StarFire™: A Global SBAS for Sub-Decimeter Precise Point Positioning

Kevin Dixon, *NavCom Technology Inc.*

BIOGRAPHY

Kevin Dixon is the GNSS Product Manager at NavCom Technology, Inc., a John Deere Company. Mr. Dixon received a B.Sc. in Mathematics and Computer Science from the University of York, England in 1986; a Postgraduate Diploma in Surveying from the University of Glasgow, Scotland in 1987 and an MBA from the University of Southern California in 2005. He holds United Kingdom Chartered Land Surveyor professional status. His 18 years of GNSS experience worldwide have included positions as Principal Surveyor with Racal Survey establishing the SkyFix™ and LandStar™ DGPS services, Geodesy Manager of the UK Hydrographic Office and GNSS Infrastructure development with Leica Geosystems. Current NavCom duties encompass GNSS technology and product development plus marketing.

ABSTRACT

The StarFire™ Global Satellite Based Augmentation System was developed by Deere and Company to provide a global Precise Point Positioning (PPP) capability for Precision Agriculture. With two USA based processing and distribution centers, StarFire has been commercially operational since 1999 and has expanded into the additional market segments of Land Survey, Construction, Military, Aerial Mapping and Hydrographic Positioning. Recent system modifications as presented in this paper have improved absolute positioning accuracies from the decimeter level to sub-decimeter.

The paper provides an evolutionary synopsis and detailed overview of the current system architecture, including the reference network, communication infrastructure, data handling, network hub processing, operational redundancy, distribution mechanism, receiver hardware and real-time monitoring. A global common satellite visibility tool has been used to determine the level of observational redundancy within the reference network and the benefit provided by recent reference station additions. The communication network infrastructure improvements establish a new benchmark for reliability and robustness with real-time monitoring now at the system component level. The central processing hubs are based upon a version of the Real Time GIPSY (RTG) suite, originally developed by the Jet Propulsion Laboratory for precise real time orbit and clock determination of GNSS. This has been refined to optimize positioning accuracy of NavCom developed GNSS hardware. Distribution of the StarFire orbit and clock parameters is via a highly optimized data stream to minimize bandwidth requirements, reduce the L-Band satellite transmission cost and ensure sufficient signal strength across the L-Band satellite footprint. Static precise point positioning performance is compared long term against International Terrestrial Reference Frame (ITRF) absolute coordinates for the global StarFire monitoring network. A kinematic dataset for an aerial platform illustrates dynamic StarFire performance with respect to ITRF based Post Processed Kinematic. Using NavCom GNSS hardware, additional comparisons in the position domain are made between StarFire, the Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay System (EGNOS). StarFire real-time orbit and clock parameters compared to International GNSS Service Final post-processed orbit and clock parameters show agreement at the decimeter level.

Combined GNSS and L-Band receiver hardware plus algorithm developments are presented with emphasis on tropospheric modeling, tidal models, integration of inertial sensors and reducing the convergence time for the precise point positioning algorithm to reach optimal accuracy. The paper also discusses RTK Extend™, the simultaneous use of Real Time Kinematic (RTK) and StarFire orbits and clocks to extend RTK positioning accuracies when the RTK base station data link is lost.

The paper concludes with a summary of the current StarFire Global SBAS PPP performance with suggestions for further research and enhancement.

INTRODUCTION

Unlike regional SBAS solutions (WAAS, EGNOS, MSAS, SNAS, GRAS, GAGAN and SCDM), StarFire is a Global SBAS, generating a single set of GPS clock and orbit corrections with global validity. The previous generation of StarFire was based upon the Wide Area Correction Transform (WCT), [Sharpe et al 2000], which still remains operational providing sub-meter performance. This paper concentrates on the current RTG implementation of StarFire developed in 2001 and realizing decimeter horizontal positioning accuracy, [Hatch et al 2003]. The principle of GNSS augmentation is to provide additional data in real-time to refine the observables used within the position solution. Simplistically, this may be in the form of a single range correction for each satellite at a fixed location (DGPS) or as frequency specific corrections for each satellite (RTK) or refined further and provided from a regional network of receivers (Network RTK). Alternatively, corrections may be determined at a more fundamental level on a global basis as per Table 1 which lists the StarFire implementation of these.

Correction	StarFire Implementation
Satellite orbit	1 Minute RTG
Satellite clock	1-2Second RTG
Ionosphere	NavCom L1/L2 Receiver Hardware
Troposphere	UNB WAAS Model (Mendes 99)
Multi-path	NavCom Multi-Path Mitigation Software and Antenna Technology
Receiver	NavCom L1/L2/L-Band Hardware
Earth Tides	Sinko Model in NavCom Receiver

Table 1 : GNSS Fundamental Augmentation

The StarFire correction stream consists of the RTG generated GNSS precise orbit and clock values differenced with respect to the GNSS broadcast ephemeris. These are optimized for near-global distribution via L-Band communication satellites. This signal is received by the NavCom StarFire receivers through the same antenna as the GPS L1 and L2 signals.

As with any GNSS, StarFire has four main segments as shown in Figure 1.

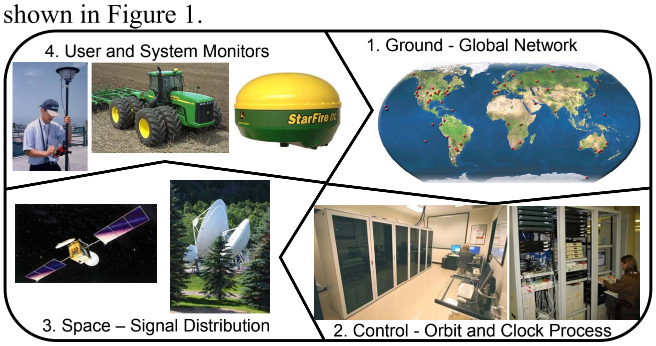


Figure 1 : StarFire GSBAS Segments

User equipment is strategically deployed throughout the global ground network to act as system monitors, thus providing a quality control feedback loop and completing the system cycle to ensure performance metrics are maintained for the global StarFire user community.

GROUND SEGMENT

The number of ground segment tracking sites are tabulated in Table 2 inclusive of other GNSS implementations and planned additions for the future.

GNSS	2002	2006	Future	Comments
StarFire	48	60	60	Global
GPS	6	12	18	Global
GLONASS		8	8	Russia only
Galileo	-----	-----	~29	Global
Beidou	-----	3	3	China only

Table 2 : StarFire and GNSS Ground Segment

Enhancements to the StarFire tracking network have included the addition of 12 stations improving station visibility in the southern hemisphere as shown in Figures 2 and 3. With the exception of South Africa, the current network has a minimum of 7 stations visible from each GPS satellite when using the station elevation mask of 7.5degrees. NavCom's in-house SatVis tool provides common station visibility and maximum DOP values for each satellite over a defined period of time to optimize the ground tracking network locations.

