Achieving 20cm Positioning Accuracy in Real Time Using GPS – the Global Positioning System

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Marconi Canada (part of the Marconi North America Group of Marconi Electronic Systems) is a recognized world leader in the design, manufacture, sale and support of high-technology electronic products for the aerospace and communications market, for both military and commercial applications. Its headquarters and principal design and manufacturing facility is located in St-Laurent, Quebec (in the greater Montreal area). Its facilities include a branch plant in Kanata, Ontario (in the Ottawa area), as well as sales and service offices across Canada. A photograph of the Company's headquarters is presented in fig. 1.

Marconi Canada is a pioneer in the design and manufacture of GPS receivers. The first receiver development took place in the early 1980s with a military receiver development for the Canadian Department of National Defence. Then, in the mid-1980s, the first commercial GPS receiver was developed. The next major development took place in the early 1990s for a GPS receiver to be installed on the new Boeing 777 aircraft. This marked the beginning of a series of successes for Marconi Canada in the commercial avionics market, and the Company is now recognized as a world leader in this area.

In the mid-1990s, a new group was created with the objective of porting our GPS technology on low-cost hardware platforms. This initiative has been a success as well, with the development of a variety of products targeted towards the consumer market, namely: automatic vehicle location systems, marine navigation, golf yardage systems, surveying systems, and also some military applications requiring commercial off-the-shelf (COTS) solutions.

1 ***The headquarters of Marconi Canada***

Glossary

ASIC	Application Specific Integrated Circuit
DGPS	Differential Global Positioning System
FEPROM	Flash Erasable Programmable Read-Only Memory
IF	Intermediate Frequency
I/O	Input/Output
OEM	Original Equipment Manufacturer
PVT	Position, Velocity and Time
RF	Radio Frequency
RISC	Reduced Instruction Set Computer
RTK	Real-Time Kinematic
UART	Universal Asynchronous Receiver/Transmitter

Introduction to GPS

The NAVSTAR (NAVigation Satellite Timing And Ranging) Global Positioning System, better known as GPS, is a radionavigation system using a network of satellites distributed over six orbital planes. GPS provides accurate 3-D position, velocity and time information, and world-wide 24-hour coverage to an unlimited number of users with all-weather operation. GPS is a one-way ranging system: signals are transmitted only by the satellites. Each GPS satellite transmits signals centred on two microwave frequencies: 1575.42 MHz, referred to as Link 1, or simply L1; and 1227.60 MHz, referred to as L2.

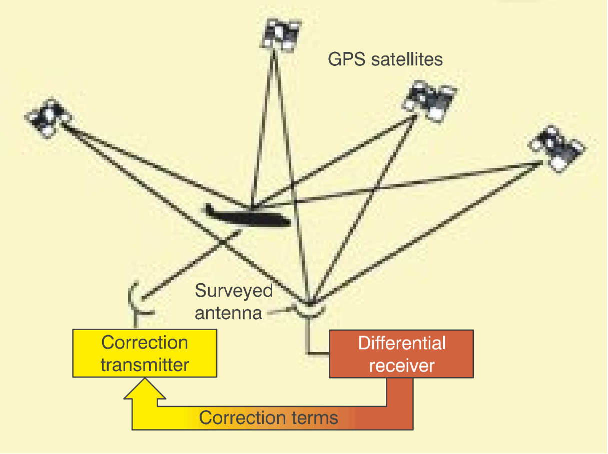
The L1 signal is modulated with (i) the Coarse Acquisition (or C/A) Code, a coarse ranging signal; (ii) the Precise (P) Code, a precise, but encrypted, ranging signal; and (iii) navigation data at 50 bits per second. L2 is modulated only with the P-Code and the navigation data. Authorized users only (U.S. Department of Defense and allies) have access to the decryption keys of the P-Code, which by its nature has much higher anti-jamming properties than the C/A-Code. Using the ranging signal and the navigation data, a GPS receiver can measure the range between the satellite and the receiving antenna, and compute the exact position of the transmitting satellite. Hence, with three satellites, the 3-D position of the receiver may be computed, and a fourth is required for solution of the time. An excellent overview of the GPS system operation is given in reference (1).

