ULTRA-PRECISE POSITIONING FOR SPORT APPLICATIONS

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BIOGRAPHY

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ABSTRACT

Starting in 2006, the Schulich School of Engineering, through its PLAN Group has developed and tested, in collaboration with Own The Podium/À Nous le Podium 2010 and Alpine Canada Alpin, an ultra-precise, ultra-light and autonomous sensor, namely STEALTH™, the *Sensor for the Training of Elite Athletes*, to support the Canadian Alpine Ski Team during training. The GPS-GLONASS based sensor has proven to operate very well under a variety of conditions and is now used routinely by the ski team. This paper will describe the requirements and trials that resulted in the current system. A description of the sensor components, assembly, mode of operation, technical specifications and performance is presented. The positioning and motion components displayed to athletes and coaches for performance evaluation are described using data collected on ski slopes in the Canadian Rockies and elsewhere.

INTRODUCTION

The use of technological advances to measure and enhance sport performance is increasingly common. Competitive athletes win or lose races by fractions of a second or a single decimetre. Numerous sport activities involve speed, distance and timing. A prime example is skiing in which case precise knowledge of the above parameters, plus rate of descent, lateral accelerations, and gate crossing times are important during training to assess skier strengths and weaknesses and remedy the latter.

GNSS has the potential to provide the above information to athletes and coaches. However equipment size, weight, power autonomy, signal tracking, accuracy, and availability performance pose major obstacles for skiing and most other sports. In this paper, the development and use of a GNSS-based system aimed at skiers is described. The ***Sensor for the Training of Elite Athletes*** (**STEALTH™**), whose development started in 2006, overcomes the above limitations and is now used operationally by the Canadian Alpine ski team during training. The project was launched by the PLAN Group of the Schulich School of Engineering, University of Calgary, in collaboration with ***Own The Podium 2010/À Nous le Podium 2010*** (OTP) and Alpine Canada Alpin (ACA). OTP is a national sport technical initiative designed to help Canada's winter athletes win the most number of medals at the 2010 Olympic Winter Games in Vancouver, and to place in the top three nations (gold medal count) at the 2010 Paralympic Winter Games. The project was deemed Top Secret until September 2009. ACA is the governing body for alpine ski racing in Canada. ACA manages the high performance programs for the athletes of the Canadian Alpine Ski Team and the Canadian Para-Alpine Ski Team who represent Canada throughout the world. NovAtel Inc provided the OEM V1G cards used in the system to ACA.

The initial technical requirements set for the wearable component of the device by ACA in 2006 were as follows:

- Detection of differences in line selection for the downhill, super-giant slalom, and giant slalom disciplines, and ski testing, at the 10 cm accuracy level
- Operation in ambient conditions to - 20˚C
- Negligible influence on skiers up to 120 km h^{-1}
- Post-mission accuracy better than 10 cm (position) and 1 ms (timing), 20 times per second
- Accuracy of 5 cm for gate survey
- Wearable device that would not exceed 500 g and would have autonomy of at least 4 hours
- Suitable data presentation to skiers and coaches

GNSS is in principle capable of meeting the above requirements using carrier phase measurements in fixed integer carrier phase ambiguity mode but many challenges arise. The first one is the weight, power autonomy, size and functionality of the wearable device, which should also be unobtrusive and safe at speeds up to 120 km h^{-1}. A second one is ease of use of the equipment, and data reduction, presentation and interpretation. Finally the high mask angles of the topography surrounding ski slopes, which can easily reach 30˚ and occasionally 40˚, can prevent successful fixed integer carrier phase ambiguity resolution. These challenges had to be met simultaneously and early on in the development of the system hardware and software.

INITIAL DEVELOPMENT AND TESTING

An initial feasibility study using GPS was carried out in Fall 2006 in both pedestrian and ski mode to confirm that a differential real time kinematic (RTK) approach was feasible under the masking conditions encountered on average ski courses, namely up to 25˚ to 30˚. A single frequency receiver was selected for this purpose, namely a NovAtel OEM-V1 unit. Low cost inertial sensors were also added to the hardware, in case needed later. A key component in such an early trial was to have an independent reference system sufficiently accurate to verify the accuracy of the system under test. A HG-1700 based NovAtel SPAN™ GPS-INS system was used for this purpose, in order to maintain continuity and accuracy during the tests. The latter substantially increased the weight and power consumption of the equipment, as shown in Figure 1, but this was still acceptable for tests of short duration. Performance of the approach was deemed sufficiently good to move to a prototype approaching the desired specifications.

