High-Sensitivity GNSS Limitations in RF Perturbed Environments

Gérard Lachapelle
Professor
Department of Geomatics Engineering
Schulich School of Engineering
The University of Calgary
2500 University Drive, NW
Calgary, Alberta, T2N 1N4, CANADA
Email: Gerard.Lachapelle@ucalgary.ca
Website: http://plan.geomatics.ucalgary.ca

ABSTRACT

Low signal power make stable GNSS signal acquisition and tracking difficult under RF perturbed conditions such as in signal shaded environments and in the indoors. These difficulties result in higher measurement noise, multipath (signal reflection) and, in some cases, signal denials and associated poor geometry. Starting in the mid 90s, methods have been developed and tested to somewhat overcome these difficulties. A review of these, which consist mainly of longer signal integration, assisted GNSS (AGNSS) techniques, and advanced signal processing methods, is presented. Associated limitations such as, thermal noise, receiver oscillator limitations, signal reflections and RF interference are discussed. Positioning capabilities and limitations are illustrated with examples in various outdoor and indoor environments as a function of signal attenuation and shading. These include natural and urban canyons. New developments to further enhance performance such as aiding with other sensors are introduced and some examples are given.

1.0 INTRODUCTION

The focus of this lecture is on pedestrian users, a challenging user group given its rapid outdoor/indoor transitions, indoor use and unpredictable trajectories. In addition, this user group generally moves in concealed terrain or under the forestry canopy in the outdoors and along buildings and recesses in outdoor urban environments when not completely indoors. In these environments, GNSS is at least partly denied and, if available, suffers from signal degradation due to higher noise, multipath (signal reflection) and poor geometry. Aiding or replacement is therefore required. Even under outdoor line-of-sight (LOS) conditions, GNSS signals may be affected by unintended or intended electronic interference, the latter becoming an increasing concern for military applications, even raising doubts as to the very use of GNSS for many military uses.

User requirements are not well defined for many applications, especially civilian ones in view of the rapid evolution of the technology and mismatch between ideal requirements and what technology can deliver. As performance increases, new applications become possible. In many cases, no technology is yet able to deliver the performance required. This is particularly true for soldiers and first responders such as rescue teams operating inside buildings where accuracies of 1 to 2 m are desirable. Such requirements help drive innovation and enhance technology.

Prior to discussing aiding of and alternatives to GNSS, selected signal characteristics and interference sources are reviewed.

2.0 SIGNALS AND INTERFERENCE SOURCES

GPS satellites are orbiting 20,000 km above the earth. Satellite transmitting antenna beams have to be wide enough to cover the planet as shown in Figure 1. The signal energy is dissipated and only a fraction thereof reaches any one point on the earth surface. As a consequence, the resulting free-space loss of 184 dB results in very weak signals available at a receiver on earth. The limited beam of the transmitting antenna and other gains nevertheless reduce this loss and the final signal strength on the earth for the GPS L1 C/A code is 160 dB (recently increased by 1.5 dB for new satellites). The nominal receiver SNR for the L1 C/A code under LOS conditions is -19 dB for a noise density of -204 dBW/Hz in a 2 MHz bandwidth. The typical detection threshold is 14 dB, hence the nominal processing gain required is 33 dB. When LOS is not achieved, additional attenuation occurs. Foliage attenuation depends on tree leaf type and moisture, the higher the moisture, the greater the attenuation. Values of up to 20 dB are common, which means that a processing gain of up to 53 dB for detection is required. The same order of magnitude holds for canyons, natural or urban. In the indoors, the attenuation depends much on the surrounding material and values of up to tens of dB occur, which means that signals cannot be acquired or tracked over certain thresholds, in which case GPS is partly or totally denied.

The normal integration time of LOS signals is 1-5 ms. An increase of the integration time of IF in-phase and quadri-phase baseband measurements improves the SNR. This is the basis of high sensitivity GNSS (HSGNSS). Assisted GNSS (AGNSS) is also used during the signal acquisition phase in the form of information on the navigation messages, Doppler shift and timing from a nearby LOS stationary receiver. This information requires a communication link and is now available on most civilian cellular networks. The effective integration time is limited by many factors, the major ones being oscillator noise and user motion induced Doppler shifts; the latter effects can be dealt with using an IMU. Low cost oscillator noise remains a limitation. In practice, integration of up to a few hundred milliseconds is used. The gain achieved with HSGNSS as compared to standard GNSS is currently of the order of 25 to 30 dB. However this comes at a cost of higher noise, namely up to about 20 m for pseudorange measurements and high multipath in natural and urban canyons and the indoors. Non-LOS multipath in not bounded; in practice multipath errors of up to 100 m occur. Some signals are simply not available due to high attenuation as a result of masking from buildings and topography, which results in geometry degradation. The dilution of precision (DOP) numerically increases and, since position accuracy is the DOP multiplied by the error (sum of all errors), position accuracy drops.

