Performance Analysis of an Integrated GPS/Loran-C Tracking System

James Carroll, Ph. D.
U.S. DOT Volpe National Transportation Systems Center

BIOGRAPHY

James Carroll has been at the U.S. Department of Transportation/Volpe Center for fifteen years. Presently, 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 in the Panama Canal. Dr. Carroll also was a co-author and primary editor of the Volpe Center GPS vulnerability assessment He has degrees in aeronautics and astronautics from MIT and Stanford, and is a member the Institute of Navigation and the IEEE. In 2002, he was awarded the International Loran Association Medal of Merit.

ABSTRACT

The rapidly increasing use of satellite navigation has begun to encompass a broad range of civilian users. The uses cover not only navigation, but also tracking and frequency/timing applications. As the uses grow, so does reliance - and a potential for unacceptable vulnerability if there is over-reliance on GPS, or any other sole means system. Systems that use GPS work very well when designed properly, and when sufficient robust ranging signals from the satellites are available. When a user receiver is unable after a certain period to form a valid positioning, navigation and timing solution, the use of appropriate backup systems and procedures is necessary.

Over the past several years the Volpe Center has installed vessel tracking and surveillance systems in several waterways worldwide. This includes systems to enhance maritime security by providing increased situational awareness. Currently, the Volpe Center is completing the installation in the Mediterranean of a new generation of transponder equipment for use by harbor protection forces in both domestic and foreign ports. This evolving technology is also being applied to surface applications in urban areas of the U.S., using positioning and timing information provided by an integrated GPS/Loran-C/dead reckoning system.

A key element in the integrated system is the enhanced Loran-C (eLoran) receiver. eLoran, an upgrade of the current Loran network in the U.S., has recently been shown to be an adequate backup system to GPS for many applications. It is a complementary system to GPS in that its signals are much less susceptible to the interference that can impair GPS, and its broadcast frequency encounters fewer line-of-sight issues. The eLoran signal also is now available in all of the 48 conterminous U.S. states, and basic Loran-C is available in much of Alaska, and elsewhere in the world. eLoran provides two-dimensional (Earth surface) positioning and precise time information for legacy system users as well as for those who have receivers that can exploit the features of eLoran.

The Volpe Center system discussed in this briefing has been tested recently in difficult urban environments (including the "urban canyons" of New York City), and in a jamming environment at military test exercises in New Mexico. Test results confirm the ability of eLoran to meet important maritime and land performance requirements in many areas where GPS is not able to function well. The dead reckoning system component also is an asset, but not all DR designs will operate effectively if there is an extended absence of a GPS fix.

I. INTRODUCTION

For the past several years, the U.S. Congress has authorized $140M to enhance the U.S. Loran-C system (Figure 1). At the same time, the evolving eLoran

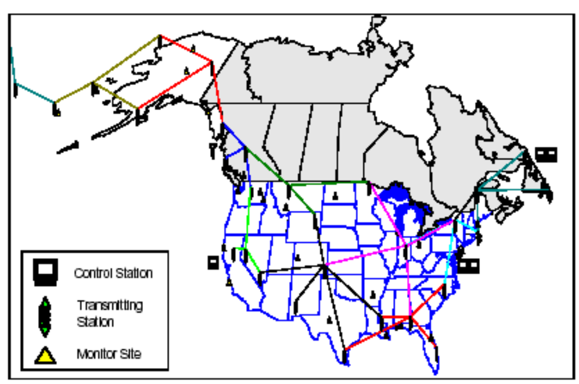


Figure 1. Loran-C System Architecture

system is being evaluated for potential use as a backup to GPS in many transportation infrastructure areas. These include navigation, positioning, surveillance, and timing and frequency based applications on air, sea and land. Some of these extend beyond transportation into communications, emergency response, and security applications.

The Volpe Center has in the meantime 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 surveillance and tracking technology 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 were provided by GPS, but tracking experience in the urban environment dictates the use of an independent backup radionavigation system.

The following classes of maritime-specific applications have been developed:

- Waterway-specific commercial operations
- Waterway operations utilizing the Automatic Identification System (AIS) standard promulgated by the International Maritime Organization, a U.N. agency
- Asset protection operations using the Volpe-developed Vessel Identification and Positioning System (VIPS).

The AIS system now running in the St. Lawrence Seaway is the first such installation in the Western Hemisphere. The VIPS is being used to support U.S. Navy asset protection in foreign ports, and in protecting the inner harbor LNG (liquid natural gas) operations in Boston.

The tracking and display application described in this paper represents a new extension of the Volpe-developed technology for these reasons: (1) operation in a land environment, including the "urban canyon," so-called because of the disruptive effects of tall buildings on radionavigation.; and, (2) the integration of GPS and Loran-C.

