High Precision Kinematic GPS Positioning Of Ski Jumpers

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BIOGRAPHY

The author received his Diploma in Geodesy in 1998 from the Technical University of Dresden. From this time on he worked in different GNSS related projects and is currently a Doctor candidate. His main fields of investigations are software development for multi sensor GNSS reference stations as well as hardware development for GPS applications in sports sciences.

ABSTRACT

High precision carrier phase based GPS positioning requires a reliable integer ambiguity fixing. Problems arise if the measured time span is very short and additional signal shadowing results in a poor geometrical satellite distribution. Exactly this situation exists if someone try's to measure the trajectory of ski jumpers with GPS. Most of the jumping hills are north orientated within deep valleys and not very suited for GPS applications.

This paper describes a successfully hardware based approach to solve the ambiguity fixing problem. The correctness and reliability of integer ambiguity fixing could be increased using only one measured epoch.

The system was successfully tested during summer and winter training on the K95 jumping hill "Fichtelberg-schanze" in Oberwiesenthal, Germany.

INTRODUCTION

It has been common practice for some time in sports science and biomechanics to use so-called video based motion analysis systems when performing measurements in the laboratory. For sports that are usually performed in the field (for example rowing, skiing and cycling), a very artificial situation arises, because locomotion in the strict sense of the term does not take place in the laboratory.

On the other hand, a three-dimensional video-based analysis in the field requires enormous equipment and personnel resources and only a small spatial cube can be studied at a time.

Improvements have been made in GPS receivers, measurement techniques and analysis algorithms. The trend in miniaturization of geodetic GPS receivers and the increasing of the hardware capabilities holds on. So the idea comes up to use satellite based techniques to measure the flight path and speed of ski jumpers more directly and more efficiently. The positioning accuracy should be in the lower centimetre range. The necessary resolution in time should be at least 20 Hz. The next sections describe the realization, the difficulties and some practical results from field tests.

HARDWARE REQUIREMENTS

From the viewpoint of the sports scientists and athletes a perfect measurement system is free of backward effects from the measurement equipment itself onto the athlete. Hence the volume and mass of a GPS receiver carried by the athlete must be less enough. In the other case safety jumps are performed only without any information about "real" jumps. The reasons are the serious healthy risks in ski jumping. Up to 100 m in height are passed within a few seconds.

An ideal system in the strict sense of the term is a video based system. The object of interest doesn't need to carry any equipment. But on the other hand, taking pictures and movies form afar cannot derive all interesting parameters. So the requirements on a GPS receiver for ski jumping are high.

THE GPS-HELMET RECEIVER

The intention was to integrate a GPS receiver into a jumping helmet. No troublesome cable connections, switches and equipment in any pockets are needed. Therefore a market analysis for small and lightweight geodetic GPS receivers was made. Finally a NovAtel OEM4-G2L board was selected for the integration into a jumping helmet. This receiver offers raw data output of dual frequency carrier phase measurements with up to 20 Hz data rate. But there was a lack of a control interface, data storage and power supply. No adequate offer for that could be found. The functional requirements were high, also a low mass, a low volume and at least the price

Fig 1: GPS-Helmet receiver and handheld display for receiver status information.

for such additional hardware components were an issue. Because of the author's knowledge himself has developed the missing parts. Fig. 1 shows a picture of the GPS-Helmet and the handheld display.

A block diagram can be seen in fig. 2. The single-chip microprocessor ATMega128 controls all the components. An AeroAnt AT2775-102 dual frequency GPS antenna is connected to the OEM4-G2L receiver. Some little modifications must be done to adapt the 5V output to the 3.3V antenna. The receiver generates 20 Hz raw data that is stored on a CompactFlash memory card. For easy data exchange a common FAT16 file system was implemented. Important receiver status information goes over a wireless UHF link to a handheld display. All parts are placed between the inner and outer shell of the lightweight KED helmet. The total mass of the measurement equipment could be reduced down to 260 g. So the GPS-Helmet is not heavier than other common UVEX or CARRERA helmets currently used.

SOME LIMITING FACTORS ON GPS

In this ski jumping application GPS is used at its physical limits. Most of the jumping hills are north orientated with direct view into the north hole of the GPS satellite constellation. Additionally, trees, buildings, mountains and the jumping hill itself shadow the satellite signals. This results in a poor geometric constellation. Only a few satellites remain for measurement purposes. In the consequence mission planning plays an important role.

