"GPS On A Chip" -- An Advanced GPS Receiver for Spacecraft

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Abstract

Three years ago, facing a growing list of stringent navigation an science requirements for future low-cost Earth missions, NASA began a program to develop a new high performance spaceborne GPS receiver. The program acquired the (inaccurate) title "GPS on a Chip" (GOAC), reflecting the long-term goal to reduce the receiver to a credit-card size package of unprecedented versatility and power. The GOAC development is a collaborative effort involving the Jet Propulsion Laboratory, the Goddard Space Flight Center, and Stanford University.

A principal goal is to produce a low-cost modular design that can be configured efficiently for a wide range of unique space applications. These include (1) real time uses such as few-meter navigation and timing, precise attitude and rate determination and pointing control, formation flying, rendezvous and proximity operations; (2) post-processing uses such as centimeter-level orbit determination for ocean altimetry and precise relative tracking for gravity recovery; (3) direct remote sensing uses such as tracking rising and setting signals as they pass through the earth's atmosphere and acquiring signals reflected off the surface of the oceans; (4) advanced utility functions from receiving and interpreting uplink commands to operating an entire satellite autonomously throughout its mission by means of a powerful embedded processor.

In late 1995, the GOAC development team laid down a set of basic requirements:

- Channels (simultaneous signals tracked): configurable from 8 to 96.
- Tracking methods: C/A, P1, P2, or "codeless" tracking assignable to any channel.
- Observables: C/A, P1, P2 pseudorange and L1, L2 continuous carrier phase.
- Code precision: <10 cm pseudorange and <0.2 mm phase (1 sec integration).
- Codeless precision: <30 cm pseudorange and <2 mm phase (1 sec integration).
- Antennas: configurable from 1 to 12 with parallel inputs.
- Data sample rates: up to 100 samples/sec (dual frequency pseudorange and phase)
- Uplink data extraction: up to 1 Mbit/sec
- Operation: on-orbit cold start in 15 min with no initialization; restart within 60 sec

In addition to providing low cost GPS receivers for spacecraft designers, the GOAC program shall be used to demonstrate several new concepts that improve the GPS receiver's functionality in orbit. Some of these new algorithms include real-time precision orbit determination, carrier phase based attitude determination on nonaligned antennas, calibration free

attitude determination, GPS-only attitude rate measurements, on-orbit Wide Area Augmentation Satellite (WAAS) capability, single antenna safehold operation, and autonomous receiver and spacecraft operations. These new capabilities are expected to greatly improve the GPS receiver's usefulness as an engineering sensor for spacecraft and lower overall satellite operating costs.

The first full version of the GOAC (the "Blackjack"), with 4 antennas and 48 parallel channels, will begin testing in the summer of 1998. Configured as a cube 10 cm on a side, it features a 4-layer, modular design. The Blackjack will weigh under 2 kg and consume about 10 watts. Initial units will be rated for about 15 Krad total radiation dose, but can be hardened to higher levels. The first two operational flights will be on the German CHAMP mission and the Argentine SAC-C mission, both scheduled for launch in the summer of 1999.

Hardware Architecture

The eclectic nature of NASA's GPS based applications cannot be efficiently encompassed by a single instrument. Therefore, the focus of much of the hardware effort was to devise a scalable, flexible architecture that could be easily manipulated into several classes of instrumentation. As a result, the GOAC design more closely resembles a high-performance digital signal processor rather than a radio receiver.

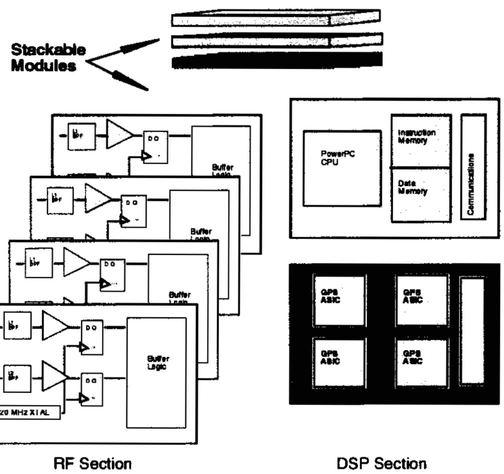

Figure 1- GOAC Modular Architecture

RF Section

The RF hardware amplifies the GPS signal as it's received from the antenna, then filters and digitizes the data streams before passing them to the digital signal processing hardware. To provide high accuracy, the GOAC design must be capable of processing both frequencies (L1: 1.6 GHz & L2: 1.2 GHz) at the 20 MHz P-code bandwidth. Each RF section is composed of two assemblies; an externally mounted, compact, filter/pre-amplifier and a quadrature RF sampling down-converter (RFSDC).

