StarFire and Real-Time GIPSY: A Global High-Accuracy Differential GPS System

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Biography

Mr. Tenny Sharpe is Director of Deere programs at NavCom Technology Inc. Mr. Sharpe received a B.S. in Physics from Case Institute of Technology in 1969 and a M.S. in Computer Science from the University of California, Los Angeles in 1976. Mr. Sharpe has over 30 years experience in the development of aerospace and industrial electronics. His specializations are software and systems design for GPS navigation systems. He is the chief architect and program manager of the StarFire WADGPS.

Mr. Ron Hatch is a principal in NavCom Technology, Inc. where he is the Director of Navigation Systems. Mr. Hatch received a B.S. degree in Math and Physics from Seattle Pacific University in 1962. His primary research is in high-precision differential GPS navigation. He has been awarded eleven patents in GPS technology. Mr. Hatch was the 1994 recipient of the Kepler Award from the Satellite Division of the Institute of Navigation and received the Thomas L. Thurlow Award from the Institute of Navigation in 2001. In June he completed a one-year term as the president of the Institute of Navigation.

Dr. Fred Nelson is Senior Staff Engineer in the Precision Farming Group of John Deere and Co. Dr. Nelson received his B.S. (1962), M.S. (1978) and PhD (1980) in Agricultural Engineering from the University of Wisconsin. He has over 20 years of engineering experience with John Deere & Co. Dr. Nelson's primary fields of research include sensors, software and system design for precision agricultural applications.

Abstract
NavCom Technology, Inc., a wholly owned subsidiary of Deere & Company, together with the Ag Management Solutions Group of John Deere, have designed and implemented a Wide Area Differential GPS (WADGPS) system, referred to as StarFire, which provides a new level of accuracy across continental distances. This continental system is being transitioned into a global system with even higher accuracy using technology developed by and licensed from the Jet Propulsion Lab (JPL). Several key developments have made this system possible. They include:

Low-cost, high-quality dual frequency receivers were developed for use as both reference and mobile receivers.

Dual frequency extended smoothing was developed which removes the two largest error sources in a WAGPS, i.e. ionospheric refraction effects and multipath effects.

A new L-Band satellite communication module was developed which uses a single, multi-function antenna to receive both the L1 and L2 GPS frequencies and also the Inmarsat L-band communication frequencies (1525-1565MHz.).

The continental WADGPS Starfire system uses correction algorithms which provided a single set of corrections for an entire continental area. This allows the use of a much smaller bandwidth to provide the corrections than that used by other WADGPS systems.

NavCom Technology is in the process of transitioning the continental WADGPS solution to a truly global solution with an improved accuracy as well. The principal source of error, which limited the solution to continental size areas, was the inaccuracy in the GPS satellite orbits. Real-time orbital corrections and clock corrections are now being continuously computed for all the GPS satellites. The technology to compute orbital corrections and clock corrections in real-time was licensed from JPL and uses their real-time GIPSY software which had been developed for NASA over many years. In addition NavCom has contracted with JPL to receive the data from JPL's extensive set of world-wide dual-frequency reference stations. These reference stations together with NavCom's reference stations provide the raw data from which are computed two sets of corrections. Every few

minutes a set of orbital corrections are computed for each GPS satellite. At a more rapid rate, every few seconds, a set of clock corrections are computed for each GPS satellite.

Currently the Inmarsat L-Band communication channel provides both the continental WADGPS corrections and the global Real-Time GIPSY (RTG) corrections. The software within the StarFire equipment is being transitioned to use the new RTG corrections. These global corrections provide a new level of unmatched accuracy for differential GPS.

The Starfire system was developed by John Deere specifically for agriculture applications. With the availability of very accurate position information on a global basis, many other applications are now being addressed.

Introduction

Figure 1 shows an overview of the StarFire WADGPS architecture. At a conceptual level, it is similar to other wide-area dGPS systems such as the Federal Aviation Administration's Wide Area Augmentation System (WAAS), Europe's EGNOS, and Japan's MSAS. However, a significant difference is the use of dual-frequency receivers rather than the single-frequency receivers. The use of dual-frequency receivers allows the direct removal of ionospheric refraction effects and, therefore, only a few reference sites are needed to achieve the high accuracy results.