A ski jump with attempt, take-off, flight phase and landing takes not more than 10-20 seconds. This duration is too short for common geometric ambiguity fixing algorithms. Former software tests with simulated measurements showed, that most of the commercial software packages couldn't process such measurements with centimetre accuracy and high reliability, [1]. It is not possible to initialise the kinematic GPS measurements for some minutes like RTK systems do. Most of the highly

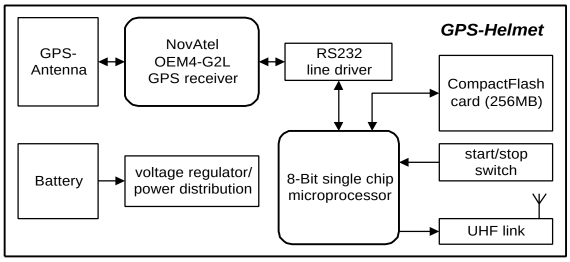

Fig. 2: Block diagram of the GPS-Helmet receiver. Not drawn: handheld display for receiver status information.

sensitive athletes do not accept any technical constraints on their training. At the end a different solution must be found. The following section describes it.

PRINCIPLE OF THE LASER LIGHT BARRIER ARRAY LLBA16

To overcome the key problem - the integer fixing of the carrier phase ambiguities of the very short kinematic tracks, a hardware-based solution was developed. The idea was to measure the helmets position independently in order to have a known point for kinematic ambiguity initialisation in the run. The double-differenced equations [2] for carrier phase measurements then can be sorted into

$$\nabla\Delta N_{a,b}^{i,j} = \frac{1}{l}\left(\nabla\Delta\Phi_{a,b}^{i,j} - \nabla\Delta R_{a,b}^{i,j} + e_{a,b(\nabla\Delta f)}^{i,j}\right)$$

with:

i,j	satellite index
a,b	station index
$\nabla\Delta N_{a,b}^{i,j}$	double-differenced ambiguity term
$\nabla\Delta\Phi_{a,b}^{i,j}$	double-differenced phase observation
$\nabla\Delta R_{a,b}^{i,j}$	double-differenced baseline vector
$\nabla\Delta e_{a,b(\nabla\Delta f)}^{i,j}$	double-differenced baseline vector.

If the position of the rovers antenna phase centre is known at one single epoch, the baseline vector R can be determined. Only the noise term e for carrier phase measurements, containing multipath effects and receiver noise remains. But using high-quality GPS receivers in a kinematic mode, these errors are not an issue. So the ambiguities can easily be fixed to integers. The kinematic GPS segment needs to be solved forward and backward in time beginning at the initialisation epoch. The two parts of the track can be assembled to the final solution after that.

The hardware solution of this idea was realised by the author and is named Laser Light Barrier Array LLBA16. Fig. 3 shows the assembly on the jumping hill table. Sixteen laser light barriers are arranged in a vertical plane perpendicular to the inrun track, see points P1-P2. The

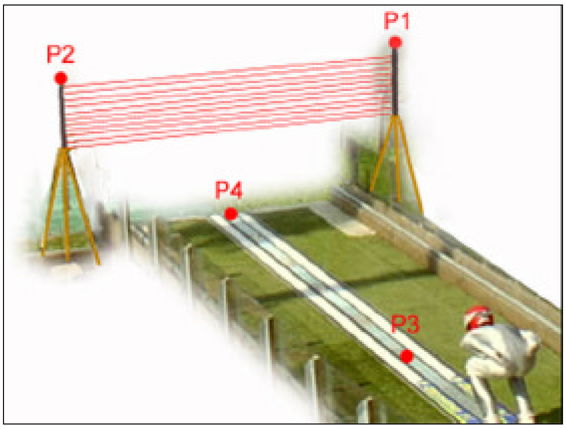

Fig. 3: Principal of the LLBA16.

tree-dimensional position of the helmet antenna is determined by the intersection of the laser light plane and a vertical plane through the inrun track (points P3-P4). The coordinates of the points P1-P4 can be obtained by a geodetic survey. Only the height of the athletes' head is variable and is measured by the light barriers of the LLBA16 system.

But kinematic GPS applications with high speed, the takeoff velocity is about 25 m/s, is a four-dimensional problem. So the GPS time of the helmets passage through the laser plane is measured too. If the helmet hits a barrier, an electrical pulse is feed into an event marker input of a GPS receiver. The leading edge triggers the creation of a time stamp laying in the receiver's memory.

