GNSS & Human Flight

WINGING IT

Aidan Walters

At left, Andrew Levson glides toward the Alberta farmlands from 12,000 feet. Note the GNSS antennas attached to his heels. Runways at Innisfail airport can be seen at left. Photo by Aidan Walters. Above, Levson back on the ground again at the end of jump day. Photo by Dave Lundquist

DRESSING UP IN SOMETHING THAT LOOKS LIKE A SUPERHERO COSTUME and flinging oneself out of an airplane might sound like a good idea to a 20-something skydiver. But is it science? More importantly, can a GNSS-outfitted wingsuit be turned into a free-falling human testbed that helps design better products and applications? Andrew Levson and colleagues at NovAtel plan to find out.

GLEN GIBBONS
EDITOR, INSIDE GNSS

In 1589, at the age of 25, Galileo Galilei toiled up the 294 steps of a 55-meter bell tower in Pisa, Italy, where he was tutoring math students at the time.

According to his pupil and later biographer, Vincenzo Viviani, Galileo carried with him two cannonballs, one twice the weight of the other. When he reached the top of the tower, he went to the lower balcony of the tilted structure and dropped the two balls simultaneously.

By demonstrating that the cannonballs' time of descent was independent of their mass — they reached the ground at the same time — Galileo thus disproved Aristotle's theory of gravity, which states that objects fall at speeds relative to their mass.

Although the truth of Viviani's account is disputed, it does support the notion that throwing things from high places occupies a venerable place in the history of scientific discovery.

In any case, no doubt exists that on August 2, 2011, Andrew Levson climbed on board a Cessna 206 and, as the aircraft reached an altitude of 12,000 feet in the wide open Canadian skies over Alberta's wheatfields, threw himself from the plane.

We know this occurred because Levson's accomplishment was chronicled, not by an admiring biographer, but by four cameras along with position and heading data logged at 20 times per second. And he repeated the jump six more times that day.

Instead of two cannonballs, Levson carried two GNSS antennas and dual-frequency receivers incorporated into his specially tailored, skydiving wingsuit. After about 55 seconds of free-fall and another three minutes of precision gliding, he reached the ground safely.

Now, Levson was about the same age as Galileo when he dropped the cannonballs off the Pisa tower. However, Levson wasn't trying to disprove some fundamental scientific law or principle by flinging himself from high places.

As befits his professional role as an applications engineer with NovAtel, Inc., Levson wanted to discover whether GNSS technology could help skydivers improve their performance in both individual

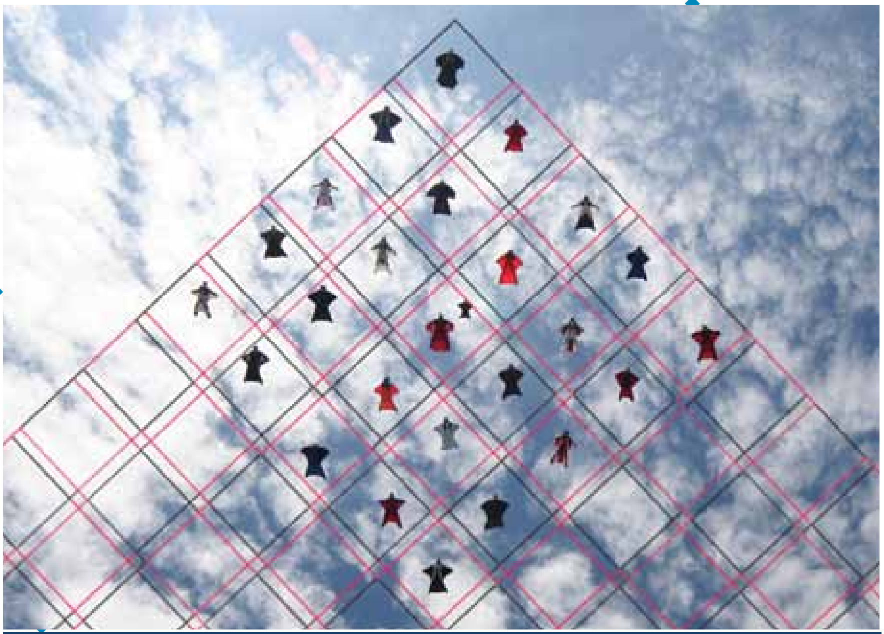


FIGURE 1 Competitive group skydiving is currently judged by overlaying a grid on a photo and evaluating location of divers within its cells. Photo by Mark Harris.

and group competitions. Because, long before he graduated from the University of Calgary's geomatics engineering department in 2007 and began work at nearby NovAtel, Levson had dreamed the dream of human flight.

Since 2000, Levson has made about 1,100 skydives, including 200 in aerodynamically advanced wingsuits — a particular passion for the last four years. Currently, he jumps about a hundred times per year, almost exclusively in one of the three wingsuits that he owns.

His motivation? "This is as close to human flight as I'm going to get."

Wingsuit jumping is an advanced specialty within skydiving — definitely not something for beginners — and adds a level of complexity to an already inherently dangerous sport.

The late-model "Vampire 4" wingsuit that Levson used in the August jumps was manufactured in Slovenia by Phoenix Fly. Each suit is custom-tailored, using 14 key measurements of a customer's body.