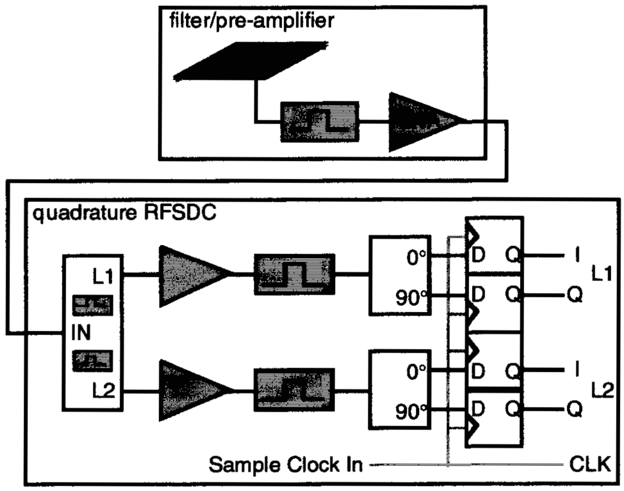

Figure 2 - RF Section

Each RFSDC directly samples a highly amplified (~100 dB gain) L-band signal at approximately 20 MHz. An anti-aliasing filter in front of two high-speed ECL samplers preselects the L1 or L2 portion of the spectrum. This architecture allows a single device (ie. the ECL "D flip-flop" sampler) to simultaneously perform one bit quantization/digitization and downconversion. The latter is accomplished when the L-band bandpass is aliased to baseband during sampling because the sample frequency was chosen to be a sub-harmonic of the both the L1 and L2 carrier frequencies.

For multiple antenna operation, an RFSDC is dedicated to each antenna, a deviation from earlier commercial designs that sequenced multiple antenna signals through a single down-converter. Since all RFSDCs are operating from the same clock reference and their bandwidths are relatively wide, grou delay and timing offset between RFSDCs are kept to below levels required for geodetic class measurements of phase and group delay. For multiple antenna operation, an RFSDC is dedicated to each antenna, an improvement over earlier commercial designs which sequenced multiple antenna signals through a single down-converter. Furthermore, all RFSDC's are operated from the same clock signal which drives the digital signal processing logic, assuring the integrity of multi-antenna phase and timing information.

Figure 3 – Stackable GPS Assy

Digital Signal Processing Section

The two-level, 20 MHz sampled RF data streams are clocked into four identical, specially designed GPS ASICs. Under SW control, these chips can be configured for a variety of signal processing tasks ranging from rapid acquisition of GPS signals using 144 correlation lags to actively arraying multiple antennas to "steer" antenna gain. Each GPS ASIC can process data from any one of 12 antennas simultaneously, allowing the digital signal processor to handle as many as 48 individual antennas continuosly.

Some other features of the GOAC DSP logic are:

- GLONASS processing
- Telemetry de-modulation
- Carrier tone tracking
- External pulse/event timing

Controlling such a large number of individual signals with great precision and accuracy necessitates a powerful computer. The GOAC design incorporates a Motorola PowerPC 603e microprocessor for software control functions. The 603e provides these important features to the GOAC architecture:

High thru-put, low power: 60 MIPS/Watt

Power consumption scalable with thru-put as well as "sleep" mode

Object oriented toolset (C++)

Mechanical

The receiver is arranged as a stack of printed wiring board (PWB) cards. High density flexible interconnects provide over 650 connections between each card in the stack.

GOAC Firmware Architecture

The GPS on a chip firmware is intended to provide service to a wide range of users ranging from the most basic navigation services to multiple antenna, multi-sensor implementations in which the GPS receiver is also a science instrument, or even the flight computer. Further, the software is designed to be scalable-the basic user above will require less electric power, flash memory, RAM and software than will users with more demanding requirements. This is implemented by combining a simple microkernel style real time executive with a dynamically linked library system and a demand driven scheduling algorithm. The firmware is written in C++ and assembly code.

