THE GPS ATTITUDE, POSITIONING, AND PROFILING EXPERIMENT FOR THE ENHANCED POLAR OUTFLOW PROBE PLATFORM ON THE CANADIAN CASSIOPE SATELLITE

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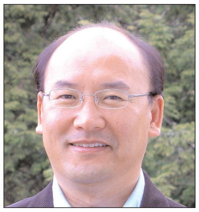
The CAScade, Smallsat and IOnospheric Polar Explorer, or CASSIOPE, is Canada's first multi-purpose small satellite, scheduled to be launched in 2011. It features two main payloads: the Enhanced Polar Outflow Probe, or e-POP, and Cascade. Together, they will achieve both a scientific and a commercial objective: e-POP will provide scientists with unprecedented details about the Earth's ionosphere, thermosphere, and magnetosphere, helping scientists better understand the cause and effects of potentially dangerous space weather, while Cascade will demonstrate a new high-capacity store-and-forward digital communications service.

e-POP consists of eight scientific instruments, one of which is the GPS Attitude, Positioning, and Profiling experiment (GAP). GAP employs five dual-frequency GPS (Global Positioning System) receivers and associated antennas to provide the e-POP payload with high-resolution spatial positioning information, flight-path velocity determination, and real-time, high-stability timing. In addition, by measuring the arrival times of the GPS signal wave fronts at each antenna against a very stable time base, the relative range between antennas can be determined, yielding real-time spacecraft attitude determination. The GAP receivers are slightly modified, commercial, off-the-shelf units that required a series of tests before they could be considered capable for use on an orbiting spacecraft. In this paper, we describe the GAP instrument and the various tests that have been performed to qualify the instrument for space flight.

Le CASSIOPE (CAScade, Smallsat and IOnospheric Polar Explorer) est le premier petit satellite polyvalent canadien dont le lancement est prévu en 2011. Il comprendra deux charges utiles principales : la sonde e-Pop (Enhanced Polar Outflow Probe) et l'instrument de télécommunications Cascade. Ensemble, ils rempliront un objectif scientifique et commercial : e-POP recueillera pour les scientifiques des données détaillées sans précédent sur l'ionosphère, la thermosphère et la magnétosphère terrestres, les aidant ainsi à mieux comprendre la cause et les effets des tempêtes solaires potentiellement dangereuses alors que Cascade assurera le tout premier service de messagerie numérique à large bande à haute capacité de stockage et de transmission.

La sonde e-POP comporte huit instruments scientifiques, dont le GPS expérimental d'attitude, de positionnement et de profilage (GAP). GAP utilise cinq récepteurs GPS (Système de positionnement global) bifréquence et des antennes connexes pour fournir à la charge utile de e-POP une information de haute résolution sur le positionnement spatial, l'évaluation du vecteur vitesse-terre et la synchronisation de haute stabilité en temps réel. De plus, en mesurant le moment de l'arrivée des fronts d'ondes du signal GPS à chaque antenne par rapport à une base de temps très stable, la distance relative entre les antennes peut être déterminée, permettant ainsi l'évaluation de l'attitude de l'engin spatial en temps réel. Les receveurs GAP sont des unités commerciales ordinaires légèrement modifiées qui requièrent une série d'essais avant d'être jugées aptes à être utilisées dans un engin spatial en orbite. Dans cet article, nous décrivons l'instrument GAP et les divers essais qui ont été effectués dans le but de le qualifier pour les vols spatiaux.



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Introduction

Over the last decade or so, GPS receivers have been successfully used for orbit and attitude determination on microsatellites and minisatellites in low Earth orbit (LEO) [*Purivigraipong et al.* 1999; *Purivigraipong and Unwin* 2001; *Cross and Ziebart* 2002]. As a result, there has been a trend in space missions to use cost-effective GPS receivers for space science and engineering experiments. The use of commercial components for spacecraft GPS receivers have also been used for other types of space missions. However, these have, so far, been restricted to low-grade single-frequency receivers and a limited range of correlator chipsets. The use of a fully commercial, geodetic grade, dual-frequency receiver with no heritage in space applications has only recently been considered for space missions [*Langley et al.* 2004; *Montenbruck et al.* 2006].

In this paper, we summarize our activities related to the design, development and validation of the GPS Attitude, Positioning, and Profiling (GAP) experiment using commercial, geodetic grade, dual-frequency GPS receivers, to be used for the Enhanced Polar Outflow Probe (e-POP) platform on the Canadian CASSIOPE (CAScade, Smallsat and IOnospheric Polar Explorer) satellite to be flown in LEO.

CASSIOPE

CASSIOPE is a Canadian satellite scheduled for launch in 2011. It is a hybrid mission designed for a wide range of tasks including: space-based communication, high capacity information delivery, and observations of the Earth's atmospheric environment. A dedicated suite of eight scientific instruments, called e-POP, will investigate space storms in the upper atmosphere and provide GPS-based navigation information. CASSIOPE has a hexagonal shape with dimensions of roughly 1.8 m × 1.25 m with a mass of approximately 500 kg. Figure 1 shows an artist's view of the CASSIOPE satellite. The nominal orbit characteristics are given in Table 1.