Sometimes characterized as "skydiving in a straitjacket," a wingsuit limits the movement of a diver's arms, legs, and overall mobility even as greater skills are needed to maintain control and fly the suit efficiently.

Depending on the organization with which he or she is affiliated, a skydiver has to make 200 to 500 regular jumps before being allowed to make one in a wingsuit.

For Levson, skydiving is less a hobby than a way of life. He met his wife skydiving, and most of his friends are skydivers. He is also a wingsuit instructor and freefall photographer.

GNSS & Skydiving

As with other extreme physical feats such as mountain-climbing, organizations have arisen that establish guidelines and monitor attempts to set individual and group records in skydiving. This can involve length, speed, and time of flight, and size and precision of mid-air formations.

According to Guinness World Records, the greatest distance flown in a wingsuit was a horizontal, straight-line distance of 23.1 kilometers (14.35 miles) by Shinichi Ito of Japan. On May 28, 2011, Ito jumped from a plane 9,754 meters (32,000 feet) above Yolo County, California, USA, and flew for 5 minutes 22 seconds.

Sports including car racing and distance running have already adopted GNSS technology to help measure and improve performance. Could the same thing happen with skydiving?

Individual distance records in the sport have in the past been measured by the position of the plane when the parachutist exits and the location of the landing site. "But the spirit of a [skydiving] record is the actual distance flown in freefall," Levson says, "and for that you need GPS."

The current official record for large group formation flying was set by 68 people in 2009 — with an unofficial mark established the previous year in a 71-way jump.

This coming September 19-23, a world record attempt will be made over Perris Valley, California: 100 wingsuits in the same formation. And, yes, Levson is planning to be there and is serving as Canadian representative for the effort.

Currently, the quality of group jumps is measured by taking a photo of the formation and overlaying a grid on the picture. (See Figure 1.) Divers have to be within a certain distance of the borders of the diamond-shaped cells of the grid. As the formation gets bigger, it gets harder to keep everyone inside designated grid locations.

Real-time GNSS could help position and align divers for the execution of a record-setting effort: GPS-equipped participants placed on the corners of the diamond could provide audio alerts to let others in the formation know if they are getting out of their zones.

A Match Made in the Heavens?

A few years after joining the high-performance GNSS receiver designer and manufacturer NovAtel in 2007, Levson got the idea of leveraging the resources of the Calgary-headquartered company into his high-flying avocation.

"I thought of it as a way to combine two of my passions in life," Levson says—GNSS and skydiving.

And when he raised the possibility with his colleagues, they—pardon the expression—leapt at the opportunity.

"I submitted a proposal to the NovAtel marketing team and they loved it!" Levson recalls. "They jumped all over it."

And it wasn't out of enthusiasm for

skydiving *per se,* but the opportunity to assess performance of the company's high-precision GNSS products under a set of unique high-dynamic conditions.

In effect, Levson and NovAtel colleagues conspired to turn his wingsuit into an aerial testbed for GNSS hardware and software.

In late 2010, Levson took a GNSS receiver board mounted in an enclosure on a personal skydiving trip to Arizona to test out the concept. This effort was undertaken with an extremely "quick and dirty" equipment setup, using nothing but readily available equipment.

Without a support team, the testing was very limited but showed that GNSS equipment mounted on a flying human body worked well in a jump. And such an effort requires a diverse set of skills and expertise.

"This activity has let me touch all these different places in the company that I wouldn't normally get to," Levson says.

Indeed, NovAtel has assembled a cross-departmental team to help shape and exploit the wingsuit testbed. In addition to Levson, team members and their roles include:

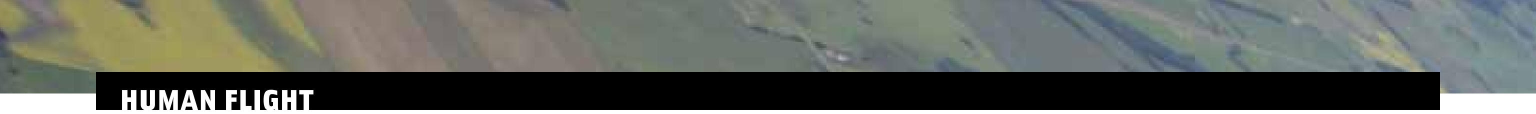
- Steve Bateman, VP of engineering, location scout plane pilot,
- Rob Watson, engineering design services, jump day set-up and data collection/analysis
- Samantha Poon, product marketing, data analysis and supporting documentation, market applications
- Thomas Morley, product validation, market application and technology benefits
- Curtis Jenkins, marketing communications, video production
- Lori Winkler, marketing communications, moral support.

"When evaluating the results [from Levson's proof of concept jump], we continued thinking about how to extract more useful data from a human-mounted GNSS system," Watson said. "It didn't take long to advance to the idea of using multiple receivers to deploy a full three-dimensional position and attitude system."

With an even more compact dual-constellation/dual-frequency receiver

Dave Lundquist

> "This is as close to **human flight** as I'm going to get."



board under development at the time, the opportunity arose for applying the company's hardware and software resources to skydiving while also testing the equipment and algorithms in an untried and challenging environment.

