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The integration of time-based single frequency double differencing carrier phasegps / micro-electro-mechanical system-based INS

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ABSTRACT

The integration of Global Positioning System (GPS)/Inertial Navigation System (INS) is used to overcome the limitations of the two systems providing integrated system better than either on a stand-alone basis. Previous research shows that the integration of stand-alone code GPS/Micro-Electro-Mechanical System (MEMS) based INS has a negative effect on the Inertial Measurement Unite (IMU)gyro measurements and may not add any improvements to the quality of individual GPS solution.Time based single frequency double differences carrier phase (TL1DD) is an accurate velocity estimation and relative positioning method based on L1 stand-alone carrier phase GPS observables. In this paper, the integration of TL1DD/MEMS-INS has been evaluated comparing to simultaneous precise navigation solution. The results show that a precise, high frequency, and reliable low-cost relative navigation solution can be obtained in open-sky areas, which can be used for a wide range of relative positioning engineering applications. The results show also and the high ability of the suggested technique to deal with cycle slips and its limitation in GPS-off areas.

key words: L1GPS, MEMS- INS, Double differencing, IMU, Kalman Filter

Introduction

GPS provides a method for directly obtaining instantaneous position and velocity estimates using satellites based passive range measurements. GPS is a whole day, all-weather, and passive system. The GPS pseudo-range between receiver and satellite is obtained by matching the satellite code with the internal code generated by the receiver and scaling the time difference by the speed of light. Pseudo-range GPS code observables can provide absolute stand-alone positioning with accuracy of a few meters which may not suitable for a wide range of engineering applications, such as mapping, cadastral surveying, geodetic control, and strictures deformation. This is attributable to the pseudo-range error sources, such as satellite errors (clock and orbit), propagation errors (ionosphere, troposphere, and multipath), and receiver errors (clock, measurements noise, and phase center variation) [1].

The carrier phase observation is formed by stripping the code from the received signal. Carrier phase observation can be measured to the level of 0.01 cycles giving millimeters accuracy. Just the fractional phase with the accumulated integer number of wavelengths can be measured by the receiver as the connection between the satellite and receiver is available. As for the initial total number of integer wavelengths, it is unknown which makes the absolute standalone one epoch based positioning impossible for carrier observations. This initial unknown number is known as the integer ambiguity.

Differencing GPS (DGPS) observations can be used for solving this problem providing precise relative positioning. Relative positioning aims at determining the coordinates of an unknown point with respect to a known point or determining the vector between the two points (baseline) and this requires simultaneous observations at the two points. With DGPS, some of GPS errors are reduced or removed based on the high correlation between these errors over short baselines. Differencing observations can be formed using code or carrier phase measurements taking one of the following forms: single, double and triple differences. Single differences can be formed between two receivers, two satellites, or two epochs. Double differences are formed between any two single differences, whereas triple differences are between the three forms of single differences, including two receivers, two satellites, and two epochs [2].
TL1DDis one of the differencing observations forms including two single differences between two

satellites and two epochs with one receiver. In this double differences technique, single frequency carrier phase observables measured by the same receiver are firstly differenced cross epochs and secondly cross satellites. These two differences lead the ambiguity to be removed as long as the connection between the satellite and receiver is continues. Furthermore, receiver clock error is removed, satellite clock error is reduced based on the stability of the satellite clock over transmission times, satellite orbit errors are reduced, ionospheric and tropospheric delays are reduced to the change across the interval, multipath remains and can be reduced based on the multipath correlation over time, and receiver measurements noise is increased. TL1DD is considered as an accurate velocity estimation method based on single frequency stand-alone GPS observables. Precise GPS relative positioning can then be achieved by integrating the velocity over epoch [3] [4] [5].

Strap-down inertial navigation is a dead reckoning form of navigation. This means that navigation is achieved by measuring direction and displacement from an initial point and orientation. This is achieved through measuring acceleration and turn rates in three orthogonal directions with accelerometers and gyros. The sensor assembly of accelerometers and gyros is termed an (IMU).INS is a navigation aid system that uses a computer, IMU which includes motion and rotation sensors to continuously calculate position, orientation, and velocity relative to a known starting point. The basic idea behind INS is to integrate acceleration and rotation measurements into relative speed of movement and direction of a moving object without the need for external references. Modern IMUs consist of three orthogonally mounted gyroscopes and accelerometers, measuring angular velocity and linear acceleration, respectively. Three magnetometers tend to be added to this system for bounding the significant drift of low-cost gyroscope with time [6].

The accuracy of INS depends mainly on the initial state accuracy, inertial sensor quality, such as accelerometers and gyros, stability and reliability of inertial sensors, and the correction models used. INS is a self-contained navigation passive, worldwide, and easy to operate and independent system. In addition, INS can be used in all weather and attitude. However, INS should be provided with initial position and rotations for achieving absolute orientation and when it has been initialized, no more help is needed for navigation. INS has become a necessary request in a great deal of application, such as the aircraft navigation, submarines and ships, tactical and strategic missiles and space craft[6] [7].

INS suffers from different type of errors, some of them can be bounded, such as those of acceleration, velocity and initial tilt, and others hard to be bounded including azimuth misalign, leveling gyro drift and azimuth gyro drift. Small errors in the acceleration and angular velocity measurement are cumulated with time to be great errors in position where each position is calculated from the previous calculated position. Therefore, the position must be regularly updated from another navigation system and the updating level depends on the quality of the sensors used and the accuracy required from the system [7].

Current developments in the MEMS construction of devices lead to manufacturing undersized and light IMUs. This has helped to open the doors for MEMS-INS to be used in more applications, such as human and animal motion capture. MEMS gyros use the "Coriolis" theorem in order to measure rotation rate. Low cost inertial sensors contain a vibrating silicon MEMS structure. When the gyro is rotated, this results in a "Coriolis" acceleration perpendicular to the input axis and proportional to the input rotation. The "deection" can be measured to derive the angular rate measurement. The advantage of this type of sensor is that it contains no rotating parts. Consequently, the sensor can be miniaturized and batch fabricated using micro-machining techniques resulting in a sensor that is small and low power. MEMS accelerometers consist of a proof mass that is suspended by compliant beams. The "deection" of the proof mass is measured under acceleration either by measuring the displacement of the proof mass (open loop), or more typically by measuring the force required to maintain its position (closed loop). This again results in a sensor with no moving parts that can be miniaturized and batch fabricated. The IMU used in this paper is Crossbow AHRS-DMU-HDX with size of (7.62, 9.5, 10.4) cm, gyro bias <3600º/h, and accelerometer silicon bias < 30mg. The inertial sensor errors of the Crossbow IMU mean that navigation errors can reach kilometers in minutes. Consequently, standalone navigation for long periods of time is not possible with such sensor technology [5] [8] [9].

