GPS + LORAN-C

Performance Analysis of an Integrated Tracking System

James Carroll

BEFORE GPS, EVEN BEFORE SATELLITES, there was LOng RAnge Navigation, or LORAN. Using terrestrial radio transmitters, it was developed during World War II for aircraft navigation. The wartime system evolved by the mid-1950s into the present day 100 kHz LORAN-C system. LORAN's standard principle of operation is hyperbolic positioning. A receiver measures the difference in times of arrival of pulses transmitted by a chain of three to six synchronized stations separated by hundreds of kilometers. The time-difference measurement derived from the signals of two stations, when multiplied by the speed of propagation of the signals, forms a line of position (LOP); the receiver could be anywhere on this line and give the same measurement. The geometrical form of this LOP is a hyperbola. Measurements using a third station provide another hyperbola, which intersects the first at the position of the receiver. There are many LORAN chains around the globe.

INNOVATION INSIGHTS
with Richard Langley

LORAN can help overcome some big-city navigation problems.

The LORAN system is being modernized to enhance its accuracy, integrity, availability, and continuity. Vacuum-tube transmitters are being replaced with solid-state designs and new primary frequency standards are being installed at transmitting stations. Manufacturers have developed compact LORAN receivers able to track multiple transmitters simultaneously and to automatically apply propagation bias corrections. Some receivers are integrated with GPS or other sensors. Receivers also feature improved antenna designs. Collectively, these improvements are known as Enhanced LORAN or eLORAN for short. Additionally, LORAN signals can be used to convey differential GPS corrections. Such a system is already operational in Europe.

Supported by the Coast Guard and the Federal Aviation Administration in the United States, a goal of eLORAN is to provide nonprecision approach for aviation users and harbor entrance and approach for marine users. Land users will benefit, too. Since LORAN has different signal characteristics from those of GPS, it can be used in locations where GPS cannot — by itself or in conjunction with GPS and other sensors. In this month's column, we look at a system that combines eLORAN with GPS and dead reckoning to overcome some of the problems in navigating in big cities.

Innovation features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 8 of this issue.

The rapidly increasing use of satellite navigation encompasses a broad range of civilian users. But not all users are sufficiently aware of important operational risks in using, say, the Global Positioning System (GPS) for positioning, navigation, and timing (PNT) applications. Systems that use GPS work very well when designed properly, and when sufficient robust ranging signals from the satellites are available. When the GPS signal cannot be used for PNT, appropriate backup systems and procedures should be used. Service providers are increasingly aware of the need to provide adequate system integrity, and to provide a seamless procedure for timely switches to and from the backup procedures. As a result, there is increasing interest in integrated PNT systems.

The U.S. Department of Transportation's Volpe National Transportation Systems Center in Cambridge, Massachusetts, has developed and installed vessel surveillance and tracking systems for maritime applications and is now applying this evolving technology to surface applications in urban areas in the U.S. Positioning and timing information is provided by a system that integrates GPS with enhanced LORAN-C (eLORAN) and dead reckoning (DR).

An important issue for the integrated GPS/LORAN system is how well LORAN and DR systems can supplement GPS when the GPS signal is not usable. Performance requirements vary with application, but a basic requirement in urban areas is reliable location of the vehicle at an intersection.

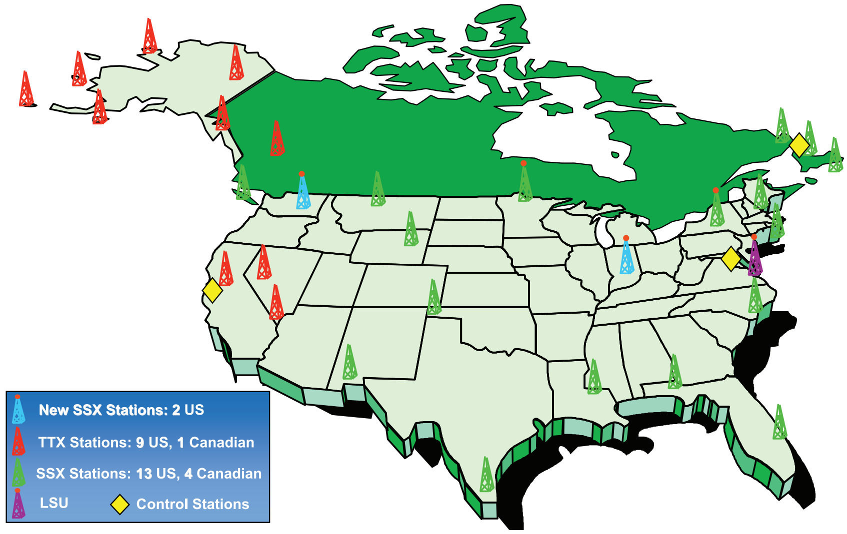
This article describes the design and uses of an integrated GPS/LORAN/DR tracking system, and presents results from performance evaluations conducted in New York City, including the lower Manhattan financial district. The results obtained show that eLORAN can be an effective backup to GPS in many areas of Manhattan, including some dominated by tall buildings or open tunnels where GPS is not able to function well.

