GNSS/INS Integration in Vehicular Urban Navigation

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BIOGRAPHIES

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ABSTRACT

In critical locations as urban or mountainous areas satellite navigation is difficult, above all due to the signal blocking problem; for this reason satellite systems are often integrated with inertial sensors, owing to their complementary features. A common configuration includes GPS receiver and an high-precision inertial sensor, able to provide navigation information during GPS gaps.

Nowadays the low cost inertial sensors with small size and weight and poor accuracy are developing and their use as part of integrated navigation system in difficult environments is under investigation.

On the other hand the recent enhancement of GLONASS satellite system suggests the combined use with GPS in order to increase the satellite availability; this can be especially useful in places with lack of GPS signals.

This study purpose is to assess the effectiveness of the integration of GPS/GLONASS with low cost inertial sensors in vehicular urban navigation

The Extended Kalman filter is used to merge the satellite and inertial information and the loosely and tightly coupled architectures are the integration strategies adopted; their performances comparison in difficult areas is one of the main purpose. Generally the tight coupling is more used in urban or natural canyons because it can provide an integrated navigation solution also with less than four satellites (minimum number of satellites necessary for a GPS only positioning); the inclusion of GLONASS satellites in this context may change significantly the role of loosely coupling in urban navigation.

In this work pseudorange and Doppler measurements are processed in single point mode; hence no differential processing is performed and no base station is necessary.

INTRODUCTION

Urban environments are critical locations for navigation systems. For Global Navigation Satellite Systems (GNSS), buildings block many of the signals, thus reducing satellite availability and weakening observation geometry, with the extreme case being solution unavailability. Buildings can also reflect the signals causing multipath phenomenon which introduces the greatest measurement errors in these areas. For these reasons, standalone GNSS is not adequate to guarantee a continuous and accurate navigation in urban areas. Correspondingly, other sensors are often sought to integrate with GNSS data.

Inertial Navigation Systems (INS) are complementary with GNSS in many aspects; INS are more accurate in the short term, they can supply data with very high rate and they can also provide attitude information [11]. On the other hand GNSS is more accurate in the long term and the error is effective time invariant [16]. Consequently, the integration of GNSS/INS is very common for applications in which the GPS alone is not sufficient. In difficult environment like urban canyons, generally high-end INS can be used, but the great challenge is using low-cost inertial sensors, characterized by their low weight and size and with poorer performance. In these cases, integration with GNSS is critical and previous studies have focused specifically on the integration with GPS. However, the use of further satellites beyond the GPS constellation can permit a performance improvement. The Russian navigation satellite system GLONASS is currently the ideal candidate to support this thesis because it is nearly fully operational and its inclusion guarantees an enhancement in satellite availability. Previous work with integrating GPS and GLONASS has shown improvements with GNSS alone [17]. However, very little work has been done to look at the integration of GPS, GLONASS and INS. With this in mind, the main contribution of this work is an initial assessment of such systems. Although GLONASS is the focus of this work, the results can be extended to the integration with the European satellite system Galileo, once it is deployed.

Different integration strategies can be used to merge satellite and inertial information for navigation purposes [10-12]. Two common architectures considered in this work are loosely coupled (LC) and tightly coupled (TC) strategies. In the loosely coupled strategy position, and/or velocity from the GNSS receiver are used to aid the INS. Consequently, it is necessary to have a Least Squares (LS) estimator or a second Kalman filter (KF) to compute the GPS navigation parameters from the observables (loosely coupled strategy is also referred to as decentralized). It is evident that for implementing this architecture at least four visible satellites ─ preferably with a good observation geometry ─ are required. For this reason, this approach is not normally adopted in urban areas. However, inclusion of GLONASS satellites in this context may change significantly the role of loosely coupling in urban navigation.

In contrast to the LC case, the tightly coupled (or centralized) strategy is based on the use of only one Kalman Filter to process both INS and GNSS data. As is well known, it can be also be used when the number of visible satellites is insufficient to perform a GNSS-only fix and therefore it is often adopted in environments with bad visibility like mountainous or city areas [12].