Scalable Performance

Because the GPS on a chip architecture is centered around a high performance CPU, many numerically intensive applications may be hosted on board. The most basic of these is performing a full sky doppler search for GPS satellites on up to 36 channels simultaneously. However, high throughput corresponds to high electric power consumption. Power is usually a scarce resorce on small satellites. To address this issue, the GOAC firmware has been designed to take advantage of the sleep modes of CPU. When the software is idle, the CPU uses virtually no power. Thus, the average power consumption of the CPU scales with the workload. In order to take advantage of this feature, user software must allow the CPU to idle. The GOAC firmware supports this by providing synchronization objects which allow user processes to idle until a particular time or event occurs.

Scalable Capabilities

In order to support a wide variety of missions as easily as possible, the GOAC firmware is built on a dynamically linked shared library architecture. This allows new capabilities to be installed which can call operating system and standard library routines which are already loaded onto the receiver. In addition, maintenance and development are simplified because new or "problem" code can be encapsulated in a small library which is quickly uploaded while the solid "core" is not changed.

Demand Driven Scheduling

In order to tie together these ingredients, the GOAC firmware implements a demand driven scheduling algorithm. This algorithm allocates resources to tasks based on a cost assigned to the resource and the priority of the task. New capabilities are added by registering the routines which produce the data and determine the cost based on the current state of the system. High level goals generate demands on the scheduler for data products. The scheduler propagates these demands by selecting the lowest cost option available. Ultimately, the desired output results or fault detection and correction algorithms are invoked. User code which uses this mechanism can be easily enhanced by providing new methods to produce a given data product. For instance, if some algorithm needs the platform attitude, the basic behavior may be to schedule simultaneous tracks on three or four antennas and do GPS attitude determination. On a spacecraft where a star camera is available, though, a much lower cost method could be added which gets the same data from the star camera.

Space Radiation Effects

Traditionally, space based electronics designs are driven by radiation effects testing and component pedigree. However, the GOAC hardware effort made no attempt to draw from the ranks of space proven components. This freed the designers to focus on designing a scalable, flexible architecture with maximum performance at minimum power. Although mostly commercial grade parts are used, initial radiation testing on the major components indicate the GOAC hardware is suitable for many low earth orbit applications. Table 1 provides some of radiation test results for key GOAC components.

Component	Radiation Tolerance (kRad)
CPU (Power PC XPC603e)	> 60
BlackJack GPS ASIC (Gate Array)	> 15
Mem. Cntr. (FPGA-ORT15A2S240)	> 40
Voltage Reg. (Max 667)	< 2.5
Voltage Reg. (Max 883)	> 10
RFSDC Assembly	> 20

Table 1 - Total Ionizing Dose (TID) Tolerance for key GOAC components

GOAC Algorithms

Project Goals

To complement the hardware development at JPL, the NASA GSFC and Stanford University research teams have developed software algorithms and testing procedures for the new GPS-on-a-chip receiver. The receiver incorporates new, state-of-the-art attitude and position determination algorithms in a modular and open software architecture. This format simplifies the upgrading and porting of the GPS algorithms to new CPU and ASIC hardware as it is developed.

Through the efforts of the GPS Laboratory and the Aerospace Robotics Laboratory, Stanford University has demonstrated revolutionary applications of GPS sensing techniques for precise real-time feedback control of autonomous systems. These demonstrations include the use of GPS sensing to: 1) control an autonomous model helicopter, 2) perform take-offs, landings, and fly a circuit with a model airplane, 3) develop an automatic landing system for a Boeing 737, 4) attitude and relative position determination and control for prototype satellites using an indoor GPS emulator, and 5) GPS based attitude determination and control of a small satellite in orbit.

The primary objective of the program is to upgrade the algorithms to account for improvements in the capabilities of the receiver, such as increased number of channels and antennas. Additional algorithms were developed to enhance the capabilities of the GPS sensing system by taking advantage of these hardware improvements, such as ``all-baselines-in-view" differential carrier phase tracking. We have also investigated methods for dealing with non-aligned antennas by compensating for the phase variation due to circular polarization, as well as phase center variations.