1.1 Loran-C Enhancement Project

A project was set up with the objective to assess the performance of integrated GPS/Loran surveillance systems in urban areas, where the GPS signal quality varies greatly, and may cause unacceptable data interruptions. In this environment, eLoran may provide operational benefits in many uses by mitigating the loss of GPS as a backup system.

Marine mobile transponder units were reconfigured to utilize land based digital data links and to process eLoran positioning and timing signals. Two state-of-the-art eLoran receivers were used in the evaluations, along with both un-augmented GPS, and GPS augmented by Nationwide Differential GPS and by Wide Area Augmentation System (WAAS) signals. The receivers were incorporated into a mobile system that can broadcast information to a command center or similarly equipped mobile units in real time. Loran performance is supplemented by using differential Loran corrections, an H-field antenna, and by a single axis gyroscope that smoothes Loran receiver output during high rate-of-turn maneuvers. After some initial testing in the Boston area, it was evident that adding a dead reckoning system would be of value in assessing GPS and Loran performance.

Data processing and presentation are controlled by software that has been steadily adapted and improved over many years of development and use in many different applications, heretofore exclusively maritime. Transview (TV32) is the Geographic Information System (GIS) software used as the tactical display for the transponder outputs. TV32 integrates radar, marine Automatic Identification System (AIS), and radio-navigation (e.g., GPS or Loran-C) transponder tracks on a single Windows-based situation display. The display content and presentation is readily customized for specific uses. In addition to the ability to display the real-time position tracks of all participating vehicles, TV32 continually records all of the data received from the mobile units. eLoran is now described in more detail.

The current ("legacy") Loran system. This Loran description is derived from Reference [1]. Loran-C is a low-frequency, terrestrial radionavigation system operating in the 90- to 110-kHz frequency band [2], [3], [4]. The U.S. Loran-C system comprises transmitters, control stations, and system area monitors (SAM) (Figure 1). The Loran-C "chain" is a basic element and consists of between three and six transmitting stations. Each chain has a designated master station and several secondary stations. Some stations have only one function (i.e., to transmit a master or secondary signal in a particular chain), but many transmitters are dual-rated, meaning that they transmit a signal in one chain and another signal for a second chain. The transmitters in the Loran-C chain transmit in a fixed 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.

Precise timing and synchronization of the Loran-C system are also important, and the Loran-C transmitters incorporate extremely accurate cesium clocks as standard equipment. The Loran-C transmitters need to be synchronized with standard time references. The U.S. Naval Observatory (USNO) provides the time synchronization to Coordinated Universal Time (UTC) for the Loran-C chains [5].

eLoran. The modernized Loran system continues to be a low-frequency, terrestrial navigation system operating in the 90- to 110-kHz frequency band and synchronized to coordinated universal time. However, this modernized Loran system 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 approaches and harbor entrance and approaches, as well as the requirements of non-navigation time and frequency applications [5]. 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.

Legacy Loran-C presently is a supplemental system for enroute navigation in the U.S. National Airspace System. It also is an accepted system for maritime navigation in the Coastal Confluence Zone, and a Stratum 1 frequency standard (along with GPS and cesium clocks) that provides time to within 100 nanoseconds of UTC, referenced to the U.S. Naval Observatory standard.

II. TRACKING SYSTEM DETAILS

An overview of the integrated GPS/Loran tracking system is shown in Figure 2. Note that the system also utilizes dead reckoning.

The test bed vehicle is a Volpe Center mini van, already available for this type of use. The van also had just about all of the electronics equipment needed for GPS-only systems: antennas, power supplies, controllers, display laptops, etc. The baseline equipment also includes provision for a data link to a fixed facility with the proper transmit-receive interface. For the marine applications,

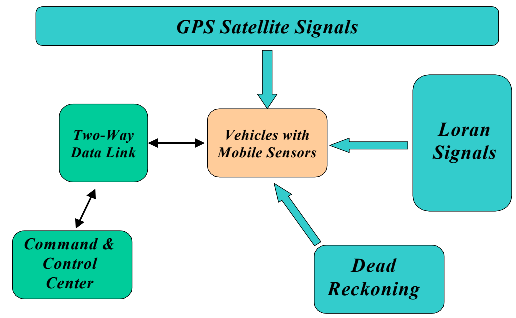


Figure 2. Tracking with GPS/Loran: the Volpe Center Mobile Test Bed

marine band VHF radios are used. For the land and urban operations, data services from both Nextel and Verizon were obtained.

The equipment generates text formatted output that follows the National Marine Electronics Association (NMEA) 0183 standard. Existing equipment, software and firmware had to be modified to accommodate the Loran and dead reckoning systems, and to add more data ports. The original purpose of this system was tracking of multiple water-borne targets. In this adaptation, there are seven positioning outputs of interest, each with its own "idea" of where the van they're in is located. Each of the seven outputs thus became "targets" on the display. The heart of the system is the integrated GPS/Loran-C system, supplemented by dead reckoning.