The spacecraft bus was designed and constructed by Bristol Aerospace Ltd., Winnipeg, Manitoba, Canada. Overall responsibility for the CASSIOPE spacecraft rests with MacDonald, Dettwiler and Associates, Richmond, British Columbia, Canada. Construction of the satellite has finished and ground testing has essentially been completed.

Cassiope is also the genus of a small family of arctic heather and so is an appropriate name for a satellite that will study the Earth's polar ionosphere.

The e-POP Mission

e-POP is a satellite mission tasked to investigate atmospheric and plasma flow processes in the polar ionosphere. Its primary science objective is to study the detailed quantitative relationship between the solar electromagnetic extreme ultraviolet energy input, the photo-ionization of the polar region of the atmosphere, and the acceleration and outflow of the polar wind plasma and accompanying neutrals to the magnetosphere. The data to be returned will help to unravel the micro-scale characteristics of plasma acceleration and outflow and its effect on radio propagation.

The e-POP satellite mission is funded by the Canadian Space Agency and the Natural Sciences and Engineering Research Council of Canada. Development work is being managed through the Department of Physics at the University of Calgary with a team of instrument principal investigators and researchers at ten Canadian universities as well as government agencies in Canada, the United States, and Japan. Several private sector companies were involved in constructing the mission hardware and spacecraft bus. The e-POP platform includes a suite of eight scientific instruments including plasma imagers, radio wave receivers, magnetometers, and cameras. Canadian research teams have provided six of these instruments, one comes from Japan and the other one from the United States. Among these instruments is the GAP experiment.

GAP Design

The GAP instrument was designed and constructed in collaboration with Bristol Aerospace. Figure 2 shows the functional block diagram and interface card of the GAP ground-test unit. The interface card used to interface the e-POP data handling unit with the receiver cards is based on Bristol Aerospace controller architecture with spaceflight heritage (the Bristol STARS controller) and an added FPGA (field programmable gate array). Some other components (such as patch antennas) also have spaceflight heritage.

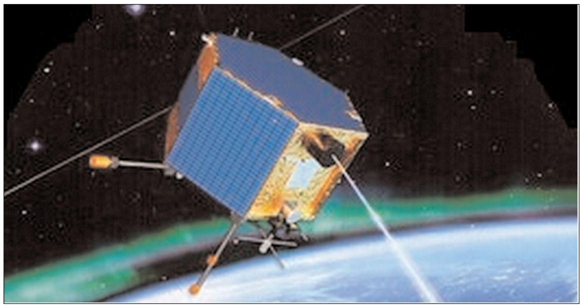

Figure 1: Artist's illustration of the CASSIOPE satellite in orbit.

Table 1: CASSIOPE nominal orbit parameters.

Semi-major axis	7280 km
Eccentricity	0.08
Apogee	1500 km
Perigee	300 km
Inclination	80^{o}

A total of five dual-frequency receivers on the satellite (numbered 0 through 4) will be used for high precision navigation, attitude determination, time synchronization, and radio occultation measurements. The four antennas to be used for clock functions, navigation and attitude determination, which together with their associated equipment is called GAP-A, are mounted on the zenith-facing side of the spacecraft and one antenna for occultation, which together with its associated equipment is called GAP-O, is mounted on the anti-ram (i.e., anti-velocity) side of the spacecraft (see Figure 3). GAP-A collects and processes simultaneous observations from three of the GPS receivers. Four receiving antennas including one spare for GAP-A are mounted in locations to minimize multipath reflections and maximize the baseline length between the antennas. GAP-O consists of a GPS receiver, with a switchable spare that will collect GPS occultation data at a 20 Hz data rate, sufficient for ionospheric tomography science.

The GAP instrument for e-POP is designed to be a multi-function instrument, providing both engineering and scientific data. Not only will it determine the position and velocity of the spacecraft in real time, it will also determine its attitude in real time and provide a clock signal to the rest of the spacecraft. Also, through post-processing downloaded pseudorange and carrier-phase data, high-fidelity spacecraft trajectory and attitude will be determined. In addition to these kinematic and clock parameters, GAP will also be used for measurements on setting or occulted GPS satellites to determine profiles of ionospheric electron density.

