The U. S. Air Force Academy GPS Flight Experiment Using The Navsys TIDGET™

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BIOGRAPHY

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Dr. Belle is Project Manager/Engineer at NAVSYS Corporation. She works on GPS applications for spacecraft tracking, real time tracking technology and the wide area augmentation system. She has ten years of experience in microelectronics and has worked in industry and at the University of Ulm, Germany. She completed her graduate studies at the Max Planck Institute for Solid State Physics in Grenoble, France and the University of Nijmegen, Holland. In 1997 she graduated from the International Space University in Strasbourg, France with a Master of Space Studies degree.

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Captain David Goldstein is an Instructor of Astronautics, Department of Astronautics, U.S. Air Force Academy. He graduated from the Air Force Academy in June 1988 with a B.S. degree in Engineering Sciences. He earned a M.S. degree in Aerospace Engineering from the University of Houston, Texas in 1994. He is currently earning a Ph.D. in Aerospace Engineering at the University of Colorado, Boulder.

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Dr. Ron Humble has a B.S. in Aeronautics and Astronautics from the University of Washington, an M.S. and Ph.D. in Aerospace Engineering from the University of Texas. He has worked for Pratt & Whitney Aircraft, the Canadian Armed Forces Aerospace Engineering Test Establishment, Lockheed Space Industries, and the University of Colorado. Presently, he is a Visiting Professor at the United States Air Force Academy.

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Major Parker is Director of Laboratories and an Assistant Professor in the Department of Astronautics at the U.S. Air Force Academy in Colorado Springs. He is Project Manager of the Falcon Gold Mission. Major Parker graduated from the Air Force Academy in 1985 with a B.S. degree in Astronautical Engineering. He earned a M.S. degree in Aerospace Engineering from the University of Colorado, Boulder 1994. He has twelve years active duty in the Air Force, 2600 flying hours including over 220 combat and combat support hours.

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Second Lieutenant Catherine O'Brien contributed to the integration and test of the payload. She graduated with a B.S. degree in Astronautics from the U. S. Air Force Academy in May 1997, and is currently working for the Department of Astronautics as a research assistant.

AMIR MATINI

Dr. Matini was a member of the NAVSYS design team for GPS equipment. He received B.S.E.E. and M.S.E.E degrees from the University of Colorado at Colorado Springs and he recently completed his Ph.D. in Electrical Engineering.

ALISON BROWN

Dr. Brown is the President of NAVSYS Corporation. She has eighteen years experience in GPS receiver technology and has several GPS related patents. She has published numerous technical papers on GPS applications and is on the editorial board for GPS World and GIS World magazines. Prior to NAVSYS, Dr. Brown was a GPS Systems Engineer at Litton Aero Products, CA, responsible for all Litton third generation GPS card set products. Dr. Brown completed her graduate studies at MIT and UCLA.

ABSTRACT

The United States Air Force Academy GPS flight experiment is intended to determine the capabilities for using the signal broadcast by the GPS satellites while at altitudes above the GPS constellation. The goal is to demonstrate the potential for new cost-effective tracking technologies using a GPS sensor for geosynchronous spacecraft.

To demonstrate this concept the TIDGET sensor has been integrated into the Falconsat spacecraft. The patented TIDGET technology allows cost-effective tracking for all GPS applications [1,2,3,4]. For this mission the TIDGET is

required to gather GPS raw data that will be transmitted to the satellite's communication subsystem. The ground stations at the University of Colorado in Colorado Springs (UCCS) and Boulder will receive telemetry data, describing the health of the satellite and GPS raw data. The GPS sensor uses a sparse sampling technique, which reduces the power consumption in comparison to a conventional receiver.

The mission concept, the payload design, and the payload integration into the spacecraft are explained. Due to the highly elliptical orbit configuration, data acquisition is only possible when the spacecraft is on the far side of the Earth, near the apogee of the orbit. At this point the velocity is low and the Doppler shift of the signal will be a minimum. GPS data are acquired every five minutes and immediately transmitted to the ground station. Data reception will be random as the Falconsat has no attitude control system. The data will be recorded at the ground station.

Post - processing of the data allows to determine the signal-to-noise ratio. The methods applied allow for the separation of the very weak GPS signal from the background noise and for determination of the spacecraft track above the constellation.

