

GNSS Solutions:

Backing up GNSS with laser radar & INS, RAIM in the city, antenna phase wind-up

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnists, Professor Gérard Lachapelle and Dr. Mark Petovello, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. Their e-mail addresses can be found with their biographies at the conclusion of the column.

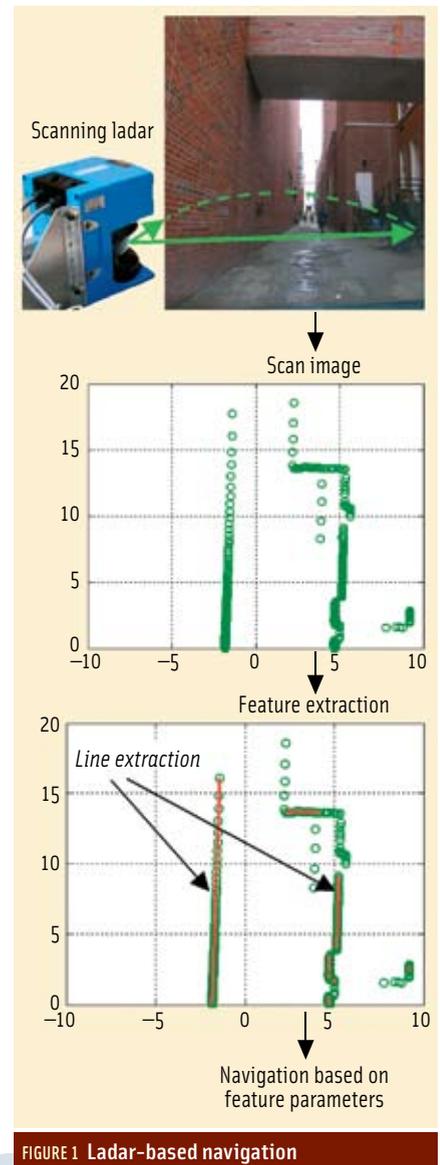
What are the benefits of combining laser radar (ladar) and inertial data for navigation?

Indoor and urban outdoor areas still pose a very challenging environment for most GNSS receivers. In such areas, buildings and other obstacles generally introduce a significant GNSS signal attenuation and create a variety of multipath reflections. Although man-made obstacles represent a significant challenge for GNSS-based localization, they can be efficiently used as localization reference points if their navigation-related features are detected and feature parameters are estimated.

Laser radars (ladars) are currently receiving significant attention for urban navigation applications (indoor and outdoor) because of their utility for autonomous navigation in unknown environments where map information is unavailable *a priori*. **Figure 1** illustrates the ladar-based navigation for a two-dimensional (2D) case.

A scanning ladar provides images of urban environments. Features are extracted from these ladar images. For example, lines may be derived from 2D images by tracing the intersection of the laser scanning plane with a planar surface (e.g., a wall of a building).

We can use changes in feature parameters from scan to scan to compute a relative navigation solution: position and orientation relative to a local frame that is generally defined



by the ladar position and orientation at the time of initialization. We can then transform this relative navigation solution into one of the commonly used navigation frames (such as East-North-Up and Earth-Centered-Earth-Fixed frames) if GNSS signals are available during a limited interval. One GNSS fix is needed for the position solution transformation, and two GNSS fixes (sequentially in time or simultaneously along a rigid baseline) are required to transform the attitude solution.

The combination of ladar and inertial navigation system (INS) technologies yields a significant potential for efficient autonomous

navigation in urban environments. To illustrate this point, **Figure 2** shows 2D trajectories reconstructed from live lidar and inertial data that were collected in two different urban canyons (in both cases, the truth trajectory is approximately a straight line, as indicated by the red segment in the images). For these canyons, the GNSS signal availability is significantly limited because most of the sky is blocked by buildings, as can be seen in Figure 2.

The trajectories shown in Figure 2 were reconstructed from measurements of a tactical grade inertial measurement unit with a 3 degree/hour gyro drift and a 0.2 milligal accelerometer bias, and lidar data collected from a laser measurement unit. The trajectory duration is approximately two minutes for both urban canyons. Accordingly, the horizontal drift of a stand-alone inertial solution was evaluated as 60 meters at the trajectory completion. The use of lidar/inertial integration clearly mitigates this drift and allows a trajectory reconstruction accurate to better than a meter.

From the system integration perspective, the main benefits of combining lidar data with inertial measurements include:

- 1) efficient matching of features in sequential lidar scan images
- 2) use of inertial coasting when features extracted from lidar images are insufficient for the lidar-only navigation; and
- 3) compensation for tilt of the lidar scanning plane using INS angular measurements.

