

# Investigation of GPS/IMU Positioning System for Mining Equipment

Final Technical Report

Period Start Date: June 2004  
Period End Date: April 2006

Principal Investigator: Ken L. Stratton

Issued Date: May 31, 2006

Contract No.  
DE-FC26-04NT42082

## **Disclaimer**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness or any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

## **Abstract**

The objective of this project is to investigate the applicability of a combined Global Positioning System and Inertial Measurement Unit (GPS/IMU) for information based displays on earthmoving machines and for automated earthmoving machines in the future. This technology has the potential of allowing an information-based product like Caterpillar's Computer Aided Earthmoving System (CAES) to operate in areas with satellite shading. Satellite shading is an issue in open pit mining because machines are routinely required to operate close to high walls, which reduces significantly the amount of the visible sky to the GPS antenna mounted on the machine. An inertial measurement unit is a product, which provides data for the calculation of position based on sensing accelerations and rotation rates of the machine's rigid body. When this information is coupled with GPS it results in a positioning system that can maintain positioning capability during time periods of shading.

<b>LIST OF GRAPHICAL MATERIALS .....</b>	<b>4</b>
<b>1. EXECUTIVE SUMMARY .....</b>	<b>6</b>
<b>2. SYSTEM CONFIGURATION – POS MC AND CAES.....</b>	<b>8</b>
COMPUTER AIDED EARTHMOVING SYSTEM .....	8
POSITION AND ORIENTATION SYSTEM FOR MACHINE CONTROL .....	9
POS MC/ CAES TESTING CONFIGURATION .....	11
<b>3. TASKS FOR THE PROJECT .....</b>	<b>13</b>
<b>4. EXPERIMENTAL .....</b>	<b>15</b>
2.1 TESTING ON EXCAVATOR AT PROVING GROUNDS .....	15
2.2 TESTING AT TWIN CREEKS MINE.....	26
<b>5. CONCLUSION .....</b>	<b>36</b>
<b>6. LIST OF ACRONYMS AND ABBREVIATIONS.....</b>	<b>39</b>

## List of Graphical Materials

Below is the list of figures in this report.

Figure 1. Computer Aided Earthmoving System Components.

Figure 2. POS MC system components.

Figure 3. Functional diagram of POSMC.

Figure 4. Testing system configuration.

Figure 5. Comparison of position for mask angle of 15 degrees.

Figure 6. Comparison of position solution for mask angle of 15 degrees.

Figure 7. Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 15.

Figure 8. Satellite availability for April 12, 2005 for testing mask angle of 15 degrees.

Figure 9. Comparison of position for mask angle of 30.

Figure 10: Zoomed in position plot.

Figure 11: Comparison of position solution for mask angle of 30 degrees.

Figure 12: Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 30.

Figure 13: Satellite availability for April 13, 2005 for testing mask angle of 30 degrees.

Figure 14: Comparison of position for mask angle of 45 degrees.

Figure 15: Zoomed in position plot.

Figure 16: Comparison of position solution for mask angle of 45 degrees.

Figure 17: Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 45 degree.

Figure 18: Satellite availability for April 14, 2005 for testing mask angle of 45 degrees

Figure 19: Comparison of position for mask angle of 45 degrees when the excavator is traveling. The tracks engaged for the duration of this test.

Figure 20: Comparison of position solution for mask angle of 45 degrees with the excavator traveling.

Figure 21: Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 45 degree when excavator is traveling.

Figure 22: Mounting positions of the GPS antenna and the ATS prism.

Figure 23: Location of the shovel.

Figure 24: Tripod location of the ATS laser relative to the shovel.

Figure 25: Enclosure containing the Applanix POS MC.

Figure 26: Standalone Trimble GPS receiver and data logging computer.

Figure 27: Comparing performance of the standalone Trimble GPS and Applanix POS MC for February 28, 2005. The blue line indicates the number of visible satellites. The green line indicates accuracy solution for Applanix POS MC and the pink line indicates accuracy solution for Trimble. Applanix POS MC accuracy threshold has been changed to match Trimble's accuracy at 10 cm.

Figure 28: Performance of the standalone Trimble GPS for February 28, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous

Figure 29: Performance of the Applanix POS MC for February 28, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous

Figure 30: Comparing performance of the standalone Trimble GPS and Applanix POS MC for March 2, 2005. The blue line indicates the number of visible satellites. The green line indicates accuracy solution for POS MC and the pink line indicates accuracy solution for Trimble. POS MC accuracy threshold has been changed to match Trimble's accuracy at 10 cm.

Figure 31: Performance of the standalone Trimble GPS for March 2, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous

Figure 32: Performance of the Applanix POSMC for March 2, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous

# 1. Executive Summary

The objective of this project is to investigate the applicability of a combined Global Positioning System and Inertial Measurement Unit (GPS/IMU) for information based displays on earthmoving machines and for automated earthmoving machines in the future. This technology will allow an information-based product like Caterpillar's Computer Aided Earthmoving System (CAES) to operate in areas with satellite shading. Satellite shading is an issue in open pit mining because machines are routinely required to operate close to high walls that reduce significantly the amount of the visible sky to the GPS antenna mounted on the machine. An inertial measurement unit is a product, which provides data for the calculation of position based on sensing accelerations and rotation rates of the machine's rigid body. When this information is coupled with GPS it results in a positioning system that can maintain positioning capability during time periods of shading.

The energy savings with the new system is calculated with the following equation where CAES Benefits is the amount of increased machine productivity with a standard GPS based CAES.

$$\text{ENERGY SAVINGS} = \\ \text{Energy Consumption Benchmark} * \text{CAES Benefits} * \% \text{ Recovery by GPS/IMU System}$$

Transitioning the surface mine into the 21<sup>st</sup> century will require advanced technologies to more efficiently extract the ore. The components in the proposed system have found wide acceptance in various industries ranging from air to land to water. There are few barriers to bringing the system to market and an off-the-shelf product could be available shortly after a commercial feasibility study is performed based on the tests for the system on a bulldozer operating in a real mining environment. An economically feasible guidance system is also a step towards machine autonomy. Machine automation is one of the objectives listed in the *Exploration and Mining Technology Roadmap*. For machine autonomy to occur, the machine must know its location all the time to operate safely and efficiently. GPS alone will not be able to provide this ability. An inertially enabled CAES system presents a realistic, economically viable way to reduce mining costs and provides machine energy savings and is a stepping-stone towards machine automation.

CAES is a tool that integrates planning and design operations to reduce costs. This product is sold by Caterpillar and Trimble and is produced by the Caterpillar Trimble Control Technologies (CTCT) Joint Venture. CAES uses on-board computers, software, GPS, and data radios and receivers to replace the manpower and time-intensive processes associated with conventional surveying. CAES allows mine engineers to transmit planning designs wirelessly to the machine's on-board computer. The on-board system displays the mine plan, showing the operator where the machine is relative to the design area, what the current surface is, where the final design surface is to be, and in the case of

loading machines, material map showing the location of the ore bodies based on the ore grade quality. CAES identifies material types and tracks operator progress for greater efficiency and control of mine operations. This same information is transmitted back to the engineering office for analysis and documentation. The office software provides the ability to create customized reports on productivity data, cycle times, volume and material type. The result is improved communications, greater production accuracy and higher energy savings.

Currently, CAES has a GPS receiver that uses a real time kinematic (RTK) method of calculating position that provides a horizontal accuracy of 2-4 centimeters and a vertical accuracy of 4-6 centimeters when the required number of satellites is in view. The goal of a combined GPS/IMU positioning system will be to achieve a comparable level of accuracy even when some of the satellites are being shaded from the view of the receiver's antenna. Testing will confirm the GPS/IMU positioning system's accuracy. Commercialization of an inertially enabled CAES is a step towards machine autonomy.

Currently inertial measurement technology (IMU) is still at the stage in which ring laser gyroscopes (RLG) or fiber optic gyroscopes (FOG) are needed in order to achieve the accuracies required for operating a ground-based machine in the type of tasks done within an open pit mine. However, there are several factors that are causing IMU technology to become smaller and cheaper. The development of micro-electro mechanical systems (MEMS) is allowing inertial components to be reduced in size and to be produced at a cost that is a fraction of today's high-end inertial systems. However, currently the MEMS based technology cannot achieve the accuracy that a ring laser gyroscope RLG or FOG can achieve. Inertial Measurement Unit (IMU) technology is evolving from the dominant Fiber Optic Gyro (FOG) and Ring Laser Gyro (RLG) technologies to Micromachined Electro-Mechanical Sensors (MEMS). MEMS technology is expected to maintain current IMU performance levels while substantially reducing weight and size. The most significant improvements, however, are expected in price where reductions of up to tenfold can be expected in the next 3 to 5 years.

## 2. System Configuration – POS MC and CAES

### Computer Aided Earthmoving System

Caterpillar has developed products that provide integrated solutions for position monitoring for mine machinery that increase productivity, making communications and planning easier and faster. Caterpillar, in partnership with Trimble Corporation, has been marketing the Computer Aided Earthmoving System (CAES) that identifies material types and tracks operator progress for greater efficiency and control of mine operations by enabling operators of dozers and shovels to accurately alter the earth's terrain. Shovel operators have reduced misclassification of material by identifying the location of the ore and the waste rock. The system can be used in the blasthole drills to improve the accuracy in drill depth and location. Dozers have been able to construct roads and ramps to desired grades in less time. Rework has also been reduced. Since CAES's production in 1997, the system has been employed by mines across the world to improve productivity, increase energy efficiency and improve safety.

CAES uses three advanced technologies.

1. Real Time Kinematic – On-The-Fly – Global Positioning System, satellite-based technology, enables a machine to locate its position (x, y, and z) within centimeters virtually anywhere on the Earth.
2. Reliable on-board electronics that include state-of-the-art computers, sensors and other ruggedized hardware capable of withstanding the severe application of the mining industry.
3. High-speed wireless communication that supports many machines over a wide area with adequate capacity to support beyond the requirements of just GPS corrections.



Figure 1: Computer Aided Earthmoving System components.

## Position and Orientation System for Machine Control

\*Information taken from SME paper written by the researchers of this project.

This technology centers around the optimal blending of inertial data acquired from an Inertial Measurement Unit (IMU), and the data generated using GPS as an aiding sensor. Depending on the application other aiding sensors such as an odometer, Doppler radar or barometric altimeter, may be used. In an open-pit mine, an Inertial/GPS system would provide continuous and accurate position information during periods of satellite shading. The advantage of Inertial/GPS technology is that it requires no additional infrastructure, being a completely self-contained system. The disadvantage is that in the absence of the aiding data its accuracy degrades with time.

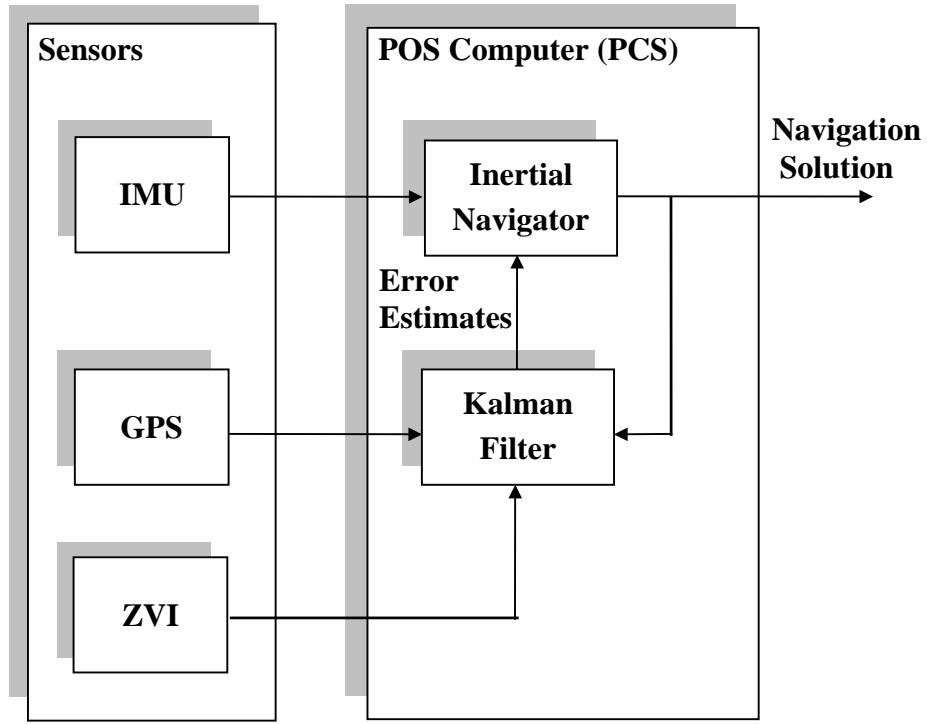
POS MC (Figure 2) consists of the POS MC Computer System (PCS) and three sensors: an Inertial Measurement Unit (IMU), a GPS receiver, and a Zero Velocity Indicator (ZVI). The modularity of the POS MC configuration allows for simple installation on a variety of mine machinery such as excavators, drills and shovels etc.



