John Deere’s StarFire System: WADGPS for Precision Agriculture

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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 Advanced Programs. 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 is currently the Chair of the Satellite Division.

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 John Deere & Co., together with the Precision Farming Group of John Deere, have designed and implemented a Wide Area Differential GPS (WADGPS) system which provides a new level of accuracy across continental distances. The system is designed for dual frequency operation and is based on several key technical developments:

> low-cost, high-quality, dual frequency GPS receivers were developed for use as both reference receivers and mobile receivers;
>
> special dual frequency extended smoothing techniques were developed which allow the use of refraction corrected measurements for both the reference and mobile receivers which are free of the two largest error sources in a WADGPS system – ionosphere and multipath;
>
> a new L-band satellite communication receiver was developed which uses a single, multi-function antenna designed to receive both of the GPS frequencies (L1 and L2) and the Inmarsat L-band communication frequencies (1525-1565MHz);
>
> WADGPS correction algorithms were developed which exploit the dual-frequency architecture of the system to generate a single set of corrections uniformly accurate across the continental U.S. resulting in lower bandwidth requirements and more centralized processing;
>
> redundant subsystems and monitoring equipment are utilized to provide a high degree of system reliability, availability and service integrity.

The paper describes the system architecture including ground infrastructure, processing techniques and user equipment. Navigation results are presented which show a new level of accuracy for WADGPS. Future directions for improvement of the system are indicated. Finally, several agricultural applications of the system are discussed as well as potential applications in other areas.

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). A network of reference/monitor sites is distributed across the continental U.S. Each site sends dual frequency observables for all satellites in view as well as system integrity information to two redundant processing hubs via terrestrial communication links. The processing hubs combine the observables from all of the sites and generate a single set of wide-area corrections based on 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 the continental U.S. service area.

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 requirements.

Although similar at the conceptual level to other WADGPS architectures, the StarFire system has several important features which discriminate it from more conventional designs. Foremost is the optimization of the system to exploit the use of dual frequency GPS receivers for both the reference sites and the mobile user equipment. This approach is made practical by the availability, within John Deere & Co., of a relatively low-cost, high-performance, compact, dual frequency GPS receiver, the NCT2000D produced by NavCom Technology Inc.