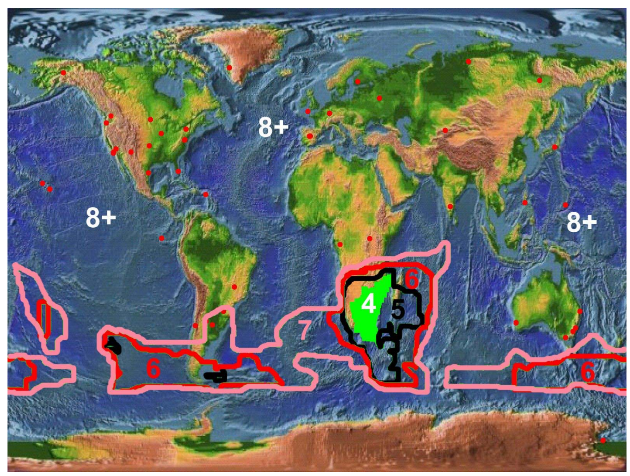


Figure 2 : StarFire Ground Segment 2002

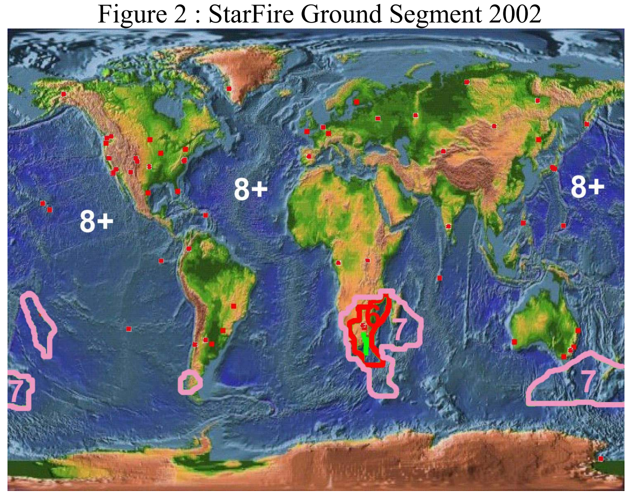


Figure 3 : StarFire Ground Segment 2006

NavCom station GNSS receiver infrastructure has been upgraded to include two NCT-2100D GPS L1/L2 engines operating from a single IGS style Choke Ring antenna, plus (where appropriate) at least one StarFire iTC user receiver to monitor the StarFire L-Band signal strength and system performance from the user perspective. There are currently 16 global sites that have StarFire system monitors.

The number of GPS receivers at each reference station plus the large number of stations that see each satellite at a particular time provides significant system redundancy and robustness. Each station is located within secure facilities, has secure communication links to the control segment, power backup and features stable minimized multi-path antenna installations. Communication options vary with the geographical location but for each reference station there are at least two from local Internet connection, Frame Relay, Landline and VSAT. Historical station downtime is minimal and the quantity of stations available ensures continued system performance even with multiple simultaneous station failures as confirmed by offline control segment scenario tests.

GNSS MONITORING

GPS performance has improved significantly with enhancements in the GPS control segment and the addition of more reference stations (Table 2), however the response time by the Master Control Station (MCS) to a failed satellite component is not immediate. In a recent example on the 2nd of June 2006, the active clock on PRN 30 failed at 20:02Z whilst over the South Indian Ocean and the satellite was eventually set unusable by the GPS MCS 12 minutes later at 20:14Z.

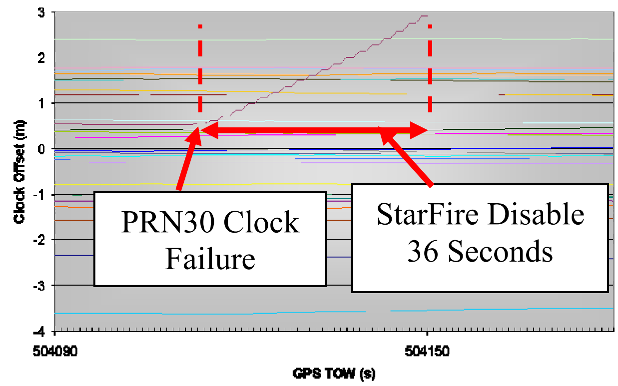


Figure 4 : StarFire Clock Corrections 02 June 2006

The StarFire system was able to stop sending corrections 36 seconds after the initial failure point as shown in Figure 4. Analysis of the nearest StarFire position monitor, located in Johannesburg, South Africa, showed no position degradation during this incident, as per Figure 5, demonstrating the value of StarFire's global monitoring capability coupled with rapid clock updates and low latency delivery rate.

PRN30 was returned to active status and set healthy on 7 June 2006. After an initialization period, StarFire corrections for PRN30 were considered for distribution on 8 June 2006 but anomalous behavior akin to Selective Availability was seen as per Figure 6. Communication with the GPS MCS confirmed that PRN30 was operating within specification and the cyclical behavior was a result of clock stabilization. Given the 5m magnitude of the variation, StarFire corrections for PRN30 were withheld from distribution to users until the clock had properly stabilized.

