EXECUTIVE REPORT

TECHNICAL SUMMARY

The Dynamics Research Group, Directorate of Space Mechanics of the Canadian Space Agency has contracted the Geodetic Research Laboratory of the Department of Geodesy and Geomatics Engineering, University of New Brunswick (UNB) to investigate the use of the TurboStar GPS receiver type from the GPS/MET mission for orbit determination of a future CSA micro/small satellite. In order to accomplish this task, a graduate student, Sunil Bisnath, was sent to the GPS/MET mission offices at the University Corporation for Atmospheric Research (UCAR) at Boulder, Colorado to study the use of the TurboStar receiver onboard the GPS/MET mission. Also, extensive research was performed at UNB in terms of literature review and data analysis in order to fulfill the requirements of the contract.

The number of space missions carrying or planned to carry GPS receivers into orbit has sharply increased in the last few years. Approximately seventy such missions have been identified and recorded in this report, from 1982 to early into the next century. The space arena presents two problems to GPS receivers designed primarily for terrestrial applications: the space environment requires space qualifying of receiver hardware and the high dynamics of spacecraft and their location with respect to the GPS constellation requires more robust algorithms be incorporated in the receivers.

The GPS/MET experiment utilises an Allan Osborne Associates Inc. (AOA) TurboStar spaceborne GPS receiver for two purposes: one, to compute the precise orbit of the MicroLab-1 satellite (the vehicle the experiment resides on) in post-processing; and two, to collect carrier phase observations from GPS satellites being occulted by the earth's atmosphere. The latter measurement allows for the computation of excess phase from these measurements and through a number of physical equations, the determination of temperature or water vapour profiles of the lower atmosphere of the earth can be determined. These profiles can be collected globally and at resolutions that are possibly higher than conventional terrestrial-based techniques.

The TurboStar receiver has been developed from the TurboRogue terrestrial geodetic receiver. Both receivers are eight channel, dual frequency (L1 and L2), P-codeless, digital, geodetic-quality receivers. For the space environment and the GPS/MET mission, a number of hardware and software alterations were made to the TurboRogue receiver. Information on the details of these modifications is not readily available due to the proprietary nature of the receiver technology. However, general descriptions of the changes have been collected and presented. The hardware modifications included the addition of heat dissipation rods, foaming of components in place to add resistance to launch vibration, partial radiation testing of components, removal of the display and keyboard interface, a 17 watt power requirement, a suitable power supply interface to access power from the spacecraft, a new serial interface, a low grade temperature controlled crystal oscillator, and a space qualified ceramic patch antenna. Three main software modifications were applied: improved boot code and low level code; improved, more robust tracking code to deal with the high vehicle dynamics; and, a software component for determining occultation events.

The receiver has to-date operated beyond expectation. An identical receiver operated in space at the 60° F upper temperature bound of the receiver design. From a cold start, approximately 30 minutes are required before the first position determination is made by the receiver. A number of small software problems were resolved by uploading new code to the receiver.

The real-time, on-orbit, receiver navigation solution was compared with the precise orbit determination (POD). The latter was determined to be a few orders of magnitude more accurate than the navigation solution. The comparison consisted of six hours worth of data, sampled at five minute intervals. The results showed a 3 dimension root sum of squares (3d rss) mean error of 46.2 metres and a standard deviation of 28.5 metres. These statistics were deemed to represent the typical results from the receiver by the UCAR staff. As another external test of the navigation solution, the Kinematic and Rapid Static (KARS) software was used to compute point position determinations. These results differed from the navigation solution at the same order of magnitude as the navigation solution itself was determined to be in error.

The POD of the MicroLab-1 orbit was performed with the MicroCosm software at UCAR. MicroCosm is a derivative of GEODYN II and contains GPS data preprocessors that GEODYN II does not incorporate. The MicroCosm software components take into account the motion of the earth, luni-solar-planetary ephemerides, reference site information, measurement modelling and related derivatives, data processing, force model and variational equations, integration and interpolation, a statistical estimation scheme, and data input and output utilities.

