Inertial-Aided Cycle-Slip Detection/Correction for Precise, Long-Baseline Kinematic GPS

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ABSTRACT

Recent techniques for long-range kinematic differential GPS positioning using the carrier phase make it possible to maintain sub-decimeter precision over many hours of trajectory determination, at a thousand kilometers from all reference receivers. An Inertial Navigation System (INS), combined with GPS, extends the usefulness of the long-range technique to find position at higher rates than with GPS alone, and helps fill in gaps in the GPS solution. Also, as shown in this paper, even a moderately accurate (and low-price) small, lightweight, and portable INS can substantially enhance the ability to detect and correct GPS phase measurement cycle slips. In the near future, inertial units are expected to become more precise and also less expensive than the one used for this test.

INTRODUCTION

The advantages of combining Global Positioning System (GPS) and inertial measurements have been known for some time [1-3]. The GPS measurements provide precise position and velocity, which can be used to align the Inertial Navigation System (INS) to obtain more accurate attitude estimates as well as to calculate the biases in the INS sensors. The inertial system provides higher data rates between the GPS updates and a robustness that allows for a gradual degradation in system navigation accuracy in case of a loss of the GPS signal tracking. Generally, for earlier GPS/INS processing procedures, GPS pseudo-range measurements, or positions derived from pseudo-range measurements, were combined with the inertial measurements [4]. Change-in-position or average velocity estimates from GPS change-in-carrier phase or Doppler measurements were also combined with the inertial measurements.

The positioning accuracy using the GPS Precise Positioning Service (PPS) pseudo-range measurements is specified to be about 15 m horizontal and 30 m vertical. Of course, actual positioning is somewhat better than these values. Differentially corrected pseudo-range positioning is still at the meter accuracy level. More recently, kinematic GPS positioning has demonstrated centimeter level accuracy for short baseline positioning [5-8] and decimeter level accuracy for long (1000 km) baseline positioning [9-11]. Such precise kinematic positioning requires successful tracking of the integrated carrier phase. Interruptions to this signal need to be detected and, if possible, corrected. For the processing of GPS-only measurements, detection of cycle slips or losses in lock require sophisticated algorithms that track a large number of satellites for detection and correction. In general, success has not been complete.

The application of an inertial system to aid the detection and correction of GPS phase measurement errors was proposed as part of a feasibility study in [12]. Here, a Litton LTN-90 Laser INS was evaluated for kinematic positioning over short baselines using a phase ratio method. The method was demonstrated to be very useful for aiding the detection and correction of cycle slips for short duration loss of signals.

This paper investigates inertial aiding for cycle slip detection and correction for long baseline kinematic GPS positioning. To encourage broad practical application, the extra hardware has to be compact and light, and the cost ratio of INS to GPS should be low. For that reason, an INS was chosen for this work that, while not yet inexpensive enough (<US$25,000), has characteristics similar to those of less expensive units that will be available in the near future. This moderately accurate (5 deg/hr, 500 μg/root(Hz)), compact (8 cm x 9 cm x 12 cm) and lightweight (1.1 kg) inertial system, the Boeing C-MIGITS II integrated GPS/INS [13], was evaluated. This system is based on Micro Electro Mechanical Systems (MEMS) technology. In the near future, similar technologies are expected to produce higher accuracy (0.1-1 deg/hr), have much lower weight and volume, and be inexpensive [14].

As a part of this study, numerical algorithms for the INS-aided kinematic GPS cycle-slip detection techniques and for the GPS/INS integration were tested using real (as opposed to simulated) data. Data were obtained from low-dynamic tests with a van driven inside the grounds of the National Institute of Science and Technology (NIST) in Gaithersburg, Maryland, in November 1997. The tests also provided data that allowed for alternative determinations of attitude, described in [15]. Therefore, a multiple-purpose test fixture was built and mounted atop a van (see Figure 1), which was driven on the NIST grounds within a region of approximately one square kilometer, at speeds up to 10 m/s (36 km/h). The test fixture consisted of a 3-meter-long beam with two GPS antennas mounted on either end, a video camera in the middle, and a C-MIGITS II GPS/INS unit to the left of the video camera in the figure. The back GPS antenna (mounted on the side of the beam toward the rear of the van) simultaneously fed the C-MIGITS II GPS receiver and a separate Ashtech Z-12 GPS receiver. Data from the front GPS antenna and the video camera were not used for the analyses discussed in this paper. The C-MIGITS II ordinarily functions as an integrated INS/GPS unit and calculates a Kalman-filtered navigation solution. However, for this effort, we calculated our own Kalman-filtered solution in a loosely coupled format where we used the raw data from the Inertial Measurement Unit (IMU), which consists of the accelerometers and gyroscopes inside the INS, and the GPS positions from the back antenna. The GPS position solutions were obtained by post-processing the Ashtech receiver data using the methods discussed in this paper.