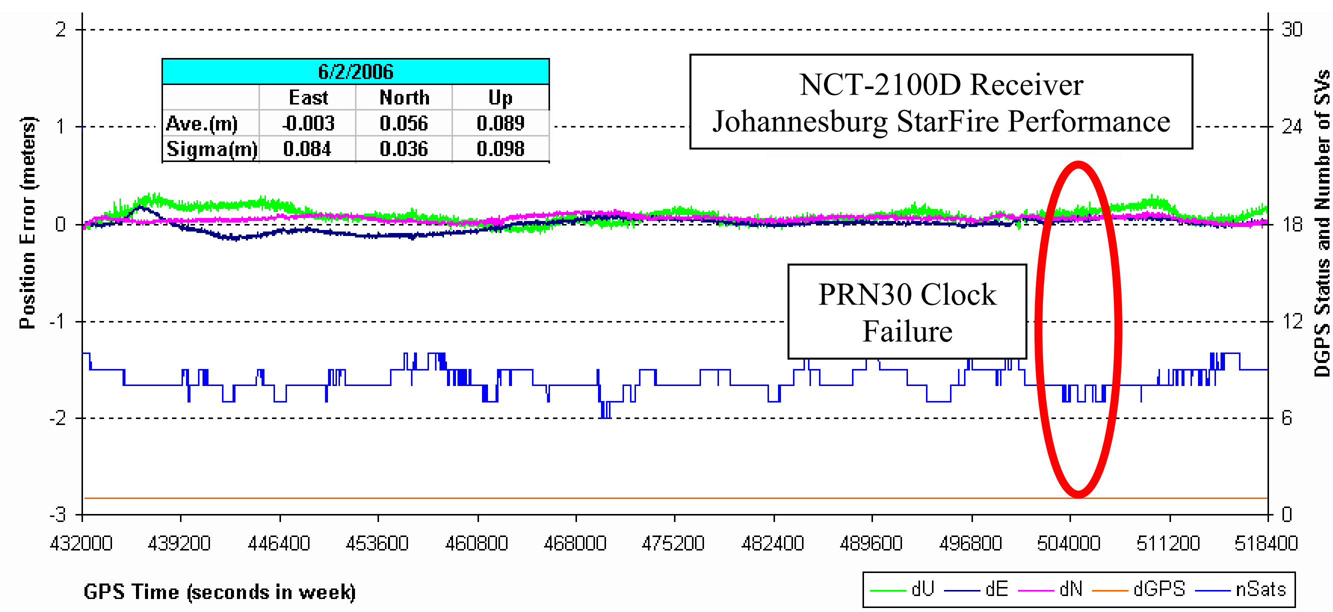


Figure 5 : StarFire Performance, Johannesburg 02 June 2006

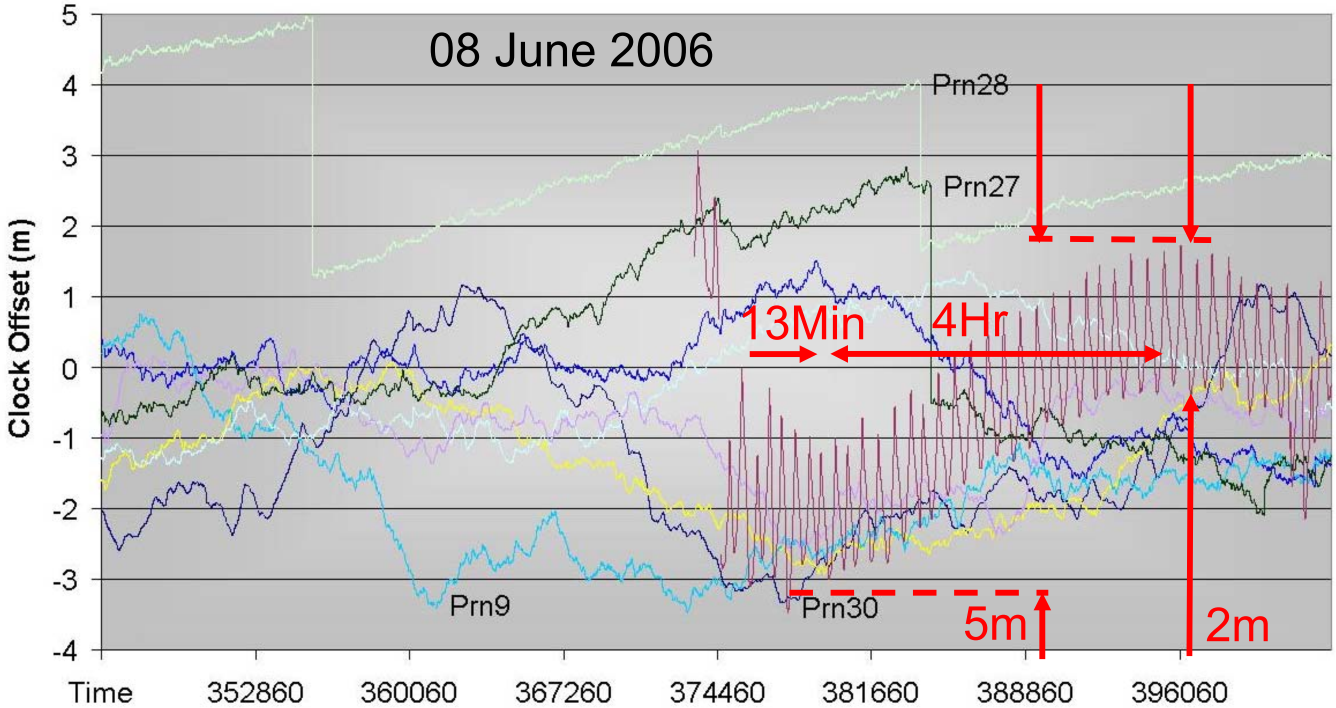


Figure 6 : PRN 30 Clock Stabilization

CONTROL SEGMENT

StarFire has two independent control centers. One is located at NavCom Technology's headquarters in Torrance, California, SW USA and the second at John Deere's corporate headquarters in Moline, Illinois, Central USA. Figure 7 shows the system data flow starting at top left and flowing through to the right.

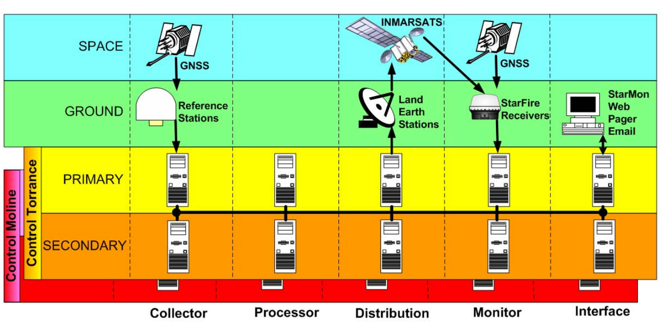


Figure 7 : StarFire System Data Flow

Each control centre receives the full complement of reference station data with a typical latency of less than 2 seconds. There are two production layers, Primary and Secondary, which handle the data independently of each other producing two sets of correction values per centre. Not shown are the Tertiary and Quaternary layers which permit testing of software updates and workflow scenarios prior to use on the production layers. For system robustness and control, all computers now use the Linux Operating System with the exception of the Interface machines which use the latest Microsoft Operating System. The communication system and entire StarFire network is protected at multiple levels from unauthorized access.

Collectors manage the data and communication links to all the reference stations, collating the GNSS observations for input into the Processors.
Processors are dual Pentium machines running RTG code. Production layers operate the same code version and state space. A 6 second buffer is used to collate the raw data for the 1Hz Clock process. The clock process is highly optimized to permit rapid calculation and uses a subset of the global reference network predominantly with atomic frequency standards interfaced to the GNSS receivers. The once per minute orbit process uses the full complement of reference stations. The resulting orbit and clock parameters are differenced with respect to the global GPS broadcast ephemeris. These are optimized for NavCom GNSS receiver hardware and L-Band distribution.
Distribution decides which production layer output will be uploaded and manages the communication links to the 3 Land Earth Stations.
Monitors are able to check the heartbeat of all system hardware components throughout the global network infrastructure. StarFire user receivers, strategically placed round the globe, provide constant system performance metrics with respect to geodetic truth and expected signal strength levels.
Interface provides control, archive and performance metrics. Out of tolerance conditions generate system alerts online and via pager with StarMon providing

network operator oversight and control. In addition, a graphical metrics portal and digital archive is provided.