Development of a belt wearable, 470 g prototype proceeded quickly thereafter to further test the concept with ACA skiers. A GPS ANTCOM antenna of 170 g was used and mounted on ski helmets. Removable storage and sufficient power autonomy for four hours were added. Functions for gate survey and skiing modes were added for ease of use. The software used to process the differential carrier phase data in fixed integer ambiguity mode was initially FLYKIN+ and then PLANSoft, the latter being capable of processing GPS and GLONASS data as described later in the paper. Software to present the GPS results in a visual format adequate for interpretation by skiers and coaches was initiated. This software was named AlpineGNSS Graphics. Following early and successful testing by the authors at Lake Louise (www.skilouise.com) in February 2007, testing with members of the Alpine ski team took place at Panorama (www.panoramaresort.com) in April 2007. Installation of the prototype on a skier with a flexible belt is shown in Figure 1. The test was equally successful from both a position and timing aspect. The belt-fitted part of the equipment was deemed to be slightly too heavy. The decision to proceed with the design of an operational system with a yet lighter belt unit and the construction of several units for operational use by ACA by Fall 2007 was made. This was successfully completed in Summer 2007, as described in the next section. Many of the OEMV1 cards were the GPS/GLONASS ready V1G model.

Figure 1: Proof of concept testing (Fall06) and field testing (Apr07)

OPERATIONAL SYSTEM

As with any engineering design problem, the field portable hardware components of the system were created to optimize certain critical parameters while making reasoned trade-offs to speed development time and ease maintenance effort while remaining within a constrained budget. The first and foremost consideration during the early design stages was that the hardware components must interfere to as minimal a degree as possible with the natural motion and comfort of any athlete using the equipment, while still providing high quality data. To this end, after selecting the core GNSS technology that would be used within the system as the NovAtel OEM-V1G GPS+GLONASS receiver, other critical parameters had to be carefully constrained to useful ranges. The parameters of weight and size were selected as paramount targets for minimization, while secondary goals were set to control physical robustness, cold weather tolerance, runtime endurance, ease of data retrieval, and finally simplicity of user interaction.

The design features, which allow the satisfaction of these diverse goals, are presented herein in a top-down fashion to allow for an easier understanding of how component pieces of the integrated system interrelate. The first major design decision was that the use of any sort of computer system running a traditional Operating System (OS) would be entirely undesirable from the point of view of size and power consumption (field endurance reduction), as the system could be tailored much more tightly to the end use by using entirely custom machine code running on an embedded micro-processor. While still capable of tens of millions of calculations per second, this type of processor has power needs on the order of a few thousandths of that required by the already selected GNSS receiver module (Microship 2009, NovAtel 2009).

The next critical design decision involved the extension of the runtime of the device in cold weather while maintaining a low weight and volume. The solution to this particular question proved to lie in the use of relatively new Lithium-Polymer chemistry-based batteries. The principal advantage to using these specific cells lay in the fact that without the requirement of a rigid outer metal shell, the cells could be molded to conform with available space under the system circuit board of the final application. Similar to the way in which iPod style devices attain small sizes using thin flexible power storage, the STEALTH hardware was architected to hold two thin cells weighing only 36 g in aggregate, but providing superior cold weather performance to that of a 1 kg lead-acid chemistry battery, while still being easily recharged in the field.

The third design consideration was that of the robust enclosure that would be needed to protect the system from possible field mishaps, while at the same time remaining lightweight and compact. To provide robust, non-metallic casing while not relying on an injection molding process, the material black Delrin was chosen to protect and reinforce the system. Providing excellent shock and impact resistance while remaining light, and requiring a maximum thickness of only 3.5 mm, the use of Delrin also allowed battery retaining grooves to be milled behind the system circuit board to further condense the layout of internal system components.