Given the above, this work aims to assess the performance improvements obtained using additional GLONASS satellites (in addition to GPS satellites) with both loosely and tightly coupled architectures. Furthermore, the results obtained with the different integrations are compared and contrasted.

GPS/GLONASS OVERVIEW

GPS and GLONASS are the main GNSS systems in use today and they are similar in many aspects, but with some essential differences. Both systems are able to provide various number of air, marine, and any other type of users with all-weather three-dimensional positioning, velocity and timing, anywhere in the world or near-Earth space. Both navigation systems are based on the concept of "one-way ranging", in which the unknown user position is obtained measuring the time of flight of signals broadcasted by satellites at known positions and epochs [1-4].

The main difference between the two systems is that GPS and GLONASS operate with different time references and with different coordinates frames [6-8]. Specifically, GPS time is related with UTC(USNO), Coordinated Universal Time (UTC) as maintained at the United States Naval Observatory. In contrast, GLONASS time is related to UTC(SU), UTC as maintained by Russia. The offset between the two time references can be calibrated, but this information is not included in the navigation messages broadcasted by the satellites.

This causes an increase in the unknowns number from 4 to 5: three coordinates of user position and the biases of the receiver clock relative to the two system time scales (one bias can be replaced by the inter-systems time offset). The problem will be overcome with the new generation of GLONASS satellites (i.e., GLONASS-M), that are planned to broadcast the offset between the time scales. In addition, the GPS and GLONASS datum difference does not require an additional state to account, because WGS84 and PZ90 are known and fixed, and they are linked by a well-defined mathematical transformation (further details are in [9]). Other differences are related to the signal nature, namely different signal bandwidths and multiple access schemes.

LOW-COST INERTIAL SENSORS OVERVIEW

The great advances in Micro Electro-Mechanical Systems (MEMS) has made possible the development of a generation of low cost inertial sensors. MEMS IMU are characterized by small size, light weight and low cost with respect to high-end inertial sensors. These features make the MEMS sensors an attractive option for applications such as vehicular navigation.

However, MEMS sensors are characterized by poorer performance too, so they can not be used in autonomous mode for extended periods but they are well suited to integrated navigation systems (usually coupled with GPS systems). MEMS sensor performance is summarized in the Table 1 where also navigation and a tactical grade IMU performance are listed for a direct comparison.

Table 1– Summary of IMU Characteristics for Different Grades of Sensors (from [11-12])

Parameter	IMU Grade		
	Navigation	Tactical	MEMS
Accelerometers			
In Run Bias (mg)	0.025	1	2.5
Turn On Bias (mg)	-	-	30
Scale Factor (PPM)	100	300	10000
VRW (g/√Hz)	-	2.16e-06	370e-06
Gyros			
In Run Bias (°/h)	0.0022	1	<1040
Turn On Bias (°/h)	-	-	5400
Scale Factor (PPM)	5	150	10000
ARW (°/h/√Hz)	6.92	7.5	226.8
Approx. Cost	>$90000	>$20000	<$2000

The turn-on bias (or bias offset) is the inertial sensor bias that occurs when the sensor is turned on. It is constant during a single mission, has a deterministic nature and can be determined during a calibration procedure [12]. The in-run bias (or bias drift) is linked to the error accumulation during the mission, it has random nature and must be modeled as a stochastic process [12]. The scale factor error is the ratio between the output signal of the sensor and the physical quantity to measure. In ideal conditions the scale factor should be unity [10]. This error has a deterministic nature but generally is modeled as a random process. The ARW (angular random walk) parameter describes the average deviation or error that will occur from integrating the noise on gyro output signal [14]. Similarly VRW (velocity random walk) parameter definition is based on the same concept for the accelerometers.