The RTG code is the latest state of the art implementation from NASA's Jet Propulsion Laboratory. This uses a number of different models as listed in Table 3.

Coordinates for the reference stations are updated at least quarterly to account for tectonic plate motion and any local variation. These coordinates accurate to ~1cm are determined from a periodic global network adjustment constrained to the International Terrestrial Reference Frame (ITRF). This is currently ITRF2000 and thus define the StarFire geodetic frame as ITRF2000(Current Epoch). The StarFire system time is steered to GPS system time via a GNSS receiver co-located at the United States Naval Observatory (USNO). USNO defines the GPS system time and contributes to the fundamental timing infrastructure of the planet. Additional reference stations with atomic frequency standards are available within the StarFire Network to act as control backups and for quality control of the clock process.

CONTROL PERFORMANCE

To assess the most recent system performance, the real-time calculated orbit and clock StarFire values were compared with the post-processed IGS Final Precise orbit and clock for the last 2 weeks of July 2006. Figures 8 and 9 provide a typical daily comparison for this period highlighting the day of 24 July 2006. In these figures, the User Range Error (URE) is a composite of the radial and clock. The high correlation of radial and clock absolute values tend to compensate for each other resulting in relatively low URE figures.

Note the partial correlation between satellites experiencing eclipse events and larger RMS values. Also there appears to be a difference between Block II/IIA and IIR/IIRM. This was investigated further for the full two weeks and RMS values produced for the full constellation, Block specific Sun and Block specific Eclipse satellites.

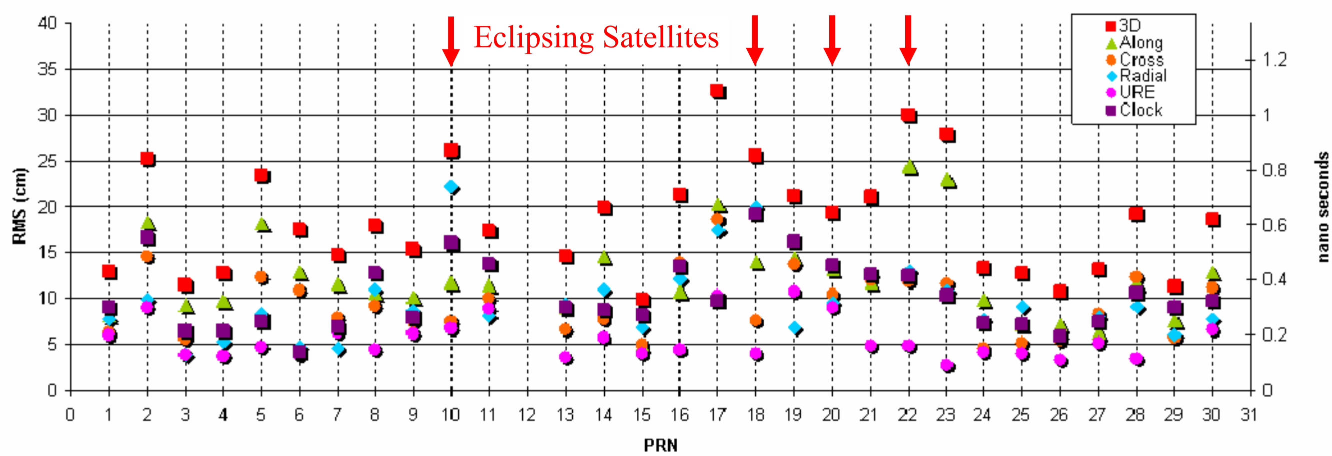


Figure 8 : StarFire Orbit and Clock Performance vs. IGS Final 24 July 2006

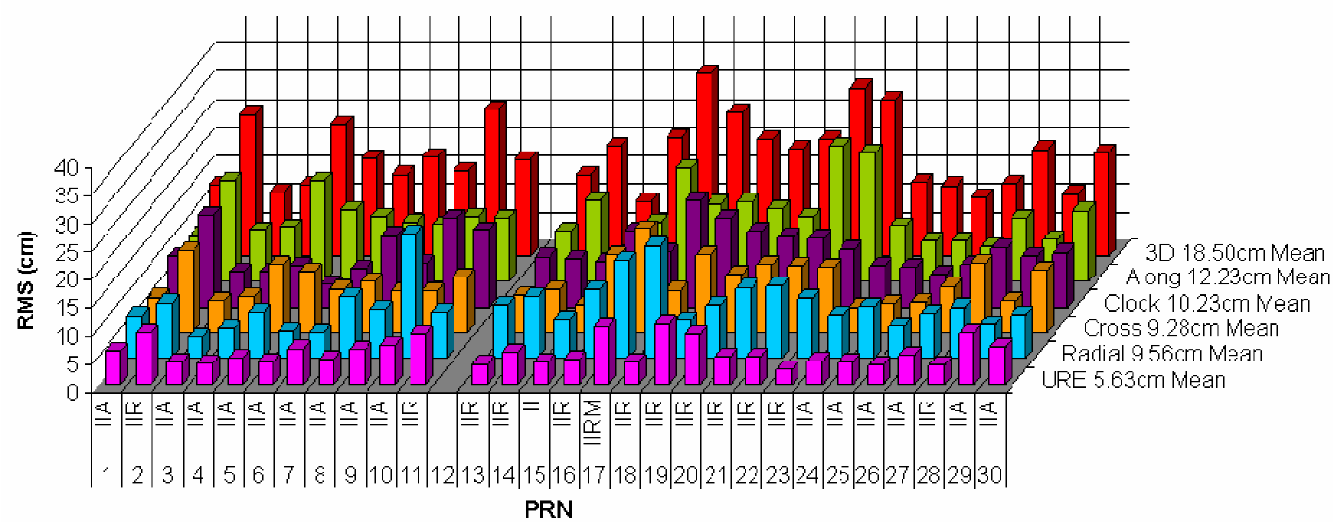


Figure 9 : StarFire Orbit and Clock Mean RMS Performance vs. IGS Final 24 July 2006