To test the fundamental MicroCosm algorithms, twenty-four hours of data from two static receivers were processed with MicroCosm and DIPOP. DIfferential POsitioning Program (DIPOP) is a UNB-designed scientific GPS software package. The published International GPS Service for Geodynamics (IGS) vector between the two stations was used as a benchmark solution. For the baseline of approximately 3 400 kilometres, the MicroCosm solution differed by 86 mm and the DIPOP solution by 37 mm. DIPOP produced a more accurate horizontal position difference than MicroCosm (-0.0040 arc seconds (-12 mm) in latitude and -0.00038 arc seconds (-8 mm) in longitude compared to -0.00126 arc seconds (-39 mm) in latitude and -0.0337 arc seconds (-95 mm) in longitude with MicroCosm), while MicroCosm produced a better height difference estimate (3.37 centimetres) than DIPOP (-10.07 centimetres).

An extensive number of UNIX Borne shell scripts were written by GPS/MET personnel to allow for the efficient interface of required data with the MicroCosm modules. To determined the orbits of the GPS satellites the carrier phase double differenced solution is obtained, using data from IGS ground stations. The carrier phase double difference solution is then computed again using data from GPS satellites, MicroLab-1 and IGS ground stations to produce the MicroLab-1 POD.

A comparison of the IGS determined GPS satellite orbits and the MicroCosm determinations for twelve days of data indicate a difference of 20.5 centimetres 3d rss with a standard deviation of 12.2 centimetres 3d rss. As a test of the MicroLab-1 orbit determination (OD) consistency, overlaps of adjacent orbital arc solutions for the same twelve days were differenced. The results show a mean error of 81 centimetres 3d rss.

Real-time, on-orbit, OD consists of inputting the receiver navigation solution to a Kalman-type filter and satellite force model. Varying degrees of accuracy can be obtained, depending on the application. OD solution accuracies of better than 100 metres 3d rss are possible. With the future removal of SA, it is foreseen that this accuracy will increase by about an order of magnitude.

Other potential uses of GPS for future CSA missions are relative positioning, attitude determination, and clock synchronisation. A spaceborne GPS receiver can presently fully accomplish the timing goals, whereas on-going experimentation will establish whether the accuracy needs of those applications requiring relative positioning and attitude determination can be readily met.

The conclusions of the study presented in this report indicate that the TurboStar receiver is a good candidate for use on a future CSA mission and more importantly, that the benefits of GPS in space should be taken advantage of by the CSA. However, the proprietary nature of the TurboStar and many other spaceborne receivers may preclude the development by the CSA of an independent, in-house GPS receiver capability should such a receiver be adopted. Such a capability might be desirous if GPS it to be integrated into a variety of future CSA spacecraft for various uses in a cost-effective manner. Therefore it may be more advantageous for the CSA to develop a receiver development partnership with either the Amateur Satellite Corporation (AMSAT) Phase 3D or European Space Agency (ESA) Global Navigation Satellite System (GNSS) receiver development groups.

EXECUTIVE REPORT DESCRIPTION

INTRODUCTION TO SPACEBORNE GPS

GPS has become the prime technology in world-wide earth surface and near surface positioning and navigation. For the same reasons of cost, flexibility, efficiency, and accuracy, it is becoming an important part of space positioning and navigation. Many space agencies and other organisations are pursuing or beginning to pursue research in spaceborne GPS.

Figure 1 illustrates this growing use of GPS in space by showing the cumulative number of spaceborne GPS missions since 1982. Three points must be borne in mind when viewing this graph. Not all of the missions that have flown or will fly are represented in the graph. For example, numerous military missions have been flown for which no documentation is available. The scheduling of the planned and proposed missions is an estimate based on Table 2.1 of the Technical Report. The majority of flights are planned for the next few years. Many more missions will probably be planned for the late 1990s and early portion of the next decade shortly. This shortage of long term planning can be seen in the relatively flat terminal portion of the graph in Figure 1.