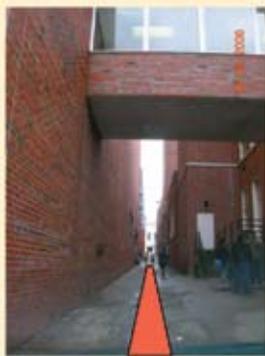
We discuss each of these benefits in greater detail in the following sections.

Use of INS for feature matching

For lidar-based navigation, the nav solution is computed using changes in the parameters of features extracted from lidar scan images over time. For example, lines can be used as features for a 2D navigation case as previously



Columbus Ohio Alley
(red segment of vehicle path)



Athens Ohio Alley
(red segment of vehicle path)

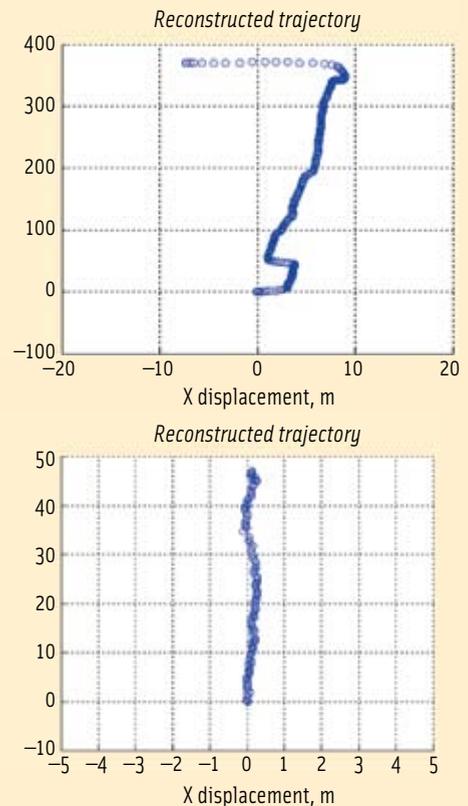


FIGURE 2 Examples of motion trajectories reconstructed from live lidar/inertial data

shown in Figure 1. Changes in line parameters (range ρ and angle α) from scan to scan are exploited to compute user position and orientation changes as illustrated in **Figure 3**.

In order to use a specific feature for navigation from one scan to the next, this feature must be found in both scans. We also must know with certainty that a feature in one scan corresponds to a feature in a subsequent scan, which requires a feature-matching procedure.

To accomplish this, we can exploit INS measurements to predict the locations of previously extracted features in the current scan image. INS-based feature predictions are then matched with features