Code Differential GPS Overview

Code Differential GPS (Code DGPS) is the regular Global Positioning System with the addition of a differential signal that conveys correction data. These data significantly increase the accuracy of the GPS navigation function and can be broadcast over any authorized communication channel. In these systems, a GPS receiver is located at a known (surveyed) position: this receiver is usually referred to as a reference station. The reference station makes measurements on the satellite's signal and estimates the measurement errors using its surveyed geodetic position. The errors include the signal transmission delays caused by the ionosphere and the troposphere, as well as Selective Availability (S/A) – an intentional signal degradation introduced by the U.S. Department of Defense, in an effort to restrict the accuracy capability of most civilian GPS users.

In layman's terms, because the reference station knows precisely where it is and computes a different position using the GPS signals, it can estimate the errors in its signal measurements. These errors, or differential corrections (that is, the difference between the true range and the measured range), are then transmitted to roving receivers by radio or other means. They can then be applied to GPS measurements from the roving GPS receiver, and used to remove the systematic (correctable) error factors, because most of these errors will be similar for the roving receivers. Note that the correlation factor between errors observed at both sites largely depends on the distance between the two receivers.

A DGPS system therefore consists of at least two units: a reference station and one (or several) roving units. The reference station broadcasts its differential data and the roving units receive it through a data port, directly connected to a radio receiver. The roving units can then display position, velocity, time (PVT) and other information, as needed for their marine, land or aeronautical applications. A DGPS system implementation is depicted in fig. 2 (note that the reference station is located on the ground and the roving unit is located in the aircraft).



2 ***Code Differential Global Positioning System (DGPS) example***

Carrier Differential GPS Overview

A different, and more accurate, differential correction technique involves tracking of the satellite signal's carrier phase, and is called carrier-phase DGPS. When a receiver navigates in carrier-phase mode, it is measuring a different GPS observable, namely the GPS carrier wave. To do so, it must measure the phase of the carrier continuously from signal lock time, t_0, in order to produce the following observable:

$$\phi_m(t) = \phi(t = t_0) + \int_{t_0}^{t} f\mathrm{d}t, \tag{1}$$

where ϕ is the received carrier phase and f is the received Doppler frequency.

In order to produce a range measurement between the satellite and the user, the following observable must then be formed:

$$\rho^{\phi}(t) = N_0 + \phi_m(t), \tag{2}$$

where N_0 is an exact number of cycles between the user and the satellite at time t_0. ϕ_m thus represents the change in cycles since time t_0.

However, the initial number of wavelengths N_0 between the satellite and the receiver is unknown. This is called the **carrier phase ambiguity** and must be estimated. In order to estimate this ambiguity, it is necessary for the roving GPS unit to use information (that is, carrier-phase measurements) from a reference station. This technique yields accuracies in the cm-range in dynamic environments and is called 'Real-time Kinematic', or RTK, GPS. A rather good (albeit brief) introduction to code and carrier-phase DGPS is presented in reference (2).

System Specifications

The RTK-capable engine developed by Marconi Canada, called the RT•Star, consists of single-frequency (L1) RTK Navigation software residing on a low-cost hardware platform for embedding in Original Equipment Manufacturer (OEM) systems. It measures 4″ × 2.65″ (100 mm × 67 mm) and consumes 2W. Details of its use, performance and specifications are presented in reference (3). This product is considered to possess one of the highest accuracy-over-price ratios in the OEM sensor industry.

The RT•Star can be configured either as a reference station or a roving unit via a command message. Communication between both is implemented via a standard radio link and the information is encoded in RTCM-104 format(4). Communication from a host computer with the GPS engine is performed via a serial port using an RS-232 Marconi-proprietary transmission protocol. The reference station is also capable of self-surveying its position.