The embedded system architecture is shown in Figure 2 and the actual hardware in Figure 3.

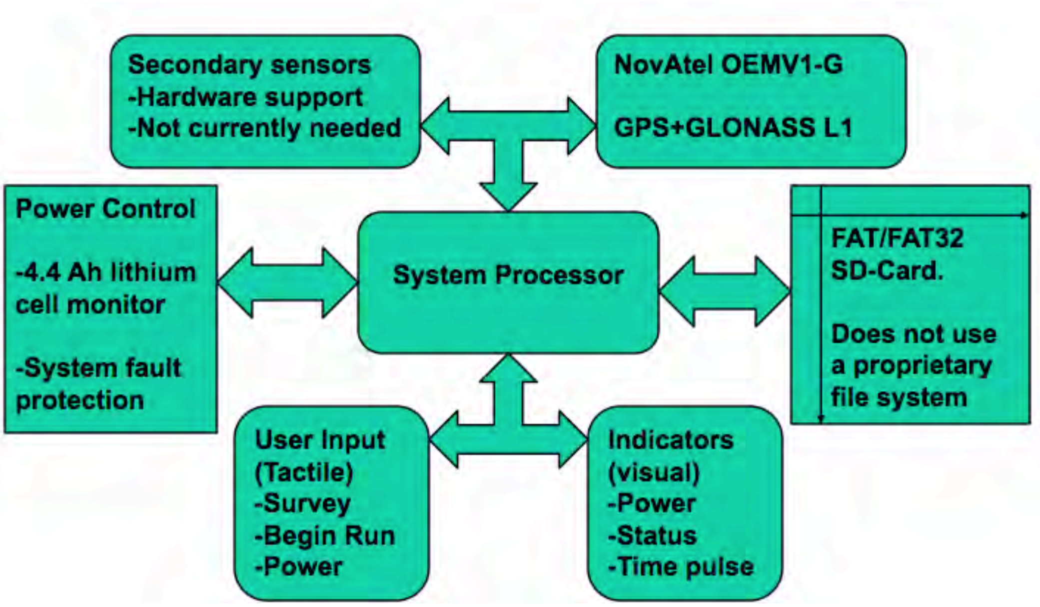

Figure 2 – Embedded system architecture

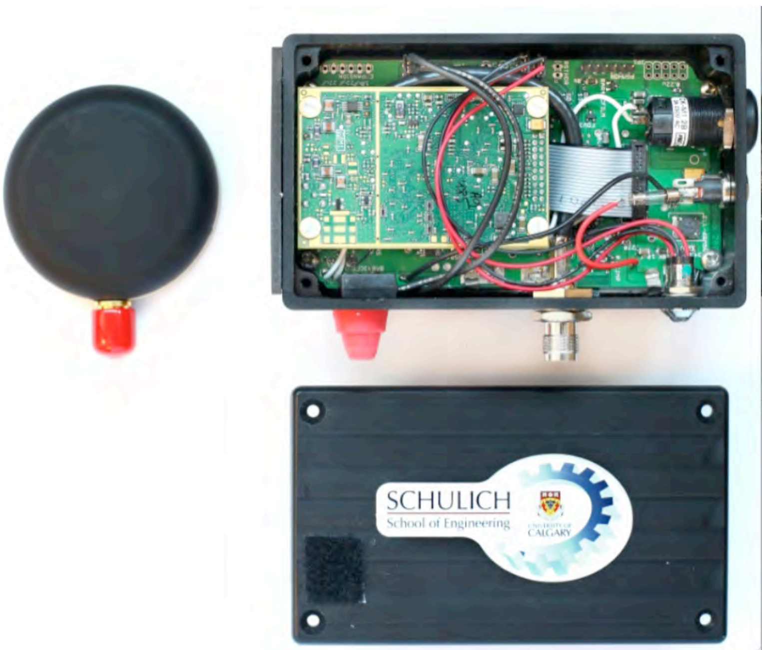

Figure 3 - STEALTH hardware

The last major design decision was to use a standard memory card format to allow ease of user data handling, while still maintaining low power size and weight. The best choice to meet these requirements that was available at the time was a ‘SD-Card’ storage media. As an interesting side effect of this decision however, many changes to the embedded operating code of the microcontroller had to be heavily modified to work around the shortcomings of the media itself. The need for this consideration stems from the fact that all flash storage media in general, including SD cards, are effectively not capable of ‘overwriting’ pre-existing data with new data directly. Instead it is necessary to purge entire blocks of storage referred to as sectors before writing may occur. Each sector must be razed to a uniform state of all 1s before the data may be written in by clearing the appropriate bits to zero. In effect, unless the state of the media is thoroughly known ahead of time, it is necessary for the file system controller to purge each unit of data storage before use, causing additional latency before writing may occur. While a file system controller was used as an intermediary between the embedded system core and the removable memory cards, it was still necessary to adapt the system core to the operating mode of the file system controller. While two modes of access are available with SD card media, only the first is available for open usage, as the openly document Serial Peripheral Interconnect (SD Association 2009) access mode is widely documented and not restricted for access, while the second and far faster interface mode is a proprietary standard requiring licensing as well as specialized hardware. While the utilization of this storage technology provided significant advantages from the point of view of the user, it did place considerable design requirements on the creation of the embedded system code operating in the system microcontroller. Because of the need to provide data buffering during the aforementioned sector erasure delays while still servicing user interaction, memory constraints were very tight. Specifically, of the 6 kilobytes (6144 bytes) of total available RAM, all save 300 bytes were required for GNSS/file system data buffering, requiring a fully interrupt driven timing, user interaction and device interface driver system to operate in only these 300 bytes.