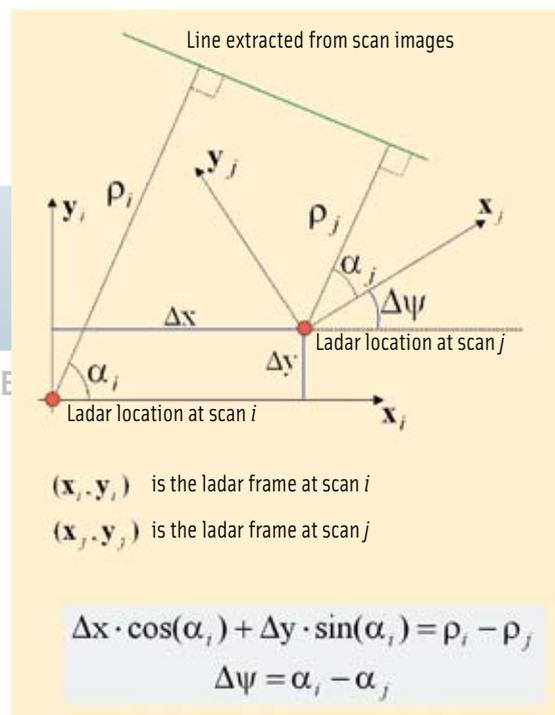


FIGURE 3 Use of feature parameters for navigation: Line feature example

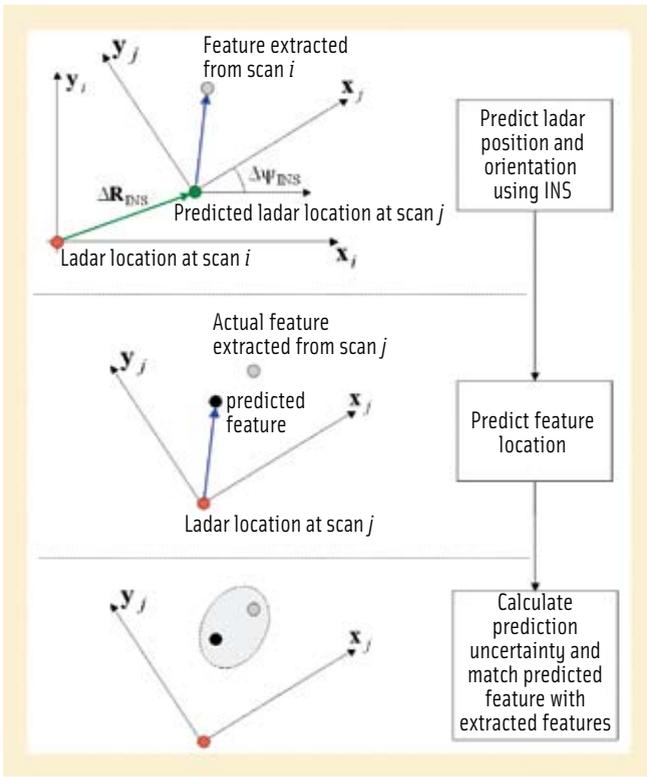


FIGURE 4 INS-aided feature matching

extracted from the current image.

Figure 4 exemplifies the feature matching procedure for a single point feature. Note that a point feature in a 2D scan can correspond, for instance, to the corner of a building.

Accordingly, user position and orientation at the current scan (scan j in **Figure 4**) are first predicted using INS outputs that include a 2D displacement vector ΔR_{INS} and a heading increment $\Delta \psi_{INS}$. Next, a feature extracted from the previous scan (scan i in **Figure 4**) and the predicted user position and orientation are applied to predict the location of the feature in the current scan (scan j in **Figure 4**). Prediction uncertainty is then evaluated to accommodate INS errors and ladar measurement errors and a search window is opened. If a feature extracted from the current scan (scan j in **Figure 4**) fits within the search window, then a match is declared.

The use of INS significantly reduces the uncertainty in a predicted feature location as compared to an unaided ladar case where we would need to apply an error-prone dynamic

motion model to predict the user displacement between scans. For the ladar/INS integration, the prediction uncertainty includes INS errors that are generally significantly smaller compared to errors in the dynamic motion model used in the ladar-only case.

Note that the INS-aided feature prediction is similar to inertial aiding of GPS receiver tracking loops, where loop filters only need to track the INS error dynamic

as opposed to tracking the full user motion dynamic in an unaided case. As a result, a considerable reduction in the loop bandwidth is generally achieved, which then allows more sensitivity and improved interference/jamming robustness.

Similarly, a reduced uncertainty in the predicted feature location narrows the search window for feature matching. This greatly reduces the probability of feature mismatches, which is one of the most critical error sources for the ladar-based navigation.

Inertial Coasting

For those cases where not enough features are extracted from ladar scan images, the navigation solution coasts on inertial data. Hence, the use of INS maintains the navigation continuity during unavailability of the ladar-based navigation solution.

An important aspect of this technique is that INS drift can still be constrained even when not enough features are available for ladar-only navigation computations. In particular, this is the case if the INS is calibrated in the feature domain: i.e., in a

tightly coupled sense where feature parameters are applied to estimate the INS error states as opposed to the use of ladar-based position and orientation (which is unavailable) for the INS calibration. As a result, INS error states can still be updated even when only one feature is extracted from the current scan image and matched to one of the previously extracted features.

We should note that coupling of inertial and ladar data in the feature domain resembles tight coupling of GPS and INS where GPS measurements (pseudoranges and/or accumulated Dopplers) are used for the INS calibration rather than calibrating the INS based on a GPS navigation solution.

Compensation for Ladar Tilt

Most of the currently used scanning ladars provide scans in two dimensions. Three-dimensional scanning ladars exist; however, these sensors are generally very costly — on the order of \$100,000 or more.

If a 2D ladar is mounted on a vehicle that is driving through a city street then the ladar scanning plane can have different tilt angles at different scans (due to vehicle motion). **Figure 5** illustrates the influence of laser scanner tilt on the feature extraction using line features as an example.

The top portion of **Figure 5** shows an untilted laser scan in the horizontal plane. The intersection of a horizontal scanning beam with a planar surface (e.g., a wall of a building) creates a line in the scan image. Next, the bottom portion of the figure shows what happens to the scan image if the laser is tilted. For this case, the original laser body frame (x, y, z) is rotated into the (x', y', z') frame, where the (x', y', z') plane is a tilted scan frame.