The RT•Star has the following features:

- 12 parallel tracking channels;
- GPS measurements sampling aligned on GPS time one-second roll-over event;
- raw measurement output rate of 10 Hz;
- time mark signal output aligned on GPS time one-second roll-over event;
- keep-alive input pin (RAM and/or real-time clock);
- dual UART (third UART optional);
- six input/output discrete control lines;
- reprogrammable operational code (FEPROM); and
- rechargeable lithium battery (optional).

The RT•Star is compatible with both active and passive antennas.

System Architecture

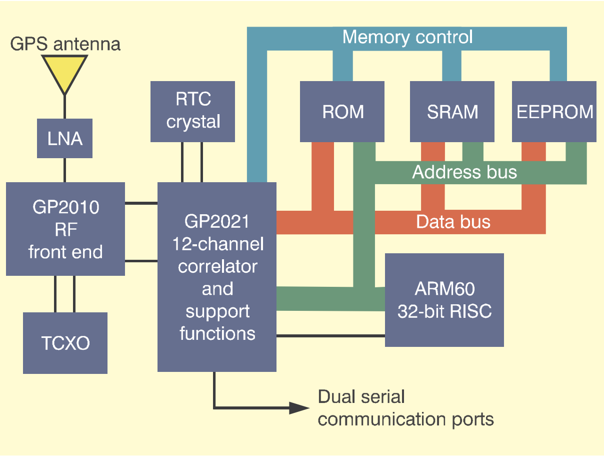
Hardware Overview

The RT•Star hardware is a highly integrated design built around three components(5):

- RF front-end,
- digital signal processing (DSP) ASIC, and
- RISC processor.

Fig. 3 depicts a block diagram of the receiver.

The RF chip, preceded by a low-noise amplifier (LNA), performs a triple IF conversion, from 1575.42 MHz to 4.3 MHz, and a 2-bit analog-to-digital conversion.



3 ***Receiver block diagram***

The temperature-controlled crystal oscillator (TCXO) is the receiver's reference oscillator.

The DSP chip includes a 12-channel GPS signal correlator and the following peripheral circuits:

- two programmable UARTs;
- real-time clock;
- programmable interrupts;
- watch-dog and reset circuit; and
- discrete I/Os.

The processor is the system's critical component. The ARM60 RISC processor was selected because it has:

- the processing power to handle 12 tracking channels;
- 30% spare capacity for customer-specific tasks; and
- low cost and power consumption.

Software Overview

The embedded software was developed using object-oriented design and programming techniques in order to yield reusable software components and to encapsulate the functions most subject to change. The major objects encapsulate the following functionalities:

- Signal Processing;
- Satellite List Management;
- I/O Management;
- Differential Data Processing; and
- Navigator.

The Navigator is the ultimate recipient of the work produced by the other objects: it receives all the data (measurements, differential data, satellite data...) and produces a PVT estimate.

Navigator Overview

A comprehensive description of the Navigator's algorithms is presented in reference (6). Only a brief overview is presented below.

One of the first steps to be performed in an RTK Navigation solution is to form two sets of observables: the single and the double-differences$^{(2)}$. Both are derived using the carrier phase observable, which is defined as:

$$\rho^{\phi} = R + c(\Delta t^{u} - \Delta t^{s} - \Delta iono + \Delta tropo) + \epsilon^{orbit} + N_0 \lambda + \eta_{\phi} \, , \tag{3}$$

where:

R	is the true range between satellite and user;
c	is the speed of light;
Δt^{u}	is the user's clock offset from true time;
Δt^{s}	is the satellite's clock offset, including relativistic effects;
$\Delta iono$	is the total ionospheric advance (the dispersive property of the ionosphere on the carrier actually causes an advance of the signal with respect to the modulated code);
$\Delta tropo$	is the total tropospheric delay;
ϵ^{orbit}	is the error introduced by the orbital data;
N_0	is the initial carrier phase ambiguity;
λ	is the signal's wavelength (19 cm for L1); and
η_{ϕ}	is the error caused by the receiver thermal noise; it is a Gaussian process with zero mean.