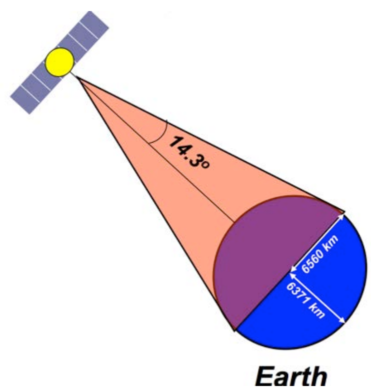


Figure 1: Satellite signal beam and energy dissipation

Signal interference comes in many forms as illustrated in Figure 2. Ionospheric scintillation was initially a problem, especially for carrier phase tracking on L2; however, thanks to improvements in phase lock loop design, this issue is now minor, even under harsh conditions. Doppler shifts induced by antenna motion is a problem for high sensitivity technology as it limits the signal integration time; this can be mitigated with the use of IMUs (inertial measuring units) to measure short term Doppler effects, such as those induced by a hand held receiver. Noise is low for LOS (line of sight) applications; when the signal strength decreases, code and noise increases accordingly, up to 20 to 25 m; mitigation using IMUs is an option when available. Signal masking results in obscuration of signals on some satellites, thereby weakening satellite geometry (increase of DOP numerical value); reflected signals result in unbounded multipath that degrades position accuracy although, in many cases, it increases availability, although with a diminished accuracy. Unintentional jamming occurring through the increasing use of low cost wireless electronic equipment is a concern and the regulated spectrum is increasingly crowded as shown in Figure 3; weak signal acquisition and tracking in the indoors is vulnerable to some frequency leakages from nearby devices. Intentional jamming is an increasing concern for civilian and military use of GNSS and counter-measures are the subject of intense research. Low cost hand-held jammers, sometime called privacy devices are now legally or illegally available on the market (see Figure 3) and are a major concern for scores of civilian applications. Spoofing aims to coerce receivers into generating false positions without detection, a major concern for military operations with unaided GPS. Portable spoofers are likely to become available and affect civilian applications. An example of the cause and consequence of a spoofer is shown in Figure 4; the spoofed signal is stronger that the real signal, resulting in false positions and misleading of the vehicle on an incorrect trajectory. Spoofing methods are becoming increasing sophisticated and counter-measures are evolving equally rapidly.