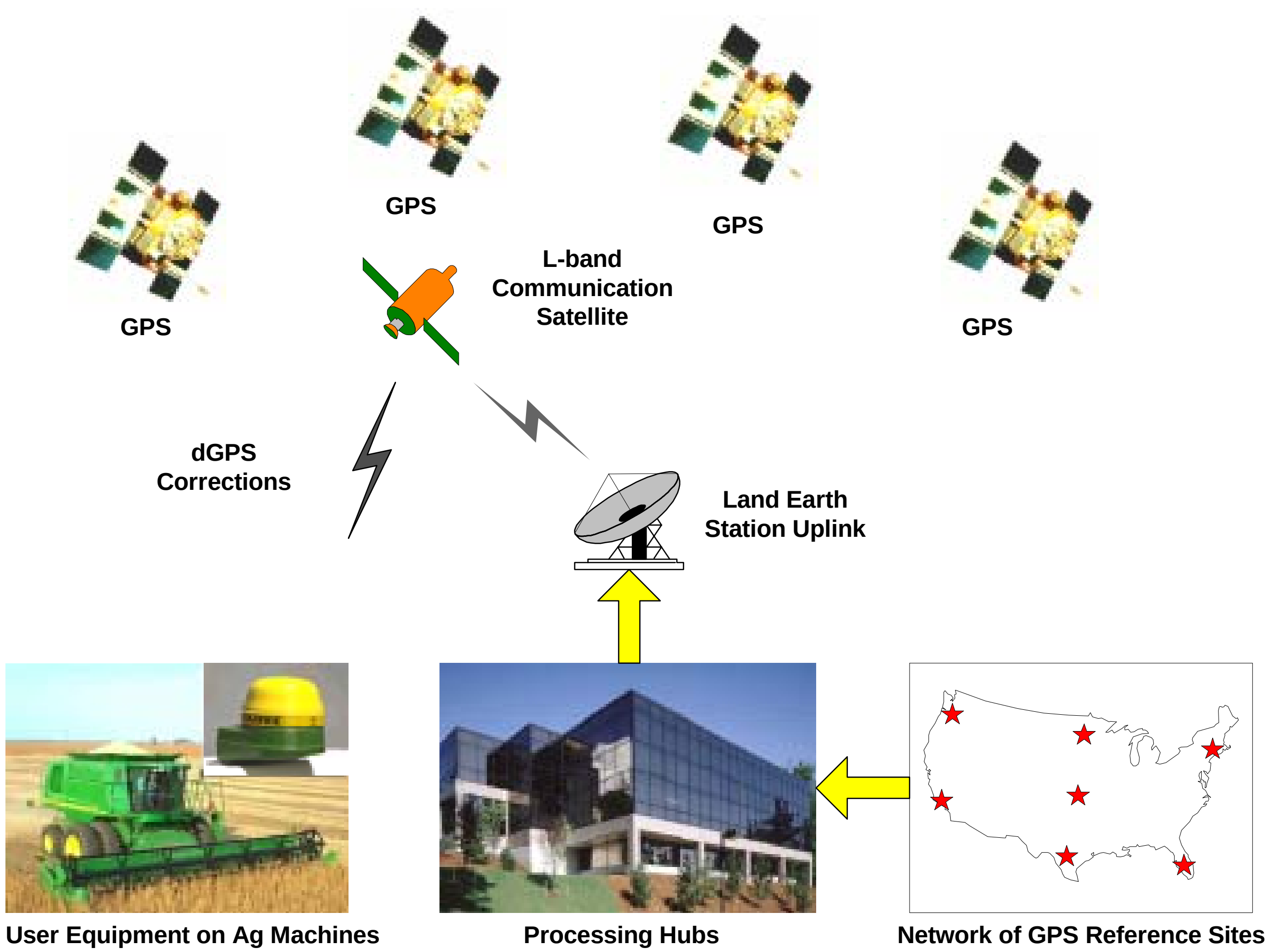

Figure 1. Overview of the StarFire WADGPS System

The seven reference sites used in the US network are shown in Figure 1. Separate sets of reference receivers are deployed elsewhere which are used to generate independent sets of WADGPS corrections around the world. There are 4 reference stations in the StarFire European Network, 5 in the Australian Network and 3 in the South American Network. Each of the networks of reference and monitor sites sends dual-frequency code and carrier-phase measurements from all receivers for all satellites in view, as well as system integrity information, to two redundant processing hubs via terrestrial and satellite communication links. The processing hubs combine the measurements from all of the sites in each region and generates a single set of wide-area corrections for each region based upon the refraction corrected measurements. The corrections are sent, via land-lines, to the land-earth station for the geostationary, L-band communications satellite where they are uplinked for broadcast to users throughout each region.

These separate continental WADGPS systems are in the process of being transitioned into a single Global Differential GPS (GDGPS) system which will provide an unprecedented level of accuracy worldwide. The communications satellites now provide both the regional corrections and the more accurate global corrections.

The StarFire user equipment receives the corrections broadcast from the communications satellite, applies them to its own observed, refraction corrected pseudoranges and performs a navigation solution. The resulting dGPS position, velocity and time are output from the user equipment to other subsystems on the platform to support mapping and control system requirements.

