PRECISE POSITIONING AND ATTITUDE DETERMINATION OF SMALL SATELLITES USING A SOFTWARE-DEFINED RADIO

Alison Brown (NAVSYS Corporation, Colorado Springs, CO, USA, (alison@navsys.com), Peter Brown (NAVSYS Ltd., Edinburgh, Scotland, (pbrown@navsys.com), and Janet Nordlie (NAVSYS Corporation, Colorado Springs, CO (janetn@navsys.com)

ABSTRACT

Current GPS technologies for satellite navigation are relatively costly, heavy, and utilize a high amount of power. This makes such systems difficult for small satellites to support. In this paper, we describe a low-cost, low-weight, low-power GPS navigation system to support smaller satellites. A key component of our solution involves our patented TIDGET-based receiver design, which takes a brief snapshot of GPS data and powers off until the next position fix is desired. The processing of the TIDGET snapshot data is implemented in a software defined radio (SDR) using a GPS software application. This approach shares the resources available within a spacecraft's SDR to support both communication and navigation functions reducing the size, weight and cost of the hardware on a micro/nanosatellite. An important aspect of the TIDGET is its modular design, which allows multiple TIDGETs to be placed on the satellite shell for full GPS visibility and robustness to satellite spin.

1. INTRODUCTION

The current state of GPS receivers for spacecraft onboard position and velocity measurements to update orbit propagators is to employ multiple stand-alone GPS receivers or a multi-antenna GPS receiver connected to different antennas placed around the spacecraft to remain in the field of view of the GPS satellites. These GPS receivers obviously require valuable resources of power, mass, volume and cost to perform their function. If a system could be developed to achieve similar performance while realizing savings in one or more of these areas, there would be a strong demand in the industry, especially as smaller spacecraft platforms gain popularity.

NAVSYS' TIDGET ("Tracking Widget") is a low cost sensor that can be used to support networked GPS positioning applications. The patented TIDGET® sensor operates by taking brief snapshots of GPS data when activated[1]. These snapshots are captured to memory and forwarded to the TIDGET Processor through a digital interface or data link for processing[2].

The TIDGET is built using the RF front-end of a commercial GPS chip (see Figure 1-1). The device is designed to operate with a variety of different types of data links providing a low-power location solution. Instead of performing the GPS signal processing using an internal baseband processor, the TIDGET device only samples and records the GPS snapshots periodically. While this requires more data to be transmitted across the wireless data link, it significantly reduces the overall power drain of the device, making this an ideal solution for low-power tracking applications. This approach is being used for a variety of commercial positioning and tracking applications.

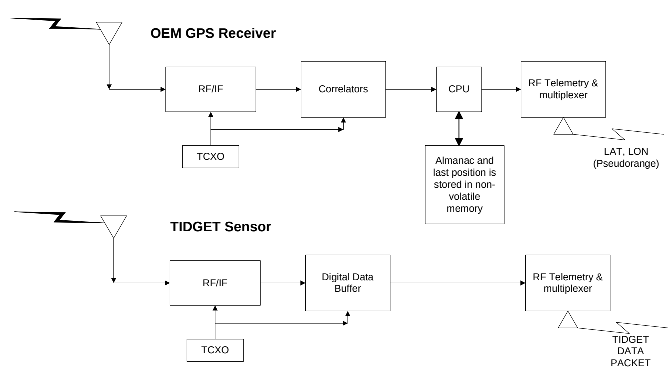

Figure 1-1 TIDGET Sensor

The NAVSYS TIDGET technology offers several key advantages over currently available spacecraft GPS receivers. TIDGET receivers are low-weight, small, and consume much less (peak and average) power than traditional receiver designs. The TIDGET receiver captures only a small snapshot of GPS data, on the order of tens of milliseconds, and does not run and draw power continuously. Also, the TIDGET is a small-form factor module that may be easily attached to the spacecraft shell. In a current design in development, we are using three TIDGET modules that are interconnected so that snapshots are synchronously collected and jointly processed. This allows the spacecraft to have full 360-degree visibility in both azimuth and elevation and can account for spacecraft spin, if necessary. The multiple TIDGET signals can also be used to estimate the attitude of the spacecraft, if sufficient common satellites are in view. The processing of the TIDGET signals is performed using a Software Defined Radio (SDR) architecture.

