GPS and GPS+GLONASS RTK

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ABSTRACT
This paper presents not only two new RTK products, but also a major breakthrough in global positioning technology, taking RTK where it has never gone before.

The first new product is the Z-Sensor, a single board implementation of Ashtech's reknowned Z12 receiver.
The second product is the GG-RTK receiver, the world's first GPS+GLONASS RTK product.

RTK has represented the peak of GPS performance for several years, but there have been severe limitations – with fewer than 5 satellites in view RTK does not work at all, or works so slowly as to be almost no better than DGPS in many applications. Now, by combining GPS and GLONASS in an RTK product, you can do RTK, for the first time ever, in places such as open pit mines, urban canyon, river valleys, etc., where GPS-only RTK simply will not work.

PAPER ORGANIZATION
The paper is organized as follows:

Background & RTK
Introduces RTK. Readers familiar with the concepts may want to skip directly to *The Products.*

The Products
The most significant product specifications.

RTK Performance
Presents the parameters by which we will judge RTK performance.

Field Test Results
Presents real-world results for both products.

Availability
How much benefit do we get from the current, partial, GLONASS constellation? More than you'd think.

Reliability of GPS+GLONASS
Addresses the ever popular topic of GLONASS reliability, and shows how the GPS+GLONASS receiver has been architectured so that, no matter how GLONASS system performance compares to GPS system performance, the GG-RTK receiver always delivers better performance and reliability than a GPS-only receiver.

BACKGROUND
To obtain precise position from a GPS receiver, we use techniques called "Differential GPS". This involves two GPS receivers. One is stationary, at a known point, we call this the "Base" receiver. The Base receiver transmits data over a radio link. A second GPS receiver, possibly moving, at an unknown point, calculates precise position by using the signals it receives from the satellites, *and* the data it receives via radio from the Base. Differential GPS usually gives about one meter accuracy. RTK is a special form of Differential GPS that gives about one-hundred times greater accuracy.

RTK
The GPS system uses a coded signal from which a receiver derives distance and thus position. The code is a string of bits, like the ones and zeros in a computer. The receiver sees this code as tick-marks on a giant tape-measure, every transition from one to zero or back appears as a tick on the "tape measure". The C/A code has ticks at about 300 meter spacing. The encoded information gives the equivalent of the numbers on a tape-measure, and the receiver uses these codes to measure position to meter-level accuracy. The military, encrypted, P-code gives even better accuracy, roughly twice as good as the best C/A code receiver. But the microwave carrier, which is there ostensibly only to carry the coded signals, provides the best "tape-measure" of all, with tick-marks at about 20cm spacing. The receiver can measure these signals to centimeter precision. The trouble is, the carrier provides the equivalent of a very precisely graduated tape-measure with no numbers on it. If the receiver software could use the code to derive the numbers on this carrier "tape-measure", it would provide GPS accuracy of centimeters. This is exactly what RTK does.