Depending on the magnitude of the tilt, the line parameters in the tilted scan will generally differ from line parameters in the horizontal scan. For instance, the line range ρ' (that is the distance from the line to the ladar) in the tilted scan differs from the line range ρ in the horizontal scan as illustrated in **Figure 5**. These

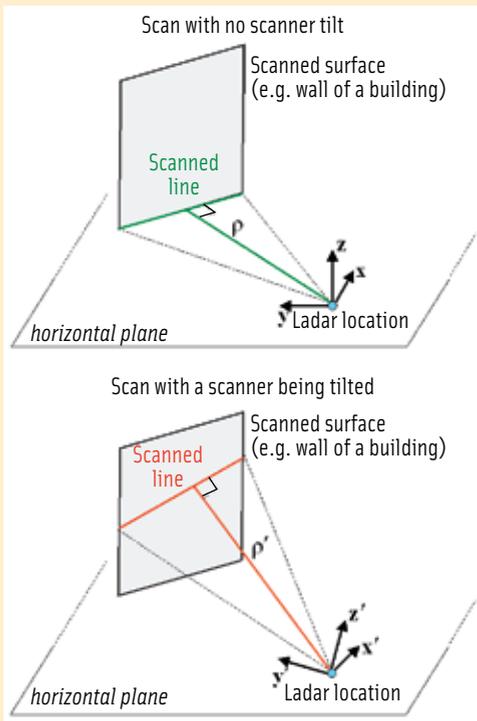


FIGURE 5 Influence of laser scanner tilt on the feature extraction

differences in line parameters are due to uncompensated laser scanner tilt and will introduce navigation errors.

INS data are applied to compensate for the tilt of the ladar scanning plane. In particular, the INS measures ladar tilt angles (pitch and roll angles). These measurements are then used to level the ladar scanning plane. Ladar leveling is performed computationally rather than physically; line parameters in the horizontal scan (computed scan) are estimated based on line parameters extracted from a tilted scan (measured scan) and INS measurements of ladar tilt angles.

In conclusion, integration of ladar data with the INS significantly improves the robustness of ladar-based

navigation by enhancing the feature matching, using INS coasting, and applying inertial data for the compensation of ladar tilt. Integrated ladar/INS solutions enable autonomous navigation in indoor and urban outdoor areas that present challenging environments for GNSS-based localization techniques.

Manufacturers

The data generated for figures 1 and 2 used a Systron Donner Digital Quartz Inertial Measurement Unit (DQI) from **BEI Technologies, Inc.**, San Francisco, California USA, and an LMS-200 ladar from **SICK AG**, Waldkirch, Germany.

ANDREY SOLOVIEV



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Is fault detection/ RAIM useful in areas of severe signal degradation, such as urban environments?

In the navigation message transmitted from its satellites, the GPS system provides users with some basic integrity information regarding the “health” or usability of the signals. However, this information is not current enough for some applications. Timely integrity monitoring is especially essential in safety-critical applications in order to ensure a certain degree of confidence in the navigation function.

Receiver autonomous integrity monitoring (RAIM) is a means of providing integrity with the capability of detecting when a satellite failure or alternatively a measurement error has occurred. Many RAIM schemes have been proposed in the literature, and they all are based on some kind of self-consistency checks among the available measurements. Traditionally, RAIM and its performance have mostly been associated with integrity monitoring tasks in aviation and other safety-critical applications, where relatively good line-of-sight signal reception conditions prevail.

Due to demands for emergency caller location identification and the increasing popularity of various location-based services, a growing need is arising nowadays for satellite-based navigation and tracking in a variety of degraded signal environments, such as in urban canyons and even indoors. Satellite-based positioning faces, however, serious challenges in these areas because man-made structures and trees cause attenuation or even total blockage of GNSS signals.

High-sensitivity receivers can provide adequate positioning capability in many of the obstructed environments using improved signal processing.



Test location in an urban canyon.

However, the application of such high-sensitivity receivers in these unfavorable environments increases the probability of tracking severely erroneous signals due to multipath propagation and cross-correlation effects, for example.

Increased measurement noise due to lower signal strengths and high levels of signal reflection prevents high-sensitivity GPS from achieving the same level of performance under obstructed signal environments as is achievable in unobstructed outdoor situations. These phenomena may result in large measurement errors and poor navigation accuracy. Therefore, RAIM-based reliability monitoring and enhancement techniques that aim at identifying and excluding erroneous satellite signals — a function known as fault detection and exclusion (FDE) — are definitely needed in signal-degraded areas.

General outlier-detection theory that uses statistical testing is directly comparable with the traditional RAIM/FDE approaches. Outlier detection, like RAIM, typically consists of

testing residuals of observations statistically on an epoch-by-epoch basis with the aim of detecting and excluding measurement errors and, therefore, obtaining consistency among the observations with assigned uncertainty levels.