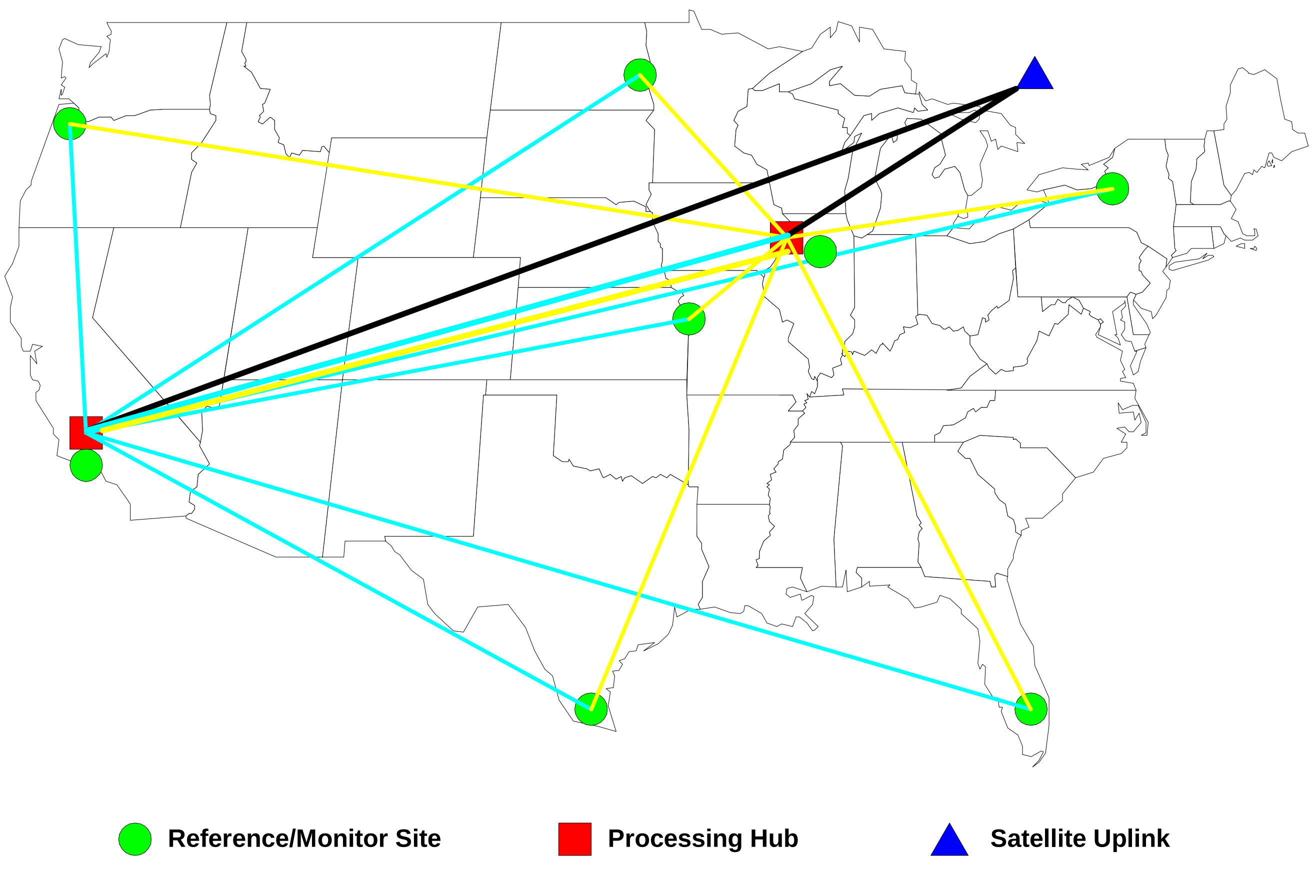

Figure 2. StarFire CONUS Ground Reference Network

StarFire Ground Reference Networks

Figure 2 shows the overall topology of the StarFire Ground Reference Network (GRN) for CONUS. It is comprised of seven reference/monitor sites, two redundant processing hubs and an uplink facility for the geostationary communications satellite.

Each of the reference/monitor sites is configured with an identical set of equipment including:

a) two redundant NCT2000D GPS reference receivers which send a full set of dual frequency observables for all satellites in view to both of the redundant processing hubs,

b) a fully packaged production StarFire user equipment unit which serves as an independent monitor receiver,

c) communications equipment (routers, ISDN modems),

d) a remotely controlled power switch and UPS module.

The main communication lines used to link the reference sites with the processing hubs are frame relay private virtual circuits (orange and blue lines in Figure 2). Each frame relay circuit is backed up with an ISDN dial up line which is activated automatically from the processing hub in the event any frame relay connection fails. The same implementation is used for the communication lines to and from the hubs and the uplink facility.

The StarFire user equipment units located at each of the reference sites, called monitor units, operate independently. They receive the broadcast correction stream from the communications satellite, perform differential GPS navigation and report their positioning results back to the processing hubs using the same communication lines as the reference receivers.
In addition to the dGPS positioning results, the monitor data includes the received signal strength of the L-band communications satellite, packet error statistics, age of differential corrections, signal strengths for the received GPS satellites, PDOP and other operating parameters. This data, from all of the GRN sites, is continuously monitored by an Alert Service processor which automatically generates E-mail and pager messages to on-call network service engineers in the event of a dGPS service failure.