With the full support of NovAtel, the team worked through 2011 to refine the concept further and move towards a full-scale deployment and test, culminating in a day-long series of test jumps and data collection. A description of the GNSS technology and products adopted for wingsuit project can be found in the section "System Configuration" near the end of this article.

A key focus of the analysis would be on the ability of the GNSS equipment to accurately measure Levson's attitude or trajectory in real-time. (See the sidebar, "GNSS Attitude Determination on the Fly.")

Jump Day

A Cessna 206 "jump plane" and pilot (Patrick Pietrzak) were arranged for the entire day of August 2 at a drop zone near Innisfail, Alberta (52°04'40" N, 114°01'30" W), about an hour and a half drive from NovAtel's offices in Calgary. The team operated out of a former Royal Canadian Air Force training facility nearby.

By 8:00 a.m., the team had begun setting up the GNSS base station and running through a checklist of the aircraft and skydiving equipment. Levson and his crew rehearsed their techniques for executing a coordinated exit of the plane and worked out specific flight plans for the day.

The team first chose to mount one antenna on Levson's helmet (with Velcro tape) and a second one on his right heel (with black "gaffer tape"). The head-to-heel baseline combined all three rotational dimensions — pitch, roll, and yaw — in a complex way, but initially seemed like a good idea to give the longest possible baseline(nearly two meters).

Using a relatively large off-the-shelf enclosure for the receiver boards– as opposed to delaying the project and designing a smaller, custom enclosure–

GNSS Attitude Determination on the Fly

ROB WATSON
NOVATEL

GNSS technology is used in various ways to find attitude or trajectory. The simplest method relies on measuring the velocity of a single receiver and interpreting the direction of that vector as the vehicle's heading.

This works for applications where a vehicle's motion is constrained to only one axis – either absolutely, as with a train, or in the typical case of a car — when being driven responsibly!

In these cases, attitude is very closely linked to trajectory (in two dimensions, anyhow). This technique is not sufficient for measuring attitude under more complex dynamics, though, or where velocities are so low that measurement uncertainty masks the signal of interest. Consequently, a practical attitude-determination system requires additional sensors.

GNSS/INS Solutions

GNSS receivers can be tightly integrated with inertial measurement units (IMUs) to form a combined GNSS/INS (GNSS/inertial navigation system). In these systems, the IMU provides rapid angular rotation and acceleration measurements, complementing the absolute accuracy of the GNSS positions.

A GNSS/INS implementation can take advantage of the strengths of each type of system to provide accurate, continuous solutions for applications involving high dynamics, frequent GNSS signal outages, and other operational and environmental factors.

Certain aspects of GNSS/INS can prove challenging for some applications, however. One particular challenge is that the orientation of the IMU with respect to the GNSS antenna must be accurately known and typically must remain fixed. This is appropriate for an installation on a rigid body, but proves challenging when considering a body with independently moving parts (such as a skydiver).

Multi-GNSS Attitude

Another solution suitable for applications with good sky visibility involves the use of multiple GNSS receivers with antennas at different locations on the vehicle or body. Geometric analysis of the vectors between the independent points can yield attitude information. With two receivers, two attitude dimensions can be measured (e.g., pitch and yaw), while a third receiver adds full three-dimensional attitude determination.

Accuracy of a GNSS-only attitude system depends on the geometry of the antenna array, measurement accuracy, and the baseline computation technique. If we take it as a given that antennas are oriented and spaced to provide good geometry, the performance comes down to the accuracy of the baseline computation technique.

The simplest baseline computation is done by differencing the positions reported by two antennas at the same time, and computing the vector between them. The resultant angle and baseline accuracy depend partly on the inter-antenna spacing (angular estimates will improve for longer baselines) and partly on the solution accuracies themselves.

A simplistic approximation of heading accuracy can be computed by just converting position error into angular error. Over a long baseline of, say, 300 meters (a typical tanker or cruise ship length), single-point RMS accuracies of 1.2 meters could provide heading accuracies on the order of

$$HeadingError \approx 2 \times \arctan\left(\frac{1.2m}{300m}\right) = 0.46^{\circ}.$$

The foregoing equation is not really accurate because it accounts for full two-dimensional error, while only the error perpendicular to the baseline is of concern; it does, however, provide a good "order of magnitude" estimate. Using the same proved valuable for simplicity but highlighted the importance of size in some applications.

The two receivers were strapped (and taped) to Levson's legs near his feet, with the battery pack strapped to one leg. A small pocket of space within the wingsuit, just above his feet, provided barely enough space for all of this equipment. The data collection PC was carried in a small backpack, worn in front of Levson's chest.

How about adding a third antenna to give a full 3D profile of jump dynamics, not just the heading?

"I would have loved to have a 3D solution including pitch and roll," says Watson. "But the wingsuit is very form-fitting and by the time we had [Levson] zipped up, there wasn't a lot of room."

Moreover, adding another receiver/antenna could create substantial changes in the mobility of a wingsuit skydiver.


Dave Lundquist

Rob Watson attaches antenna cable to the antenna on Andrew Levson's heel.

After the first two jumps with the above arrangement on August 2, on-site analysis showed that the head-mounted antenna was experiencing longer signal outages than the one on the foot. The culprit was suspected to be the aircraft wing immediately overhead blocking signals while

approximation on a shorter baseline of 10 meters — a small aircraft's wingspan, for example — that same heading error increases to nearly 14 degrees.