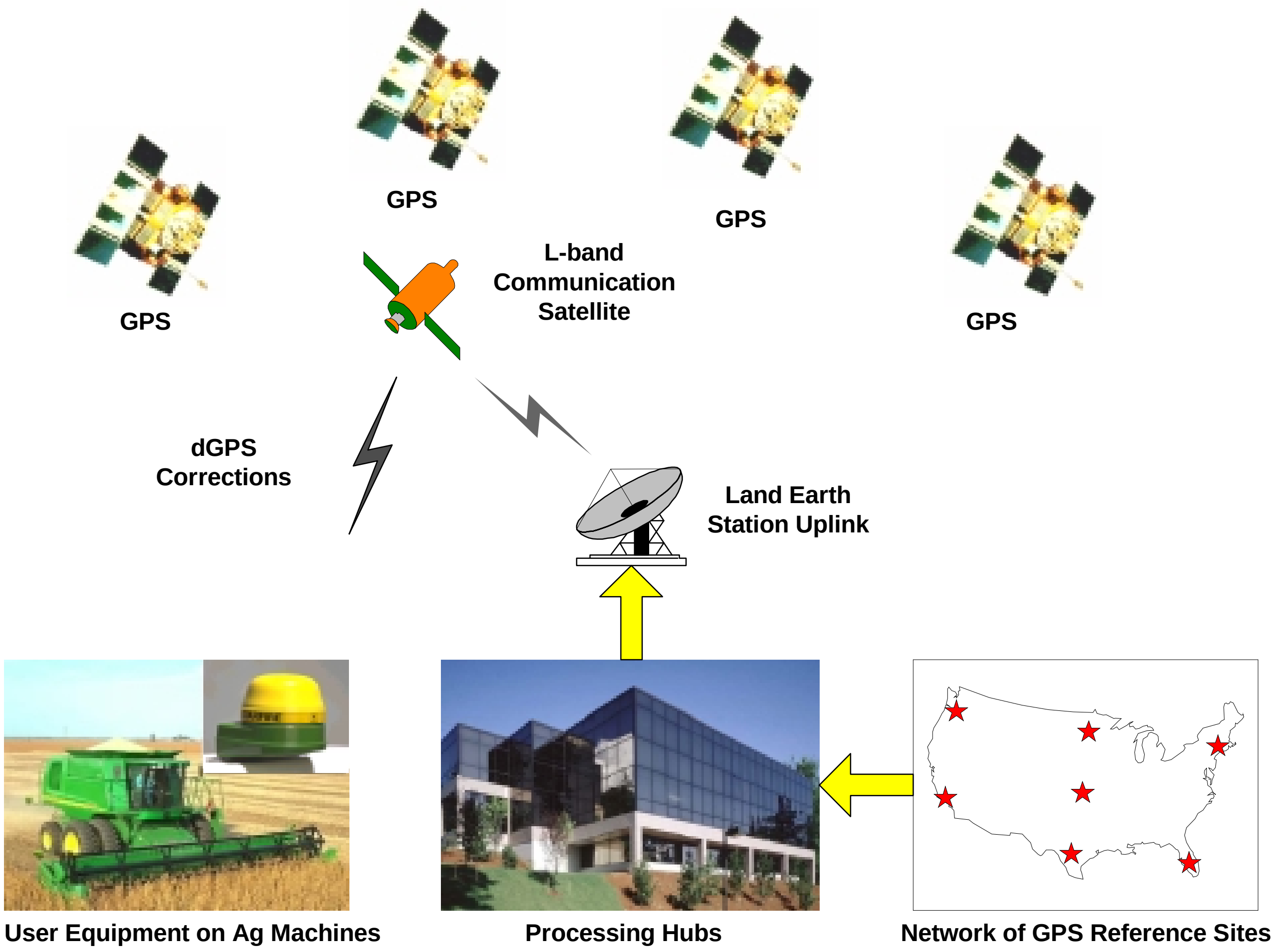


Figure 1. Overview of the StarFire WADGPS System

StarFire Ground Reference Network

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.

