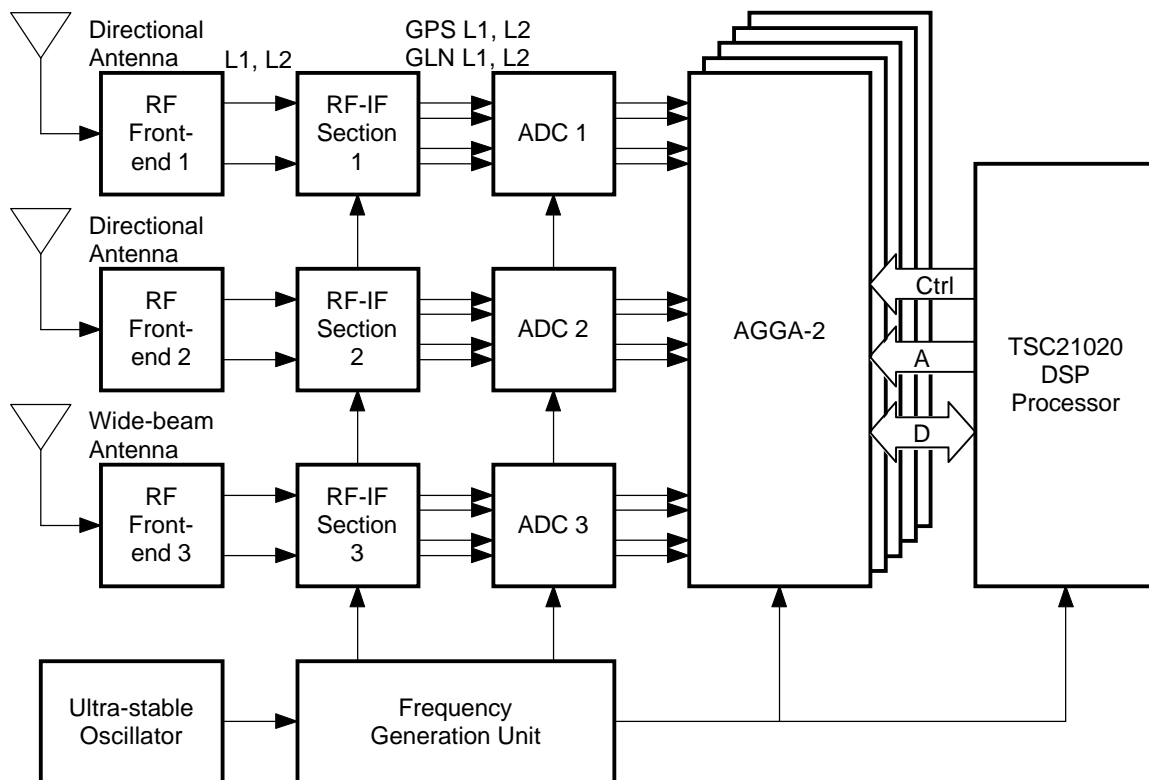


Figure 2: Sensor for Atmospheric Sounding with five AGGA-2

For high-precision applications, conventional RF circuitry such as local oscillators and mixers combined with discrete comparators or 2-bit Analog-to-Digital Converters (ADCs) have to be used, similar to the case above. Alternatively, a more advanced Digital Down-Conversion front-end ASIC can be developed, providing complex samples of down-converted signals to the AGGA-2. For these applications the higher rate P-code or Y-code needs to be demodulated, leading to the AGGA-2 typically operating at 20 to 30 MHz. An architecture of a sensor for atmospheric sounding is shown in Figure 2.

A microprocessor is needed to configure the AGGA-2, to support signal acquisition, to close the tracking loops and to perform the calculations of position, time, attitude etc., as applicable. The AGGA-2 is directly compatible with the ERC32 SPARC chip set [7] and the planned single-chip SPARC processor for applications with high reliability requirements, as well as the TSC21020 Digital Signal Processor [8] typically used in instruments requiring high floating point performance.