**Figure 2: POS MC System Components**

The ZVI outputs a TTL-level (Transistor-Transistor Logic) signal indicating whether the mining vehicle is stationary or not. In the case of an excavator, the signal indicates whether the vehicle's tracks are engaged. POS MC uses the ZVI information to improve the accuracy of the positioning data during a GPS outage.

During its operation, POS MC constantly calibrates its sensors to maintain the best possible performance. The POS MC function is illustrated in Figure 3.



**Figure 3: Functional Diagram of POS MC**

The POS MC's embedded Inertial Navigator runs an inertial navigation algorithm, which solves Newton's equations of motion using the acceleration and angular rate data from the IMU. The Kalman Filter compares the inertial solution with corresponding data from the GPS receiver and the ZVI estimating the inertial navigation errors. The Inertial Navigator then adjusts the navigation solution using the Kalman Filter estimated errors. This process of inertial navigation, error estimation, and error correction forms a closed error regulation loop that keeps the Inertial Navigator data consistent with the aiding sensor data.

The Kalman filter-based blending of the GPS and inertial data can be achieved in a number of ways depending on the desired level or “tightness” of the integration algorithm.

The *loosely-coupled* implementation blends the inertial navigation data with the position and velocity output from the GPS. If the number of visible satellites is sufficient for the GPS to compute its position and velocity, i.e. four or more satellites, then the GPS position and velocity are blended with the inertial data. Otherwise, if the GPS data is not available, the system will operate in free-inertial (unaided) mode.

POS MC offers tightly-coupled implementation, which optimally blends the inertial data with raw GPS observables from individual satellites (ranges and range rates). In this case if the number of visible satellites drops below four, the inertial navigator is still aided by the GPS. The result is improved navigational accuracy when compared to the free-inertial operation. An additional advantage of tightly-coupled integration is the improved re-acquisition time after satellite signal loss. The inherent benefits of tightly-coupled data blending become readily apparent in the accuracy and integrity of the resulting navigation solution.

## **POS MC/ CAES Testing Configuration**

The interface goals between the system components should allow for switching between INS and Trimble data through to CAES as well as to allow for quick reversion to standard CAES configuration and provide debug and logging capability. Figure 4 shows the components that are necessary for the successful testing and implementation to the existing CAES. The details such as the pin connections and the specific power source in the figure may be changed as needed. On the top portion of the figure, the current system takes data readings with a Trimble receiver and sends the information to the CAES to update the layout of the work area. The components for the INS/GPS is enclose inside a Hoffman box. In the enclosure, there is the power converter, three wireless serial radios (2 from Intuicom and from Trimble – TC900), the Applanix POS MC and a PIC microcontroller.

Through Caterpillar's experience in testing and implementation of new equipment at worksites, there is a high cost associated with down time of any piece of equipment. Thus, it is in the interest of equipment suppliers to minimize this down time during testing. The incorporation of a switching circuit in the Hoffman box is designed to accomplish this task. The switching circuit built by Caterpillar was intended to allow the INS receiver to be integrated with CAES in a way that the system would fail to Trimble if necessary and to provide useful system diagnostics and logging. The POS MC receiver has to be modified (by Applanix) to output a Trimble-style packet. Both the INS and Trimble/CAES packets are received and parsed by the switching circuit, and one of them is then passed back out to the CAES display.

The serial streams from both receivers are sent to the two sides of the Microchip PIC16F876 microcontroller, and the common junction is passed back out to the CAES. The digital output will, when high, switch an optical relay from its normally closed position. High represents the POS MC packet and low for the Trimble. This setup has the benefits of relieving the PIC microcontroller of having to process two received packets and one transmit serial stream simultaneously, as well as providing for a fail-safe way to delay with power failures in the enclosure. Fail to Trimble during malfunction or power loss.

TC900 serial radio receives the GPS corrections from the based station and relays that to the INS. Serial radio #2 could be used for debugging purposes for the INS. Serial radio #3 is used to send information from the switch to a PC in the engineering office for analysis. The microcontroller will send out a status packet that contains the current GPS time, satellite and INS modes and sources visible. The packets are complete Trimble-style packets from the sources in the order: Trimble, POS, Trimble, and POS. The binary packets are first expanded into ASCII hex digits, and then the entire message is sent out over the stats serial radio. These packets form files are named according to the current date, and at midnight the current files are zipped up and a new one created.

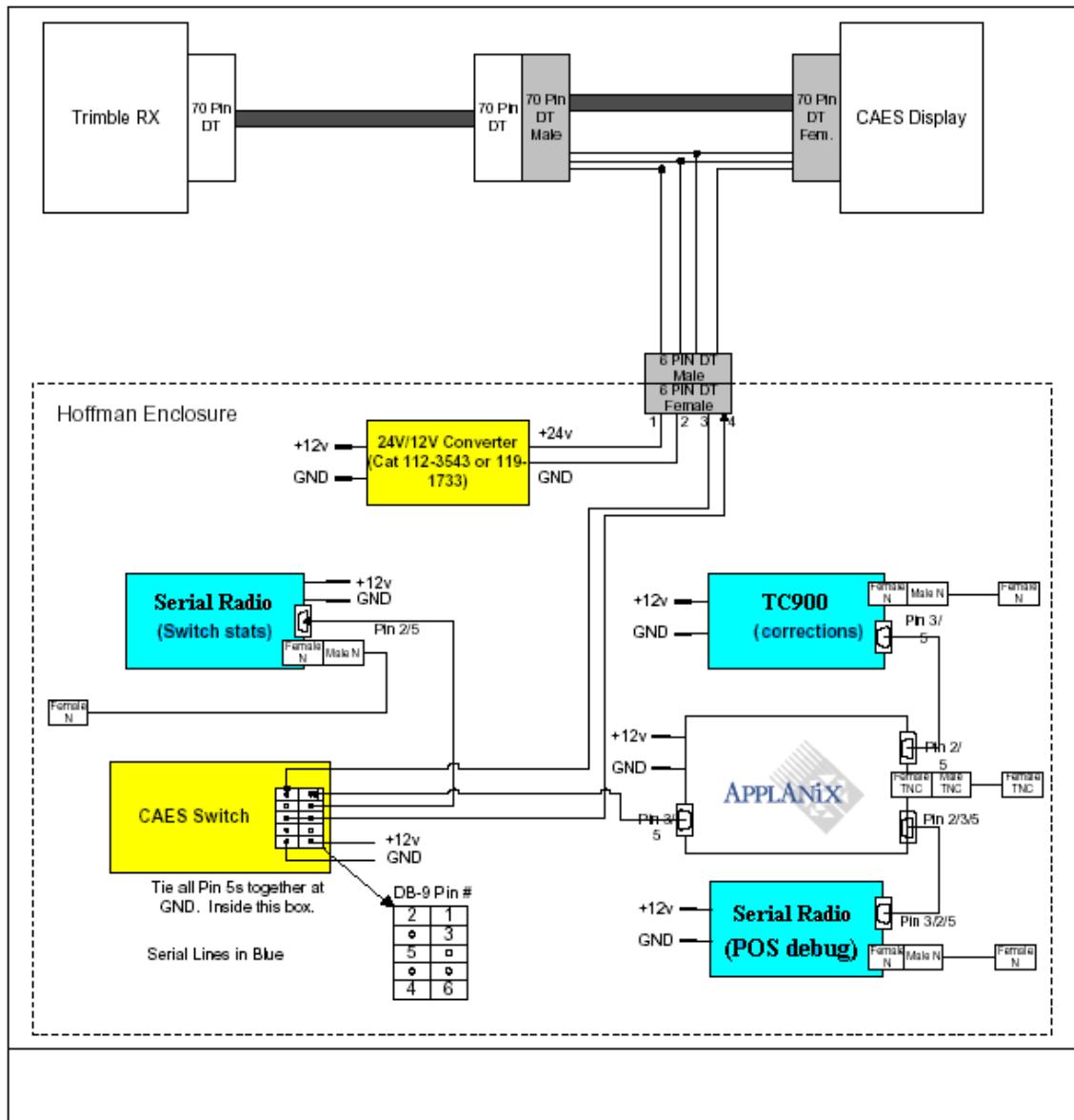


Figure 4: Testing system configuration

### 3. Tasks for the Project

Task 1.0 – Test the current system with ATS for accuracy:

Caterpillar and Applanix engineer work together with a robotic total station (ATS) to determine the accuracy of POS MC. Currently POS MC is 6-8 cm off the Trimble position in the Northing and Easting direction while it is 20 to 30 cm off in the vertical direction. The ATS verifies these measurements so that modifications can be made to accommodate them. Alternate sources of ground truth may also be considered depending upon the performance of the ATS in this application.

Task 2.0 – Determine commercial viability of a cheaper IMU:

The system currently installed on Newmont's Twin Creeks mining shovel has an expensive IMU model Litton LN200, which reduces its commercial viability. The commercial viability study will reveal the range of performance that is acceptable to the mines while keeping the cost down. The targeted low cost IMU is the Honeywell HG 1700.

Task 3.0 – Putting together a new system with the HG1700 IMU:

Caterpillar will build a new test system with enclosure, micro-controller switch and data collection hardware/software with the smaller version of POS-MC chassis. The system should be ruggedized for mine testing and commercialization. Tests will be conducted on a hydraulic excavator at Caterpillar's Peoria Proving Grounds. Its accuracy will be verified with ATS before it is installed at Twin Creeks. Applanix will have to modify POS MC to output the appropriate records in the 40h Packets.

Task 4.0 – Test new system on the shovel at Newmont's Twin Creeks:

Mine personnel will assist in the installation of the system to the site's shovel. The mine personnel's knowledge about the daily operations and the maintenance schedule will limit the shovel's down time for the installation. It is imperative to have a well-defined list of steps to carry out the installation of the new system. The list will include the responsibilities of all the parties involved in the installation, all the necessary hardware and the procedure needed to install each component in an orderly manner.

Mine operators do not want to stop a machine in order to allow engineers to collect data for analysis purposes. Off the machine, but in view of the Intuicom RS232 radios or a repeater, will be a monitoring/data-logging computer. This will most likely be a desktop machine with a connection to a wireless radio. This machine, running custom software, will receive and record all statistical data being sent by the microcontroller, as well as have access to the debug port of the Applanix system. Caterpillar will be able to remotely access this machine via a modem connection. Data will be routinely downloaded from this machine and analyzed using Caterpillar's custom analysis software for CAES.

Applanix will collect data through the POS Controller program. The Controller user can select the specific data set to be recorded and the appropriate recording rate. This gives a

complete record of events for post-processing analysis. All raw sensor data and POS-generated data can be recorded on an internal drive. Analysis of the data will focus on how well the system is able to track the machine's position during the various operator maneuvers. The analysis will be done using Applanix's post-processing software.

Task 5.0 – Determine viability of integrating POS MC to AQUILA's drill monitoring products:

AQUILA makes information-based products in drill monitoring, control and guidance systems designed specifically for mining. AQUILA's DM1 to DM 6 make drilling and blasting operations more accurate and productive. This reduces energy throughout the entire mining process because the desired fragmentation is achieved at the mining face. AQUILA's suite of products is equivalent to CAES for drills.