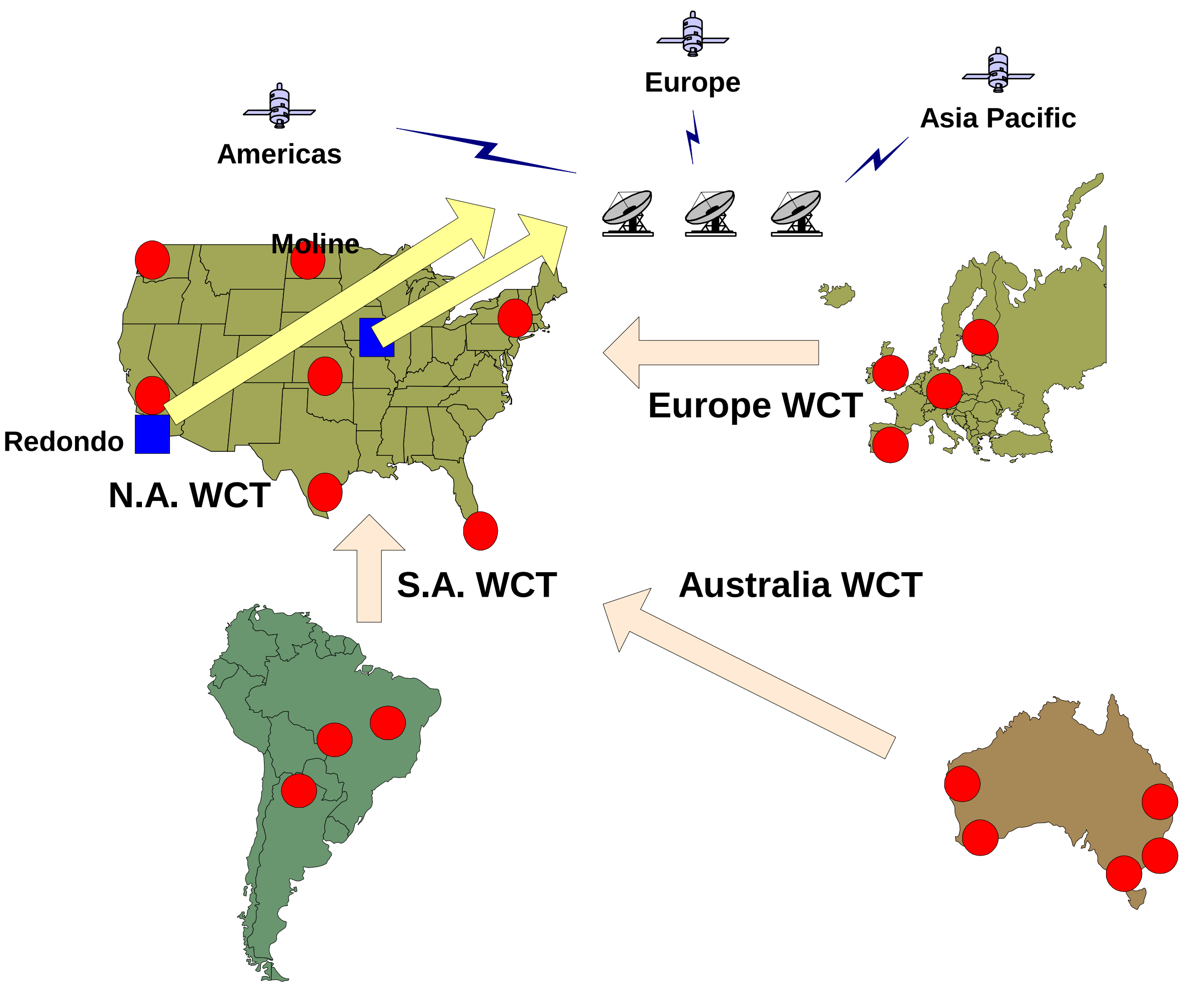

Figure 3 The Four Regional WADGPS Networks

The three other regional networks are shown together with the CONUS network in Figure 3. The structure and operation of the three additional WADGPS regional networks are almost exact copies of the structure and operation of the CONUS network. However, the communication of the data between the reference and monitor receivers takes advantage of the Internet and, in some cases, satellite communication links as well. The processing hubs for these regional networks is co-located with the CONUS processing hubs at the Redondo and Moline locations and shares the communication links and redundant structure of the CONUS network.

The network of global reference stations, used to provide both orbit and clock corrections for all satellites at all times, does not currently share any of the regional network locations. Eventually, all of the regional sites will be incorporated into the global network of reference stations. Currently only the global reference sites operated by JPL for NASA, identified by the red flags in Figure 4, are used in computing the global corrections. The Internet and satellite links are used to bring the dual-frequency measurements from these global references back to the processing hubs at Redondo and Moline. Since the hubs receive data from more than 30 reference sites, the corrections are robust and the loss of data from one or more sites would not affect the accuracy significantly. Like the other networks, duplicate processing at both Redondo and Moline are used so that an automatic switch of the data uploaded to the communication satellites occurs if a failure is detected in one of the hubs.

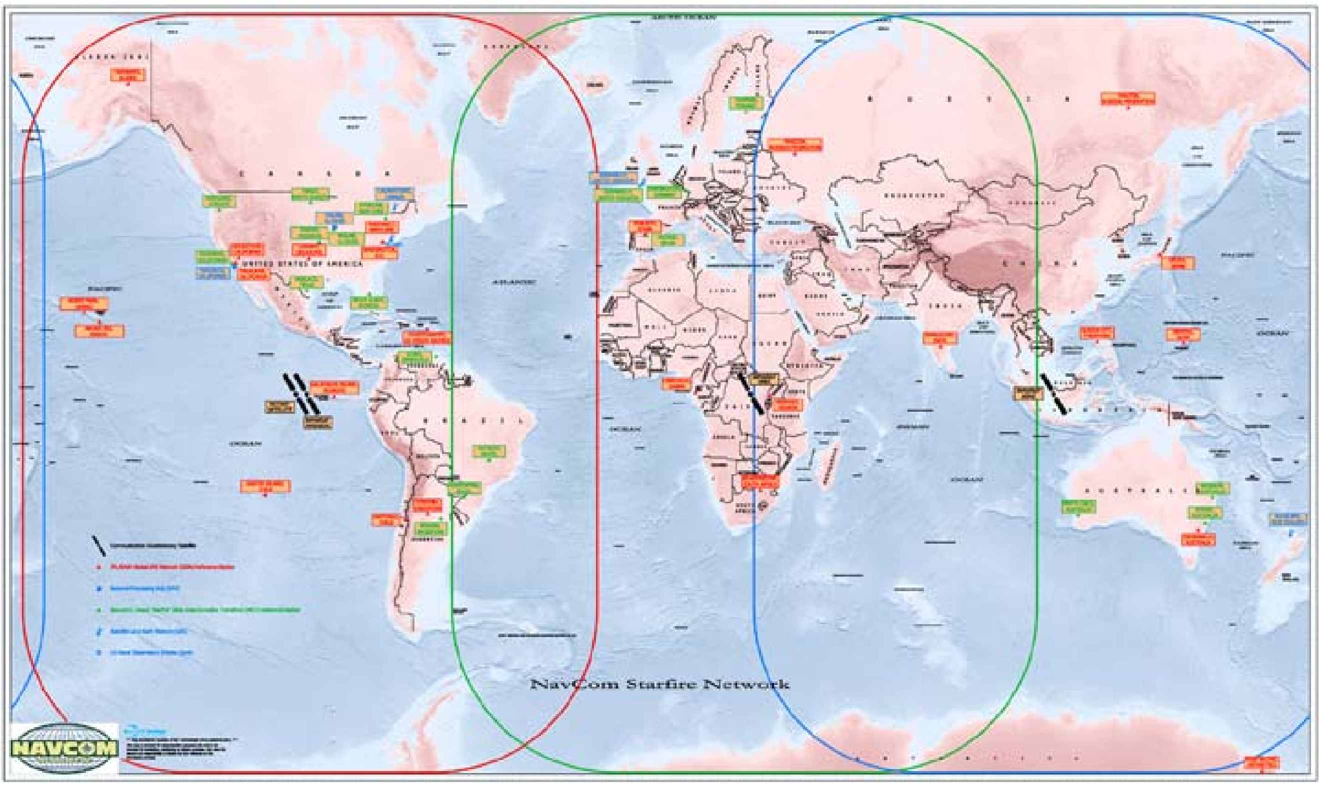

Figure 4 The Global NASA Network of Reference Stations

Hub Processing Software

The algorithm used at the processing hubs to compute the StarFire WADGPS corrections for the regional networks is called the Wide Area Correction Transform (WCT). The WCT uses the following inputs:

a) dual frequency observables (CA code pseudoranges, L1 carrier phase, P2 code pseudoranges and L2 carrier phase) for all of the GPS satellites tracked at the GRN reference receivers, delivered at 1Hz in real time,

b) broadcast ephemeris records from the GRN reference receivers delivered in real time,

c) a configuration file defining the precise location (±2cm) of each of the GRN reference receiver antennas as determined from network solutions based on the IGS worldwide control stations.