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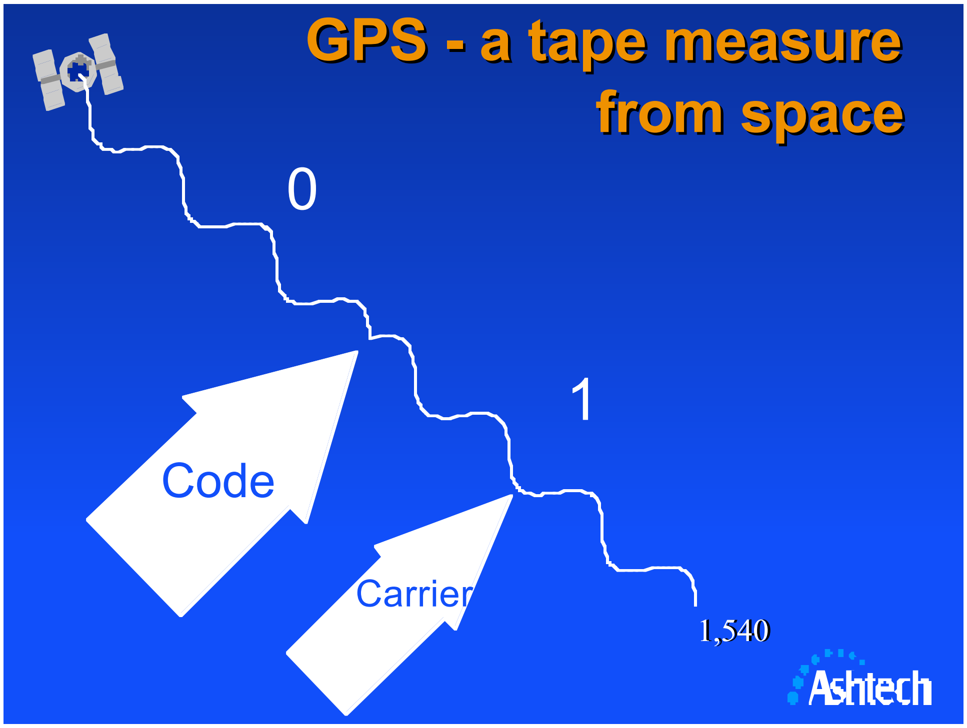
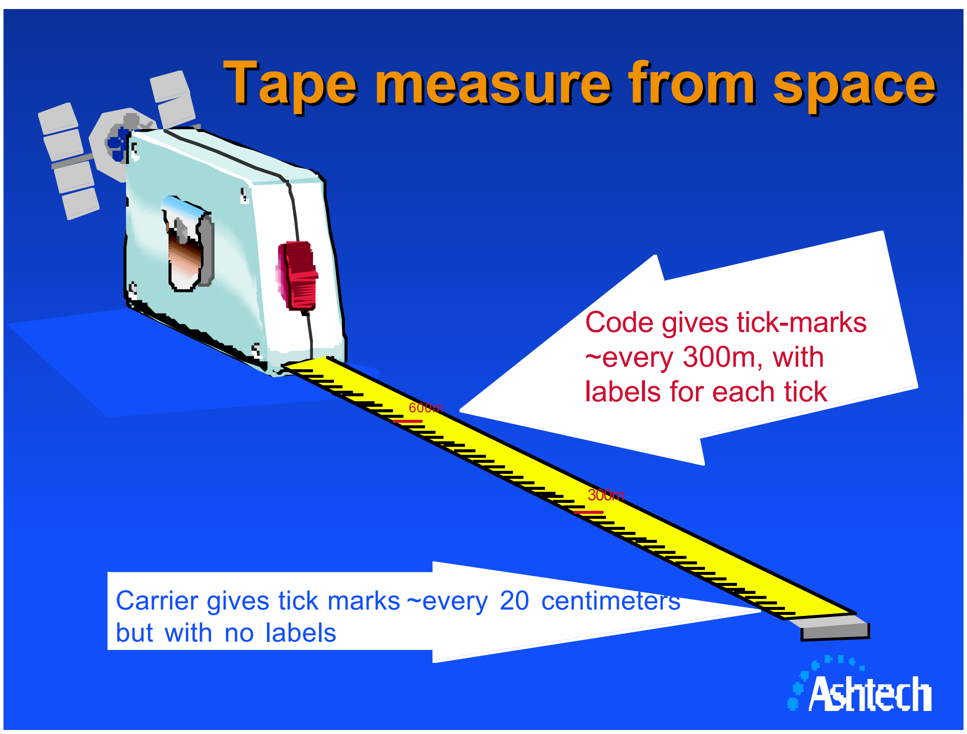




The GPS satellites provide the equivalent of a tape measure from space. The tape has labeled tick-marks at ~300m intervals (the code), as well as unlabelled tick-marks at ~20cm intervals (the carrier). A receiver can measure the code to 1m precision, and the carrier to one centimeter precision. A receiver that can compute the 'labels' on the carrier can then deliver centimeter position accuracy. This is what RTK receivers do.
What about GLONASS? GLONASS is the Russian GPS, and is almost identical in operation to the United States GPS.