Task 6.0 – Build POS MC for drills with HG 1700:

If task 5.0 indicates viability, Caterpillar will build a new test system with enclosure, micro-controller switch and data collection hardware/software with the smaller version of POS-MC chassis that will interface with AQUILA's system. The system should be ruggedized for mine testing and commercialization. Test will be conducted on a hydraulic excavator at Caterpillar's Peoria Proving Grounds. Its accuracy will be verified with ATS before it is installed at Twin Creeks.

Applanix will have to modify POS MC to output the appropriate records and formats acceptable to AQUILA.

Task 7.0 – Test with AQUILA DM product at Newmont Twin Creeks:

If Task 5.0 indicates viability and when Task 6.0 is completed, this task will repeat Task 4.0 for testing the POS MC system with the AQUILA system for a blasthole drill.

Task 8.0 – Commercial feasibility study:

The packets of information sent through the wireless serial radio will be collected at the desktop PC. These packets will be post-processed to indicate the POS MC uptime, POS MC utilization, and compare the errors from the POS MC system to the Trimble RTK performance when there are enough satellites visible for the Trimble RTK receiver. The POS MC uptime and utilization will indicate the value added. Overall, a GPS-augmented machine needs to outperform a machine using only GPS with enough cost savings to justify the additional cost of the system.

A commercial feasibility study will be performed based on the data analysis from the mine testing. The study will focus on the cost reduction and the energy savings for the mine by integrating the combined GPS and IMU positioning system into CAES and AQUILA products. Specific numbers will be provided for the number of hours the GPS/IMU is active as well as the time to recover the cost of the new system. The study will also address the size of the market and other applications for the system based on the current price. The costs points at several volume levels will be determined.

## 4. Experimental

### 2.1 Testing on Excavator at Proving Grounds

The following results are tests done by changing the mask angle of the POS MC and standalone Trimble GPS receiver instead of disconnecting the antenna or using the building to simulate satellite shading. Both Trimble receiver and POS MC are using the same GPS antenna from the MS 840. The POS MC has a BD950. The stationary testing period is in excess of 5 hours while the test conducted for traveling is approximately 35 minutes.

Table 1 shows positions of POS MC and Trimble GPS receiver compare with that of ATS for different mask angles. The columns with 15, 30 and 45 are data collected with the excavator being stationary. As the mask angle is increased, the values for POS MC compare to ATS maintain relatively constant meaning it is able to maintain its position even as the number of visible satellite decreases. In contrast as the mask angle increases, the Trimble GPS receiver's positions compared to ATS's position begins to deviate. It is not able to maintain its position. In the last column label 45 traveling, the excavator's tracks are engaged for the duration of the test. The tracks are used to travel as well as to rotate the machine because the excavator is not able to swing left. Only swinging right will cause the ATS to lose its line of sight to the prism on the machine. If the excavator was able to swing without the tracks, the performance of the POS MC would have been better because POS MC takes advantage of the Zero Velocity Indicator to limit the drift in the accelerators.

**Table 1: Comparing the POS MC and Trimble receiver positions with the ATS position with different mask angles. Unit is in meters.**

POS MC Height	Mask Angle			
	15	30	45	45 traveling
Median	0.037368	0.066429	0.032517	0.059226
Mean	0.035897	0.060517	0.032484	0.056734
RMS	0.042864	0.077368	0.037027	0.066966
Min	0	0	0	0.000003
Max	0.181509	0.51523	0.119196	0.197218
Std Dev	0.020999	0.039662	0.017709	0.031256
POS MC Northing/Easting				
Median	1.606177	1.607011	1.606436	1.214469
Mean	1.605916	1.606846	1.607611	1.127463
RMS	1.606238	1.607214	1.606645	1.229566
Min	1.493219	1.424845	1.384207	0.09622

Max	1.747018	1.788903	1.692758	1.831984
Std Dev	0.013917	0.025534	0.025931	0.192101
Trimble Height				
Median	0.017092	0.506895	16.75947	31.54301
Mean	0.014504	0.209561	5.037797	61.77454
RMS	0.021518	0.753877	46.70722	43.89167
Min	0	0.000022	0.000065	0.000388
Max	0.098153	2.107846	198.4745	62.13787
Std Dev	0.013072	0.558024	43.59716	30.52329
Trimble Northing/Easting				
Median	1.598754	1.678182	6.641556	9.068644
Mean	1.59922	1.620591	2.206606	12.84707
RMS	1.59877	1.68909	12.85404	12.10937
Min	1.538208	1.174476	0.440637	0.652037
Max	1.628357	2.428861	64.29347	20.82025
Std Dev	0.007051	0.191648	11.00535	8.025409

Figures 6, 11 and 16 show the solution of the Trimble receiver and POS MC along with the number of satellites for mask angle of 15, 30 and 45 degrees, respectively, for the stationary test. The solutions are indicated by the numbers 1 to 4: 4 indicates Fix, 3 for Float, 2 for DGPS and 1 for Autonomous.

Figures 7, 12 and 17 compare the positions from POS MC and Trimble receiver with that from ATS. POS MC and Trimble receiver use the same antenna. This is located a nominal distance of 1.5 meters from the ATS prism in the Northing/Easting plane. The height difference between the ATS prism and the antenna is approximately 35 cm. This amount is deducted before the values are generated for these figures.

Mask angle 15 degrees → Figures 5 to 8

Mask angle 30 degrees → Figures 9 to 13

Mask angle 45 degrees → Figure 14 to 18

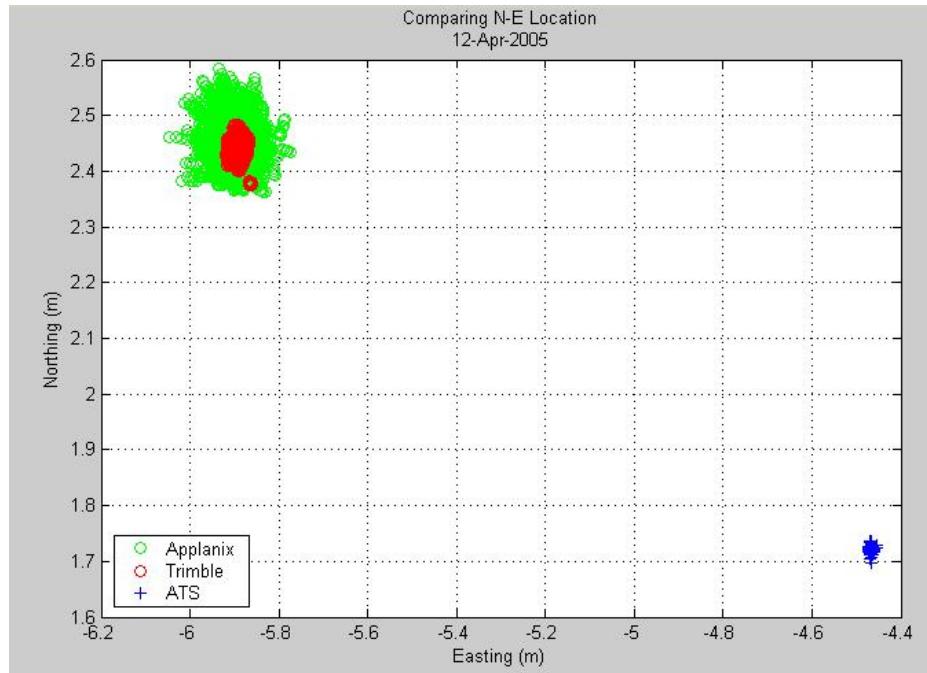
Mask angle 45 degrees for traveling and rotating → Figure 19 to 21

Figures 5 to 8 shows the results with the mask angle set to 15 degrees. Both Trimble receiver and POS MC give a Fix solution. Figure 5 shows the position of the ATS, POS MC and Trimble receiver. Figure 6 shows the solution and the satellites. Figure 7 shows the statistics comparing the Trimble receiver and POS MC position to ATS. Figure 8 shows the possible number of satellites available for the test date April 12, 2005. This graph is created with Trimble Planning Software available on Trimble's website.

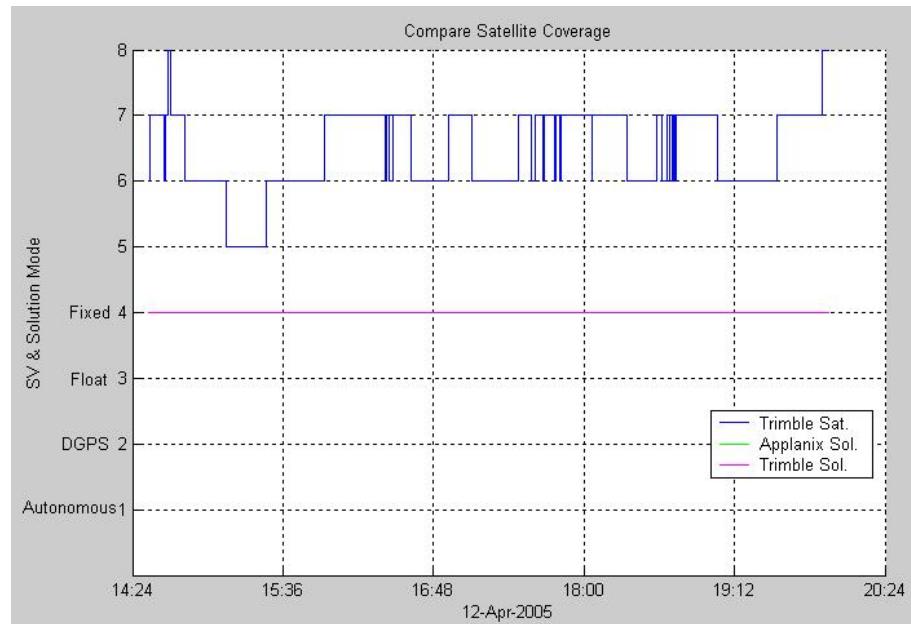
Figures 9 to 13 shows the results with the mask angle set to 30 degrees. Figure 9 shows the position of the Trimble receiver with greater variation as the number of the satellites is reduced while the POS MC maintains its position. Figure 10 shows a zoomed in view of the position plot. POS MC maintains a tight range on its position. Figure 11 shows that POS MC maintains a Fix solution even as the Trimble solution fluctuates back and forth between DGPS and Fix. Again, the number of satellites seen by POS MC is for a mask angle of 0 while the POS MC algorithm only uses satellites with 30-degree mask angle. Figure 12's statistics confirms that the Trimble position error is increasing. Comparing these values to those taken with a mask angle of 15 degrees, the two sets of data are similar for POS MC while Trimble's numbers have a wider discrepancy. Figure 13 shows the number of satellite available for the test date April 13, 2005.

Figure 14 to 18 shows the results with the mask angle set to 45 degrees. Figures 14 and 15 show the positions from Trimble, ATS and POS MC. Trimble position varies widely as confirmed by figure 16 and 17, the position solution and the statistical values compared to the ATS respectively. Trimble spends most of the time between autonomous and DGPS mode while POS MC maintains a Fix solution. Figure 18 shows the number of satellite available for the test date April 14, 2005 for mask angle of 45 degrees.

Figure 19 to 21 shows the results with the mask angle set to 45 degrees with the excavator traveling. Figure 19 shows the movements of the excavator. It travels to a location and rotates simulating the digging process. It repeats this sequence of motion for the duration of the test. Figure 20 shows that the POS MC solution is Fix when it's traveling and rotating with its tracks. This test did not take advantage of POS MC's Zero Velocity Indicator, which limits the drift in the accelerators when the tracks are not engaged. Figure 21 shows the statistics of POS MC's performance compared to ATS. Even though the values deviated from the stationary tests, they are still significantly better than the performance of the standalone GPS receiver.



