Real-time positioning system performance has either been a few centimetres or a few metres. Satellite Based Augmentation Systems (SBAS) currently under development should provide a low cost solution with potentially sub-metre accuracy. One fully operational SBAS, available on a global basis, has pushed the technological boundary even further, providing real-time decimetre accuracy irrespective of distance from the reference sites.

Decimetre accuracy – without base stations

By Kevin Dixon

Laser and optical based systems such as total stations will continue to dominate those applications which require the highest accuracy at short ranges and in areas with little satellite coverage. Although there are research efforts underway to develop centimetre accurate indoor and short range wireless ranging systems, these will take time to appear in the marketplace. This article concerns recent developments, some still underway, for satellite-based positioning systems capable of sub-metre and even sub-decimetre accuracy.

Primary error sources

In order to evaluate the satellite positioning options available, the primary error sources contributing to the corrections need to be understood. Reference and rover errors include:

- **Satellite Orbit**
- **Satellite Clock**
- **Ionosphere**
- **Troposphere**
- **Multipath**
- **Earth Tides**
- **Receiver Clock**
- **Receiver Biases**

How these are all handled can be placed into two broad classes: Ground Based Augmentation Systems (GBAS) and Satellite Based Augmentation Systems (SBAS).

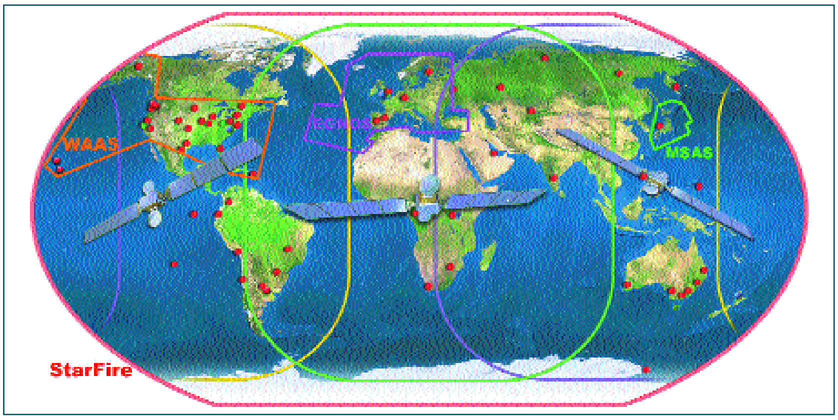
GBAS

GBAS provides relative positioning. These positioning options determine corrections at the Earth's surface either at individual sites or averaged over a region. These corrections are an amalgam of primary reference error sources and are transmitted to the user via radio or satellite link. User coordinates are determined relative to the reference site(s). Accuracy degrades with distance from the individual reference site or the regional boundary, primarily because of differential ionospheric and tropospheric effects, satellite orbits and clocks. Examples of correction services include:

- **Beacon DGPS**
- **Commercial DGPS**
- **RTK / Network RTK**
- **Widelane RTK**

Widelane RTK is a relative newcomer, which is only available in the few areas of the world that require high accuracy on a regular basis for oil and gas exploration surveys.

Figure 1: SBAS and StarFire Service Areas plus StarFire Reference Stations



SBAS

SBAS provide absolute positioning; that is they do not determine position relative to some fixed point of the Earth's surface. Instead, they determine a position within a space-based reference frame, thus it may also be considered the Space Domain group. Satellite communication links are used for some of the GBAS so the term SBAS does not relate to the communication link used but instead describes the nature of the corrections, that they are for the satellites. This class includes:

- **Standalone GPS**
- **WAAS**
- **EGNOS**
- **MSAS**
- **StarFire**

Augmentation for standalone GPS consists of satellite orbit and clock updates which are generated by the GPS Ground Control Segment and distributed to the user with an ionospheric model in the GPS signal structure. It is this basic principle of determining each error source instead of amalgamating them which distinguishes SBAS from GBAS. Figure 1 shows the SBAS and StarFire service areas and the global reference stations that are used for the StarFire system. The reference network infrastructure, quality of hardware, algorithm sophistication, and the speed with which this is accomplished, all contribute to the positioning accuracy attained by the user.

WAAS/EGNOS/MSAS

Currently under development are the Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay System (EGNOS) and the MTSAT Satellite Augmentation System (MSAS). All three address the need for reliable accurate positioning of aircraft with the side benefit that these services are available to everyone within the transmitting satellite footprint. A summary of the key differences appears in Table 1 including the Initial Operational Capability (IOC) dates. Note that WAAS, EGNOS and MSAS corrections will be received over a much wider area than they are currently planned to be valid for. For example, WAAS corrections can be received in Africa but the resulting position accuracy may be worse than standalone GPS performance.