The table summarizes the components used in the tests.

TRANSPONDER COMPONENTS
Starlink GPS
Reelektronika Loradd integrated GPS/LORAN/WAAS
Locus Satmate 1030, with rate gyro
uBlox SBR-LS dead reckoning and GPS output
Nextel or Verizon data link

There is considerable flexibility in configuring the outputs of interest, depending on the test objectives. The configuration used in assessing urban canyon performance recorded:

- Four GPS outputs: one augmented (WAAS), one integrated with Loran, two standard
- Two Loran outputs: one integrated with GPS, one standard

- One DR GPS-conditioned output, replaced on GPS loss with odometer and rate gyro (uBlox) output

In many instances, a GPS or Loran output was allocated among two or more NMEA messages. Figure 3 shows some example messages obtained from an integrated system test. Each line is a separate message or data log, and each line can be generated by a different receiver. While the NMEA standard is fairly precise, there is enough flexibility 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 timestamp, TV32 will add one if necessary.

The messages are recorded on a "first-come, first-served" basis. Thus, for example, if one receiver provides a Loran fix about every five seconds, the receivers that update every second can expect their "usual" pattern to be interrupted.

TV32, and any software that reads text data, will parse receiver outputs for the data elements, or fields, which arrive comma delimited in each message. By the NMEA 0183 standard, the message header is the first message field. For example, the data log with "$GPGGA" as the header provides basic GPS fix data. See the following table:

$GPGGA Data Log Fields	
No.	**Data Element**
1	Header
2	UTC time (hhmmss.ss)
3 – 6	lat/lon (ddmm.mm, N/S)
7	GPS quality (1-6)
8	Number of satellites tracked
9	Horiz. Dilution of precision (HDOP)

Fields 10 through 14 contain data such as height above mean sea level, geoidal separation, age of GPS data, and checksum information. Data for the other headers follows a similar pattern.

```
$LCLCD,9610,129,071,,,115,071,136,030,106,-191,107,-412*61
$LCGLC,9610,0.0,A,,,29658.0232,A,41180.0079,A,58421.9709,A,72894.2738,A*08
$GPVTG,-125.36,T,,M,0.000,N,0.000,K,E*17
$LCGLL,3348.8677,N,10638.8221,W,,A,A*4A
$GPGGA,040001.00,3348.33468,N,10640.32874,W,6,0,99.99,1441.7,M,-24.5,M,,*5A
$GPVTG,,,,,,,,,N*30
$LCHDT,241.7,T*2D
```

Figure 3. Sample NMEA Messages

Loran-C receiver data logs that adhere to the NMEA standard have a header beginning with "$L," while the GPS-related data logs begin with "$G." There are several Loran-C data logs that can be recorded at each position fix. Figure 3 shows most of these: $LCLCD contains the Loran chain (GRI 9610 in the Figure 3 example) tracked, as well as signal-to-noise ratios and envelope to cycle differences (ECD) for each transmitter station in the chain. $LCGLC has GRI, the master station time-of-arrival, signal status, and secondary station time differences (relative to the master). Data from both of these headers is useful for monitoring Loran performance.

Continuing, $LCGLL provides Loran-measured latitude and longitude data (formatted like the GPS data in $GPGGA), UTC time of fix (usually: the two consecutive commas in $LCGLL above indicate UTC time is not provided by this particular receiver); and $LCHDT Loran heading in degrees, where "T" in the following field indicates the value is "true heading."

Finally, the NMEA 0183 standard allows for proprietary data logs. Reelektronika, for example, has provided a proprietary header "$PRLK" (not shown in Figure 3) 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 integrated GPS/Loran-C fix. Depending on system configuration, from ten to twenty data logs per second can be recorded. This produces large amounts of data over, say, a five hour data gathering session.

III. PERFORMANCE ASSESSMENT, NEW YORK

GPS performance in the "urban canyon" is well-known to be very poor [6]. When combined with a dead reckoning system, most of the location issues are effectively mitigated. The Wall Street area of New York City is exceptionally difficult, both because of the very tall buildings and narrow streets. Poor geometry results when only a small portion of the sky is visible to the GPS antenna. This is a signature characteristic of the GPS L1 (civil) band. Multipath, the reflection of radionavigation ranging signals, is also a major detriment to acceptable performance.