The dual frequency observables are used to form smoothed, refraction corrected pseudoranges which are free of ionosphere delay and, due to extended smoothing with the carrier phase, virtually free of multipath. These are then normalized with respect to receiver clock offsets and modeled site troposphere delays. Finally, the normalized pseudoranges for each satellite are combined in a weighted average to form a single, wide area pseudorange correction for that satellite. A similar process is performed using the finite difference of the carrier phase to generate pseudorange rate corrections. The ensemble of these corrections for all satellites in view is formatted into a tightly packed, binary message and sent from the hub to the uplink facility for broadcast on the geostationary communications satellite.

Because the WCT uses refraction corrected pseudoranges, the resulting WADGPS corrections are free of the errors caused by spatial decorrelation of ionosphere delays which are inherent in single frequency corrections. When dual frequency mobile receivers are used which employ the same refraction corrected techniques, a single set of corrections can be used across the entire continental service area with uniform, high accuracy.

Two major advantages result from having one consolidated set of corrections for the entire service area:

a) Bandwidth requirements on the geostationary communications satellite are minimized. This results in a significant cost savings since the price of leased satellite channels is roughly proportional to the broadcast power required which is directly proportional to the bandwidth required.

b) The correction computation algorithm, including the final weighting, is done at a centralized facility (at the processing hubs) instead of being performed by the user equipment based on location dependent models. This enables improvements and upgrades to the WCT to be made, in most cases, without requiring changes to the algorithms in the mobile user equipment. This is a significant logistic benefit when, as is the case now with StarFire, thousands of user equipment units are deployed across the continental U.S.

The processing software used to generate the global corrections requires the same set of inputs as is used for the regional processing. However, the specific data comes from the global NASA network of reference receivers. Further, the real-time GIPSY (RTG) processing software used within the processing hubs at Redondo and Moline is that developed by JPL and licensed to NavCom. Changes to the software to improve the efficiency of the transmitted corrections have been made by JPL in coordination with NavCom. Orbit corrections for each satellite are generated and transmitted every five minutes and clock corrections for each satellite are generated and transmitted ever two seconds. The correction data is sent via the land-lines to the uplink facility and is broadcast from the communications satellites using the same channels as the regional corrections. Because of the efficiency of the correction data both the regional corrections and the global corrections can be sent over the same channel and the user equipment can select which correction stream to use.

StarFire User Equipment

Figure 5 shows the major components of the StarFire user equipment.

a) A multi-function antenna assembly is used which is capable of receiving the L1 and L2 GPS frequencies as well as the Inmarsat receive frequency band. The gain pattern of this antenna is designed to be relatively constant even at lower elevation angles. This allows for an efficient link budget when the unit is operated at higher latitudes where the elevation of the geostationary communications satellite is low.

b) An L-band receiver was developed to acquire, track, downconvert, sample and demodulate the StarFire data stream broadcast from the geostationary communications satellite. The receiver is frequency agile across the Inmarsat receive band under software control.

c) A state-of –the-art, dual frequency GPS receiver module, designed and produced by NavCom, provides the most important enabling technology in the user equipment.

Connections for the external interfaces of the StarFire user equipment are provided through a sealed 10-pin connector. Power connections include main, battery and programming voltage inputs. Data interfaces include CAN Bus and RS232 serial.

An alternate packaging of the StarFire equipment is shown in Figure 6. This package uses an external remote tri-band antenna to receive the two GPS frequencies and the L-band communication satellite signal.

The NCT2000D Dual Frequency GPS Engine

The NCT2000D is a compact, high-performance, dual frequency GPS engine aimed at OEM applications. In the StarFire user equipment, it is mounted inside the lower housing and interfaces to the digital board of the L-band receiver via an RS232 serial port. The StarFire corrections are input from the L-band receiver and 1, 5, or 10Hz PVT data is output to the L-band receiver for transmission via the external interfaces (RS-232 and CAN Bus).

The NCT2000D has ten, full dual frequency channels and two WAAS channels. It produces GPS observables of the highest quality suitable for use in the most demanding applications including millimeter level static surveys.
Key features of the NCT2000D include:

a) A patented multipath reduction technique is built into the digital signal processing ASICs of the receiver.

This greatly reduces the magnitude of multipath distortions on both the CA code and P2 code pseudorange measurements. When combined with extended, dual frequency code-carrier smoothing,