The antenna selected is the ANTCOM GG, capable of GPS/GLONASS tracking and shown on Figure 3. Its diameter is 67 mm, its height 20 mm, and mass 113 g. It uses a TNC connector for robustness.

GPS/GLONASS RTK Approach

Post-processing of the GPS and GLONASS code and carrier phase measurements collected by the hardware component is done using the PLAN Group’s PLANSoft™ processing software. PLANSoft™ is an RTK processing engine that incorporates both GPS and GLONASS data. It also implements the following features:

- A Kalman filter with a velocity random walk dynamic model
- Automatic calculation of the base station position to a single point accuracy of a few metres
- L1-only phase ambiguity resolution using LAMBDA followed by a sequential search
- Forward and reverse processing and combining
- Misclosure-based ambiguity validation
- Innovation-based fault detection.

Using GLONASS in RTK processing presents a special challenge. Conceptually, RTK is based on double-differenced (DD) phase measurements, which isolate the carrier phase ambiguities. This can be written as

$$\nabla\Delta\phi = \left(\frac{\Delta\rho_j}{\lambda_j} - \frac{\Delta\rho_i}{\lambda_i}\right) + c\Delta dT\left(\frac{1}{\lambda_j} - \frac{1}{\lambda_i}\right) + \nabla\Delta N + \varepsilon_{\nabla\Delta\phi}$$

where $\nabla\Delta\phi_i$ is the DD phase measurement, in units of cycles,

$\Delta\rho_i$ is the single-differenced (SD) range to the i^{th} satellite,

λ_i is the wavelength of the signal from the i^{th} satellite,

$c\Delta dT$ is the SD clock offset in units of distance,

$\nabla\Delta N$ is the DD ambiguity,

$\varepsilon_{\nabla\Delta\phi}$ is the phase error term.

In the case of GPS, the wavelengths of signals from different satellites are the same, so the clock offset is eliminated. This is not the case with GLONASS, which uses frequency division multiple access (FDMA). The phase parameterization can be converted to units of distance and rearranged as follows:

$$\nabla\Delta\Phi = \nabla\Delta\rho + \lambda_j\nabla\Delta N + \left(\lambda_j - \lambda_i\right)\Delta N_i + \varepsilon_{\nabla\Delta\Phi}$$

where $\nabla\Delta\Phi$ is the DD phase measurements, in units of distance.