4. THE AGGA-2 FUNCTIONALITY

An AGGA-2 implements twelve single-frequency channels, each capable of tracking a GPS or

GLONASS C/A-code signal. Depending on how high complexity can be integrated in the chosen technology, this number might be increased to fifteen channels just before layout and manufacture. Pairs of single-frequency channels can be configured for attitude determination according to the Hybrid Parallel-Multiplex Architecture. For example, one twelve-channel AGGA-2 can track nine satellites for position and time, of which three satellites also being used for attitude determination. Three single-frequency channels together with a P-code Unit can be configured into one dual-frequency channel capable of tracking GPS or GLONASS C/A-code on L1 and P-code and L1 and L2; thus one twelve-channel AGGA-2 can be configured with four dual-frequency channels. Such configurations can be repeated as well as mixed. An overview of the AGGA-2 is shown in Figure 3.

The input interface has eight independent 2-bit digital inputs. Several input formats can be accepted with either real or complex input data, although the latter requires two inputs per signal to be used, effectively halving the number of antennas that can be connected to an AGGA-2. The Real-to-Complex Converters convert real input signals into complex signals.

For each single-frequency channel, the AGGA-2 includes an Input Selector, a Final Down-converter, Carrier and Code-rate Generators for the replica carrier

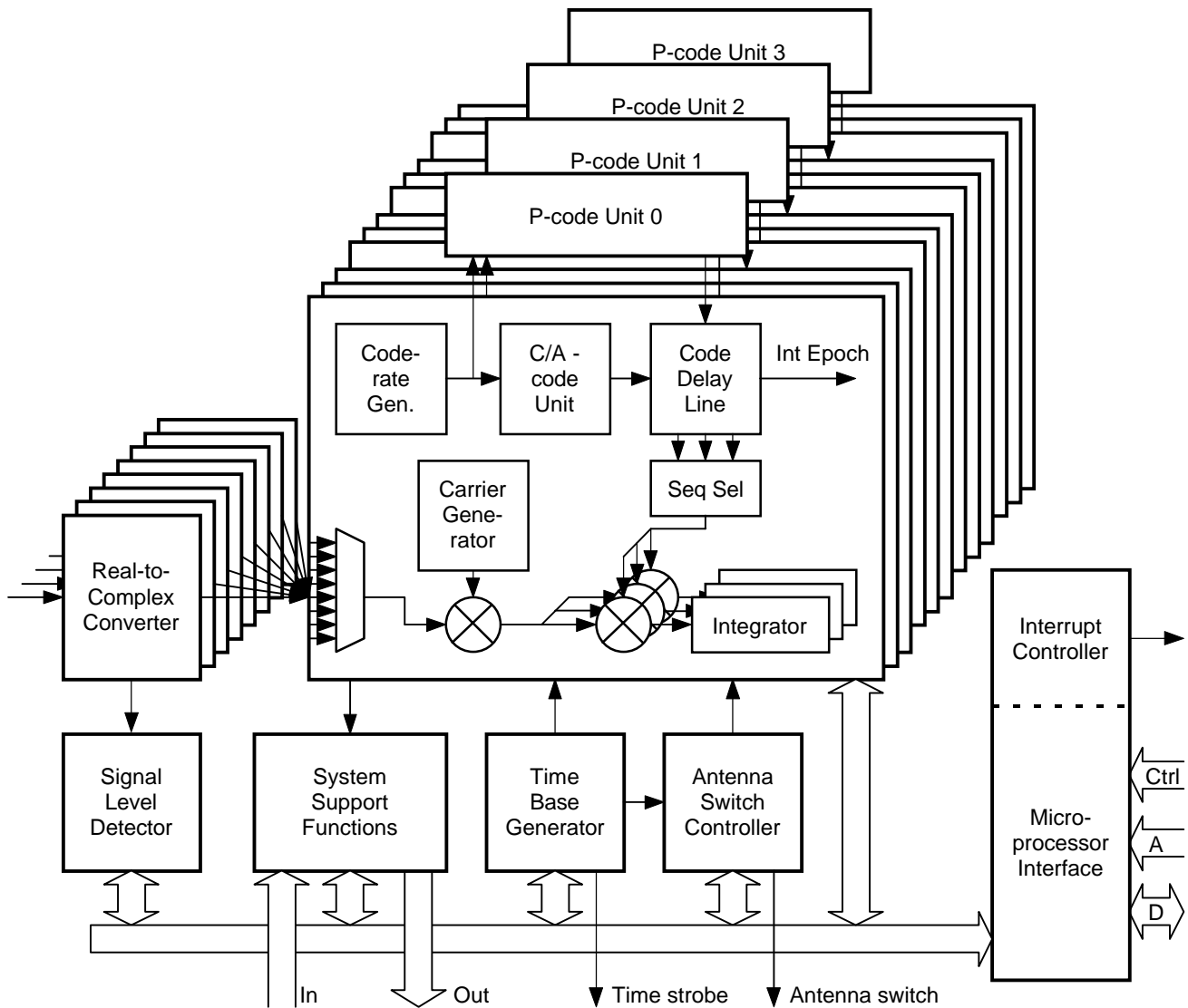


Figure 3: Block diagram of a twelve-channel AGGA-2

and code-rate in the form of Numerically Controlled Oscillators (NCOs), a C/A-code Unit for the replica code sequence, a Code Delay Line for spacing the replica code, and three complex Correlators. Furthermore, for each group of three single-frequency channels, a P-code Unit for replica P-code generation and adaptive semi-codeless tracking is included.

AGGA-2 functionality and features worth highlighting include:

- Digital removal of the GLONASS FDMA channelisation in the Final Down-converter;
