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Satellite mapping in cities: how good can it get?

Society needs better maps of its ever-more congested cities – particularly for buried utilities, the locations of which are approximate at best. One of the most convenient surveying methods is to use global satellite-navigation systems, but 'urban canyons' are not ideal for satellite reception. This paper looks at the current and future status of the world's global navigation satellite system (GNSS) constellations and the advantages they offer for positioning surveys. Tests using a satellite-navigation system simulator show that a large proportion of urban areas are indeed difficult to position to centimetre level using a single satellite constellation alone, but this could improve significantly with the addition of further constellations in the near future.

In the UK alone there are over 4 million km of buried pipes and cables – a combination of water, sewage, gas, electricity and drainage. It is also estimated that there are four million holes dug every year on British highways and footpaths by utility companies so they can install new services and maintain existing ones.[1]

One of the possible options for positioning and locating utilities is using a global navigation satellite system (GNSS), the best-known example of which is the USA's global positioning system, or GPS. There are other systems currently in partial operation, such as Russia's Glonass, or in development, such as Europe's Galileo and China's Compass.

To work effectively in real time and at cm level of accuracy, GNSS technology needs to be able to receive signals from five or more satellites orbiting the Earth to obtain accurate coordinates. This can be a problem in urban environments where large buildings and other obstructions can block the signal.[2] In addition, large buildings and other structures can cause attenuation and 'multipathing' of the signals – a significant cause of reduction of signal quality.

As part of the University of Nottingham's research into the positioning of buried assets in built-up environments through the 'Mapping the underworld' and 'Vista' projects, researchers are studying the possibility of using GNSS alone to position and locate buried assets. For this purpose, current and future satellite constellations have been researched and a GNSS simulator has been developed to investigate the impact current and future navigation satellites might have on this specific problem.[3]

Existing and future GNSS

GPS

Currently there is only one fully operational GNSS constellation, the US government's GPS. The current GPS constellation consists of 31 medium Earth-orbiting satellites at an altitude of 20 200 km in six different planes.[4] This arrangement means that at any time of day, on any part of the Earth at least four GPS satellites, the number required to solve for *x*, *y*, *z* positions and time difference, will be visible above the horizon unless the view of the sky is obstructed by some object, such as a building or vegetation.

The first experimental GPS satellite was launched in 1978. The initial constellation comprised 12 block I satellites, which were enhanced and gradually replaced by block II and IIA satellites. Since the original GPS constellation became fully operational in 1995, satellites have been upgraded and replaced as their operational lives come to an end (Figure 1) or as technology improves and new demands are placed on the system. However, mean life-expectancy is proving much greater – almost double – than the design life.

Currently there are seven of the latest GPS block IIR-M satellites in orbit (Figure 2); these are modernised with the new military M-code and the second civil signal L2C code. L2C will provide improved accuracy and redundancy.[5] Block IIF satellites, which are currently under construction,[6] will provide the new L5 signal which will be tasked with providing safety of life applications. The modernisation of GPS will continue with the introduction of the block III satellites and new ground and control segments with a scheduled completion time set for 2013. In September 2007, the USA announced that selective availability, which is the means whereby the civil GPS signal is degraded to the advantage of the military signal, will not be available on block III satellites.[7] Selective availability has not operated on GPS satellites since 2000 but removing this capability from future GPS satellites removes one of the uncertainties in GPS positions.

Glonass

The Russian equivalent of GPS is Glonass and has been developed and maintained by the Russian military. The first Glonass satellites were launched in 1982, but the system was not a fully-functional navigation constellation until

Figure 1. Launch of the USA's seventh GPS IIR-M satellite on 24 March 2009 (NOAA)

Figure 2. The latest GPS block IIR-M satellites provide improved accuracy and redundancy (NOAA)

1995.[8] Due to economic difficulties, the Glonass system deteriorated to only seven satellites in 2001.

Since that time the Russian government has been working to re-establish its GNSS system by continuing to launch new Glonass satellites. This is being done in collaboration with the Indian government, which has contributed to this financially and has also agreed to launch some Glonass satellite in return for use of the military signal. In 2008 there were 16 Glonass satellites in orbit of which 15 were operational. Glonass was scheduled to have 18 fully-operational satellites by the end of 2008 (Figure 3).