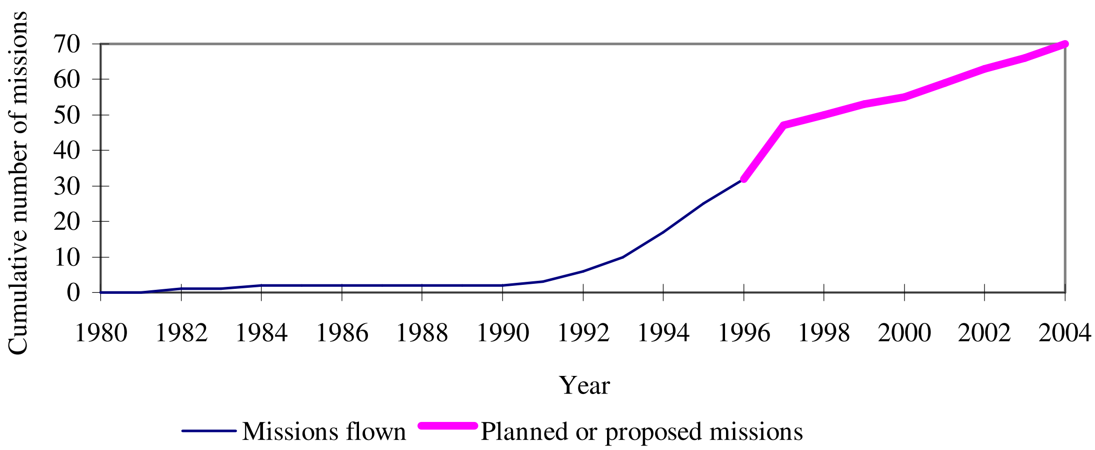

Figure 1. Cumulative spaceborne GPS missions.

RECEIVER TECHNOLOGY REQUIREMENTS

A number of obstacles must be overcome by GPS manufacturers and application groups in the transition from terrestrial GPS to spaceborne GPS. These include augmentation of both hardware and software components. Space-qualified hardware components are required. They must be vibration-tested for launch, and radiation- and heat-tested for the space environment. The power requirements for a receiver in the spacecraft environment will usually be more stringent than for terrestrial receivers. The same can be said for weight and volume constraints. Interaction with other spacecraft systems typically requires a different configuration than terrestrial, autonomously-operating receivers. Downloading and uploading links to earth receiving station(s) are required. LCD displays and tactile user interfaces are not required except in some cases of manned missions. The placement of the receiver antenna on the satellite is very important. Different antenna gains and gain patterns may be required. And, multiple antennas can be used to possibly avoid shading and for attitude determination.

In terms of receiver software, software designed for terrestrial receivers is not usually designed to handle the high rates of motion characteristic of satellites. For example, terrestrial Kalman filter algorithms may not be able to cope with the receiver dynamics. Receiver start-up is also a challenge, since a GPS satellite has to be approximately positioned with respect to the receiver and then “locked onto” to begin the position determination process. An ephemeris can be uploaded to the receiver, but a more robust procedure would have the receiver proceed from a cold start to acquire GPS satellite signals autonomously. Satellite tracking software must be upgraded to allow the receiver to track the higher Doppler shifted GPS signals and to schedule the much shorter signal reception windows for each GPS satellite.

The choice of processing software depends on the positional accuracy required, or the orbit determination accuracy and on the signals being observed: code and/or carrier phase data. The latter can provide more accurate results as well as velocity. Orbit determination can be performed in real-time, on-orbit, or via post-processing. Much research has been devoted to post-processed precise orbit determination (POD) and a substantial portion of the time spent at UCAR was used to study this processing strategy. For high precision orbits with GPS, good receiver technology goes hand-in-hand with good POD software.

GPS/MET EXPERIMENT

The GPS/MET experiment program offices are located at the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado. The experiment uses the GPS receiver to determine the precise orbit of the MicroLab-1 satellite by making observations to GPS satellites that are in a clear field of view. The LEO precise orbit is derived by downloading the receiver carrier phase and code measurements and processing them with the POD software. The experiment also uses this receiver to make observations to GPS satellites that are being occulted (signals delayed and raypaths bent) by the earth's atmosphere. The difference in the occulted signal phase measurements and the phase computed from the non-occulted signal LEO POD is used to determine excess carrier phase caused by the occulted GPS signals. From these excess phase profiles, refractivity profiles and subsequently, temperature and water vapour profiles can be derived from standard equations of atmospheric physics (refer to e.g. Melbourne *et al.* [1994] or Ware *et al.* [1996] for a more detailed description). All of these data are available to the scientific community for weather, climate and other scientific research through the Internet (see gpsmet [1996]).