INTRODUCTION

"Cost-effectiveness" plays an important role when planning a space mission. Low-cost spacecrafts such as small satellite systems and micro-satellites require reliable, light weight components with low power consumption. Low-cost tracking systems can help to reduce the overall mission costs. The Global Positioning System (GPS) is an ideal means for earth-orbiting satellite tracking applications, but up to now has been limited to orbits below the GPS constellation.

Conventional GPS receivers, as installed on spacecrafts, have drawbacks with regard to mass, power consumption and initialization procedure. Such a receiver must have four satellites in view, lock onto their signals and then demodulate the navigation message from the satellites, a procedure that can take up to several minutes.

The patented TIDGET technology, applicable to a wide variety of tracking applications, is an ideal device for tracking small satellites and micro-satellites because of its simple design, low power consumption, low cost and high reliability. The only requirement is to ensure sufficient data to be relayed back to the tracking center where the location of the sensor is determined. The TIDGET as the payload of the Falcon Gold drives the design of the satellite. The anticipated results are the evaluation of the GPS data, by post-processing and depending on the quality of the data, the orbit can be determined.

MISSION CONCEPT

The mission architecture encompasses the mission-subject, which is the part interacting with the payload, the payload itself, the subsystems of the spacecraft bus, the launch system and the orbit.

The subject of the Falcon Gold Mission [5] is the GPS constellation in 26,500 km with their antenna beams pointed toward the Earth. A spacecraft in an orbital position above the constellation can only receive the GPS signal from satellites of the far-side of the Earth. The antenna beam width is wide enough so that the signal can pass by the Earth.

The orbit of this mission is highly elliptical, a geotransfer orbit with its perigee in 286 km and its apogee in 35,735 km.

The payload is the TIDGET sensor. The spacecraft itself is a small satellite consisting of a communications subsystem, a power subsystem, a thermal subsystem and the structure. It contains no propulsion system and no attitude control system.

The ground segment has been developed in cooperation between the Air Force Academy and the University of Colorado at Colorado Springs (UCCS). A broad-band receiver down-converts the signal received by the parabolic antenna and sends it to a Terminal Node Controller (TNC). The TNC will demodulate the base-band signal and then the remaining data are transferred to a computer. The data are recorded on a tape for post processing.

The spacecraft will be mounted on an Atlas/Centaur. Mission duration depends on the power subsystem and is estimated to be seventeen to twenty days. The Falconsat will remain attached to the Atlas/Centaur during the whole mission. The last stage of the launch vehicle will go into a geotransfer orbit and stay there until the orbit decays.

SPACECRAFT ARCHITECTURE

The payload of the Falcon Gold spacecraft is the TIDGET sensor. The received GPS raw data are transferred to a flight computer, a micro-controller that additionally receives telemetry data from the other subsystems. The micro-controller sends the data to the TNC that modulates the incoming data stream, thus creating a base-band signal. The UHF transmitter adds the carrier frequency of 400.475 MHZ and transmits the signal to the ground station. The process of data acquisition and data transfer is initiated by the flight computer every five minutes. All subsystems are mounted on the structure. The following schematics shows the spacecraft architecture.

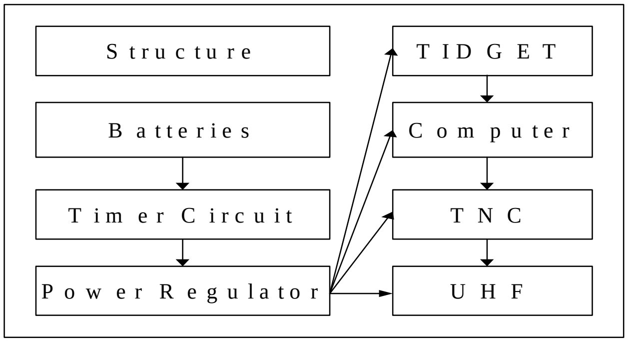


Figure 1: Spacecraft Architecture

The structure is the basis that mechanically supports all other spacecraft subsystems and provides the interface to the launch vehicle. The structure of the Falconsat is made of three parts: an adapter plate, which is the interface to the launch vehicle, a subsystem box for the communication subsystem, the flight computer, the payload and an additional box for the power system.

The electrical power subsystem consists of NiMH battery cells with each battery pack containing ten cells, a thermal breaker and a fuse for thermal protection. Additionally, a diode wired in series with each pack is used to prevent reverse charging, which could decrease the available power and create an unsafe increase in the temperature of the battery pack.