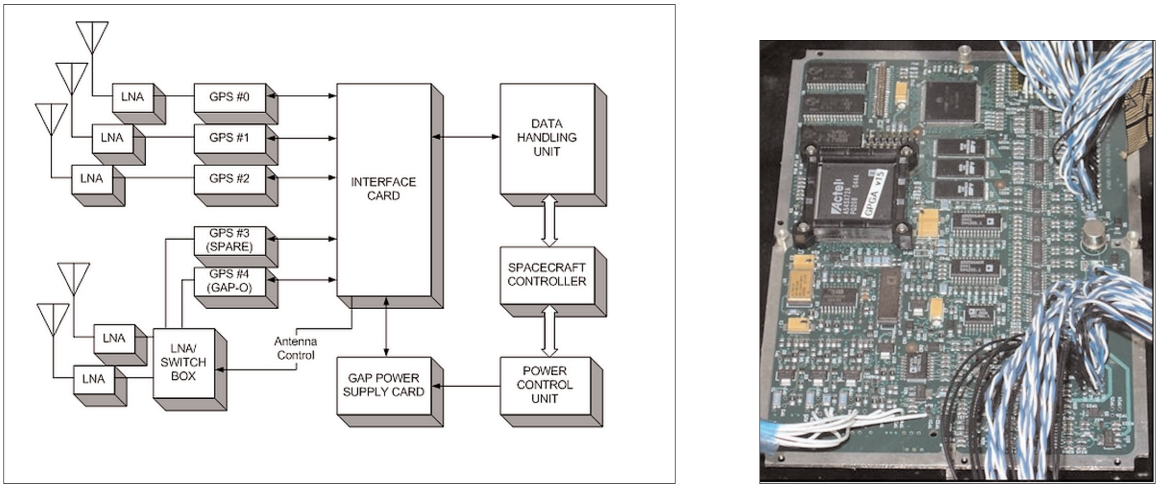

Figure 2: GAP instrument functional block diagram (left) and ground-test interface card (right).

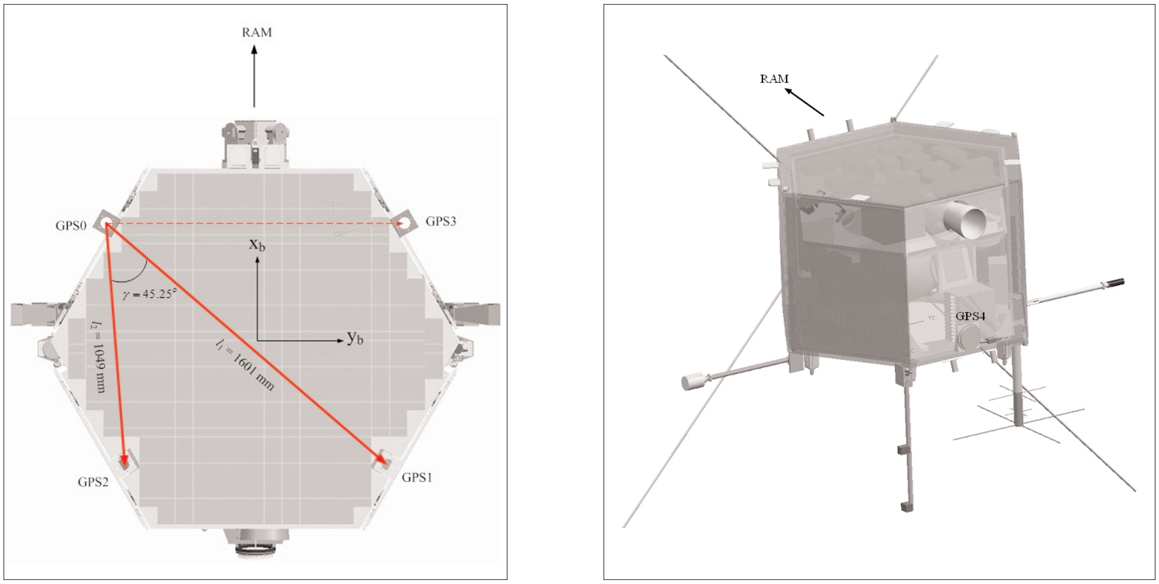

Figure 3: GAP-A antenna/baseline geometry (left) and GAP-O antenna (right).

Receiver Selection

The design of GAP is based on the use of commercial-off-the-shelf (COTS) GPS receiver technology. Early in the mission design, it was decided to base the GAP instrument on a COTS dual-frequency receiver rather than a space qualified one. The decision was based primarily on economics. The GPS receiver cards used are NovAtel OEM4-G2L dual-frequency units [*OEM4-G2L Data Sheet* 2003]. The OEM4-G2L is a small, high-performance, self-contained receiver with a rich heritage of novel receiver design. The NovAtel OEM series of receivers have been used in a wide variety of demanding applications including machine control, deformation monitoring, and airborne applications. Four of the receivers are fed by zenith-facing Sensor Systems S67-1575-14 microstrip patch antennas and the fifth by a modified NovAtel GPS-702 "pinwheel" antenna. Spectrum Microwave 26-dB low noise amplifiers are used between the antennas and the receivers.

The five GPS receiver cards are housed in a stacked aluminum enclosure together with an antenna switching card, which permits switching the occultation antenna between two of the receiver cards (see Figure 4). An additional enclosure houses a power supply card and an interface card. The interface card interfaces the e-POP data handling unit with the receiver cards.

As GAP was developed to use a fully commercial, geodetic grade, dual-frequency receiver with no heritage in space applications at the time development work began, an extensive series of tests has been carried out to help determine the viability of using a COTS GPS receiver for a satellite mission. These include GPS signal simulator tests to validate the signal acquisition and tracking performance, as well as environmental (radiation and thermal characteristics) tests to demonstrate the survivability of the receiver hardware under space conditions. Since our testing was performed, an OEM4-G2L has been flown on the University of Toronto's Canadian Advanced Nanospace Experiment 2 (CanX-2) nanosatellite with good performance reported [*Space Flight Laboratory* 2009].