LORAN-C

For the past several years, the U.S. Congress has authorized a total of about $140 million to enhance the U.S. LORAN-C system (**FIGURE 1**). At the same time, the evolving modernized LORAN-C system is being evaluated for potential use as a backup to GPS in many transportation infrastructure applications. These include navigation, positioning, surveillance, and also timing- and frequency-based applications in the air, at sea, and on land. Some of these extend beyond transportation into the communications, emergency response, and security domains.

Here, we will look at another extension of this technology to land applications in urban areas, using positioning and timing information provided by an integrated GPS/LORAN-C system. The original LORAN-C system, now about 60 years old, is nearing completion of a significant upgrade and enhancement effort funded by the Federal Aviation Administration (FAA). Known as Enhanced LORAN or eLORAN, it is a very complementary system to GPS. Its signals are much less susceptible to the interference that can impair GPS, and its broadcast frequency in the very-low-frequency (VLF) range of the radio spectrum has minimal line-of-sight issues. eLORAN has recently been shown to be an adequate backup system to GPS for many applications.

Legacy LORAN-C. LORAN-C (LOng RAnge Navigation-C) is a low frequency, terrestrial radionavigation system operating in the 90 to 110 kHz frequency band and providing coverage of U.S. coastal waters and the conterminous 48 states, part of Canadian coastal waters, the Great Lakes, most of mainland Alaska south of the Brooks Range, the Gulf of Alaska, the Aleutians, and into the Bering Sea. Coverage also exists in other regions of the world, including northwest Europe and the Far East. The LORAN-C system comprises transmitters, control stations, and system area monitors. The legacy LORAN-C chain is a basic system element. It consists of between three and six transmitting stations. Each chain has a designated master station and several secondary stations.



▲ **FIGURE 1** North American LORAN-C system architecture circa 2003. SSX: solid-state transmitter; TTX: tube-type transmitter; LSU: LORAN Support Unit. All transmitters in the conterminous 48 states are now of solid-state design.

The transmitters in the LORAN-C chain transmit in a fixed time sequence. The length of time in tens of microseconds over which this sequence takes place is termed the group repetition interval (GRI) of the chain. Chains are identified, differentiated, and discussed in terms of their GRI.

The LORAN-C transmitters emit pulses of radio frequency (RF) energy at precise instances in time. Position determination is based on the measurement of the difference in time of arrival of these RF energy pulses. Each master-secondary pair enables determination of one line of position, measured by the difference in arrival time of the two signals; a minimum of two lines of position is required to determine a location or "fix" on the Earth's surface.

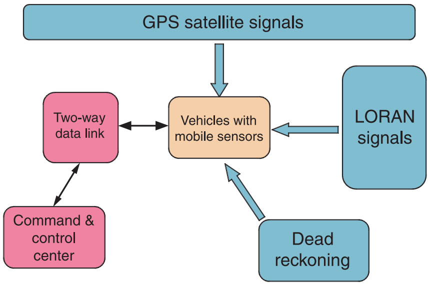
Precise timing and synchronization of the LORAN-C system are keys to system performance, and the LORAN-C transmitters incorporate highly accurate cesium clocks as standard equipment. The transmitters need to be synchronized with standard time references. The U.S. Naval Observatory provides the time synchronization to Coordinated Universal Time (UTC).

eLORAN. The modernized U.S. LORAN-C system also operates in the same frequency band as legacy LORAN-C and is synchronized to UTC. However, this modernized system, now almost 85 percent complete, has a recapitalized infrastructure and a new communication modulation method that enables operations that satisfy the accuracy, availability, integrity, and continuity performance requirements for non-precision aircraft approaches and harbor entrance and approaches, as well as the requirements of non-navigation time and frequency applications. Required changes to the current system include modern solid-state transmitters, a new time and frequency equipment suite, modified monitor and control equipment, and revised operational procedures that new receiver technology can exploit.

Integrated Tracking System

The FAA, with Volpe Center support, established a project to assess the performance of integrated GPS/LORAN tracking systems in the urban environment, where GPS signal quality varies greatly. Marine mobile transponder units were re-configured to utilize land-based digital data links and to process eLORAN positioning and timing signals. State-of-the-art LORAN receivers were used in the evaluations, along with receivers providing both un-augmented and augmented GPS (the FAA Wide Area Augmentation System — WAAS — and Nationwide Differential GPS). The receivers were used in a mobile system that can broadcast information to a command center or other mobile units in real time.

The Volpe Center has in the meantime



▲ **FIGURE 2** Tracking with GPS/LORAN: The Volpe Center mobile test bed

been developing and extending to diverse applications a GPS-based tracking and situation display technology that can be used not only operationally with the core tracking system, but also can support the performance assessment of candidate tracking system architectures. The system is called Transview.

Volpe has recently installed customized versions of Transview in several waterways worldwide. This not only includes systems that provide important navigation and tracking information for commercial and personal users, but also systems that enhance maritime security by providing increased situational awareness. A new generation of transponder equipment is being developed for operational use by harbor protection forces in both domestic and foreign ports.