MEMS-INS has become commonly used due to the significant low-cost, tiny size and the spinning-wheel less. As a result, noise, inertial forces and mechanical failures can be avoided. MEMS based gyros have many advantages over conventional gyros, such as power independent memory, very low power consumption, not including bearings, lubricants or fluid, very short start up time, and very rugged and reliable. On the other hand, they are very sensitive to temperature changes, analogue output requires sampling, high gyro drift rates (20 to 30 degrees/hour), and not accurate enough for higher performance applications [5].

The integration of GPS/INS can help to overcome the limitations of the two systems providing integrated system better than either on a stand-alone basis. For example, INS position error drifts with time, whereas GPS solution is time independent. Also, INS outputs are relatively high frequency, whereas GPS solution is low frequency. INS is totally self-contained and autonomous operation, while GPS is dependent on the availability of satellites. Attitude capability is limited in the case of GPS comparing to INS which can provide accurate and high rate attitude data. The need of initialization is another limitation of INS where it just provides relative positioning and rotations. This is not the case with GPS which can self-initialize in flight. In the integrated system, INS aids GPS to reduce susceptibility to jamming, sensitivity to vehicle "manoeuvres", velocity errors and satellite acquisition and reacquisition times. On the other hand, GPS helps INS to reduce propagation of errors with time and to provide initial positioning and rotating. This integration can be carried out in one of three main integration levels, namely: Un-Coupled (UC), Loosely Coupled (LC), and tightly coupled [6] [7] [8].

UC integration is the simplest level of integration as the INS indicated position and velocity are reset at regular intervals of time using the position and velocity estimated by GPS. This method engages minimum changes to both systems and it does not help to enhance the performance and avoid jamming. Also, when GPS is hidden, the quality of positioning solution decreases rapidly.

LC integration is the typical integration of stand-alone INS and GPS. In this integration level, GPS is run autonomously and, at the same time, INS/GPS integrated solution is enabled. The estimated position and velocity, provided by INS and GPS, are compared and the differences are inputted to the estimation filter. The advantage of this approach comes from its redundancy where two navigation solutions are provided: that of stand-alone GPS and the other of GPS/INS integration. This integration approach can be used with any INS and GPS receiver if the necessary number of GPS satellites is available. Also, loosely integration has high flexibility and modularity as well as less computation and complexity due to the independent operation. When GPS is hidden or less than the necessary number of satellites are available, the INS stand-alone solution based on Kalman Filter (KF) is used to fill in the gap which will drift with time depending on the stability of the accelerometers and gyros used [8].

The integration of GPS/INS sensors with different levels of quality has been widely investigated to reduce the high cost of the system. Previous investigations has included the integration of dual frequency GPS/low-cost INS, and the integration of low-cost GPS/tactical grid INS. Recently, the integration of low-cost GPS/INS sensors has started to be studied and investigated to know the advantages and limitations of such integration level and find out whether it can be used in engineering applications. The results of these investigations, in general, show that the integration of low-cost GPS/INS sensors has a negative effect on the precision of the gyro measurements and may not add any improvements to the quality of individual GPS solution [8].

In this paper, the integration of TL1DD/MEMS-IN Susing KF will be investigated with two integration levels, namely UC and LC. TL1DD and MEMS-INS are error cumulative with time, but with different cumulating rates. Theoretically, TL1DD is more precise than MEMS-INS, especially when dealing with high vibration levels. Based on that, TL1DD will be used to enhance the performance of MEMS-INS over time, and as the same time, the last will be used to fill in the gaps when losing GPS solution or dealing with unfiltered cycle slips. Integration system of High quality 50Hz DGPS/tactical grid INS will be used to evaluate the results of the suggested system. Tests in different GPS environments will be carried out in this paper for reliable investigations and the results will be discussed in details showing the advantages and limitations of the suggested integration technique.

The Integration Mathematical Description

TL1DDNavigation Solution

The GPS carrier phase observable in meters can be written as [4] [5]:

$$CP_{(s,r)(k)} = p_{(s,r)(k)} + c(dT_{(s)(k)} - dt_{(r)(k)}) + dion_{(s,r)(k)} + dtrop_{(s,r)(k)} + dor_{(s)(k)} + E_{(s,r)(k)} + L*N \ldots (1)$$

where,

$CP_{(s,r)(k)}$:the carrier phase observation (m)
$p_{(s,r)(k)}$: the true range between receiver *(r)* and satellite *(s)* at epoch *(k)*
c : the speed of light
$dT_{(s)(k)}$: the clock error of satellite *(s)* at epoch *(k)*
$dt_{(r)(k)}$: the clock error of receiver*(r)* at epoch*(k)*
$dion_{(s,r)(k)}$: the ionospheric delay error between receiver *(r)* and satellite *(s)* at epoch *(k)*
$dtrop_{(s,r)(k)}$: the tropospheric delay error between receiver *(r)* and satellite *(s)* at epoch *(k)*
$dor_{(s)(k)}$: the orbit error of satellite *(s)* at epoch *(k)* (m)
$E_{(s,r)(k)}$: the measurement noise including multipath between receiver *(r)* and satellite *(s)* at epoch *(k)*
L : the carrier wavelength (m)
N : the unknown integer ambiguity (cycle)

The true range between receiver *(r)* and satellite *(s)* at epoch *(k)* can be written as:

$$p_{(s,r)(k)} = ((X_{(s)} - X_{(r)})^2 + ((Y_{(s)} - Y_{(r)}) + ((Z_{(s)} - Z_{(r)}))^{0.5} \quad \ldots (2)$$

where,

X, Y and Z : the satellite and receiver Cartesian coordinates.