Tracking Tests

As a first test, the capability of the receiver to properly acquire and track GPS signals under the increased signal dynamics of an orbiting spacecraft was verified. At an orbital speed of roughly 7.5 km/s, Doppler shifts of up to 40 kHz may be encountered that far exceed the design specification for a terrestrial or aircraft GPS receiver. Likewise, the receiver must be able to cope with much higher line-of-sight acceleration that amounts to roughly 1 G for a receiver in low Earth orbit but might even be much larger when tracking a boosted launch vehicle. The high-signal dynamics is of particular concern due the fact that geodetic receivers should employ tight tracking loop bandwidths in order to minimize the tracking noise. This might result in steady-state tracking errors and, in extreme cases, a loss-of-lock whenever the receiver is subject to increased acceleration or jerk.

To assess the tracking performance of a spaceborne GPS receiver, artificial GPS signals were generated using a Spirent STR4760 signal simulator, which closely match the signals received by a LEO spacecraft. The Spirent STR4760 signal simulator supplies 12 channels of L1 (C/A-code+Pseudo-Y) and L2 (Pseudo-Y) [*SimGEN User Manual* 2005]. The signal level of the GPS signal simulator was set to +14 dB (referred to the GPS-specified guaranteed signal strength of -130 dBm for L1C/A, -133 dBm

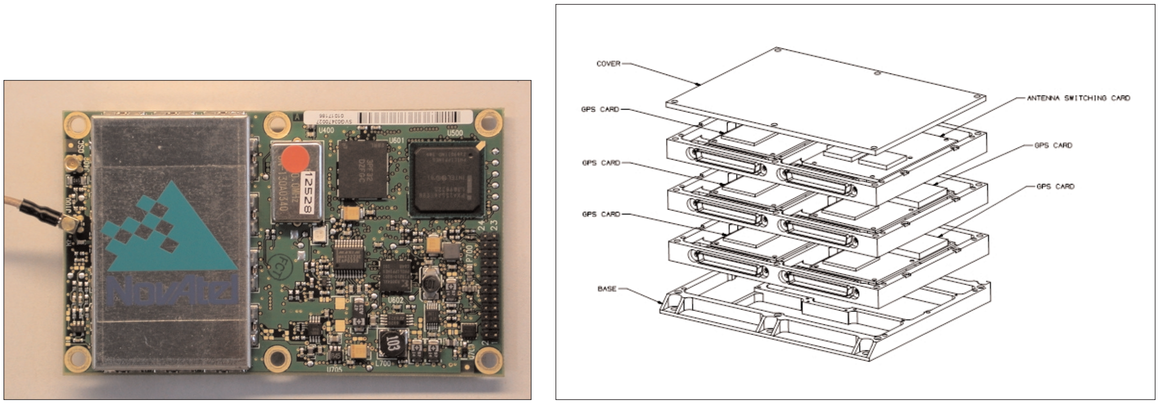

Figure 4: The NovAtel OEM4-G2L dual-frequency GPS receiver card (left) and a stacked aluminum enclosure in which the five GPS receiver cards and an antenna switching card are housed (right).

for L1P(Y) and -136 dBm for L2P(Y)). This results in C/A-code carrier-to-noise-density ratios (C/N_0) of about 38-48 dB-Hz and P2 code C/N_0 values of about 31-43 dB-Hz, roughly matching those obtained with standard ground-based antennas. The simulation was configured for a spacecraft orbiting the Earth in a near-polar orbit of 450 km altitude, 87° inclination, and an eccentricity of 0.005, rather than the expected CASSIOPE orbit. The epoch, which coincides with the ascending crossing of the equator, was chosen as 6 November 2001, 00:00 GPS Time, i.e., the beginning of day 2 of GPS week 1139. Consistent with this epoch, the GPS constellation was modeled based on the actual GPS almanac for week 1138. All relevant test data was collected in a simulation run of two hours.

The raw measurements and the navigation solution obtained by the receiver were compared against the simulated values. Overall, the tests demonstrate that high-precision dual-frequency tracking of LEO satellites using an OEM4-G2L receiver is feasible even with unmodified, standard firmware. Operation of the receiver at the higher than normal signal dynamics is made possible by a safe cold start capability and robust tracking loop settings. Even though the receiver achieved a 3D navigation status without any user intervention in all tests, additional commands for setting the approximate receiver velocity or for position-velocity aiding based on orbital elements would, however, be highly desirable to improve the time-to-first-fix (TTFF). The results of the tracking tests conducted at the ESA/ESTEC Radio Navigation Laboratory in Noordwijk, The Netherlands, were reported in [*Montenbruck* 2003] and presented at the 2nd ESA Workshop on Satellite Navigation User Equipment Technologies [*Langley et al.* 2004]. A comprehensive TTFF test of the OEM4-G2L receiver using the CASSIOPE orbit parameters was performed using the Spirent STR4760 signal simulator at the Geodetic Research Laboratory, UNB [*Serrano* 2006] (see Figure 5). Subsequent tests using the UNB simulator were performed to further characterize positioning accuracy over a 24-hour period. A plot of the receiver's estimated RMS position errors is shown in Figure 6.

