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PiVoT GPS Receiver

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BIOGRAPHY

Miriam Dvorak Wennersten is a computer engineer at the NASA Goddard Space Flight Center. She is currently leading the PiVoT 1.0 and PiVoT 1.5 development. She has been working on embedded software systems her entire 12 year tenure at Goddard. She has numerous software programs in orbit on NASA satellites. She has a Bachelor of Arts degree in Computer Science from La Salle University and a Masters of Science degree in Computer Science from Johns Hopkins University. ..

Anthony V. (Vince) Banes, Jr. is an embedded systems engineer for Orbital Sciences Corporation on contract with NASA Goddard Space Flight Center, and has extensive experience in navigation systems, electronic warfare systems, and voice switching for the FAA. He has taught computer science classes for Embry-Riddle Aeronautical University. He has a Bachelor of Science Degree in Mathematics from Baylor University, and a Master of Science Degree in Business from Troy State University.

Gregory J. Boegner, Jr. is a senior electronics engineer at the NASA Goddard Space Flight Center with approximately 15 years experience designing analog and digital systems in the fields of communications, embedded control, and digital signal processing. He has worked for the U.S. Department of Defense, ASRC Aerospace Corporation, and as an independent consultant. He has a Bachelor of Science Degree in Electrical Engineering from Drexel University in Philadelphia.

Lamar F. Dougherty is a Design Engineer at the NASA Goddard Space Flight Center with approximately 15 years experience designing digital systems, specifically in the field of microprocessors. He has worked for Westinghouse Electric Corporation, Kaman Sciences Corporation, and Fairchild Space and Defense Corporation. He has a Bachelor of Science Degree in Electrical Engineering from West Virginia University.

Bernard L. Edwards is a systems engineer at the NASA Goddard Space Flight Center, and has extensive experience in digital communication systems and signal processing. Previously he was with the U.S. Department of Defense, holding a variety of technical positions from project engineer to department manager. He has taught courses at the Naval Postgraduate School and at DoD facilities worldwide. He has a Bachelor of Science Degree in Electrical Engineering, a Master of Science Degree in Electrical Engineering, and a Master of Science Degree in Computer Science all from the Johns Hopkins University.

Joseph Roman is an Electronics Technician with a Communications background in the U.S. Navy as a Cryptologic Maintenance Technician. He has worked at Goddard Space Flight Center for nine years. He is very experienced with the electronics assembly of Attitude Control Systems and parts research and procurement.

ABSTRACT

NASA Goddard Space Flight Center has built an open architecture, 24 channel space flight GPS receiver. The CompactPCI PiVoT GPS receiver card is based on the Mitel/GEC Plessey Builder-2 board.

PiVoT uses two Plessey 2021 correlators to allow tracking of up to 24 separate GPS SV's on unique channels. Its four front ends can support four independent antennas, making it a useful card for hosting GPS attitude determination algorithms. It has been built using space quality, radiation tolerant parts. The PiVoT card will track a weaker signal than the original Builder 2 board. It also hosts an improved clock oscillator.

The PiVoT software is based on the original Plessey Builder 2 software ported to the Linux operating system. The software is POSIX complaint and can easily be converted to other POSIX operating systems. The software is open source to anyone with a licensing agreement with Plessey. Additional tasks can be added to the software to support GPS science experiments or attitude determination algorithms. The next generation PiVoT receiver will be a single radiation hardened CompactPCI card containing the microprocessor and the GPS receiver optimized for use above the GPS constellation.

PiVoT was flown successfully on a balloon in July, 2001, for its first non-simulated flight.

INTRODUCTION

The PiVoT is a space flight GPS receiver designed in-house by the Goddard Space Flight Center's (GSFC) Guidance, Navigation, and Control Center (GNCC). PiVoT is an open architecture receiver in both the hardware and software. The GPS card, based on the Mitel/GEC Plessey GPS Builder-2 card, is a 3U CompactPCI card with 2 correlators for a total of 24 channels. Four RF front-ends allow the system user to utilize up to four antenna inputs.

