GSM-Distributed RTK for Precise Analysis of Speed Skiing

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ABSTRACT

The applications to dynamic sports for an accurate analysis of trajectories represent a new perspective for carrier phase-based GPS positioning. Introduced in competitive skiing, the GPS technique provides all the qualitative data for a complete analysis of position/velocity/acceleration so that the measured trajectories can be compared throughout the entire track. Consequently, it can help the athletes to find the fastest line and to identify any technical errors. This ensures an enhancement of the efficiency of the trainings to optimize the performances of the skier, as well as that of the equipment. This kind of analysis requires decimetric positioning of the skier at a 5Hz pace or higher.

This paper presents a technique that combines modern lightweight GPS-RTK dual frequency receivers with standard GSM mobile phones and trajectory filtering/smoothing procedures. This approach was successfully applied in February 2004 during the FIS-World Cup race in Leysin, Switzerland and in April 2004 during the season's final race of the professional circuit held in Verbier, Switzerland. Racers and their coaches request the assistance of such a system in future contests.

INTRODUCTION

Speed skiing is the fastest non-motorized sport on the Earth with the most experienced skiers often exceeding speeds of 200 km/h: the Swiss Jonathan Moret, World Junior Champion, has reached an amazing 248.105 km/h. Such speeds raise questions with respect to the accuracy and reliability of the distance measurements of the track.

Traditionally, speed-skiing timekeeping is carried out with the help of a fixed time clock capable of accuracies to within 1/1000th of a second and controlled by photoelectric cells placed at the entrance and the exit of a 100m timing zone. The guarantee of the 100m-long separation between those cells requires involvement of a land surveyor. This expert determines the most suitable placement of the timing zone guided by the acceleration sensations of a voluntary skier.

Offering instantaneous position and velocity measurements of high accuracy, satellite techniques such as carrier phase-based positioning can be used to optimize the placement of the timing zone around the point of highest speed (Figure1). This technique is also suitable for the authentication of the 100m-long separation between the two sensor stations as well as for periodical checks of the 100m to ensure that the calculations remain valid.

In this paper we explore real-time measurement techniques combined with modern means of communication to determine the performance of speed skiers and to define of an optimal layout of the timing sensors. The introduction of GPS-RTK coupled with GSM phones leads to a rigorous approach in these aspects.

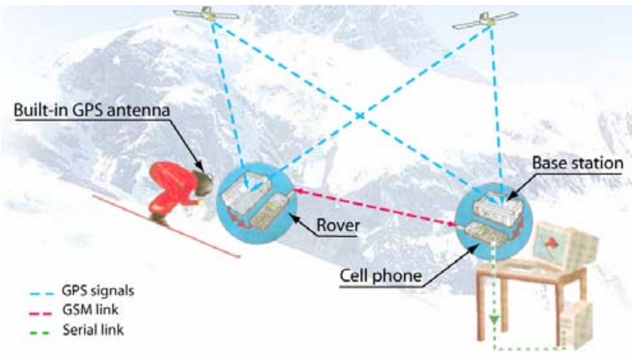

Figure 1: Principle of real-time position of velocity tracking by GPS measurements

IDENTIFICATION OF A SUITABLE FORMAT OF GPS CORRECTIONS

It is a well-known fact that the positioning error of GPS can be reduced to 3-5 cm in receiving 5kbit/s of corrections in the RTCM-RTK format, provided that the mobile receiver is located at less than 10 km to the reference station [1]. More precisely, in the context of real-time positioning, RTCM messages 18 and 19 are of primary interest, and the minimal amount of broadcasted data is quantified by:

(1) [bytes/s] = [30-bit word] $\times 5 = f \times 2 \times FREQ \times (3 + 2 \times N) \times 5$

Where f represents the measurement rate; *FREQ*, possible value of 1 or 2, gives the mono or bi-frequency characteristics of the receiver; N represents the number of satellites.