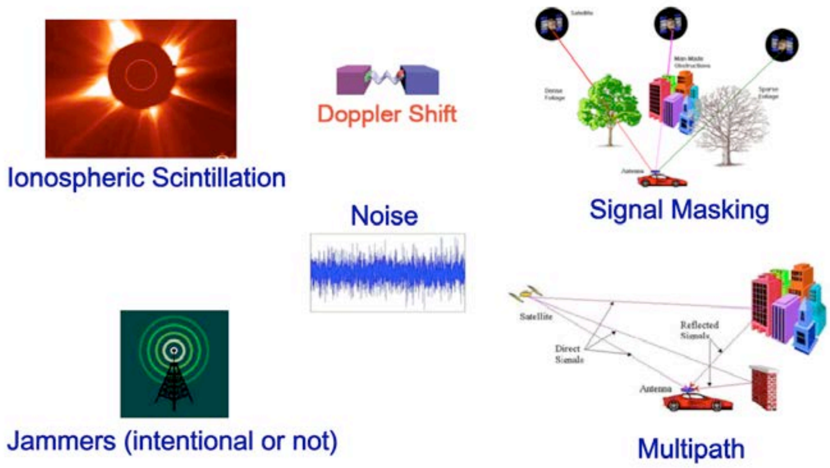


Figure 2: Interference sources

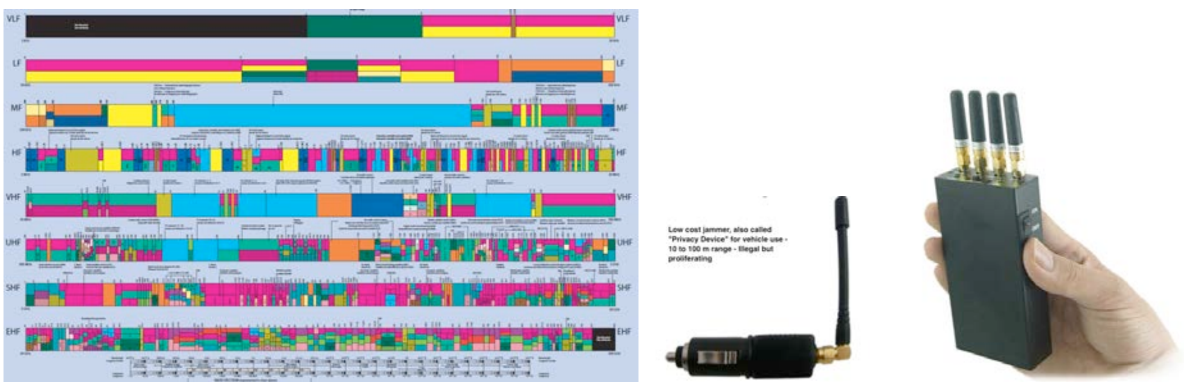


Figure 3: Non-intentional and internal electronic interference

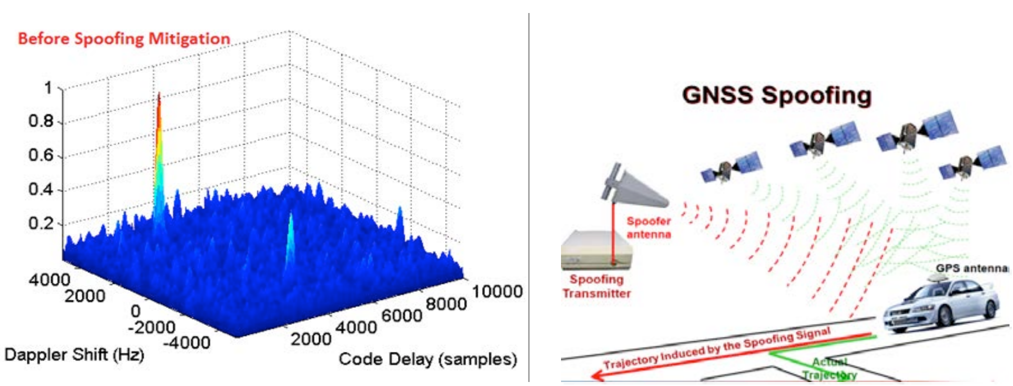


Figure 4: GNSS spoofing cause and consequence on a vehicle trajectory

3.0 HSGNSS PERFORMANCE EXAMPLES

Examples are given herein using hand-held HSGPS receivers aided with barometers, which help not only the height component, but the horizontal components as well through the additional redundancy.

The first example, shown in Figure 5, consists of vehicular (blue) and pedestrian (red) trajectories determined with three different high sensitivity units simultaneously in selected streets of downtown Calgary where nearby buildings reach 60 stories, creating signal attenuation, multipath and poor geometry. The route was driven three times consecutively with the vehicle and walked once. The two trajectories on the upper part of the figure were obtained with a GPS unit equipped with a helix antenna; the remaining four trajectories were obtained with GPS-GLONASS units equipped with microstrip antennas. The vehicle was driven at velocities up to 50 km/h while the pedestrian was walking on sidewalks, much nearer to buildings. The vehicle trajectories are better than the pedestrian ones due to the above and, possibly, to more effective position filtering due to the higher velocity of the vehicle as compared to that of the pedestrian.