TURBOSTAR RECEIVER

A modified, terrestrial Allen Osborne Associates, Inc. TurboRogue geodetic GPS receiver, called the TurboStar, is onboard MicroLab-1. The TurboRogue was redesigned from the bulky, less efficient Rogue receiver initially designed at the Jet Propulsion Laboratory (JPL). The TurboStar is an eight channel, dual frequency (L1 and L2), P-codeless, geodetic-quality GPS receiver designed for terrestrial use. The semicodeless cross-correlation technique is used.

The signal processing is provided by two identical application specific integrated circuit (ASIC) chips. These chips perform the digital code and carrier tracking. The particular ASIC chips used are high density, sub-micron, semi-custom very large scale integration (VLSI) processing chips, developed at JPL specifically for GPS processing. Each chip allows for the tracking of four satellites on four distinct channels. For each satellite tracked, the chips generate a receiver phase and receiver code, perform Doppler removal and code cross-correlation. The resulting cross-correlation values are sent to the microprocessor at a nominal 50 Hz rate [Meehan *et al.*, 1992]. Two RS-232-C serial ports are provided for communications. A low grade, cellular phone-type oscillator has been used. The rationale for this was that an operational system was required quickly and not a perfect system. Also, this aided in keeping costs within budget. Block diagrams are not available for this receiver design.

The software controlling the VLSI chips runs on an Advanced Micro Device (AMD) 29050 microprocessor. This is a powerful 32-bit Reduced Instruction Set Computer (RISC). The software operations are multi-tasked. Data storage is performed in real-time onto removable credit-card-size flash memory modules. Current flash card technology allows for 40 Mbytes of non-volatile storage on a card. Slow, stable memory was the goal. Flash memory is used to upload new images (where an image is the name given for a set of instructions), PROM memory is used, and SRAM is also used for high speed data transfer to copy images.

The receiver includes a fail-safe in the boot code, which is very simple, but robust. This typically makes the receiver very capable of finding its position, even from a cold start, given sufficient time. There is also a fail-safe to recycle power if the receiver locks-up. There is also a software component for scheduling occultation events. When the software computes the times that the receiver antenna will receive occulting GPS signals, it changes the receiver data sampling rate from 0.1 to 50 Hz. The software needs to have knowledge of the location of the occulting and non-occulting GPS satellite(s), LEO satellite, and high rate GPS data collecting ground stations.

This TurboStar on GPS/MET (one of three original such specifically modified receivers in existence) weighs 2.3 kg, has approximate dimensions of 22.9 × 22.9 × 5.1 cubic centimetres. The receiver requires 17 watts of power. For the latest version of the flight receiver, P/N 8490455, the power requirement has been halved. It is predicted that power consumption will again be halved in the next one to three years. The receiver has been put through all space qualifying tests, except for full radiation testing [Melbourne *et al.*, 1994 and Exner, 1996b]. It is expected that a GPS receiver in low-earth orbit will experience under 10 krad of total dosage radiation (TDR) during a mission spanning several years and it has been stated that “most electronic components can tolerate such radiation levels” [Clark *et al.*, 1994]. The components were foamed in place to add resistance to launch vibration. Heat dissipation rods were incorporated into the receiver / satellite bus assembly. Aside from radiation and launch vibration, the spacecraft environment is relatively benign; the thermal environment in the satellite consists of temperatures in the approximate range of 5 to 15°C, on-orbit vibrations are small in magnitude, and the vacuum environment poses no serious problems [Clark *et al.*, 1994].

Qualitative performance of the receiver to-date

Even though the receiver is not fully space-qualified, it has performed quite well. The mission's length of six months has been extended for at least another six months, in part due to the reliability of the receiver. The time to first fix (TTFF) from a cold start has, in practice, taken approximately 30 minutes. A variety of problems resulted in 7 or 8 uploads of new “image cards” to-date. These cards contain new code. And there has been one hard latch-up event in 12 months of operation, so-far [Exner, 1996]. In a recent use of one of the other two prototypes on the second Wake Shield Facility mission, the receiver’s upper temperature bound was reached, approximately 60° F. The receiver suffered no adverse affects [Schutz, 1996].