In this paper, we describe the design of the TIDGET receiver developed for small satellite operations and describe the benefits of this approach and the processing employed within the SDR to perform both positioning and attitude determination.

2. SATELLITE TECHNOLOGY

Satellite technology has become an indispensable part of modern society - being used for everything from mapping and weather forecasts to communications. For both military and commercial applications, satellites are becoming smaller and smaller. Some companies are developing a new spacecraft generation called microsatellites or microsats[3]. These small satellites can provide navigation, weather predictions, and Earth observation just like traditional satellites, but are faster to build and much cheaper. About 400 microsats have been launched in orbit over the last 20 years for scientific, commercial, and military purposes, and innovative new small satellite products for remote sensing, geostationary communications and navigation are currently being developed.

The attractiveness of microsats is their low investment and operational costs, their flexibility in making changes, and the short system development cycles. The lighter a satellite is, the less it costs to send into orbit, which results in launch costs being significantly lower for microsats than conventional satellites. Manufacturers are also leveraging commercial technology and modular architectures to reduce the cost of the microsat avionics. These approaches are significantly lowering the cost for microsat production costs. A typical microsat can cost as little as $10 million, including production and launch cost, as opposed to hundreds of millions for traditional satellites. The Space TIDGET solution significantly reduces the size weight and cost of the onboard navigation components, making it an attractive option for microsat applications.

3. SPACE TIDGET AVIONICS

The proposed Space TIDGET avionics solution is illustrated in Figure 3-1. The major cost impact for space electronics is the ruggedization and qualification needed for the space environment. While commercial GPS space products are available, they are significantly more expensive than conventional commercial grade receivers, averaging in the $50,000-$350,000 range. With our proposed TIDGET approach, only the GPS RF and digital sampling electronics are needed to be qualified for the space environment. The TIDGET processing is performed using a Software Defined Radio (SDR) architecture.

As shown in Figure 3-1, our first implementation of the Space TIDGET tracking system will downlink the TIDGET sensor data using the ground station communications link for processing on the ground using a SDR at the ground station. This will provide precision GPS positioning of the spacecraft. For future spacecraft, we plan to port our TIDGET processing software so that it can run within the spacecraft onboard processor. The TIDGET SDR application is being designed to allow porting to a variety of processor types.

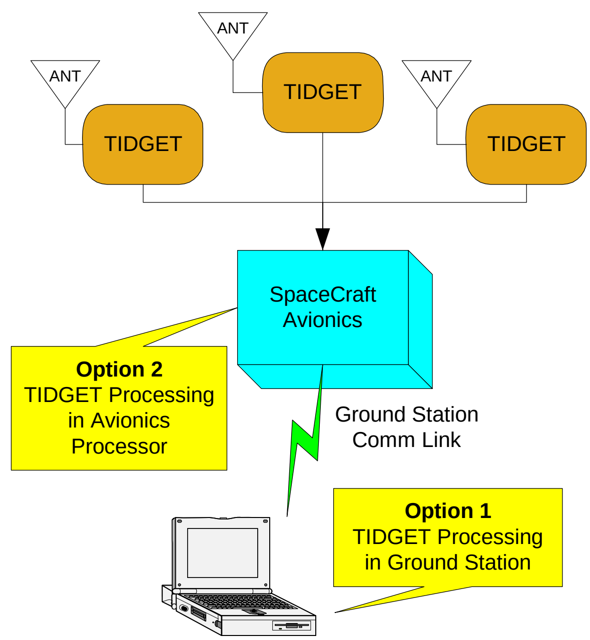

Figure 3-1 Proposed Space TIDGET Architecture

Our planned implementation is to have three single-element antennas installed, each connected to a single TIDGET sensor (Figure 3-2). This alternative allows optimal processing of the TIDGET signal outputs to achieve a high accuracy combined solution without degradation of the GPS signals. The multiple antennas also allow for rough attitude estimation to be performed using the GPS signals.