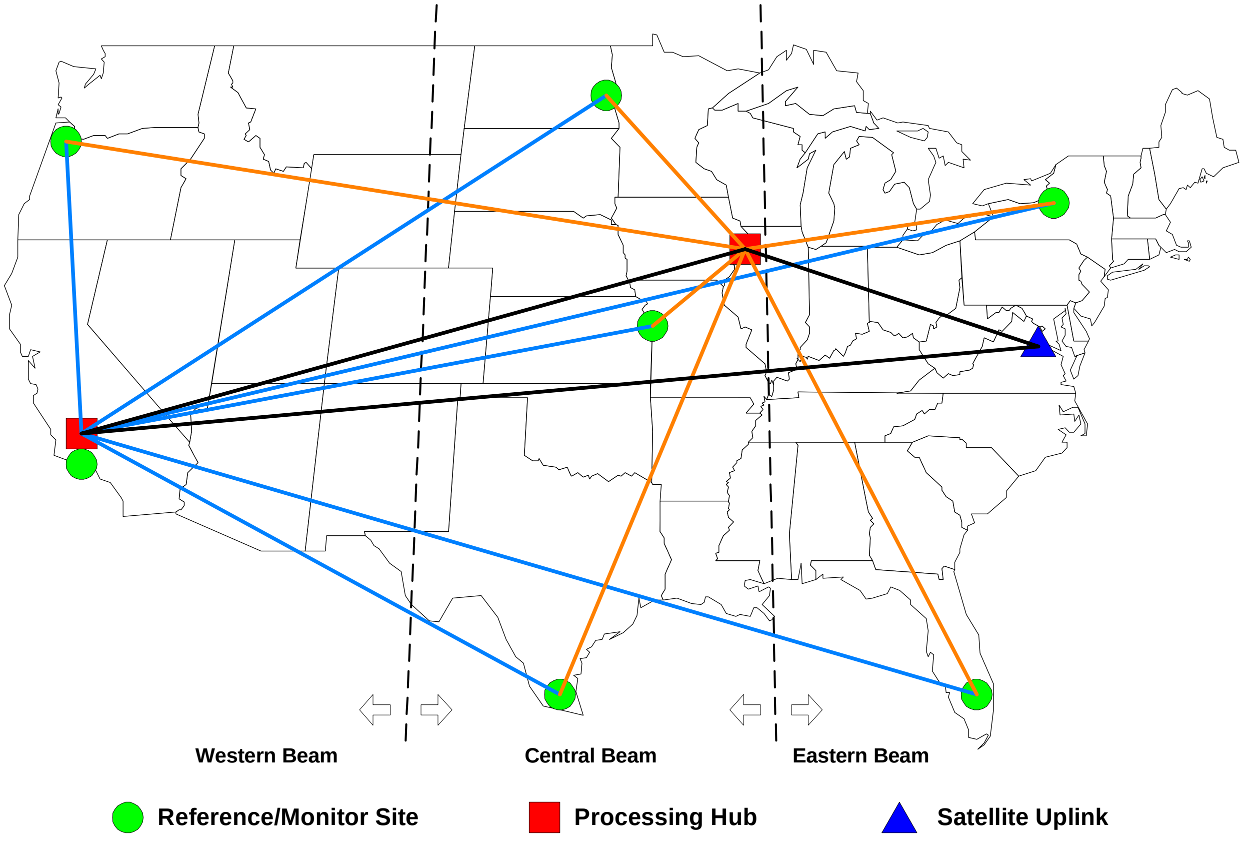


Figure 2. StarFire Ground Reference Network

Wide Area Correction Transform (WCT)

The algorithm used at the processing hubs to compute the StarFire WADGPS corrections is named 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, 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.

StarFire User Equipment

Figure 3 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.

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. StarFire WADGPS corrections are input from the L-band receiver and 5Hz 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, 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 and thus accelerate 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 fully compatible with the StarFire correction signal. Dual frequency code and carrier phase measurements are used to form smoothed, refraction corrected code pseudoranges. These are adjusted with the StarFire WADGPS corrections and used in a weighted least-squares fix to generate PVT estimates. PVT estimates are output at either 1Hz or 5Hz under software control.