An important goal of the combined GPS-on-a-chip research effort was to develop the engineering plans for a new GPS receiver that offers significantly improved functionality while at the same time, reducing power, weight, and size. The requirements definition for this new sensing system was performed by analyzing the limitations that have already been established during the navigation applications with current GPS receivers, by identify the needs of future space applications such as *formation flying*, and by prototyping a new receiver system called *Orion*. The Orion receiver provides (although not in a single chip module) many of the features desired in the final design.

A key component of the GPS sensing system is the antenna array. With the increase in the number of channels per receiver provided by the GPSOAC architecture, it is possible to use many, non-aligned antennas on a single vehicle. This significantly enhances the ability of the receiver to maintain signal lock during large scale re-orientation maneuvers, and has been the primary focus of work to date.

Orion Receiver Development

This section summarizes the results of some recent tests of the synchronization of two GPS receiver cards based on the Mitel Plessey 'Orion' design. These tests are a follow on to initial work done during the summer of 1997 using the GEC Plessey (now Mitel) GPS Builder 2 receiver design. A key benefit of using the Mitel GPS hardware is that this provides access to the GPSBuilder Software (marketed as the "GPS Architect" Toolkit). This software is entirely written in C code. Complete access to the source code has allowed us to extensively modify the code phase and carrier phase tracking loops, the signal acquisition algorithms, the cycle-slip detection routines, the input/output routines, and the frequency search region during startup. At that time, differential carrier phase measurements were successfully collected between two receivers by synchronizing the 10MHz oscillator between the cards.

Starting in February 1998, the GPSOAC algorithm work has been moved to the Mitel Plessey 'Orion' receiver board design, to enable standalone operation of the receiver on a small moving platform. The original Orion design has been modified to provide two RF antenna inputs and an external clock input. To synchronize multiple Orion cards, a clock circuit with etched traces on a copper clad board was used to achieve the necessary high frequency performance. After tuning the oscillator circuit for stable operation, the clock generation circuit was transferred to a printed circuit board designed to provide communications and power conditioning to multiple receiver cards. A 2 card, 4 antenna input, 24 tracking channel version of this receiver has been created, giving the capability of producing 3-D attitude solutions. This receiver is suitable for the algorithm development goals of the GPSOAC project, in particular for the test of attitude determination algorithms using measurements from an array of non-aligned antennas.

A series of tests were conducted to determine the contribution to the differential carrier phase (DCP) measurement noise due to the synchronization method. The results in the next two figures show the error in DCP measurement for zero antenna baseline, with the receive antenna stationary in Figure 5 and moving in Figure 6. A splitter was used to route the antenna signal into all four RF inputs on the receiver and integrated carrier phase was tracked for a period of roughly two minutes at a 1 Hz data rate. Measurements were made of the integrated carrier phase from an array of indoor pseudolite transmitters in a high multipath environment. The bias in the DCP data has been removed to show only the error.

The results for the stationary case show that error in the DCP measurement between tracking channels on the same RF input is very small (STD 0.2 mm), and is within the resolution of the integrated carrier phase measurement. When DCP measurements are made using two RF front ends on the same card, the error grows to a STD of 1.5 mm. And for a DCP measurement between two RF front ends on separate cards, the STD of the measurement error is only 2.2 mm. This test shows that it is possible to make DCP measurements with comparable error characteristics to single board receivers (such as the Trimble TANS Vector) using multiple boards synchronized at the 10 MHz clock level. Previous issues concerning the stability of the synthesized 40 MHz sample clock on separate cards due to thermal gradients have proved not to be a problem, probably due to the constant thermal environment for all cards inside a single enclosure. The problem of having a phase bias contribution due to the length of the clock transfer line can be resolved using floating point bias resolution techniques, and is no different than resolving a non-integer line bias.

The results for the moving antenna case are shown in figure 4, and show comparable, if slightly higher (3-4 mm) DCP noise than the stationary case. The error is slightly higher due to the presence of two cycle slips during the data collection period. These slips occurred when the antenna was moved quite rapidly from side to side, but the cycle slip detection algorithm was able to detect and correct for the integer wavelength jump in the DCP data.