**Figure 5: Comparison of position for mask angle of 15 degrees.**



**Figure 6: Comparison of position solution for mask angle of 15 degrees.**

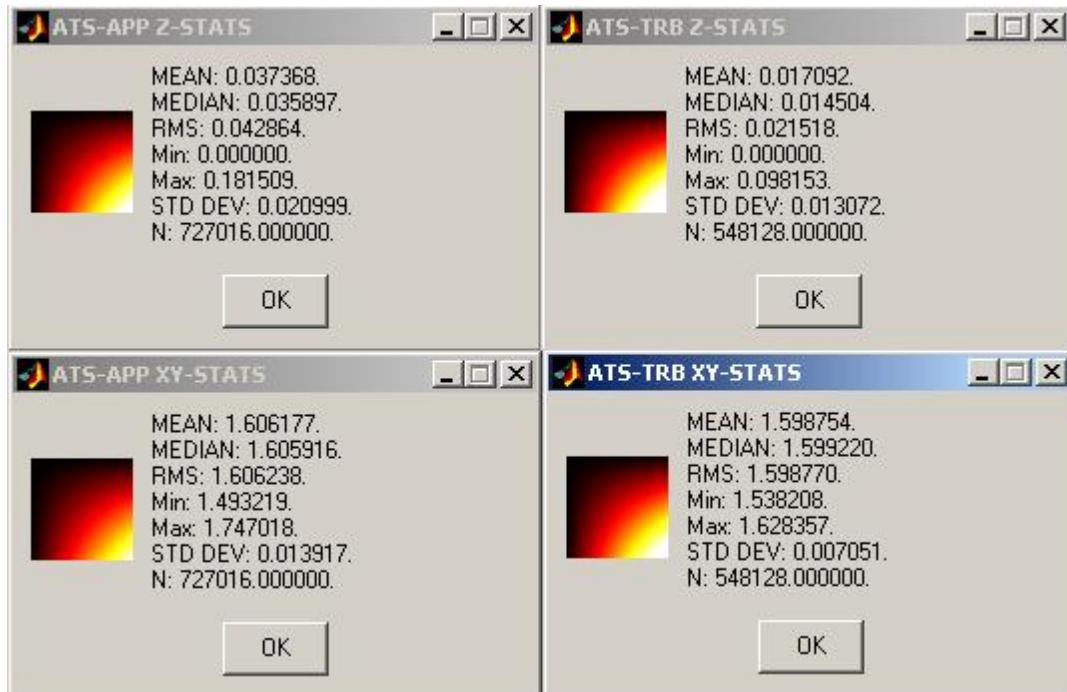


Figure 7: Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 15.

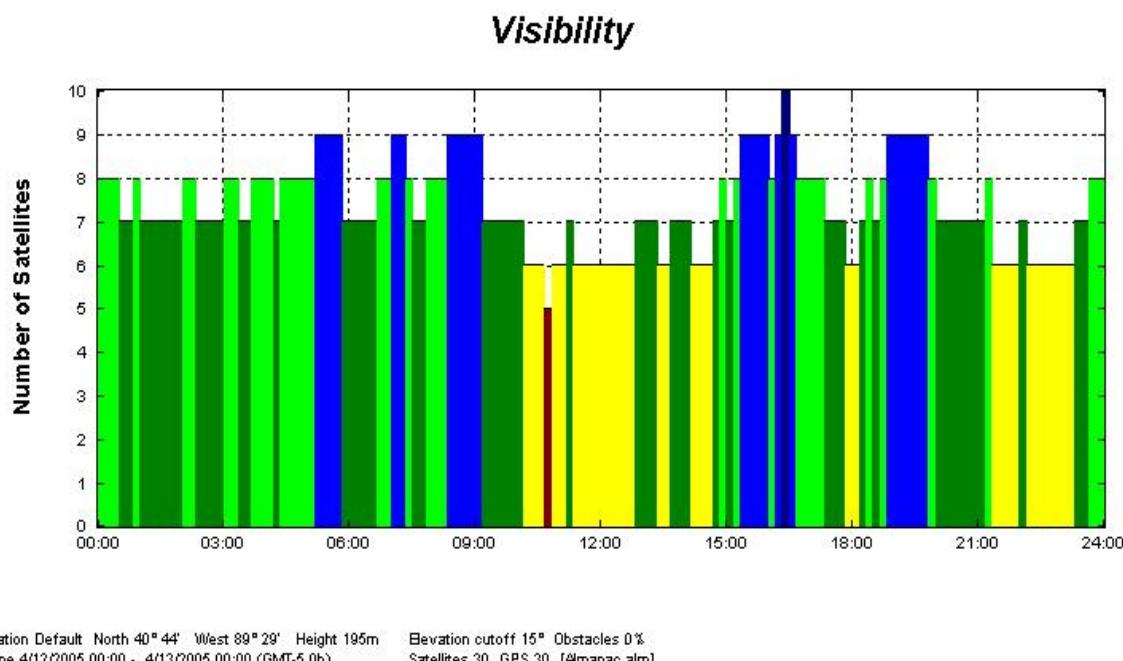
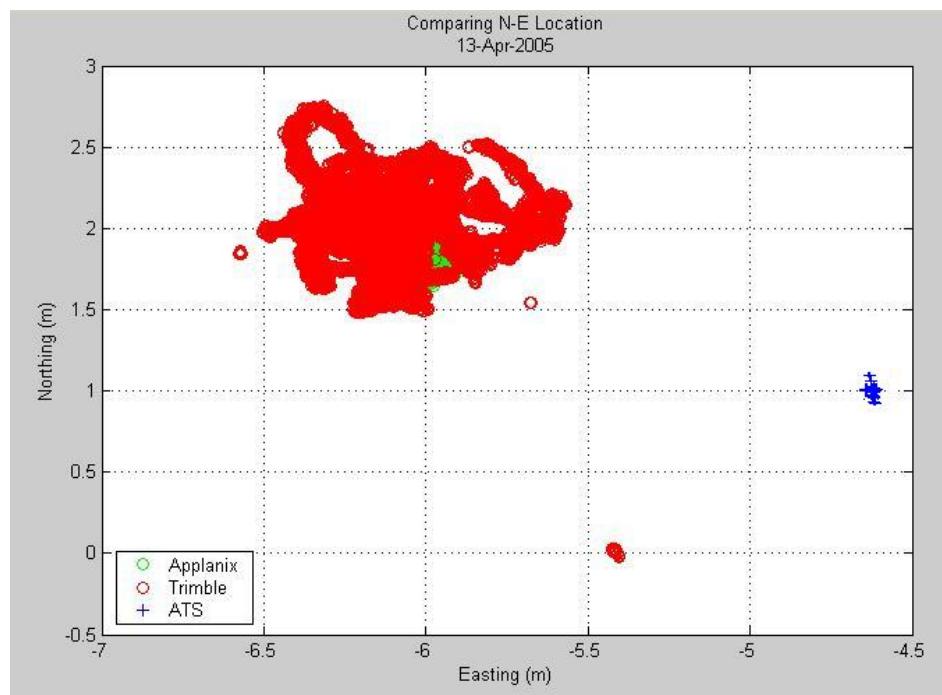
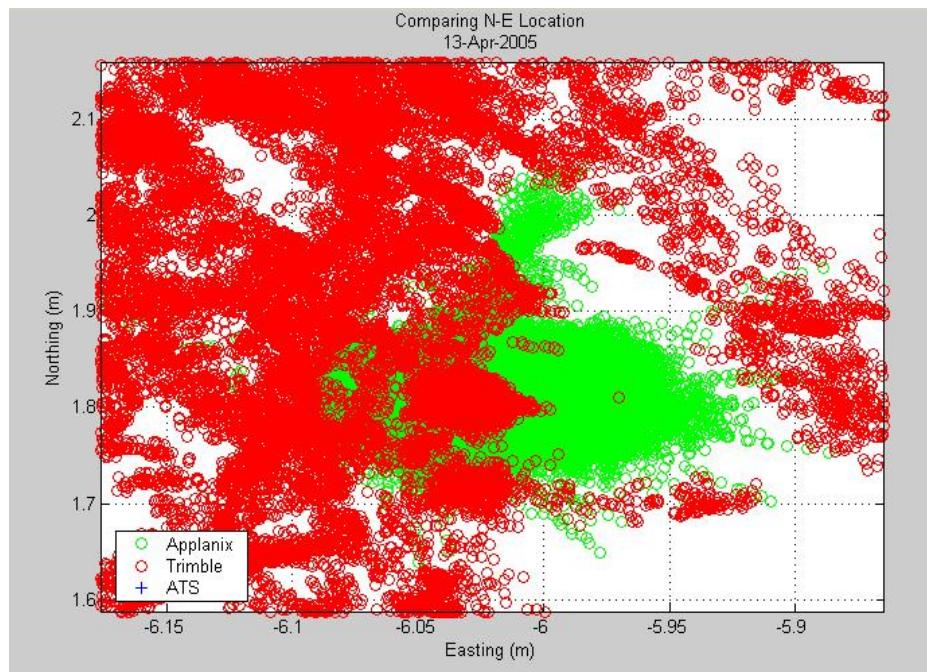


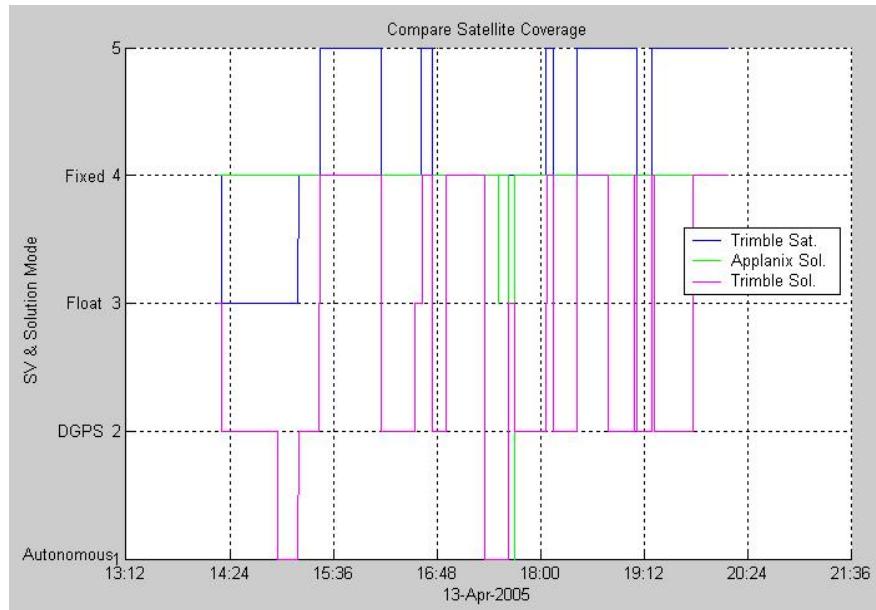
Figure 8: Satellite availability for April 12, 2005 for testing mask angle of 15 degrees.



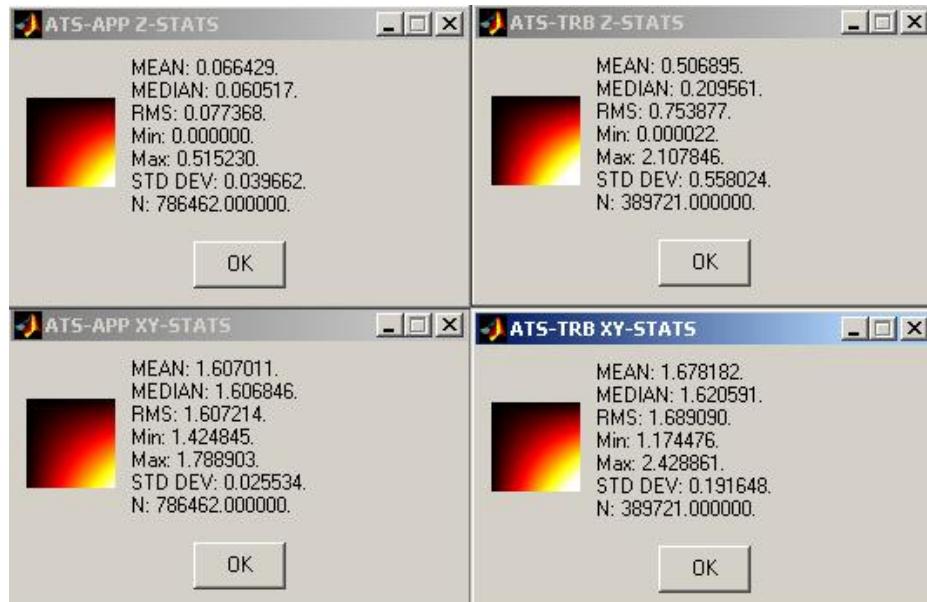
**Figure 9: Comparison of position for mask angle of 30.**