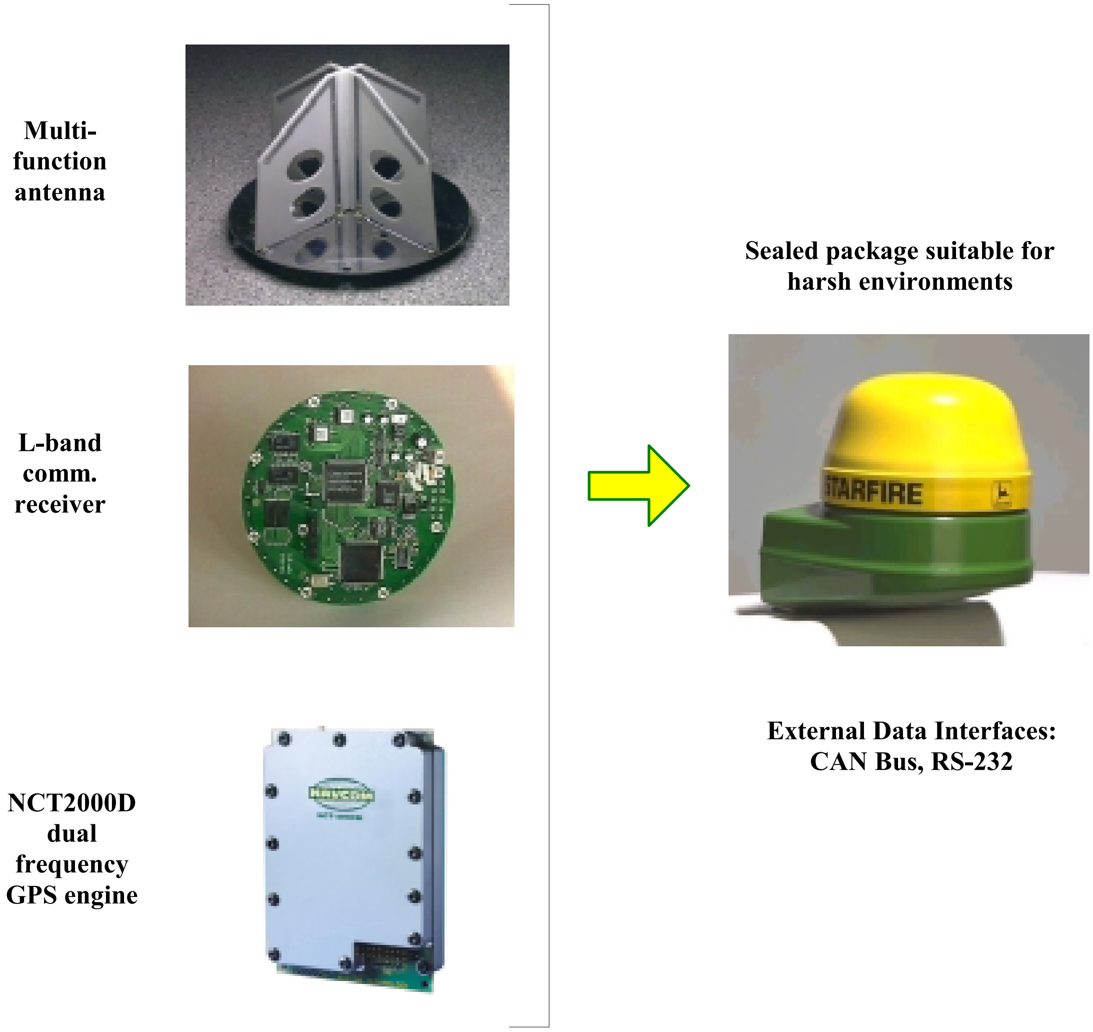


Figure 3. Major Components of the StarFire User Equipment

StarFire Positioning Accuracy and Test Results

Figure 4 shows position accuracy results for a 24 hour test on a stationary control point taken on August 27,2000.

Figures 5a. through 5c. show expanded plots for three one-hour segments extracted from the 24 hour test.