The performance and the cost of an IMU strongly depends on the gyro quality [10]. From Table 1 we can see that the turn on bias of MEMS gyro is about 5400 deg/h, while it is negligible in the navigation and tactical grade sensors. Also the in run bias can be 1040 deg/h in MEMS sensors, while is about 1 deg/h in a tactical grade gyro. These parameters provide a good assessment of MEMS performance with respect to higher grade sensors.

GNSS/INS INTEGRATION: IMPLEMENTATION

INS and GNSS system integration is very common, because the systems are complementary in many aspects. INS is more accurate in the short term, it can supply data with very high rate and it can also provide attitude information. On the other hand GNSS is more accurate in the long term and the error is effective time invariant. The following sections describe the two most common integration approaches.

Loosely Coupled Approach

The LC strategy is also referred to as “decentralized” and includes a KF to combine INS and GNSS parameters. Another KF or a LS estimator is used to compute the GNSS navigation solution. The LC scheme is showed in Figure 1.

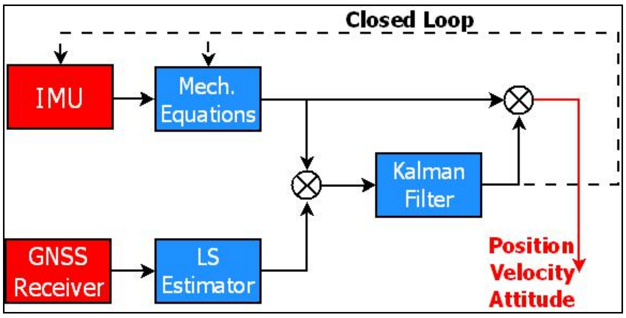

Figure 1 – Loosely Coupled Scheme

In this work, the GNSS measurements are processed in single point mode, so no differential corrections are applied and the deployment of a reference station is unnecessary. Only pseudorange (PR) and Doppler observables are used. Doppler measurement is linked to the PR derivative by the formula (1):

$$PR_{dot} = D_1 * \lambda \tag{1}$$

with λ being the carrier wavelength (meters), D_l being the Doppler measurement (Hertz) and PR_{dot} being the pseudorange rate (meters/seconds).

To compute the GNSS fix, a LS estimator is preferred herein to simplify a direct LC/TC comparison. To account for the fact that satellite measurements at low elevation angles are generally noisier [3], the measurements are weighted by a sin(el) factor, with “el” being the satellite elevation angle [11]. To consider also the different accuracy related to the PR and Doppler observables, the weight (reciprocal of variance) associated to the generic measurement is expressed by

$$w_{ii} = \sin\left(el\right) / \sigma_m^2 \tag{2}$$

where σ^2_m is the pseudorange variance σ^2_{PR} or the pseudorange derivative variance σ^2_{PRdot}.

The GNSS solution is obtained using the WLS (weighted LS) method, whose equation is:

$$\mathbf{\Delta x} = \left(H^T W H\right)^{-1} H^T W \mathbf{\Delta \rho} \tag{3}$$

with ***Δρ*** being the vector of measurements compensated by a priori information, H being the geometry matrix, ***Δx*** begin the unknown vector of corrections from a priori to updated state, and W being the diagonal weighting matrix whose elements w_{ii} are from formula (2).

The inertial solution is obtain applying the mechanization equations for a strapdown configuration to the accelerations and angular rates from the IMU. For this work, the INS mechanization is implemented in the local East-North-Up (ENU) frame.