However, it is necessary to note that the coordinates of the reference station are also transmitted, yet at a lesser rate than that of the corrections. Nine 30-bit words are necessary to give the position of the reference station, which generates a peak output of:

(2) [bytes/s] = $f \times (2 \times FREQ \times (3 + 2 \times N) + 9) \times 5$

The CMR (Compact Measurement Record) message, recently approved for public use, was developed by Trimble to deliver the corrections over communication lines of reduced bandwidth (2400 bauds). In its most recent implementation, the CMR+, the position of the reference station is transmitted in separate segments instead of a single block, as it is done with the RTCM message. The formula describing the peak output is:

(3) [bytes/s] = $f \times (6 + N \times (8 + (FREQ - 1) \times 7) + 16)$

A numerical example helps to illustrate these concepts. At the time of the signal reception of 7 satellites, at the rate suitable for trajectography needs, i.e. 5 Hz, a dual-frequency receiver broadcasts at peak output:

- $5 \times (2 \times 2 \times (3 + 2 \times 7) + 9) \times 5 = 1925$ bytes/s = 15400 bps of RTCM corrections,
- $5 \times (6 + 7 \times (8 + 1 \times 7) + 16) = 635$ bytes/s = 5080 bps of CMR+ corrections.

In order to limit bandwidth and thereby avoid the saturation of most of the communication lines, we will base our experiments on the RTK-CMR+ corrections.

TRANSMISSION OF GPS CORRECTIONS

The choice of a suitable format of corrections is only one aspect of the deployment of the GPS-RTK technique. Extreme attention should be paid to the means of broadcasting such data, which must comply with the stringent ergonomic conditions of speed skiing. Moreover, our application requires the communication link to be bidirectional as the GPS-RTK solutions are reported to the base-station. This means that in case of radio-communication also the rover station needs to be paired with a sufficiently strong transmitter. Experience has shown that the use of the radio as a transmitter involves a significant degradation in the performance of the athlete, which had led us to investigate the use of a reliable and portable communication link.

The term “portable” immediately brings to mind the cell phone, there being many models equipped with a modem weighing less than 100 grams, battery included. The assured coverage by the three national service providers making up the cellular network offers an ideal choice for the transmission of RTK corrections.

When making a communication link with its counterpart, a cell phone establishes a connection so that the GSM network is transparent to the data. This simulates a true point-to-point connection, as if the recipient of the call were directly connected to the application (or the peripheral) controlling the modem of the cell phone. Thus, any GSM connection procedure defines a specific line where the information exchanged between the two modems circulates (Figure 2). This technique is in the development stage with private-sector partners offering a service for RTK by GSM corrections, but in a format and at a rate incompatible with the trajectory calculation of athletes.

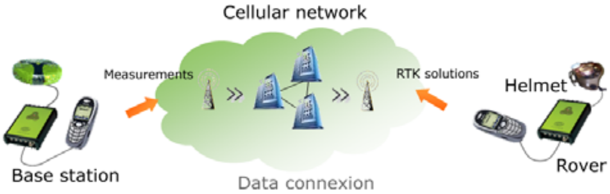

Figure 2: Broadcast of GPS corrections via GSM

TRAJECTORY FILTERING AND SMOOTHING

The determination of carrier-phase ambiguities lies in the core of RTK. Although the years of research improved on its rapidity and reliability this process still remains sensitive in dynamic environments [1]. Falling back on trajectory estimation via the Kalman filter to resolve measurement outliers is not sufficient in the environment of downhill skiing [2].

Here more sophisticated methods need to be used where positioning improvements are sought by imposing constraints of continuity and smoothness on trajectory restitution. Research with alpine downhill data showed that the trajectory modelling via smoothing piecewise cubic splines [3] has several advantages over other possible interpolants [4]. Its adaptive weighting scheme provides a form of spatial filtering across all trajectory components that effectively reduces high frequency noise and bridges over data outliers. Furthermore, it can supply smooth transitions when sudden position ‘jumps’ due to change in satellite constellation or ambiguity fixing are encountered.

To better illustrate this process an example from [4] in depicted in Figure 3. It represents a real case of a bad GPS data period of float ambiguities due to deprived phase data, producing a jerk in the trajectory followed by a few epochs of no positioning solution (complete loss of lock). The smoothing spline with uniform weight distribution (dotted line) results in a somewhat smoothed but still apparent jump at the fixed/float transitions, while the smoothing spline with a proper variation of weights (full line) is closer to the real trajectory taken by the skier as verified on the video-footage during his passage of the gate. As our experience with this filtering method has only been positive, the same approach was followed in speed skiing.