The surveillance and tracking technology embodied in Transview is based on two important ideas: (1) availability of navigation signals in space, and (2) a two-way communications link between each mobile unit and similarly equipped fixed or mobile units in the coverage area. The Volpe Center system was designed for surface applications involving several mobile units on either land or water. Positioning and timing signals are provided primarily by GPS, but tracking experience in the urban environment dictates the use of an independent backup radionavigation system, and LORAN is a strong candidate to back up GPS.

TABLE 1 Transponder Components

Starlink GPS
Reelektronika Loradd integrated GPS/WAAS/LORAN
Locus Satmate 1030, with rate gyro and H-field antenna
u-blox SBR-LS dead reckoning and GPS output
Nextel or Verizon data link

The tracking and display application described in this article represents a new extension of the Volpe-developed technology because it now supports:

- Operation in a land environment, including the "urban canyon," so-called because of the disruptive effects of tall buildings on radionavigation; and
- Integration of GPS, LORAN, and dead reckoning.

GPS/LORAN System. An overview of the integrated GPS/LORAN tracking system is shown in **FIGURE 2**. Note that the system also uses dead reckoning, which was installed specifically for testing in the urban environment.

The test-bed vehicle is a Volpe Center minivan, already available for this type of use. The baseline equipment also includes provision for a data link to a fixed facility with the proper transmit-receive interface. For marine applications, marine band very-high-frequency radios are used, and for land and urban operations, data services from both Nextel and Verizon cellular telephone networks may be used as dictated by their respective network coverage.

The equipment generates text-formatted output that adheres to the National Marine Electronics Association (NMEA) 0183 standard. The original purpose of this system was tracking of multiple water-borne targets. In this adaptation, which compares performance of multiple systems, there are many positioning outputs of interest, each with its own "idea" of where the test van is located. Each of the outputs thus becomes a target. The heart of the system is the integrated GPS/LORAN system, supplemented by DR and consisting of a pair of LORAN receivers including one with an integrated GPS receiver and a pair of GPS receivers including one with DR output. The Reelektronika Loradd and Locus Satmate 1030 receivers each provide multiple NMEA records for both GPS and LORAN, and the DR system provides two GPS NMEA records.

TABLE 1 summarizes the components used in the tests. There is considerable flexibility in configuring the outputs of interest, depending on the test objectives.

Data Extraction. Each record of the outputs is a separate message or data log that can be produced by a given receiver. While the NMEA standard is fairly precise, it is flexible enough to allow minor format variations that can help place a message with its source. The Transview software, TV32, also allocates data-port identifications to avoid confusion. In addition, because most messages do not have a time stamp, TV32 will add one if necessary.

Another aspect of the data extraction effort involves the nature of much of the LORAN NMEA data. LORAN performance metrics can be station-specific, unlike the ensemble nature of most of the GPS metrics (that is, these are not satellite-specific in general). This means that, since between five and nine LORAN transmitter signals can be tracked in New York City at any one time, this number times the six or so performance metrics of interest add up to a rather large accounting challenge — large numbers of variables per update cycle. One New York City analysis generated 93 distinct output variables of interest, including the various time variables.

Examples of LORAN station-specific metrics (one for each GRI from a particular transmitter being "read" by the receiver) are: horizontal dilution of precision, signal quality, time of arrival, time difference, signal-to-noise ratio, and envelope-to-cycle difference. Update cycles range from 1 to about 5 seconds.

Finally, the NMEA 0183 standard allows for proprietary data logs. Reelektronika, for example, has provided a proprietary header "$PRLK" followed in the second field by specific internal sub-headers and receiver-specific data. The Loradd receiver uses this header, for example, to log its internally generated GPS-conditioned LORAN fix. Depending on system configuration, from 10 to 20 data logs per second can be recorded. This produces large amounts of data over, say, a 5-hour data gathering session. It is not uncommon for a 4- or 5-hour data run to generate a 50 megabyte text file. The NMEA messages were parsed into Matlab scripts for the analysis presented in this article.