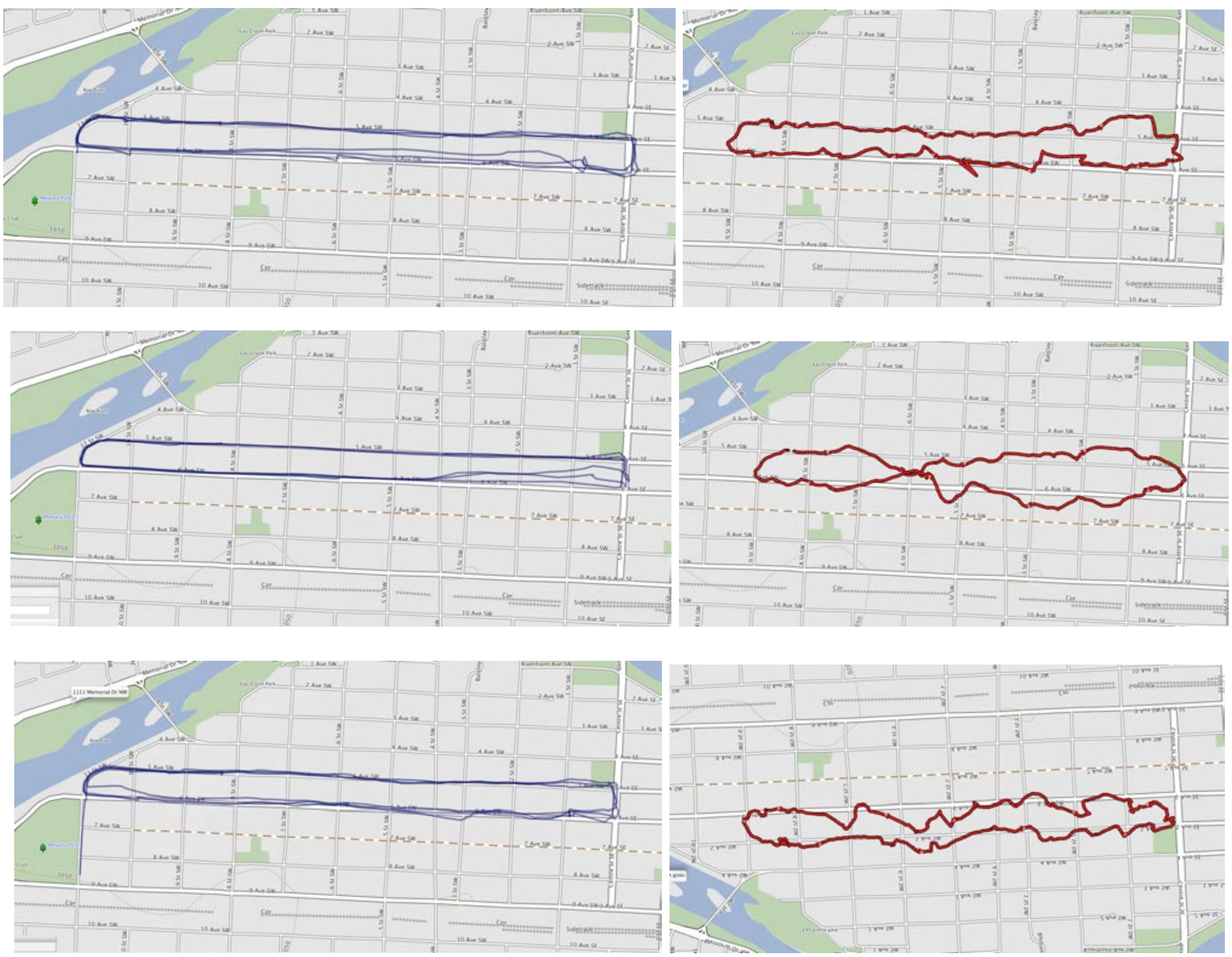


Figure 5: HSGNSS trajectories in urban canyons (Vehicle on left, pedestrian on right)

The vehicle trajectories deviate from the streets by up to 50 m but are generally within a few tens of metres, which is remarkable given that receivers would have locked on reflected signals in many cases. Commercial vehicle navigation systems use the integration of GNSS with maps to enhance performance and generally perform well in most city cores; additional aiding with wheel, steering and inertial sensors available in modern vehicles is also possible (e.g. Li 2012). For off-road vehicles, wheel slippage and uneven terrain limit the effectiveness of some of these sensors. The pedestrian trajectories are noisier due to the reasons given earlier and are off by up to half a block or about 50 m in the south-north direction. In urban canyons, the satellite geometry at the time of the test matters and the above results are not necessarily reproducible at any time of the day.

The next example, shown in Figure 6, consists of a pedestrian test with several hand held HSGNSS receivers, including a GPS-GLONASS unit in a natural canyon with mask angles of up to 80˚. The narrow canyon runs east-west, is 1.5 km long and was travelled forth and back on exactly the same route. The C/No values shown in Figure 7 reveal attenation of up to 25 dB from the maximum of 50 dB-Hz observed; LOS signals are limited and attenuation is caused by multipath. Some satellites were not available as the attenuation was too high. This is a classic case of poor DOP, high noise and high multipath. Differences between units and between forth and back trajectories reach 100 m. Comparisons with a reference trajectory known to an accuracy of 1 m results in the same error level. The other segments running roughly south-north are outside the canyon and are more accurate because due to better LOS conditions. The GPS-GLONASS unit did not perform better than the GPS ones because the high mask angle and high multipath and noise defeated the advantage of additional satellites in this case. Reliability is also an issue which will be discussed later. Given the exceptionnaly harsh conditions encountered in this environment, near continuous availability of unaided GPS in hand held units with an accuracy of 100 is impressive and useful for many location/navigation needs but clearly fail to meet sub 10 m requirements.