The difference between INS and GNSS solutions are used as input measurements to the KF. The WLS covariance matrix is used as measurements covariance matrix R (formula (4)):

$$R = \mathrm{cov}\left(\Delta\mathbf{x}\right) = \left(H^T W H\right)^{-1} \qquad (4)$$

The LC KF state vector is:

$$\boldsymbol{\delta}\mathbf{x} = \left[\boldsymbol{\delta}\mathbf{P} \quad \boldsymbol{\delta}\mathbf{V} \quad \mathbf{E} \quad \boldsymbol{\delta}\mathbf{b}_a \quad \boldsymbol{\delta}\mathbf{b}_g\right]^T \qquad (5)$$

with ***δP*** the position error vector, ***δV*** the velocity error vector, ***E*** the attitude error vector, $\boldsymbol{\delta b_a}$ the accelerometer bias error vector, and $\boldsymbol{\delta b_g}$ the gyro bias error vector. The bias error vectors $\boldsymbol{\delta b_a}$, $\boldsymbol{\delta b_g}$ are modeled as 1st order Gauss-Markov processes and include both “in-run” and “turn-on” biases.

Tightly Coupled Approach

The TC strategy is also referred to as “centralized”, because there is only a central KF processing GNSS observations and INS data. The TC scheme is showed in Figure 2.

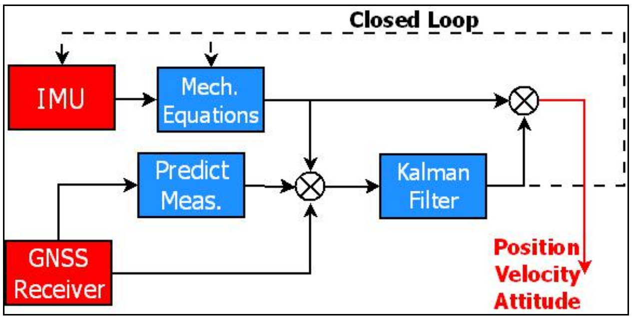

Figure 2 – Tightly Coupled Scheme

The difference between PR and Doppler observables and predicted range and Doppler (computed using INS position and velocity) is used as input measurements to KF. The associated measurements covariance matrix is defined taking into account the inherent accuracies of GNSS measurements and the elevation-dependent accuracy as in the LC case.

The TC KF state vector has the same 15 INS stases as LC (formula (5)), augmented with GPS receiver clock bias and drift. If GLONASS system is included, a further state (the GPS-GLONASS inter-systems time offset) must be considered and in this work it is modeled as a random constant stochastic process.

Both loose and tight strategies are herein implemented in closed loop configuration meaning the navigation and bias error states output from the KF are used to correct INS inputs. The closed loop configuration is necessary when low performance INS is used to reduce the inertial error growth [10,12], which in turn, satisfies the small angle assumptions used to derive the INS error equations.

TEST DESCRIPTION AND EQUIPMENT

The data collection was carried out in a vehicle in downtown Calgary, Canada on 22nd July 2010 in the afternoon (about 2:00 pm local time). Downtown Calgary is a typical urban scenario, characterized by skyscrapers and so it is a difficult environment for satellite navigation because of blocking and multipath problems. The test started in a parking lot where the satellite visibility was good and the operational conditions can be considered semi-open sky (4-10 visible GPS satellites). The second part of the test was held in a demanding urban canyon with poor satellite coverage (0-6 available GPS satellites). The test trajectory and the visibility during the path are shown in Figure 3 and Figure 4.