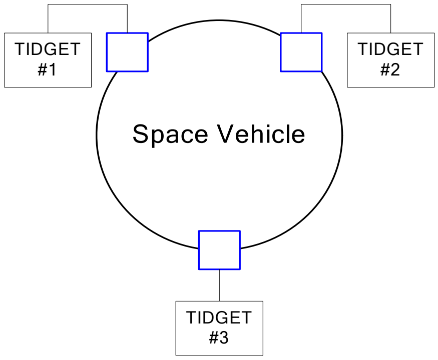

Figure 3-2 Multiple Antenna Installation for Attitude Determination and All-Around Visibility

4. SPACE TIDGET HARDWARE

The hardware for the Space TIDGET consists of a stack of three identical circuit boards, Figure 4-1 (approx 3" x 3" x 0.45"), each with the following connectors: avionics host connection (power, control and data), GPS antenna connection, and stack-thru connector. Of the three boards in the stack, the host computer can configure any one board as Master, with the remainder as Slaves. If the Master hardware fails, the avionics host can select an alternate unit as Master.

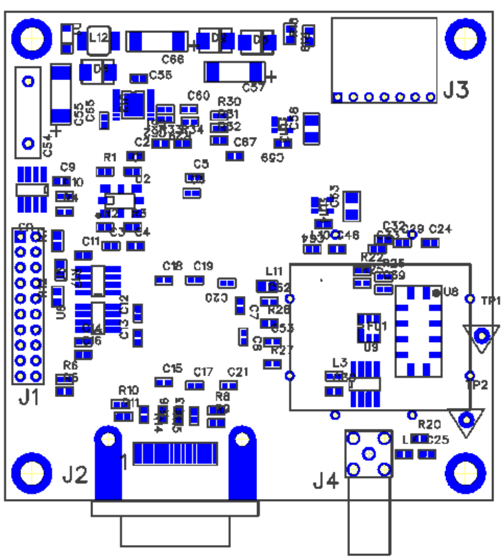

Figure 4-1 Space TIDGET Circuit Board

The avionics host connection consists of:

- DC supply (10v to 40v range)
- RS422 clock and synchronous data lines (data to host and data from host) (These signals are bussed between all boards and may access all boards through a single connection.) and TTL level control strobe and Output Enable Strobe.
- Master select control line and Power Enable Control line.

The electronics of each board comprise a Low-Noise Amplifier (adequate for use with either active or passive GPS antennas), an integrated GPS front-end (RF to digital baseband), a CPLD programmable logic device an associated data cache SRAM memory chip, a TCXO, buffers and line drivers, and a switching regulator.

The TCXO master reference is distributed from the Master to the Slave boards via the stack-thru connector, frequency synchronizing all GPS boards.

The Master Unit acts as system timing controller (under overall avionics host command via a serial command protocol) commanding either single-shot GPS snapshots (precisely synchronous between all GPS elements) or precisely timed (with the Master TCXO) sequences of GPS snapshots. The GPS RF circuitry is automatically powered on and off by the CPLD logic to minimize overall power consumption.

Once snapshots have been captured to the cache memory, the avionics host may read the individual snapshots in sequence via the serial connection.

The hardware is built using commercial parts (extended temperature range), with the TCXO being specified for a high vibration/shock environment, and several other parts having a successful space track-record.

Thermal problems are largely avoided due to the very short time (50 milliseconds) that the heaviest current-draw portion of the circuit is powered to take the infrequent GPS snapshots.