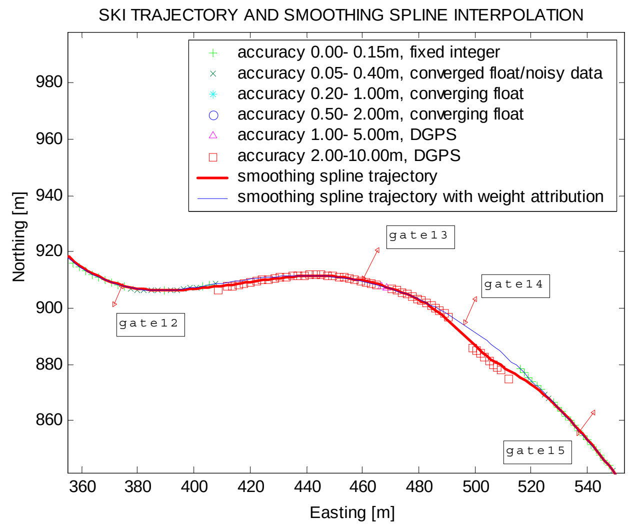

Figure 3: Downhill trajectory modeled by smoothing splines. Case of bad GPS data period with float ambiguities producing a trajectory 'jump' followed by some epochs of complete loss of lock (no data). Skier's head with the GPS antenna attached to his helmet sometimes leaps outside the gate in the effort to steer the skis as close as possible to the inside pole.

APPLICATION DEVELOPMENT AND EXPERIENCE

During the speed skiing races in Leysin and Verbier, Switzerland, the use of GPS in combination with GSM to determine the trajectography and velocity of the athletes in real time has proven successful. Voluntary skiers are equipped with high-quality GPS receivers that transmit their position and velocity at a rate of 10Hz via the GSM network. A laptop gathers and analyses all the GPS data, displaying the quality of the communication link and the speed of the skiers in real time (Figure 4).

The above-mentioned smoothing algorithm is applied to each of the trajectories to bring the position to the centimetre level. As this precision is compatible with the positioning of the timing gates, we can interpolate the moment at which the athletes reach the gates and calculate the average speed between gates (Figure 5). Then, a most favoured location of the timing gates is computed for each athlete and the overall average of all contenders is considered as an optimum.

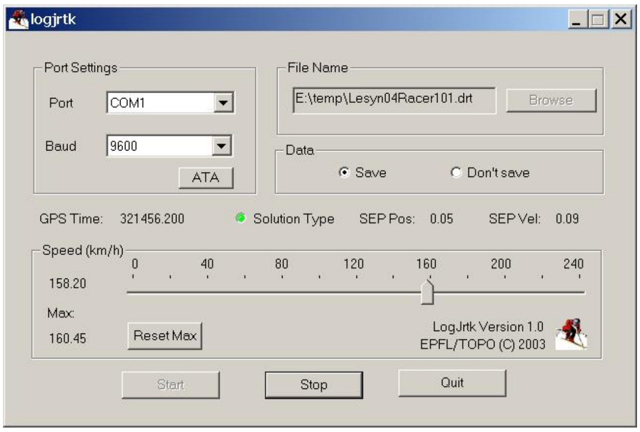

Figure 4: Real-time speed and position monitoring of RTK solution via GSM link.

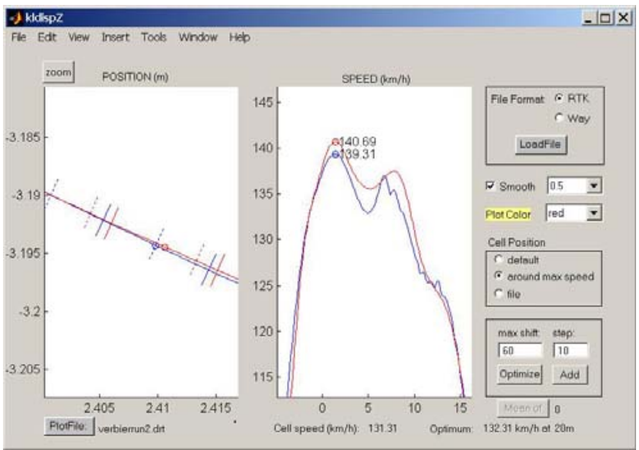

Figure 5: Trajectory filtering, display and calculation of an optimal position of the timing zone.

Table 1 illustrates the agreement between official FIS (Fédération Internationale de Ski) and GPS timing for two different antennas. We can conclude that GPS timing is sufficiently precise when the carrier phase differential techniques guarantee 0.1m positioning accuracy. Of course this is easily achievable when exploiting data on both GPS frequencies.