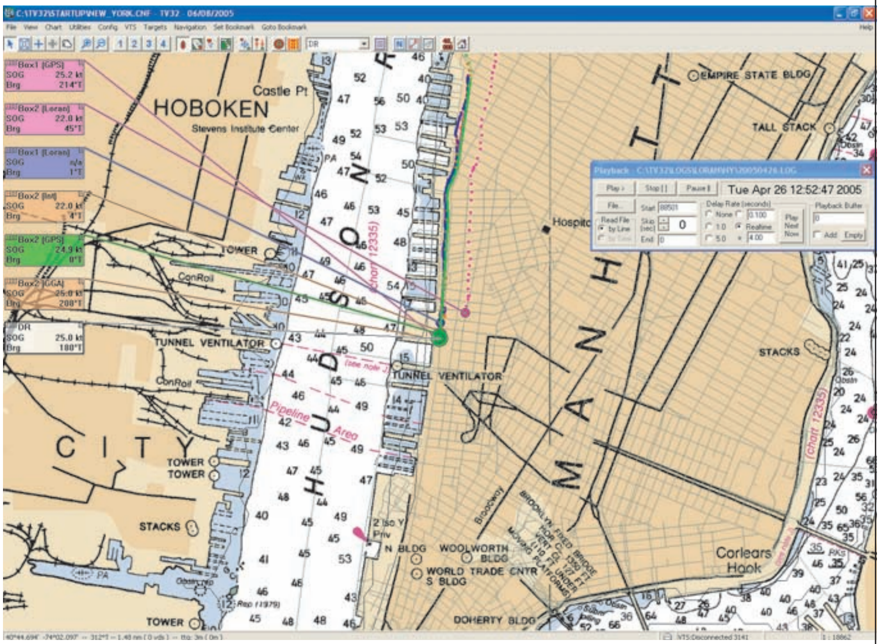
Performance Assessment

GPS performance in the urban canyon is well known to be very poor. When combined with a dead-reckoning system, however, most of the location issues are effectively mitigated. The Wall Street area of New York City is exceptionally difficult due to the skyscrapers and narrow streets that characterize the area. Poor geometry results when only a small portion of the sky is visible to the GPS antenna. Multipath, the reflection of radionavigation ranging signals, is also a major detriment to acceptable performance.

LORAN operates in the VLF band, making the LORAN signal less subject to blockage than GPS. LORAN also has a ground surface conductivity property that enables its signal to follow terrain and reach areas blocked to GPS. However, LORAN also is plagued by multipath. The advance in LORAN technology in recent years raised again the possibility of using LORAN as a backup to GPS within a large city. Using only LORAN to locate reliably a vehicle on a particular corner of any New York block remains an unrealistic goal. However, detailed testing may yield data that can point to a valid use for LORAN in this environment.

Initial integrated system tests in Boston's financial district confirmed that LORAN will not reliably outperform GPS. There are areas where LORAN signals can persist longer than GPS, but this probably won't justify LORAN as a primary backup to GPS in a large city. A DR system was acquired and added to the integrated tracking system, so that a "truth" reference could be established for quantifying GPS and LORAN performance more exactly.

Data were gathered in New York City in April 2005. The tests covered not only the Wall Street area, but more benign locations in Manhattan, the Bronx, and Brooklyn. Based on test data examined to date, two areas of interest will be discussed in this article: the west side of Manhattan and Wall Street. The west-side data are more typical of an "average" performance zone found in many cities. There aren't enough tall buildings to significantly disrupt DR, GPS, or LORAN performance. DR can provide the "truth" reference for analysis of the west-side data. The Wall Street area is possibly the most severe urban canyon anywhere. A DR capability is necessary for reliable tracking near Wall Street.



▲ **FIGURE 3** Heading south on 11th Avenue

Potential users of integrated tracking systems in New York City have differing requirements. Reliable location of the nearest intersection to the vehicle is likely a foremost requirement, and it will be the implied standard in the subsequent analysis.

West-Side Results. **FIGURE 3**, a computer display using TV32, shows a very good performance area both for GPS and LORAN. The van is just north of the Holland Tunnel entrance. Data "bubbles" in the upper left corner depict the simultaneous tracking of seven "targets." These include two LORAN, one DR, one integrated GPS/LORAN, and three GPS outputs.

One of the two LORAN outputs (Locus Satmate) is tracking right over the GPS solutions in Figure 3, indicating some possibilities that need further examination. So-called additional secondary (phase) factors (ASFs), which account for the effect of ground conductivity, are being applied here, but they may be supplemented in the Satmate receiver with an integrated GPS/LORAN solution. A fortuitous combination of LORAN self-canceling errors is possible but unlikely.

The second LORAN track is very evident. It is the maroon track shifted mostly east of the others by a few hundred yards (meters). This is typical of observed LORAN performance in the great majority of test locations. It is indicative of a LORAN solution unaided by ASF corrections.

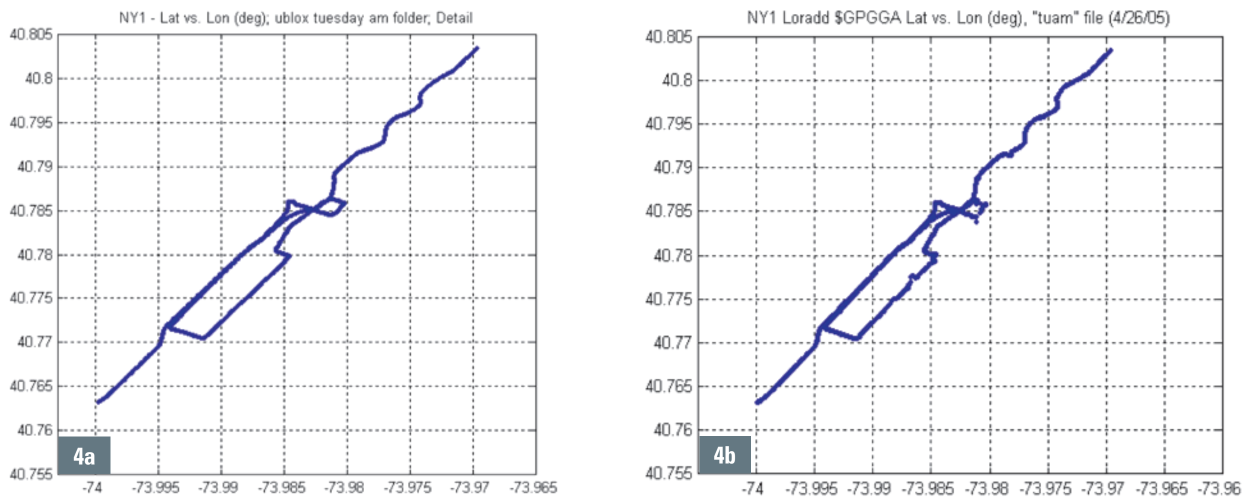
FIGURE 4a shows a Matlab plot of the DR-derived position in an area just north of the area shown in Figure 3.