The Guidance, Navigation, and Control Center at Goddard decided to build a space flight GPS receiver because of the lack of availability of open-source receivers on which to develop algorithms that could then be tested and used in a real space environment. The original PiVoT hardware and software design was based on the Mitel/GEC Plessey Builder-2 development platform.

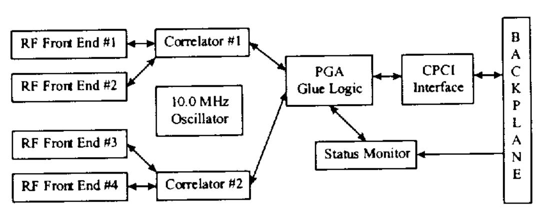
Hardware

The Plessey Builder-2 test set consisted of open-source GPS software and an ISA bus GPS hardware card that could be plugged into nearly any personal computer capable of running the MS-DOS operating system. The original Builder-2 card came standard with one correlator, one front-end (and hence, one antenna input), and was capable of tracking up to 12 channels of GPS data. The GP2021 correlator has inputs for two front-ends, and a version of the Builder-2 card could be purchased with the card populated with both front-ends.

The original PiVoT GPS card used the Plessey Builder-2 ISA card as a baseline for the design. Several key changes were made to the existing design. The bus interface was changed from ISA to CompactPCI. The card had two correlators instead of one, and four front-ends instead of two. The original design for the PiVoT card also had an Intel 196 microcontroller for on-card tracking loop closure. The 196 was then determined to not have sufficient processing power to track twenty-four channels, and that section of the card remains unpopulated. All parts on the PiVoT GPS card were selected with radiation tolerance in mind.

Most electronic parts used for the first generation PiVoT meet Military and Space grade specifications, however several of the parts were manufactured to Industrial grade specifications only. Radiation screened parts were chosen when available, however other parts were chosen based on similar parts' radiation performance history. For example, the GPS chipset, designed by Mitel/Plessey was manufactured with a process similar to some previously screened parts. Preliminary radiation screening was performed on the Mitel/Plessey GPS chipset with positive results up to 25Krads. Electronic parts for future versions of the PiVoT GPS Receiver are being researched and purchased targeting higher radiation environments.

Today, PiVoT version 1.0 receiver block diagram looks like this:



PiVoT v1.0 receiver

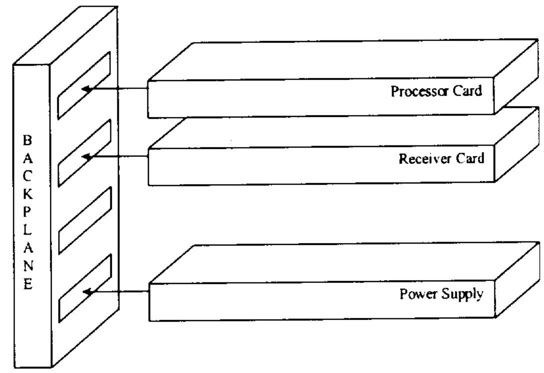
The 10.0 MHz oscillator provides the reference for the phase lock loop, local oscillators in each RF Front End and the clock for the correlator functions. This reference oscillator was carefully chosen to have a low (1 part per billion) root Allen variance to aid the GEODE software. The oscillator is radiation tolerant, and provides better than 1-ppm frequency accuracy over the full temperature range.

The four RF Front Ends are based on Mitel/Plessey's GP2015 GPS Receiver Front End chip. This chip performs the down conversions and digital sampling of the civilian GPS signal at 1.57542 GHz. The design differs from Mitel's Builder-2 only in part selection, layout and routing. Higher-grade parts of similar or same values were chosen for environmental concerns and size constraints. By employing a two-sided layout with 12 layers, we were able to reduce the total area of each Front End, shorten all critical nets, and provide better shielding. This effort resulted in a 1.2 square inch circuit for each RF Front End, with much better immunity to electrical noise from other cards in the PCI enclosure. On each side, a ring around each RF Front End allows for further shielding by soldering down a box to cover the circuit. This added shielding has not yet been needed.