Figure 4. StarFire Dual Frequency Navigation, 24 Hours

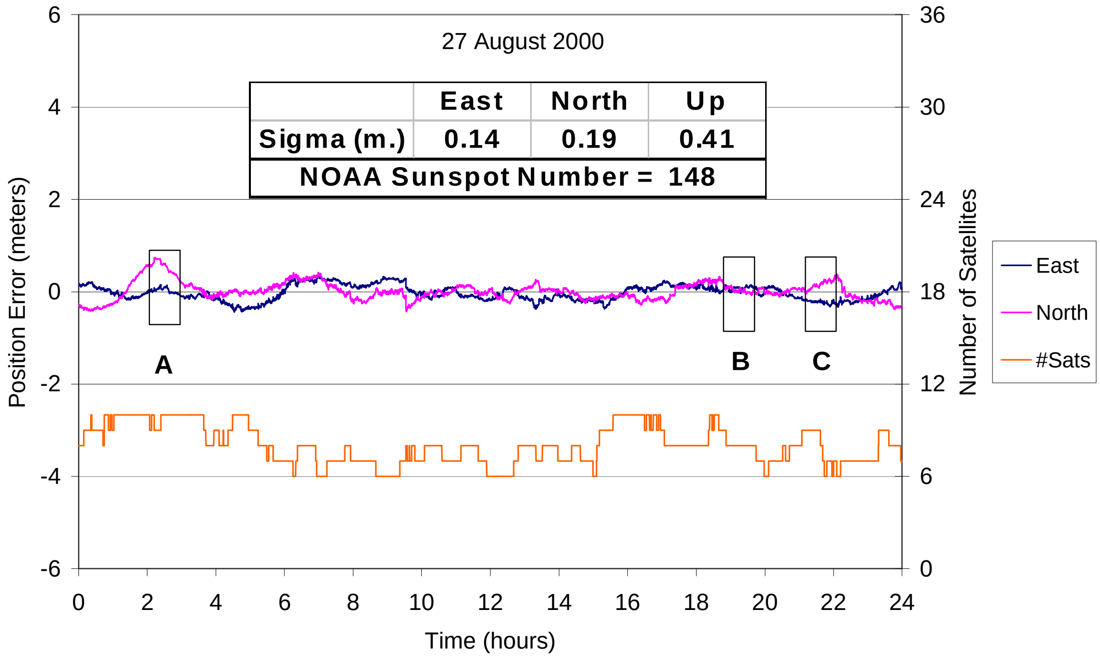


Figure 5a. StarFire Dual Frequency Navigation 1 Hour

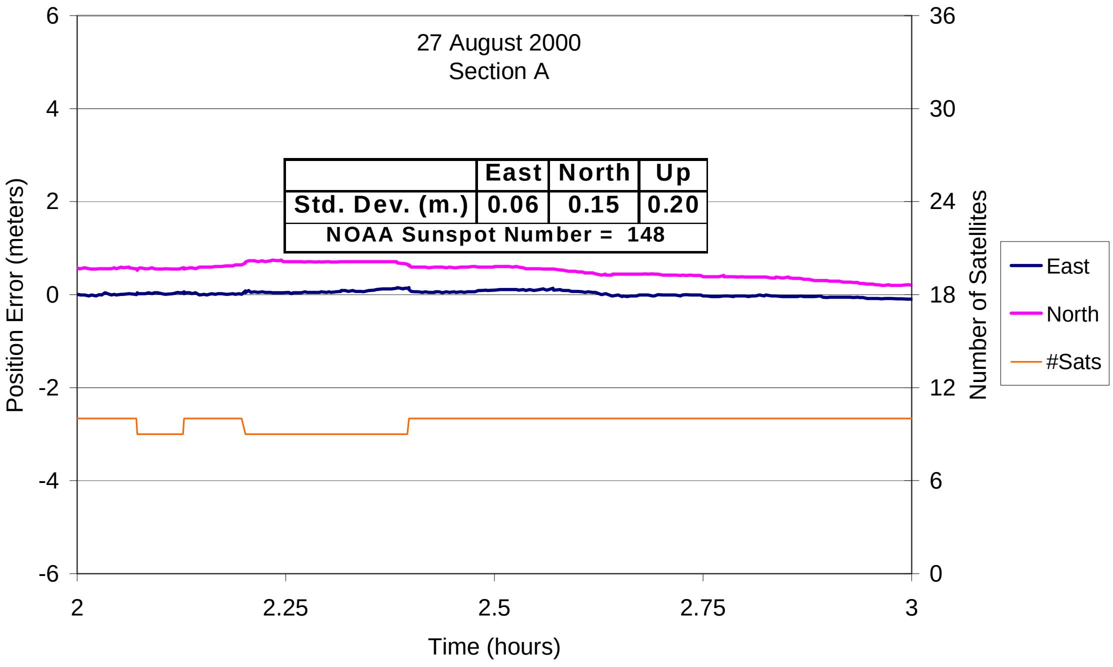
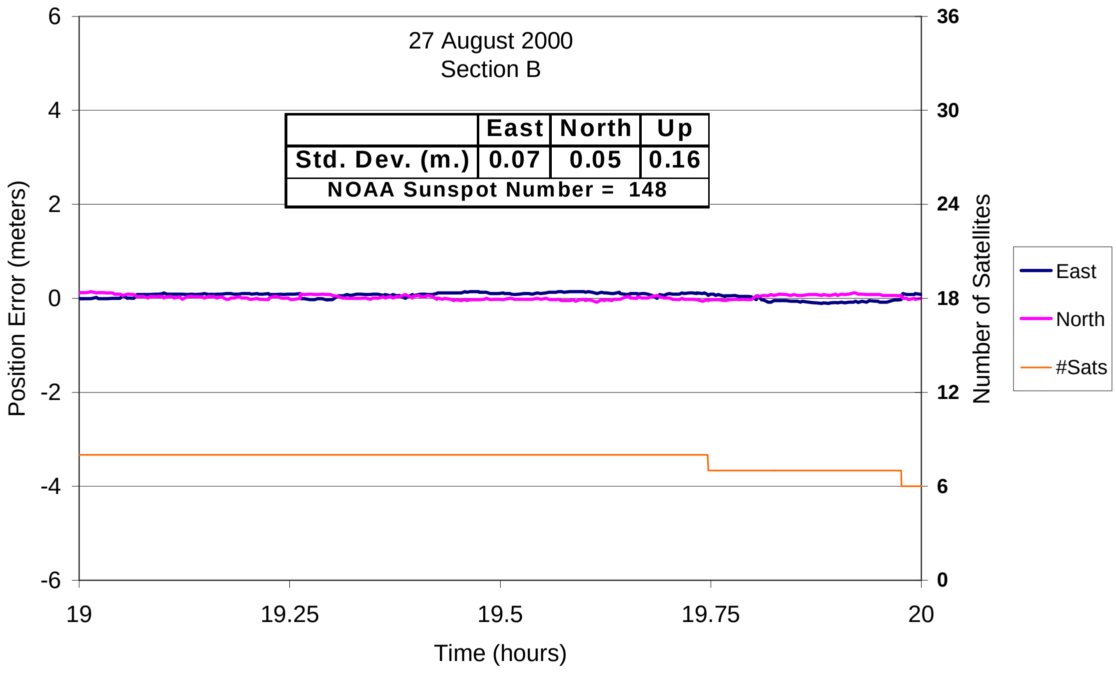
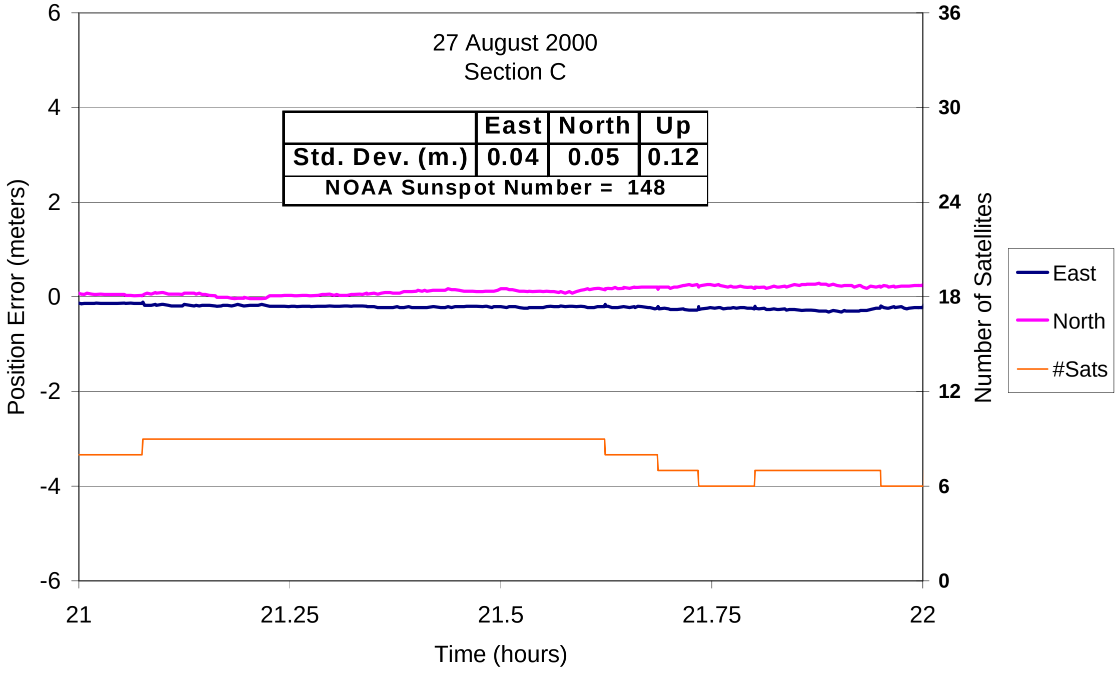


Figure 5b. StarFire Dual Frequency Navigation 1 Hour



	East	North	Up
Std. Dev. (m.)	0.07	0.05	0.16
NOAA Sunspot Number = 148			

Figure 5c. StarFire Dual Frequency Navigation 1 Hour



	East	North	Up
Std. Dev. (m.)	0.04	0.05	0.12
NOAA Sunspot Number = 148			

The smoothness of the one hour plots is a direct result of the extended, dual frequency, code-carrier filtering techniques used for both computation of the corrections and navigation in the user equipment.