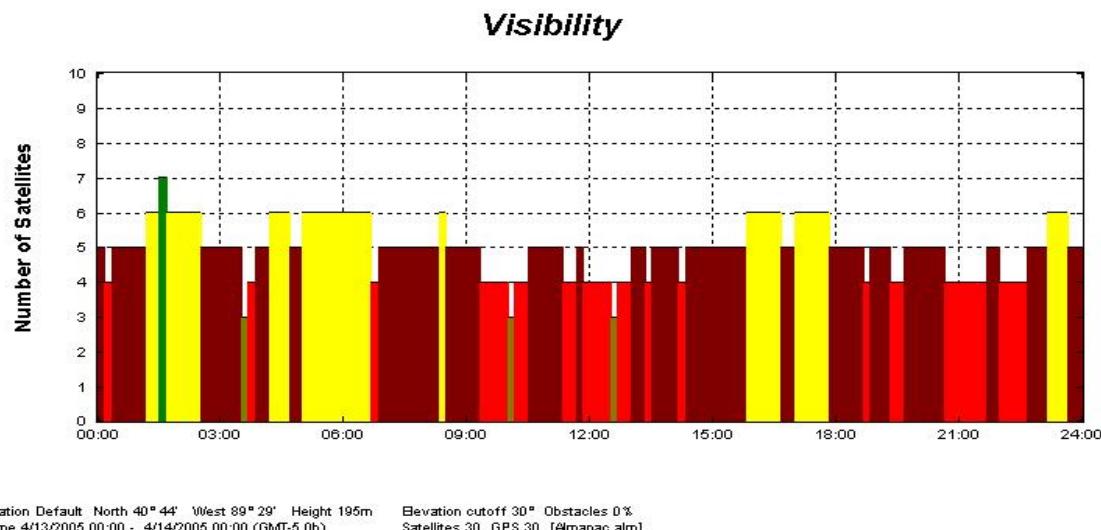
**Figure 10: Zoomed in position plot.**



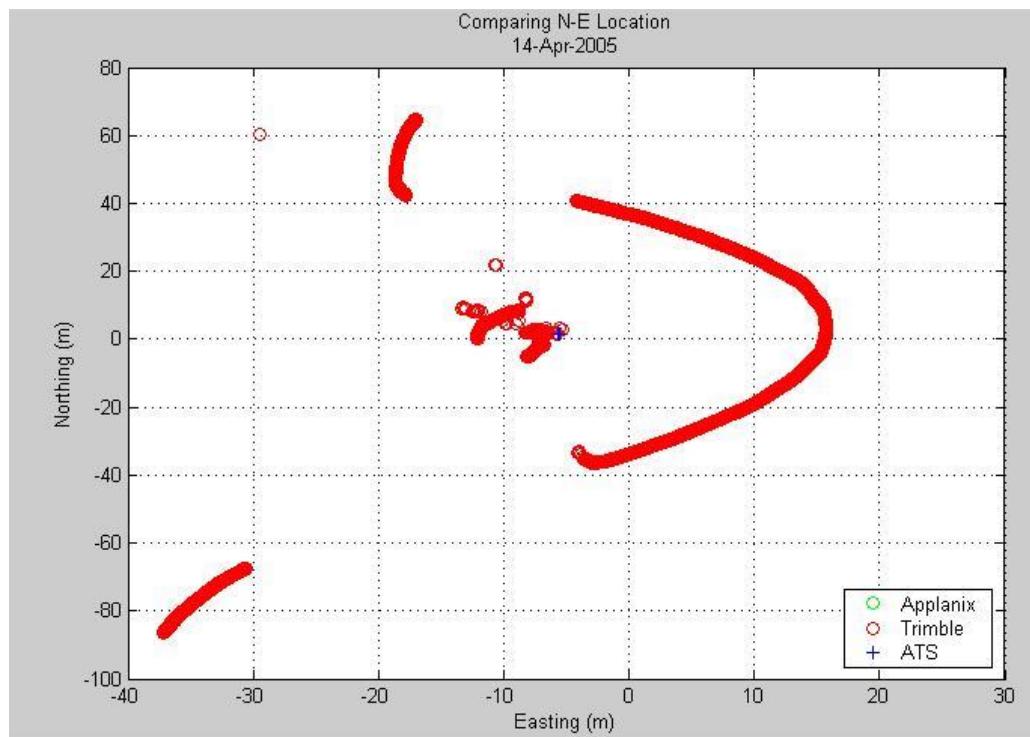
**Figure 11: Comparison of position solution for mask angle of 30 degrees.**



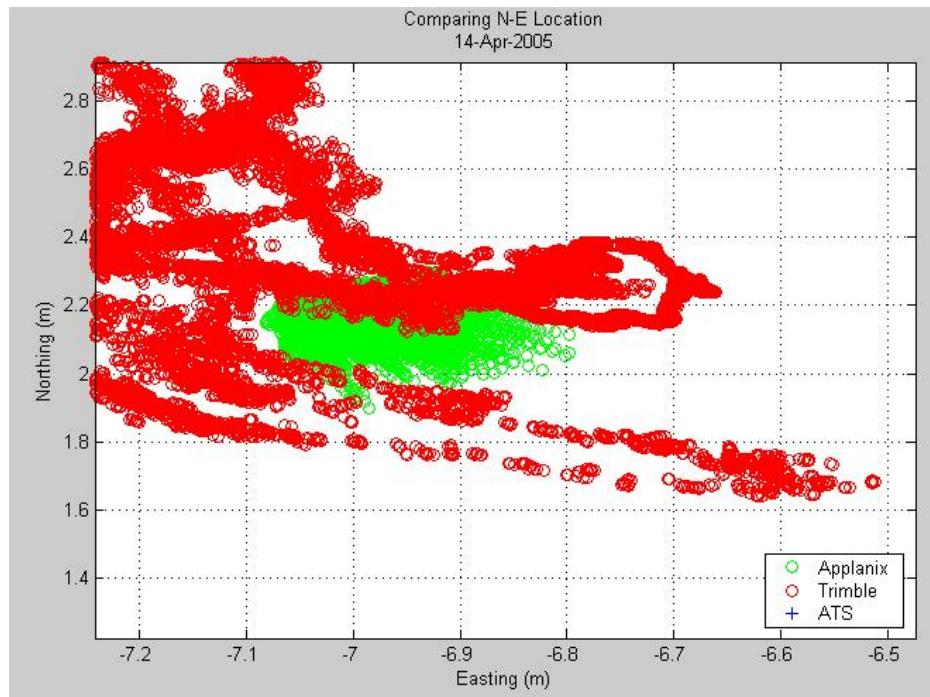
**Figure 12: Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 30.**



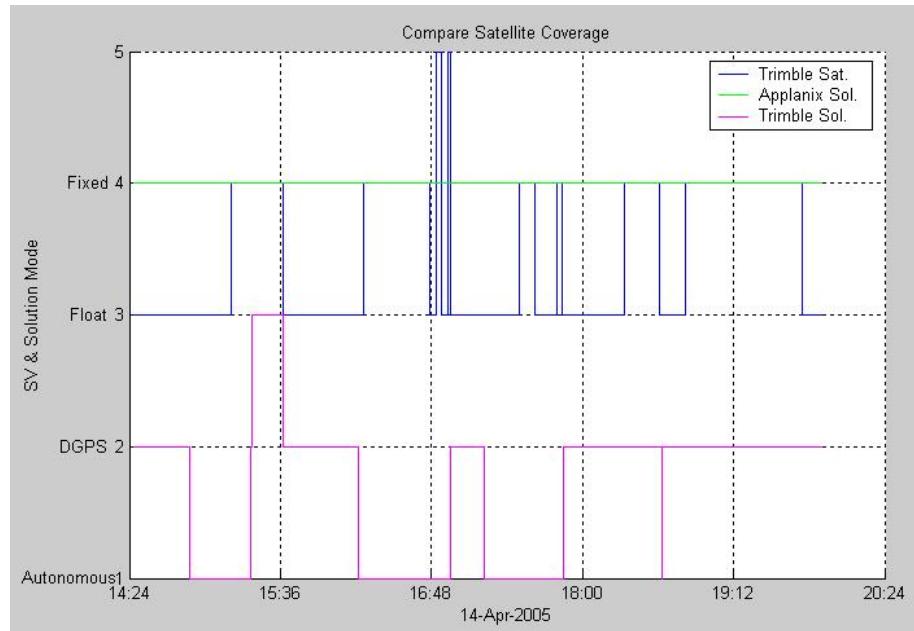
**Figure 13: Satellite availability for April 13, 2005 for testing mask angle of 30 degrees.**



**Figure 14: Comparison of position for mask angle of 45 degrees.**



**Figure 15: Zoomed in position plot.**



**Figure 16: Comparison of position solution for mask angle of 45 degrees.**

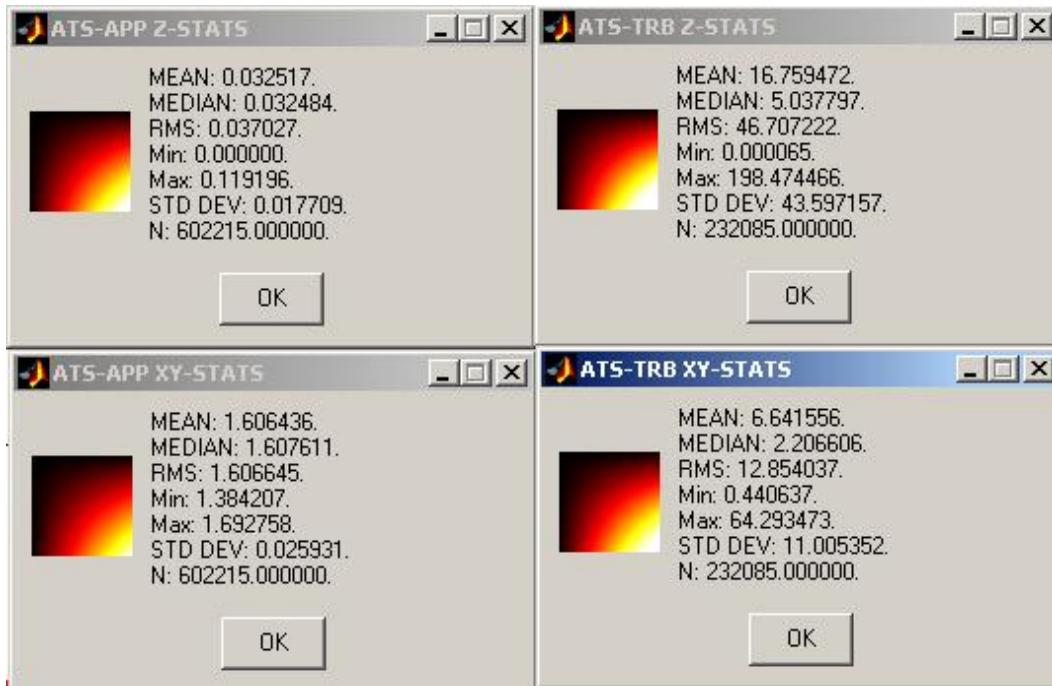


Figure 17: Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 45 degree.