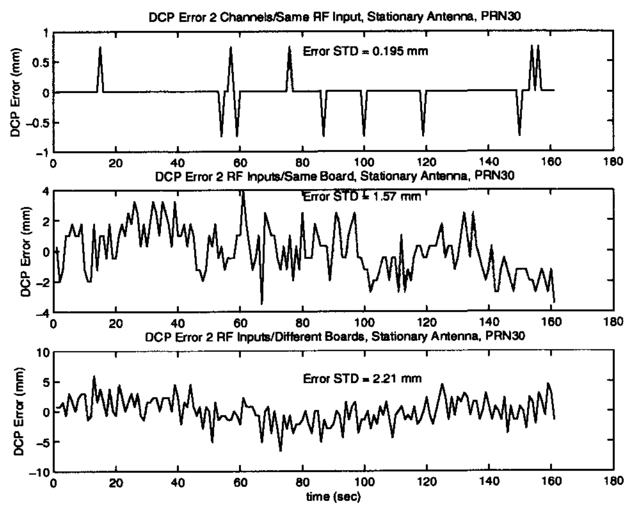

Figure 5 - Stationary Antenna DCP Error Results

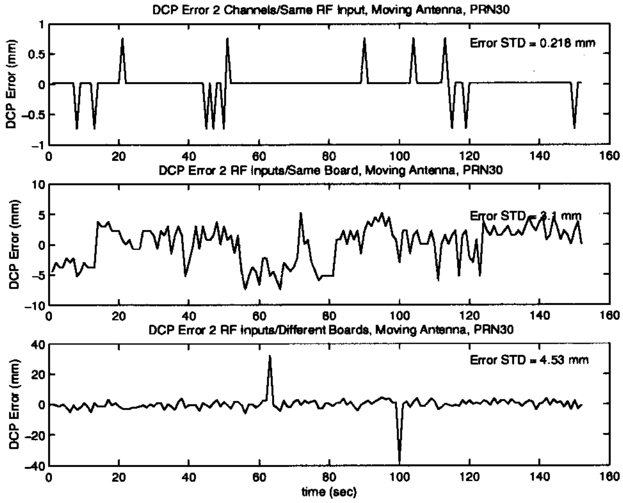

Figure 6 - Moving Antenna DCP Error Results

2-D Attitude Determination Tests

A series of experiments were conducted to test new attitude determination algorithms developed for the GPSOAC receiver architecture. The goal of these experiments was to test new attitude estimation algorithms that compensate for the line of sight dependent DCP errors that are introduced when measurements are made from an array of non-aligned antennas. The most significant error is from the right hand circular polarization (RHCP) of the incoming GPS signal. An airbearing 2D vehicle was used to simulate the zero-G dynamics of a rotating spacecraft. This vehicle had four antennas with adjustable tilt angles, an onboard power and communication system, and pressurized gas supply. For these tests, the antenna signals were routed to a GPS receiver offboard the vehicle. This provides a flexible development environment for testing the new estimation algorithms, but also limited the vehicle from having continuous rotation due to antenna cable windup. Subsequent 3-D tests used an Orion receiver onboard a vehicle capable of non-planar rotation.

The GPS attitude receiver used for these tests consisted of four GEC Plessey Builder 2 receiver cards installed in a single ISA card cage, with a total of 8 antenna inputs (only two were used for these tests) and 48 tracking channels. The cards have the capability of being synchronized to a single 10 MHz oscillator, allowing differential carrier measurements to be made between any two antenna inputs. This receiver architecture represents the desired qualities of a next generation spacecraft receiver, in the modular expandable hardware and open architecture software. The GPS designer can match the desired number of tracking channels and antenna inputs to the sensing application.

The 2-D airbearing laboratory vehicle was spun on the granite table at rotation rates up to 1 rad/sec, and measurements were made of the DCP between two antennas for the six pseudolite transmitters. Data was collected simultaneously from the overhead vision system of the position and rotation of the vehicle on the table to serve as a truth measurement. The DCP measurements were post processed to determine the attitude of the vehicle, which in this case is just the rotation angle about vertical. The results for three antenna array cases are summarized in Table 1. The three cases are; 1) Aligned antennas, 2) Non-aligned antennas - same tilt angle, and 3) Non-aligned antennas - different tilt angles.