System reliability is enhanced by vibration testing of the assembly during the test phase, over-specifying component values (capacitors, etc.) where appropriate to give performance margin, and temperature testing each assembly. Further reliability may be achieved by judicious use of the system redundancy (once launched, the host can disable a failed unit, and can select any unit as Master), since the system can operate (with slightly reduced functionality) with at least one board disabled.

5. TIDGET SOFTWARE PROCESSING

The TIDGET processing software is based on the Software GPS Receiver (SGR) application that NAVSYS had previously developed for tracking GPS signals on a Software Defined Radio (SDR)[4]. This includes the components shown in Figure 5-1 and summarized in Table 5-1.

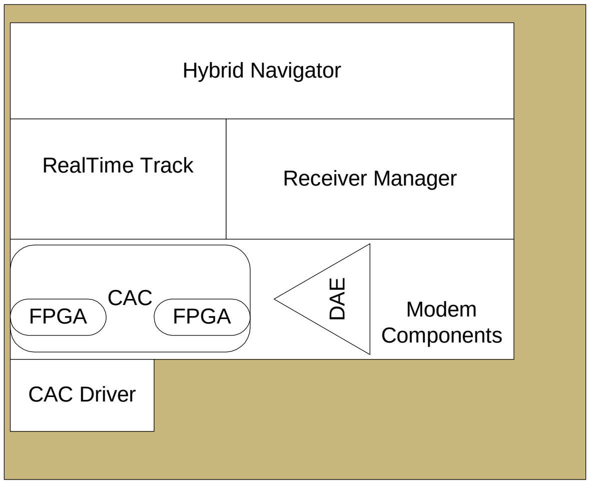

Figure 5-1 Software GPS Receiver (SGR) Components

Table 5-1 Functions performed by Software GPS Receiver Components

Component	Functions Performed
Modem - DAE	RF/Digital Conversion
Modem - FPGA	Code Generation, Correlation & Carrier Mixing
CAC Driver	FPGA interfaces (e.g. NCO settings and Correlator Outputs)
Real-Time Track	Real-Time Code & Carrier Tracking loops and NAV data demodulation
Receiver Manager	GPS SV position calculation and SV selection
Hybrid Navigator	Position/Velocity Calculation (Least Squares or Kalman Filter)

The TIDGET processing software executes on the received TIDGET messages as they are received using the components shown in Figure 5-2 and summarized in Table 5-2. The major distinguishing factors between these two software implementations are described in Table 5-2.

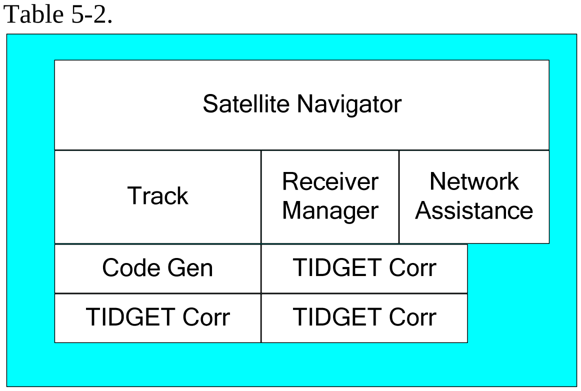

Figure 5-2 TIDGET Processor Components

Table 5-2 Functions performed by TIDGET Processor Components

Component	Functions Performed
Code Gen	Code & Carrier Generation using Code phase/Doppler Prepositioning
TIDGET Corr	Code & Carrier correlation of TIDGET data
Track	Assisted Code & Carrier Tracking loops for all TIDGET sensors
Receiver Manager	GPS SV position calculation and SV selection Code phase/Doppler Prepositioning with GPS/Satellite position/velocity
Network Assistance	Receives GPS NAV data through Network
Satellite Navigator	Position/Velocity Calculation (Orbital Kalman Filter)

GPS Signal Sampling and Correlation

The SGR performs the GPS signal sampling and correlation functions in the Modem components. The TIDGET sensor onboard the spacecraft performs the RF down conversion and sampling functions that the Digital Antenna Element (DAE) performs in the SGR. With the SGR, the code generation and correlation is performed within the FPGA components, which are controlled by the individual track channels. With the TIDGET, the code generation is performed in software using prepositioning data generated from the a-priori estimate of the satellite position and velocity. This has the advantage that only a single set of GPS code and carrier reference signals need to be generated for all of the TIDGET data sets to be processed. The TIDGET data correlation can be performed either in software or firmware for each of the TIDGET data sets.