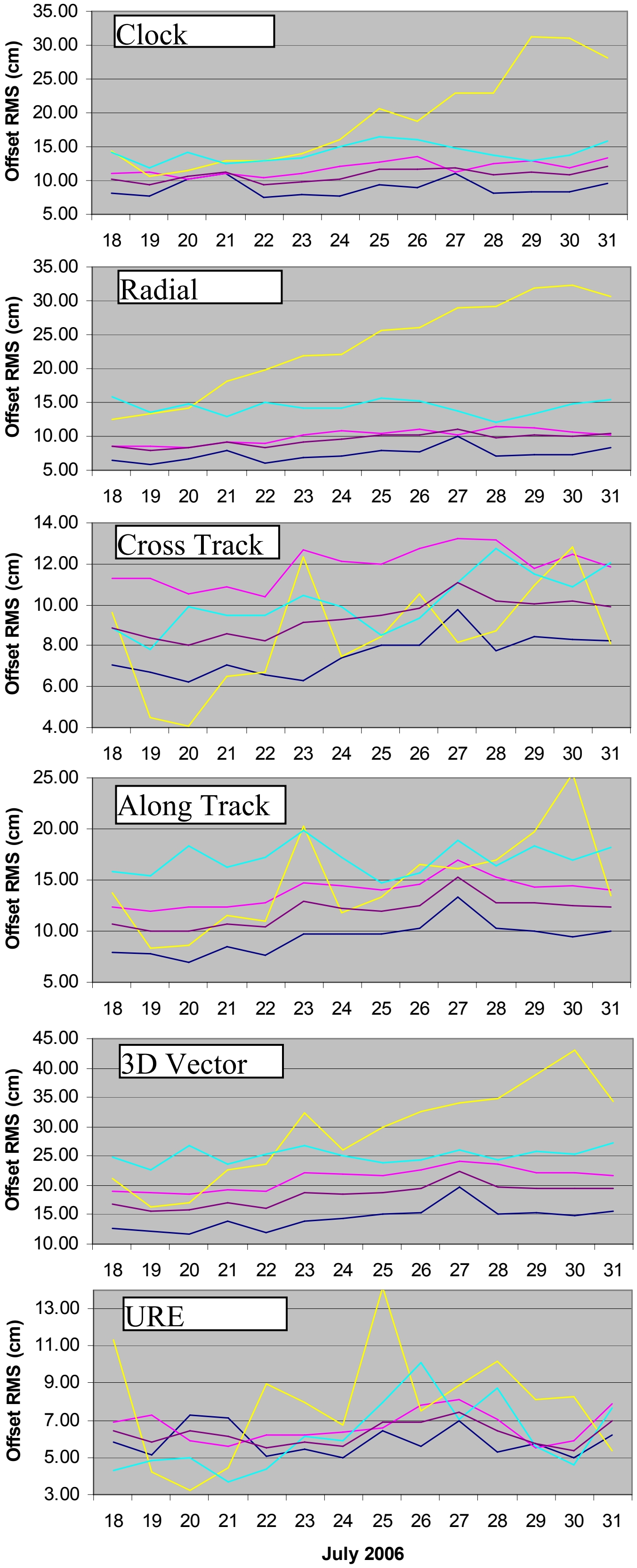
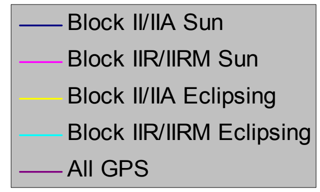


Figure 10 : StarFire vs. IGS Final Comparison



The comparison between StarFire real-time orbits and clocks versus IGS post processed Final orbits and clocks as shown in Figure 10 shows Block II/IIA Eclipsing to be an outlier. During this period, only one II/IIA, PRN10, was in eclipse. With the exception of PRN10, User Range Error agrees at the 6-8cm level. Given that IGS Final has an orbit accuracy of 5cm and a clock accuracy of 0.1ns (≡3cm), this was an unexpectedly close comparison especially given that StarFire is real-time and IGS is a post processed combination from multiple analysis centers. The data would also suggest that eclipsing satellites require more investigation into their behavior.

Model	**RTG**
Geopotential	JGM3
Solid Tide (Dynamic)	Wahr 3x3 47 constituents
Solid Tide (Kinematic)	Included
Pole Tide	Included
Ocean Tide	CSR + TEG2B 20x10 767 constituents
Ocean Loading	Included
Troposphere	Neill
Solar Pressure	T20
Relativity (Dynamic)	Included
Relativity (Kinematic)	Included
Phase Windup	Included

Table 3 : RTG Models Currently Used

SPACE SEGMENT

The StarFire space segment consists of 3 Inmarsat satellites providing global L-Band distribution with the exception of the North and South Poles as per Figure 11. Table 4 provides details of the areas covered, the geo-stationary longitude, satellite name, Inmarsat satellite type and ID plus the Land Earth Stations used for uplink of the StarFire signal.

Area	Long.	Name	Sat.	Land Earth Stn.
Americas	098°W	PAC-E	2-F2	Laurentides, Canada
Europe Africa	025°E	IND-W	3-F5	Goonhilly, England
Asia Pacific	109°E	IND-E	2-F4	Auckland, New Zealand