The performance level stated by the Federal Aviation Administration for L1 receivers equipped with WAAS will be approximately 7m horizontal and vertical. However, some consumer handheld GPS manufacturers have been advertising a performance of less than 3m horizontal. . Figure 2 indicates the recent change in the EGNOS test signal as seen at Zweibrucken in Germany. The first 24 hours of the updated correction stream with a NavCom dual-frequency receiver has an accuracy similar to WAAS.

The May 2002 newsletter published by the EGNOS System Test Bed reported an accuracy of 0.7m horizontal and 0.9m vertical with the current test signal. Figure 2 demonstrates that this performance has been surpassed.

Initial performance data for the MSAS ground control segment in sending corrections via a radio link was presented at the ION GPS2002 conference as 4.3m horizontal and 7.5m vertical. The MTSAT-1R satellite, which will transmit MSAS correction data, is currently scheduled for launch in Summer 2003.

StarFire

The StarFire system has been developed by NavCom Technology Inc and Ag Management Solutions, both components of Deere and Company, and is operated by NavCom to address the need for reliable accurate positioning globally. StarFire has transitioned from its early days as a set of Wide Area DGPS networks to a robust unified network with a single set of corrections valid for the entire Earth.

The global set of corrections is based on technology called Real Time GIPSY (RTG) developed by the Jet Propulsion Laboratory (JPL) for the National Aeronautics and Space Administration (NASA). A network of more than sixty geodetic GPS receivers is distributed globally to ensure that multiple sites are capable of seeing every GPS satellite. Many of these reference sites contribute their data to the International GPS Service for Geodynamics (IGS) and thus ensure that the geodetic control for StarFire is tightly coupled to the International Terrestrial Reference Frame. Atomic clocks which contribute to Universal Time are used to directly steer some of the GPS reference stations such that these can be used as a clock reference for the entire StarFire network. All raw data observables are sent via redundant data links to two independent geographically separate control hubs. The RTG algorithm coupled with additional proprietary NavCom StarFire hub code takes into consideration the following:

SBAS	IOC	Area	Corrections	Sites	Hubs	Correction Link
WAAS	Summer 2003	USA, Puerto Rico	GPS, Ionosphere	25	2	2 Inmarsat Satellites, (Additional Satellite)
EGNOS	Summer 2004	Europe	GPS, Glonass, Ionosphere, (Galileo)	34	4	2 Inmarsat Satellites, (Artemis Satellite)
MSAS	2005	Japan	GPS, Ionosphere	6	2	(MTSAT-1R, MTSAT-2)
StarFire	2002	Global	GPS	62	2	3 Inmarsat Satellites

Table 1 : SBAS Characteristics (Indicates Future)

- **Geopotential**
- **Solid Tide**
- **Polar Tide**
- **Ocean Tide**
- **Troposphere**
- **Solar Pressure**
- **Relativity**
- **Phase Wind-up**
- **GPS Yaw**
- **Satellite Clocks**
- **Reference Site Clocks**
- **Reference Receiver Biases**

Figure 4 : C-Nav Hardware

GPS satellite orbit corrections are calculated and transmitted every minute. Satellite clock corrections are calculated much more frequently. Corrections are transmitted by both control hubs to all Land Earth Uplink stations for onward transmission to the user via three Inmarsat satellites. Figure 1 shows the footprints of these three Inmarsats where StarFire corrections can be received. StarFire corrections are applicable