In TL1DD, the first single differencing is formed between one receiver (r), one satellite $(s)$and two adjacent epochs $((k)$ & $(k+1))$. The single differencing equation can be written as:

$$SD_{(s)(r)(k+1,k)} = CP_{(s,r)(k+1)} - CP_{(s,r)(k)} \ldots (3)$$

$$SD_{(s)(r)(k+1,k)} = [\, p_{(s,r)(k+1)} + c(dT_{(s)(k+1)} - dt_{(r)(k+1)}) + dion_{(s,r)(k+1)} + dtrop_{(s,r)(k+1)} + dor_{(s)(k+1)} + E_{(s)(r)(k+1)} + LN] - [\, p_{(s,r)(k)} + c(dT_{(s)(k)} - dt_{(r)(k)}) + dion_{(s,r)(k)} + dtrop_{(s,r)(k)} + dor_{(s)(k)} + E_{(s)(r)(k)} + LN\,] \ldots (4)$$

Where,

$SD_{(s)(r)(k+1,k)}$: single differencing between receiver (r), satellite (s) and two adjacent epochs $((k)$ & $(k+1))$

From the single differences, the double difference ambiguity is removed as long as the integer ambiguity remains constant and the receiver keeps lock the satellite signal. Satellite clock error is reduced based on the stability of the satellite clock over transmission times. Satellite orbit errors are reduced significantly based on the high correlation between the satellite orbit errors over time. Ionosphere and troposphere errors are reduced to the change in delay across the interval. Multipath remains and can be reduced based on the multipath correlation over time. However, receiver clock error is doubled and receiver measurements noise increases. The final formula of single differences equation can be written as:

$$SD_{(s)(r)(k+1,k)} = p_{(s)(r)(k+1,k)} - c\, dt_{(r)(k+1,k)} + E_{(s)(r)(k+1,k)} \ldots (5)$$

The second differencing in TL1DD is carried out between two single differences, similar to that in equation (3), cross two satellites *(s)* and *(j)*. This can be written as:

$$DD_{(s,j)(r)(k+1,k)} = SD_{(s)(r)(k+1,k)} - SD_{(j)(r)(k+1,k)} = [\, p_{(s)(r)(k+1,k)} - c\, dt_{(r)(k+1,k)} + E_{(s)(r)(k+1,k)}\,] - [\, p_{(j)(r)(k+1,k)} - c\, dt_{(r)(k+1,k)} + E_{(j)(r)(k+1,k)}\,] \ldots (6)$$

Where,

$DD_{(s,j)(r)(k+1,k)}$: double differences between one receiver *(r)*, two epochs *(k+1)* & *(k)*, and two satellites *(s)* & *(j)*.

Receiver clock error is cancelled out in the double differences. This is extremely important for getting accurate results where the oscillators in low-cost receivers vary in frequency with temperature and pressure making the receiver clock unreliable [6]. The final formula of double differences equation can be written as:

$$DD_{(s,j)(r)(k+1,k)} = p_{(s,j)(r)(k+1,k)} + E_{(s,j)(r)(k+1,k)} \quad \ldots (6)$$

The only unknowns in this equation are the receiver Cartesian coordinates in the two epochs *(k)* & *(k+1)*.The changes in the receiver positions between the two epochs can be determined by fixing the coordinates of the receiver at epoch *(k)*(as zeros for example) and solving for the receiver coordinates at epoch (k+1).To determine the relative position of the receiver at epoch*(k + 1)*from*(k)*, the double differences equation should be written as [10] :

$$b = A\,X + v \quad \ldots (7)$$

Where,

b : the measurement victor with a size of (number of epochs -1, 1)

X : the parameter victor with a size of (number of epochs * 3, 1) which include the change in Cartesian position across the interval

A : matrix with a size of (number of epoch -1, number of epoch * 3) which relates the parameters to the states

v : a vector of random noise with a size of (number of epochs -1, 1)

This equation can then be solved using least squares method as following, where *w* is the weight matrix with a size of (number of epochs -1, number of epochs -1) which is based on the average satellite residuals obtained from the stand-alone code positioning calculations [10].

$$X = (A^T\,w\,A)^{-1} A^T\,w\,b \quad \ldots (8)$$

TL1DD Solution: Statistical Tests, Cycle Slips Detection & Fixing

As the GPS carrier phase measurements are a part of the integration solution, dealing with cycle slips is essential where the connection between satellite and receiver tends to be lost, especially in urban areas. In this case, a random integer number of cycles is added to the carrier phase measurements in the GPS data file. Cycle slips can be detected by comparing the differences between the code and carrier phase measurements of two adjacent epochs which is the method used in this paper.

Code positioning provides continuous solution as long as four satellites can be detected and it is not necessary for the same satellites to be detected for adjacent epochs, where code positioning in each moment is independent solution. When adequate number of satellites is available, the carrier measurement including cycle slip is removed for more precise solution. As the receiver clock error is removed with TL1DD, the minimum number of satellite required to get the relative positioning is 3 [5].

Based on that, if the number of free-cycle slips phase measurements is less than 3, pseudo-range measurements have to be used for fixing the gab in phase measurements to get the relative solution. With just 3 satellites or less, evaluating the quality of code measurements may not be easy as no solution can be obtained. In this case, the integration between TL1DD/MEMS-INS can be useful for fixing cycle slips, and INS measurements should be provided with bigger weights for more precise solution. Satellite residuals should be continually investigated to remove the outliers using Data Snooping Method.

Firstly, the covariance matrix of satellite residuals should be determined. Then, the square roots of the diagonal elements are extracted giving the standard deviation of each observation. The rate between the residual of each observation and its standard deviation should fluctuate between 0 and 3 depending on the required confidence level. With 99% confidence level chosen in this paper, the critical rate is nearly 2.6 so any value bigger than this is detected as an outlier with 1% probability of rejection the observation when it should be accepted (type 1 error) [10]. Figure (1) shows the steps followed for filtering TL1DDsolution and fixing cycle slips.