The block diagram of the LLBA16 system can be seen in fig. 4. The different channels receive the transmitted laser light individually. A microprocessor checks the state of each channel. If one barrier is activated, a measurement cycle starts. All 16 channels are sampled with a frequency of 4 kHz until the athlete leaves the laser plane. A crystal oscillator controls the sample interval. A time series of dark/bright-information for each barrier is stored into a CompactFlash memory card. Later the highest beam hit and the helmet shape must be identified.

IMPROVING THE LLBA16'S VERTICAL RESOLUTION

The distance of the laser beams primarily determines the vertical resolution of the LLBA16 system. The mechanical housing of the laser modules allows a minimum clearance of 4 cm, but this is not sufficient for the ski jumping application. Due to the known helmet shape and the velocity *v* of the jumper an improvement can be made. The point of interest *P*, see fig. 5, can be determined with mm-accuracy.

The outer helmet shell seen in a vertical plane is nearly a circle with the radius *r*. The length of the chord *S* can be

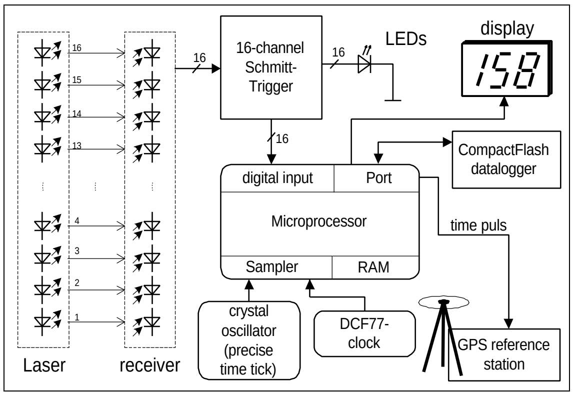

Fig 4: Block Diagram of the Laser Light Barrier Array LLBA16.

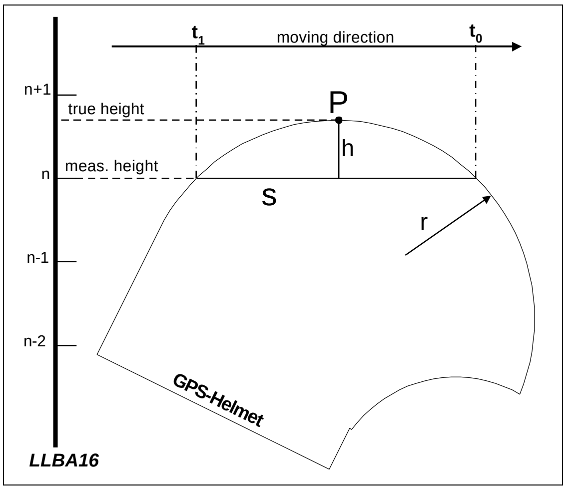

Fig. 5: Geometrical relationships between measured and true height of the GPS-Helmet.

determined using the samples from the LLBA16 and the speed *v* of the helmet during the transition.

$$S = v(t_{out} - t_{in})$$

Whereas t_{in} and t_{out} marks the time of the trigger event and the uncover event of the highest beam. The length of the sagitta *h* follows from

$$h = r - \sqrt{r^2 - \frac{S^2}{4}}\,.$$

The velocity is known at 0.5 m/s level, a crystal oscillator with a standard deviation of about 10 microseconds times t_{in} and t_{out}. Only the radius of the helmet shell cannot be determined very precisely, because a helmet in general has not a spherical surface. Using a standard deviation of 2 cm for radius *r*, the error law propagation shows a standard deviation for the sagitta *h* between 3 mm and 10 mm, depending on the length of *h*. This is a sufficient accuracy for GPS initialisation purposes.

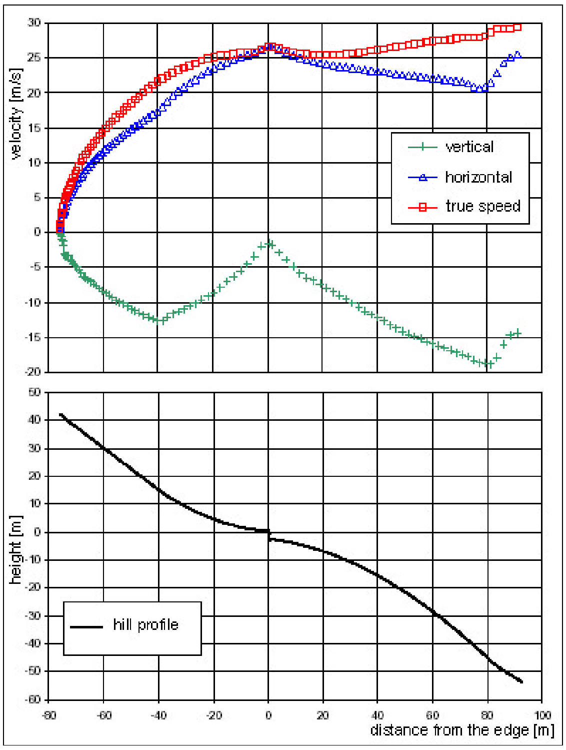

Fig. 6: General velocity profile of a ski jump.