The problem is magnified on even shorter baselines until, at some point, the vector is meaningless. Clearly, further refinement of the individual solution accuracies is needed for short baselines.

If receivers can be operated in a dual-frequency real-time kinematic (RTK mode), individual solution accuracy can be improved to the range of one centimeter or better, assuming a relatively short distance to a reference base station. With such accuracy, we can now theoretically achieve a sub-degree heading accuracy over a baseline as short as one meter.

In fact, even as distance from a fixed base station increases, this heading accuracy would not degrade significantly on short-baseline installations because errors would remain highly correlated on the installed antennas. At very long distances from base stations, though, integer ambiguity resolution becomes less reliable and increases the probability of a large blunder affecting position accuracy.

Although the accuracy from a dual-RTK setup is attractive for many applications, there is a significant drawback to using RTK in such a system: it requires a fixed base station installation somewhere, and for this base station to be in communication with all receivers installed in the attitude-determination system.

Furthermore, each receiver must be in communication with a central processing system that reduces raw positions to attitude vectors. These communication links could be either complex to install or completely unavailable.

Multi-GNSS Attitude with a Moving Baseline

There is a way to achieve the RTK-level of heading accuracy without a base station. NovAtel has developed an RTK-based "moving base" solution that greatly simplifies the task of determining heading and baseline from multiple GNSS receivers.

Much as in the RTK method, a "Master" receiver with this proprietary design periodically sends correction data to one or more similarly configured Rover receivers, along with its own position at the same time. The Rovers then compute their own position relative to the Master using, ideally, fixed-integer RTK techniques. (Less accurate "float" solutions are also possible under poor signal conditions.) In effect, the equipment adapts the traditional RTK mode to function with a different base position at every epoch.

As compared with the dual-RTK method described earlier, this proprietary design has some clear advantages. First, the base infrastructure (i.e., fixed base station) and communications requirements are markedly reduced.

Without a requirement for absolute accuracy to be at the centimeter level (needing only the relative accuracy for attitude determination), receivers can operate in a single-point mode with no need for ground-based differential corrections. Additionally, the NovAtel system's computations are done on-board the Rover receiver with native firmware features, eliminating the role of a central processor to accomplish that same task.

The second advantage to this moving-base solution is less obvious: an inherent increase in heading/baseline accuracy occurs when using it as opposed to a dual RTK solution. In a two-receiver setup, the dual-RTK method involves two independent baselines (Base – Rx1, Base – Rx2) with an associated inaccuracy for each baseline. Differencing these two positions could double the inaccuracy in some circumstances.

Conversely, operating those same two receivers in the moving-base mode computes only a single baseline (Moving Master-Rover), and usually that will be a shorter baseline than in an RTK setup (Fixed Base-Rover).

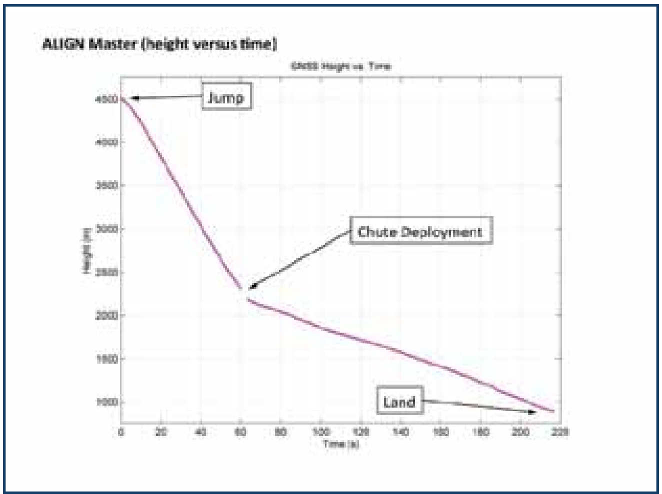


FIGURE 2 Real-time vertical positions of a jump

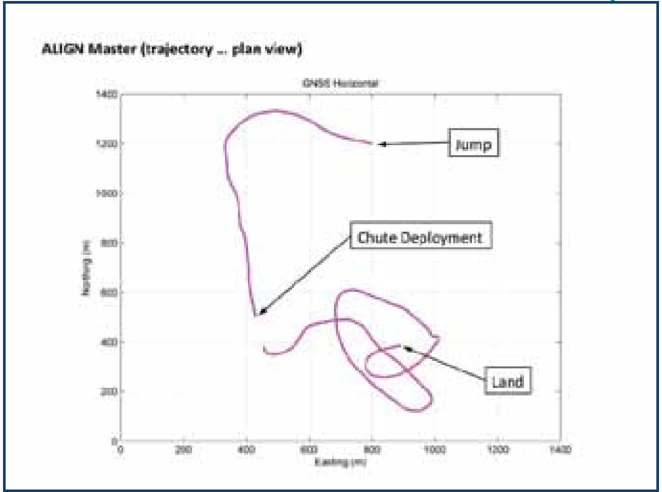


FIGURE 3 Real-time trajectory logged from Master receiver

Levson climbed out of the plane door and got ready to jump.

