ABSTRACT
NavCom’s next generation StarFire GNSS system performance is described in this paper. The StarFire GNSS system is a Global Satellite Based Augmentation System (GSBAS) developed entirely by NavCom Technology. Significant improvements have been made to each component of the system including the ground reference network, new proprietary real-time orbit and clock generation, dual redundant delivery of corrections via commercial communication satellites, and the GNSS receiver navigation software. Among the most significant improvements is the incorporation of orbit and clock corrections for GLONASS satellites. At the same time, the orbital and clock correction accuracy for GPS satellites has been dramatically improved and the receiver navigation software has been modified to take advantage of both the GLONASS satellites and the improved orbit and clock accuracy for GPS. Each component of the StarFire GNSS system is described below and the improved performance is compared to that of the legacy StarFire GPS (only) system and is illustrated with comparative test results.

INTRODUCTION
NavCom Technology recently launched their next generation StarFire GNSS system, which enables current models of NavCom StarFire receivers to achieve sub-decimeter navigation accuracy using both the U.S. Global Positioning System (GPS) and the Russian GLONASS system. StarFire provides global Precise Point Positioning (PPP) capability for various applications, such as precision farming, land survey, machine control, aerial navigation, and marine survey. The StarFire GNSS system includes NavCom’s Global Navigation Satellite System (GNSS) reference receiver network, communication infrastructure, data collection system, network data processing to compute precise clock and orbit corrections, real-time correction distribution, and the StarFire receiver hardware and software. NavCom Technology has made numerous advancements in Satellite Based Augmentation Systems (SBAS) over the past 15 years and has continued to improve receiver performance to a customer base that now consists of multiple thousands of users. The first StarFire Wide Area Differential GPS correction service, originally named Wide Area Correction Transform (WCT), was introduced by NavCom in 1998. Like the current system it used dual-frequency GPS measurements for navigation and precise point positioning. This continental WADGPS StarFire system delivered better than 30cm position accuracy for users in North America.

In 2002, NavCom introduced a truly global StarFire GPS augmentation service. Using a global reference receiver network and an enhanced version of the Real-Time GIPSY (RTG) clock and orbital correction software licensed from Jet Propulsion Lab (JPL), corrections are generated for all of the GPS satellites at two independent processing centers. The StarFire clock and orbital corrections are currently uplinked to six geo-stationary satellites and broadcast from them to the user receivers. NavCom GPS receivers are able to use the StarFire GPS service to achieve better than 10cm RMS accuracy for a variety of applications. A diagram of the system operation is shown in Figure 1.

The recently introduced next generation StarFire GNSS augmentation service offers the following enhancements and new capabilities:

1. Reference Site Updates - The global reference receiver network used in the new StarFire GNSS system is wholly owned and operated by NavCom Technology. This homogenous StarFire reference receiver network enables NavCom to provide higher system reliability and to modify and improve the satellite correction accuracy.
2. **Clock & Orbit Innovation** - The data center software, which generates the clock and orbit corrections for the StarFire GNSS system, now uses NavCom developed proprietary software. This software incorporates innovative clock and orbit real-time estimation algorithms. This hub processing software produces 4 cm clock corrections for GPS satellites and 13 cm clock corrections for GLONASS satellites. As far as we can determine, the orbit and clock corrections which we generate are competitive with the orbit and clock accuracy formed by the International GNSS Service (IGS) from a weighted average of orbits and clocks generated by from 8 to 10 academic institutions and international government agencies.

3. **Expanded Rover Performance** - With the StarFire GNSS service, the NavCom StarFire receivers use both GPS and GLONASS satellites for precise navigation. The system availability, accuracy, and reliability of the navigation performance of StarFire receivers have been significantly improved.

4. **Legacy StarFire GPS Operation** - The StarFire system continues to broadcast the StarFire GPS service (pre-April 2011) along with the new StarFire GNSS service to maintain compatibility with legacy receivers. NavCom Sapphire based receivers running the latest firmware are able to compute position solutions using either the new GNSS service or the older GPS service. This provides increased reliability and inherent receiver redundancy.

In short, the StarFire GNSS system is not merely a simple step to include GLONASS satellites into the existing StarFire GPS system. Instead, it is a revolutionary upgrade to the entire StarFire system, including new reference sites and processing software. Each component of the system is described below.

**STARFIRE GNSS NETWORK**

In the new StarFire GNSS system, both GPS and GLONASS range measurements are provided by the newly deployed global reference receiver network. In this network NavCom SF-3050 receivers are collocated at each reference site to provide system redundancy. All of the GNSS data collected at these sites is transmitted back to geographically separated and independent StarFire processing centers in real-time. An additional StarFire receiver is used to monitor the signal strength of the StarFire L-band signal, as well as, the positioning performance of the StarFire system at each reference site. There are StarFire GNSS reference sites strategically located on every continent other than Antarctica. This allows each GNSS satellite to be tracked by at least five or more reference sites simultaneously.

**STARFIRE GNSS CLOCK AND ORBIT ESTIMATION**

The core technology used in the StarFire GNSS system is NavCom’s innovative real-time GNSS satellite clock and orbit computation engine. This state-of-art software computes and predicts the orbit and clock of GNSS satellites in real-time using the raw GNSS measurements from NavCom’s global reference receiver network. This software can determine the satellite orbit with an accuracy of 5cm (1-sigma) for GPS and 14 cm (1-sigma) for GLONASS satellites in real-time.