A fully-operational constellation of 24 (21 operational, three active spares) satellites, orbiting the Earth at an altitude of 19 100 km in three planes (eight satellites in each plane) is proposed to be completed by 2010.[9]

Galileo

Galileo is the first civilian-operated and -maintained GNSS. There are currently two Galileo test satellites in orbit, *Giove-A* launched in December 2005 and *Giove-B* launched in April 2008. Galileo is scheduled to be fully operational by 2014.[8] When Galileo is fully operational it will provide 30 (27 operational with three active spares) additional satellites to the total GNSS satellites available. These will orbit the Earth at an altitude of 23 222 km in three orbital planes (ten in each plane).[10]

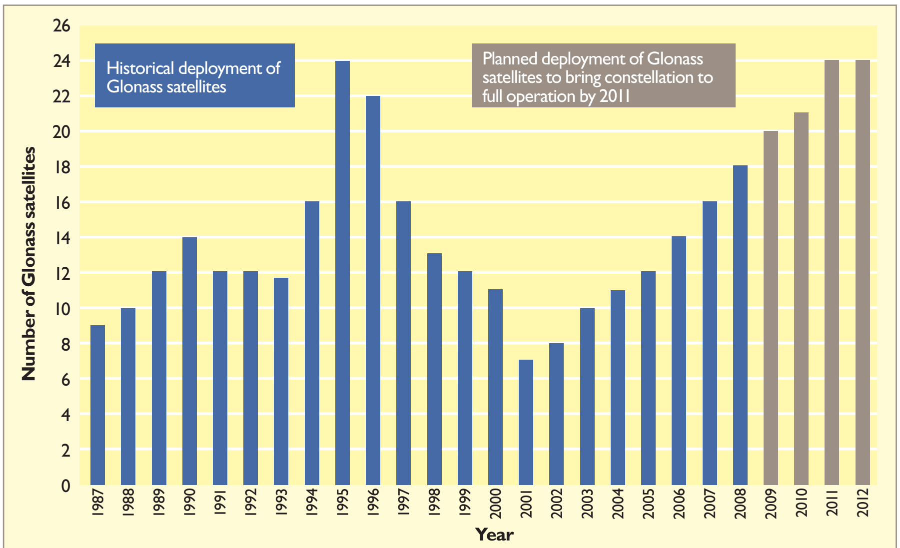

Figure 3. Russia's Glonass constellation should be back to full strength by 2011

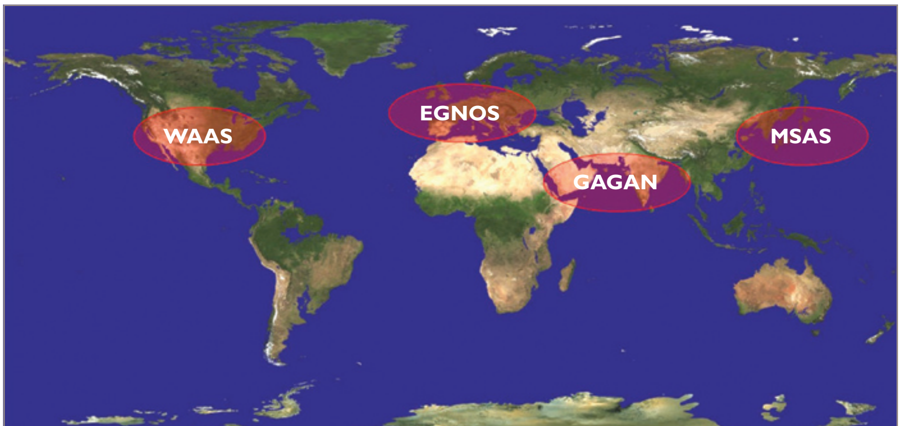

Figure 4. Location of the four main satellite-based augmentation systems

Compass

China currently operates its own GNSS, called Beidou-1, which differs slightly from the three constellations described previously. Beidou-1 consists of only four satellites, three in geostationary orbits over China and the latest one placed in orbit in a medium Earth orbit similar to GPS. This limits the coverage to China and the surrounding area (coverage from 70°E to 140°E, and from 5°N to 55°N),[11] but gives the advantage of requiring fewer satellites to obtain a three-dimensional position therefore reducing the maintenance and running costs of the system.