So, the remaining jumps took place with one antenna mounted on each foot. In this arrangement, Levson's roll and yaw (heading) could be measured independently, (from the HEADING log's pitch and heading outputs, respectively), but the team was left with no information on his pitch. (Being offset 90 degrees from Levson's direction of travel, the "heading" field itself measures his heading, when adjusted by 90 degrees, but the pitch measurement corresponds to his roll attitude. See Figure 2 in the sidebar "In-Office Data Processing and Analysis.")

In any case, given that the original head/foot configuration did not allow the data for each dimension to be decorrelated from the others, the new arrangement proved better for analysis despite the shorter baseline.

In total, Levson conducted seven test jumps on the event day, with an average interval of about 90 minutes between jumps during which the team repacked the parachute, verified the data integrity, and carried out a rudimentary data analysis to decide on any changes in the jump procedure for the next round.

Each jump was videotaped and photographed in the air and from the ground by the following personnel: ground photographer, Dave Lundquist; ground videographer: Curtis Jenkins (NovAtel); in-air photos/video, Aidan Walters and David S.

Levson and the in-air photographers choreographed their jumps to avoid collisions as they moved around each other as they carried out preplanned photo or video opportunities.

Dave Lundquist

Rob Watson helps Andrew Levson gear up for a jump.

Data Collection and Analysis

At the conclusion of each test jump, Levson terminated the data collection after landing safely. As he walked from the landing zone to the hangar, the data collection PC began data postprocessing with NovAtel's proprietary analysis utilities. This gave the team near-immediate access to basic satellite visibility, single-point position, velocity, and availability data.

The ground team was able to examine this data for outages and performance effects while the jump team prepared for the next jump. This analysis, correlated with video footage of the jumps, is actually what led to the decision to change to a foot-mounted antenna setup after struggling with wing-induced outages on the first two jumps.

The wingsuit equipment used a firm-

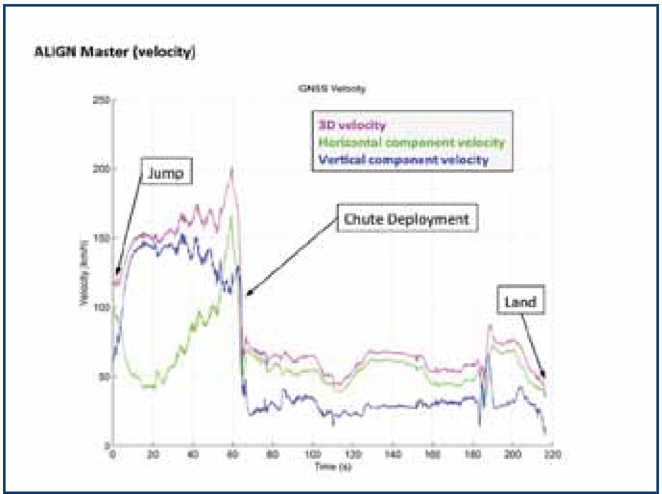


FIGURE 4 3D velocity during a jump

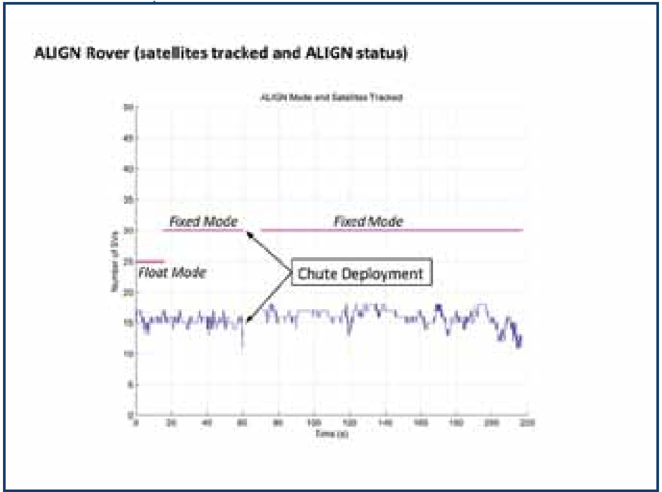


FIGURE 5 Satellites tracked during a jump. Marked decrease of SVs at 60 seconds reflects chute deployment and reorientation of antennas.

ware option that generates high-precision, real-time heading and pitch angles between two receivers.

Figure 2 shows the vertical results of a jump output using this firmware as recorded on the Master receiver. Acceleration into glide trajectory after Levson exits the plane is followed by parachute deployment after about one minute. At this point, a momentary loss of satellite tracking occurs due to the antennas pointing toward the ground as Levson's orientation changes rapidly.

After a few seconds, the satellite signals are reacquired. Average rate of descent during the chute stage is 30 km/h (8.5 m/s). Total duration of the flight (jump to landing) is 217 seconds.

Figure 3 shows the real-time record of the Master receiver's trajectory, while **Figure 4** records the Master's 3D velocity and separate horizontal and vertical components.

The latter figure shows the rapid increase in vertical velocity immediately after Levson jumps and a rapid decrease in horizontal velocity. His horizontal speed increases at the 50–60-seconds mark when Levson accelerates away from the camera. Vertical descent slows after chute deployment from more than 130 kph to about 30 kph.