GPS/MET receiver navigation solution analysis

To determine the accuracy of the TurboStar receiver aside from quoting these values from the receiver specifications documentation, a test of the GPS/MET receiver navigation solution was carried-out by UNB and UCAR personnel. The navigation solution is determined by the receiver, and therefore consists of real-time, on-orbit position determinations. This solution uses primarily dual frequency carrier phase observations, as well as C/A and P-code observations. In the presence of AS the cross-correlation procedure is used. A Kalman filter is not present in the receiver software, but a least squares filter is used [Snow, 1996]. A sample time series of solutions has been differenced from the corresponding LEO POD solutions. The latter are used as “truth” since their accuracy is approximately four orders of magnitude better than that of the navigation solution. Table 1 gives a summary of the accuracy of the receiver’s navigation solution, the most important aspect of which is that the average 3d rss displacement error of the solution is 46.2 metres. These results were deemed to be typical of the GPS/MET TurboStar receiver [Schreiner, 1996b].

Statistic	Component error in metres			
	Radial	Along-track	Across-track	3d rss
Min.	0.5	0.4	0.3	11.5
Max.	128.4	101.2	75.4	161.8
Mean	27.7	25.3	16.2	46.2
Std. dev.	24.6	21.5	14.8	28.5

Table 1. Typical errors in receiver navigation solution.

Comparison of navigation solution and KARS results

As a further test of the GPS/MET TurboStar navigation solution, the UNB-modified KARS (Kinematic And Rapid Static) software was utilised to produce solutions with the KARS software and to compare these solutions with the receiver's navigation solution. The MicroLab-1 code data were used to compute position determinations with KARS by means of a straightforward least squares solution using the single difference method. These determinations were compared with the navigation solution from the receiver. Figure 2 illustrates the results with two reference stations. The differences in the components range from approximately -150 metres to +150 metres. There appears to be no large differences between the solutions computed using the different stations.

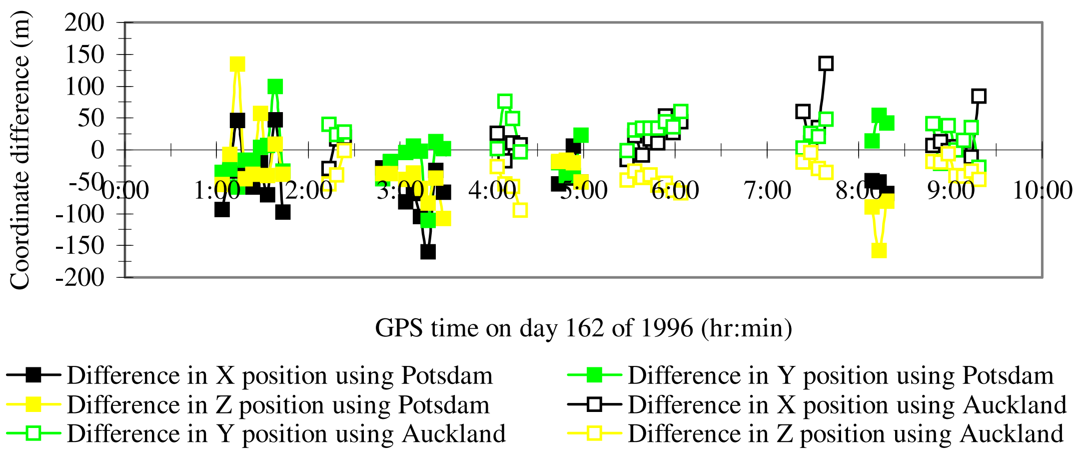

Figure 2. Differences between navigation solution and KARS.

Collaborations with TurboStar developers

Present literature gives the impression that the TurboStar is a fully developed, production spaceborne receiver. A more accurate assessment would be that the receiver is in a continuous development stage. This receiver is typically tailored for specific applications, in specific spacecraft. Two missions are planned for this year involving the use of the TurboStar receiver: one, Danish and one, South African. Close links between AOA, JPL and the groups developing the satellites are facilitating the production of receivers for each mission. From the viewpoint of the GPS/MET mission, AOA and JPL consist of two groups of personnel with a substantial receiver knowledge base and the abilities to aid a mission requiring a GPS sensor. Therefore, it's a matter of retaining their services for the development of a GPS sub-system for a particular application, rather than simply purchasing a piece of technology "off the shelf".