Typically, 24 hour accuracy results are less than 30 cm., one-sigma, per horizontal axis. Results compiled over the last year, including the onset and peak of solar cycle #23, show this level of performance to be relatively independent of solar activity and its associated ionosphere disturbances. Accuracy performance has also been found to be independent of location within the service area. Both of these results are attributed to the dual frequency, refraction corrected techniques on which the StarFire system is based.

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, at this point in time, is the single largest agricultural application of StarFire. In this 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 6 shows a StarFire unit mounted on a John Deere combine.

Figure 6. 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. Figure 7 shows an example of a yield map produced by John Deere's JDmap software package.

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. Figure 8 shows an example of such an assisted steering display.

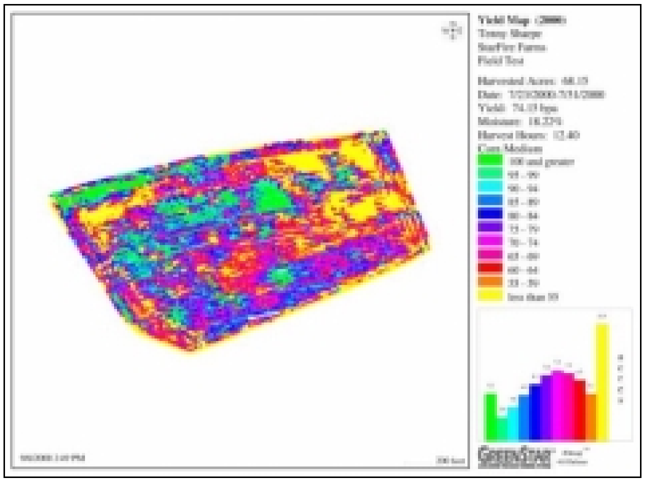


Figure 7. Yield Map Example

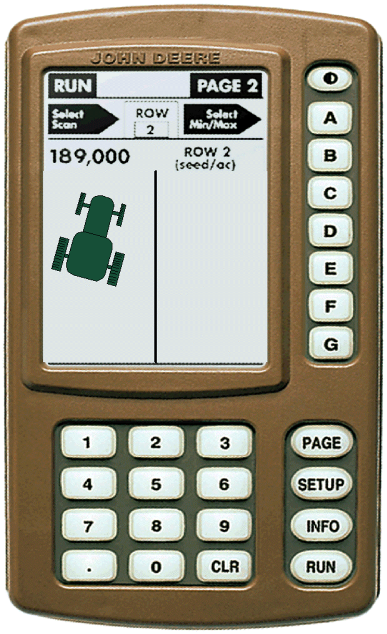


Figure 8. Operator Assisted Steering Display Concept

In an automatic steering system, 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.

The position accuracies required for yield mapping, assisted and automatic steering are shown in Table 1.

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.)

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

The accuracy for a number of the field operations shown in Table 1 can be met by the StarFire system with its current level of performance.

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.

Future Developments Planned for StarFire

Work has begun at NavCom Technology to improve the StarFire system performance in several areas:

1) Estimation of GPS satellite broadcast orbit errors will be addressed. This is one of the largest remaining error sources in the system and, if successfully reduced, should yield a substantial improvement in overall accuracy.

2) Estimation of unmodelled, reference site, troposphere errors will be undertaken. With all-in-view tracking throughout the Ground Reference Network, sufficient observability should be available to achieve this.

3) Navigation modes which use kinematic techniques with floating carrier phase ambiguities will be investigated.

4) Extension of the StarFire system into more regions will be considered as the availability of L-band global beams continues and as StarFire is moved into markets beyond agriculture.

Conclusion

The StarFire system, including its major subsystems, has been described in detail. Key enabling technical developments have been identified and discussed. Position plots and statistics showing excellent accuracy performance have been presented. Applications of StarFire in agriculture and other fields have been described.

Acknowledgements

The StarFire system would not have been developed without the sponsorship, vision and perseverance of the John Deere Precision Farming Group especially the contributions of Mr. Terrence Pickett.