Note that in eqn. (3), R is the true range between the satellite and the user. Geometrically, this can be expressed as:

$$R = \sqrt{(x^{s} - x^{u})^2 + (y^{s} - y^{u})^2 + (z^{s} - z^{u})^2} \, , \tag{4}$$

where x^{s}, y^{s}, z^{s} are the satellite's coordinates as provided by the satellite's navigation data and x^{u}, y^{u}, z^{u} are the unknown user's coordinates.

A single-difference across satellites is defined as the instantaneous difference in the carrier phase measurement made by the same receiver observing two satellite signals simultaneously. The single-difference operator is denoted as ∇. From n satellites $(n-1)$ single-differences can be formed. The simplest way of forming these $(n-1)$ observables is by selecting a reference satellite, s^{*}, and applying the operator ∇ as follows:

$$\nabla\phi_{s^{i},s^{*}} = \phi^{u}_{s^{i}} - \phi^{u}_{s^{*}} \, , \tag{5}$$

where $\phi^{u}_{s^{i}}$ represents the phase measurement by the user of satellite i.

Expanding eqn. (5) using eqn. (3) shows that the receiver clock errors are removed in the resulting single-difference observable.

To form the next observable, a double-difference, a set of $(n-1)$ single-differences must be formed with measurements from the roving user. Hence a set of $(n-1)$ single-differences are formed with measurements received by the reference station on the differential link. A double-difference would read as follows:

$$\Delta\nabla\phi^{r,u}_{s^{i},s^{*}} = \nabla\phi^{r}_{s^{i},s^{*}} - \nabla\phi^{u}_{s^{i},s^{*}} \, . \tag{6}$$

The property of this observable is that satellite clock errors are removed. Expansion of eqn. (6) with eqns. (3) and (5) yields an equation in which the unknowns are:

$\Delta\nabla R$,	the value of the geometric distance of the double-difference across satellites and receivers;
$\Delta\nabla iono$,	the value of the double advance of the carrier because of the ionosphere across satellites and receivers;
$\Delta\nabla tropo$,	the value of the double-differenced delay of the carrier because of the troposphere across satellites and receivers;
$\Delta\nabla N_0$,	the double-differenced ambiguity expressed in cycles (it is itself an integer since it is the algebraic sum of four integers);
$\Delta\nabla\epsilon^{orbit}$,	the value of the double-differenced orbital errors across satellites; and
$\Delta\nabla\eta_{\phi}$,	the double-differenced phase noise (the sum of four Gaussian processes with zero mean).

Because $\Delta\nabla\eta_{\phi}$ may be neglected if the receiver has relatively low phase noise, as well as $\Delta\nabla\epsilon^{orbit}$ (beyond the scope of this text), and because $\Delta\nabla iono$ and $\Delta\nabla tropo$ may be modelled, only $\Delta\nabla N_0$ remains to be properly estimated in order to solve for R. Fortunately, N_0 is a constant, hence it may be estimated over time using the carrier phase observables.

So, as we can see, a set of synchronized carrier phase measurements (that is, measurements that are sampled at the same time) from the reference station and the roving unit is required at the latter. One problem which arises is that the data link that provides the carrier measurements from the reference station has a given transmission latency. Consequently, the roving unit will receive its reference measurements with a typical latency of 1 to 2 seconds. Because a Navigation solution is required for the current time, the roving unit will have to have some means of extrapolating the reference measurements for the current time (that is, coincident with the unit's measurement time); then time-matched double-differences can be produced. This extrapolation process is implemented using Position-Velocity-Acceleration (PVA) tracking filters, which are not discussed here, but interested readers may find details on these filters in reference (7).