The Correlators (Mitel/Plessey's GP2021's) each handle 12 simultaneous GPS C/A code signals. They each receive digitized signals from two Front Ends. They provide the functions of tracking, despreading (correlating), and demodulating signals from any of the satellites received, through control of the processor in an adjacent CPCI slot.

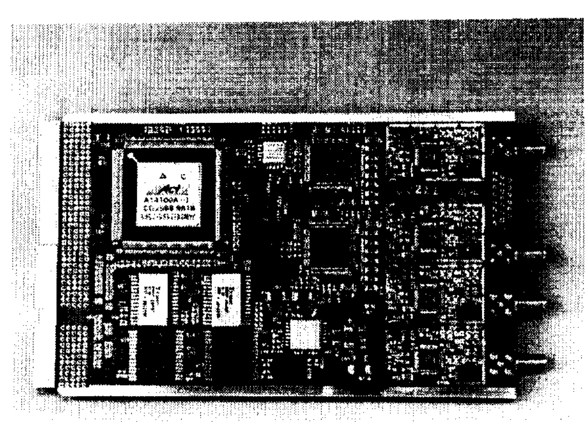
Three voltages, +5, +12, and -12, their currents from the power supply, and two temperatures, one on this card and one on the power supply can be monitored by this card. The three voltages are directly converted by the on board analog to digital converter. Three current sense resistors located on the power supply board provide voltage proportionate to the total current draw. These voltages are passed to the receiver card across the back plane (on unused lines) for conversion. The temperature sensors provide a voltage proportionate to temperature. These voltages, (the one on the power supply board is also passed across the back-plane) are also converted by the analog to digital converter in the Status Monitor section of this board.

The PGA Glue Logic and CPCI Interface provide all the remaining functions necessary to make this board work and communicate to the processor on another card in the CPCI enclosure. This card requires +5, +/-12 and draws approximately 7.5W when fully populated. Preliminary radiation testing has shown that this board should survive a total dose of better than 25Krad. Further radiation testing will be performed this October.



PiVoT System

We have put this receiver card with a processor board into a custom enclosure with a three-slot CPCI back plane plus a power supply board. This leaves one open slot for future options. Our power supply is designed to interface to a spacecraft 28-volt supply and provide +3.3, +5, and +/-12 to PCI specifications. The power supply is built with latch-up protection and is radiation tolerant. The processor board, built by EMS Technologies, utilizes a PowerPC 603, and is radiation hard to 25Krad. The enclosure allows for taller components on the bottom side of each CPCI card than the CPCI specification and also allows for a piece of aluminum to be inserted between each card for mechanical, thermal, and EMI/RFI concerns. This enclosure is very rugged, it has survived the violent impact at the end of a balloon mission without any damage to any part. When populated in the configuration shown, this system draws 18 watts at 28 volts.



PiVoT 1.0 CompactPCI board

Software

The PiVoT GPS software is based on the original Plessey Builder-2 software. The original software was compiled in an MS-DOS environment and utilized its own internal task-switching system. The first port of the software by the PiVoT team was targeted to a StrongArm 110 microprocessor embedded system. The internal tasking system of Plessey was converted to the Nucleus real-time operating system by Accelerated Technologies, Inc. The closing of tracking loops was handled as a high priority interrupt. For the embedded system, the original Plessey display software also had to be changed to output via RS-232 to any VT100 terminal emulator. All keyboard command inputs also had to be transmitted to the system via RS-232. In a flight environment, the commands and telemetry would replace the keyboard and display transmissions on the RS-232.

The StrongARM port had to be abandoned when the actual CompactPCI StrongArm microprocessor card we purchased was determined to be inadequate to the task of tracking 24 GPS channels. By clever linking of the code to run the tracking loops out of cached memory, the StrongARM PiVoT could track up to 6 channels. Unfortunately, another version of a CompactPCI StrongARM card could not be located to replace the custom-built card we had, and the entire embedded development was shelved temporarily.

In order to proceed with software development, the software was ported to the Linux operating system. Now the software could run on any ordinary personal computer running Linux. The software can be run using either the original Plessey Builder-2 ISA card or the new PiVoT PCI card. In order to plug a PiVoT CompactPCI card into a personal computer, a simple CompactPCI to PCI adapter can be used. Another lab version of the PiVoT receiver is a CompactPCI rack with a CompactPCI processor card plugged in as the motherboard, running Linux. A Pentium 133 microprocessor has proven capable of tracking all 24 channels on the PiVoT card.