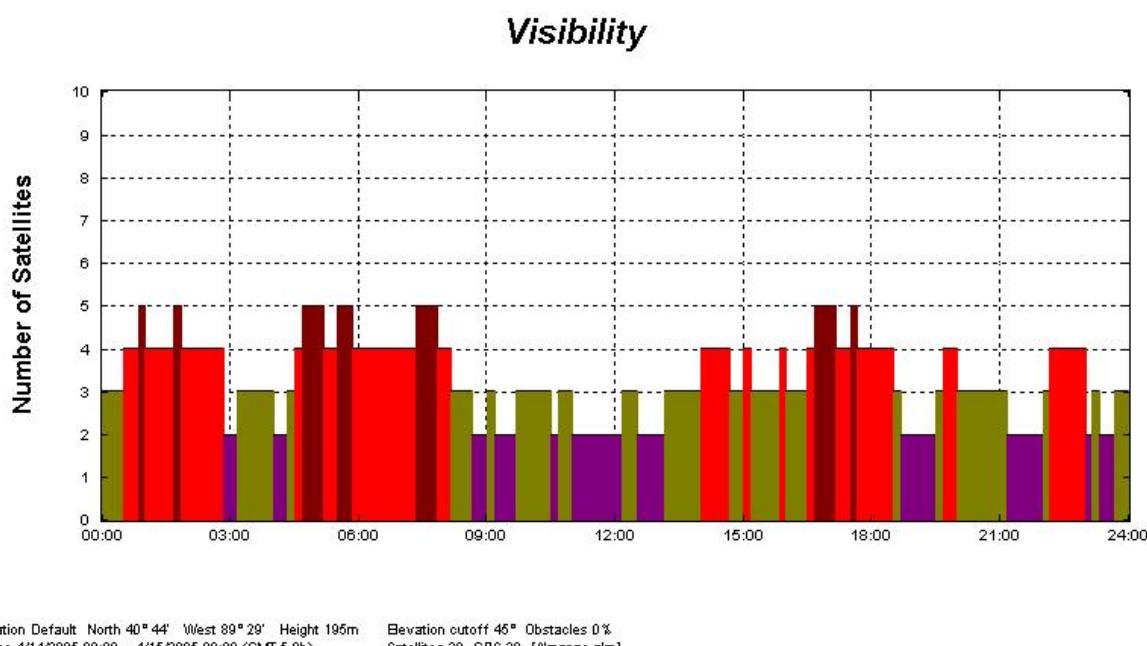
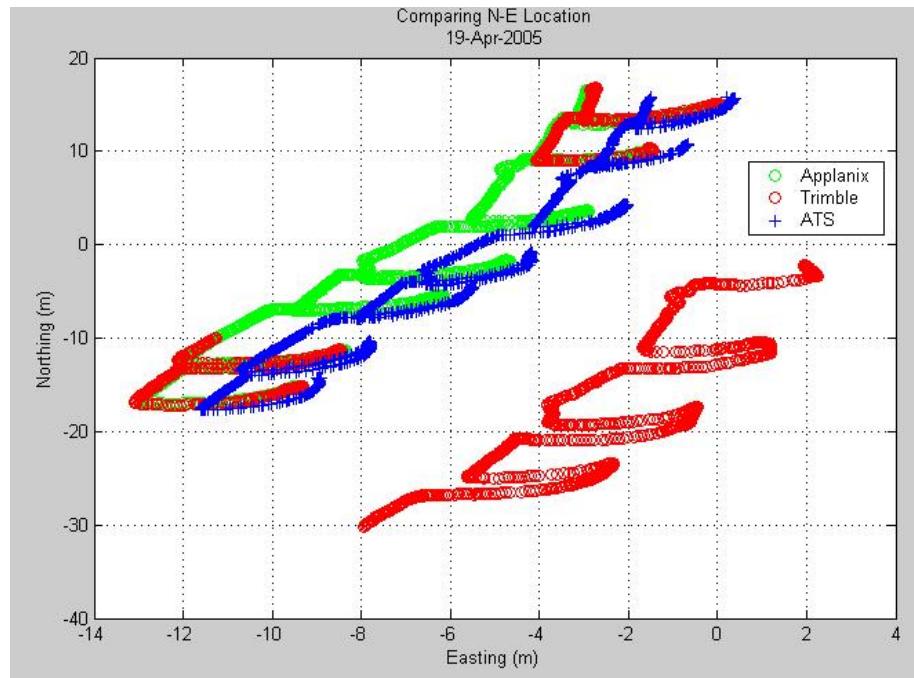
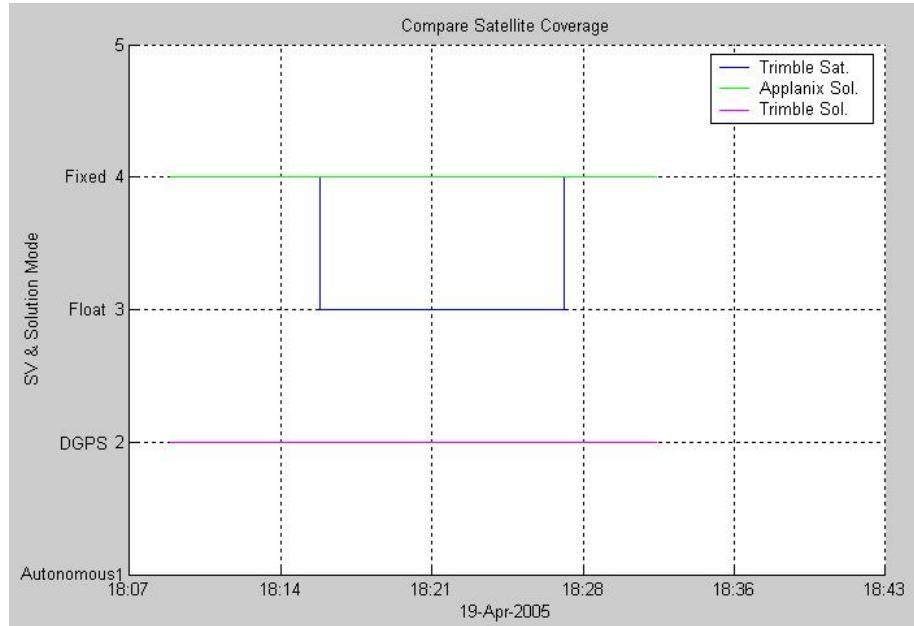


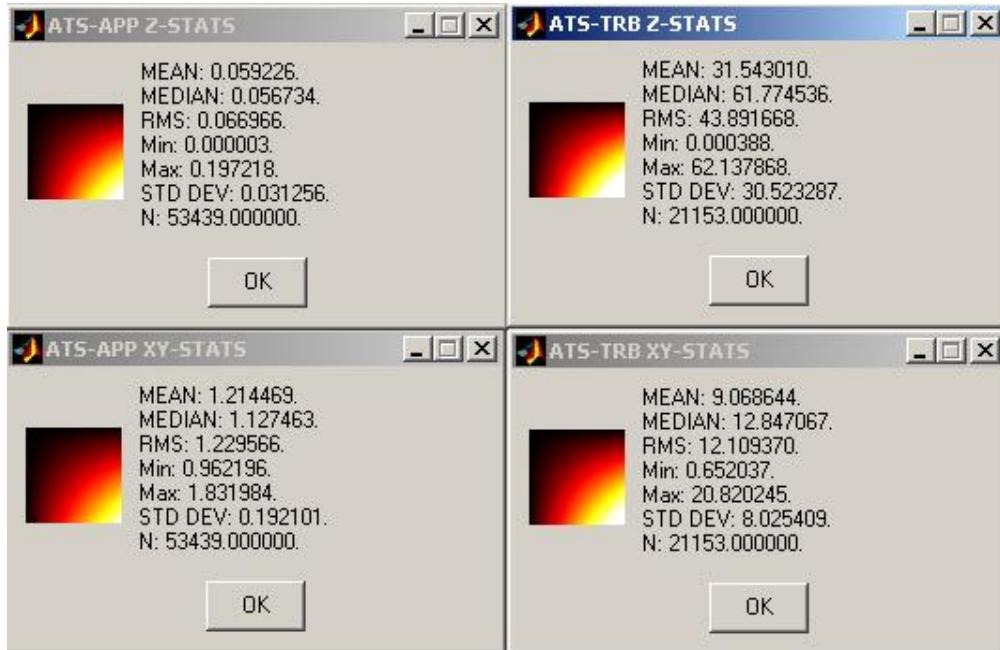
Figure 18: Satellite availability for April 14, 2005 for testing mask angle of 45 degrees



**Figure 19: Comparison of position for mask angle of 45 degrees when the excavator is traveling. The tracks engaged for the duration of this test.**



**Figure 20: Comparison of position solution for mask angle of 45 degrees with the excavator traveling.**



**Figure 21: Statistical comparison between POS MC and Trimble positions to ATS for mask angle of 45 degree when excavator is traveling.**

## 2.2 Testing at Twin Creeks Mine

When Applanix POS MC system was initially installed at Twin Creeks mine. Twin Creeks was in the process of expanding its pit. Figures 22 to 26 show the installation and testing of the inertial aided Applanix POS MC. The shovel is working in a shallow area of the pit clearing alluvium. Because of the relatively shallow depth, the shovel has good satellite coverage.

On the week of February 27<sup>th</sup> to March 3<sup>rd</sup> 2006, the shovel was operating in the deeper area of the pit. The inertial aided POS MC accuracy threshold was changed from 50 cm to 10 cm to match the configuration of the Trimble receiver used in the mine. This new setting allowed for a direct comparison of a standalone GPS receiver and the inertial aided POS MC. Figure 27 to 32 show the performance of inertial aided POS MC with the new accuracy setting. Figure 27 and 30 compares the satellite coverage and solution mode of the standalone Trimble GPS receiver and Applanix POS MC system for February 28, 2006 and March 2, 2006. Figure 28 and 31 show the performance of GPS receiver for the duration of 24 hours on February 28, 2006. Figure 29 and 32 shows the performance of POS MC system for the duration of 24 hours on February 28, 2006 and March 2, 2006. Table 2 compiles satellite shading period for the standalone Trimble receiver and Applanix POS MC system and the percentage rate of recovery of POS MC system.



**Figure 22: Mounting positions of the GPS antenna and the ATS prism.**



**Figure 23: Location of the shovel.**



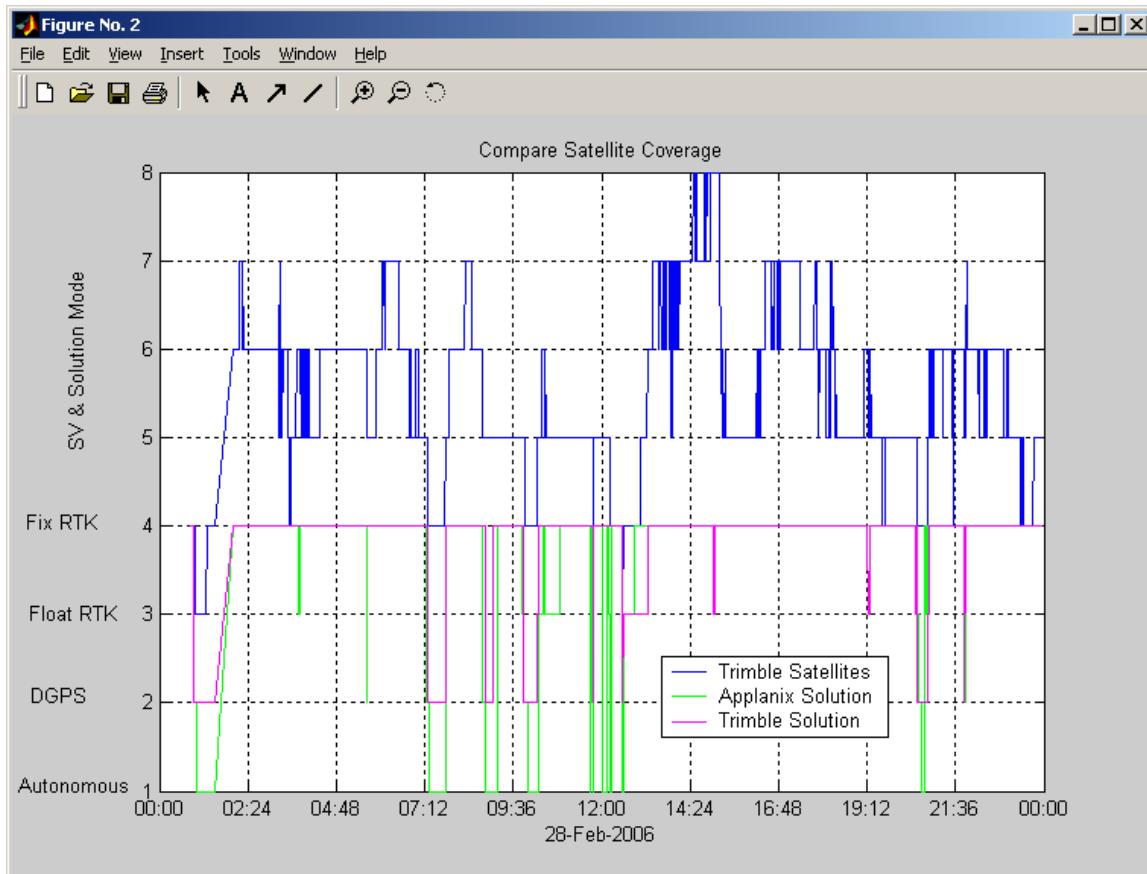
**Figure 24:** Tripod location of the ATS laser relative to the shovel.