RTK stands for "Real Time Kinematic", but it means real-time-centimeters. A brief dig through the layers of GPS history uncovers the origins of the terminology. The first use of GPS for centimeter position relied on static receivers which collected only carrier data, hours of data, to be processed later on desktop computers. This was called "*static*" surveying. The technique evolved till minutes, not hours, of data was enough, "*rapid-static*". Later techniques required only one static initialization of the receiver. From then on, as long as the receiver maintained phase-lock, it could be moved and the data would still yield centimeter accuracy when processed back in the office. This was "*kinematic*" surveying. With faster and smaller computers, the desktop processing moved into the GPS receiver itself, providing results in the field, in real-time. Hence "Real Time Kinematic".
There used to be a distinction between RTK with static initialization and RTK on-the-fly, but any modern RTK receiver that cannot do on-the-fly initialization is not worth bothering about.

THE PRODUCTS

Both products are available in two standard configurations: Base and Remote. Remote units have RTK capability, standard. Base units can provide Differential corrections and RTK data, at the same time, so you can operate DGPS and RTK remote units simultaneously with the same base station.

Both products conform to the RTCM standard for Differential and RTK data. So any other receiver (from any manufacturer) that also conforms to the RTCM standard can be used compatibly as a Base or Remote unit with an Ashtech Remote or Base, respectively, as long as it tracks the correct signal (dual frequency GPS, compatible with Z, or single frequency GPS+GLONASS, compatible with GG-RTK).
The Z Sensor also supports a more concise RTK format, as an alternative to RTCM, to reduce bandwidth requirements for RTK. The GG-RTK receiver achieves low bandwidth requirements, using the standard RTCM format, thanks to the low drift rate of GLONASS errors, and the fact that it is a single frequency receiver.

Both receivers provide high rate RTK updates with *no* extrapolation of old positions. Every position is based on a fresh set of range measurements at the Remote receiver.

Z Sensor

Specification hilites:

- 12-channel, all-in-view, full wave length code and carrier phase on L1 and L2
- Z-tracking (all observables, even with A-S on)
- Horizontal accuracy (1σ) 1cm.
- Vertical accuracy (1σ) 2cm.
- 10 Hz RTK position output
- Less than 30ms latency
- RTK on-the-fly initialization: > 99.9% reliability
- RTCM messages: 1, 2, 3, 6, 16, 18, 19, 22
- Power Consumption 7.5W

Form Factors:
Z-Surveyor: Injected molded plastic housing, including display, integral battery, removeable PC-Memory Card, and optional internal radio.
Z-Surveyor FX: Metal waterproof housing including display, internal PC-Memory Card, and optional internal radio.
Z-Sensor: Metal housing, no display, no memory, optional internal radio.
OEM Boards: The Z-Sensor is based on a single-board design. The boards are available for OEM purchase. Contact Ashtech for details.

For full specifications see product data sheets.

GG-RTK

Specification hilites:

- 12 channels GPS, L1 code and carrier
- 12 channels GLONASS, L1 code and carrier
- Horizontal accuracy (1σ) 1cm.
- Vertical accuracy (1σ) 1cm.
- 5 Hz RTK position output
- Less than 100ms latency
- RTK on-the-fly initialization: > 99.9% reliability
- RTCM: 1, 2, 3, 9, 16, 18, 19, 22, 31, 32, 34
- Power Consumption 2.6W (Sensor) 1.8W (Board)

Form Factors:
GG-Surveyor: Metal housing, no display, internal PC-Memory Card, optional internal radio.
GG-RTK Sensor: Metal housing, no display, no memory, optional internal radio.
GG RTK OEM Board: Eurocard format.
Any existing GG24 receiver can be upgraded to a GG-RTK with no hardware changes.
For full specifications see product data sheets.

RTK PERFORMANCE

RTK is a special form of Differential GPS. It is differes from conventional DGPS in three major respects:

1. Typical accuracy is one hundred times as good as DGPS.
2. There is an initialization period following power-on. This initialization calculates the integer number of carrier phase wavelengths. This is known as "fixing the integers".
3. There is a non-zero probability that the initialization will be wrong.