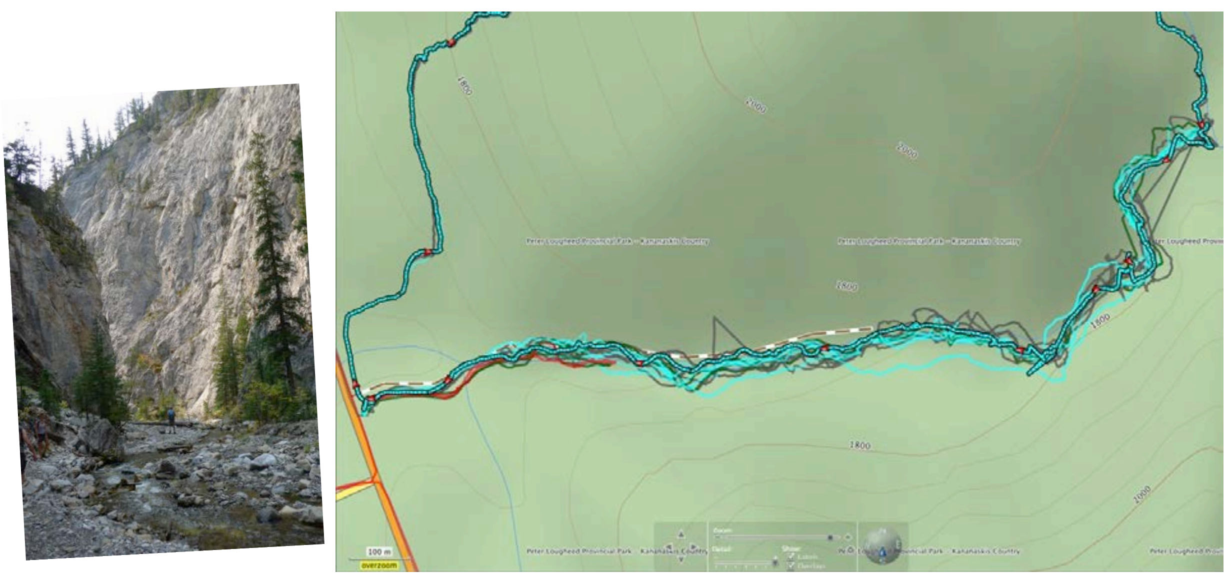


Figure 6: HSGNSS in natural canyon

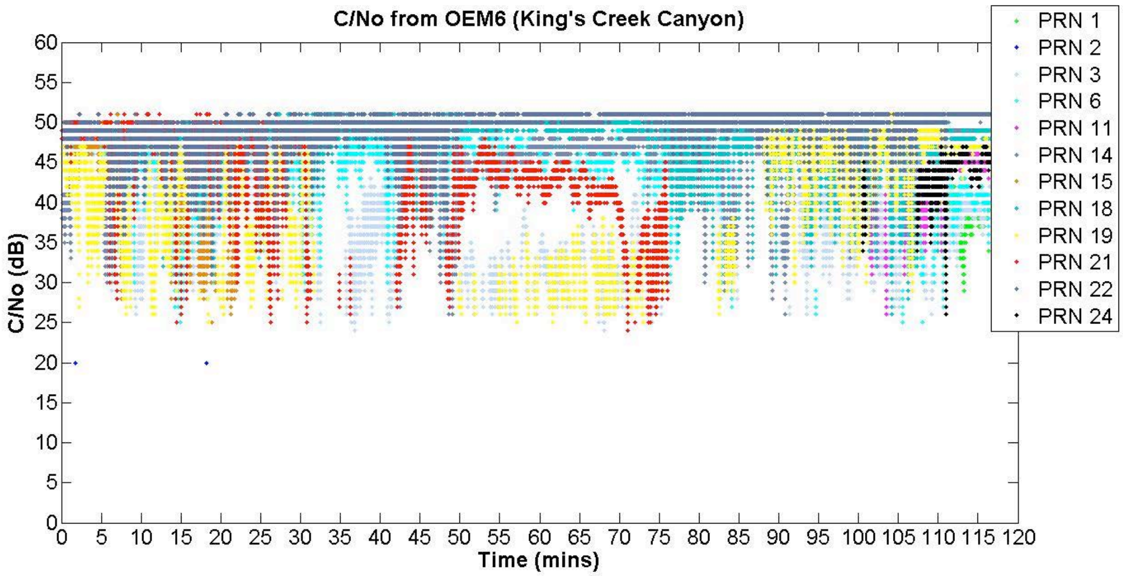


Figure 7: C/N₀ in natural canyon

4.0 NAVIGATION IN PARTLY AND TOTALLY DENIED GNSS ENVIRONMENTS

Technologies to aid or replace GNSS in these environments are evolving rapidly and a full review is beyond the scope of this lecture. Excellent reviews are provided by Mautz (2012) and Deak et al (2012). Two types of technology that can be used over wide areas are reviewed herein, namely ground-based RF technologies and self-contained sensors.

5.0 RF Technologies

Three competing technologies primarilly aimed at E911 (North America) location for first responders were assessed independently by the U.S. FCC Communications Security, Reliability and Interoperability Council III – WG3: E911 Location Accuracy in late 2012 (CSRIC 2013) as an alternative and/or complement to GPS. Solid evidence on their performance is therefore available and these technologies are consequently selected herein for review. The Test Bed was located in the San Francisco Bay area and the environments ranged from urban to rural. The metrics used were *location accuracy, latency (Time To First Fix), scatter, uncertainty, yield (% of calls with delivered location), reported uncertainty and location scatter*. These location methods are basically 2D horizontal given the difficulty of having transmitter in a non-coplanar configuration. However, barometry, especially if used in differential mode, can provide the vertical dimension, which is important for location in high rise buildings. Summary descriptions of these three technologies are as follows:

NextNav: A TDOA (Time Difference of Arrival) approach uses time synchronized transmitters broadcasting spread-spectrum signals at a 1.023 MCPS chipping rate (similar to GPS L1 C/A code) in the 900 MHz band; navigation messages contain the fixed positions of the transmitters and the timing information necessary for position calculation on the user handset. The transmitters can be deployed to cover specific areas and were deployed in this case to cover the test area

Polaris Wireless: It uses RF pattern matching (RFPM), also referred to as RF fingerprinting, that is RF pattern matching to compare mobile measurements (signal strengths, signal-to-interference ratios, time delays, etc.) against a geo-referenced database of the mobile operator's radio environment.

Qualcomm: Its AGPS/AFLT location method has been in use since 2000. It uses CDMA pilot signals on available mobile phone networks and a TDOA approach to calculate positions. Augmentation with AGPS is used when available in mobile phones.