GPS/MET PRECISE ORBIT DETERMINATION (POD) SOFTWARE

The precise orbit determination (POD) software used by the GPS/MET mission for processing of receiver data is the MicroCosm® package. This software package is a derivative and full implementation of the GEODYN II Version 8609 precision orbit and geodetic parameter determination software system developed for NASA's Goddard Space Flight Center. The major differences between the two pieces of software are that MicroCosm is specially capable of determining precise GPS satellite orbits, whereas GEODYN II is a generic POD software; and moreover, MicroCosm incorporates more sophisticated preprocessing software which allows for the input of GPS data. The MicroCosm software components take into account the motion of the earth, luni-solar-planetary ephemerides, reference site information, measurement modelling and related derivatives, data processing, force model and variational equations, integration and interpolation, a statistical estimation scheme, and data input and output utilities [Hughes Corp., 1993].

The problem of precise orbit determination is divided into two parts in MicroCosm®: the orbit prediction problem solved by means of Cowell's method of direct numerical integration of the satellite equations of motion in rectangular coordinates and the parameter estimation problem solved, based on the solution of the former, by a partitioned Bayesian least squares statistical estimation procedure, operating in a batch mode. To determined the orbits of the GPS satellites the carrier phase double differenced solution is obtained, using data from International GPS Service for Geodynamics (IGS) ground stations. The carrier phase double difference solution is then computed again using data from GPS satellites, MicroLab-1 and IGS ground stations to produce the MicroLab-1 POD. Along with MicroCosm®, an extensive number of UNIX Borne shell scripts have been written by GPS/MET personnel to allow for the efficient interface of required data with the MicroCosm® modules.

Results of MicroCosm software comparison with DIPOP

The testing of the MicroCosm software POD capability also requires the testing of the fundamental MicroCosm algorithms. The strategy used to test these algorithms is the baseline test. MicroCosm has been used to compute the components and length of a baseline and this solution has been compared with the solution from another high-quality, scientific software, in this case the UNB-developed DIPOP GPS software. The result is an indication of the strength of a MicroCosm solution relative to other scientific GPS processing software.

The components and length of a known baseline between two stations of the IGS network were determined using MicroCosm with the coordinates of one of the stations (Goldstone, California) held fixed to the IGS published values and the IGS coordinates of the other station (Algonquin, Ontario) used as the unweighted *a priori* values in the processing. Data were collected for the entire day 284 of 1995.

The results of the test are given in Table 2. The first two sets of rows present the resulting baseline length components, and differences of the computed baseline components from the IGS-published components, for the IGS MicroCosm and DIPOP data. The next two sets of rows give the results in more appreciable ellipsoidal coordinates. The final rows present the baseline distances computed from the produced coordinates, the difference between these distances and the IGS published distance and the resulting accuracies. Looking at the values of the MicroCosm and DIPOP ellipsoidal component differences from the IGS published components, it is apparent that for this baseline DIPOP produces a better horizontal solution than MicroCosm and that MicroCosm produces a more superior vertical solution. Overall, MicroCosm produces a baseline vector with a length error that is approximately 25.3 parts per billion (ppb) and for DIPOP 10.9 parts per billion. This indicates that, for the length, the DIPOP solution is 2.3 times better than the solution given by MicroCosm. As stated above, this is the result for one baseline only. Even so, a verification of the fundamental MicroCosm algorithms has been given.

Quantity	IGS	MicroCosm	DIPOP
Δ X (m)	3 271 743.736	3 271 743.654	3 271 743.715
Δ Y (m)	295 314.068	295 313.998	295 314.131
Δ Z (m)	885 001.487	885 001.484	885 001.401
Δ X - IGS value (m)	--	-0.082	0.021
Δ Y - IGS value (m)	--	-0.070	-0.063
Δ Z - IGS value (m)	--	-0.003	0.086
$\Delta\ \phi$	10° 31' 50".31843	10°31'50".31717	10° 31' 50".31803
$\Delta\ \lambda$	38° 49' 04".37519	38°49'04".37078	38° 49' 04".37481
Δ h (m)	-785.6410	-785.6073	-785.7487
$\Delta\ \phi$ - IGS value	--	-0".00126 (-0.0387 m)	-0".00040 (-0.0123 m)
$\Delta\ \lambda$ - IGS value	--	-0".00441 (-0.0950 m)	-0".00038 (-0.0082 m)
Δ h - IGS value (m)	--	0.0337	-0.1007
Δ Length (m)	3 402 167.707	3 402 167.621	3 402 167.670
Length -IGS value (m)	--	0.086	0.037
Baseline length accuracy	--	25.3 ppb	10.9 ppb

Table 2. Results of the baseline comparison between the MicroCosm and DIPOP software, compared to IGS values.