The Linux version of the software has the tracking loop software residing in the kernel as kernel modules. Only the kernel can access hardware with the Linux operating system, so the tracking loop modules pass the data back to user space and the application program via a shared memory block. Whenever changes are made to the tracking loops, the modules have to be reloaded into the kernel.

A key feature of the PiVoT GPS receiver is the availability of the source code. Most GPS receivers are highly proprietary regarding hardware and software configuration. This can lead to reverse engineering to determine if solutions are being filtered, etc. if the data coming out of the receiver is not exactly what the user expects. The open-source aspect of PiVoT allows for the algorithm development and customization of satellite selection, acquisition, and tracking.

The Linux software version of PiVoT has proven to be an ideal system for GPS algorithm development and testing. The software is self-hosted, meaning that changes to the software can be made and compiled on the same machine on which it is running. Reloading the software is as instantaneous as simply re-running the software, rather than having to download it to an embedded system via serial or network connections. These capabilities have been extensively used as improvements were made to the original Plessey software to make it suitable for an orbital environment.

Some of the changes to make the original Plessey software work on an orbital receiver include removing height limits and changing Doppler bin widths and dwell times. For tests involving highly elliptical orbits, a flag was added to indicate the antenna direction. A satellite selection algorithm designed specifically for space-use has to be added. Also, the PiVoT receiver still needs to have a solid space flight cold-start mode implemented. The GEODE navigation filter has been added to the receiver software as a separate software task.

GEODE, the GPS-Enhanced Orbit Navigation System, is a NASA-developed software package that improves the accuracy of GPS-generated three-dimensional position and velocity fixes. GEODE produces true orbit determination, not just positioning with GPS. In simulations using NASA satellite data, GEODE-filtered GPS data produced position accuracies to better than 20 meters and velocity measurements to better than 0.03 meters per second (both results are 1 sigma). [1] (http://geons.gsfc.nasa.gov)

The PiVoT software feeds the GEODE task measurement data and GPS ephemeris data in real-time. PiVoT also must feed the GEODE configuration commands, and accept any telemetry generated by GEODE for output. The ephemeris data is fed to GEODE as it is received. The measurement data is sent to GEODE before the main estimate state routine of GEODE, which generates the current state vector, is called. Eventually, the state vector generated by GEODE will be the state vector that PiVoT outputs for position, velocity, and time to the spacecraft upon request.

The existing Linux version of the PiVoT receiver has been tested on the GSS STR4760 simulator located at Goddard Space Flight Center and maintained by the Guidance, Navigation, and Control Center. The PiVoT has even tracked satellites in highly elliptical orbit scenarios.

The configuration of PiVoT is flexible. The current box design has a spare compact-PCI slot which could host a number of different options, including, but not limited to: a 1553 card, a micro-gyro card, a magnetometer card, and even an ethernet card to support TCP/IP in space.

Balloon Flight

PiVoT's first flight opportunity was in July, 2001 on the In-FOCUS balloon flown from the NSBF, Palestine, TX. Previous to this mission, PiVoT had been operating typically as a lab receiver, using a industrial qualified CompactPCI rack containing a 3U Pentium processor, IDE harddrive and network connection. The design and construction of the mechanical enclosure and power supply was conducted separately, so the only missing piece was a flyable microprocessor card. For this flight, an industrial grade Pentium 400 MHz CPU with an extended temperature rating was selected. The IDE harddrive was replaced with a 128Mbyte solid state FLASH IDE-style drive.

Since Linux is not an ideal embedded operating system for this situation, the solution for a quick-turnaround was to treat the PiVoT the same way as a regular PC in the lab. The FLASH drive was divided into two partitions: the DOS boot partition and the Linux partition. The processor boots from the small (2Mbyte) DOS partition using the Syslinux boot utility. Then, the initialization function for Linux was modified so that when it has completed all other system initialization, it will initialize the GPS kernel and start the main GPS application task. In this way, the PiVoT receiver would begin searching for SV's within 30 seconds after power was applied.