Radiation Testing

In the series of signal simulator tests described above, the receiver appeared to be capable of supporting the increased signal dynamics of an orbiting satellite. However, it remained unclear whether the employed MINOS-4 correlator chip and the Intel PXA250 microprocessor (which is manufactured in a 0.18μ process [*Intel PXA250* 2002]), would tolerate the radiation environment typically encountered in LEO. To address this question, a total ionizing dose (TID) radiation test was performed at the Fraunhofer Institute for Technological Trend Analysis (FhG/INT) in Euskirchen, Germany, using a Cobalt-60 gamma ray source. Similar tests with the German Aerospace Center's (DLR's) COTS-based GPS Orion and Phoenix receivers have demonstrated a representative total dose tolerance of 15 krad but demonstrated an increased rate of cycle slips and a systematic frequency offset of the reference oscillator in proportion to the applied total dose [*Markgraf and Montenbruck* 2004a].

Due to the pronounced cost of the OEM4-G2L, it was decided to avoid a destructive test and limit the applied total dose to a value of 10 krad. This would allow subsequent use of the receiver in other tests. In accordance with the concept proposed in [*Markgraf and Montenbruck* 2004a], the total dose test of the OEM4-G2L GPS receiver was performed in a zero-baseline configuration, in which the test receiver and a reference receiver were jointly connected to a roof-top antenna. In this way, the impact

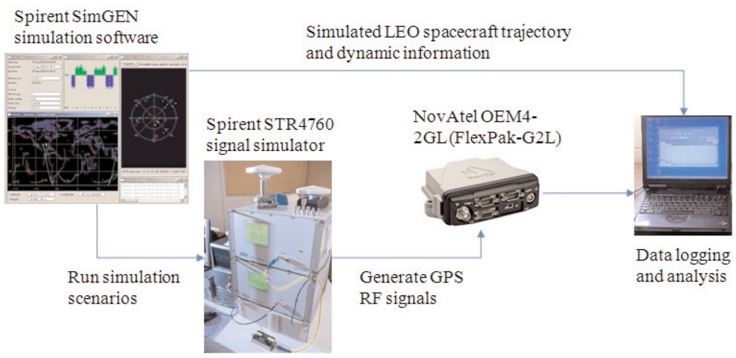

Figure 5: Spaceflight performance verification test setup.

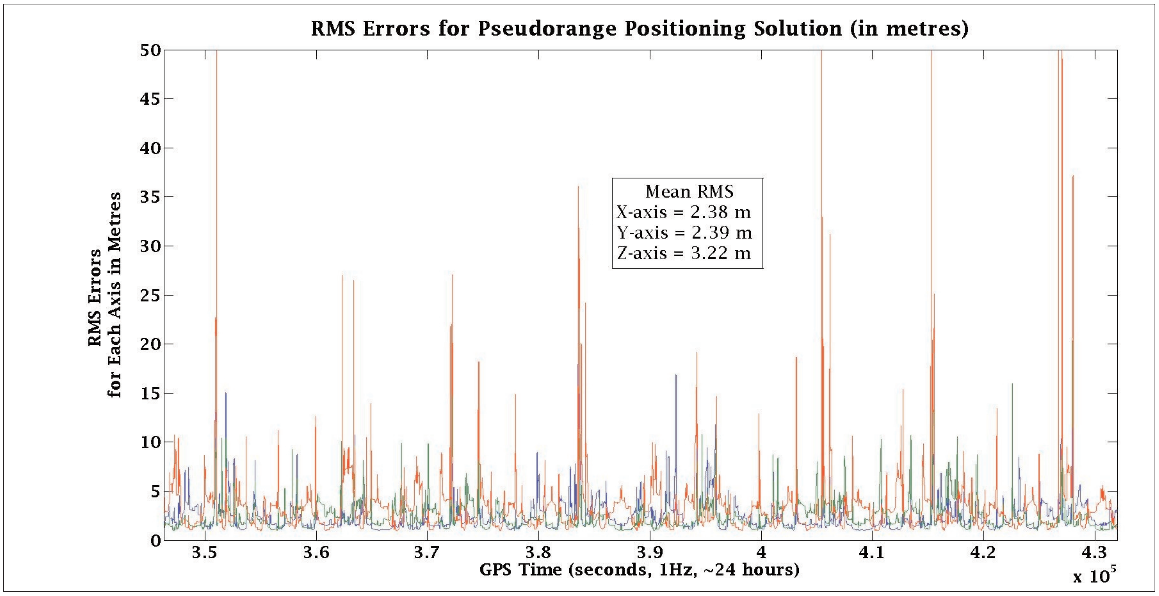

Figure 6: RMS position errors of the OEM4-G2L receiver on the CASSIOPE satellite, estimated by using the Spirent STR4760 signal simulator.

of ionizing radiation on the tracking performance (oscillator drift and navigation accuracy) was studied along with physical parameter changes (current increase) monitored in traditional radiation tests. The overall test setup is illustrated in Figure 7.

Two radiation tests have been conducted on different receivers. A preliminary report on the first radiation test was completed [*Markgraf and Montenbruck* 2004b] and, with an update on the second test, presented at the 2nd ESA Workshop on Satellite Navigation User Equipment Technologies [*Langley et al.* 2004]. During testing, the low-voltage monitor on the receiver board, a TCM811 integrated circuit, failed. This device is used to monitor the input power to the board and hold the microprocessor in a reset condition until the voltage reaches about 4.08 V. The TCM811 has been removed from all GAP receiver boards and reset logic has been provided on the GAP interface card. Overall, and despite the low-voltage monitor failure, the radiation tests demonstrated a surprisingly high robustness of the OEM4-G2L GPS receiver against ionizing radiation despite the use of advanced (and potentially sensitive) electronic components. However, it should be kept in mind that single event effects have not been assessed within the TID test.