PRACTICAL TESTS

Some practical tests took place during summer and winter training sessions with the German ski jumping team. The LLBA16 system as well as the GPS-Helmet operated very reliable. The investigations were preceded together with sport scientists. Position and velocity information derived from the GPS processing are the fundamentals of the sport scientific analyses. The following section shows some of the possible data interpretations.

SELECTED RESULTS

With the GPS-Helmet the trajectory and velocity can be measured for one single point – the athlete's head. Fig. 6 shows the typical velocity profile of a ski jump, divided into horizontal and vertical components. In the lower part the jumping hill is drawn.

Simplified spoken for the athlete, trainer and sport scientists it is an important question to maximize the inrun speed in order to achieve a maximum jumping length. But nobody has a simple cooking recipe for how to do that. So only hard training will get success. With the GPS-Helmet now exists a tool to verify the efficiency of different athletically efforts.

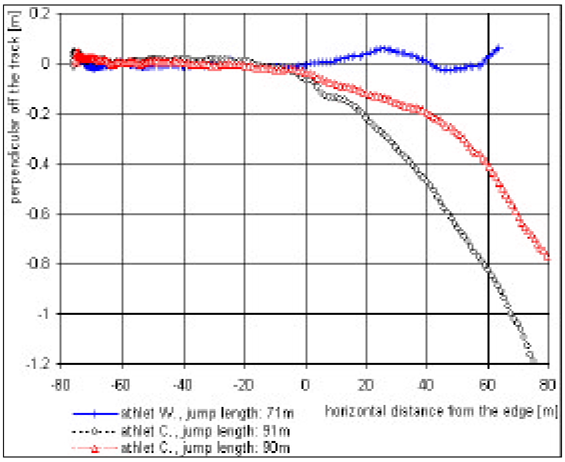

Fig. 7: Perpendicular deviation from the inrun direction for three different jumps. The abscissa zero marks the edge of the jumping table.

A second issue is the flight path direction. Imagine a jump length of about 90 m measured by the jury. Due to asymmetric power evolution effects during takeoff the direction of the flight path may be not in line with the inrun track. The resulting true (slant) flight path can be up to 0.5 m longer, but the jury ignores this. So the athlete's try to jump straight ahead. Such effects are difficult to measure using video-based techniques. With the GPS-Helmet a very comfortable solution exists to investigate the athlete's manoeuvre during the flight phase.

DISCUSSION AND FURTHER INVESTIGATIONS

The fast availability of results is very important. Individual feedback to the athlete directly after a jump would help to optimise the training process. Currently no completely automatically data flow is implemented. Further measurement equipment should be linked together for fast data exchange. So it seems to be possible to calculate all the stuff just in the time between two jumps.

A second issue is the helmet receiver itself. Using the LLBA16 system for integer ambiguity fixing there is no need for a dual-frequency GPS receiver. The baseline to the reference station is very short and so ionospherical effects are eliminated completely. So the efforts from the manufacturers should be checked for lightweight single-frequency receivers with raw phase data output and high measurement rates, at least 20 Hz. The mass of all the equipment can be reduced, because also a small single-frequency antenna is sufficient.

A further point of interest is the combination of measured flight paths with numerically simulated ones. There exist some software packages for simulation of human body and body segment motions. These complex software systems solve the differential equations of motion in order to get the inner and outer forces in such way, that a simulated ski jumper flies along the observed path. Some important parameters like aerodynamically resistances have to be considered. Latter can only be determined in wind tunnel tests. The introduced motion of the athlete's body often is observed by video but can also achieved from GPS measurements. The numerical results of a simulated ski jump finally can be veryfied by a directly measured flight path.

ACKNOWLEDGMENTS

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REFERENCES

[1] Blumenbach, Th., Augath, W.: GPS-Anwendungen in der Sportwissenschaft. In: Proceedings of the DGON Symposium POSNAV 2003. Dresden, Germany. pages 345-351. (in German)

[2] Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J.: Global Positioning System Theory and Practice. 5th rev. edition. Springer-Verlag Wien New York, 2001.