The test plan for PiVoT was to prove the current PiVoT hardware and software design could operate in near-space conditions. Since there was not enough time to procure a fully qualified processor, no major expectations were placed on the survivability of the CPU. The FLASH drive was an off-the-shelf item with no modifications made for the balloon environment. The receiver card and the power supply were designed for space flight, and were expected to operate normally during the entire mission.

The PiVoT was configured to have each of the four RF channels connected to its own antenna. Due to time constraints, the PiVoT field team members were only allowed to install the receiver to the gondola and connect the power and telemetry cables to the rest of the balloon systems. The antennas and mounting brackets were installed by the balloon technicians and the PiVoT team was not able to fully test the configuration before launch.

The PiVoT software was modified to store some of the mission data at regular intervals throughout the mission. Since the size and write-speed of the FLASH drive is limited, this data was stored only once every 15 seconds. The data record consists of the computed time, position, and velocity of the receiver, the clock oscillator offsets and drift values, and the signal to noise ratio for each receiver channel.

The PiVoT software was also modified to send the position data once a second via an RS-232 serial port to the balloon's onboard GRISS flight processor. This data message was formatted to emulate the Rockwell NavCore receiver. This NavCore receiver had been used on previous missions and the balloon flight computer would need no modifications to accept the data. Therefore, the telemetry data IDC allowed for GPS position data if such data is available. Since the InFocus mission did not require the position information, the GPS data was collected and transmitted to the ground station, but was not needed for the final mission data analysis.

The mission flew on the 6th of July, 2001 for about 6 hours. All the PiVoT hardware was recovered and returned to Goddard Space Flight Center for post mission analysis. Form this data the following conclusions were made:

1. The data on the FLASH drive was recovered.
2. The receiver collected GPS data during the entire mission.
3. The Pentium processor worked right up to the end of the mission, but subsequent tests of the processor have failed in the lab.
4. The PiVoT receiver card has been fully tested in

the lab and is still fully functional.

5. The telemetry data was successfully sent to the balloon's onboard flight computer.

PiVoT ported to PowerPC ESP603 and Nucleus

The Pentium solution for the balloon flight was adequate because radiation and power were not limiting factors for the receiver. To transform the lab version of PiVoT into a true space flight receiver, a new CompactPCI microprocessor had to be found. The ESP603 Enhanced Space Processor PowerPC card by EMS Technologies was selected. This PowerPC card was designed for low earth orbit applications. The board uses error detection and correction circuitry to prevent single event upsets. The total power drawn by this board is approximately 9 watts. The PiVoT software team must still port the software to this new board.

The Linux solution, while ideal for the lab, cannot guarantee hard real-time performance. For the PowerPC card, PiVoT will be ported again to the Nucleus real-time operating system. This will decrease code size, and increase real-time performance due to lower operating system overhead. Targeting a specific board architecture with Nucleus is also significantly simpler than porting Linux.

A final, flight version of the PiVoT GPS receiver box will be available by early 2002. This includes the flight enclosure, microprocessor, and flight GPS card. The total power requirement for this box will be approximately 18 watts. It was hoped a lower power processor card could be found to lower the power requirement.

PiVoT 1.5

After the initial design of the original PiVoT box (PiVoT 1.0), it was determined that the power requirement was too high for most spacecraft. Its source code availability makes it attractive as an instrument for incorporating GPS science algorithms. However, the power requirement would continue to be a drawback. This led to the concept of the PiVoT 1.5 card, which incorporated all lessons learned from the PiVoT 1.0 development.

The goals for the PiVoT 1.5 card are: low power (<6 watts), radiation tolerant, 24 channels of GPS data, 4 antenna inputs, improved front-ends, 3U CompactPCI interface, and on-card processing. The output from the card will be position, velocity, and time, via either RS-232 or across the PCI backplane.