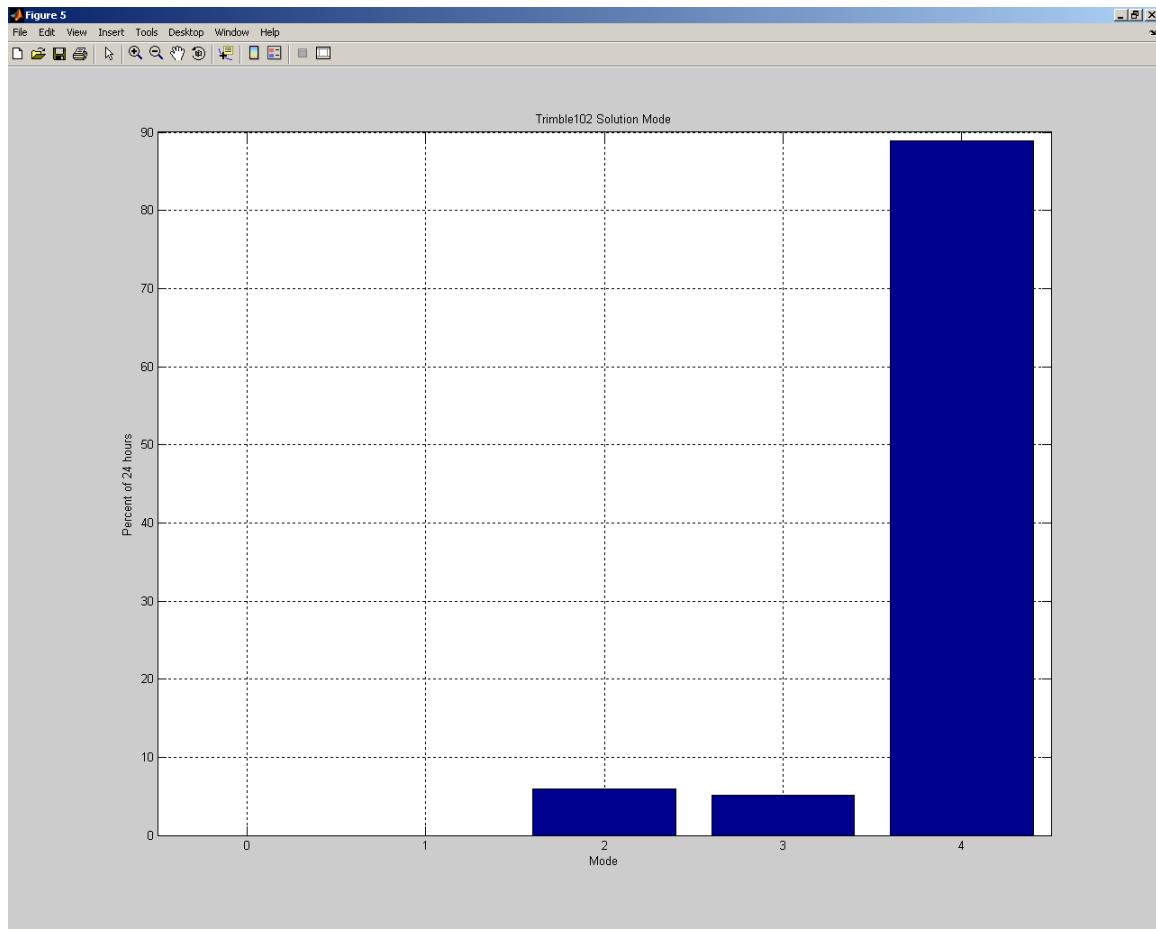
**Figure 25:** Enclosure containing the Applanix POS MC.



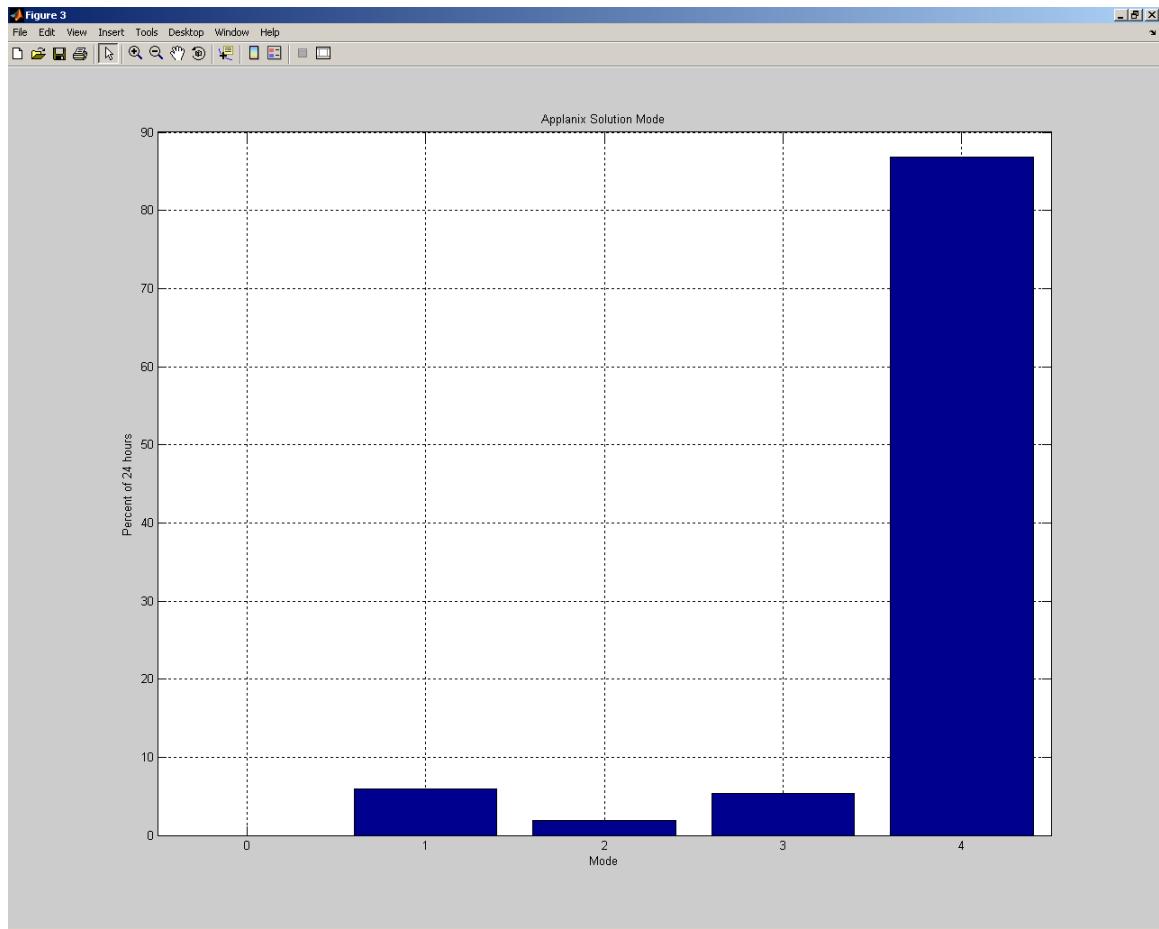
**Figure 26: Standalone Trimble GPS receiver and data logging computer.**



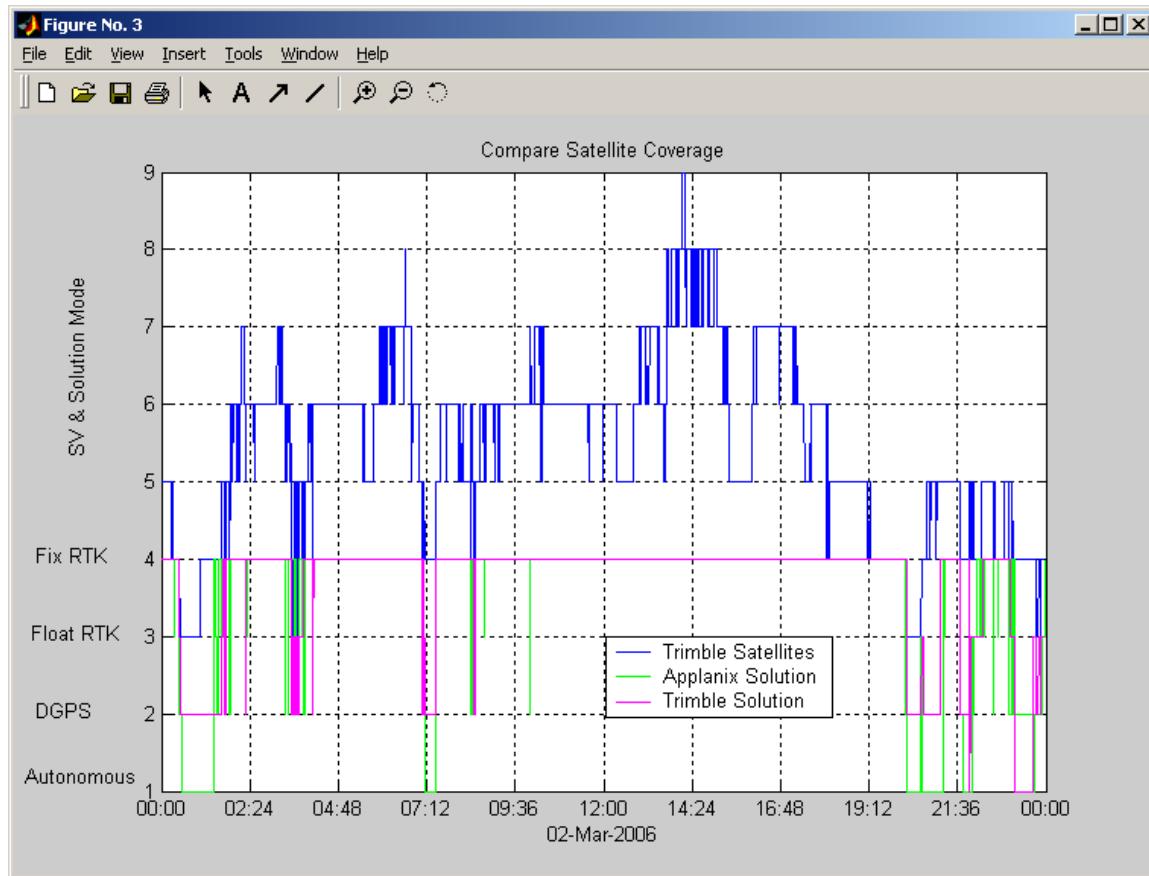
**Figure 27: Comparing performance of the standalone Trimble GPS and Applanix POS MC for February 28, 2006. The blue line indicates the number of satellites visible. The green line indicates accuracy solution for Applanix POS MC and the pink line indicates accuracy solution for Trimble. Applanix POS MC accuracy threshold has been changed to match Trimble's accuracy at 10 cm.**