Figure 2 shows a typical 24-hour real-time orbit error plot. This particular graph, using data obtained on April 9th, 2010, was generated by taking the final orbit product from the International GNSS Service (IGS) as truth reference. There were 29 GPS and 16 GLONASS satellites available at that time and the average orbit accuracy was 3.96 cm for all GPS satellites and 8.69 cm for all GLONASS satellites. This compares to the 17 cm typical orbit accuracy of the StarFire GPS service. Thus, the new StarFire GNSS corrections have been significantly improved. The new clock and orbit software is designed to expand gracefully as future constellations, such as...
Galileo and/or COMPASS satellite systems become available.

The two StarFire receivers shared a standard NavCom GNSS rover antenna and they were exposed to the same multipath conditions. In this setup, one of the receivers navigated using the StarFire GNSS service, while the other navigated using the legacy StarFire GPS service. The results show that the new StarFire GNSS solutions had much smaller temporal variation over a 24-hr period after convergence. In addition, the bias observed in StarFire GPS height solutions did not exist in StarFire GNSS solutions.

Table 1 shows the position error statistics of StarFire GNSS navigation for these sample results. The RMS errors of the local level frame from the surveyed position are: East 2.16 cm; North 2.22 cm; and Up 6.78 cm. The corresponding numbers of the legacy StarFire GPS are: East 6.57 cm; North 6.80 cm; and Up 17.44 cm, which were obtained with the same hardware in identical signal conditions. This constitutes a three to one improvement in the horizontal accuracy and almost the same in the height. Figure 4 shows the number of satellites used in both StarFire modes. It is clear that the PDOP (Position Dilution of Precision) using the StarFire GNSS navigation was always below 2 when aided by the extra GLONASS satellites. By contrast, the PDOP of the legacy StarFire GPS navigation occasionally went up to more than 4. (Note: Actual user error and performance results may vary as a result of many factors including environmental and atmospheric effects.)

Figure 3: StarFire navigation performance in open sky condition

These test results demonstrate the new StarFire GNSS service has significantly mitigated the low frequency temporal variations in position errors, as well as vertical bias seen in the legacy StarFire GPS...
solutions. NavCom has continued to be an industry leader by providing SBAS corrections to worldwide customers in real time which have advanced the state of the art in reducing convergence time, improving vertical accuracy and increasing reliability.

Table 1: Statistics of StarFire position errors

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<thead>
<tr>
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<th>StarFire GNSS</th>
<th>StarFire GPS</th>
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<tbody>
<tr>
<td>RMS East [cm]</td>
<td>2.16</td>
<td>6.57</td>
</tr>
<tr>
<td>RMS North [cm]</td>
<td>2.22</td>
<td>6.80</td>
</tr>
<tr>
<td>RMS Up [cm]</td>
<td>6.78</td>
<td>17.44</td>
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Figure 4: Satellite geometry in open sky condition

HEAVY PARTIAL SHADING DYNAMIC TEST

StarFire GNSS delivers improved position performance in challenging signal conditions, such as heavily shaded areas, compared with the legacy StarFire GPS. The addition of GLONASS satellites allows navigation in situations where it would otherwise not be possible due to an insufficient number of available GPS satellites. However, in our heavy shading tests there was such heavy shading, that at three times the number of satellites dropped below the four needed to maintain navigation. While the StarFire GNSS maintained lock longer and recovered sooner, both the new system and the legacy system suffered from the decreased accuracy present during the pull-in convergence period. The improved performance during the pull-in time is best measured statistically as described in the next section.

CONVERGENCE TEST

The inclusion of GLONASS satellites in the StarFire GNSS system not only improves system availability in challenging conditions, as described in the previous section, it also is able to reduce the convergence time. In order to achieve high precision navigation solutions, the StarFire navigator must accurately determine the carrier phase ambiguity states in the Kalman filter. The length of time taken to determine the phase ambiguity states has a strong correlation with the PDOP. As was shown above in Figure 4 the addition of GLONASS measurements in StarFire GNSS substantially improves the PDOP and thereby enables ambiguity resolution and improved accuracy more quickly.

Figure 5 depicts the convergence time versus the position error in the horizontal plane based on a 24-hour real-time data set collected in an open sky environment. During this data collection period, the SF-3050 StarFire receiver was intentionally power cycled every sixty minutes. After each power cycle, the StarFire receiver re-started the convergence process. The plots show the solution statistics of sixty 1-minute bins from two StarFire receivers, one of which navigated in StarFire GNSS mode (the green trace) while the other operated in StarFire GPS mode (the blue trace). With the addition of GLONASS satellites, the time to reach the same position accuracy on both receivers is always shorter for StarFire GNSS compared with that for the StarFire GPS receiver. The trend shows that the GLONASS satellites significantly benefit the convergence performance.

In general the convergence of the StarFire GNSS receiver to a given accuracy is approximately twice as fast as the legacy StarFire GPS receiver. This improvement significantly reduces the system warm-up time and increases the efficiency and up-time of StarFire service to end users.

CONCLUSIONS

The next generation of StarFire has been introduced by NavCom Technology. The new StarFire GNSS includes the ability to make use of the GLONASS satellites.
satellites and is expandable to include the future use of other navigation satellites; e.g. Galileo and Compass satellites. In addition, NavCom has developed new orbit and clock correction software which is capable of providing a new level of navigation accuracy. The net result is a system which conservatively provides an accuracy that is between two and three times more accurate than the legacy StarFire GPS system. The improved accuracy and robustness of the new StarFire GNSS system is unexcelled by any competitive system and establishes a new standard for Satellite Based Augmentation Systems (SBAS).