Table 4 : StarFire Satellites

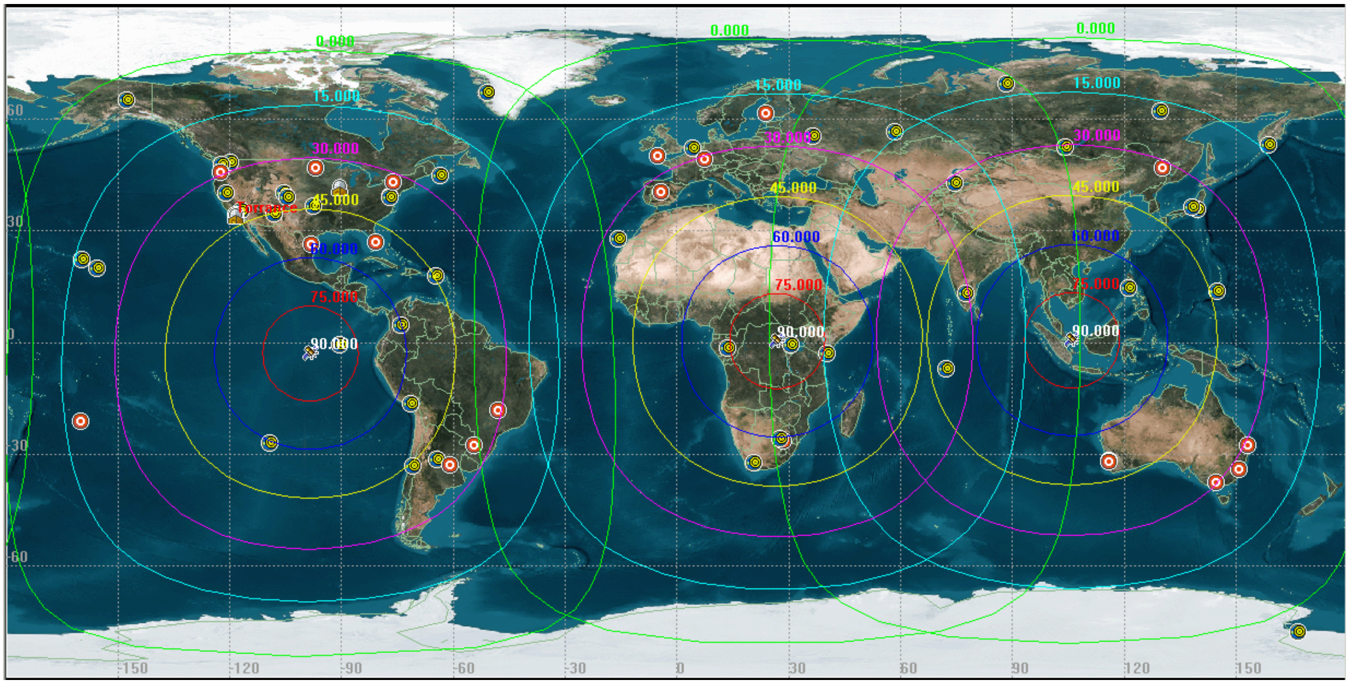


Figure 11 : StarFire Space Segment with Elevation Look Angle Contours

Each of the 3 Land Earth Stations has a Primary and Secondary layer of equipment and each layer receives corrections from both Control Centers. Communication between the Control Centers and the Land Earth Stations is via Internet and VSAT with a backup landline.

The 3 communication satellites are constantly monitored by Inmarsat to ensure service continuity with backup channel capacity available on adjacent satellites covering the same regional areas. In addition, the StarFire Network monitors provide received L-Band signal strength to confirm the satellite transmitted signal power level. Signal power level is higher at the outer edges of the signal beam to provide a more uniform signal strength across the full satellite footprint on the earth.

Distribution uptime for the StarFire signal has been 99.997% for the last 12months. This was a 16minute interruption due to a communication satellite outage.

USER SEGMENT RECEIVER TECHNOLOGY

There are more than 40,000 StarFire receivers deployed worldwide for use in an increasingly diverse set of applications. At the heart of every current StarFire receiver is NavCom's Touchstone 4 ASIC precise GPS L1/L2 technology plus NavCom's L-Band receiver. These coupled with a tri-band antenna for L1/L2/L-Band reception minimize equipment installation. John Deere has complete control of the generation of StarFire corrections and the development and manufacture of StarFire receiver technology to ensure a consistent and accurate performance level for the StarFire system as a whole.

The positioning algorithm within StarFire receivers uses a Kalman filter to solve for the satellite and receiver channel biases plus the code phase floating ambiguities. Least Squares is then used to calculate the position based upon phase smoothed refraction and bias corrected code observables. Enhancements of the algorithm include the addition of the Sinko Earth tide model. Unlike terrestrial augmentation methods which are earth crust fixed and thus include earth tides, StarFire is space based, requiring earth tides to be compensated for at the receiver. Modifications to the Tropospheric model (Mendes 1999) has facilitated the adoption of StarFire for aerial applications with their rapid and large height variations.

The same receiver technology is extremely flexible providing the following alternative modes and performance levels:

1. SBAS <30cm RMS (WAAS)
2. RTK 2-3cm RMS
3. Post Processed Kinematic ~1-3cm
4. Post Processed Static <1cm

A novel and patented technique known as RTK Extend, blends the StarFire and RTK to provide a more robust RTK solution.

Different form factors facilitate the use of StarFire for various applications as per Figure 12.

John Deere
StarFire iTC Receiver
- Integrated
- Agriculture
- Inertial Sensors

NavCom
SF-2050 and VueStar™
- Modular
- Machine Control
- Offshore
- Military
- Aerial

NavCom
SF-2040 StarFire Receiver
- Integrated
- Li-Ion Battery
- Portable
- Land Survey

Figure 12 : StarFire Receiver Options

APPLICATIONS

Agriculture. John Deere customers are using StarFire for Precision Agriculture, the benefits of which include:

1. Agronomy cost efficiency
2. Minimal overlap between parallel passes
3. Field performance metrics
4. Reduced seed and fertilizer usage
5. Night-time harvesting
6. Precise implement placement avoids stripping out water drip lines.

The StarFire iTC receiver is fully integrated with antenna and inertial technology and is capable of determining exact wheel placement of the tractor or combine harvester irrespective of the slope of the field. This avoids the need for external components and makes the unit extremely portable from one vehicle to another.

Offshore. The increasingly high energy price is pushing oil and gas exploration deeper offshore. Precise positioning at the decimeter level has hitherto been unavailable far offshore. The accuracy of StarFire on a global basis improves the resolution of seismic exploration surveys and the location of sub-sea structures (Roscoe-Hudson et al 2001). The recent spate of intense hurricanes in USA have required very precise positioning to ensure the safety of construction vessels salvaging damaged offshore platforms whilst avoiding seabed pipes dragged out of location. A novel application is precise sea-level monitoring by intelligent station keeping buoys, contributing to a better understanding of the ocean and providing data for tsunami warning systems.

Land Survey. Surveyors have found the flexibility of the StarFire receiver to be an advantage in remote areas where RTK is not available, problematic or costly to implement. Decimeter accuracy is sufficient for many survey and mapping tasks. The StarFire RTK Extend feature permits RTK type accuracy when the RTK base station is temporarily lost, saving the time needed to move the RTK base station.

Military. StarFire is more accurate than Military GPS and has been used for:

1. Global Hawk UAV positioning
2. Autonomous robotic vehicles in the DARPA Grand Challenge Race
3. To benchmark other aircraft positioning sensors
4. Unexploded Ordnance (UXO) clearance
5. US Naval Hydrographic Surveys

Aerial Survey. Digital photogrammetry and airborne Lasers to create digital elevation models (LIDAR) have been used extensively as a cost effective means of surveying large areas, especially long linear projects. Traditionally, this would require an array of GNSS ground stations to be established in the survey area and manned for the duration of the flight with data then post processed. This increases both the cost and time to delivery to the end customer. Having StarFire real-time decimeter positioning avoids costly GNSS ground infrastructure and speeds up delivery.

USER PERFORMANCE

An added benefit of the NavCom StarFire receiver algorithm development has been the enhancement of positioning performance with WAAS SBAS in North America. Figure 13 provides a typical performance graph for 24 hours compared against StarFire performance at the same location and time.