Thermal Vacuum Test

The thermal characteristics of the OEM4-G2L receiver board operating in a vacuum were unknown. Therefore a thermal vacuum (TVAC) test was conducted to help define the thermal model of the GAP receivers that would be used for the overall thermal model of the GAP instrument. The results of the test would also be used to determine what thermal mitigation schemes, such as thermal staking, might be necessary.

An OEM4-G2L receiver board was subjected to a TVAC test using facilities at Bristol Aerospace. The receiver was tested from –35°C (-40°C unpowered) to +50°C in a small vacuum chamber under a vacuum of about 10^{-5} torr. The board was outfitted with about 13 thermistors that were monitored during the test. Before the test, the receiver's MINOS-4 ASIC was removed and resoldered with thermal compound added between the ASIC and the board since it was suspected that it might be a significant heat generator. Facilities did not exist to remove and replace the ball grid array PXA250 microprocessor so that it, too, could be thermally staked. During the test, the board was powered and connected to an external antenna while its voltage and current were monitored,. Raw pseudorange and carrier-phase data were collected at a 1Hz data rate. As confirmed, by post-processing the collected data, the receiver performed normally throughout the test.

Attitude Determination

A rapid, precise and reliable GPS-based attitude determination system for spacecraft should be able to compete with existing space-deployed attitude systems such as star sensors. The precision of spacecraft GPS attitude determination is mostly at

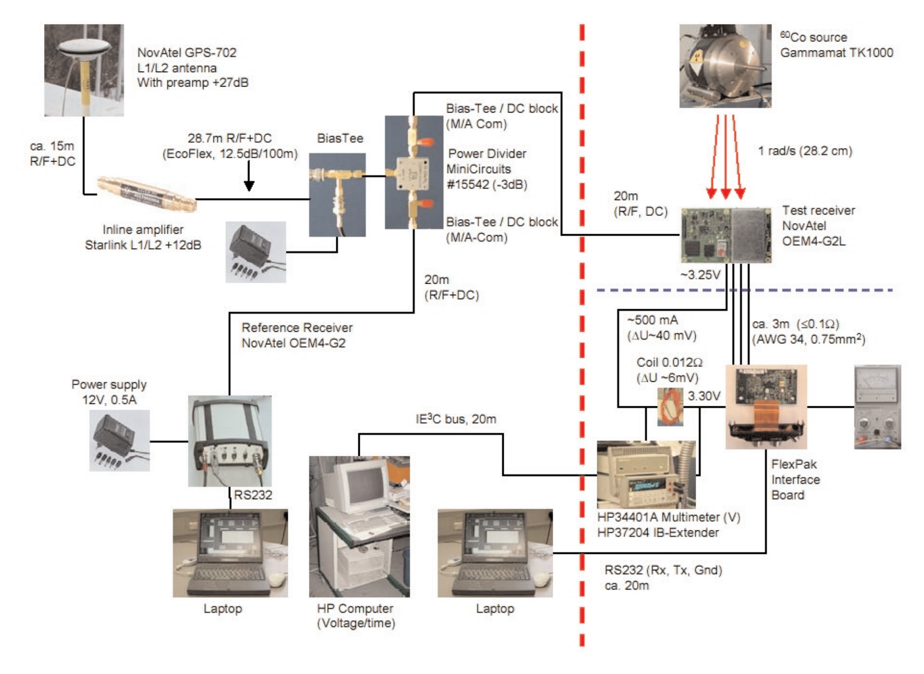

Figure 7: Test setup for OEM4-G2L total ionizing dose test [*Markgraf and Montenbruck* 2004b].

the 0.5-1.0-degree level [*Campana et al.* 1999; *Giulicchi et al.* 2000]. Unfortunately, due to the limited resources of microsatellites, most of the methods discussed in the papers would be difficult to run effectively in real time. In terms of attitude precision attainable from a GPS attitude determination system, multipath and the baseline length between the antennas will be the principal limiting factors.

The GAP-A experiment serves a number of purposes. As mentioned previously, it provides an accurate absolute time reference, spacecraft position, and velocity information to the data handling unit. Also, it performs real-time spacecraft 3-axis attitude determination. Table 2 outlines the performance requirement of GAP-A. More precise results will be achievable by post-processing the down-linked data; e.g., 0.5 degree accuracy for post-processed attitude.

The GAP-A real-time attitude determination system is based on the UNB RTK (real-time kinematic) engine which has been used for various scientific and engineering applications [*Kim and Langley* 2003]. It includes differential carrier-phase ambiguity resolution and position/velocity estimation. The attitude of the spacecraft is determined by estimating a rotation matrix $\boldsymbol{C}_b^n$ between the body frame (*b*-frame) and the navigation frame (*n*-frame) using two baseline vectors (i.e., GPS1-GPS0 and GPS2-GPS0) and one vector orthogonal to them (i.e., the cross product of the two baseline vectors) as illustrated in Figure 8.