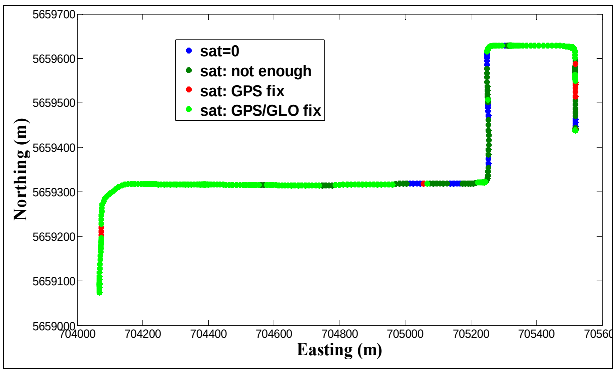

Figure 3 – Test Trajectory

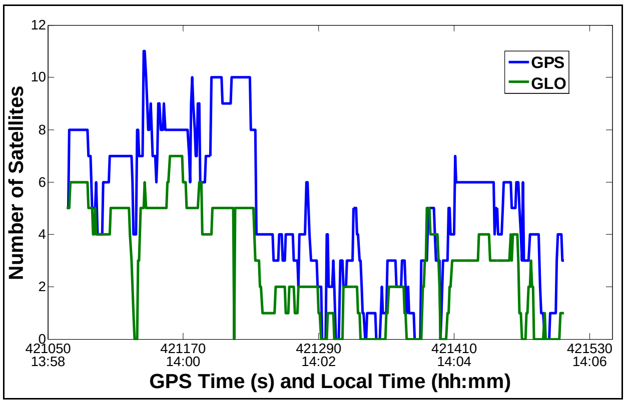

Figure 4 – Satellite Visibility

The test equipment consists of a satellite receiver and a MEMS IMU to perform the experiment and more accurate devices as reference. Specifically, the NovAtel Receiver ProPak V3 — able to receive GPS and GLONASS satellite signals — and a Crista IMU from Cloud Cap Technology are used to test the different configurations.

The reference solution is obtained using the NovAtel SPAN (Synchronized Position Attitude Navigation), an integrated system consisting of the OEM4 NovAtel receiver and the HG1700 tactical grade IMU. The SPAN data are processed by NovAtel's Inertial Explorer software using phase and Doppler measurements in double difference mode. The baseline separation (relative to a base station located on the University of Calgary campus) varied between 6-7 km. The reference solution used the tight strategy. The reference solution accuracy in these conditions is summarized in Table 2.

Table 2 – Reference Solution Accuracy

Reference Accuracy	
Position	dm level
Velocity	cm/s level
Attitude	<1deg

All the equipment was placed on the roof of the car as showed in Figure 5.

Figure 5 – Equipment

RESULTS AND ANALYSIS

As mentioned before, the purpose of this work is to compare the performance of GPS and GPS/GLONASS integrated with low cost INS with particular focus on assessing the benefits of including GLONASS. Both loose and tight integration strategies are tested to determine if the type of integration plays a significant role.

To this purpose, four processing configurations are considered: GPS/INS in loose integration (GPS/INS LC) and in tight integration (GPS/INS TC), and GPS-GLONASS/INS in loose and tight mode (respectively indicated as GG/INS LC and GG/INS TC).

Good Visibility Testing

The first part of the test is marked by a good satellite visibility and the results of the four configurations are very similar as showed below [Figures 6 and Table 3 about position error, Figure 7 and Table 4 about velocity error, Figure 8 and Table 5 about attitude error].

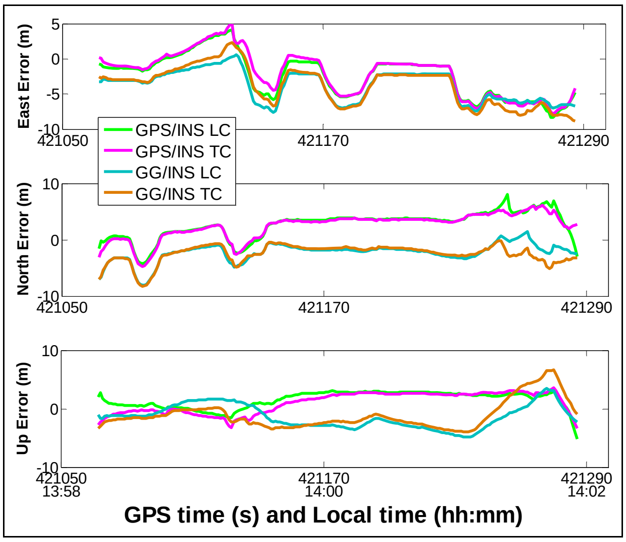

Figure 6 – Position Error Behavior in Good Visibility Condition

Table 3 – RMS and Maximum Position Errors in Good Visibility Condition

Solution	RMS Error (m)			Max Error (m)		
	East	North	Up	East	North	Up
GPS/INS LC	3.8	3.5	2.1	8.3	8.0	5.1
GPS/INS TC	3.7	3.3	2.0	7.8	6.0	3.5
GG/INS LC	4.4	2.8	2.4	7.5	8.0	4.8
GG/INS TC	4.6	2.9	2.6	8.8	8.2	6.4