The communication subsystem is the interface between the satellite and the Earth. It is used to transmit and receive telemetry, tracking and command data at a special RF frequency assigned to the mission. The communication system of the Falcon Gold mission transmits telemetry data, that describe the health of the spacecraft and payload data from the GPS sensor. The system consists of a Terminal Node Controller, a transmitter and an antenna. The function of the TNC is to modulate the received digital data stream coming from the flight computer. This base-band signal is transferred to the transmitter where the carrier frequency is added. The frequency allotted to this mission is 400.475MHz. The TNC sends the data out at a rate of 9600 baud.

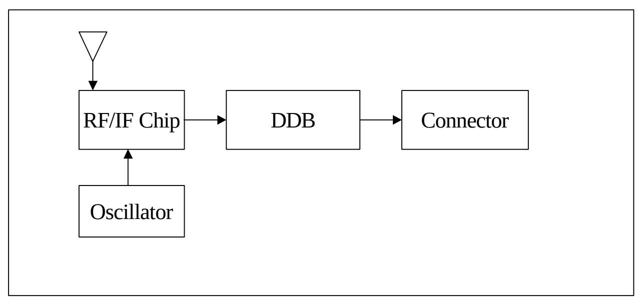
To provide sufficient thermal protection a thermal blanket is used. The lowest temperatures will not exceed less then 0EC and the temperature during operation will be about 20EC. It will be mounted on the structure using permanent adhesive.

PAYLOAD DESIGN AND INTEGRATION

The payload of the Falcon Gold Mission is the TIDGET sensor. The TIDGET uses a sparse sampling technique to take a short snapshot of GPS data in a digital data buffer, and then transmits these GPS raw data back to the processing and control center. It has many advantages compared to a conventional GPS receiver. The simple design reduces the cost and the weight, which makes it very attractive for special applications as spacecraft tracking. In this particular application it acquires GPS raw data every five minutes for 40 milliseconds. The TIDGET sensor can be operated with a DC voltage between +6V to +9V. Within this range it will draw a current of 120mA for data acquisition and data transfer. In standby mode the current will not exceed the micro-amperes range. For Falcon Gold the TIDGET operates with a DC voltage of +8V±0.5V, which results in a maximum power of 960mW±60mW. Thus voltage regulation is necessary.

The sensor is mounted inside the spacecraft such that it can be shielded and connected to the antenna with a cable that is designed for the RF transmission.

Figure 2: TIDGET sensor [1,2,3]



The system consists of a patch antenna and a RF board. The antenna receives the L1 (1575.42MHz) frequency of the GPS signal. Band-pass filters are used to center the received signal spectrum to the L1 frequency.

The TIDGET device includes a preamplifier, a down-converter and a low pass filter. The down-converter changes the RF frequency to an intermediate frequency (IF) which is easier to handle. The digital data buffer stores the data and transfers them to a connector, which is the interface to the micro-controller. The data are sampled for 40ms every five minutes. An EPROM contains the data acquisition time for the TIDGET, which is 40ms and the data transfer rate, which is 9600 baud.

Thermal constraints are given due to the fact that the sensor uses commercial off the shelf parts. The operating temperature for those devices is between 0EC and 50EC. The maximum thermal output for the TIDGET board is estimated to be 1 Watt.

To activate the TIDGET the micro-controller sends a +5V signal to the TIDGET, which turns the power on. 20ms after this pulse was sent out the logic at the TIDGET is activated and the sensor starts to acquire the GPS data. As soon as the first bits are transferred, the micro-controller has to time-tag the data. The reset stays on until the last bit is transferred to the computer and is then turned off. The power is turned off 20ms later. The data transfer rate is 9600 baud; therefore the TIDGET is active for 12 seconds before going back to "sleep"-mode. After the data transfer is completed the sensor stays "asleep" for five minutes.

The post-processing of the GPS data requires to add a time-tag to the data in the moment when the snapshot is taken. To add the timetag to the GPS data the microcontroller clock is set to the TNC time. The TNC will be set to UTC time. The accuracy required is in the order of milliseconds. However, the clock, providing the timetag is only has an accuracy of 1 second. Therefore an additional timetag is added to the data as soon as they are received at the ground station. .