GPS Satellite Tracking

With the SGR, each individual channel operates independently tracking a single GPS satellite. For the TIDGET, we have multiple TIDGET data sets for each satellite to be tracked. By including states in the tracking loops for the satellite position and the delta pseudo-range and carrier-phase for each TIDGET sensor, it is possible to improve the tracking loop performance for the composite set of signals and improve the reliability of the lock detection to handle rapid signal fades.

GPS NAV Data Collection

The SGR demodulates the GPS NAV data within the tracking channels and uses this to unpack the GPS ephemeris data that is needed to calculate the GPS satellite positions and velocities. With the TIDGET solution, we can obtain the satellite ephemeris information through the ground network. This allows more accurate positioning by using precise ephemeris available either from military sources[5] or from commercial networks[6].

Navigation

The SGR calculates a navigation solution using the Hybrid Navigator component that can estimate position and velocity using either stand-alone GPS or using a Kalman Filter to estimate errors on an inertial solution. The Space TIDGET processing software uses a variant of this navigation filter to estimate the position, velocity and attitude of the spacecraft orbit. Instead of using state propagation from an inertial model though, the orbital dynamics equations of motion are used to propagate the spacecraft states instead.

The design approach adopted for the TIDGET processing leverages much of the existing code developed for the SGR. The design enhancements in the tracking and navigation algorithms will provide improvements in the GPS satellite signal observations and the resulting orbital and attitude solution for a spacecraft.

6. CONCLUSION

The NAVSYS Space TIDGET technology offers several key advantages over currently available spacecraft GPS receivers.

- The TIDGET receivers are low-weight, small, and consume much less (peak and average) power than traditional GPS receiver designs.
- The TIDGET solution offers "on demand" processing. In other words, as long as the navigation solution is not needed in real time, the GPS data snapshots may be processed on an as needed basis, when convenient for the processor. In this way, multiple snapshots may be queued/stored for later processing, if the processor is currently being tasked for other applications.
- The TIDGET offers an inexpensive modular solution, which allows for multiple TIDGET sensors to be installed in the spacecraft. This can be used to provide all-around (4π steridian) field of view. This is advantageous for a spinning or tumbling solution where GPS satellites rapidly fall in an out of view of a single antenna, and can also be used for attitude determination.

7. ACKNOWLEDGEMENT

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8. REFERENCES

[1] A. Brown, "The TIDGET – A Low Cost GPS Sensor for Tracking Applications," ION 5th International Technical Meeting, Albuquerque, September 1992

[2] GPS Tracking System, Brown, Alison, K., and Sturza, Mark (to NAVSYS Corporation) US Patent 5,379,224, January 3, 1995, Application 11/29/1991

[3] Jason Guarnieri, Greg Hegemann, Greg Spanjers, James Winter, Martin Tolliver, Jeff Summers, Greg Cord, "The MDA MicroSatellite Target System (MTS) for DoD Radar Calibration," IEEE Aerospace Conference 2007, Big Sky, Montana, March 2007

[4] Alison K. Brown, Lynn Stricklan, and David Babich, "Implementing a GPS Waveform Under the Software Communication Architecture," 2006 Software Defined Radio Forum, Orlando, Florida, November 2006

[5] Talon NAMATH Tactical Control Station http://www.af.mil/news/story.asp?id=123036716

[6] NASA Global Differential GPS System http://www.gdgps.net/