The above parameterization contains the DD range $\nabla\Delta\rho$, the DD ambiguity $\nabla\Delta N$, and the SD ambiguity of the reference satellite ΔN_i. The latter term must be estimated separately, as it is not observable with DD measurements. Many methods for this estimation are available in the literature: e.g. use of a common oscillator (Keong & Lachapelle 2000), code-minus-carrier (Wang 2000), and the use of SD measurements in the estimation (Habrich et al 1999). The latter approach is used in PLANSoft™. SD measurements are used to estimate the position, velocity, clock states and SD ambiguities as

$$x_{SD} = \begin{bmatrix} pos & vel & offset & drift & \Delta N \end{bmatrix}$$

These states are transformed to the DD domain. Specifically, the SD ambiguities are transformed to DD ambiguities. The SD ambiguity of the GLONASS reference satellite is also obtained in this manner. The states in the DD domain are outlined below:

$$x_{DD} = \begin{bmatrix} pos & vel & \Delta N^{GLONASS\ BASE} & \nabla\Delta N \end{bmatrix}$$

The DD ambiguities are resolved to fixed integers if possible, or real numbers otherwise. The algorithm is outlined in the flowchart shown in Figure 4.

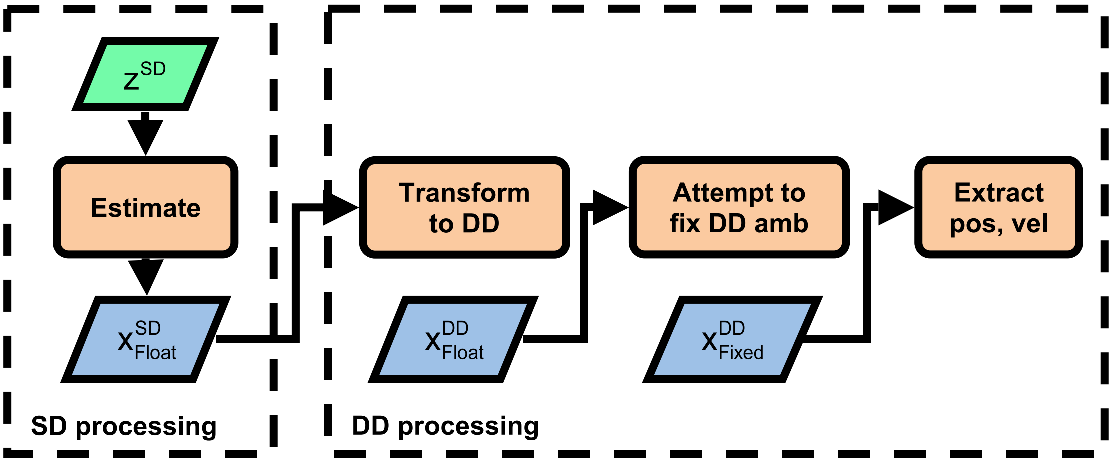

Figure 4 – GNS/GLONASS RTK algorithm flowchart

FIELD PROCEDURES

The procedures for using STEALTH™ in the field are divided into three categories:

- ***Base station***
  The base station is located on the upper slope to maximize satellite signal availability. The maximum distance to skiers on the course is usually less than 2 km. A NovAtel OEMV3-G receiver attached to a 702-GG antenna is used. It is pre-programmed to log measurement data to a MicroSD memory card at a rate of 20 Hz for use in differential processing. The antenna is statically mounted on a tripod as shown in Figure 5.

- ***Gate survey***
  Every course features gates that either define intervals for timing (e.g. start, intermediate, finish) or dictate the direction of the course. These must be accurately surveyed as they essentially define the course setup. The STEALTH™ hardware comes in two configurations: a gate configuration and a skier configuration. The gate unit is attached to a survey rod with an ANTCOM GG antenna, as shown in Figure 5. The gate hardware units have a timing feature that visually indicates 30-second intervals to the user.

  To survey the gates, the user goes to each gate, presses the survey button, and stands still with the survey rod level for 30 seconds (the interval indicated by the visual timing feature). Post-processing of the static gate survey data determines the gate positions to an accuracy of 5 cm or better.