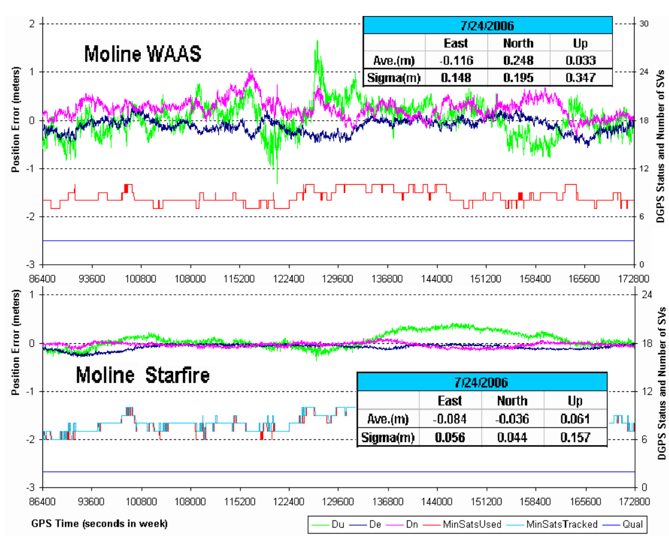


Figure 13 : WAAS vs. StarFire Performance

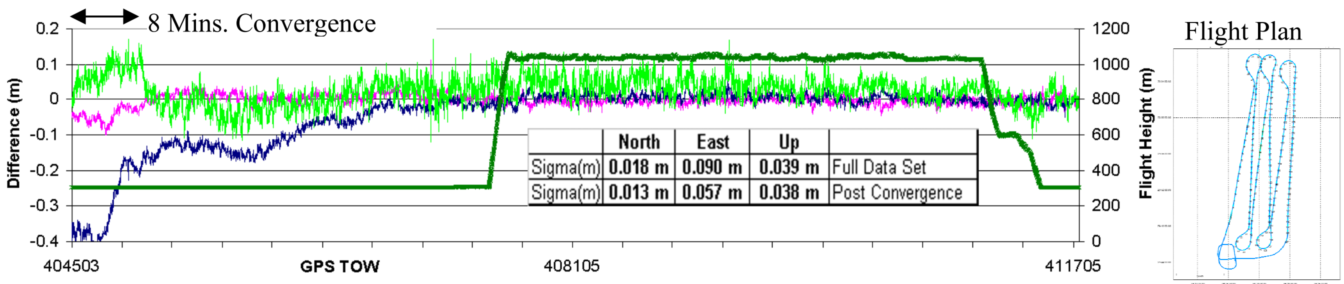


Figure 14 : Flight Real-Time StarFire minus Post Processed Kinematic L1/L2

Dynamic performance of StarFire is amply illustrated by the flight dataset in figure 14 which shows the difference between real-time StarFire positions and post processed kinematic. Some GNSS receivers, when experiencing large height changes, can introduce a height bias due to the way that the troposphere is modeled. Note the stability of height during the rapid climb indicating the consistency of the receiver tropospheric model.

Figure 14 also illustrates a startup convergence time during which the StarFire receiver determines the satellite and receiver biases to optimize the position solution. Convergence times can be eliminated by the use of the QuickStart feature. This requires a known ITRF position for the StarFire receiver. StarFire compatible ITRF coordinates may be determined from previously surveyed positions using a converged StarFire receiver, precise post processing or by a RTK base station. For example, a tractor operated with a StarFire receiver will have converged StarFire positioning available when it is parked in the open at the end of the work period. The final position can be used to QuickStart the StarFire receiver when it is switched on at the start of the next tractor work period. Figure 15 illustrates a QuickStart procedure at the left of the plot and a loss of StarFire corrections for 20minutes at the right of the plot. The statistics after the QuickStart are all sub-decimeter. After the loss of StarFire corrections represented by the vertical blue line, horizontal position is still at the decimeter level 20 minutes later.

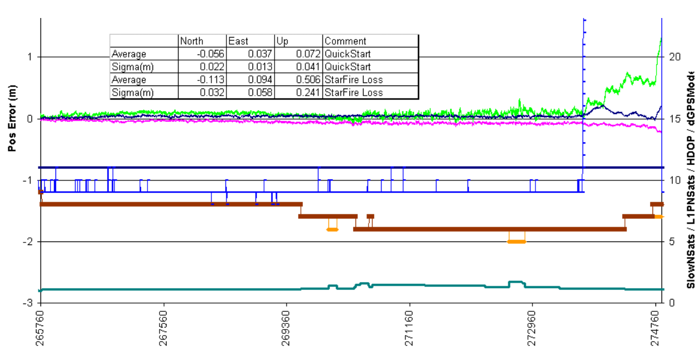


Figure 15 : QuickStart and StarFire Loss Example

USING IGS FINAL ORBITS AND CLOCKS

To assess the performance of the NavCom StarFire positioning algorithm, IGS Final orbits and clocks were used to constrain StarFire orbits and clocks via an 11th order interpolation. The resulting correction stream was then used to rerun StarFire datasets and compare the resulting positions against the standard StarFire determined positions. This was done for six geographically diverse sites as shown in Table 5.

24 July 2006		FULL DATA SET			POST CONVERGENCE		
StarFire Orbit+Clock	Convergence	North	East	Up	North	East	Up
Weslaco, USA	24Mins	0.071	0.085	0.200	0.047	0.079	0.168
Rosario, Argentina	18Mins	0.065	0.068	0.148	0.047	0.045	0.133
Zweibrucken, Germany	24Mins	0.076	0.087	0.148	0.038	0.077	0.136
Johannesburg, S.Africa	9Mins	0.055	0.048	0.163	0.036	0.042	0.145
Jiamusi, China	16Mins	0.046	0.077	0.155	0.036	0.074	0.144
Sydney, Australia	14Mins.	0.038	0.084	0.187	0.033	0.056	0.145
IGS Final Orbit+Clock							
Weslaco, USA	26Mins	0.054	0.080	0.213	0.049	0.072	0.159
Rosario, Argentina	12Mins	0.043	0.068	0.177	0.040	0.038	0.169
Zweibrucken, Germany	24Mins	0.062	0.085	0.187	0.047	0.081	0.159
Johannesburg, S.Africa	9Mins	0.076	0.061	0.161	0.040	0.046	0.142
Jiamusi, China	17Mins	0.048	0.117	0.204	0.042	0.095	0.168
Sydney, Australia	14Mins.	0.039	0.066	0.185	0.022	0.034	0.148

Table 5 : StarFire Positioning versus IGS Final

The convergence times in minutes and sigma values in meters show little difference between the two sets as indicated by the number of amber colored cells with differences less than 1minute or 1cm. Convergence times are given for accuracies less than 10cm in each axis.

GEODESY

As discussed earlier, StarFire Geodesy is the latest implementation of ITRF at the current epoch. StarFire can be used as is, but to relate it to existing databases or data constrained to a local geodetic reference frame, a 4D transformation is required. This takes into account the relationship between the local geodetic reference frame and ITRF at a fixed epoch plus the vector change that has occurred between the fixed epoch and the current epoch. National geodetic infrastructure is increasingly being defined with respect to ITRF at a specific epoch with an associated vector change field to account for tectonic plate motion. These available parameters permit a precise relationship between StarFire positioning and local mapping and can usually be found within GNSS Survey Controller devices.