In good visibility condition GPS/INS LC and TC configurations yield similar position results. The inclusion of GLONASS marginally worsens the position errors because of the inherent system accuracy (Figure 6 and Table 3). In this condition all the considered configurations yield almost imperceptible velocity differences (Figure 7); only the GLONASS inclusion provides a slightly improvement (Table 4). These results are expected since, in good satellite visibility conditions, GNSS/INS solutions are dominated by the GNSS solution with the inertial sensors largely playing the role of an interpolator.

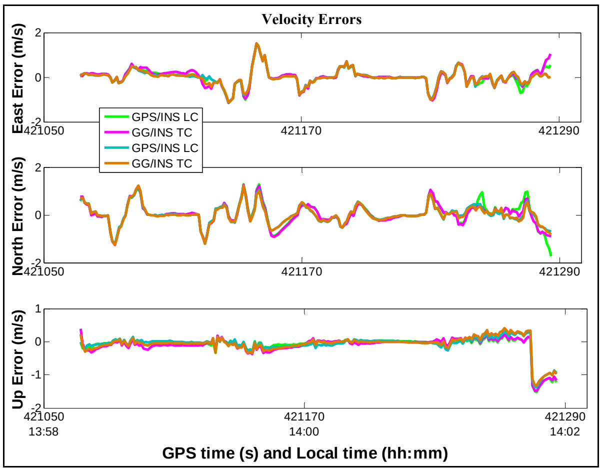

Figure 7 – Velocity Errors Behavior in Good Visibility Condition

Table 4 – RMS and Maximum Velocity Errors in Good Visibility Condition

Solution	RMS Error (m/s)			Max Error (m/s)		
	East	North	Up	East	North	Up
GPS/INS LC	0.37	0.47	0.30	1.4	1.7	1.5
GPS/INS TC	0.38	0.44	0.31	1.5	1.2	1.4
GG/INS LC	0.34	0.39	0.28	1.5	1.2	1.3
GG/INS TC	0.34	0.39	0.28	1.5	1.2	1.3

Regarding the attitude error assessment, only slight differences can be noticed among the considered configurations (Figure 8 and Table 5). In this case, the inclusion of GLONASS reduces the maximum azimuth error (Table 5) but does not significantly improve the RMS error.

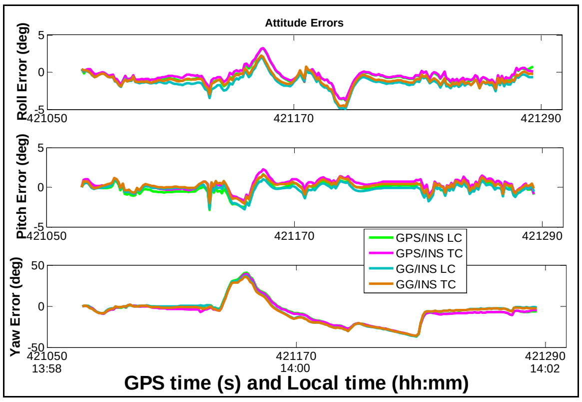

Figure 8 – Attitude Error Behavior in Good Visibility Condition

Table 5 – RMS and Maximum Attitude Error in Good Visibility Condition

Solution	RMS Error (deg)			Max Error (deg)		
	Roll	Pitch	Yaw	Roll	Pitch	Yaw
GPS/INS LC	1.1	0.7	16.4	3.7	2.8	40.8
GPS/INS TC	1.0	0.7	16.3	3.7	2.2	39.3
GG/INS LC	1.6	0.6	16.3	4.9	2.8	37.1
GG/INS TC	1.4	0.6	16.0	4.6	2.0	36.3

Poor Visibility Testing

The second part of the test is marked by poor satellite coverage due to obstructions from buildings and the differences between the four configurations become more meaningful.