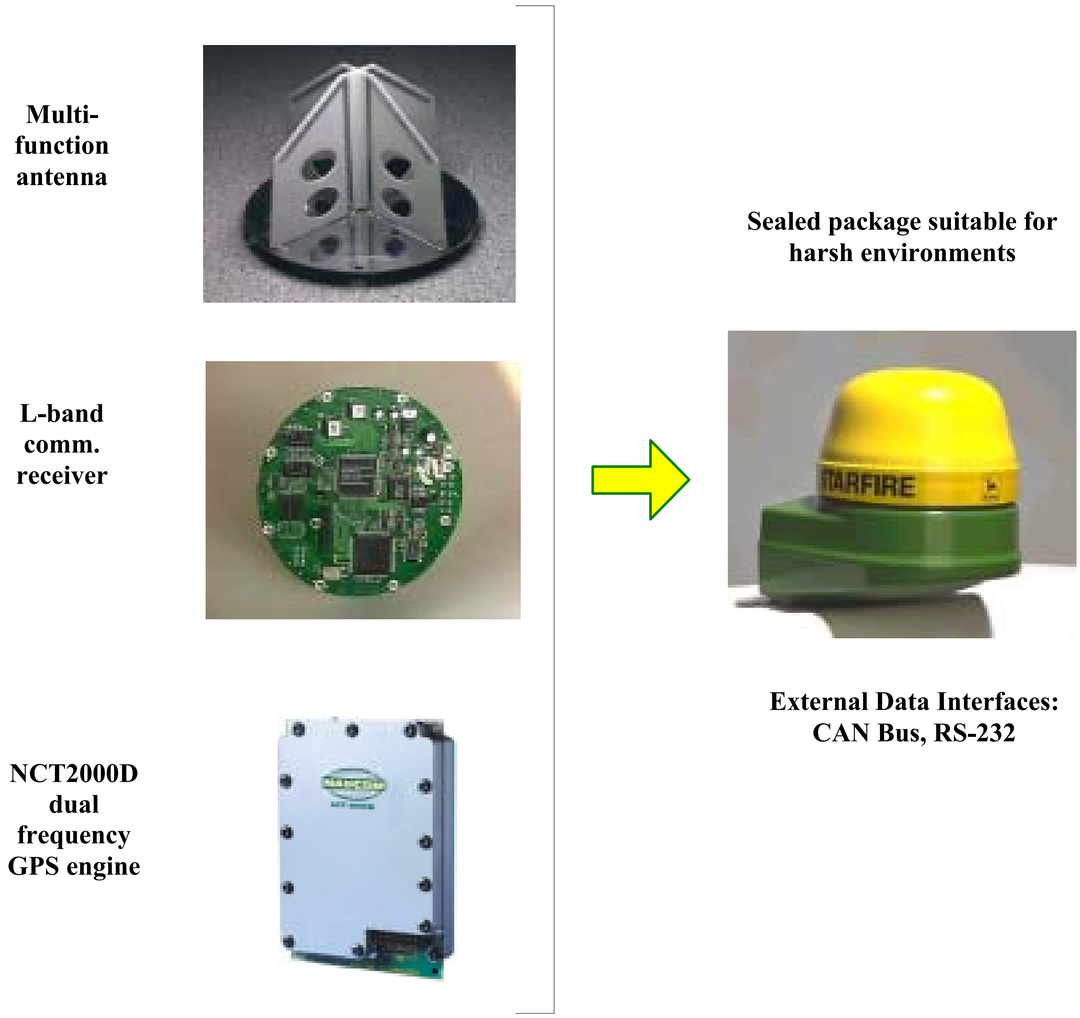

Figure 5. Major Components of the StarFire User Equipment

multipath errors in the code pseudorange measurements are virtually eliminated.

b) A patented technique is used to achieve near optimal recovery of the P code from the anti-spoofing Y-code resulting in more robust tracking of the P2/L2 signals.

c) The compact size (4" x 3"x 1") of the NCT2000D allows it to be readily integrated into the StarFire package.

d) A high resolution 1pps output signal, synchronized to GPS time, is provided by the NCT2000D. This signal is used by the L-band communications receiver to calibrate its local oscillator, which aids the acquisition of the StarFire correction signal. This technique has also been patented by NavCom.

The measurement processing of the NCT2000D software version in the StarFire user equipment is designed to be

Figure 6. Alternate packaging of the StarFire User Equipment

fully compatible with the both the StarFire regional correction signal and the global correction signal. Either of the correction streams can be used depending upon the control software within the StarFire unit. Dual frequency code and carrier phase measurements are used to form smoothed, refraction corrected code pseudoranges. When the regional correction stream is used, the smoothed code measurements are adjusted with the StarFire regional corrections and used in a weighted least-squares fix to generate PVT estimates.

The global corrections are processed a bit differently within the NCT2000D receiver. Specifically, a greater reliance is put on the carrier phase measurements and a floating ambiguity estimate is made of the whole-cycle ambiguities. All of the measurement data from all satellites is used to make this ambiguity estimate as accurate as possible. In addition, a constrained estimate of the tropospheric refraction is made using the data from all the satellites. This constrained solution removes some of the unmodeled tropospheric refraction effects. The resulting PVT estimates are output at either 1, 5, or 10Hz under software control.

StarFire Positioning Accuracy and Test Results

Figures 7, 8 and 9 shows the position accuracy obtained by using the global StarFire corrections for 24 hours at three test sites around the world. The one-sigma accuracy per horizontal axis rarely exceeds 10 cm. As expected, the accuracy is not dependent upon geographical location. The accuracy obtained by using the StarFire global corrections in within a StarFire receiver cannot be equaled by any other global system. Furthermore very few, if any, regional networks can match these results.

Agricultural Applications of the StarFire System

StarFire equipment is currently used in a number of agricultural applications including yield mapping, field documentation, operator assisted steering and automatic steering.

In terms of sheer numbers of units, yield mapping is the single largest agricultural application of StarFire. In this