Loradd Receiver. The Loradd integrated receiver produces its own GPS output, which matches the DR result very well (**FIGURE 4b**).

The Loradd receiver also generates LORAN outputs, including basic LORAN and a GPS-conditioned LORAN. The addition of these outputs to the Loradd GPS output seen in Figure 4b is shown in **FIGURE 5**. The GPS output is blue, as before, and also more granular, to match slower fix times for the LORAN receivers (5-second updates for LORAN outputs, 1 second for GPS).

The red plot, which matches the reference GPS plot very well, is the Loradd GPS-conditioned LORAN solution. The basic, or pure, LORAN output (the green plot) from the Loradd receiver does not have real-time ASF updates like the Satmate in Figure 3. Its offset with respect to GPS is normal to good, except where the loop is. A longitude error is prominent in the latitude band 40.770 to 40.785 degrees.

The number of LORAN transmitters



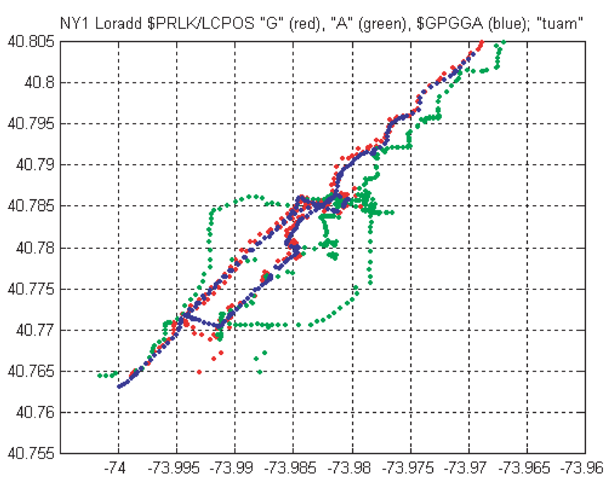
▲ **FIGURE 4a and 4b** Dead reckoning (a) and Loradd GPS (b). Latitude vs. longitude, West Side (degrees).

tracked by the receiver falls below five only for an instant, another indicator of very good performance along Manhattan's west side (since LORAN is a two-dimensional positioning system, fewer transmitters are needed for a good LORAN fix than are needed by GPS receivers).

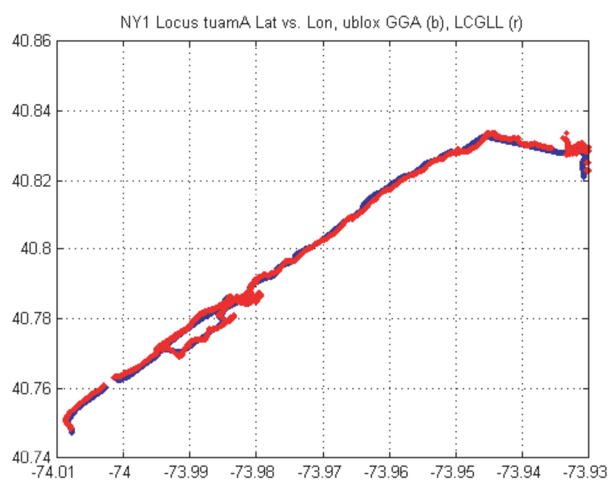
Satmate Receiver. As stated earlier, the Satmate receiver produced excellent LORAN results using dynamic ASF corrections, and possibly also some GPS conditioning. The performance was captured on TV32 (Figure 3), and Matlab plots reaffirm this result. **FIGURE 6** shows latitude vs. longitude plots for the DR baseline (blue) and the Satmate LORAN (red).

Wall Street Results. The most significant tracking system performance difference between the west side of Manhattan and the Wall Street area is the regular loss of lock on GPS and, to a lesser degree, LORAN ranging signals to enable a reliable fix. In anticipation of this situation, the DR system was added to maintain a "truth" location performance reference for both GPS and LORAN. The u-blox DR system can operate for a while without GPS, as it has an odometer sensor for along-track distance and a rate gyro for bearing changes.