Table 1: Validation of GPS timing

Antenna Type	FIS Timing	GPS Timing
L1 active small	138.56 km/h	138.2 km/h
L1/L2 airborne	141.37 km/h	141.3 km/h

As seen in Figure 5, the virtual displacement of the 100m timing zone along the trajectory of the skiers allows an optimal determination of the positioning of the timing gates. Table 2 demonstrates this in more detail. It shows that the optimal position of the first gate was actually located 50m lower than the one determined by the physiological sensations (accelerations) of the skiers themselves.

Table 2: Optimal positioning of the timing gates

No.	+10m	+30m	+50m	+70m	+80m	+90m
1	139.7	143.0	**145.8**	143.0	142.9	142.0
2	144.1	147.7	**149.5**	**150.1**	149.0	148.0
3	143.6	148.3	**155.3**	152.0	149.8	142.2

DISCUSSION AND OUTLOOK

This experiment enabled us to develop a thorough technique for timing gate placement, yet it also exposed certain inherent disadvantages in using GSM as the communication link.

- A cell phone that is not run by GPS receiver firmware needs specialized programming in the form of non-normalized Hayes commands!
- The establishment of a connection can take several minutes whereas the patience of some competitors is limited.
- The call invoicing is based on elapsed time due to the reserved and exclusive link between the two stations.
- The data transfer speed is limited to 9600 bps.

However, one can notice that on-line radios, which output continuous flows of Internet Protocol Packets, have become well-established services. Real-time GPS data transfer requires relatively less bandwidth compared with these applications. Consequently, the dissemination of RTK corrections over the Internet constitutes an interesting alternative to the use of the GSM link. The mobile Internet is intimately linked to GPRS, a radio data transmission service that uses packet switching on a GSM network. We are currently investigating an entirely mobile solution of a networked transport of RTCM via Internet Protocol, implying establishment of a GPRS connection between the base station and the rover.

Hence, the GPRS system, and later the UMTS (Universal Mobile Telecommunication System), offers an even more flexible solution for the transmission of RTK corrections. Such a method not only facilitates the system initialization but also simplifies tracking several competitors at the same time. The evolution of our system will follow this path.

On the side of performance analysis the developed utilities allow rapid monitoring of skiers track and subsequent decision-making for optimal timing-gate layout. Coupling racers' trajectories with the digital terrain model may lead to the development of new training tools based on virtual reality (Figure 6). Here, several trajectories can be compared at the same time from different perspectives and criteria. Ultimately, real video footage could be integrated within such tools. This would allow relating the qualitative performance to individual techniques.

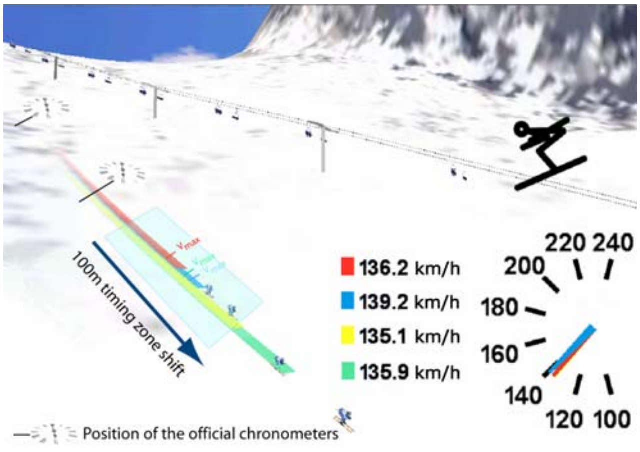

Figure 6: Insertion of skiers' trajectory in virtual reality offers a powerful means of interactive performance analysis (© Dartfish).

CONCLUSIONS

GPS-RTK causes a great deal of excitement among land surveyors and researchers insofar as it provides an alternative to the post-processing of GPS data. The use of GSM communication channels offers a significant improvement over the traditional radios in ergonomic aspect, which opens the door to new sport applications. Moreover, the data link is perfectly bidirectional, which allows reporting RTK-results back to the base station over the same channel. Coupled with trajectory restitution tools, such information allows real-time monitoring of racers' performances.

The measurement system has been validated on several occasions and its assistance has been requested for future contests.

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