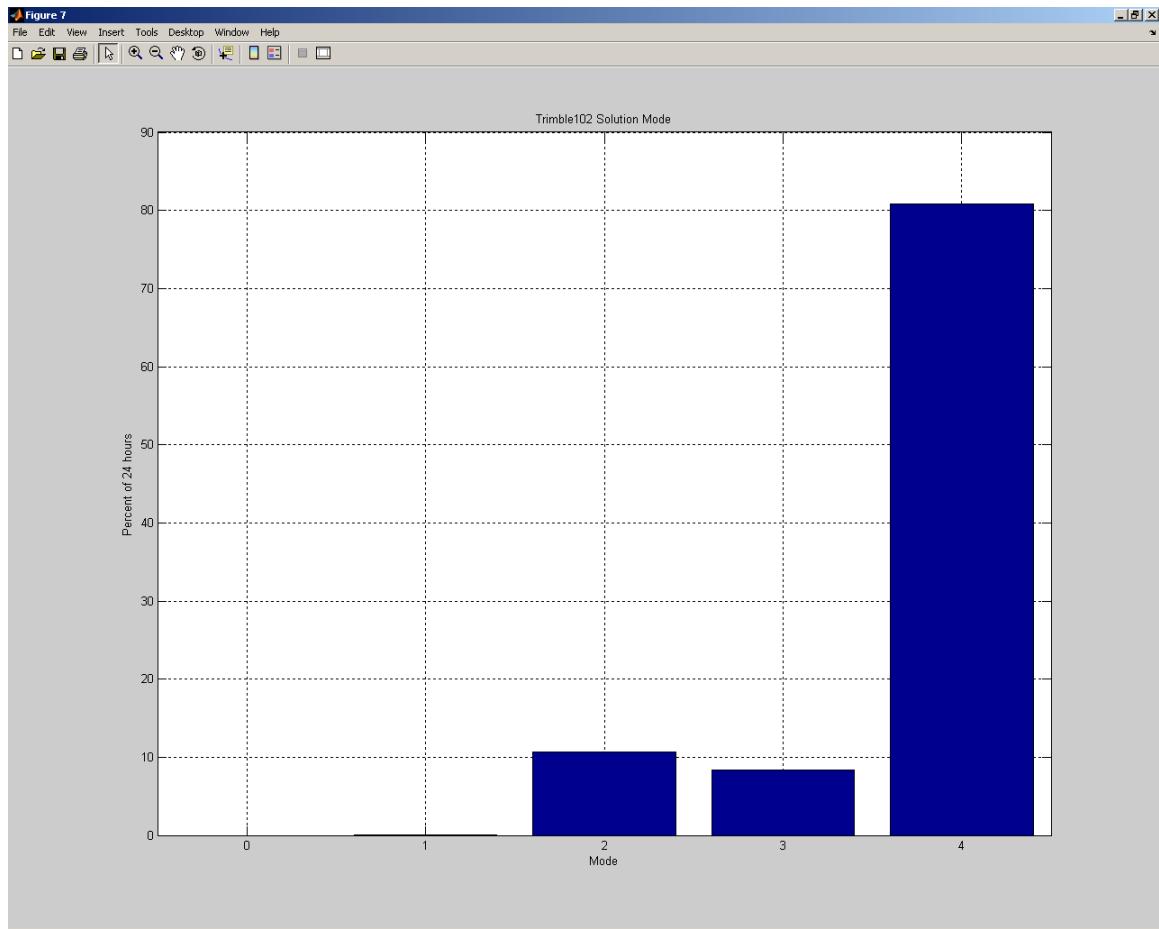
**Figure 28: Performance of the standalone Trimble GPS for February 28, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous**



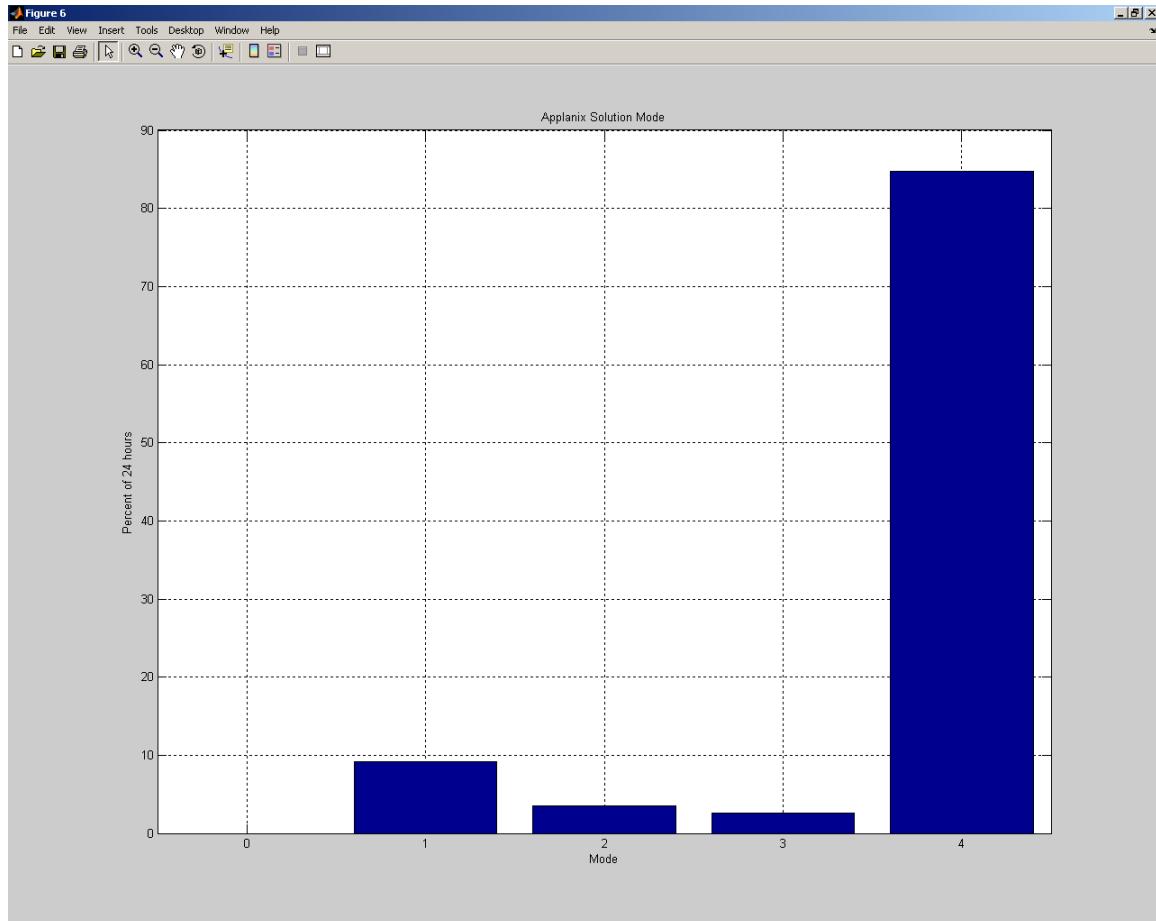
**Figure 29: Performance of the Applanix POS MC for February 28, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous**



**Figure 30: Comparing performance of the standalone Trimble GPS and Applanix POS MC for March 2, 2006. The blue line indicates the number of satellites visible. The green line indicates accuracy solution for Applanix POS MC and the pink line indicates accuracy solution for Trimble. Applanix POS MC accuracy threshold has been changed to match Trimble's accuracy at 10 cm.**



**Figure 31: Performance of the standalone Trimble GPS for March 2, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous**



**Figure 32: Performance of the Applanix POS MC for March 2, 2006. Charter indicates the percent of time in a 24 hour period that the accuracy mode that the GPS receiver is in. 4->Fix, 3->Float, 2->DGPS, 1->Autonomous**

**Table 2: Comparing inertial aided POS MC and standalone Trimble receiver outage period with accuracy set at 10 cm and percentage of POS MC recovery rate during outage period.**

Date	Standalone Trimble GPS Outage (min)	Applanix POS MC Outage (min)	Applanix POS MC Recovery (min)	Percentage Recovery of POS MC (%)
27 Feb. 2006	14	9	5	35.71%
28 Feb. 2006	116	128	0	0%
1 Mar. 2006	139	128	11	7.91%
2 Mar. 2006	207	193	14	6.76%

## 5. Conclusion

The objective of this project is to investigate the applicability of a combined Global Positioning System and Inertial Measurement Unit (GPS/IMU) for information based displays on earthmoving machines and for automated earthmoving machines in the future. With improved performance, the GPS/IMU system would require machines to spend less time performing a task, thus, reducing the energy consumed. This technology will allow an information-based product like Caterpillar's Computer Aided Earthmoving System (CAES) to operate in areas with satellite shading. Satellite shading is an issue in open pit mining because machines are routinely required to operate close to high walls that reduce significantly the amount of the visible sky to the GPS antenna mounted on the machine. An inertial measurement unit is a product, which provides data for the calculation of position based on sensing accelerations and rotation rates of the machine's rigid body. When this information is coupled with GPS it results in a positioning system that can maintain positioning capability during time periods of shading. Results from this investigation has thus far been mixed.

While Applanix POS MC system does have performance improvement over a standalone GPS receiver when comparing the periods when the GPS receiver's solutions drop below Fix, the improvements were not as significant as originally expected and the POS MC has a tendency to drop out of Fix solution when the GPS receiver solution is Fix. In the duration of this investigation, numerous methods were used to evaluate the performance of POS MC system. The system was initially tested using a metal building to shade the satellites. This approach cause concerns about multipathing because of the metal. The mast angle was also change on the standalone GPS receiver and the POS MC so as to restrict where the systems looks for satellites. This eliminated the number of satellites seen by the systems and the POS MC had good results but aspects such as PDOP were not fully reflected in the POS MC calculation. The ultimate evaluation was to install the POS MC system on a hydraulic shovel operating in a real mining environment at Newmont's Twin Creeks mine.

During the final phase of the testing at Twin Creeks mine, the shovel was working at a deeper part of the pit. The duration of satellite shading during this period is longer as shown in figures 27 to 32. Table 2 shows that POS MC system maintained a Fix solution longer than a standalone GPS receiver during satellite shading period with 10 cm accuracy setting. How long POS MC system was able to maintain the Fix solution varied. This result looks promising but detail analysis shows that Applanix POS MC system maintained Fix solution when standalone Trimble receiver is at Float solution mode. When the standalone GPS solution mode drops below Float, POS MC system was not able to maintain Fix solution and degrades to DGPS and autonomous mode. This is due to constant short movement of the shovel with its tracks during earthmoving operations, which will reduces the accuracy of the inertial unit during long satellite shading periods.

The Applanix POS MC system was designed with the consideration that the shovel's operations consist of constant rotation of the upper part of the shovel while the lower part of the shovel remain stationary during earthmoving operations. It was not anticipated that during actual earthmoving operations in the mine, the lower part of the shovel does not remain stationary most of the time. Thus, the prolonged usage of tracks during earthmoving operations decreases the positional accuracy of the POS MC system during satellite shading periods.

**Table 3: Compares the performance of standalone Trimble GPS and inertial aided Applanix POS MC at different satellite range.**

	<b>Number of Satellites: 6 – 9</b>	<b>Number of Satellites: 4 – 5</b>	<b>Number of Satellites: 2 – 3</b>
Standalone GPS: Trimble MS840	Fix RTK (Maintain high accuracy during normal GPS coverage)	Solution degrades to Float RTK and DGPS during satellite shading periods	Solution degrades to DGPS during satellite shading periods
GPS/IMU System: Applanix POS MC	Fix RTK (Maintain high accuracy during normal GPS coverage)	Maintain Fix RTK for an average of 7.4% of the time during satellite shading periods	Solution degrades to Autonomous
PDOP range	2.0 – 6.0	6.0 – 9.0	6.0 - 10.0
Duration of satellite shading during a test period (4 days)	N/A	406 minutes	70 minutes
Applanix POS MC solution during satellite shading over test period (4 days)	N/A	Maintained Fix solution for 30 minutes	Does not maintain Fix solution

Table 3 summarizes the performance of the standalone GPS and Applanix POS MC system. The POS MC system does have some performance improvement compared to standalone GPS. However, the improvement is not as significant as originally expected. During the test period, the POS MC was able to maintain fix accuracy for an average of 7.4% during satellite shading periods where 4 to 5 satellites are visible. During satellite shading periods where 2 to 3 satellites were visible, POS MC was not able to maintain Fix accuracy and the solution degrades to Autonomous mode.

Analytical analysis by Applanix Corporation shows that there is a possibility for improving the performance and accuracy of the POS MC system by integrating angle sensor and ground speed sensor. Unfortunately, angle sensors that are currently available in the industry are expansive. Using these expansive sensors will increase the cost of the

POS MC system, thus defeats the purpose of developing a lower cost inertial aided POS MC.

## 6. List of Acronyms and Abbreviations

1. POS MC – Position and Orientation System for Machine Control
2. IMU – Inertial Measurement Unit
3. CAES – Computer Aided Earthmoving System
4. GPS – Global Positioning System
5. ATS – Robotic Total Station
6. INS – Inertial Navigation System
7. TTL – Transistor Transistor Logic
8. ZVI – Zero Velocity Indicator