The whole process of capturing the snapshot and sending the data to the control center only takes a few seconds.

The transmitted data are received by the ground and processed to recover the window of GPS satellite measurements. The PC workstation developed by NAVSYS is capable of recovering the measurements from all visible satellites and computing a solution.

DETERMINATION OF THE SIGNAL-TO-NOISE RATIO

The goal of the project is to determine the value of the signal-to-noise ratio for the received signal. In the following part the algorithms used are explained.

The GPS raw data are sampled at a rate of 2 Mbits /second. The In-phase (I) and quadrature phase (Q) values of the PSK-signal are quantized to 1 bit. The snapshot takes 40 ms.

To determine the SNR, the parameters for 1 ms coherent sums are determined first.

If only noise is present, the expected values of the In-phase and quadrature phase signal components, based on random walk statistics and the fact that I and Q are independent, are

$$E[(I^2+Q^2)] = E[I^2] + E[Q^2] = 2000 + 2000 = 4000 \qquad (1)$$

With a sample rate of 2 Msamples/ sec, there will be 2000 samples in 1 ms and therefore $E[I^2] = E[Q^2]=2000$. Thus equation (1) can be rewritten as

$$E[1\text{ ms counts}] = E[\text{noise}] = 4000 \qquad (2)$$

If a signal is present the expected values of the counts can be written as

$$E[1\text{ ms counts}] = E[\text{signal+noise}]=E[\text{signal}]+E[\text{noise}] \quad (3)$$

The expected value of the signal can be related to the S/N ratio present after integration. If the S/N ratio is expressed as a linear ratio then

$$E[\text{signal}]=S/N*E[\text{noise}] \qquad (4)$$

Equation (3) can be rewritten as:

$$E[1\text{ ms counts}]=E[\text{signal+noise}]=(S/N+1)*4000 \qquad (5)$$

With a 1 ms integration time, which gives a bandwidth of 1000 Hz, the post-integration signal-to noise ratio (S/N) is related to the carrier to noise density (C/No) as follows:

$$S/N=C/(No*B)=C/(No*1000) \qquad (6)$$

or in dB

$$S/N\text{ dB}=(C/No\text{ dBHz}) - (30\text{ dBHz}) \qquad (7)$$

In the presence of a signal, equations (5), (6) and (7) can be combined to equation (8).

$$E[1\text{ ms counts}]=[10^{(C/No\text{ dBHz - 30dBHz})/10}+1]*4000 \qquad (8)$$

or as carrier to noise density:

$$C/No\text{ dBHz} = 10*\log\{[E(1\text{ ms counts})/4000]-1\}+..$$

$$..+30\text{dBHz} \qquad (9)$$

A non-coherent integration will cause the counts to increase linearly with the number of summations. This means that a snapshot of 40 ms will lead to

$$E[40\text{ ms counts}] = 40*E[1\text{ ms counts}] \qquad (10)$$

which changes equation (9) to

$$C/No\text{ dBHz} = 10*\log\{[E(40\text{ ms counts})/40.4000]-1\}+..$$

$$. .+30\text{ dBHz} \qquad (11)$$

The difference between coherent and non-coherent integration is that a coherent integration causes the expected value of the signal to separate from the expected noise value. Non coherent integration causes variance about the expected values to decrease. Thus a 40 ms counts will have less deviation from the expected value than the 1 ms counts.

The carrier-to-noise density expected in this experiment can range between 32 dB to 46 dB.

The first values were determined by post-processing of data, gathered during a balloon test flight of the Falcon Gold spacecraft. The results varied between 36 dB and 42 dB. After thermal, high vacuum and explosive tests the TIDGET was activated again and the collected data were processed. They showed a carrier-to-noise density of 38 dB to 42 dB.

CONCLUSION

For the first time the TIDGET sensor will be used in space. The goal of this experiment is to determine the signal-to noise ratio of the GPS signal above the constellation which will provide the basis for the development of low-cost tracking technology for geotransfer and geosynchronuous orbits. The tests show that the probability to get reasonable data that can be post-processed is high, about 95%.

The TIDGET is an ideal device for spacecraft tracking due to its low cost, simple design, and high reliability. The data from this experiment will also allow to calculate the orbit. The U.S. Air Force Academy GPS flight experiment is the first step to develop a real time tracking technology for spacecrafts with the TIDGET sensor.

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