Figure 1. Test fixture shown on tripods. The fixture was mounted on top of the van for the ground tests.

INERTIAL NAVIGATION SOLUTION

It is well known that inertial navigation systems (INS) develop unacceptable levels of drift after times as small as tens of seconds in the case of low-grade units such as the type used for data collection in this study. The level of drift can be sharply limited by combining the inertial and GPS data through Kalman filtering.

Toward this end, computer software was developed for an 18-state Kalman filter for combining the GPS and inertial data -- referred to as the INS/GPS Kalman filter. The filter error state vector is given by

$$\delta\vec{x} = \begin{bmatrix} \delta\vec{r}^{\,e} \\ \delta\vec{v}^{\,l} \\ \delta\vec{\varepsilon}^{\,l} \\ \delta\vec{a}^{\,b} \\ \delta\vec{\omega}^{\,b} \\ \delta\vec{\chi}^{\,e} \end{bmatrix} \tag{1}$$

where the δ indicates an error state. Here, $\vec{r}^{\,e}$ is the position vector in earth-fixed, earth-centered (ECEF) coordinates, designated by superscript-*e*; $\vec{v}^{\,l}$ is the velocity in the local geographic frame, designated by superscript-*l*; and $\vec{\varepsilon}^{\,l}$ is the attitude-triplet, consisting of the roll ϕ, pitch θ, and heading ψ angles, referenced to the local geographic frame. The next two state vector elements are estimates of the accelerometer bias $\delta\vec{a}^{\,b}$ and the gyro drift $\delta\vec{\omega}^{\,b}$, which are both given in the body or IMU frame (designated by superscript-*b*). They are both modeled as first-order Markov processes. The last element, $\vec{\chi}^{\,e}$, having units of distance, is an attempt to model the GPS position measurement as a first order Markov process, rather than as white noise. This was found to model the observed measurements much more accurately than a white noise model. The system equations are more fully described in [15].

The position and velocity components of the process noise follow directly from the accelerometer white noise, while the process noise of the attitude follows from the gyroscopic white noise. The process and measurement noise parameters, as used in the simulations, are given in Tables 1 and 2. Please see [15] for the numerical relationships between these parameters and the process noise elements. Note that the Markov parameters for the GPS position measurements, which are used to augment the state vector, are considered part of the process (as opposed to measurement) noise, in contrast to the white noise of the GPS position measurements, which are considered part of the measurement noise. These parameters were deduced through a few different methods: using a combination of published parameters [13], analysis of the IMU and GPS data, and adjustment of the parameters to obtain agreement between the observed state covariances and Kalman filter measurement residuals. For the GPS measurements, the white noise terms represent the uncorrelated portion of the measurement *differences*, while the first-order Markov parameters are derived from a calculation of the auto-correlation of the measurements, all for the non-moving case. Finally, the initial state variances are given in Table 3. The exact choice of these parameters is not so crucial, as they affect only the initial convergence of the Kalman filter.