In assessing RTK performance we thus address all three issues: reliability, speed and accuracy.

RELIABILITY - The best RTK receivers offer greater than 99.9% reliability. To put this in context: suppose you turned on your RTK receiver once per day, the receiver fixed integers and from then on maintained lock on at least 4 satellites all day, then your receiver would fix integers incorrectly about once every three years.
Both the Z-Sensor and GG-RTK receivers provide greater than 99.9% reliability, as well as providing the user with control of the reliability. The user may choose from three "formal reliability" settings, corresponding to probabilities: 95%, 99% and 99.9%. The receiver guarantees that the achieved reliability is greater than the formal reliability setting. The greater the reliability the slower the initialization.

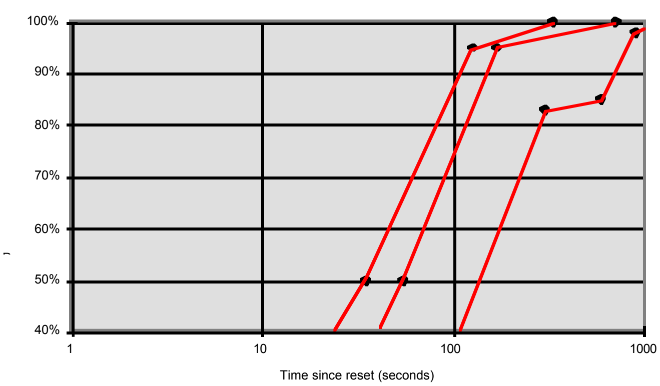
SPEED -
RTK initialization is split into two stages, the acquisition phase (when the satellites signal is acquired) and the integer fixing stage (when the integer numbers of wavelengths are computed). The GG-RTK receiver is always faster than a dual-frequency receiver for the acquisition phase (because it only needs to acquire the single-frequency C/A code, which is easy). On short baselines (<1km) the GG-RTK receiver is also faster than dual-frequency receivers for the integer-fixing stage. On medium and long baselines the Z receiver is faster than GG-RTK for the integer fixing stage. Typical times to fix integers are 30 seconds through 2 minutes.

ACCURACY - Once the integers are fixed correctly, RTK accuracy is at the centimeter-level. During the integer fixing phase, while the integers are being fixed they are modeled as real numbers (or *floating-point* numbers), and the position is referred to as a "*float*" solution. Float solutions have accuracy ranging from DGPS levels (meter level) to decimeter level, depending on how long the receiver has been tracking the signals.
If the integers are fixed incorrectly, the position will have float-solution accuracy, but the statistical indicators available in the field will make it look like it has centimeter accuracy. This will persist until the satellite geometry changes, and the receiver realizes its mistake. At this time the receiver will return to float mode, and then fix the integers correctly. The satellite geometry changes when new satellites come into view or, if this does not happen in time, when the satellites move enough in the sky (usually 2 - 10 minutes is required).

FIELD TESTS

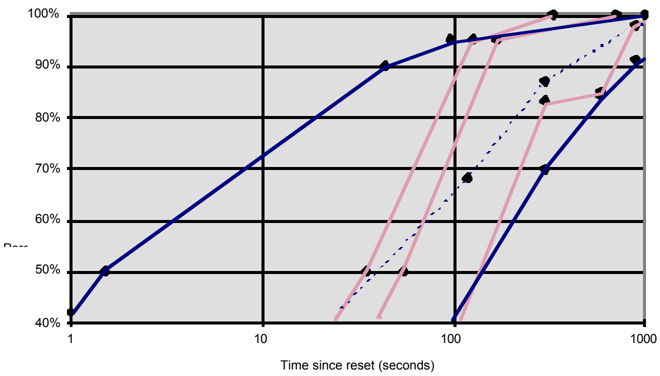
We present results achieved by the two new products, Z-Sensor and GG-RTK. The initialization results are summarized in the next two figures. These figures represent the results of, literally, thousand of tests. For each test the receiver is allowed to fix integers, and the time it takes to do this is recorded, then the receiver is reset. This gives us a measure of the integer-fixing phase of RTK initialization. Tests were done both for static and dynamic cases, the time to initialize is the same whether the receiver is static or dynamic.