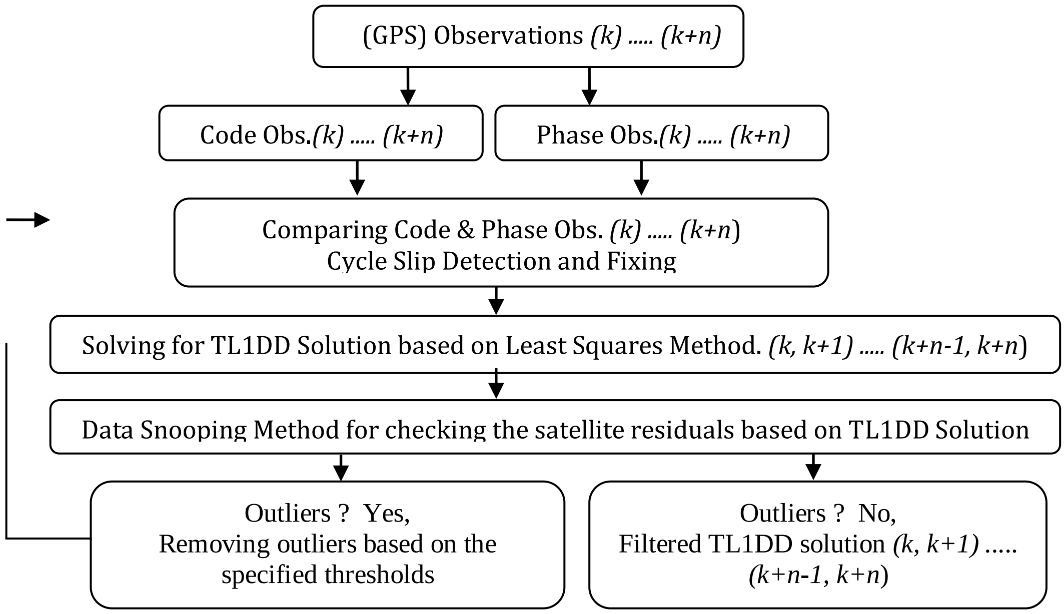

Figure 1: TL1DD solution: statistical tests, cycle slips detection & fixing

The Integration of TL1DD/MEMS-INS

Un-Coupled (UC) Integration

UC integration is the simplest level of integration as the INS indicated position and velocity are reset at regular intervals of time using the position and velocity estimated by TL1DD. This method engages minimum changes to both systems and it does not help to enhance the performance and avoid jamming. Also, when GPS is hidden, the quality of positioning solution decreases rapidly as the navigation solution will depend completely on the MEMS-INS solution. The UC navigation solution can be obtained using the following formulas:

$$X, Y, Z_{TL1DD(k+1)} = X, Y, Z_{TL1DD(k)} + \Delta X, Y, Z_{TL1DD(k,\, k+1)} \quad \ldots (9)$$

$$X, Y, Z_{IP(k+2)} = X, Y, Z_{TL1DD(k+1)} + \Delta X, Y, Z_{INS\,(k+1,\, k+2)} \quad \ldots (10)$$

Where,

$X, Y, Z_{TL1DD(k)}$: X, Y, Z coordinates of the GPS antenna initial position of at epoch *(k)* (equals zero in the case of relative positioning, and the absolute initial position for absolute navigation)

$X, Y, Z_{TL1DD(k+1)}$: X, Y, Z coordinates of the GPS antenna at epoch *(k+1)*

$\Delta X, \Delta Y, \Delta Z_{TL1DD(k,\, k+1)}$: TL1DD solution (the relative change in GPS antenna positions between epoch *(k)* and *(k+1)*

$X, Y, Z_{IP(k+2)}$: X, Y, Z components of the integrated navigation solution at epoch *(k+2)*

$\Delta X, \Delta Y, \Delta Z_{INS(k+1,\, k+2)}$: INS navigation solution (the relative change in the positions of IMU center between epoch *(k+1)* and *(k+2)*

Loosely Coupled (LC) Integration

LC integration is the typical integration of stand-alone GPS and INS. In this integration level, GPS is run autonomously and, at the same time, GPS/ INS integrated solution is enabled. The estimated position and velocity, provided by INS and GPS, are compared and the differences are inputted to the estimation filter. The advantage of this approach comes from its redundancy where two navigation solutions are provided: that of stand-alone GPS and the other of GPS/INS integration. This integration approach can be used with any INS and GPS receiver if the necessary number of GPS satellites is available. Also, loosely integration has high flexibility and modularity as well as less computation and complexity due to the independent operation.

When GPS is hidden or less than the necessary number of satellites are available, the INS stand-alone solution based on KF is used to fill in the gap, which will drift with time depending on the stability of the accelerometers and gyros used [6] [7].

KF filters measurements based on the expected changes of these measurements over timeand the statistical properties of the system measurement errors. The filter determines the minimum error estimate of the states based onthe linear relation between the measurements and these states. The states are composed of values that adequate to define the system motion [7].KF consists of measurement model and dynamic model which will be illustrated here to define the basic elements as related to the integration of TL1DD /MEMS-INS. As for the equations of propagation and update steps, they are well documented in different sources and there is no point for repeating here. The measurement model defines the mathematical linear relationship between the measurements and the filter states. The discrete measurement model at the epoch *(k)* can be defined as:

$$Z_{(k)} = H\,U_{(k)} + v_{(k)} \ldots (11)$$

where,

$Z_{(k)}$: the vector of measurements at epoch *(k)*

$U_{(k)}$: the system state vector at epoch *(k)*

H : the design matrix measurement which defines the linear relationship between the states and the measurements

$v_{(k)}$: the measurement residual vector

The dynamic model describes the change in the state vector parameters over time. The discrete dynamic model between epochs *(k+1)*&*(k)* can be given as:

$$U_{(k+1)} = M\,U_{(k)} + W_{(k)} \ldots (12)$$

where,

M : the state transition matrix that defines the relation between state vector parameters over time.

$W_{(k)}$: the system noise is approximated based on the sampling interval, the spectral density matrix and standard deviations of the driving noise of the system.