The GPS/INS Kalman filter was first run in its normal mode, i.e., processing inertial measurements at 10 Hz and GPS measurements at 1 Hz. From this run, the values of the state vector elements were calculated, along with the associated variance-covariance matrix, *P*. For GPS cycle-slip detection, the quantity of most interest is the position. Hence, the 3 x 3 sub-matrix of *P*, constituting the expected position errors-squared, were tabulated for each of the GPS update times, for instants both just before (superscript -) and just after (superscript +) the update. In addition, if Δx is the change in position between epochs *t* and *t+DT*

$$\Delta x(t, DT) = x(t+DT)^{-} - x(t)^{+} \tag{2}$$

its variance-covariance matrix *DP*, was also calculated. *DP* is given by

$$\begin{aligned} DP &= P(t+DT)^{-} + P(t)^{+} \\ &\quad -[P(t)^{+}\Phi(t,DT)^{T} + \Phi(t,DT)P(t)^{+}]\,. \end{aligned} \tag{3}$$

Here, t is the time at the previous GPS update and DT is the interval up to the present epoch. The INS impulse response matrix between times *t* and *t+DT* is given by $\Phi(t, DT)$. The duration of the processing interval was 1250 seconds in the stationary case and 2100 seconds in the moving case. Next, the effect of GPS outages was simulated by making the GPS measurements available or unavailable for fixed intervals. For the sake of simplicity, the “duty cycle” was kept at 0.5; i.e., the GPS measurement-available interval was the same as the GPS measurement-unavailable interval. The simulated GPS outages were 5, 10, 15, 20, 25, and 30 seconds. Since the length of the total processing interval was 2000 seconds for the moving case (after allowing the filter 100 seconds to converge), a total of 33 to 200 GPS on-off cycles were processed. As the GPS-outage interval was increased, the variance of the change-in-position also increased.

Table 1. Process noise parameters: the first four correspond to the IMU and the last two to the GPS position.

Accelerometer white noise	12000 μg
Gyroscope white noise	0.35 deg/root(hr)
Accelerometer bias, 1st order Markov	200 μg/root(Hz)
Gyroscope drift, 1st order Markov	3 deg/hr
GPS position, 1st order Markov, x, y	0.01 m
GPS position, 1st order Markov, z	0.03 m

Table 2. GPS measurement noise parameters.

GPS position white noise, x and y	0.002 m
GPS position white noise, z	0.005 m

Table 3. Initial state standard deviations (square root of variance).

Position, x and y	0.03 m
Position, z	0.09 m
Velocity, x and y	0.03 m/sec
Velocity, z	0.09 m/sec
Roll and pitch	0.1 deg
Heading	1.0 deg
Accelerometer bias	600 μg
Gyroscope drift	9 deg/hr
GPS position bias, x and y	0.03 m
GPS position bias, z	0.09 m

After the GPS/INS processing was completed, the position, change-in-position, and respective variance-covariance information was used for the GPS cycle-slip detection. This is described in the next section.

CYCLE-SLIP DETECTION

The change $\Delta\rho_{ij}$ in the range ρ_{ij} from station i to satellite j caused by Δx, the change in position between epochs t and $t+DT$ as defined in equation (2) (after correcting for the lever-arm from the INS unit to the GPS antenna with vehicle attitude information from the INS), is given by the scalar product:

$$\Delta\rho_{ij} = u_{ij}\, \Delta x(t, DT) \qquad (4)$$

where u_{ij} is the unit vector pointing from station to satellite. Single-differencing $\Delta\rho_{ij}$ between two satellites, and subtracting from the triple-differenced carrier phase wide lane, one gets a residual value r_w consisting of GPS and INS noise, plus any wide-lane cycle slip that may have occurred between epochs t and $t+DT$. If the combined GPS and INS uncertainties in Δx add up to less than 43 cm (half a wide lane), and assuming u_{ij} does not change significantly over DT, then rounding off the residual to the nearest integer gives the value of the wide lane cycle slip:

$$\Delta N_w = Nearest\ Integer[r_w / \lambda_w] \qquad (5)$$

where λ_w is the wide-lane wavelength. Notice that $\Delta x(t,DT)$ is a function of the estimated position at $t+DT$ obtained *before* updating the INS with GPS. Therefore, r_{ij} in equation (5) cannot be affected by possible cycle slips in the carrier phase. The precision of the triple-differenced wide lane is about 5 cm, while the change in position, as determined with the INS, has an uncertainty that depends on DP according to equation (3), and it is likely to be the dominant part of r_{ij}. According to equations (3) and (4), this uncertainty is:

$$u_{ij}\, DP(t, t+DT)\, u_{ij}^T \qquad (6)$$

Assuming this uncertainty is small enough to allow for a reliable determination of ΔN_w, then one may proceed to find the L1 and L2 cycle slips as follows:

$$\Delta N_1 = Nearest\ Integer[(LI - \Delta N_w\, \lambda_2)/(\lambda_1 - \lambda_2)] \qquad (7)$$

$$\Delta N_2 = \Delta N_1 - \Delta N_w \qquad (8)$$

where λ_1 and λ_2 are the L1 and L2 wavelengths (19 cm and 24.5 cm), with ϕ_1 and ϕ_2 being the corresponding phases, and $LI = \lambda_1\phi_1 - \lambda_2\phi_2$, is the ionospheric observable. After some experimentation, it became clear that the use of LI made for the most reliable results. The only reservation is that equation (7) holds as long as the change in ionospheric refraction over DT is less than $0.5|\lambda_1 - \lambda_2|$ = 2.7 cm. This may not be true if DT is longer than 20 seconds, particularly during periods of strong scintillation. However, as long as ΔN_w is determined correctly (using $\Delta\rho_{ij}$ from the INS), the errors for L1 and L2 are bound to obey $\Delta N_1 = \Delta N_2$, with $|\Delta N_1| \sim 1$ to 2 cycles. This would cause errors in the ionosphere-free combination (or Lc, the main data-type for long-range positioning) of between 0.1 and 0.2 m. These small Lc "cycle-slips" can be accommodated by relaxing the respective Lc bias estimate in the GPS Kalman filter by 0.5 cm, every time that a cycle slip is discovered in a double-difference.

LONG-RANGE GPS KINEMATIC TRAJECTORY

The van was driven inside the grounds of NIST for part of the 5 hours of the test, as shown in Figure 2, and the rest of the time it was stationary. There were two dual-frequency receivers, with their antennas mounted at the front and at the back of the beam on top of the van. The "front" receiver data had some unexplained problems, so only data from the "back" receiver were used for cycle-slip detection. The back antenna was positioned very precisely relative to a nearby marker (KENF) using carrier-phase data with conventional on-the-fly ambiguity resolution. The resulting kinematic trajectory was deemed correct to a few centimeters, and it was used as control, to verify the correctness of the long-range navigation of the same antenna. The van receiver was positioned kinematically relative to two fiduciary sites simultaneously: one at the National Imagery and Mapping Agency (NIMA) in St. Louis, Missouri, and another at a location in Maine (MAIN), 1127 km and 953 km from Gaithersburg, respectively, as shown in Figure 3. The three sites (NIMA, MAIN, KENF) first had to be positioned precisely relative to IGS sites in the Central/Eastern USA: at New Liberty (NLIB), at NASA Goddard SFC (GODE), and at Westford, Massachusetts (WES2). This was done using the data collected at these sites during the test, IGS station data for the same period, and the final IGS SP3 precise orbits.

All receivers collected data at 1 Hz. The elevation cutoff was 15 degrees. Observations were processed as double differences. Only the carrier phase observations were used (except for a few ancillary calculations that require the pseudo-range). All the static and kinematic GPS processing was made using software developed by the first author, primarily for very-long-baseline, precise positioning in post-processing. This software implements ideas described in [9,10]. It currently runs under UNIX, LINUX, Windows 95, 98, and NT. (All the GPS data-processing was done on a Pentium II Laptop PC.)

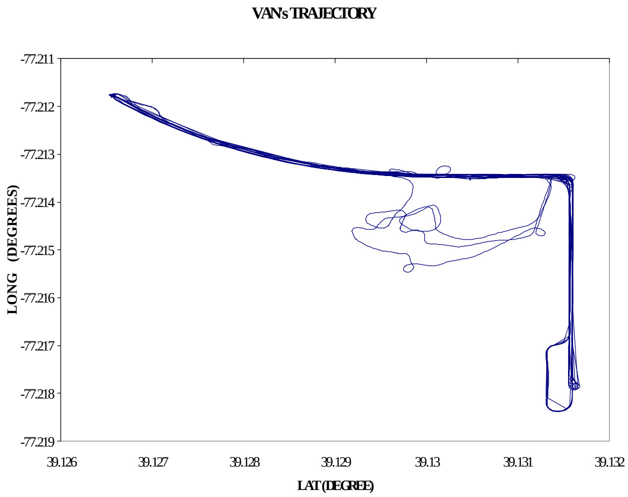

Figure 2. Position of the van during test inside the NIST grounds, in Gaithersburg, Maryland.