A common miss-conception is to consider all WGS84 positions to be equivalent to ITRF. The original definition of WGS84 was accurate to ~2m. The current implementation of WGS84 by the GPS is closely aligned to ITRF to a few centimeters. What must be factored into any comparison between StarFire positions and an existing WGS84 position is when and how the WGS84 position was defined.

LOOKING FORWARD

The development and availability of new GPS frequencies and codes will require an upgrade in the StarFire Ground Segment. This is expected to improve upon GPS orbit and clock determination as more satellites are launched. An increase in transmission bandwidth will not be required because the corrections are orbit and clock for each GPS satellite. Alternative ground based augmentation systems which provide values for each signal and code per satellite will need increased bandwidth to transmit their data.

Other GNSS systems such as GLONASS, Galileo, QZSS, Compass and IRNSS will also require a change in the StarFire Ground Segment. Support of new GNSS systems will require additional orbits and clocks to be added to the StarFire correction stream increasing the bandwidth but this is expected to be much less of an increase than required by ground based augmentation systems. Table 6 illustrates the relative quantity of observables to be transmitted for augmentation. StarFire is a global data stream with orbit updates not so frequently required as clock updates, whereas Ground Based Augmentation Systems are local requiring updates every second for a smaller number of satellites visible. The percentage differences in bandwidth between orbits+clocks versus GBAS are considerably greater when the actual bits per observable are taken into consideration plus optimization.

GNSS	StarFire Total(Obs*Sats*Hz)	Local GBAS Stn. Total(Obs*Sats*Hz)
GPS L1/L2	30.5 (Orbit*30*1/60 + Clock*30*1)	40 (4*10*1)
GPS L5	0	20 (2*10*1)
GLONASS L1/L2	24.4 (Orbit*24*1/60 + Clock*24*1)	32 (4*8*1)
GLONASS L3	0	16 (2*8*1)
GALILEO E1, E5A, E5B, E6	30.5 (Orbit*30*1/60 + Clock*30*1)	80 (8*10*1)
Compass C1, C5, C6	30.5(Orbit*30*1/60 + Clock*30*1)	60 (6*10*1)
Total Now	30.5 (100%)	40 (+31%)
Total Future	115.9 (+280%)	248 (+713%)

Table 6 : Augmentation Bandwidth Requirements

Looking forward, figure 16 provides a potential GNSS development timeline for GPS, Glonass, Galileo and QZSS. Reality will differ. The GPS satellites have lived much longer than originally designed and whilst providing excellent value, this has delayed the launch of new functionality. Glonass was fully operational but funding issues in recent years have reduced the constellation and usability. Statements from President Putin and increased funding based upon a high energy price fueled Russian economy will hopefully return Glonass to full strength. Concerns remain over the Galileo program with a recent overspend of €400M and continuing discussions over commercial terms and risk sharing with the concessionaire. Having 30 satellites built, launched and fully operational by the end of the decade is an aggressive schedule, especially when compared with previous GNSS system development and deployment. Japan's QZSS is currently committed to one satellite, India's 8 satellite IRNSS and China's 30 satellite Compass systems are currently in planning and evaluation stages.

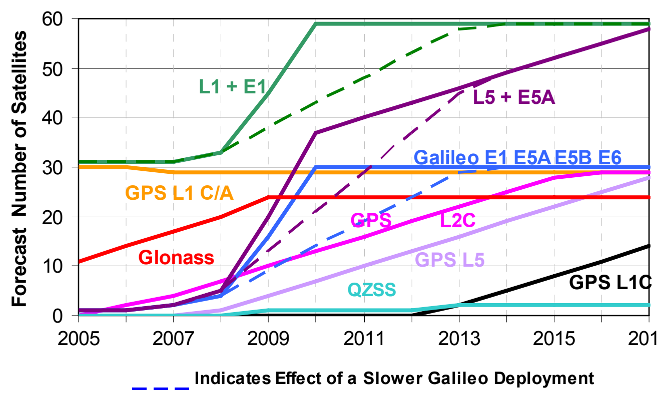


Figure 16 : Potential GNSS Timeline

CONCLUSIONS

The extensive 60 station global monitoring network for StarFire has a faster response time than the GPS Master Control Station to anomalous GPS behavior. In the example of 02 June 2006, this was 12 minutes versus StarFire's 36 seconds.

StarFire uses a tighter tolerance for GPS satellite signal performance. The GPS MCS considers a 5m clock variation over 4hours and a 2m variation over 6.5minutes to be within specification as per the example of PRN30 on 08 June 2006.

StarFire clock and orbit corrections for the GPS satellites provide a User Range Error < 8cm RMS compared with IGS Final clocks and orbits.

The NavCom WAAS positioning algorithm demonstrates a standard deviation of <30cm Horizontal and <40cm Vertical.

The StarFire positioning algorithm has a standard deviation of <10cm Horizontal and <20cm Vertical and is capable of sub-decimeter performance after convergence. Convergence times depend upon the satellite conditions available during the convergence period. Convergence times vary from 09-24 minutes for an accuracy less than 10cm in each axis.

Convergence times are eliminated with the QuickStart feature provided that an ITRF position compatible with StarFire is used. StarFire compatible ITRF coordinates may be determined from previously surveyed positions using a converged StarFire receiver, precise post processing or by a RTK base station.

It is possible to lose StarFire corrections for a period of up to 20 minutes and still maintain decimeter horizontal accuracy.

The technique of using precise orbits and clocks as used by StarFire requires less observables and bandwidth for augmentation than traditional GBAS. This difference will become greater in the future as GNSS systems are enhanced and deployed.

Testing of the StarFire positioning algorithm using IGS Final post-processed orbits and clocks showed no noticeable positioning improvement compared to the use of StarFire real-time orbits and clocks.

Suggested areas of further research are modeling satellites during eclipse, block specific effects, satellite and receiver bias optimization and future GNSS use.

ACKNOWLEDGMENTS

This paper would not have been possible without the generous support of my colleagues at NavCom Technology.

REFERENCES

Hatch R, Sharpe T and Galyean P; "A Global, High-Accuracy, Differential GPS System"; ION NTM 2003, Institute of Navigation National Technical Meeting, Anaheim, 22-24 Jan 2003.

Mendes V. de Brito; "Modeling the Neutral-atmosphere Propagation Delay in Radiometric Space Techniques"; a Ph.D. dissertation published as Department of Geodesy and Geomatics Engineering Technical Report No. 199, University of New Brunswick, Fredericton, New Brunswick, Canada, April 1999.

Roscoe-Hudson J, Sharpe T; "Globally Corrected GPS (GcGPS): C-Nav GPS System"; Dynamic Positioning Conference, 18-19 Sep 2001.

Sharpe T, Hatch R and Nelson F; "John Deere's StarFire System: WADGPS for Precision Agriculture "; ION GPS 2000, 13th International Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, 19-22 Sep 2000.