- ***Ski runs***
  The skier configuration of the hardware is mounted on a flexible belt, which is worn by the skier. This unit is attached to an ANTCOM GG antenna, which is mounted on the skier's helmet. The skier hardware units have a time-tagging feature. The

system, as mounted on a skier, is shown in Figure 5.

At the beginning and end of each run, the skier stands still for 30 seconds. This is to give time for the phase ambiguities to converge in the RTK processing. Before the skier crosses the start line, another user presses the time-tag button, which records the GPS time at which the skier starts skiing. The user does the same just after the skier crosses the finish line.

Figure 5 - Base station, gate survey unit and skier equipped with STEALTH™

DATA DISPLAY WITH ALPINEGNSS GRAPHICS™

After data collection in the field and post-processing with PLANSoft™, the skier trajectories are displayed in the PLAN Group's interactive display software, AlpineGNSS Graphics™. Figure 6 shows a screenshot of the software. The trajectories of the skiers are projected into two views: parallel to the hill face, and a cross-section of the hill, giving a height profile. The start and finish lines are used to define the extent of the race course. In addition, the parameters of interest listed below are shown in the display. These parameters are derived from the 3D position and velocity information available from RTK post-processing.

- Elapsed time, speed along track
- Distance travelled
- Speed
- Acceleration along and across track
- Turn radius
- Total run time
- Average speed

An interactive cursor can select any section of the course, displaying the above parameters at the cursor position. Intervals can be defined to analyze turns. In particular, the speed into and out of the interval is provided, allowing analysis of how specific lines taken by the skier contribute to speed gained or lost through the turn.

The display also toggles between the interactive cursor and a real-time playback of the skier trajectories. Runs from different skiers are time-synchronized according to time elapsed from the start line. Across track accelerations reach several g's for the antenna on the helmet, which is still likely significantly lower than the corresponding values at the ski level.

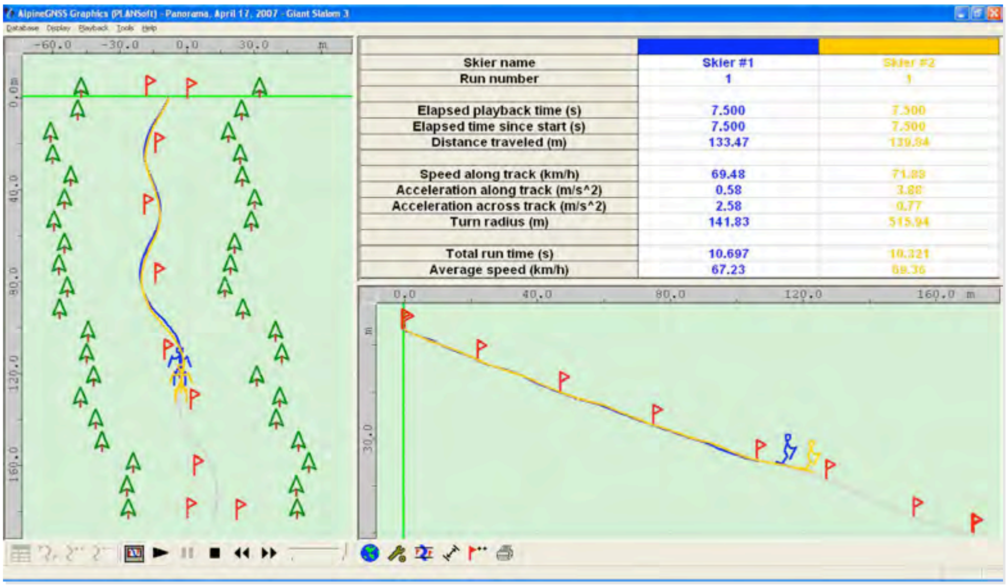

Figure 1 - AlpineGNSS Graphics™ screenshot

TEST RESULTS

STEALTH™ has been used successfully since Fall 2007. Sample results obtained in 2009 at two locations are presented below.