- 2-bit signal processing for reduced SNR loss in the Analogue-to-Digital Conversion (ADC) compared to the typical 1-bit or 1.5-bit implementations;
- Three complex correlators per channel to support fast acquisition, multipath mitigation, etc. For example, with one AGGA-2 up to 144000 code phase/Doppler frequency bins can be searched per second;
- Adaptive semi-codeless tracking of the GPS Y-code, offering better performance than other semi-codeless tracking schemes;
- Support for the Hybrid Parallel-Multiplex attitude determination scheme;
- Generation of a Pulse-Per-Second strobe signal synchronous to GPS or GLONASS system time;
- Flexible programming of parameters affecting the receiver performance, such as integration period, integration dead-time, measurement period and antenna switch period;
- Calibration support for high-accuracy applications.

The functionality of each separate channel is highly programmable and supports several channel slaving schemes. Examples of configuration parameters include: selection of GPS or GLONASS C/A-code or P-code; selection of a combination of Early, Precise, Late or Early-Late despread sequence for integration; setting of the chip spacing and the integration period; etc. Examples of channel slaving include single or dual frequency operation; fast-acquisition; enabling of the Hybrid Parallel-Multiplex attitude determination mode.

Some circuitry is common to all channels, such as the Time Base Generator, the Antenna Switch Controller for Hybrid Parallel-Multiplex attitude determination, the 32-bit Microprocessor Interface including the Interrupt Controller and System Support Functions such as Input/Output ports and provision of calibration signals.

5. HERITAGE AND DEVELOPMENT STATUS

An initial breadboard was designed by the Institute for Satellite Navigation (ISN) at the University of Leeds (UK) [10]. The objective was to prove the feasibility and function of a combined GPS/GLONASS receiver, mainly targeted to Precise Orbit Determination and Atmospheric Sounding. This breadboard employs approximately 20 Field Programmable Gate Arrays for a receiver with eight dual-frequency channels, occupying a full rack and consuming some 50 W.