Beidou-1 is an experimental system that currently provides users with accuracies of 20–100 m. In November 2006 China announced that it plans to develop its current constellation into a fully-global satellite-navigation system named Compass (Beidou-2). This constellation will consist of a total of 35 satellites, five of which are in geostationary orbits and the other 30 will be in medium Earth orbits[11] similar to those of GPS, Glonass and Galileo.

China initially announced that Compass was scheduled to be complete by the end of 2008, but that it would be definitely operational by 2010. Compass will be a military navigation system but the Chinese government plans to provide free access for civilians to data with accuracies of up to 10 m.

India and Japan

Other proposed GNSS systems include India's regional navigational satellite system, which will consist of geostationary satellites providing positioning throughout India, and Japan's quasi-zenith satellite system, which would consist of three geostationary satellites that supplement other GNSS satellites over Japan and the surrounding area, aiding the use and availability of GPS in very high-rise cities.

Augmentation systems

In addition, satellite-based augmentation systems have been made available. The wide-area augmentation system (WAAS) is one such system that is currently fully operational. It has been developed by the Federal Aviation Administration in the USA to increase the accuracy, integrity and availability of GPS signals, primarily for the navigation of aircraft and ships. The system consists of around 25 ground-based stations that monitor the GPS signal along with two master stations on either side of the USA. These stations calculate corrections for the GPS signals to errors caused by the atmosphere, the difference in predicted and actual orbits of the satellites, and timing biases; these corrections are then uploaded to geostationary satellites that transmit the message to any WAAS enabled receivers.[12] The system currently only covers North America.

Other countries are putting together their own augmentation systems to provide a similar service (Figure 4). In Europe, the European geostationary navigation overlay service (EGNOS) is currently operating, providing corrections for both GPS and Glonass now and for Galileo in the future. Japan currently operates its multi-functional satellite augmentation system (MSAS) and the Indian government proposes to develop and operate its own GPS aided geo-augmented navigation (GAGAN).

Australia's answer is a ground-based augmentation system (GBAS). This has a similar basic principle to the US ststem, whereby reference stations are used to calculate range corrections to the satellites. Instead of using low Earth-orbiting satellites to transmit the corrections and reliability information, ground-based radio transmitters are used.

A system of systems

By 2014 GPS, Glonass, Galileo and Compass should all be fully operational and available – at least at some level – free of charge to the general public for use in activities ranging from location-based services and vehicle navigation to structural monitoring. If all four of these constellations were fully operational as proposed, then there would be 120 GNSS satellites in total. GNSS receivers that can receive information from all four of these constellations are already on the market.

The availability of a greater number of satellites will help to overcome some of the problems to be addressed in both the 'Mapping the underworld network' and 'Vista' research projects. An investigation into the availability of GPS signals for positioning in the urban areas of Leeds and London[13] found that GPS positions were only possible on 60% of the points surveyed. In the future, a greater number of satellites should mean an increase in the percentage of points suitable for satellite positioning.

Interoperability and compatibility of GNSS is a critical issue when there will be multiple GNSS operating. However the systems are not built upon the same technology and therefore differ from each other in many ways. They are, however, designed to be interoperable with each other. Interoperability and compatibility are the two driving mechanisms by which to obtain a GNSS 'system of systems'. At the same time, the independence of these systems is of great importance to their integrity and the competition between them.[14]

Nottingham test network

A test network has been established around the University of Nottingham to try out the various positioning techniques and combinations mentioned above.

The test network was carefully coordinated using a combination of precise levelling, total station and GPS observables.[15] The network comprises points with known coordinates in a variety of scenarios, from open-sky scenarios to an urban canyon environment. Figure 5 illustrates the test network as well as the various difficult scenarios encountered.

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Figure 5. The GNSS test network at the University of Nottingham campus includes a variety of difficult 'urban' scenarios including tall buildings (A), urban canyons (B) and bridges (C)

GNSS simulation

The project has developed software that will allow simulation of GNSS in different scenarios. This allows the user to input a digital elevation model and GNSS orbits data. The simulator uses almanac files that can be downloaded on a daily basis for the operational GPS and Glonass satellites. Almanac files contain the orbital parameters for each satellite in that particular constellation. Almanac data for the future Glonass, Galileo and Compass constellations have been created using the nominal orbit values for each of these constellations. In the case of Glonass, which already has some operational satellites, the gaps in the constellation have been filled in using these nominal values. Both the files for Galileo and Compass have been created entirely from the nominal orbit values. Almanac files are created and loaded into the software using the interface (Figure 6).[3]