Nakiska, Canada (www.skinakiska.com)

STEALTH performance was tested at this ski facility, which was the site of the Calgary 1988 Winter Olympics, in March 2009. The slopes feature a typical environment for ski racing with mask angles from the surroundings reach 25°, with most less than 15°. There were between 7 to 11 GPS and 3 to 8 GLONASS satellites visible at the time of the test. Seven runs were skied by the first author, with speeds of 25 to 55 km h^{-1}. The ski time for each run was five to six minutes. Flags were placed in the snow at the top and bottom of the hill to test repeatability and thus accuracy. At the beginning and end of each run, the skier stood still over the flags for 30 seconds. The expected agreement between each run was about 30 cm horizontally and better than 10 cm vertically. The system was performing in GPS/GLONASS mode and the performance of GPS, GLONASS and combined GPS/GLONASS could be inter-compared. Circular mask angles of 10˚, 20˚ and 30˚ were superimposed on top of the natural but irregular masks caused by the topography.

Table 1 shows the percentage of fixed integer ambiguities for GPS, GLONASS and GPS/GLONASS for each of the three superimposed mask angles described above, using PLANSoft™. All topographic features were below 30˚. The use of GPS/GLONASS results in a 100% success rate with superimposed mask angles of 10˚ and 20˚, confirming the advantages of more numerous satellites. In practice, a value of 10˚ would be used. Table 2 shows the agreement at the beginning and end of the runs where the skier stood still at verification for 30 s. **Error! Reference source not found.** shows the static positions at the start and end of each run. The agreement is within the expected values quoted earlier and shows that the ambiguities were correctly resolved with a high degree of reliability.

Table 1 - Percentages of fixed integer ambiguities - Nakiska tests (Mar09)

	% of runs with correctly fixed ambiguities			Comments
Elevation mask	GPS	GLONASS	GPS/ GLONASS	
10°	57%	43%	100%	
20°	57%	43%	100%	Longer convergence time required for GPS and GLONASS
30°	29%	Could not compute solutions	86%	GPS PDOP > 4 for five of seven runs

Table 2 - Agreement of run positions

		Horizontal	Vertical
Start	Standard deviation (cm)	11	1
	95% confidence (cm)	27	2
End	Standard deviation (cm)	17	3
	95% confidence (cm)	42	6
Expected accuracy (cm)		30	10

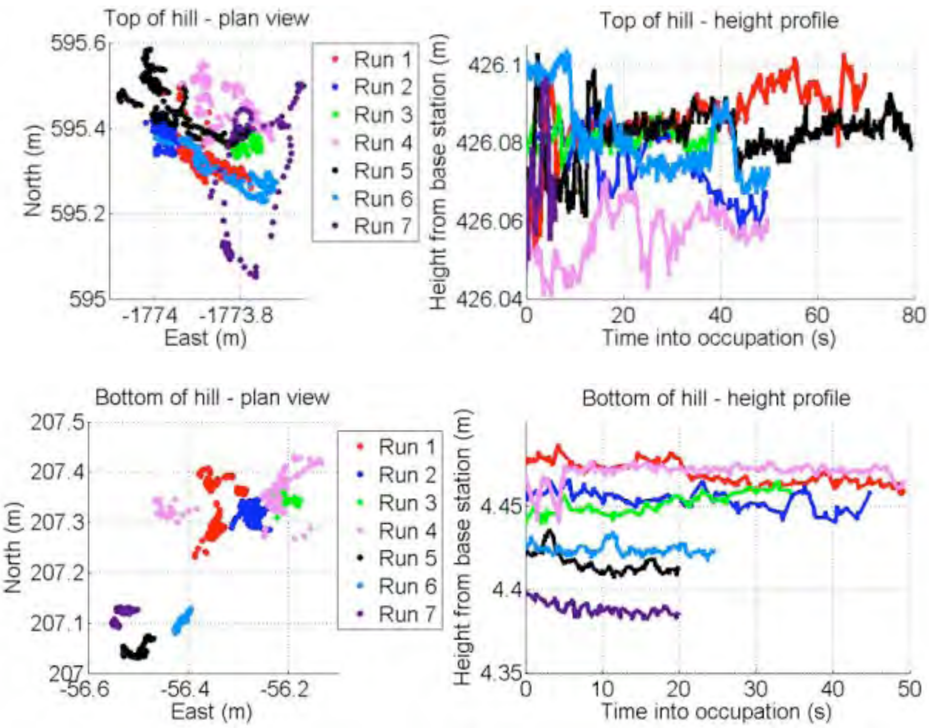

Figure 7 - Positions at start and end of runs

Portillo, Chile (www.skiportillo.com)