The CSRIC report provides a detailed description of the test results for each of the metrics used. Table 1 shows the horizontal error statistics in metres for the four indoor environments selected. Each statistic is based on up to over 5,000 calls and is therefore representative of the true capability of the technologies tested. The NexNav technology provided the best results with 95^{th} percentile errors of 60 to 200 m; deployment of the system on a large scale is not however available at this time. The currently available Qualcomm technology delivered an accuracy of 300 to 500 m. All above accuracy results would help first responders in some situations but fall short of the accuracy needed to identify buildings in urban areas, let alone people or rooms within specific buildings. This demonstrates the challenge of precise indoor location without instrumented buildings.

Another ground-based RF technology used for specific outdoor and indoor location/navigation, either in stand-alone mode or in conjunction with GNSS, is Locata (e.g. Rizos et al 2010). It is a variation of the pseudolite concept where ground based transmitters precisely time synchronized to each other use a 10 MHz chipping rate to lower noise and multipath. The latter is a problem for any ground transmitter; Locata mitigates the problem with directional phase array antennas. A transmitting power of 1 W results in ranges of up to several km. Use of carrier phase can yield cm-level accuracy, as GPS does. Locata is best used for indoor LOS location in large hangars and outdoor location in contained areas such as open pit mines and for civilian/ military test areas; in outdoor situations, integration with GNSS is the natural approach to further improve accuracy and reliability.

Horizontal Error Statistics (m)									
Building ID	Total Number of Calls	67^{th} Percentile	90^{th} Percentile	95^{th} Percentile	Average Error	Standard Deviation	Max Error	Min Error
NextNav_All Dense Urban Buildings	4859	57.1	102.4	154.0	57.5	64.9	1059.2	0.6
NextNav_All Urban Buildings	4238	62.8	141.1	196.1	69.5	99.9	4367.2	2.1
NextNav_All Suburban Buildings	3581	28.6	52.9	62.2	27.2	99.7	5854.2	0.4
NextNav_All Rural Buildings	820	28.4	44.9	60.3	70.3	1231.5	35255.9	1.5
Polaris_All Dense Urban Buildings	5372	116.7	400.1	569.3	150.3	193.3	1656.1	2.2
Polaris_All Urban Buildings	3874	198.4	447.8	729.9	203.0	225.9	3131.9	0.4
Polaris_All Suburban Buildings	3489	232.1	420.7	571.4	215.1	161.9	1089.1	8.4
Polaris_All Rural Buildings	726	575.7	3005.1	3072.3	845.6	961.3	5809.2	66.2
Qualcomm_All Dense Urban Bldgs	5145	155.8	267.5	328.1	136.4	94.7	722.5	0.5
Qualcomm_All Urban Buildings	4338	226.8	449.3	507.1	233.9	547.7	18236.7	1.6
Qualcomm_All Suburban Buildings	3716	75.1	204.8	295.7	92.0	173.6	4639.4	0.2
Qualcomm_All Rural Buildings	709	48.5	210.1	312.3	639.9	2999.2	27782.4	1.0

Table 1: CSRIC ground-based RF location technologiy test results

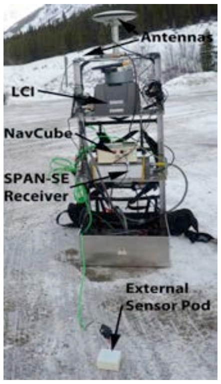
6.0 Self Contained Sensors and Examples

These are used either to aid replace GNSS. IMUs/Inertial navigation systems (INS) are the most commonly used for either and contemporary and emerging technologies are described in detail in this lecture series by Hopkins & Barbour (2013a). They can provide 3D navigation and orientation information about the platform on which they are mounted without external aiding, albeit with time dependent error growths; integration with GPS is common given the complementary nature of the two technologies. Other commonly used sensors, also discussed in (Hopkins et al 2013b, Raquet 2013) include magnetometers, barometers and, increasingly, vehicle or body mounted cameras. Magnetometers suffer from near field disturbances that can be corrected under certain conditions (Afzal 2011) but can otherwise provide absolute orientation, a much needed measurement when GNSS is degraded or not available and/or to mitigate gyro drifts in INS. Cameras can provide orientation changes under specific conditions. Other aiding sensors are described in (Mautz 2012).

Inertial sensors provide excellent short-term accuracy. In weak signal environments, the opposite is true for GNSS. The combination of both systems is therefore challenging for an estimation point of view. This is illustrated using the natural canyon example described earlier. During the test conducted in Winter 2013, a standard GPS unit (NovAtel OEM6) and Analog Devices Inc (ADI) IMUs integrated in the NavCube (Morrison et al 2012) fixed to a rigid aluminium backpack, were also used in addition to a u-blox HSGPS unit, as shown in Figure 6 (Dhital et al 2013). The ADI gyro and accelerometer specifications are shown in the figure. A 1-m accuracy reference trajectory was independently provided using a high grade NovAtel SPAN GNSS-INS system. All code, carrier phase and inertial sensor measurements were processed with software developed by the authors.