As a first attempt to miniaturize the ISN design, the digital electronics was redesigned by IMEC (B), yielding the AGGA-0 chips delivered in July 1998. While the AGGA-0 does not represent the final design, it allows breadboard test activities to be initiated while the flight-worthy AGGA-2 design is being finalized.

The AGGA-2 development started in January 1998 by the Microelectronics section at ESTEC, supported by Dr Neil Howard from Veridical Solutions (UK) who was part of the design team for the original breadboard at ISN. As a first step, the AGGA-2 Functional Specification [9] was established, as far as possible backwards compatible with the AGGA-0, reviewed and agreed by several parties in Industry, including Austrian Aerospace (A), Dornier (D), LABEN (I), Matra Marconi Space (F) and Saab-Ericsson Space (S).

As the AGGA-0 design could not be reused for a flight-worthy chip, a new internal architecture and clocking strategy were established and the corresponding VHDL (VHSIC Hardware Description Language) model was written. Results from initial synthesis runs indicate a gate count reduction of 30% together with a speed increase of 20%, compared to the AGGA-0 design. The power consumption is also expected to decrease by roughly 20%.

The verification and detailed design is planned to be completed in November 1998, leading to first prototypes to be available in the first quarter of 1999. A Preliminary Data Sheet, fully describing the AGGA-2 functions and operation, will be issued before the end of 1998.

The baseline technology is the ATMEL/TEMIC/MHS MG2RT 0.5 μm radiation tolerant CMOS Gate Array, with the MG1RT technology being the backup. The target power consumption at 3 V supply is 0.1 W for GPS L1 applications (at 3 MHz), 0.4 W for GPS/GLONASS L1 applications (at 15 MHz), and 0.8 W for dual-frequency applications (at 30 MHz). The AGGA-2 also supports 5 V operation for applications where a separate 3 V supply is not available. The AGGA-2 will be packaged in a 160-pin leaded Ceramic Quad Flat Pack (CQFP) with 25 mil pin pitch.

First tests on the breadboards containing the AGGA-0 samples began in August 1998. Should serious shortcomings be detected during these tests, an AGGA-1 based on the AGGA-2 design would be manufactured in a commercial fast turn-around technology, for example from Chip Express. However, at the time of writing it appears that there will be no need for an AGGA-1.

6. DEVICE AVAILABILITY AND EVALUATION

The AGGA-2 will be available to European Industry on equal conditions as an Application Specific Standard Product (ASSP), supported by a complete Data Sheet. This will allow companies to develop new GPS and GLONASS applications without the need to design a highly complex ASIC. In preparation for that, the AGGA-0 design and samples are used to validate the digital signal processing through various simulation and test activities.

A bit-true model of the AGGA-0 has been written at Austrian Aerospace (AAE) in the C language, with the goal of simulating and verifying the AGGA-0 functions and performance, and to support the analysis of results from the breadboards. The model includes all the functionality needed for instrument applications, as well as generation of suitable GPS and GLONASS signals. Because of the heavy computation burden, the simulations can cover only a few minutes of operation, which however is sufficient to determine the overall correctness of the AGGA-0 and of the tracking firmware. The AGGA-0 simulations will be completed in September 1998, and the bit-true model should be useful also for further AGGA-2 design evaluation and for assessing new tracking firmware.

Several European companies have already started breadboarding activities with own, national or ESA

funding, initially using AGGA-0 samples. The targeted applications range from navigation receivers to Atmospheric Sounding sensors. Two of these breadboarding activities, funded under ESA contract, are further described below. In addition, invitations to tenders have been issued for EGNOS reference stations and for evaluating the AGGA-0 for Spacecraft Control applications, and at the time of writing the proposals received were being evaluated.