To detect a measurement error, least squares residuals (or Kalman innovations) can be statistically tested after parameter estimation in navigation. In the fault-detection function of the statistical testing, a null-hypothesis states that the adjustment model is correct and the statistical distribution assumptions match reality.

This contrasts with the alternative hypothesis that states that the adjustment model is not correct, i.e., not consistent with the observation set, in which case, a fault is assumed. If a fault is detected and sufficient redundant signals are available, fault exclusion may be applied with more specific alternative hypotheses in order to isolate the erroneous satellite signal.

To check the system consistency, RAIM/FDE functions can only be performed on over-determined solu-

tions with redundant measurements. Reliability monitoring serves to determine whether or not anything has gone wrong with the basic postulates that have been assumed. Typically, RAIM/FDE includes the assumption of normally distributed errors with only a single erroneous measurement being present at a single time instant. Moreover, successful RAIM/FDE generally requires the measurement errors to follow a zero-mean Gaussian distribution. Traditionally, in order to stay within the integrity requirements of the safety-critical applications, RAIM/FDE functionality cannot be implemented if the satellite geometry (dilution of precision or DOP) is poor.

In the context of personal satellite navigation, the use of fault detection algorithms is not inhibited by such integrity requirements. However, challenges for reliability monitoring are numerous and, therefore, degraded areas are very tough for RAIM/FDE. Occurrences of faulty measurements (e.g., due to multipath, echo-only signals, etc.) are higher, and a high probability arises for encountering multiple, simultaneous observation errors.

Error detection and isolation can to some extent cope with the multiple blunders if performed iteratively. However, because diagnosing outliers is much more difficult when several of them exist simultaneously, the assessment of such multiple errors often imposes a heavy computational burden on the receiver. The assumptions made regarding the statistical distribution of the measurement error also need to be met sufficiently well for successful error detection and exclusion to be achieved. Therefore, reliability monitoring result is not always fully trustworthy in degraded signal areas.

At the same time, signal redundancy is lacking in many cases, which restricts the ability to apply RAIM/FDE. Due to the mutual coupling of observations in the navigation solution, erroneous rejection of a good observation may also occur, especially in the presence of large or multiple measurement errors.

In situations where redundancy is

generally poor, however, we sometimes need to retain a measurement detected as erroneous in order to achieve better accuracy for the obtained position estimate as the result of improved satellite geometry provided by the additional measurement. Furthermore, if there are more erroneous observations than observations with acceptable quality, no amount of reliability monitoring can enhance the result. Thus, integrity monitoring can, in such cases, only mark the result as unreliable.

Another substantial challenge for successful FDE is proper variance modeling of the navigation measurements in order to obtain a sufficiently realistic covariance matrix for the adjustment problem and to detect the outliers in the degraded signal environment. Nevertheless, performing sufficient failure monitoring and isolation with necessary precautions is essential for improving reliability and accuracy in environments with compromised line-of-sight signal reception.

In the following discussion, we present the results of applying FDE techniques to a static urban canyon test as a general demonstration of the usefulness of RAIM/FDE in a typical signal-degraded area. The data for the test has been gathered in an urban canyon in Calgary, Canada, in an environment that contains lots of signals degraded by multipath.

The accompanying photo shows the environment in which the test took place and **Figure 1** presents satellite-wise the pseudorange errors with respect to signal strength. As can be seen, the pseudorange measurements include errors of several hundreds of meters. **Figure 2** presents the postprocessed results in terms of horizontal position error with respect to time of a weighted least-squares (WLS) adjustment, and the same with additional RAIM/FDE processing to enhance reliability.

The weighted scheme in the least-squares adjustment is based on down-weighting measurements with lower signal strengths. Applying basic statistical testing (here, iterative RAIM/FDE) results in the maximum error



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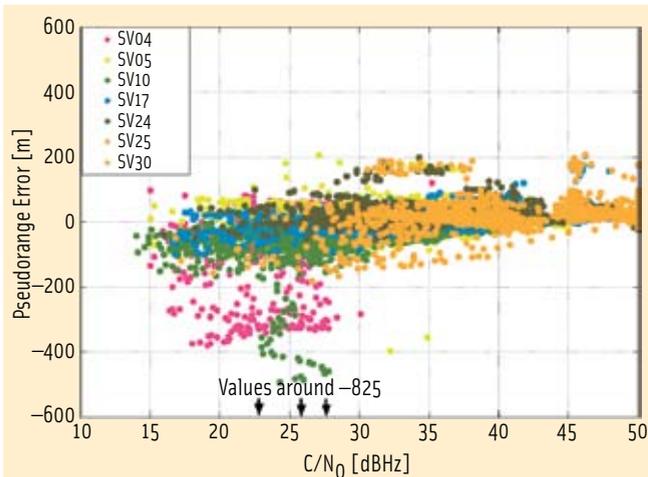


FIGURE 1 Pseudorange errors encountered in the test scenario

being decreased from almost eight kilometers to less than 200 meters while navigation solution availability is only decreased by seven percent due to some navigation estimates being marked as unreliable.