In the case of integrating TL1DD/MEMS-INS, the vector of measurements includes six observations; three observations from the relative or absolute positioning of epoch (*k+1*):

$$(X_{TL1DD(K+1)}, Y_{TL1DD(K+1)}, Z_{TL1DD\,(K+1)}) \ldots (13)$$

The three values describing the 3 dimensional changes in positioning between epochs *(k+1, k+2*)determined by MEMS-INS:

$$(\Delta X_{INS\,(K+1,\,K+2)}, \Delta Y_{INS\,(K+1,\,K+2)}, \Delta Z_{INS\,(K+1,\,K+2)}) \ldots (14)$$

As there are no unknowns, the $Z_{(k)}$ and $U_{(k)}$ are the same vector, H is a (6*6) unit matrix, and $v_{(k)}$ equals zero as illustrated in equations (15) & (16).

$$Z_{(k+1)}=U_{(k+1)}=|X_{TL1DD\,(K+1)}\ \ Y_{TL1DD\,(K+1)}\ \ Z_{TL1DD\,(K+1)}\ \Delta X_{INS\,(K+1,\,K+2)}\ \Delta Y_{INS\,(K+1,\,K+2)}\ \Delta Z_{INS\,(K+1,\,K+2)}|^{T} \ \ldots (15)$$

$$H=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \ldots (16)$$

As for the dynamic model, the system state vector at the epoch *(k+2)*includes three observations from the absolute code positioning for this epoch:

$$(X_{TL1DD\,(K+2)},\ Y_{TL1DD\,(K+2)},\ Z_{TL1DD\,(K+2)}) \ \ldots (17)$$

And the three values describing the 3D changes in positioning between this epoch and the previous epoch and the system state vector can be defined as can be described as:

$$(\Delta X_{INS\,(K+1,\,K+2)},\ \Delta Y_{INS\,(K+1,\,K+2)},\ \Delta Z_{INS\,(K+1,\,K+2)}) \ \ldots (18)$$

$$U_{(k+1)}=|X_{TL1DD\,(K+2)}\ \ Y_{TL1DD\,(K+2)}\ \ Z_{TL1DD\,(K+2)}\ \Delta X_{INS\,(K+1,\,K+2)},\ \Delta Y_{INS\,(K+1,\,K+2)},\ \Delta Z_{INS\,(K+1,\,K+2)}|^{T} \ \ldots (19)$$

The smoothed integrated positioning in epoch *(k+2)* can be defined as:

$$X,Y,Z_{IP(K+2)} = X,Y,Z_{\,TL1DD\,(K+2)} + \Delta X,Y,Z_{\,INS\,(K+1,\,K+2)} \ldots (20)$$

To relate the state vectors in epoch *(k+1)* with that in epoch *(k)*, the state transition matrix *(M)*takes the size of (6 *6) and can be written as:

$$M=\begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \ldots (21)$$

The standard deviations ofTL1DD measurements used in the system noise vector *W(k)*in the dynamic modelcan be computed using signal to noise ratio obtained directly from GPS receiver "RXMRAW" message. The standard deviation of TL1DD measurements rounds about millimeters in multipath-free environment and in the case of multipath environments, the quality of GPS carrier phase measurements reaches the quarter of GPS wavelength (5cm) as a maximum value [1]. As TL1DD technique depends on the differencing between epochs, the quality of measurements might be increased or decreased based on the correlation between the directions of the reflected signals. This means that the quality of the navigation solution might be within millimeters level, and can reaches nearly one decimeter in the worst cases. This is not the case with MEMS-INS measurements, where the precision level is nearly a few decimeters.LC integration of TL1DD/MEMS-INS is presented in the following workflow diagram, which has been implemented by the author in Matlab.