Austrian Aerospace (AAE) develops a breadboard mainly intended to rapidly evaluate the AGGA-0 functionality. The test set-up includes an existing breadboard with the ADSP21020 processor and two commercial ADC boards. An RF down-converter has been built with commercial components based on the dual-stage down-conversion scheme of [10]. The signals at the input can be generated in three ways: by an arbitrary wave-form generator followed by up-conversion RF circuitry; by the GPS/GLONASS signal simulator at ESTEC; and by an outdoor active antenna. The evaluation started in August 1998 and will progressively cover all the AGGA-0 functionality relevant to the atmospheric sounding application. In the final tests signals representative of an in-orbit observation scenario will be acquired and tracked. Results will be used to validate specifications applicable also to the AGGA-2, such as the SNR implementation loss.

Saab-Ericsson Space (SES) together with AAE develop a breadboard according to the architectural and detailed design of the GRAS (GNSS Receiver for Atmospheric Sounding) instrument. GRAS is due to fly on the MetOp satellites to be launched in 2003, and on other future Earth observation missions. An instrument for both ionosphere and atmosphere monitoring, called the GPS Occultation Sensor (GPSOS) and based on the GRAS design, is also being developed by SES and AAE for the United States National Polar Orbit Environmental Satellite System (NPOESS). The GRAS breadboard has the main aim to demonstrate the operation of the complete hardware chain, including evaluating the implementation losses, and the operation of the on-board software. With minor upgrades, it will be used also for GPSOS breadboard tests. An advanced approach has been chosen for the IF circuitry, where the second down-conversion is performed digitally after analog to digital conversion of the signals at ~140 MHz. This allows to miniaturise the RF circuitry using a Digital Down-Conversion ASIC, at the cost of a small increase in SNR loss compared to an analog down-conversion scheme. At least four AGGA-2 devices will be used in the GRAS instrument, providing a minimum

of sixteen dual-frequency channels, of which six are for atmospheric sounding observations while the remaining ones are used for navigation and Precise Orbit Determination.

7. REFERENCES

- [1] J. B. Serrano, P. Bernedo, P. Gonzales, P. Silvestrin, *A GNSS-based Attitude Determination System for Low-Earth Observation Satellites*, Proc. ION GPS-95 Int'l Meeting, Palm Springs, Sept. 1995
- [2] B. W. Parkinson, J.J. Spilker (editors), *Global Positioning System: Theory and Applications*, Vol. 1 and 2, American Institute of Aeronautics and Astronautics (AIAA), 1996
- [3] P. Silvestrin, E. Aardoom, G. Brodin, J. Cooper, P. Daly, D. Walsh, *GNSS Receiver Design for Attitude Determination*, Proc. Third Int'l Conference on Spacecraft Guidance, Navigation and Control Systems, Noordwijk, Nov. 1996
- [4] J. Potti, J. C. Carmona, P. Bernedo, P. Silvestrin, *An Autonomous GNSS-based Orbit Determination System for Low-Earth Observation Satellites*, Proc. ION GPS-95 Int'l Meeting, Palm Springs, Sept. 1995
- [5] *GP2010 Global Positioning System Receiver RF Front End*, GEC Plessey Semiconductors data sheet ref. DS4056-2.4, June 1995
- [6] *STB5600 GPS RF Front-end IC*, STMicroelectronics data sheet, August 1998
- [7] *TSC691E Integer Unit: User's Manual*, Temic Semiconductors data sheet Rev. H, Dec. 1996
- [8] *TSC21020 Radiation Tolerant 32/40-Bit IEEE Floating-Point DSP Microprocessor*, Temic Semi-conductors data sheet Rev. D, May 1998
- [9] *AGGA-2 Functional Specification*, ESA ref. TOS-ESM/PS/001 Issue 3, May 1998
- [10] S. Riley, N. Howard, E. Aardoom, P. Daly, P. Silvestrin, *A Combined GPS/GLONASS High Precision Receiver for Space Applications*, Proc. ION GPS-95 Int'l Meeting, Palm Springs, Sept. 1995

Note: This paper is available in PDF format at URL: <ftp://ftp.estec.esa.nl/pub/vhdl/doc/AGGA2Intro.pdf>