One realizes that the estimated state vector X is composed of two basic sets of parameters:

$$X = \{User\ Model \mid Measurement\ Model\}$$

The observability on these two sets is quite different. The user model represents the dynamics of the roving user. This set must be updated at the basic rate of the Navigator. However, the measurement model builds its observability on the change of geometry of the satellites that compose the unknown ambiguity. A fast update rate will not significantly improve the observability on the measurement model because of the high accuracy of the carrier phase measurements.

The Navigation function is therefore separated into two processes:

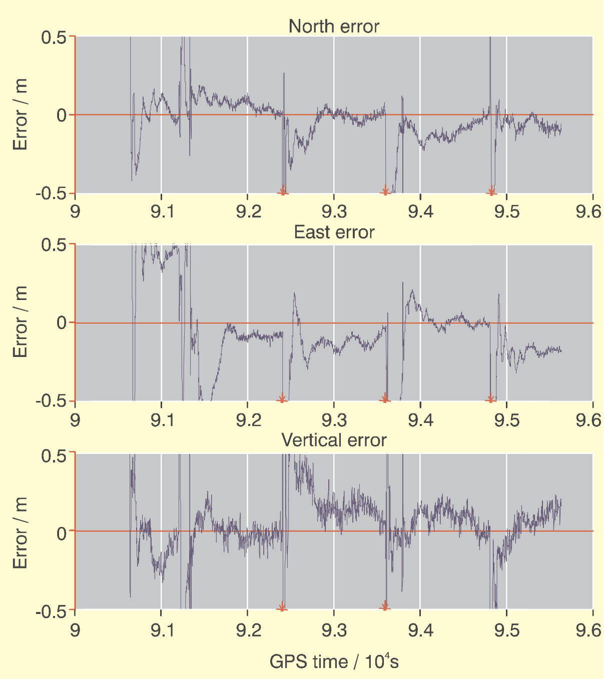
- a Kalman filter that acts upon reference station and roving unit measurements sampled at the same time. Because of the data link latency, this solution is typically old by a few seconds. This filter is referred to herein as the 'Off-Line Filter'; and
- a Kalman filter that acts upon extrapolated reference station measurements and roving unit measurements sampled for the current time. The update rate of this filter is currently at 1Hz. It is referred to herein as the 'On-Line Filter'.

These findings therefore suggest that the purpose of the Off-Line Filter is to estimate the ambiguity vector (measurement model) in the background. Because the dynamics of the ambiguities are very small (they tend towards constants), this filtering can be executed at a rate significantly lower than the required navigation rate.

The On-Line Filter is thus used to provide user PVT estimates at the nominal navigation rate. It will use the ambiguity vector computed by the Off-Line Filter.

Static Tests

A series of tests was carried out using three surveyed antennas located on Marconi Canada's roof, in order to establish the accuracy, convergence time and functional behaviour of the RT•Star in static mode.



4 ***Sample reset test***

Repeatability and convergence time were tested by forcing a system reset every 20 minutes over a period of 24 hours. A sample of one reset test is shown in fig. 4. The reset times are marked with a cross on the time axis. It is observed that the system repeatedly converges towards zero error.

Table 1 shows some statistics generated from the results. The 3-D r.m.s. error reaches 20 cm after approximately 7 minutes.