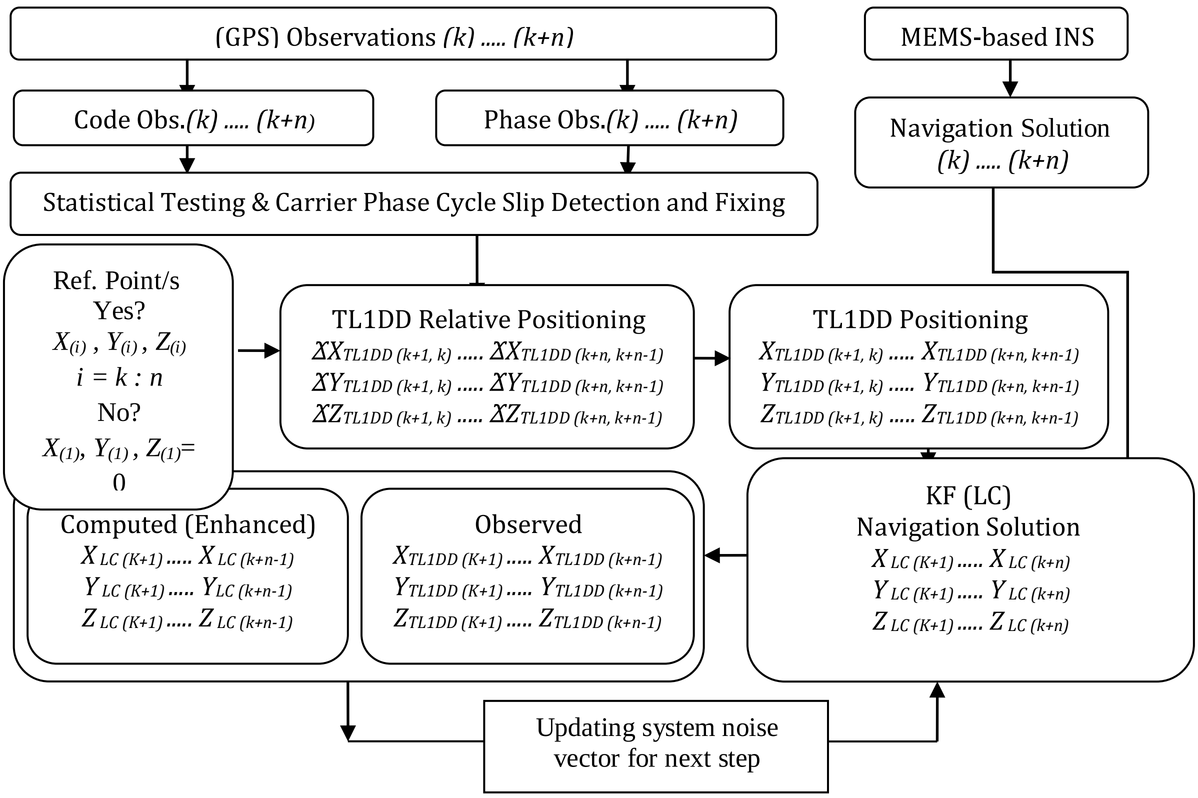

Figure 2. Workflow diagram of TL1DD/MEMS-INS LCintegration

As the two navigation techniques, integrated in this paper are relative, relative navigation solution can be obtained. If absolute positioning is required, at least one absolute 3D geo-referenced point should be available at any place throughout the trajectory and should be as accurate as possible, where the quality of the integration solution depends mainly on this point. Providing more than one accurate reference point through the trajectoryhelps on reducing TL1DD error cumulating, where each positioning solution is based on the previous one.

Tests, Results &Discussion

The integration of TL1DD/MEMS-INS has been tested in different GPS environments. Integration of Leica10Hzdual frequency GNSS receiver with 50Hz tactical grid INS has been used in the tests with Benghazi University reference base station as a reference for evaluating the suggested techniques. Using 10Hz dual frequency receiver gives also the ability to extract 1 Hz & 10Hz single frequency stand-alone code positioning, and as a consequence, TL1DD solution can be determined. The integration of DGPS/INS helps to evaluate the performance of TL1DD/MEMS-INS integration when GPS signals are relatively or completely obstructed. The receiver's antenna has been fixed on the top of car, and initial 3D displacements and rotations between the GPS antenna phase center and the two IMUs used in the test (GPS-IMU arms) have been determined using total-station. Data for nearly an hour has been collected in different GPS environments including open sky areas, limited GPS coverage with high multipath, and GPS signals hidden areas.

This variation in sites can help to investigate the effect of cycle slips and high multipath on the quality of the integrated solutions. Figure(3) shows parts of the test sites. Waypoint software has been used for processing the collected GPS raw data to provide mobile single point positioning (stand-alone code positioning) as well as DGPS/INS integration solution. TL1DD/MEMS-INS integration for UC&LC solutions has been implemented by the author in Matlab.

Figure 3:Parts of the test site (Up left: open-sky, up right: multipath environment, down left: partially open-sky, down right: nearly GPS signals hidden area)

Figures (4) , (5), & (6) illustrate 3D Root Mean Square Errors (RMSE) of LC and UC integration for TL1DD/MEMS-INS, in open-sky GPS, limited GPS coverage, and GPS signals hidden area, respectively, comparing to high quality 50Hz DGPS/INS navigation solution.It is important to note that the suggested technique is assumed to start from known point.

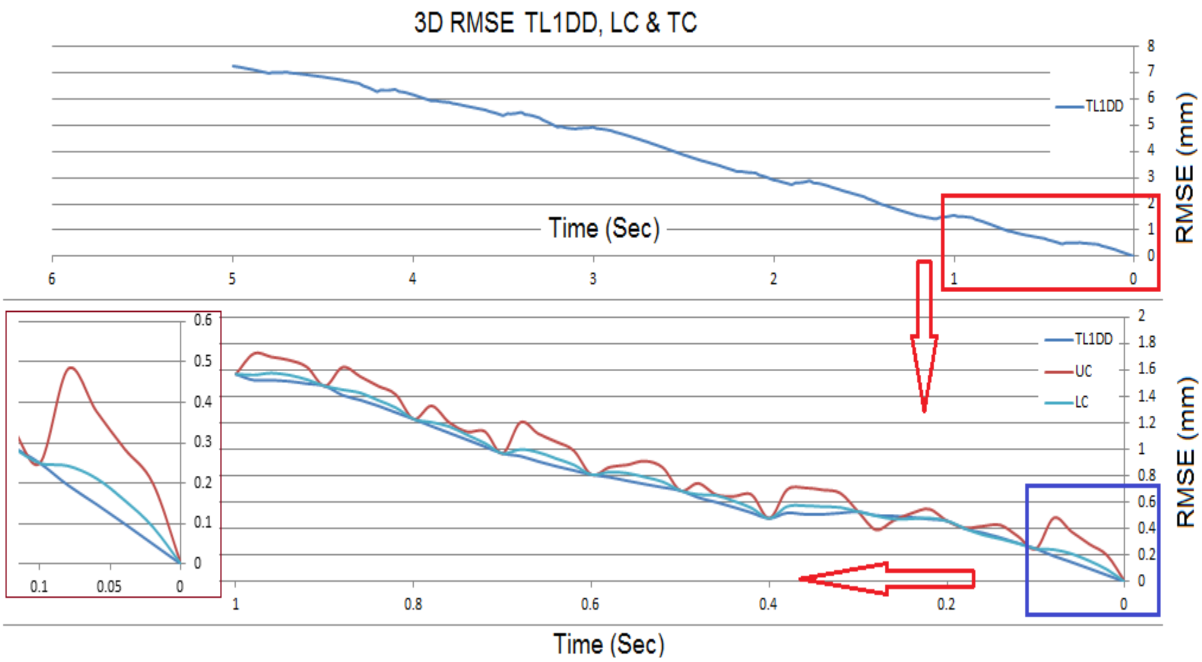

Figure 4:3D RMSE of TL1DD/MEMS-INS (open-sky)