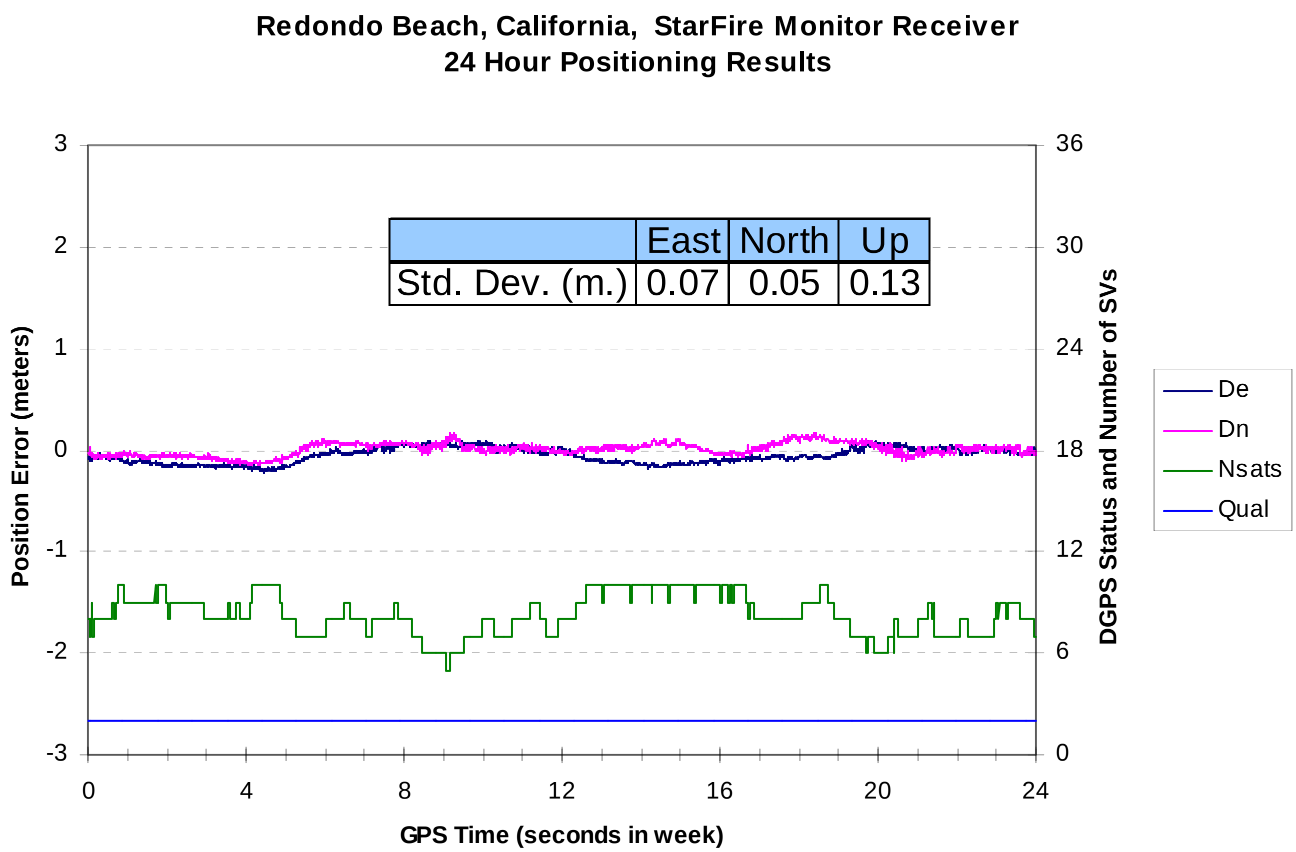

Figure 7 StarFire Results in California using Global Corrections

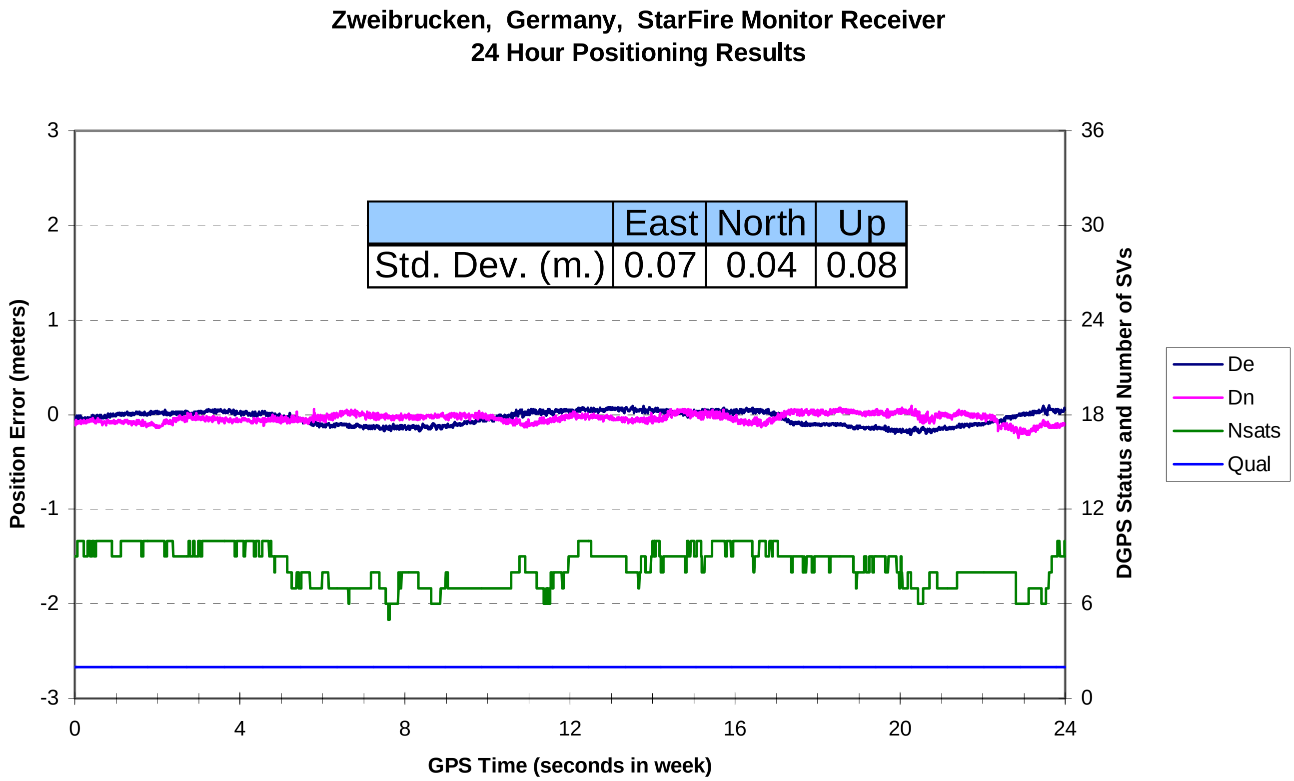

Figure 8 StarFire Results in Germany using Global Corrections

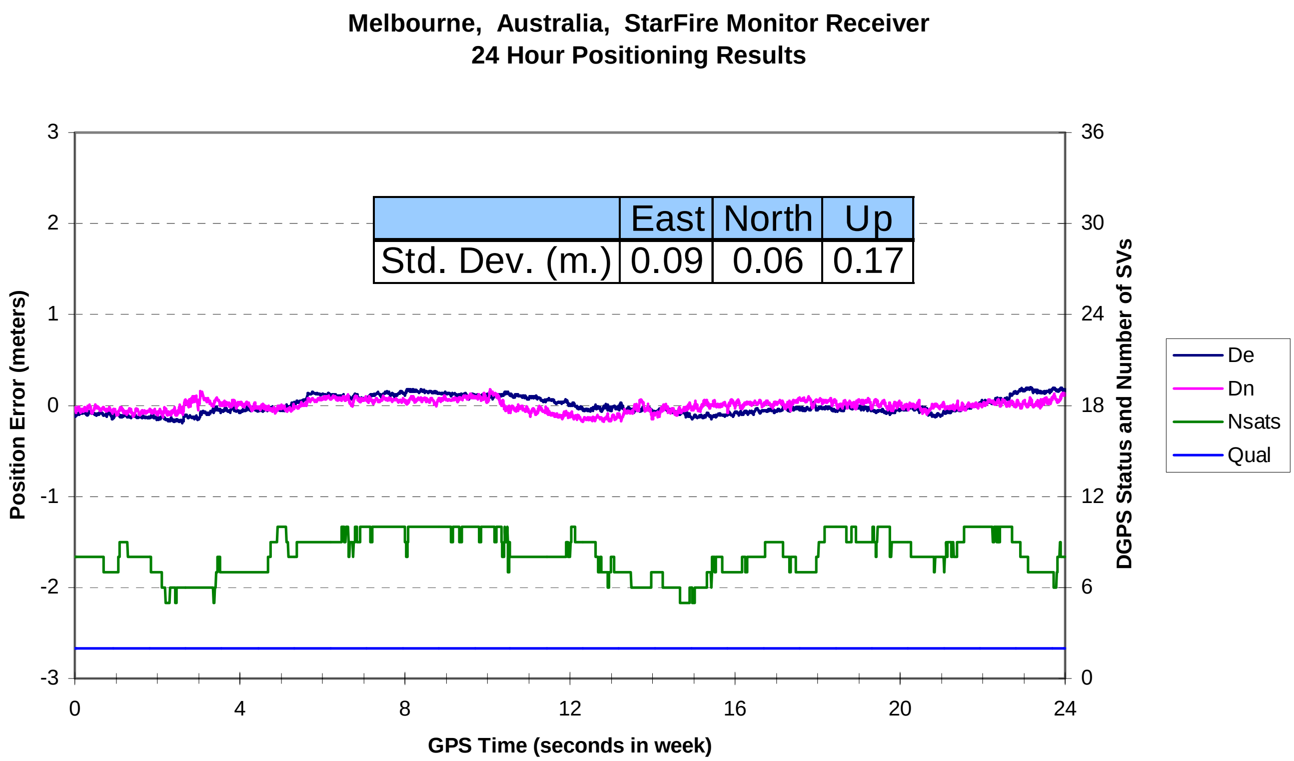

Figure 9 StarFire Results in Australia using Global Corrections

application, the precise real-time position of a harvesting machine, typically a combine, is recorded simultaneously with data from yield sensors which measure the amount of crop being taken. Figure 10 shows a StarFire unit mounted on a John Deere combine.

Figure 10. StarFire Unit on a John Deere Combine

After the field has been harvested, the recorded data is moved from the combine to a personal computer and processed into a color coded map with statistics which show the yield distribution as a function of position.

Operator assisted steering involves presentation of a graphic display, which shows a driver the current deviation of the machine from a planned course. The driver manually controls the machine to minimize the displayed deviation.

Even before the implementation of the global corrections and the resulting accuracy, the use of the StarFire system in automatic steering systems was increasing rapidly due

Table 1. Position Accuracies Needed for Automatic Steering for Selected Field Operations

Field Operation	Position Accuracy (2σ horiz.)
Fertilizer application (anhydrous)	12" (30 cm.)
Fertilizer application (bulk)	18" (46 cm.)
Heavy Tillage	12" (30 cm.)
Finish Tillage	18" (46 cm.)
Planting	10" (25 cm.)
Spraying (pre-emerge w/o markers)	18" (46 cm.)
Cultivating	2" (5 cm.)
Harvesting	10" (25 cm.)
Stalk Chopping	10" (25 cm.)