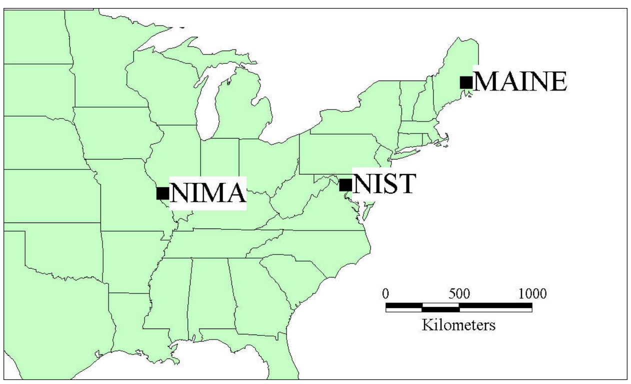

Figure 3. Geographic location of marker KENF at NIST and of the distant fiduciary stations NIMA and MAIN.

The idea is to validate the GPS data before calculating the present kinematic position and updating the INS filter. Therefore the cycle slip detection should be done with both INS and GPS filters in constant communication with each other. This was not possible, because the software available allowed only separate INS and GPS processing. In practice, except during rare transients after starting or re-starting the GPS filter, this filter is well-converged and the estimated trajectory is therefore very close to one post-processed using both filter and smoother. Therefore, the INS filter was updated with a post-processed GPS trajectory.

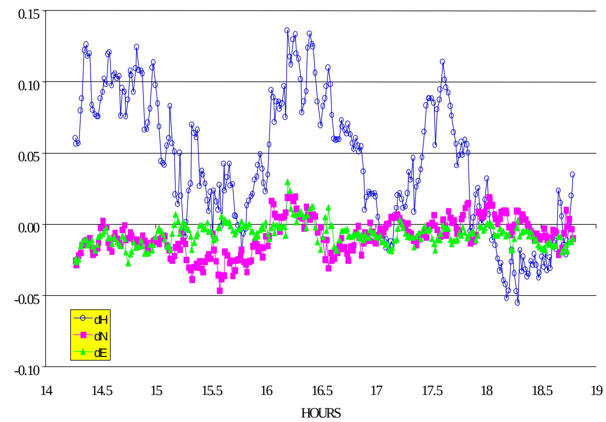

Figure 4. Agreement between long-range and short-range positioning of back antenna on the van at NIST. Long-range distances: MAINE (952 km), NIMA (1127 km). Short-range: KENF (<1 km). dH, dN, dE are in meters.

Figure 4 shows, at 1-minute intervals, the discrepancies in position (Height, East, and North) between the long-range-determined trajectory of the van, and the short-baseline control trajectory. The larger discrepancies are in height, as it could be expected, while the agreement is better (<5 cm) for horizontal position. The three-dimensional RSS discrepancy, over all 1-Hz epochs in the entire 5-hour period, was 6 cm.

CYCLE-SLIP DETECTION RESULTS

Cycle-slip detection took place at the end of gaps. A gap was a period in which all GPS positions were ignored, as if non-existent, and were not used to update the INS. Every gap was preceded by a period of equal length, in which the precise GPS position updated the INS once every second. Gaps followed periods with GPS repeatedly throughout intervals of about half an hour during which the vehicle was either standing still or in movement (the GPS trajectory was obtained in a single kinematic solution for the entire 5 hours in which receiver data was collected.). The idea was to simulate a situation where a complete loss of lock, or some other problem, caused all GPS data to be temporarily lost or edited out. If the change in ambiguity (cycle slip) across the gap can be detected and corrected exactly, the precision of GPS positioning can be maintained. At the end of the gap, the INS was used to test the GPS double differences for possible cycle slips and help determine their value, if any were found. Because of the lack of GPS updates, the uncertainty in the INS position was greatest at that point. (The GPS position was used to update the INS only *after* checking for cycle slips.) This was a simulation of one of the most severe situations in which cycle slips may occur, since a complete loss of information on all satellites is rare. The results for the case when the vehicle was standing still were the best, with the percentage of successful cycle slip identification being better than 95% for gaps of up to 15 seconds. However, this is not particularly interesting, because cycle slips in double differences can be resolved quite well over stationary periods much longer than 15 seconds without any need for INS assist. During those periods when the vehicle was moving, the accuracy of the GPS-updated INS position was worse than in the stationary case, and so was the percentage of successful cycle slip identification. This is due primarily to the greater amount of process noise affecting the IMU sensors, as well as that in the tracking loops of the GPS receiver. Table 4 shows the percentage of cycle slips that were detected successfully, for various gap lengths. When testing (with modern receivers) for such rare events as cycle slips, the most likely error is a *false positive*: "detecting" a cycle slip that is not there. "Correcting" this non-existing slip could mean planting one where originally there was none.