The GPS/INS position results in both LC and TC modes are not satisfying; as can be noticed in Figure 9 and Table 6. The GPS/INS LC solution has a great drift in the East component and GPS/INS TC has a great error in the North component. Inclusion of GLONASS indeed provides great improvements in the position solution.

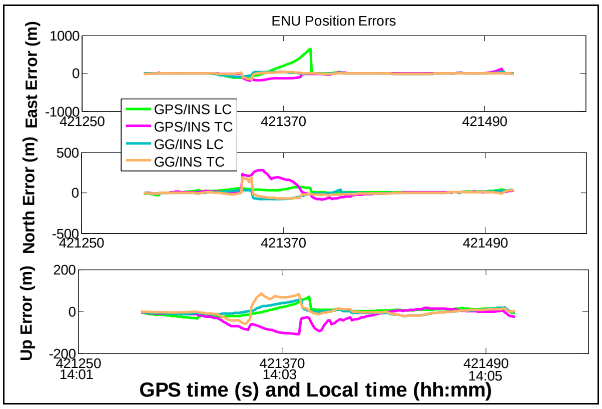

Figure 9 – Position Error Behavior in Poor Visibility Condition

Table 6 –RMS and Maximum Position Errors in Poor Visibility Condition

Solution	RMS Error (m)			Max Error (m)		
	East	North	Up	East	North	Up
GPS/INS LC	119.8	27.3	18.5	648.7	72.5	69.7
GPS/INS TC	61.0	84.3	45.5	192.8	280.1	110.2
GG/INS LC	27.1	29.1	16.3	99.7	79.7	57.4
GG/INS TC	25.5	37.7	28.9	161.2	195.6	84.1

The GG/INS TC contains noticeably greater maximum errors on all the components with respect to LC solution. This phenomenon is caused by the presence of blunders, due to measurements strongly affected by multipath, as is typical of urban canyons. The presence of blunders is clearly showed in Figure 10, where the maximum value of the innovation vector for each epoch is plotted versus time. It is notable that during the first part of the test with good satellite coverage the innovation vector is small, while great peaks are present during the second part of the test.

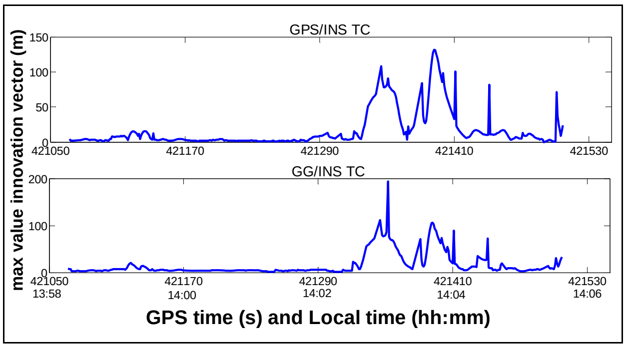

Figure 10 – Maximum Value of Innovation Vector as function of Time for Tight Integration Solution

LC configuration is less sensitive to these blunders, because blunders are present above all in severe urban canyon, where the number of available measurements is often less than 4 and thus not usable in LC.

The same limits appear to affect GPS/INS velocity solutions (both LC and TC), and blunder effects look more evident in GG/INS TC solution than in GG/INS LC (Figure 11 and Table 7).