TABLE 1

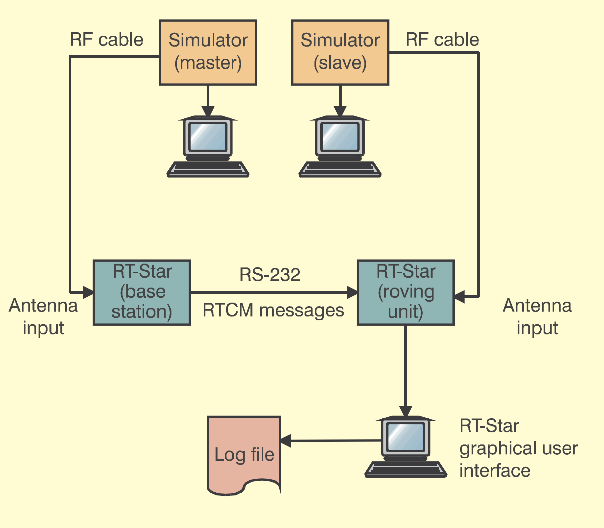
Reset Tests Statistics

Time after reset (minutes)	North r.m.s. error (cm)	East r.m.s. error (cm)	Vertical r.m.s. error (cm)
5	23	8	12
10	8	6	8
20	7	3	6

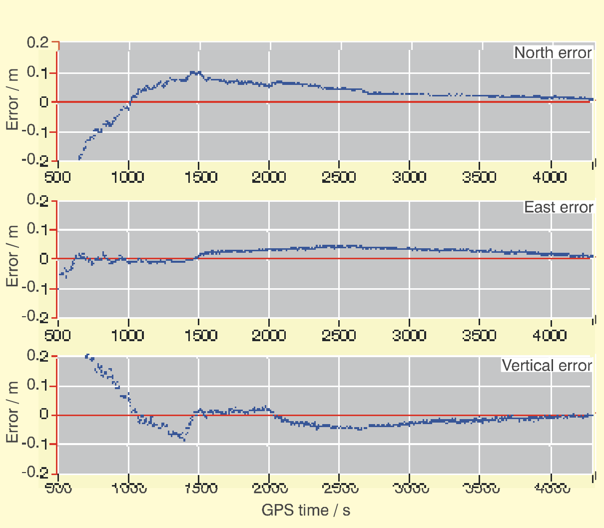
Kinematic Tests

Two types of kinematic tests were performed:

- GPS signal simulator tests to verify the absolute accuracy of the solution; and
- field tests to verify real-life accuracy and functionality of the system.



5 ***Simulator test set-up***



6 ***Simulator test position errors***

GPS Signal Simulator Tests

The purpose of the simulator test was to verify the accuracy of the RT•Star in a normal dynamic environment. Two Nortel model STR2760 GPS signal simulators were set up in differential mode to carry out this test. Fig. 5 depicts the test set-up.

The test simulates an aircraft performing dynamic manœuvres. The scenario is as follows:

- the aircraft is static for 10 minutes;
- it accelerates linearly with a 1g acceleration up to 100 m/s;
- it climbs to an altitude of 1 km;
- it then completes a square path at a constant speed of 100 m/s with 10 minutes between each turn;
- it touches ground and decelerates to 0 m/s; and
- it remains static for 5 minutes.

The position solution generated in real time by the RT•Star was logged and then compared to the truth file of the simulator, which is a file containing the true vehicle position at each GPS second. The results were processed with the MATLAB™ data analysis tool (provided by the MathWorks Inc.) and the North-East-Down position errors are presented in fig. 6.