The test was made over periods when no cycle slips had been detected above an elevation cutoff of 15 degrees, during a previous, careful analysis of the data. Small, non-zero cycle slips in L1 and L2 were then added to all double differences to be tested, at the end of each simulated gap. Success meant (a) detecting every simulated cycle slip, and (b) estimating correctly its known value. For various gap intervals, Table 4 (a-b) gives the percentage of correct wave lane estimation, correct L1 and L2 estimation, and the number of trials.

Table 4a. Inertial-aided cycle slip detection and correction across gaps, van stationary.

Gap (sec)	%Wide Lane detected	%L1, L2 corrected	Trials
5	100	99.9	1534
10	100	99.9	761
15	100	99.8	506
20	98.6	98.4	367

Table 4b. Inertial-aided cycle slip detection and correction across gaps, van moving.

Gap (sec)	%Wide Lane detected	%L1, L2 corrected	Trials
5	99.7	99.1	2635
10	93.8	93.4	1314
15	84.8	84.3	868
20	67.2	66.6	638

(Since correct detection in L1 and L2 is possible only after successfully finding the wide lane cycle slip, the percentage of the former is always the smaller.) The results shown here correspond to an INS updated with long-range GPS position of sub-decimeter RSS precision, which is the situation to be expected over most of the long-range navigation period. However, there are important cases when the precision can be much worse. Of particular interest is the transient after a start or a re-start of the GPS navigation Kalman filter (following complete loss of lock). To understand the possible degradation in cycle slip detection, the RSS uncertainty of the change in position across the gap, $\Delta x(t,t+DT)$ was computed as the root-squared trace of matrix DP (see equations (2) and (3)). For different levels of long-period uncertainty in GPS position: 0.03, 0.06, 0.12, 0.25, and 0.5 meters, the INS uncertainty worsened by no more than 30%, suggesting that a transient degradation of up to 0.5 meters in GPS precision may not have a big effect on cycle slip detection. With low-to-moderate PDOP, better than 0.5-meter uncertainty can be achieved within 5 minutes of starting the GPS filter without a priori position information.

CONCLUSIONS

Because of practical limitations, the cycle-slip detection test had to be made by processing the INS and GPS data separately. In future studies, the INS and GPS navigation Kalman filters should operate together. The results of this test may not apply to the relatively brief and rare transients when either filter is being started or re-started. The following conclusions should be relevant most of the time, when both filters are in steady-state regime.

Long-range kinematic GPS with carrier phase can maintain sub-decimeter precision over many hours of trajectory determination, a thousand kilometers from the nearest reference site. INS, combined with GPS, extends the usefulness of the long-range technique, making it possible to find position at higher rates than with GPS alone, and filling in gaps in the GPS solution. Further, it can be used to increase the reliability of long-range solutions by helping detect and correct cycle slips.

As shown in this paper, even a moderately accurate (and low-price) INS, which is also small, lightweight, and portable, can substantially enhance the ability to detect and correct cycle slips. The post-processed test results demonstrate a fairly high, 99.1%, inertial-aided detection and correction rate for GPS data gaps of 5 seconds for a low dynamic platform. For larger data gaps, the rate drops off, mainly due to larger change-in-position errors of the IMU. In the near future, inertial units are expected to become more precise and also less expensive than the one used for this test.

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