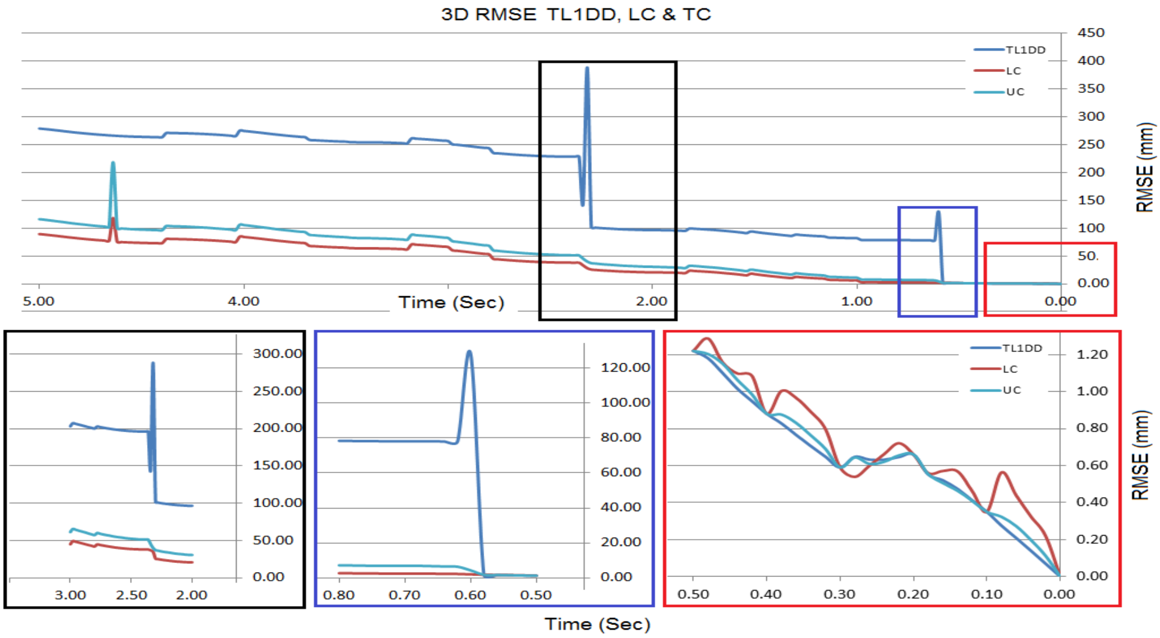

Figure 5:3D RMSE of TL1DD/MEMS-INS (limited GPS coverage)

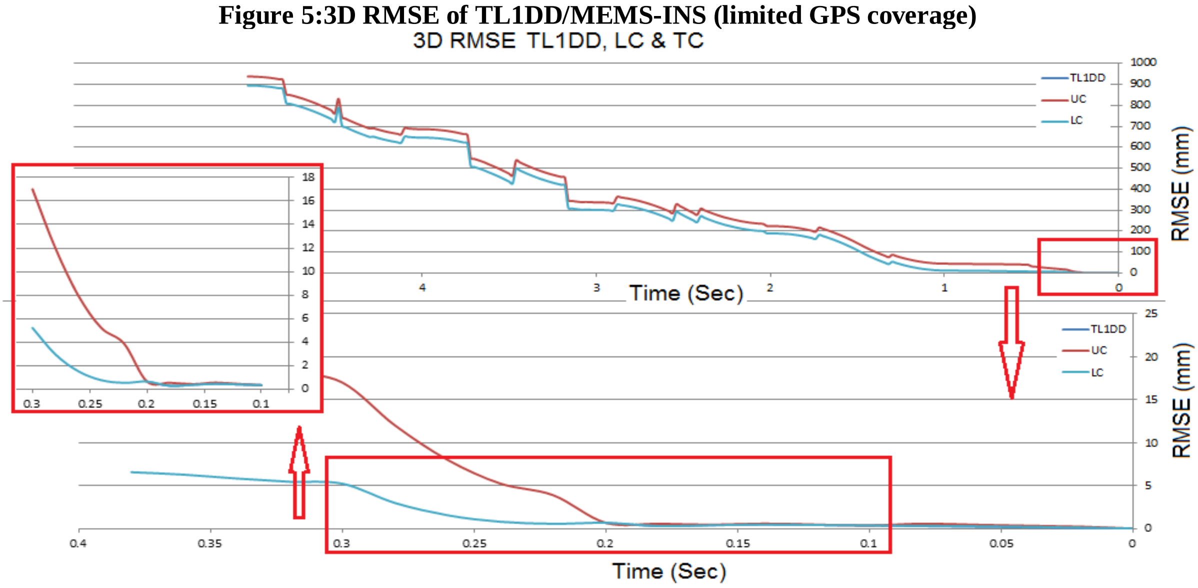

Figure 6:3D RMSE of TL1DD/MEMS-INS (GPS-off area)

Starting with open-sky GPS area, it is clear from figure (4) that LC solution has provided more stable solution comparing to UC solution. This can be attributed to utilizing forward and reverse KF to smooth the less precise navigation solution obtained from MEMS-INS using the more precise navigation solution achieved from TL1DD. With 10HzTL1DD solution and two way KF, the chance for 50Hz MEMS-INS errors to be grown up is limited. However, with 1HzTL1DD solution, INS errors can be more significant, especially in the mid of the period between two epochs. In the case of UC solution, it is clear from the figure that MEMS-INS errors are growing up starting from the beginning of each epoch, reaching the maximum by the following TL1DD solution. This is expected with UC solution as no smoothing techniques are used and as the integration solution is based on the individual MEMS-INS observations throughout the period between each two epochs. The other point can be noted is that even with the ability of the two navigation solutions to follow up the general trend of the reference solution, the value of RMSE in both solutions are growing with time by nearly a few millimeters/second. This can be referred to the mane dependency of the two navigation solutions on the TL1DD solution, in which the errors are cumulative providing relative solution degraded with time.

Moving on to the limited GPS coverage area, it is clear from figure (5) the effect of cycle slips on the quality of TL1DD solution. As the area is surrounded by huge tress and high buildings, cycle slips is highly expected to appear, where the connection between GPS satellites and receivers has a high percentage to be lost. The other reason of losing the connection is the high multipath effect,where the area is surrounded by high buildings and the site is a suitable environment for multipath and reflecting signals. Multipath effect can reach several meters in high multipath environment using code measurements and several centimeters for carrier phase. In this test, Right Hand Circular Polarization (RHCP) pinwheel antenna has been used to mitigate the effect of reflected signals. The transmitted signals from satellites are RHCP and this polarization is changed based on the reflection angle and the number of reflections. Therefore, using an antenna with RHCP helps to reject the reflected signals with left hand circular polarization (LHCP). However, reflected signals might have RHCP by reflecting the signals twice or more and the GPS receiver may not be able to deal with such signals. In some receivers, such as that used in the test, narrow correlation technique is used to deal with the received multipath signals, where the direct signal can be signified from that reflected based on the arriving time and the signal strength. In the case of just receiving the reflected signal where the satellite is hidden, it tends to be difficult to detect the multipath effect even using such technique [5].