The *n*-frame is defined as a local geodetic frame which has its origin coinciding with that of the sensor frame, with the x-axis pointing towards geodetic north, z-axis orthogonal to the reference ellipsoid pointing down, and y-axis completing a right-handed orthogonal frame (i.e., the north-east-down system). On the other hand, the *b*-frame is defined as an orthogonal axis set which is aligned with the roll, pitch and heading axes of the vehicle (i.e., forward-transversal–down systems. The rotation matrix $\boldsymbol{C}_b^n$ from *b*-frame to *n*-frame can be defined as:

$$\boldsymbol{C}_b^n = \begin{bmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\sin\theta \end{bmatrix}, \quad (1)$$

Table 2: GAP performance requirements.

Description	Accuracy (3σ)	Remark
Position	10 m	Real time
Velocity	0.25 m/s	
Time	1 μsec	
Attitude	5 deg	Real time
	0.5 deg	Post-processed

where ϕ, θ and ψ are the three Euler angles; i.e., roll, pitch and yaw, respectively. Then, the Euler angles can be determined from C_b^n by the following equations:

$$\begin{aligned} \phi &= \operatorname{atan2}(c_{32}, c_{33}) \\ \theta &= -\tan^{-1}\left(\frac{c_{31}}{\sqrt{1-c_{31}^2}}\right) \\ \psi &= \operatorname{atan2}(c_{21}, c_{11}) , \end{aligned} \tag{2}$$

where c_{ij} $(1 \le i, j \le 3)$ is the (i,j)-th element of C_b^n and atan2 is a four quadrant inverse tangent function. The coordinates of any one baseline in the *b*-frame and *n*-frame are related by:

$$x_{j,n} = C_b^n x_{j,b} \text{ or } x_{j,b} = (C_b^n)^{-1} x_{j,n} = C_n^b x_{j,n},\ j = 1,2. \tag{3}$$

Attitude Performance Test

To demonstrate the capabilities of the attitude software, three different hardware systems were used as GAP software test beds, including a laptop computer (IBM T30 Pentium 4-M 1.8 GHz), the Bristol SPP (System Platform Processor) controller, and the GAP interface card EM (Express Module). The Bristol SPP controller is a multipurpose controller board developed for sounding rocket missions. It features a Motorola DSP56309, 128 KB SRAM (Static Random Access Memory), Flash Memory, and two RS-232 serial ports. The GAP interface card EM is based on the Bristol STARS controller architecture with added FPGA.

As illustrated in Figure 9, a 3-axis motion table was built using stepper motors and stepper motor controllers (Pontech STP100). Also, an Ethernet-to-serial controller Sollae EZL-400s was integrated into the test bed. This add-on device enabled the motion table to be accessed and controlled from a remote location. The rotation angles measured by each stepper motor can be used as the reference for attitude solutions computed using the three GPS receivers. To accomplish this end, the stepper motors and GPS receivers are synchronized in time. Subsequently, the PC-version attitude software was integrated into the software for the Bristol STARS controller developed with Tasking's C compiler (version 3.5) [*Tasking* 2002]. To communicate with the Bristol SPP controller and the GAP interface card EM via the Bristol DSP56309 EVM (EValuation Module) [*Motorola* 1999], the Tasking CrossView debugger was used. The final version of the attitude software was designed to fit in the EM's external 256 KB SRAM for Y memory. An overview of the real-time attitude system was presented in [*Kim and Langley* 2007].

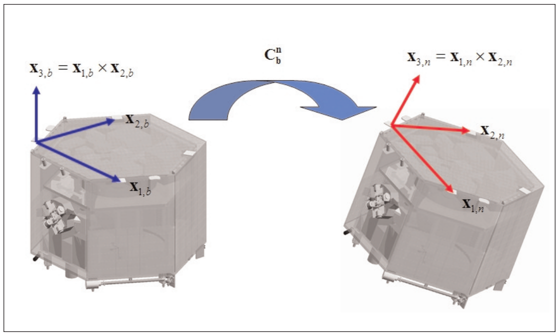

Figure 8: GPS RTK-based attitude determination.

Further testing of GAP was carried out at the University of Calgary's Institute for Space Research, which is leading the development of e-POP, and at Bristol Aerospace. During the rooftop test at the Institute for Space Research, live GPS data were recorded using the Data Handling Unit Card (DHUC) and post-processed to assess the performance of the attitude software on the GAP interface card EM (see Figure 10). Later, the data were further analyzed under real-time simulation scenarios using the Command and Data Handling unit (C&DH) of the spacecraft bus emulator at Bristol Aerospace (see Figure 10). Subsequently, additional testing took place during the Spacecraft Assembly, Integration and Test (S/C AI&T) program for the e-POP payload at the Canadian Space Agency's (CSA's) David Florida Laboratory (DFL) in Ottawa.

Roll-Out Test

In accordance with the CASSIOPE S/C AI&T program, GAP roll-out testing was performed at CSA DFL in Ottawa during 11-12 August 2009. Throughout the testing, the spacecraft was in full flight configuration except that the booms were stowed. Purge was connected to other scientific instruments (e.g., imaging rapid-scanning mass spectrometer, suprathermal electron imager and neutral mass and velocity spectrometer). S-band antenna hats were used to command the spacecraft and power was supplied through the AI&T connector on the spacecraft.