Significant velocity changes at 183-187 seconds reflect moves made to take another photo. Maximum velocities during the flight: horizontal, 164.5 kph; vertical, 150.8 kph; and 3D, 199.8 kph.

Figure 5 illustrates the number of satellites tracked by the Rover receiver during various phases of flight as well as the ambiguity resolution mode (float and fixed-integer) of the signal-processing. The figure data reflect generally good satellite tracking throughout the jump with a momentary dip in the number of satellites at the 60-second mark during chute deployment due to a change in Levson's orientation that caused antennas on heels to point to the ground.

Of the five jumps conducted in the foot-to-foot configuration, two suffered from data outages caused by the collection PC itself. This small laptop was not designed to sustain the type of shock and forces associated with a parachute opening; so, these failures were not really surprising.

For the remaining three jumps, team members continued the work back at NovAtel's offices with extended post-processing and analysis. They generated trajectories for each antenna as well as heading, pitch and baseline solutions, and then compared these against the real-time position and heading data.

These analyses showed a close correspondence between the results of the real-time and postprocessed data. For more detailed discussion of these results, see the sidebar "In-Office Data Processing and Analysis."

Not Jumping to Conclusions

The NovAtel team believes they still have a good deal of work ahead in exploring the possibilities that the wingsuit project seems to point to and optimizing future system design.

From a test point of view, adding an inertial measurement unit to the wingsuit system might help with accuracy checks and strengthen the independent "truth" component, Morley says. The company actually came out with a GNSS/INS product a couple a months later that would be small enough to use in this type of testing.

Morley wants to know "how robust is the heading vector and how can we apply it within a distributed architecture."

He points out that the orientation of antennas was suboptimal and "used out-of-the-box algorithms that were not tweaked for this."

Nonetheless, the performance of the wingsuit-based system, particularly the real-time ambiguity resolution, "totally exceeded my expectations," says Morley. "It's rare that I'm pleasantly surprised."

Beyond the Wild Blue Yonder

Despite the exciting and novel use of the human body as a testbed, NovAtel has a higher set of expectations about the commercial benefits of its efforts in support of Levson's high-flying addiction.

After all, even if GNSS technology were adopted for measuring in-air performances, skydiving probably will never represent the kind of addressable

In-Office Data Processing and Analysis

THOMAS MORLEY, SAMANTHA POON, ROB WATSON
NOVATEL, INC.

With high-quality data sets obtained in the foot-to-foot configuration, we set about on postprocessing the data to extract more information about the NovAtel wingsuit system's performance in the free-fall environment.

This was a multi-step process involving several NovAtel utilities and techniques, which we will describe here.

Step 1: Video Time-Synchronization

Each jump was videotaped by an in-air videographer. In order to correlate effects observed in the data with real-world dynamics seen on the video (including such important events as time of the jump itself), we created a very simple synchronization method.

After the videographer had begun filming during the airplane's flight up, he shot a short sequence of our wingsuit flyer, Andrew Levson, hitting a key on the collection PC to create a time mark in the GPS data itself. At this point, the data PC output an obvious visual cue (a color change), which was then correlated with the GPS time mark in post-mission analysis.

For the rest of the jump, the video was run continuously with events measured from the synchronization mark. Using this method, we fairly easily correlated several events in the video with obvious changes in dynamics.

Step 2: Base Station Coordinates

Our static base station at the Innisfail Airport collected data for approximately 12 hours continuously during the event day. To use it as a reference station for the individual jumps, we needed to determine its coordinates as precisely as possible.

We used GrafNav, a NovAtel product from our Waypoint Products Group, in PPP (precise point positioning) mode, accessing downloaded precise satellite ephemeris and clock information to estimate a position. The long (12-hour) data set, combined with precise post-mission information, yielded a base station estimate accurate to approximately two centimeters or better, based on the solution standard deviation. Given that this is roughly two orders of magnitude better than typical single-point accuracy, we deemed it accurate enough to serve as a reference position for further postprocessing.

Step 3: Aerial "Truth" Trajectories

In our wingsuit application, we lack a defined "truth" to compare against. To get our best possible estimate, though, we processed the raw range data collected by each airborne receiver (at 20 hertz) in differential mode with GrafNav. This software resolves carrier-phase ambiguities in much the same way as a real-time kinematic (RTK) application, but it processes the data both forwards and backwards to improve ambiguity resolution in the case of outages.

Using GrafNav, we were able to obtain a roughly centimeter-level of accuracy for each receiver for the majority of each flight (except as limited by data outages). Obviously the raw range data used to create the GrafNav "truth" is the same as that used to generate the real-time single-point solution; so, the two trajectories are fundamentally correlated.

However, the addition of fixed base station data to the GrafNav solution allows us to detect and reject any major blunders in range data. With this, we are confident that those GrafNav solutions identified as having fixed-integer ambiguities are, in fact, correct to within about two centimeters. Howevers, the uncertainty in the base station position (± two centimeters) is still a factor.

"Truth" Heading/Pitch

As with the single-point position, we also lack truth data for receiver-to-receiver heading and pitch.