The purpose of wanting to simulate present and future GNSS constellations as part of the 'Vista' and 'Mapping the underworld network' projects is to investigate the advantages, given by additional satellites, to positioning in urban areas. Building-height data, for the area being investigated, are therefore required to model any obstructions that might block the GPS signal. Building-height data can be imported in either raster or vector format. Some of the limitations of this method of simulation are that the orbits are only calculated from almanac files and therefore are not precise and will have some differences from reality. In addition to this, building-height data are only accurate to 1 m and this introduces errors. Whether vegetation is included within the model is another important factor.

Testing reliability

To test the reliability of the software, a GPS almanac file and a building height model, created from photogrammetry, were imported into the software to calculate which features would block signals (Figure 7). No vegetation was included in this particular model. A GPS receiver was set up in the same area and data were recorded. The satellites available from the simulation software and the GPS receiver over this period of time were compared and the results are shown in Figure 8.

This test shows some differences between the number of satellites predicted to be available by the simulator and what was actually available to a receiver in the field at the chosen time. A total of 473 (8·2 %) of the 5758 epochs recorded

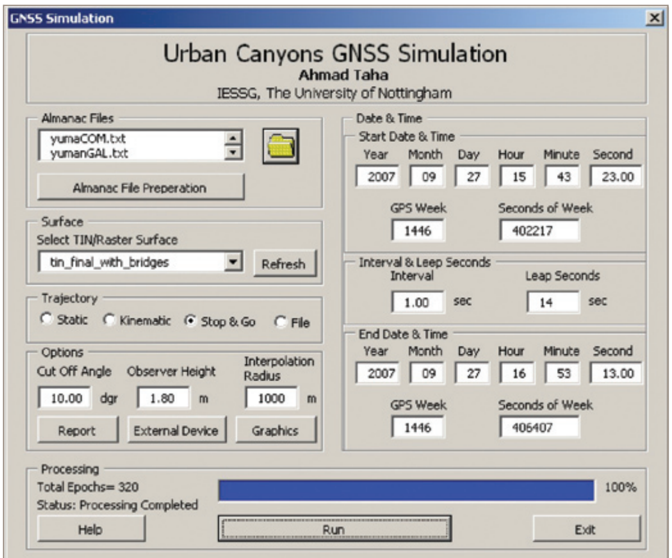

Figure 6. The GNSS simulation software interface enables real and theoretical almanac data for satellite orbits to be entered

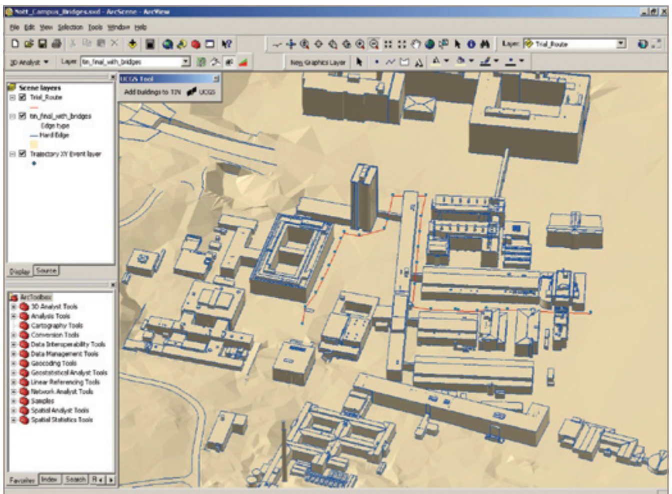

Figure 7. A digital elevation model of the university campus was used in the GNSS simulator