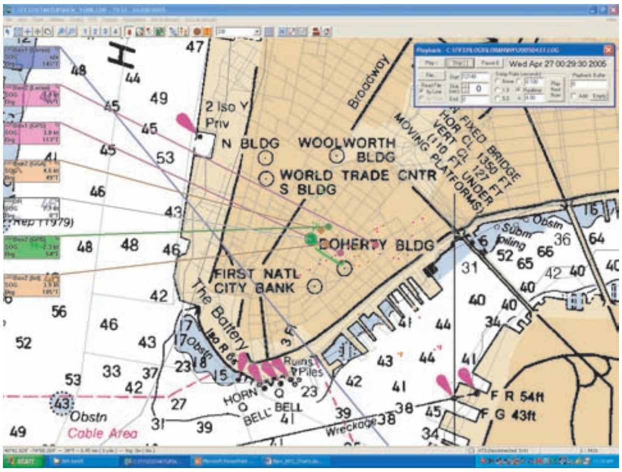
FIGURE 7 dramatizes the markedly different performance level relative to that in Figure 3, shortly after entering the Wall Street area from the south (it isn't possible now to actually drive along Wall Street, for security reasons). The GPS and LORAN solutions have become fully unusable. One LORAN solution has gone off the map. Dead reckoning, the green track just below "DOHERTY" in Figure 7, is active and working well at this point. As long as a good GPS signal is available, the DR output will be fixed to GPS. Volpe Center testing in New York City indicated that, when the DR had no GPS fix for about 30 to 45 minutes, the unit's GPS input in fact became destabilizing.



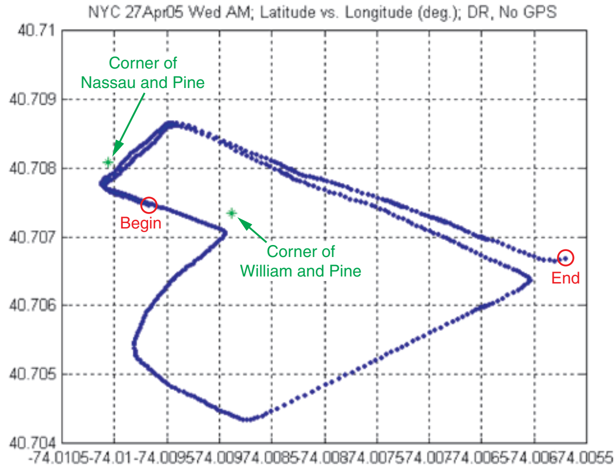
▲ **FIGURE 5** Loradd GPS (blue, cf., Figure 4b), LORAN (green), and GPS-conditioned LORAN (red). Latitude vs. longitude plot, West Side (degrees).



▲ **FIGURE 6** Dead reckoning (blue) and Satmate LORAN (red). Latitude vs. longitude, West Side (degrees).



▲ **FIGURE 7** Onset of blockage and multipath effects near Wall Street.



▲ **FIGURE 8** Recorded DR track, without GPS aiding, Wall Street. Data record began at the red circle on the left, and ended on the right-side red circle. The two green asterisks marking the Pine Street intersections with William and Nassau streets are located by averaging the precision DeLorme/Google data.

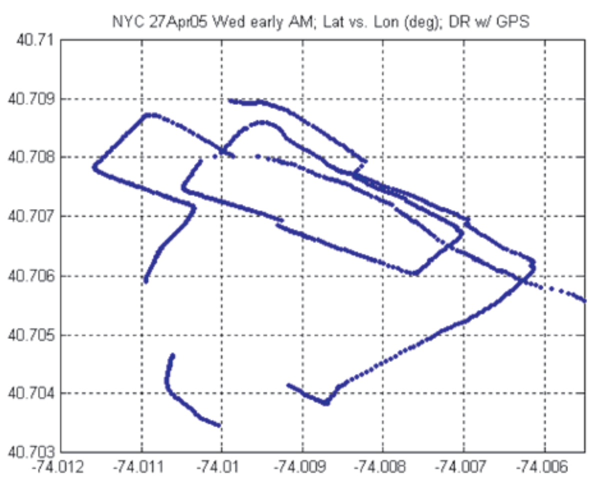
DR and Truth Reference. DR performance for the system examined deteriorates in two ways. The more common way is due to drift error in the heading gyro output. This error grows steadily over time unless the GPS signal has a good fix often enough to keep the gyro error contained. In areas like Wall Street, where GPS can be unreliable for extended periods, there is no check on this error. The Volpe Center test plans called for a few circuits of the Wall Street area, in part to add to the difficult environment.

The second problem may be more specific to the u-blox DR unit used in the Volpe tracking system. For some time after the GPS signal became unusable for navigation, it apparently was still being used by the DR unit. Doing so added significantly to the overall DR system error.

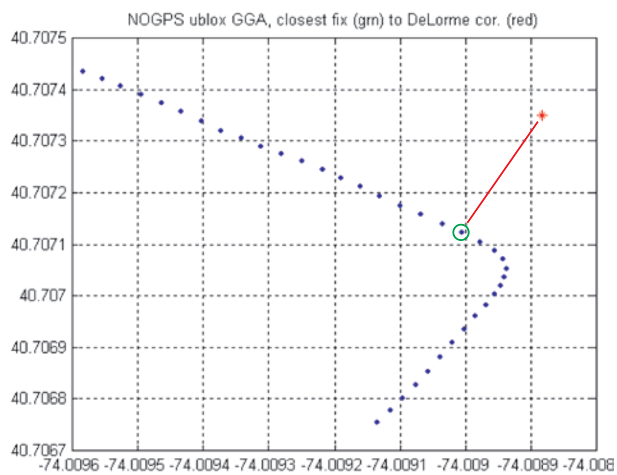
Analysis of Wall Street area performance in the Matlab environment proves insightful. The test area of interest is bordered roughly by Nassau, Liberty, Pearl, William, and Pine Streets. Wall Street is just south of Pine.