Figure 8 shows time series of the horizontal and vertical errors in the canyon for the forth and back runs. The static period at the far end of the canyon is under LOS and was omitted not to bias the canyon results. Three results are given for each graph, namely for the unaided u-blox HSGPS receiver (red), NovAtel OEM6 standard GPS receiver and combined u-blox-IMU solution (black). The first surprising result is the better accuracy values obtained with the standard NovAtel OEM6 (33 m RMS horizontal and 27 m vertical) as compared to those for the high sensitivity u-blox unit (40 and 63 m, respectively). Availability was about the same for both units and many multipath signals would have been used in both cases. Results based on the integration of the u-blox data with the ADI inertial sensors show both the advantages and challenges of integrated solutions under such environmental conditions. RMS accuracy improves to 17 m (horizontal) and 11 m (vertical), however maximum errors exceed 80 m. The solution is therefore not suitable for many applications where 100% availability and maximum error bounds are required. In such applications, especially those inside buildings where other signals are available (e.g. WiFi), GNSS will increasingly be abandoned in favour of a combination of such signals with user borne IMUs, magnetometers, barometers and cameras. One of the advantages of this approach is power saving on wireless devices. While WiFi and other such signals of opportunity may be available for certain first responder applications, they may not be available due to power outages and building damages in other applications. GNSS-IMU integration is also important to enhance reliability and counter jamming and spoofing. The u-blox-IMU results shown in Figure 9 were obtained with an adaptive variational Bayes (VB) approach in an attempt to detect outliers (Dhital et al 2013).

Another advantage of GNSS and inertial sensors mounted on humans is their activity classification. This is the subject of intense research and applications include first responders, soldiers, dangerous offenders and the monitoring of elderly people, as well as wellness and sport performance. As an example, Bancroft et al (2012) were able to detect 13 different human activities using such sensors; the paths leading from sensor measurements to each of these activities are shown in Figure 10.



	Parameter	ADIS16488	LCI
Gyroscopes	In-Run Bias Stability (1σ)	6.25 °/hr	<1.0 °/hr
	Angular Random Walk (1σ)	0.3 °/√hr	<0.15 °/√hr
	Rate Noise Density	23.8 °/hr/√Hz RMS	4 °/hr/√Hz RMS
Accelerom	In-Run Bias Stability (1σ)	0.1 mg	<1 mg
	Velocity Random Walk (1σ)	0.029 m/s/√hr	0.03 m/s/√hr
	Noise Density	0.067 mg/√Hz RMS	7.5e-5 mg/√Hz RMS

Figure 8: NavCube Integrated GPS-INS system used in natural canyon test and IMU specifications