Antenna Tilt Angle	Attitude Error Uncompensated Mean STD	Attitude Error Compensated Mean STD
1)Aligned Antenna Array Tilt angle 1 = 0 deg Tilt angle 2 = 0 deg	0.37 1.42 (deg)	0.36 1.40 (deg)
Non-aligned Antenna Array Tilt angle 1 = 17.5 deg Tilt angle 2 = 17.5 deg RADCAL case	0.58 4.24	0.51 4.21

2)Aligned Antenna Array Tilt angle 1 = 90 deg Tilt angle 2 = 90 deg	8.86 8.84	3.27 4.23
3)Aligned Antenna Array Tilt angle 1 = 0 deg Tilt angle 2 = 90 deg	Estimation failed	3.29 5.32

Table 1 – Experimental results for attitude estimation

For the aligned antenna case 1), the attitude estimate error is the same for the compensated and uncompensated cases, showing that the effects of the LOS dependent phase components in the measurement have been removed in the differencing. For the non-aligned case 2), there is an increase in the estimate error if the RHCP phase is not included in the estimation, but the error can be reduced through compensation. And for case 3), where the increasing bias due to the RHCP phase is present, the attitude estimation fails if the RHCP is not compensated for, but similar estimate accuracy results to the previous cases can be achieved if the RHCP is included in the estimation algorithm.

The overall accuracy of these attitude estimates is worse than predicted in simulation due to the unmodeled measurement effects found in our test environment. The most significant is multipath reflected signals, but also important are the phase center variations of the antenna with LOS, which is predicted to be a maximum of 2 cm. The effect of the cable torques was not modeled in the iterated extended Kalman filter, leading to an unmodeled process noise. The 3-D vehicle tests model these effects or mitigate their impact.

3-D Attitude Determination Tests

In previous 2-D work[1], the results of an experimental planar demonstration of attitude determination using measurements from a non-aligned antenna array were presented. Attitude estimation was done (in post processing) using a passive spinning platform with only single degree of freedom rotation, in a laboratory environment that had very significant reflected multipath signals. The experiment used a 2-D air cushion vehicle on a granite table top with a single antenna baseline measurement to highlight the importance of compensating for the differential carrier phase due to RHCP when the antennas have dissimilar visibility to a given transmitter. This work showed that post processed attitude solutions could be obtained using new estimation algorithms that mitigated the effect of the dominant RHCP error in the measurement.

Recent tests extend the previous demonstration to a 3-D experiment with a non-aligned antenna array. For this experiment, a spinning 3-D test platform was constructed to allow for full motion attitude sensing and closed loop control. The test platform has a non-aligned array of four antennas connected to a center node which is suspended from an overhead cable. The platform uses reaction wheels for three axis attitude control, and rate gyros as a reference attitude truth sensor. These tests are performed in a new laboratory environment with larger transmitter distances and less multipath errors. These changes should provide more accurate carrier phase sensing. The experiment platform is used to demonstrate real-time attitude estimation, including real-time RHCP bias estimation. A comparison of two techniques for compensating for the RHCP of the incoming GPS wavefront has been completed, one which explicitly includes the RHCP in the measurement model, at the cost of higher computational load, and another method that subtracts the predicted RHCP phase component from the carrier phase measurements.

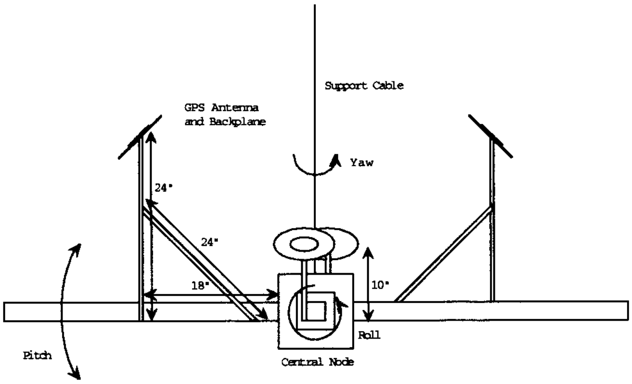

Figure 7 - 3-D test vehicle with non-aligned antenna array.

Acknowledgements

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References

[1] J.C. Adams and J.P. How, "GPS Attitude Determination on Spinning Spacecraft with Non-aligned Antenna Arrays," in Proceedings of the ION National Technical Meeting '98, Long Beach, CA, Jan. 1998.