Thus, although fault detection is not always possible in difficult signal environments due

to an insufficient number of observables, when available it is always critical in securing significant enhancements to navigation reliability and accuracy as shown in the brief demonstration of Figure 2. FDE is an essential part of navigation integrity monitoring and reliability assurance — even in deteriorated signal environments.

Multipath mitigation and cross-correlation detection techniques are naturally needed in low-level receiver processing. However, methods used to enhance navigation reliability can also provide an additional security feature for ensuring a reliable position estimate, because maximum and average error levels significantly decrease when RAIM/FDE is applied.

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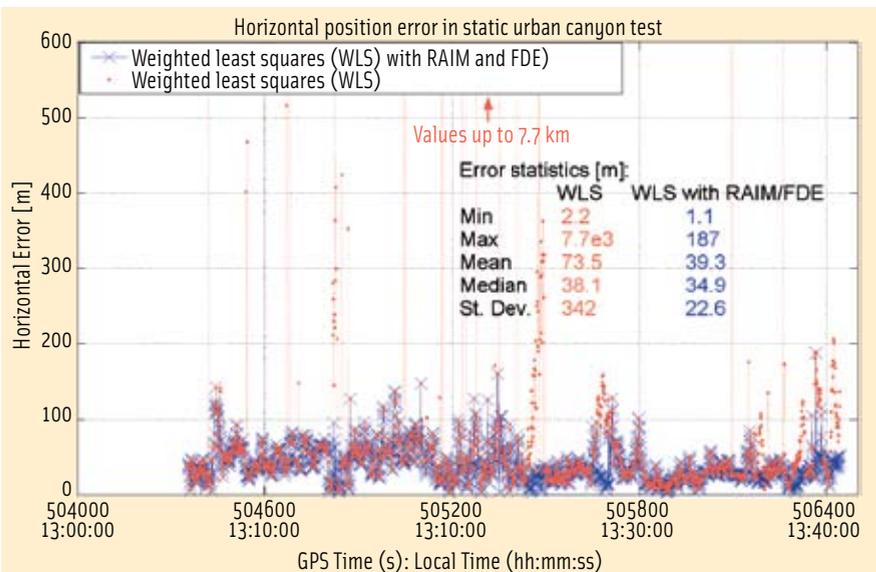


FIGURE 2 Horizontal position errors obtained with weighted least squares (WLS) and WLS with RAIM/FDE.

“What is carrier phase wind-up? What is its effect on GNSS performance/operation?”

Carrier phase wind-up refers to the change in measured carrier phase by a GNSS receiver caused by variations in the relative orientation between the transmitting and receiving antennas. This phenomenon

is of concern for positioning, navigation, and timing applications because the observed change does not represent a variation of transmitter/receiver range and, hence, will result in carrier phase-based ranging errors.

To understand this phenomenon, we must first consider some characteristics of electromagnetic (EM) waves and the specific EM waves transmitted by all GNSS constellations. An EM wave consists of orthogonal electric and magnetic fields that are transverse to the direction of propagation. **Figure 1(a)** illustrates this motion for an electric field.

Transmitted GNSS EM waves are polarized; that is, the lines of electric flux maintain a particular transverse orientation with respect to the direction of propagation. If the electric field oscillates in only one direction the wave is said to be linearly polarized. Referring again to **Figure 1(a)**, we have vertical linear polarization.

A wave can also be composed of two orthogonal plane EM waves of differing amplitudes and differing in phase. **Figure 1(b)** shows the electric fields for such a configuration, with the two waves having equal amplitudes and differing in phase by 90 degrees.