Results of GPS and MicroLab-1 POD analysis

A number of tests have been performed by UNB in an attempt to determine the accuracy of the GPS and MicroLab-1 satellite orbit solutions produced with the GPS/MET program suite and will be discussed in this section. Also, some tests performed by GPS/MET personnel are presented here.

To determine how well the GPS satellite orbits are determined, IGS ephemerides can be used as the “truth” and MicroCosm solutions can be differenced from them. These differences for all satellites for an observing session can be computed. Figure 3 illustrates these values for 12 days of solutions, with 9 075 weighted observations per day, from day 284 to 295 of 1995. The component values are absolute displacements and are given in ECEF coordinates. The error in each component is approximately equal and the 3d rss total error displacement is 20.5 cm for these days. The component and 3d rss errors are reasonably constant from day to day, except for days 287 and 288. UCAR personnel were unaware of these relatively large errors, and could not comment on the reason(s) for the magnitude of these errors once the data were presented. If these data were removed, the overall 3d rss mean would be reduced to 12.5 cm.

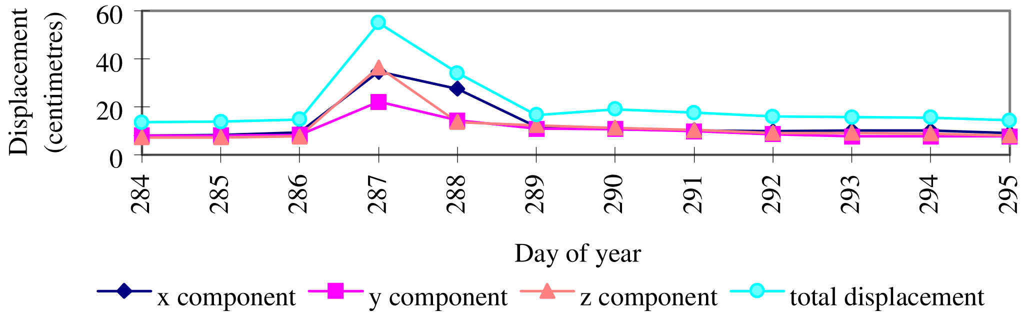

Figure 3. IGS - UCAR GPS satellite position error components.

A measure of the accuracy of the MicroLab-1 orbit determinations is the closeness of the overlap of adjacent orbital arc solutions. Three hour overlaps are observed and compared in the GPS/MET processing. This procedure incorporates data from both the start of the new arc and the end of the previous arc. Table 3 contains overlap statistics for, on average, 25 000 double difference observations per day, for day 284 to 295, 1995. On average, the MicroLab-1 orbit for these days is determined to approximately 80 centimetres with respect to its previous orbit. It can be expected that the higher bound of this error be approximately 1.5 metres [Schreiner, 1996a].

Statistic	Error component in metres			
	Radial	Cross-track	Along-track	3d rss
Min.	0.05	0.17	0.06	0.19
Max.	0.43	0.63	1.20	1.40
Mean	0.29	0.40	0.61	0.81

Table 3. MicroLab-1 arc overlap statistics for days 284 to 295 (from Schreiner [1996a]).

REAL-TIME, ON-ORBIT, ORBIT DETERMINATION

On-orbit, OD is invariably performed in real-time or near real-time in the GPS receiver. And conversely, to perform real-time orbit determination with GPS, it is most efficient to incorporate the OD software into the receiver. Software code in the receiver or in another system on-board the satellite must convert the receiver-derived state vector to an orbit determination. The simplest case is an osculating ellipse for a single epoch. A more comprehensive orbit determination would involve the use of a satellite force model with the state vectors and a Kalman filter.

Real-time, on-orbit, OD results are found sparingly in the literature. Therefore, navigation solutions, post-processed and simulated results are also included in this discussion. As such, Table 4 describes the potential real-time OD accuracy attainable with GPS receivers on-board various satellites or the results for data used to determine the orbits. Continued developments in receiver technology will improve limiting factors such as receiver signal to noise ratios and code tracking capabilities. And the announced removal of Selective Availability (SA) in the next four to ten years will definitely allow for better absolute positioning.