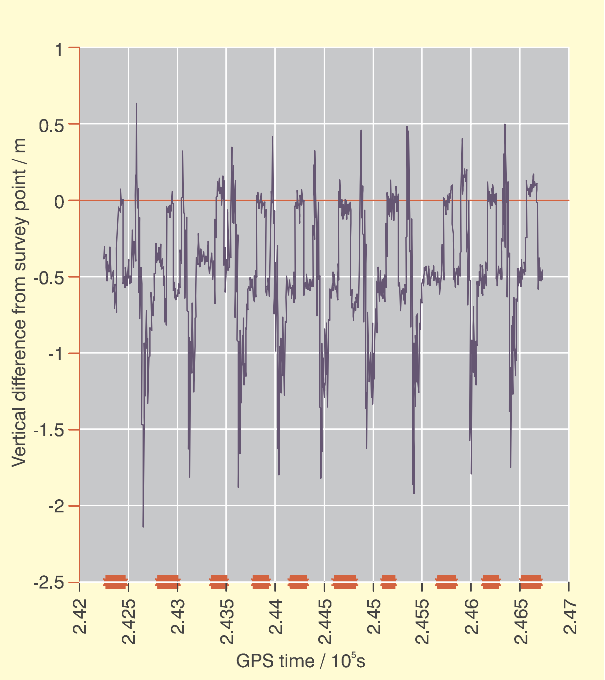
Field Tests

The purpose of these tests was to verify the accuracy and the functionality of the RT•Star in a real-life environment. Several kinematic baseline tests were performed using a reference station located on the Company's roof and a vehicle equipped with an antenna and an RT•Star. The vehicle followed a route located in an urban zone with a surveyed geodetic marker situated on the route. The test procedure is as follows:

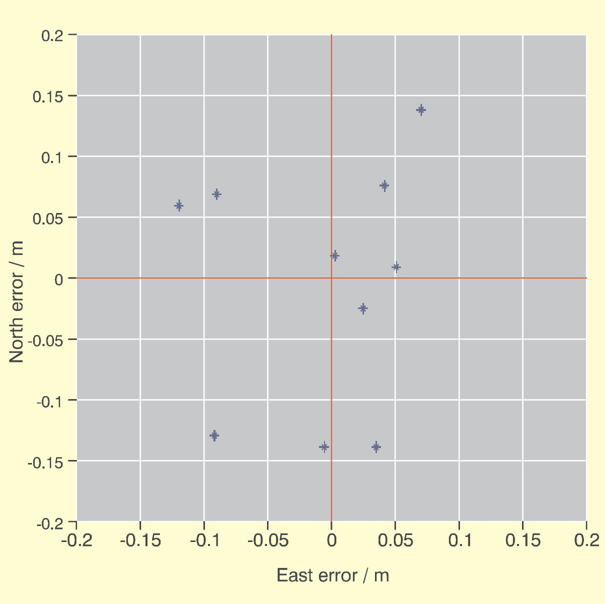
- the antenna is fixed to a surveying rod set on top of a geodetic marker located in front of the Company building;
- system is powered-on and remains static for 2 minutes;
- the antenna is relocated on the vehicle's roof (the operator triggers a signal that logs the time at which the antenna is removed);
- the vehicle drives around the Company site and stops at the geodetic marker;
- the antenna is removed from the rooftop and set on top of the marker (the operator triggers a signal that logs the time at which the antenna is set);
- the antenna remains static for approximately 2 minutes, the operator triggers the removal time log and relocates the antenna on the vehicle.

The above routine was repeated ten times.

Fig. 7 shows the position in the vertical plane. The red marks on the time axis represent the periods at which the antenna was located on the survey point. It is observed that repeatable results are obtained at each run.



7 ***Vehicle vertical difference***



8 ***Horizontal position error on survey point***

The error in the horizontal plane of the computed position of the marker at each run is presented in fig. 8.

Conclusions

The tests conducted on the RT•Star show that 20 cm positioning accuracy can be obtained in real time using GPS. Furthermore, the results have been proven to be repeatable.

The RT•Star (fig. 9) is considered an excellent trade-off between low-cost code differential GPS systems delivering 1 metre accuracy levels and high-end two-frequency RTK systems offering an accuracy level of only a few centimetres. It is suited for a variety of applications, namely precision agriculture, aircraft positioning and machine control. It also gives the user the flexibility to configure the receiver either as a reference station or a roving unit via a command message.

Acknowledgement

This paper is based on a presentation, entitled 'Precise Kinematic Positioning Experiments with a Low-Cost RTK GPS Engine', given by the author at the IEEE Position Location and Navigation Symposium '98 in April 1998 at Palm Springs, CA, USA, and published in the conference proceedings.