As available RF windows to the outdoors did not meet the viewing requirements for GAP testing, an RF transparent enclosure was built to allow the spacecraft to be rolled outside the facility to allow exposure to the GPS satellite signals. The spacecraft handling fixture with the spacecraft mounted on it is shown in Figure 11. The handling fixture could control the spacecraft in two orientations. These two

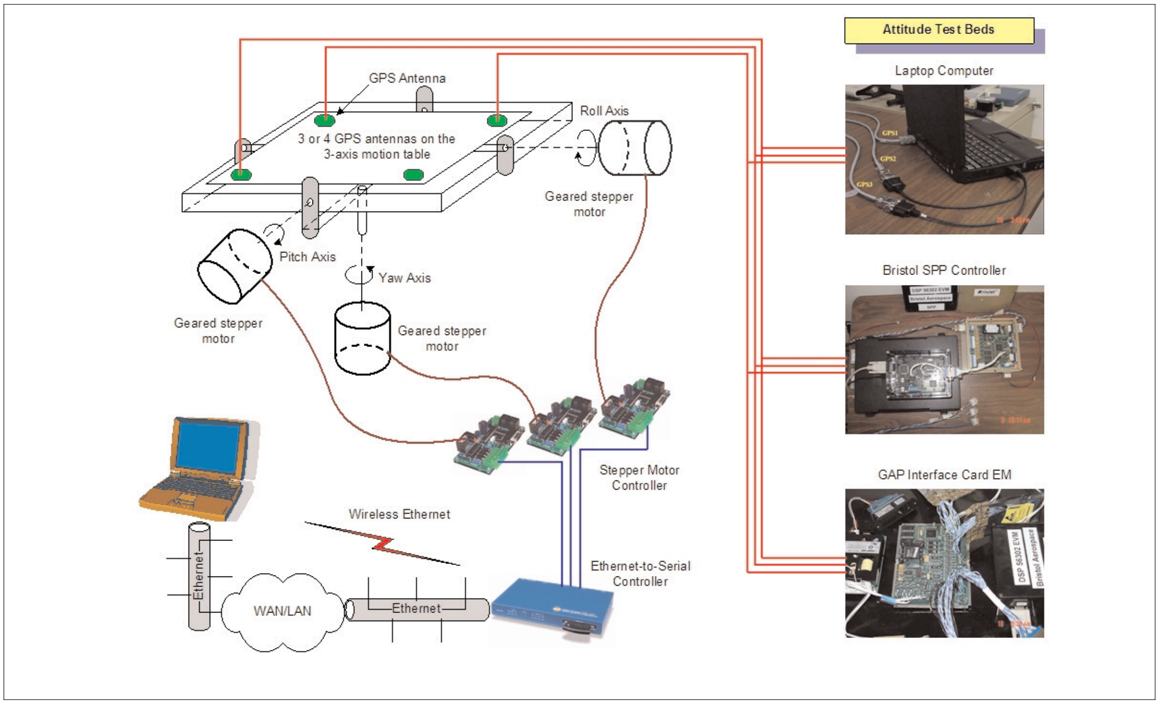

Figure 9: GAP software test bed configuration.

Figure 10: Rooftop test of the GAP EM card (left) and real-time simulation test using the C&DH emulator (right).

were achieved by merely rotating the handling fixture by 90° or 180° prior to each excursion “outside.”

The objective of GAP-O testing was to confirm that the GAP-O antenna is able to see GPS satellites setting over the horizon. To achieve this end, the spacecraft was tilted with the spacecraft handling fixture so that the GAP-O antenna was pointing toward the horizon. The duration that GAP-O has to see a particular satellite is typically less than 5 minutes prior to setting. GAP-A testing was performed to confirm that GAP-A is able to provide attitude solutions at a 1 Hz data rate in at least two static orientations once the GAP-A antennas see, simultaneously, a minimum of 6 GPS satellites with a reasonably good geometry and signal quality. Performance analysis results were reported in [*Kim* 2009].

Conclusions

As one of eight scientific instruments for the e-POP mission, GAP provides an accurate absolute time reference, as well as spacecraft position and velocity information to the data handling unit. Also, it performs spacecraft 3-axis attitude determination. Early in the mission design, it was decided to base the GAP instrument on a COTS dual-frequency

Figure 11: Spacecraft roll-out testing orientation for GAP-O (left) and GAP-A (right).

receiver rather than a fully space-qualified one. This decision raised the issue of whether a receiver intended for terrestrial applications could withstand the rigours of spaceflight. A series of tests were carried out to help determine the viability of using a COTS GPS receiver for a satellite mission.

The tests conducted provide good evidence for proper functioning of the OEM4-G2L receiver in a LEO satellite and opens up new prospects for future low-cost science missions. Once qualified, the use of a geodetic grade COTS receiver offers a factor of ten or more cost saving compared to presently available dual-frequency GPS receivers for space applications. Among others, an OEM4-G2L receiver has already been flown on the CanX-2 mission.

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