We do have two methods to obtain semi-independent esti-

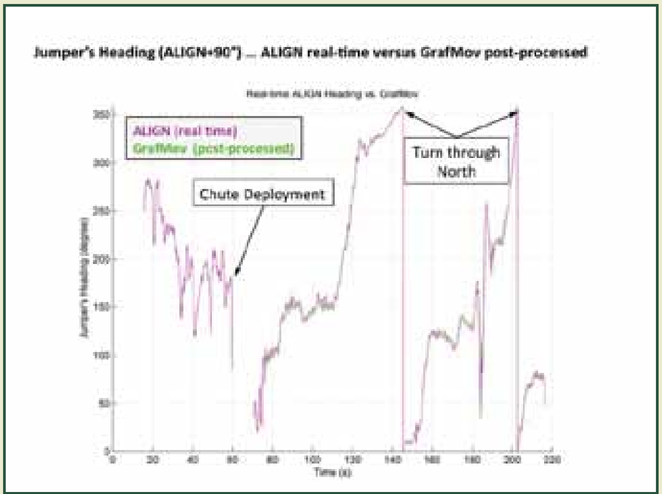


FIGURE 1 Comparison of jumper's heading, real-time versus postprocessed

FIGURE 2 Jumper/ALIGN heading offset

mates of "truth" heading/pitch, though. The first is to use a difference of postprocessed GrafNav solutions (discussed previously). In concept, this would be similar to computing heading between two receivers operating in RTK mode, with the associated accuracy.

The second method involves using GrafMov software, another NovAtel product from our Waypoint Products Group, to compute a moving-baseline solution between the two airborne receivers, in much the same way that ALIGN itself works. The added redundancy of having both forward and backward processing with an independent engine gives added confidence that we are likely to identify any major blunders.

In addition to the GrafMov/GrafNav ALIGN calculations, we have one further constraint on our data that serves as an excellent sanity check of the real-time ALIGN solution. With the antennas mounted on Andrew's heels, the baseline length between them was constrained during free-fall to a maximum of roughly 90 centimeters by his wingsuit.

Given this knowledge, we can very easily identify any major blunders in the ALIGN solution when the baseline length is reported to be longer than this. So, even though we are operating without a true "fixed" baseline, we still have an absolute limit based on physical parameters that provides us with more opportunity to check our performance.

Step 4: Extracting Accuracy Statistics

For both position and ALIGN data, we have assessed accuracy using a proprietary position analysis utility — a console-based application specifically designed to compare unit-under-test data points to either a fixed or moving "truth."

Type	Test Data	"Truth Data"
Pos Accuracy	Real-time Single-Point	GrafNav Fwd/Rev
ALIGN Accuracy	Real-time ALIGN	Dual GrafNav Fwd/Rev (difference)
ALIGN Accuracy	Real-time ALIGN	GrafMov Moving Baseline Fwd/Rev

In all, we compared several different versions of test data with the reference data output by both GrafNav and GrafMov:

Figure 1 compares the jumper's heading in real-time ALIGN versus GrafMov postprocessed results. The results have been filtered to show only data when real-time ALIGN is in fixed ambiguity mode. Note that the ALIGN trajectory is offset at right angles to the jumper's heading as a result of the wingsuit setup and geometry (**Figure 2**).

Figure 3 compares the jumper's real-time heading (purple data points) against results from two different postprocessed methods:

- GrafMov heading (green data points) was established by processing forwards and backwards through the data, with an independent processing engine from that used by the real-time ALIGN firmware.
- GrafNav (blue data points) shows two RTK trajectories calculated by processing forwards and backwards through the data, with the heading then computed from RTK position (right heel) to RTK position (left heel). This method produces statistically less accurate results than computing a relative heading.

Figure 4 compares the real-time ALIGN heading with that calculated by two types of postprocessing software. (Results are filtered to show only data when real-time ALIGN is in fixed ambiguity mode.) Antenna separation between ALIGN Master and ALIGN Rover is approximately 60 centimeters on average.

The data indicate that the agreement between ALIGN and GrafMov is closer than ALIGN/GrafNav because the former heading is statistically more accurate than the GrafNav heading (based on two RTK positions).

Differences between GrafMov heading and ALIGN heading are as follows: <0.25° (50th percentile), <3.0° (90th percentile), <3.5° (95th percentile).

The heading "noise" appearing between 183 and 187 seconds is due to a high-dynamic turn that resulted in reduction in horizontal component of ALIGN Master-ALIGN Rover pair, which in turned decreased the heading accuracy. IG