to the excellent short term accuracy. In automatic steering applications the machine is steered to follow a pre-planned course by a control system comprised of position sensors, a computerized control algorithm, electro-hydraulic or electro-mechanical steering controls and feedback sensors. The operator may take control of the machine manually to execute turns or unplanned maneuvers but the repetitive, row-following operations are done automatically. This leaves the operator free for other tasks such as monitoring the performance of a towed implement.

Typical position accuracies needed for yield mapping, assisted and automatic steering are shown in Table 1

Applications Beyond Agriculture

The enhanced accuracy of the StarFire system makes it a natural fit for many applications outside of agriculture including:

Land survey and geographic information systems,

Construction equipment guidance and control,

Marine survey and resource exploration,

Hydrographic mapping and dredging systems,

Land transportation tracking applications, such as railway monitoring, which require high levels of position accuracy.

Conclusion

The StarFire system, including its major subsystems, has been described in some detail. Key enabling technical developments have been identified and discussed. Position plots and statistics showing excellent accuracy performance have been presented. The use of StarFire System in agriculture has been described. Its use in many other fields is beginning to be exploited. There is no other global positioning system which is as economical to use and as precise as the StarFire system using the global correction stream broadcast over Inmarsat regional satellites.

Acknowledgements

The StarFire system would not have been developed without the sponsorship, vision and perseverance of the Advanced Management Systems group of John Deere. The contributions of Mr. Terrence Pickett are especially noteworthy.