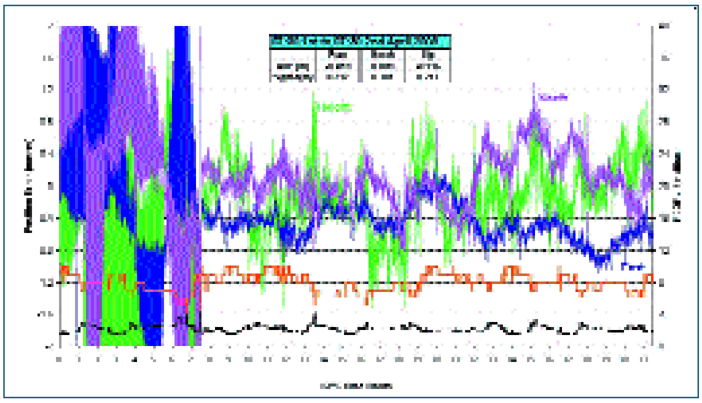


Figure 2 : EGNOS Performance with a NavCom NCT-2000D L1/L2 Receiver

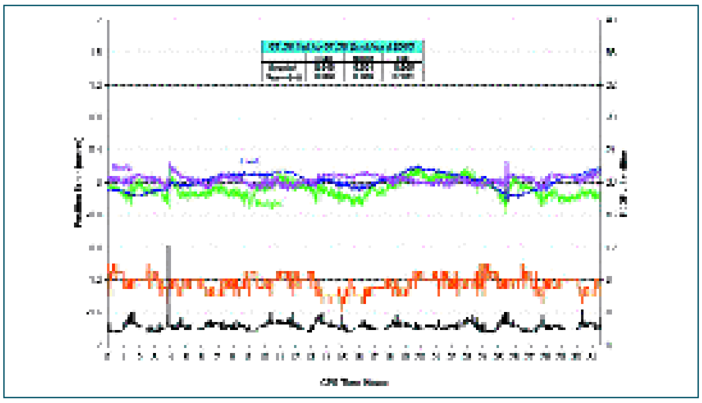


Figure 3 : StarFire Accuracy in Germany

System	Horizontal Accuracy	Vertical Accuracy	Typical Range
Total Station	0.01-0.02m	0.01-0.03m	3kms
RTK/Network RTK	0.01-0.05m	0.02-0.10m	10-20kms(Radio link)
SBAS StarFire	0.05-0.10m	0.10-0.20m	Global
Widelane RTK	0.10-0.20m	0.20-0.40m	500-800kms(Satellite link)
SBAS WAAS L1/L2	0.40m	0.60m	USA and Puerto Rico
SBAS EGNOS	0.40m	0.60m	Europe
Commercial DGPS	2m	5m	2000kms
SBAS WAAS L1	3m	7m	USA and Puerto Rico
Beacon DGPS	5m	10m	100-150kms

Table 2: Typical Positioning Accuracies (1 Sigma) and Ranges

worldwide, distribution and use of the corrections outside of the Inmarsat satellite footprints was recently done by JPL on an airborne platform in the Arctic using an Iridium satellite phone. All StarFire receivers incorporate an L-Band antenna and demodulator for decoding the corrections, plus a dual frequency geodetic GPS engine that removes local ionospheric effects. The NavCom positioning algorithm uses the WAAS tropospheric model, redundant satellite observables and time to model the local multipath and troposphere.

The number of reference stations used, the absolute tie to Universal Time, the algorithms, geodetic quality hardware and the frequency of correction updates, enables StarFire to surpass the performance from Standalone GPS, WAAS, EGNOS and the currently indicated performance of MSAS. Figure 3 shows the performance in Zweibrucken, Germany of a StarFire user receiver. The University of Minnesota recently conducted independent tests for a snow-plough heads-up display for use in white-out conditions. In a dynamic evaluation, they concluded that RTK and Network RTK using a variety of other manufacturers' hardware demonstrated a horizontal accuracy better than 10cm; the NavCom StarFire receiver demonstrated a horizontal accuracy better than 20cm.

Figure 6: On the pole StarFire solution

Hardware

Deere and Company is a $13billion concern with thousands of NavCom StarFire GPS sensors incorporated into a variety of John Deere agricultural vehicles worldwide. This amount of business for dual-frequency sensors in the tough agricultural environment has proven the reliability and robustness of the NavCom GPS engine.

C&C Technologies Inc., an international offshore surveying company has packaged the NavCom dual-frequency NCT-2000D GPS engine, L-Band demodulator and a NavCom patented quad-feed turnstile antenna in a single integrated package called C-Nav. Figure 4 shows the C-Nav system which can provide WAAS, EGNOS or StarFire positions plus raw dual-frequency data for post processing and is typically used for offshore exploration, dynamic positioning and hydrographic surveys worldwide.

The core components are now available in a modular package seen in Figure 5 which is suitable for backpack, vehicle, boat or aircraft mount but has the added benefit of onboard RTK capability using an external radio. Thus a single system

Figure 5: Modular NavCom StarFire System

can be used for establishing static geodetic control, as an RTK base station or used as a rover for SBAS positioning, with RTK precision available when within range of an RTK base station. Figure 6 shows an alternative fully integrated solution for use by surveyors and GIS professionals.

Conclusions

Those interested in sub-metre accuracy can see that, as summarised in Table 2, Satellite Based Augmentation Systems can provide more choice for positioning system selection. Public and commercial SBAS, coupled with a volume manufactured geodetic grade GPS sensor, provide a simple cost effective means of realising high accuracy positioning. The inherent redundancy of the SBAS technique creates an extremely robust positioning service which can continue even with multiple reference station failures.

The decimetre positioning accuracy and global coverage of StarFire makes high accuracy positioning simpler to accomplish worldwide, whether it be auto-steering for agriculture, the furthest reaches of the Oceans, flying high over the Arctic or local survey data collection.

A combination of static geodetic processing, RTK and SBAS in one unit provides positioning flexibility which can help fulfil the needs of GIS professionals, land and hydrographic surveyors worldwide. GW

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