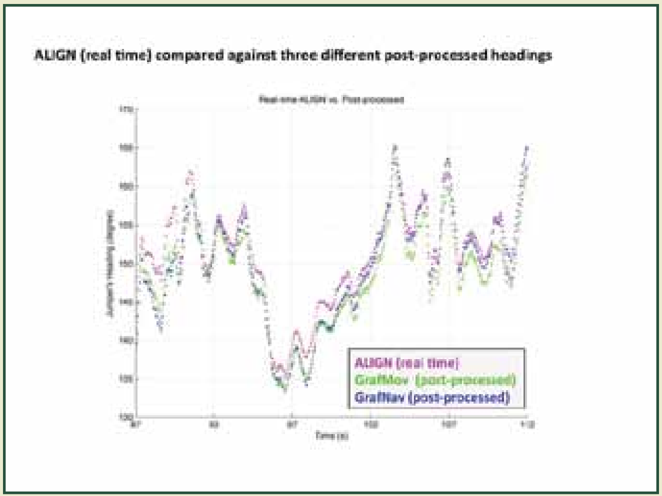


FIGURE 3 Real-time heading versus postprocessed results

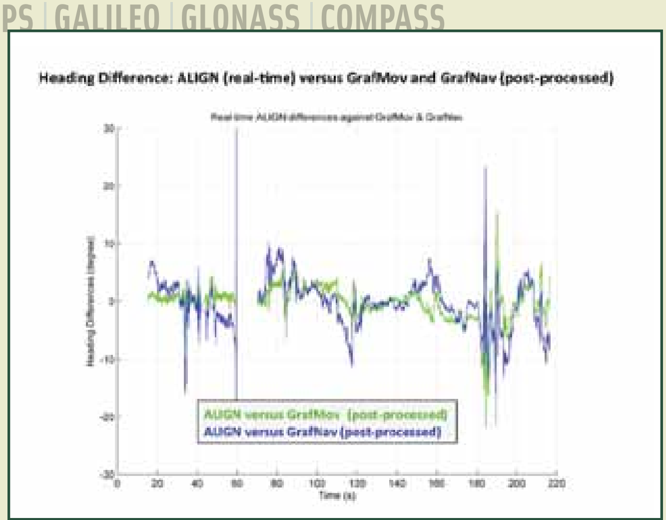


FIGURE 4 ALIGN heading versus postprocessed results

Aidan Walters, flying very close behind Levson to capture some pictures. Photo taken from ground by Dave Lundquist.

market that, for instance, precision agriculture or surveying does.

The NovAtel engineering, product development, and marketing team has just begun to think about applications that could be supported by a productized version of the wingsuit system.

Search and rescue or firefighting are areas that come to mind, with the first person out of a plane guiding others down to a landing site determined by the initial touchdown point. Peer-to-peer relative vectoring would eliminate the need to send data back to a base station or require team members to try to hit a preplanned location.

Managing swarms of unmanned aerial vehicles (UAVs) is another possible application of the lessons learned from the wingsuit project. More generally, the wingsuit experience and technologies supporting it could be turned into systems for mid-air deconfliction and collision avoidance.

The possibility for an improved aerial delivery system fires Morley's imagination. With his background in the Canadian Air Force, Morley sees the potential to create a set of self-assembling packages — jeeps, food, and ammunition, for example — that land in appropriate rows on the ground next to each other.

In such a system, air crews would not have to sort packages in the plane, but sleds or containers, outfitted with a relative vectoring system would arrange themselves in space as the parachutes float down.

"You don't have to have a point on the ground," Morley says. "You just let the operation happen in real-time."

Of course, as a supplier of OEM solutions, NovAtel's job is not to build the end-user equipment for a particular application. "That's up to our customers to do," he says.

"But I can tell them," Morley adds, "if we can make it work on the back of Andrew's heels at 100 kilometers per hour jumping out of an airplane, it will probably work for your application."

System Configuration

Both the NovAtel OEM628 and the new OEM615 receiver (still under development at the time) were attractive possibilities for deploying on a human body.

The wingsuit team eventually concluded that the 615's smaller size and power consumption were ideal for a man-mounted solution, while still allowing the use of dual-frequency GPS + GLONASS ALIGN firmware with up to 50-hertz raw measurement logging. At the time of test, OEM6 firmware version 6.100 had very recently been released and was used without modification during the August jumps.

While the OEM615 receiver itself is slightly less than 36 cubic centimeters in size and only 24 grams, the team ended up modifying an existing enclosure product for this jump session in order to easily support power and communications. This enclosure increased the volume of each receiver package to roughly 525 cubic centimeters and 300 grams — clearly not an optimal solution.

Power was provided by a 1.3 A-h, 12-volt battery (approximately 200 cubic centimeters, 450 grams); this battery was larger than needed for a 30-minute jump session, but provided enough power for multiple tests over the entire day.

The jump team obtained three compact (69 millimeter diameter; 22 millimeter height; 162 grams) L1/L2 GPS/GLONASS active antennas, the G5Ant-2AMNS1 from NovAtel's subsidiary, **Antcom Corporation,** Torrance, California, USA. Finally, for data collection the team employed an ASUS Eee PC from **ASUSTeK Computer Inc.**, Fremont, California USA with data logged via USB in a console-based script.

The data collection could have also been done using a much smaller flash memory device, but using the PC offered two advantages: First, with the PC the team was able to monitor GPS tracking during ascent in the jump plane to prevent extended losses of lock. Secondly, the console interface was used to provide a straightforward visual time synch signal for the in-air videographer. With this synchronization, they were able in post-mission to correlate observed GPS signal behavior with the jumper's dynamics in-flight.

To support post-processing analysis the team also set up a NovAtel SMART-MR10 receiver in the drop zone and collected static carrier phase and pseudorange data for the entire day of test (approximately 12 hours). Although the SMART-MR10 is not typically meant to serve as a precise base station, it is equipped with the same Pinwheel Antenna technology as NovAtel's survey-grade GPS-700 series of antennas and includes an integral OEMV-3 receiver that is commonly found in surveying equipment.