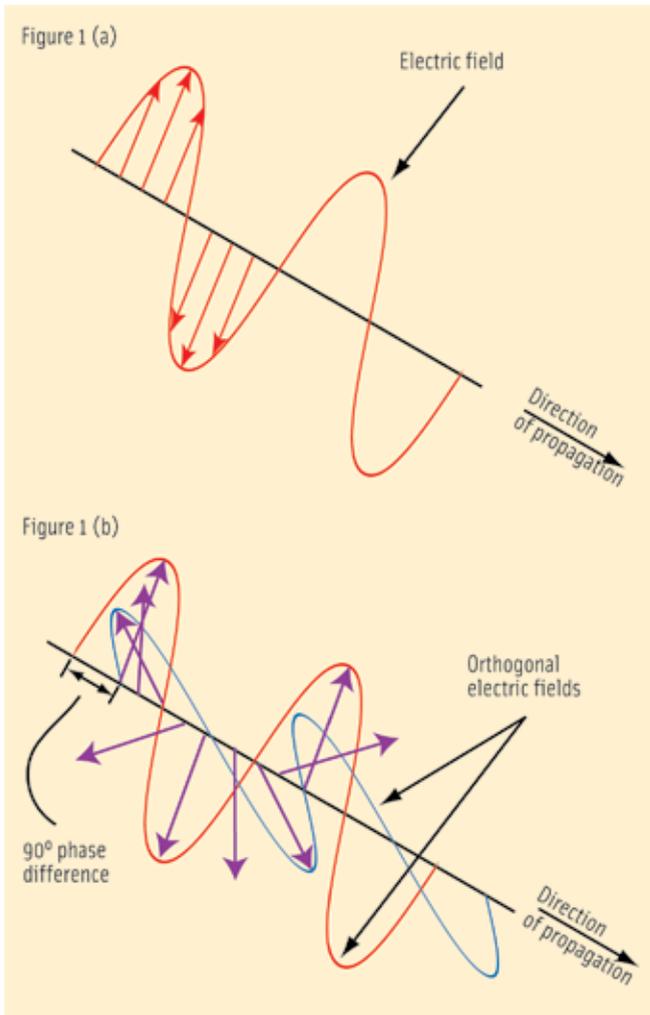


FIGURE 1 EM wave polarization. (a) Vertical linear polarization. (b) Right circular polarization (RCP).

Such a composite wave is referred to as a circularly polarized wave because the vector sum of the two waves rotates in a circle (shown by the purple arrows).

To further categorize these waves, if the wave appears to be rotating circularly counterclockwise approaching an observer, this it is called right circularly polarized. Similarly, an apparent clockwise rotation of an approaching wave is called left circularly polarized. GNSS EM waves are right circularly polarized (RCP).

Part of the rationale for this polarization is that the atmosphere (e.g., Faraday rotation in the ionosphere) can alter linear polarization orientation; therefore Earth-bound circularly polarized signals transmitted from space can be efficiently sensed by GNSS receiving antennas without significant power loss.

transmitter and receiver relative orientation result from a number of complex motions. In terms of transmitter rotations, GNSS satellites undergo two forms. The first involves slow rotations for solar panel orienting to the sun.

The second entails much faster rotations (yaw maneuvers) that occur during portions of the year (called eclipse seasons) when a satellite is eclipsed from the sun by the Earth. During such orbits, a satellite will execute rapid rotations after coming out from the shadow of the Earth and when it is closest to the sun to best orient its solar panels to the sun.

Receiver antennas may also undergo rotations in kinematic applications. This geometry and the carrier phase wind-up phenomenon's clear relationship between transmitting and receiving antenna orientation, as well as

Given this "corkscrew" motion of GNSS waves, we can easily imagine an apparent shift in a wave, if a relative rotation is introduced between the signal source and observer. Now going back to the first question of what is carrier phase wind-up? It is the change of GNSS receiver measured carrier phase due to an orientation change of either the transmitting or receiving antenna with respect to the other antenna. Other names used to describe this phenomenon are "phase wrap-up" and, if referring to receiving antenna rotation, "rotational Doppler."

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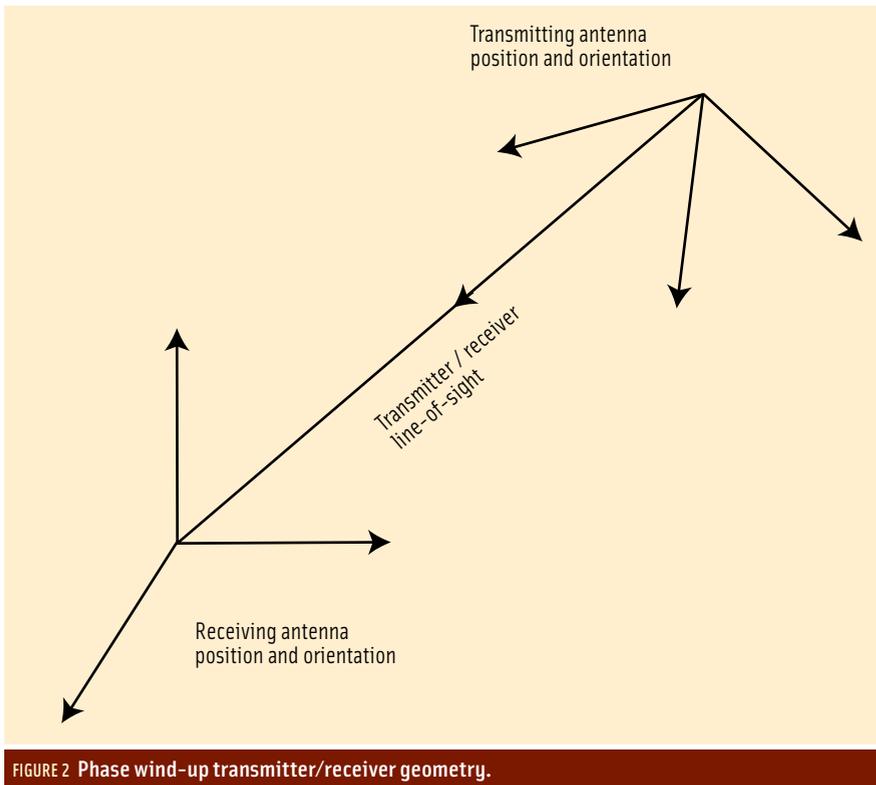