The first plot shows the results for the Z receiver. The results are organized into three baselines: short (<1km), medium (3 to 7 km) and long (19 km). For the long baseline tests, data was logged to a PC and processed on the PC to give an approximation of what we expect to see in real time. PC-processed data is shown as a dotted line on the plots. Real time data collected so far agrees closely with the data processed on the PC, but, where we have not collected enough real-time data to give meaningful statistical results (i.e. thousands of tests) we show only the PC-processed results.



Z Receiver, RTK intialization, integer-fixing phase. Short, Medium and Long baselines

The second plot shows results for the GG-RTK receiver, collected and displayed in a similar way. The Z Receiver results are shown, in light grey, on this plot for reference.



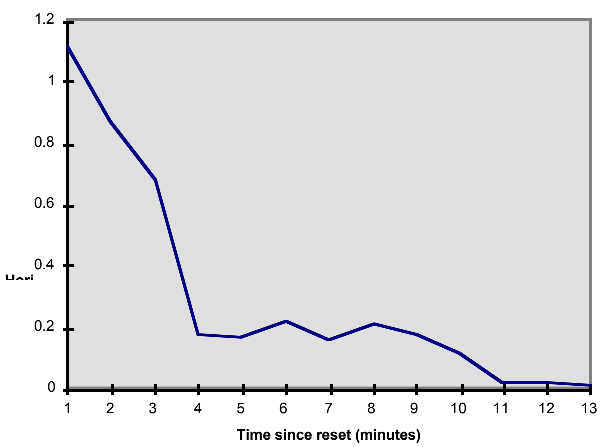
GG-RTK Receiver, RTK intialization, int.-fixing phase. Short, Medium and Long baselines

The above data was all collected with the default reliability setting, which is: formal reliability = 99%. In both cases (Z and GG-RTK) the achieved reliability exceeded the formal reliability.

The results show two things very clearly:

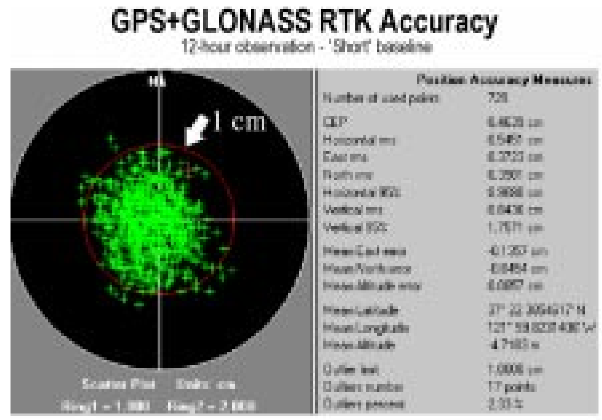
1. For short baselines GG-RTK is much faster than dual-frequency GPS-only RTK, with integer-fixing initialization occuring within 1.5 seconds in 50% of tests.
2. For longer baselines dual-frequency GPS-only RTK is faster than GG-RTK.

What about floating point accuracy? The following plot shows the typical behavior seen when the GG-RTK receiver does take a long time to fix integers. In this example the receiver took 11 minutes to fix integers on a 7km baseline, but the floating point accuracy converged to 20 centimeters within a few minutes - ideal performance for applications requiring 10-20 cm aaccuracy levels, such as guidance and machine control.



Float solution convergence of GG-RTK

Once the solution is fixed, horizontal accuracy is 1cm 1σ with degradation of 1 part per million on long baselines. A GPS paper wouldn't be complete without a scatter plot showing accuracy, and so here it is:



This plot was obtained from 12 hours of GG-RTK position data, with a short baseline. In this example the accuracy is well better than the specified accuracy. The horizontal rms accuracy of these RTK positions is 0.5cm. The worst case error is 1.3cm