This card will be a highly flexible solution for spacecraft desiring GPS capabilities. Because the navigation solution is output from the card, no external microprocessor card is needed. This CompactPCI can be plugged into any spacecraft bus that is utilizing the CompactPCI backplane. In this case, the PiVoT card would be used as a slave on the PCI backplane. If the spacecraft is not utilizing the CompactPCI backplane, the PiVoT 1.5 card can be placed into the original PiVoT enclosure, modified for only one slot, and be delivered as a complete system, with navigation output via RS-232. If some other output is required (such as 1553), then the box can be modified for an additional slot and the appropriate interface card can be added.

Next Generation PiVoT GPS Receiver

GSFC is also developing the Next Generation (NexGen) PiVoT GPS Receiver for use in high Earth orbits (HEO) and geostationary orbits (GEO). Earth Science and Space Science researchers are envisioning distributed spacecraft and formation flying missions in HEO, and GPS is an enabling technology to provide the required onboard orbit information to coordinate the multiple spacecraft. Acquiring and tracking GPS signals in orbits above the GPS constellation, however, is much more challenging than using GPS in low Earth orbits (LEO). There are important differences in geometrical coverage, signal power levels, and vehicle dynamics. For example, there are rarely four or more satellites visible simultaneously at HEO and there are significant periods in which no signals are available. The GPS receiver will also have to be designed to survive the extremely severe radiation environment encountered in such orbits. The NexGen PiVoT will be a software based GPS receiver, and will not use any industry available GPS chipsets to do signal processing. In building this receiver, GNCC will have a complete understanding of the GPS signal in HEO and GEO orbits and how to best build a space qualified receiver to operate there. Doing as much of the signal processing in software as possible will provide the most flexibility and allow GNCC to investigate ideas that drastically deviate from a conventional hardware approach.

Currently, GNCC has a non-real-time software GPS receiver working in MATLAB (registered trademark of the Math Works, Incorporated) that does signal acquisition, tracking, and demodulation. GNCC partnered with the U.S. Air Force Research Laboratory's Sensor Directorate at Wright-Patterson Air Force Base in developing this software. It acquires and tracks GPS signals with a carrier to noise ratio (C/N0) as low as 27 dB-Hz. A receiver that can acquire and track weak signals is critical for use in high altitude orbits. The acquisition algorithm is based on a paper by Dr. Mark Psiaki of Cornell University, "Block Acquisition of Weak GPS Signals in a Software Receiver". The algorithm averages signals over multiple GPS code periods and multiple navigation data bits to achieve weak signal acquisition. It uses the Fast Fourier Transform (FFT) and inverse FFT to process one code period (1 ms) at a time to speed up computations. The software has been tested with simulated and digitized GPS signals. The next step is to port the software to a commercial-off-the-shelf Digital Signal Processor (DSP) in order to test the algorithms in a real-time environment.

After the algorithms have been verified in the GNCC Formation Flying Testbed, they will be "ported" to radiation hardened components. Radiation hardened components and single event upset tolerant software are required for a receiver to work in high altitude orbits. A coherent RF front-end will be used to down-convert GPS signals from four different antennas to near baseband. The PGAs will do signal acquisition, tracking, and demodulation. The GPS data streams will be passed to a radiation-hardened microprocessor to produce usable navigation data. Like in the case of the existing PiVoT GPS receiver, NexGen PiVoT will be using the GPS Enhanced Orbit Determination (GEODE) software as an onboard navigation filter. The same microprocessor will also be running algorithms to determine the spacecraft attitude.

Finally, NexGen PiVoT will support sparse sampling of GPS signals to drastically conserve power for those missions that can tolerate relatively large position and velocity errors. The receiver will be "awakened" from a "sleep mode" to occasionally sample GPS signals for short intervals. A software based GPS receiver easily supports this idea since it can process a "snapshot" of data rather than continuously tracking the signal as a pure hardware receiver would do. The sampled data can be processed either onboard the spacecraft or telemetered to the ground. Ground processed data can be further uploaded to the spacecraft and projected ahead for later use.

ACKNOWLEDGMENTS
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REFERENCES

1. http://geons.gsfc.nasa.gov

Moreau, Michael C., "GPS Receiver Architecture for Autoomous Navigation in High Earth Orbits", Ph.D. thesis for University of Colorado, 2001.