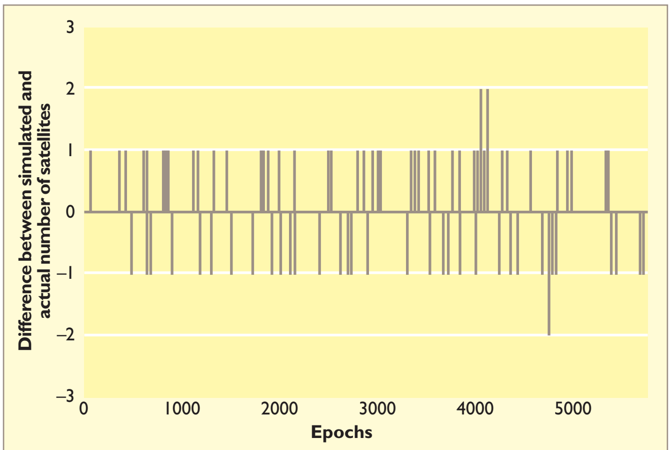

Figure 8. The simulator accuracy was tested by measuring the differences between actual and simulated number of GPS satellites – 8·2% of nearly 6000 epochs showed a difference of one or more satellites, with just four epochs showing difference of two satellites.

were different by at least one satellite, there are four epochs where there is a difference of two satellites. These differences are caused by errors in the model, including the fact that vegetation is not included, as well as differences in the predicted orbits of the satellites (given in the almanacs) and the actual orbits of the satellites.

Effect of extra satellites on availability

Using the previously established Nottingham campus network, tests have been carried out to investigate the effect that additional future constellations may have on the ability to use GNSS to position, in real time to centimetre level, in urban areas. The simulator allows the user to choose which constellations to simulate. Known points in the most difficult environment for GNSS positioning were selected as the points to be used in the simulation.

Several different scenarios have been tested: GPS only, GPS and Galileo, GPS with Galileo and Glonass, and finally all four constellations, namely GPS, Galileo, Glonass and Compass. In this test the coordinates of 32 known points in the campus network were used in the simulator. The GNSS software was used in its 'stop and go' mode, the receiver was simulated to move along the campus network and to stop on each of the 32 known points for 10 epochs. The simulated variation of the number of satellites is shown in Figure 9.

It is known that for the receiver to be able to compute a real-time position from GNSS satellites, signals from at least five GNSS satellites signals must be available. Figure 9 shows that when only using GPS, six of the known points are simulated to have less than the five satellites required at this specific time. If Galileo was fully operational and could be used, then the software simulates that none of the known points would have less than the required number of satellites. It therefore follows that the addition of Glonass and Compass would have no points with less than five satellites available either. The average number of satellites available over the whole network increases from seven using only GPS to 12 using GPS and Galileo, to 17 using GPS, Galileo and Glonass, and finally to 22 using all four constellations.

Effect of extra satellites on geometry

As well as the number of satellites affecting the availability of positions using GNSS, the 'satellite geometry', which describes the position of the available satellites in relation to each other and in relation to the receiver, is also critical. The satellite geometry is described using the dilution of precision (DOP) values. Figure 10 shows the variation of the positional DOP values calculated from the simulated satellite constellations.

A DOP value of six or more represents the cut-off point when the satellite geometry becomes bad for positioning.

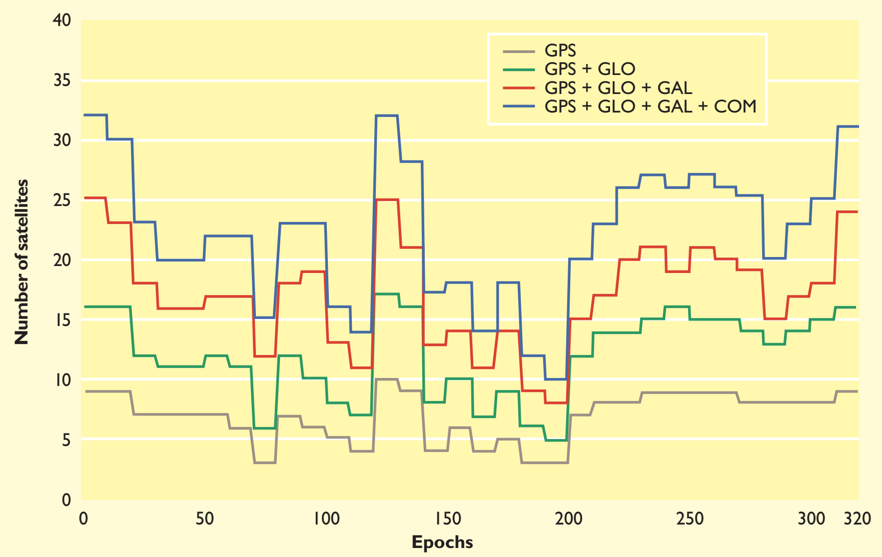

Figure 9. Simulator results for the number of available satellites at each of 32 points on the test network (10 epochs at each point) – with GPS alone, six points have fewer than the required five satellites, but the problem is resolved with the addition of any of the other constellations