High multipath effect can disturb the correlation between the codes of direct signals and those generated by the receiver and as a consequence, connection might be lost resulting cycle slips. The multi-reflected signals might have RHCP which can be received by the antenna without any rejection. If the direct signal is already received with the reflected signal, the code correlation between satellite and receiver could be affected leading the connection to be lost. If just the multipath signal is received without the direct one, two scenarios are expected; in the first, just one reflected signal is received and the connection with the satellites is not affected, and the second scenario is when more than one reflected signal from the same satellite are received by the antenna. In this case, the connection with the satellite might be affected depending on the strength of the received signals. Moreover, increasing the level of multipath in the area often creates an electromagnetic noise around the antenna which can affect the antenna directivity. This means that the radiation pattern will not be the same in all directions and accordingly signals facing the low gain antenna side may not be received degrading the positioning quality [5].

Some post processing techniques utilize the satellite residuals to mitigate the multipath effect where satellites with significant residuals are removed and the position is recalculated again. However, this can be applied with static carrier phase DGPS using dual frequency receivers and short baseline where the majority of errors are cancelled out or mitigated to great extent, except that of multipath and receiver noise. In the case of stand-alone code positioning, it is difficult to use satellite residuals for detecting the multipath effect where the ionosphere effect might have an effect on the satellite residuals more than that of multipath. However, removing observations with residuals bigger than three times the standard deviation of the whole observations always can improve the results. When losing the connection between GPS satellites and receiver, random integer number of cycles is added to the carrier phase measurements in the GPS data file which has a direct effect on the quality of TL1DD solution as it is a relative error cumulative method. In this paper, cycle slips are detected by comparing the differences between the code and carrier phase measurements of two adjacent epochs. When adequate number of satellites is available, the carrier phase measurement including cycle slip is removed for more precise solution. As the receiver clock error is removed with TL1DD, the minimum number of satellite required to get the relative positioning is 3. However, when the number of free-cycle slips phase measurements is less than 3, pseudo-range measurements have to be used for fixing the gab in phase measurements to get the relative solution. With just 3 satellites observed in two adjacent epochs, evaluating the quality of code measurements may not be easy as no code solution can be obtained and TL1DD solution will still be possibly achieved even with extremely degraded quality. When the number of observed satellites is less than 3, no TL1DD solution can be computed resulting cycle slips. When cycle slips are detected, MEMS-INS is used to fill in the gaps. With LC integration, forward and reverse KF is used for smoothing the navigation solution providing prices results during the short periods of cycle slips as can be seen from figure (5).Furthermore, the quality of UC navigation solution is less than that of LC, where the first depends on unsmoothed MEMS-INS solution between epochs and when detecting cycle slips or loosing TL1DD solution. However, when TL1DD solution returns backeven with cycle slips, with good quality, LC & UCnavigation solutions return also back to depend on TL1DD solution as clear from the figure. In the left side of figure(5),there is a jump in the two navigation solutions comparing to the reference solution. This can be attributed to road"bumps" over which the platform has passed with relatively high speed. Low-cost IMUs, such as that used in this paper, tend to be provided with low-quality accelerometers and gyroscopes which translate such sudden and random movements to huge changes in position. Vibrations have less effect on LC than UC where forward and reverse KF are working on smoothing the integration solution and absorbing parts of sudden and up-normal movements.

In the third part of the test trajectory, the GPS antenna has been switched off as a simulation of passing the platform throughout a long underground tunnel. Using high quality DGPS/INSintegration system as a reference provides the ability to evaluate the suggested technique even when GPS signals are hidden, where tactical IMUs can woke alone effectively for long period without supporting from DGPS. This can be referred to the high stability of the 3D gyro-meters and accelerometers used in such level of tactical navigation sensors. As for the integration of TL1DD with MEMS-INS, both LC and UC solutions have degraded considerably with time reaching a level of meters in minutes. LC solution has been better than UC solution at the beginning of the GPS hidden period affected by the smoothness of forward KF, but then the solution has started to be degraded nearly by the same rate of UC solution. It is clear from the figure that no cycle slips have been recorded at the beginning of GPS hidden period, which can be attributed to losing the GPS signal sat the same time by switching the antenna off.

Conclusion

In this paper, the integration of TL1DD/MEMS-INS has been investigated to find out the possibility of providing high frequency, low-cost, relative, and precise navigation solution. The suggested integration technique has been tested in different GPS environments including open-sky, limited GPS coverage and GPS-off area. Integration of 10Hz dual frequency GNSS receiver with tactical grid INS has been used simultaneously with Benghazi University reference base station as a reference for evaluating the results. The results show that a precise and reliable low-cost relative navigation solution can be obtained in open-sky and a way from high multipath effect, which can be used for a wide range of relative positioning engineering applications. The quality of the navigation solution is degraded with time by nearly 1.5 to 2 mm/sec based on the quality of TL1DD solution. With high frequency GPS data, such as 10Hz, both UC and LC integration levels works well, where the chance of IMU errors to grown up is limited. However, with low-frequency GPS data, LC integration solution is better, which can be referred to utilizing forward and revers KF. In limited GPS coverage and high multipath environments,TL1DD suffers from the effect of cycle slips. However, LC and UC solutions showed high ability to overcome this limitation, fixing cycle slips, and filling the gaps, providing continued precise navigation solutions with the same rate of RMSE in open-sky. LC has provided better quality and high ability to absorb unwanted movements affected by the capability of KF to smooth MEMS-INS data. In general, the two navigation solutions even in open-sky or limited GPS coverage are degraded with time as the technique is relative and error cumulative. When GPS signals are hidden completely for a few minutes, LC solution has started to fellow the true trajectory for a few second, but generally, LC and UC solutions have failed to provide any considerable results or even follow the general trend of trajectory, reaching a level of meters in minutes. The following step will be studying the possibility of enhancing low-cost GPS/INS integration using TL1DD and utilizing extended KF for smoothing the results.

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