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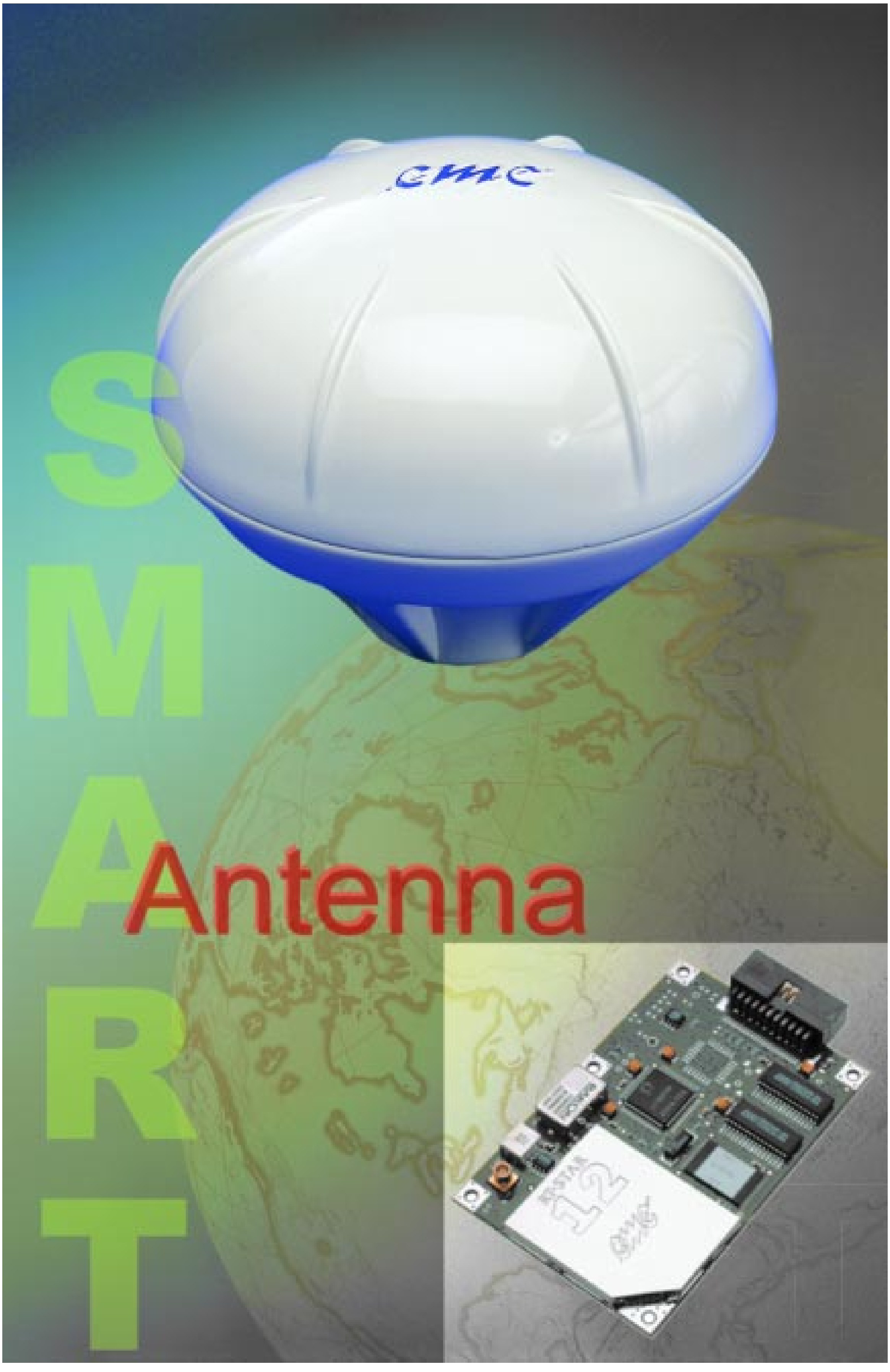

9 ***The RT•Star smart antenna unit: an RT•Star (shown inset) embedded in a GPS antenna***