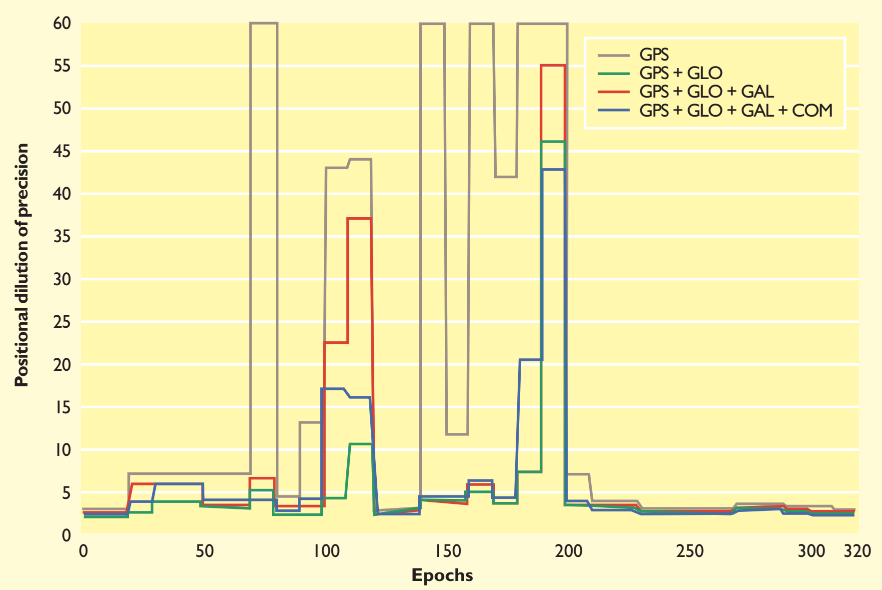

Figure 10. Simulator results of the positional dilution of precision at each of 32 points on the test network (10 epochs at each point) – with GPS alone, only half the points had less than the maximum dilution value of 6, and even with three constellations two points next to a bridge still failed

Immediately it can be seen that using GPS alone gives very large positional DOP values in the areas closest to buildings. When only using GPS, 16 of the 32 points used in the test had positional DOP values greater than 6. After introducing the Galileo constellation into the simulator, only four of the tests points gave values of greater than 6. Using three constellations, only two points recorded values greater than 6. It should be noted that the areas between epochs 100–120 and 180–200 were close to a bridge, therefore seriously restricting the view of the sky.

Conclusion

The 'Mapping the underworld' and 'Vista' projects aim to improve the locating, positioning and recording of utilities in all environments. As part of these projects researchers at the University of Nottingham have been investigating techniques for providing positions to less than 10 cm in all environments, including urban canyons, 100% of the time.

GNSS would be a convenient tool to use for this kind of positioning. However, due to the need for line of sight between the receiver and the satellite, using the GNSS satellites that are currently available does not provide positions to the required level 100% of the time. In the future, it is planned that additional GNNS constellations will become fully operational and current GNSS will be upgraded.

To investigate whether GNSS alone could be a solution to this problem, a GNSS simulator has been developed that simulates both current and future GNSS. The results of the investigation show that using GPS for the purpose of positioning to less than 10 cm in urban areas is difficult, but predict that the availability of positions using GNSS in the future will be significantly improved. The results predict that using two fully-operational GNSS constellations would provide good quality positions in all areas in the campus test site apart from those very close to or underneath bridges.

The DOP values in the bridge areas do not drop below 6 even when using all four constellations, suggesting that it may not be possible to obtain positions that are accurate to less than 10 cm 100% of the time in very difficult positioning environments. A solution to the problem could be the use of Pseudolite technology or other positioning systems, such as integrated navigation systems, to augment the GNSS. Research is ongoing at Nottingham in the integration of these technologies.

Work is also ongoing in moving toward a new version of the simulation software that would include algorithms for predicting multi-pathing and the effect this phenomenon would have on the accuracy of certain positions. Other future improvements may include being able to simulate the use of Psuedolite and other technoliges to augment the GNSS.

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