The analysis data shown in **FIGURE 8** covered more than a full circuit in the test area, albeit not the complete test run. The figure shows the DR location output without GPS aiding (GPS antenna detached from the DR unit.). The scenario examined here began in time at the left-side red circle and continued clockwise to the right-side red circle. The effect of gyro drift, to be examined further below, is evident here also. At the end point in Figure 8, the DR location is closer to the wrong intersection. The final leg to the stop point should be on top of the adjacent leg, as they both are on Liberty Street.

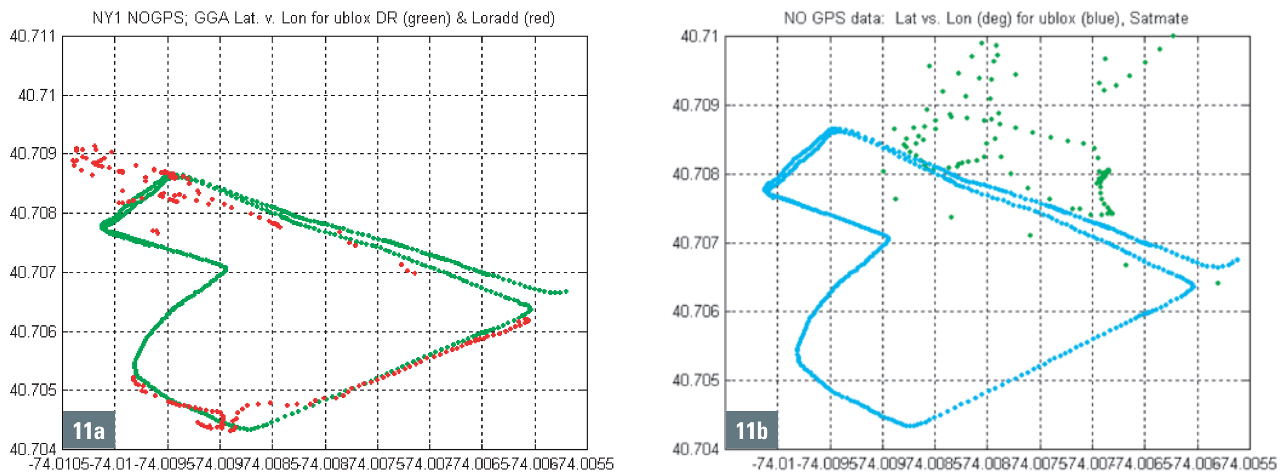
Green asterisks in this figure mark intersections determined within about 5 feet (1.5 meters) using DeLorme and Google Earth measures. While the precision between the DeLorme and Google measurements is very high, the absolute location of the intersec-



▲ **FIGURE 9** Recorded DR track, with GPS aiding, Wall Street. This run repeats the run shown in Figure 8.



▲ **FIGURE 10** Recorded DR track, without GPS aiding, Wall Street (see Figure 8). The closest offset distance (red line) to the "surveyed" DeLorme/Google point is about 130 feet (37 meters).



▲ **FIGURE 11a and 11b** GPS (a) and LORAN (b) location results vs. the DR reference, Wall Street.

tions was not validated.

Intersection location is an important capability for an urban tracking system, and DR components need to provide an adequate truth reference when location components like GPS or LORAN cannot. **FIGURE 9** shows a prior test run that is essentially the same scenario as that shown in Figure 8. The Figure 9 test began at least 30 minutes after the DR equipment was activated and using GPS aiding. The de-stabilizing effect of not disengaging the GPS antenna after GPS had been lost for several minutes is evident.

When the GPS antenna is removed (or perhaps some tuning of the DR system done), DR without GPS aiding is a reasonable truth reference until the gyro drift effect grows too large.

Looking closer at the DR with no GPS aiding track (**FIGURE 10**), note that the DR track corner is not the closest geometrical point to the reference (red asterisk).

GPS and LORAN Performance. As stated above, a reasonable truth reference for the Wall Street results addressed here is the track produced by DR without GPS aiding (Figure 9). GPS and LORAN performance for this scenario is much worse, not surprisingly, than unaided DR (even unaided DR suffers from gyro drift effects near Wall Street after about 45 minutes). **FIGURE 11a** shows the baseline DR reference (green) and the Loradd GPS (red) tracks, and **FIGURE 11b** shows the same DR baseline (now blue) and the Satmate LORAN (green) tracks. Axis limits hide the fact that there were about twice as many "good" LORAN points as GPS points. Of course, none of the non-DR points seen in this figure have much value, except the Loradd track at the bottom of Figure 11a. Other performance metrics were investigated, including "distance into scenario," but space considerations preclude their discussion here. For details, see the paper cited in "Further Reading."

Conclusions

LORAN is no cure-all for the environments in which these systems were tested, but it continues to offer promise in mitigating GPS loss. The two LORAN receiver systems tested in New York City showed inconsistent but promising performance in some sections of the city, including the difficult financial district.