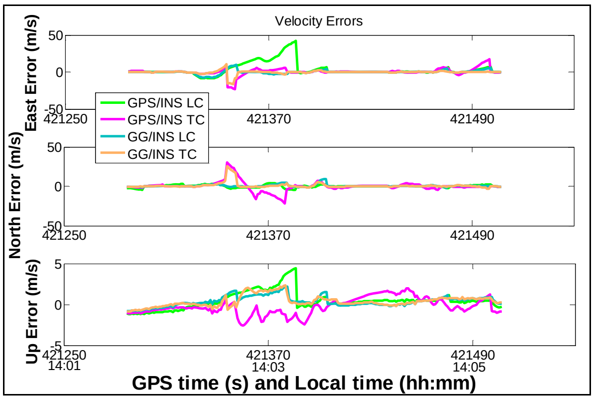

Figure 11 – Velocity Error Behavior in Poor Visibility Condition

Table 7 –RMS and Maximum Velocity Errors in Poor Visibility Condition

Solution	RMS Error (m/s)			Max Error (m/s)		
	East	North	Up	East	North	Up
GPS/INS LC	9.7	1.7	1.1	41.7	4.6	4.4
GPS/INS TC	4.6	6.2	1.0	22.7	30.3	2.5
GG/INS LC	2.5	1.7	0.7	9.5	9.6	2.2
GG/INS TC	2.6	3.6	0.7	16.6	25.6	2.3

The attitude error analysis confirms the benefits of using GLONASS with GPS, but in this case the GG/INS TC configuration provides a smaller maximum azimuth error (Figure 12 and Table 8).

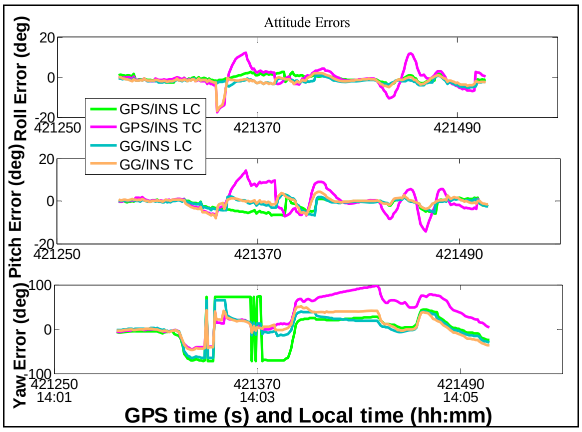

Figure 12 – Attitude Error Behavior in Poor Visibility Condition

Table 8 – RMS and Maximum Attitude Errors in Poor Visibility Condition

Solution	RMS Error (deg)			Max Error (deg)		
	Roll	Pitch	Yaw	Roll	Pitch	Yaw
GPS/INS LC	1.7	2.8	41.2	4.7	6.8	74.0
GPS/INS TC	4.7	5.1	50.7	17.6	14.3	97.6
GG/INS LC	2.3	2.0	27.8	5.3	6.6	65.4
GG/INS TC	2.9	2.1	26.7	16.7	8.1	51.1

CONCLUSIONS

This work looks at the integration between GNSS systems and MEMS-INS sensors to improve the navigation performance especially in difficult scenarios as urban canyons.

In good visibility condition the simple GPS/INS integration provide satisfying results, but in critical environment it is not sufficient to provide good performance. The inclusion of GLONASS measurements yields great improvements of the integrated solution in urban areas, allowing an accuracy of about 20 meters in position, about 2 m/s in velocity, about 2-3 degrees in roll/pitch angles and about 25 degrees in azimuth.

For the used data, GPS/GLONASS/INS solutions are similar for loose and tight integration cases; tight solution suffers more of the blunders issue and so the best results in this test are obtained in the GPS/GLONASS/INS loose coupling configuration.

FUTURE WORK

The future developments of this work will focus on the inclusion of blunder detection and exclusion in the navigation software, in order to avoid the accuracy loss that affects performance in critical areas.

Another way to improve the system performance can be the further augmentation of the INS states, considering also the scale factor terms. This should reduce the errors during GPS/GLONASS outages in loose integration and should yield an improvement in all the tight solutions.

Finally, further tests and analysis are planned.

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