Satellite	Solution accuracy	Comments
MicroLab-1	46 m	navigation solution
WSF-02	62.6 m	post-processed l.s. fit of an orbit to nav. sol'n.
DARPASAT	350 m	navigation solution compared to range vectors

SFU	200 m ± < 200 m	real-time, on-orbit OD
PoSAT-1	1.5 km	receiver turned on for only one orbit per day
EUVE	10 to 15 m	post-processed in a simulated real-time scenario

Table 4. Orbit determination accuracies attainable with GPS receivers on board various satellites.

OTHER RECEIVER-DERIVED MEASUREMENTS AND THE USEFULNESS OF THESE QUANTITIES FOR POTENTIAL CSA MISSIONS

Other potential uses of GPS for future CSA missions are relative positioning, attitude determination, and clock synchronisation. The main application of relative spaceborne GPS positioning is, as noted in the previous section, for real-time spacecraft rendezvous and docking. Automated GPS-based systems are seen as a promising technique to be used for this evolving and expanding application. In attitude determination an array of GPS antennas (e.g. four) are placed on the rigid structure of a spacecraft an provide carrier phase and code data to the spaceborne receiver. A spacecraft bus architecture can be used to supply GPS-derived time to synchronise all spacecraft subsystem clocks. A spaceborne GPS receiver can presently fully accomplish the timing goals, whereas on-going experimentation will establish whether the accuracy needs of those applications requiring relative positioning and attitude determination can be readily met.

CONCLUSIONS

At least two dozen different spaceborne-capable GPS receivers have been flown, are presently in operation, or are in development. By 2005, approximately seventy space missions will have included at least one GPS receiver for positioning, and/or attitude determination, and/or timing tasks. The GPS/MET Experiment is a success and illustrates how GPS data can be used for purposes other than the three primary applications of positioning, attitude determination and timing.

Due to the proprietary nature of the TurboStar hardware and software, completion of all of the contract tasks requiring detailed receiver information was not possible. The TurboStar is a quasi-space-qualified receiver, modified from a terrestrial TurboRogue receiver. The first TurboStar in operation in an orbiting spacecraft has performed nearly flawlessly, producing navigation solutions that are in error by approximately 46 metres 3d rss, compared to the POD solution. The KARS position solutions are of the same order of accuracy compared to the receiver navigation solutions (87 metres 3d rss), as the navigation solutions are to the results of the POD analysis (46 metres 3d rss). Collaboration with the TurboStar developers would not necessarily result in the transfer of technology and knowledge, but rather only the purchasing of equipment.

To test the fundamental MicroCosm algorithms, twenty-four hours of data from two static receivers were processed with MicroCosm and DIPOP. The published International GPS Service for Geodynamics vector between the two stations was used as a benchmark solution. For the baseline of approximately 3 400 kilometres, the MicroCosm solution differed by 86 mm and the DIPOP solution by 37 mm. The comprehensive GPS/MET MicroCosm/UNIX scripts POD software suite can determine GPS satellite orbits to within approximately 20 cm 3d rss of IGS GPS satellite orbits and can determine MicroLab-1 orbits to approximately 80 cm 3d rss.

In terms of absolute position, improvements are still being made in on-orbit, orbit determination and precise orbit determination. Aside from orbit determination, spaceborne GPS receivers can be used for attitude determination, relative positioning, and time synchronisation. All of these applications can realistically aid future CSA space missions, but research is needed to adapt various techniques to CSA-specific requirements.

RECOMMENDED SUBSEQUENT RESEARCH

It is the recommendation of this report that the CSA pursue the use of GPS on future CSA satellites by aligning with a group developing a spaceborne receiver. Two receiver development projects presently exist where partnerships can possibly be pursued: the AMSAT receiver development and the ESA GNSS receiver development. We will briefly describe both projects and the possibilities of CSA alignment with these projects.

Given an agreement with a receiver group, UNB's relationships with personnel from both candidate groups and UNB's GPS knowledge, it is proposed that the University, under authorisation and funding from the CSA, aid in the development of the receiver to quickly expand CSA's GPS knowledge-base and in doing so, to benefit CSA's future missions. The contributions would most likely be in the form of algorithm development, analyses and simulations.