It still appears that LORAN would be of little help in the Wall Street area unless aided by DR. A real-time optical system could calibrate the digital map measurements. A real advantage to LORAN would be realized when jamming or extended unavailability of GPS occurs. In this case, a LORAN/DR combination could be beneficial in most areas of Manhattan, especially for emergency, rescue, or security operations. This would set a framework for even better performance as LORAN technology evolves. Finally, LORAN's edge on GPS in signal penetration is evident in areas like the open tunnel under the United Nations Building. The DR system, blocked from GPS for several minutes, performed well in this area of Manhattan.

When the urban canyon and to some extent the jamming environments are better understood, and when eLORAN design details are fully implemented in a production receiver, LORAN should become an even more valuable element in the future radionavigation and timing mix.

Acknowledgments

This article is based on the paper "Performance Analysis of an Integrated GPS/Loran-C Tracking System" presented at The Institute of Navigation National Technical Meeting, held in Monterey, California, January 18-20, 2006. The author wishes to thank Mitch Narins of the FAA for his leadership on this important project, and Dr. Ben Peterson of Peterson Integrated Geopositioning, LLC, for his technical insight. The statements and opinions in this article are the author's only, and they do not necessarily reflect policy or opinions of the U.S. Government. ⊕

JAMES CARROLL has been at the Volpe Center for 15 years. He is working on integrated navigation systems in the areas of performance analysis and integrated system testing. Prior activities at the Volpe Center include directing a successful project to install a vessel communications, tracking, and navigation system at the Panama Canal. He also was a co-author and primary editor of the Volpe Center GPS vulnerability assessment. He has degrees in aeronautics and astronautics from the Massachusetts Institute of Technology and Stanford University, and is a member of The Institute of Navigation and the Institute of Electrical and Electronics Engineers.

FURTHER READING

Volpe Center Integrated Tracking System

"Performance Analysis of an Integrated GPS/Loran-C Tracking System" by J. Carroll in *Proceedings of The Institute of Navigation 2006 National Technical Meeting,* Monterey, California, January 18–20, 2006, pp. 615–628.

"Use of an Integrated GPS/Loran Tracking System in the Urban Environment" by J. Carroll, H. Wychorski, K. Chin, D. Phinney, and B. Long in *Proceedings of the 61st Annual Meeting of The Institute of Navigation,* Cambridge, Massachusetts, June 27–29, 2005, pp. 354–362.

LORAN-C

Loran-C User Handbook, Commandant Publication COMPDTPUB *P16562.6,* U.S. Coast Guard, 1992. Available online: http://www.navcen.uscg.gov.

Specification of the Transmitted Loran-C Signal, Commandant Instruction COMDTINST M16562.4A, U.S. Coast Guard, 1994. Available online: http://www.navcen.uscg.gov.

Loran-C Operations Manual, NAVCEN Instruction M16562.1, and changes dated June 25, 1999, U.S. Coast Guard.

Enhanced LORAN-C and GPS

Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications, prepared for the Federal Aviation Administration Navigation Services Directorate, March 2004.

Earlier Study on Use of LORAN-C, GPS, and DGPS in Built-Up Areas

Evaluation of Radionavigation Systems in an Urban Environment by B. Peterson, CAS report no. 14–94, U.S. Coast Guard Academy Center for Advanced Studies, New London, Connecticut, September, 1994.

"Evaluation of Radionavigation Systems in an Urban Environment" by B. Peterson, M. McKaughan, L. Miller, and S. Bartlett in *Proceedings of The Institute of Navigation 1995 National Technical Meeting,* Anaheim, California, January 18–20, 1995, pp. 293–302.

Dead Reckoning and GPS

"Continuous Navigation: Combining GPS with Sensor-Based Dead Reckoning" by G. zur Bonsen, D. Ammann, M. Ammann, E. Favey, and P. Flammant in *GPS World,* Vol. 16, No. 4, April 2005, pp. 47–54.

Corrections

Some information in the June 2006 Innovation column "Searching for Galileo" was incorrect. The date of GIOVE-A's launch was December 28, 2005. Equation 4 should read: $I_j = A_I \{b_{mod(j-m,4092)} d_{floor[\{j-m\}/4092]} - c_{mod(j-m,8184)} s_{mod(floor[\{j-m\}/8184],25)}\} + V_{Ij}$ for $j = 0, 1, 2, \ldots$

The sentence on page 71 should read: "We chose the new U_m reference period to be the s_1 reference period."

GPSWorld.com – Setting Our Sites On You!

GPSWorld.com now features industry-specific microsites for faster access to focused news and analysis surrounding Global Positioning System, Galileo, and other positioning and navigation-related technologies.

Survey & Construction | Military & Government | Avionics & Transportation | LBS | Ag & Natural Resources | Utilities & Communications | System Design & Test

- Survey & Construction
- Military & Government
- Avionics & Transportation
- Location-Based Services
- Agriculture & Natural Resources
- Utilities & Communications
- System Design & Test

Log on today and discover why GPSWorld.com is the trusted source for 120,000 high-tech professionals in the GPS and GNSS community. ***www.gpsworld.com***

GPS World