FIGURE 2 Phase wind-up transmitter/receiver geometry.

direction of line-of-sight is illustrated in **Figure 2**.

Given the geometric relationships described here, phase wind-up can be modeled reasonably well as a function of the satellite body coordinate unit vectors (requiring a realistic satellite yaw model, especially during eclipse periods), the local receiver unit vectors, and the satellite-receiver unit vector. When the transmitting and receiving antenna boresights are aligned, simple rotation needs to be considered. However, when the boresights are not aligned (as is usually the case), the orientation difference between antennas must be included in the calculation.

Phase Wind-Up's GNSS Effects

So what is the impact of phase wind-up on GNSS operation and performance? One reason for phase wind-up's lack of notoriety in terms of GNSS error sources is that it typically has been negligible in most applications. Let

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us discuss its effects on relative, then point, positioning.

In most relative positioning processing, double-differencing is employed. For the majority of applications, this differencing cancels the bulk of wind-up errors as the effects observed by either receiving antenna are very similar (consider Figure 2.)

Recent research has also pointed to residual wind-up adversely affecting ambiguity resolution for high-precision, short-baseline real-time kinematic GNSS positioning.

On very long baselines (i.e., thousands of kilometers), however, transmitter/receiver geometry is no longer similar, and phase wind-up-induced positioning errors can be as large as a few centimeters. For such long baselines, the relative receiver antenna orientation differs drastically due to earth curvature, and therefore inter-receiver differences result in non-negligible differential wind-up terms. As a result, when processing baselines on the order of hundreds of kilometers, phase wind-up can be essentially neglected, but the effect can reach up to a few centimeters for baselines that are thousands of kilometers long.

Recent research has also pointed to residual wind-up possibly adversely affecting ambiguity resolution for high-precision, short-baseline real-time kinematic GNSS positioning. (See Editors' Note at end of article for more information.) Again, double-differencing will negate the common-mode wind-up errors, but if a relative orientation difference exists between the receiving antennas (due to roving receiver dynamics), residual wind-up effects may prohibit ambiguity resolution.

For point positioning, the effect is typically ignored as antenna rotation results in a drift in the receiver clock

estimate. If however, the receiving antenna undergoes significant rotation, thus inducing an observed frequency shift, the receiver may have problems acquiring and maintaining lock.

For precise point positioning (PPP), in which satellite orbits and clocks are held fixed, not correcting for wind-up will result in decimeter-level positioning errors. Therefore to make the most of this contemporary processing methodology, carrier phase wind-up must be modeled.

Editors' Note: For information on the computation of phase wind-up and its effect on long baseline processing: Wu, J.T., and S.C. Wu, G.A. Hajj, W.I. Bertiger and S.M. Litchen (1993). "Effects of antenna orientation on GPS carrier phase." *Manuscripta Geodetica*, 18: 91-98

For information on the effect of phase wind-up on receiver acquisition and tracking: Tetewsky, A.K., and F.E. Mullen, "Carrier Phase Wrap-Up Induced by Rotating GPS Antennas," 52nd ION Annual Meeting (1996)

For information on the effect of phase wind-up on short baseline RTK processing: Kim, D., and L. Serrano and R.B. Langley, "Compensation of the Effect of Carrier Phase Wind-Up for Improving Performance of a GPS RTK Vehicle Navigation System," ION GNSS 2005

For information on the effect of phase wind-up on precise point positioning: Kouba, J., and P. Heroux, "Precise Point Positioning using IGS Orbit and Clock Products," *GPS Solutions*, 5(2): 12-28, (2001)

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