Training and ski testing by ACA skiers took place at the Portillo, Chile, in September 2009. This is a ski slope that has among the highest topographic mask angles encountered so far, namely 20° to 40°. Satellite visibility was accordingly reduced to five to eight GPS and three to five GLONASS satellites. The runs on the slope segment utilized were short at 30 to 40 s each. Speeds varied between 50 and 120 km h^{-1}. Under such extreme conditions of mask angles and short trajectory times, integer ambiguity determination becomes tenuous. Table 3 shows the percentage of fixed integer ambiguities for GPS and GPS/GLONASS, in addition to the position and velocity accuracies estimated by the software. Again, the addition of GLONASS is very beneficial to enhance performance and results in a success rate of 76%. The estimated position accuracy is as expected for fixed ambiguity solutions. The high topographic mask angles and short run durations contributed to this lower success rate.

In the example shown in Figure 8, STEALTH™ is used to identify differences between two runs. The fastest (green) and slowest downhill runs (brown) are highlighted. The system identified the fastest run as having sharper corners around gates. The timing accuracy was within that of a separate system used by the skiers.

Table 3 - Performance at Portillo for ski testing

	Successful fix rate	Estimated position RMS accuracy (cm)	Estimated velocity RMS accuracy (km/h)
GPS-only	53%	2.3	0.29
GPS/GLONASS	76%	1.8	0.22

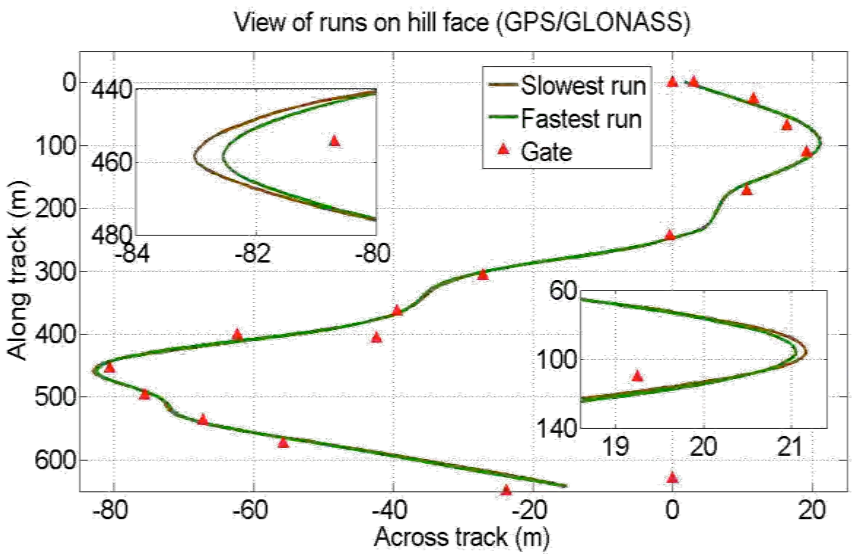

Figure 8 - Training run differences

CONCLUSIONS

STEATH™, which consists of a highly portable field rugged unit, *PLANSoft™* and *AlpineGNSS Graphics™* software, is now used routinely and successfully by the Canadian Alpine Ski Team. The ease of use through straightforward interaction with the device in the field and the interactive data presentation and interaction with *AlpineGNSS Graphics™* proved essential for the acceptance of the technology. While on most ski courses, the use of GPS/GLONASS results on successful integer ambiguity resolution, there are cases such as the ones presented here using data collected in Portillo, Chile, where the success rate is lower at 75% due to extreme mask angles of up to 40˚. In these cases, the use of a multiple frequency approach and a cascading ambiguity resolution scheme would likely help, but at the cost of higher weight and power consumption at this time. The use of inertial sensors remains a possibility but the same constraints as above apply.

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