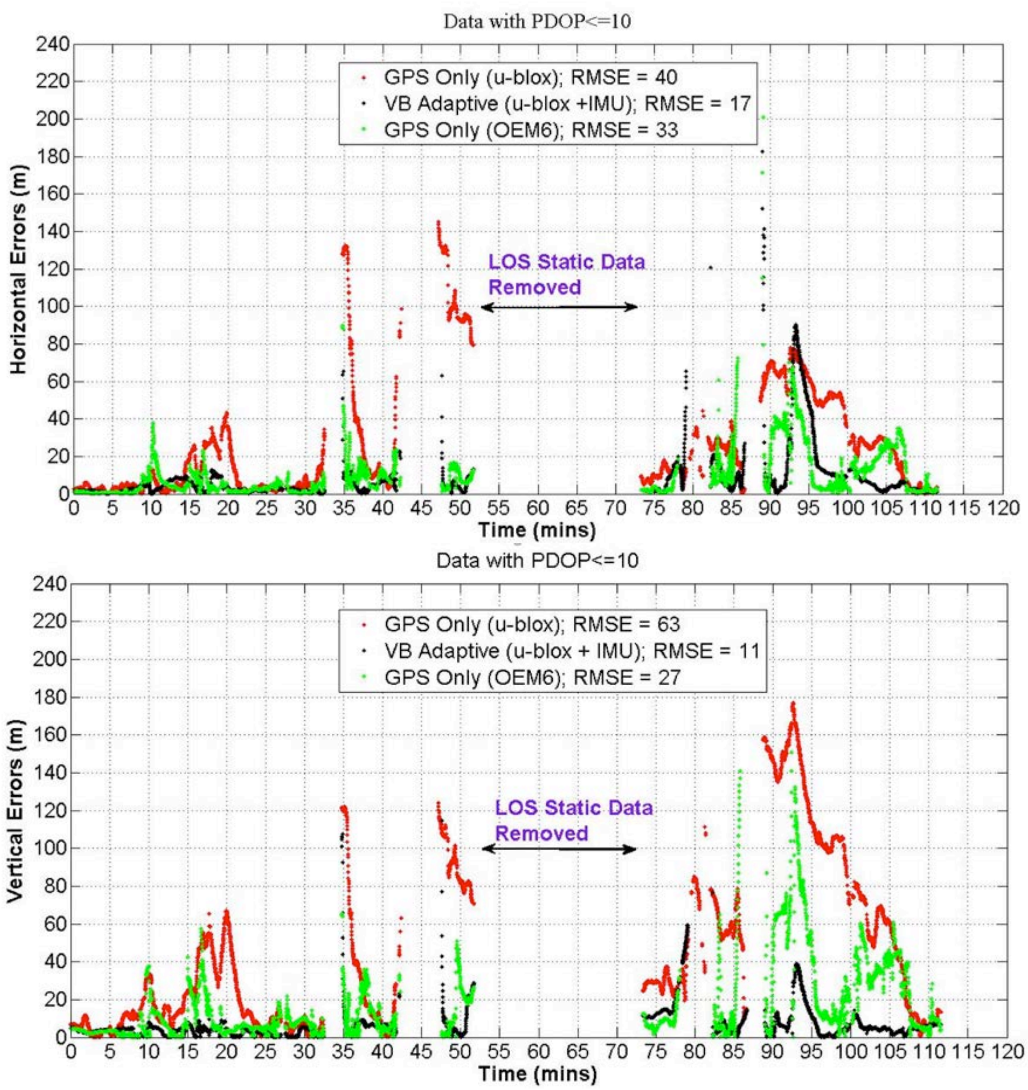


Figure 9: Natural canyon horizontal and vertical errors using GPS and GPS-INS

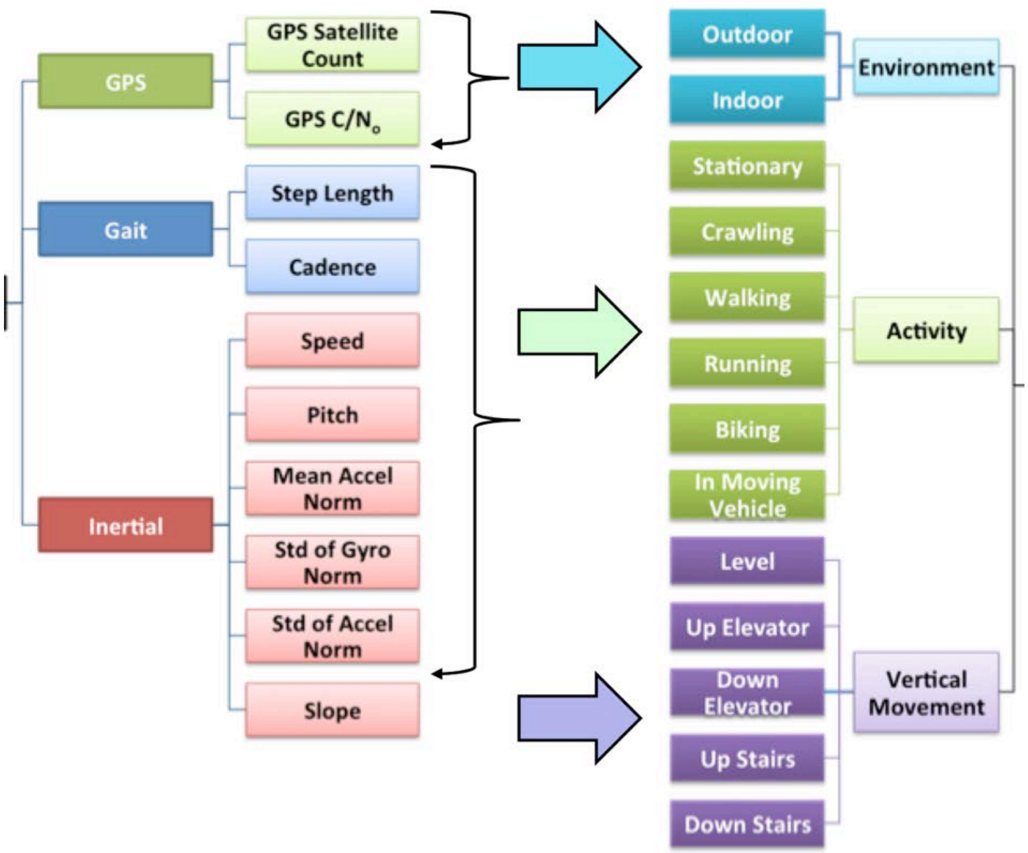


Figure 10: Human activity classification using GPS-Inertial sensors

7.0 CONCLUSIONS

Unaided High Sensitivity GNSS in weak and perturbed signal environments has progressed much during the past 15 years and delivers performance levels previously unthinkable; performance now appears to have reached a limit. Combination with self-contained sensors, especially inertial sensors, and estimation method enhancements are key to extending availability and enhancing accuracy and reliability. Challenges remain pertaining to the optimal combination of dissimilar measurements, namely noisy GNSS and accurate IMU measurements. For metre level accuracy inside buildings or other structures, GNSS use will likely be abandoned in favour of self-contained sensors, the more so given the rapid improvements taking place with the latters.

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Note: Most references are available on the Internet. Some are available on PLAN.geomatics.ucalgary.ca

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