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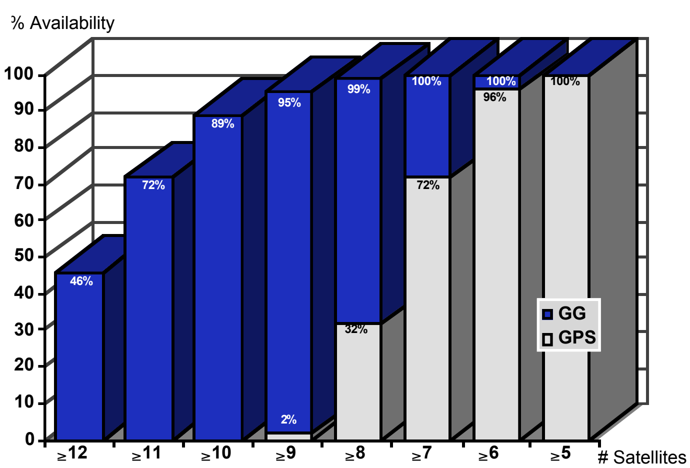
AVAILABILITY

The current satellite constellations provide 25 healthy GPS satellites, and 40 healthy GPS+GLONASS satellites. For RTK initialization, 5 satellites are required. This is no problem if the whole sky is visible, and, as already shown, dual frequency GPS-only RTK performance is similar to single-frequency GG-RTK when the whole sky is visible. However, there are occassions when there is no comparison between a GPS-only system, and a GPS+GLONASS system, and this is when large parts of the sky are blocked, such as in an open-pit mine, urban canyon, or river valley. To demonstrate this we did a simulation with a 30° mask angle (this is typical for an open pit mine). In this environment, 5 or more GPS sats are available only 6 hours per day, and the 6 hours is fragmented throug the day, making RTK a practical impossibility in these environments - if you only have GPS. But, with the combined GPS+GLONASS constellation the availability of 5 or more satellites improves by 300% to 18 hours per day.

The following plot shows today's satellite availability, comparing what you get with 25 satellites, to what you get with 40 satellites. The plot shows what percentage of the time the indicated number of satellites are visible. This plot was generated by doing an 8-day simulation, with a 10 degree mask angle.



Satellite availability, Kansas City, September 1997

SATELLITE RELIABILITY

What about the performance of the satellites themselves? There have been documented cases, for both GPS and GLONASS, of the satellite clocks generating errors of thousands of kilometers in *stand-alone* positions for many minutes before the respective system control set the satellite to "unhealthy".

For GG-RTK we automatically enable RAIM (standard) whenever you set up a base station. If the base station sees errors on the order of 100m, then RTK (or Differential) , simply removes the errors as part of the normal operation. If the base station sees an unexpected error (e.g. worse than 1km) on any satellite, then it knows something is wrong, and it immediately removes that satellite from the set of broadcast data, and then the remote station stops using the satellite too.

So, what many think is the BIG issue for GPS+GLONASS, satellite reliability, is a non-issue for RTK or Differential, if you're using an Ashtech base station.

The remote unit operates its own RAIM algorithm to detect and repair cycle slips. The remote receiver also weights measurements appropriately, so that the combined GPS+GLONASS position is always at least as accurate than either system alone.

COST

This paper ends with the bottom line - cost. Both new receivers are available at significant cost reduction over competing products. The Z receiver has been cost reduced by integrating what used to be on 5 circuit boards into one single board. The GG-RTK receiver is even less costly for a surprising reason - adding GLONASS to RTK reduces cost. Here's how:

The second GPS frequency is encrypted. This means that dual frequency GPS systems for civilian use have to perform significant extra processing to extract the observables from the encrypted signal. This makes the receivers more complex and therfor more costly. By using GLONASS instead of the second GPS frequency to provide the extra observables required for RTK, the cost of RTK systems has been significantly reduced.

CONCLUSION

There are now two options for RTK: dual-frequency-single-system and single-frequency-dual-system. Dual frequency systems have advantages on longer baselines, and present users with a cost-performance trade-off for anything but short baselines. The trade-off becomes noticeable at baselines of around 5km. For shorter baselines there is no trade-off, single-frequency-dual-systems not only costs less, but perform better than dual-frequency GPS-only RTK.

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