Loran-C operates in the 95 – 105 kHz band, not nearly as prone to blockage as GPS is. Loran also has a ground surface conductivity property that enables its signal to follow terrain and reach areas that are blocked to GPS. However, Loran also is plagued by multipath. The advance in Loran technology in recent years re-surfaced the question of using Loran as a backup to GPS within a large city. While using Loran alone to locate a vehicle on a specific corner of a New York block was not felt to be a realistic goal, renewed 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 signals provided by the receivers tested will not reliably outperform GPS. There are areas where Loran's signal can persist longer than GPS, but this distinction probably won't justify Loran as a primary backup to GPS in a large city. A dead reckoning system was acquired and added to the integrated tracking system, so that a "truth" reference could be established for quantifying Loran performance more exactly.

Testing in New York was in late April 2005. The tests covered not only the difficult Wall St. area, but also more benign locations. The van measured data during a full circumferential route around the edge of Manhattan, and in sections of Brooklyn, in addition to the Wall St. area.

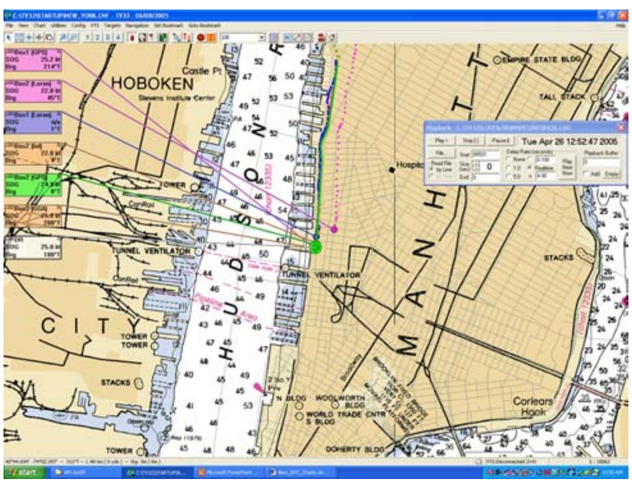


Figure 4. Heading South on 11th Avenue.

Figure 4 shows a very good performance area both for GPS and Loran. The van is just north of the Holland Tunnel entrance. This is a view presented on a computer display using TV32. Data "bubbles" in the upper left corner show the simultaneous tracking of seven "targets." The topmost bubble is a GPS output, followed by the two Loran outputs. The fourth bubble from the top shows the Loradd integrated GPS/Loran solution, and the next two boxes show GPS solutions. The bottom-most bubble shows the SBR-LS (dead reckoning) output, which at this location is a GPS solution, indicating that signal is valid.

One of the two Loran outputs is tracking right on top of the GPS solutions in Figure 4, indicating some possibilities that need to be examined further: differential Loran measurements (additional secondary factors (ASFs)) are being applied here, GPS solutions are being combined with a Loran solution, or a fortuitous combination of Loran errors that are self-canceling.

The second Loran track is very typical of observed Loran performance in the great majority of test locations. There is very consistent and steady tracking, but with about a 400 yard offset. This is indicative of a Loran solution unaided by the addition of ASF corrections. ASF offsets arise from conductivity differences of the signals broadcast by each of the tracked Loran transmitters, relative to a known conductivity baseline.

Enhanced Loran-C receivers – receivers than can exploit all of the features of eLoran - have the ability to utilize dynamic ASF corrections as they traverse a particular locale. ASF values can be surveyed over an area of interest, as the large part of this offset is spatial. That is, it will be the same when the Loran receiver returns to that point. There also is a temporal but slowly-varying ASF variation. Proper utilization of the ASF corrections can greatly reduce the typical offset seen in Figure 4. The technology for doing this is well understood, and it is at hand. It is critical to emphasize here that the Loran receivers used in this testing are developmental.

Figure 5 shows a markedly different performance level, shortly after entering the Wall St. area (It isn't possible now to actually drive along Wall St., for security reasons). The GPS and Loran solutions have become fully unusable. One Loran solution has gone off the map. Dead reckoning is active and working well at this point.

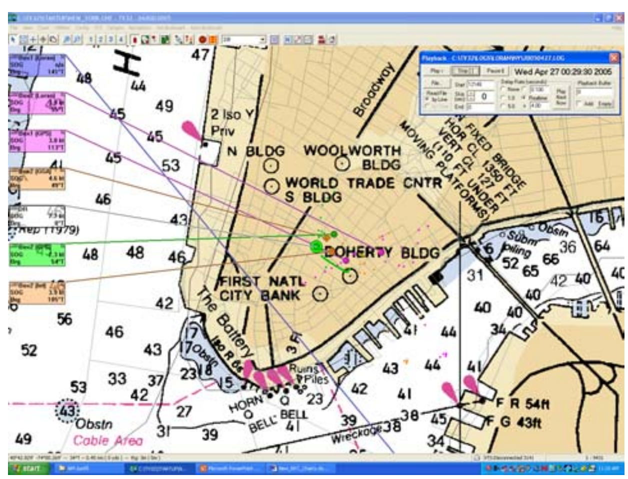
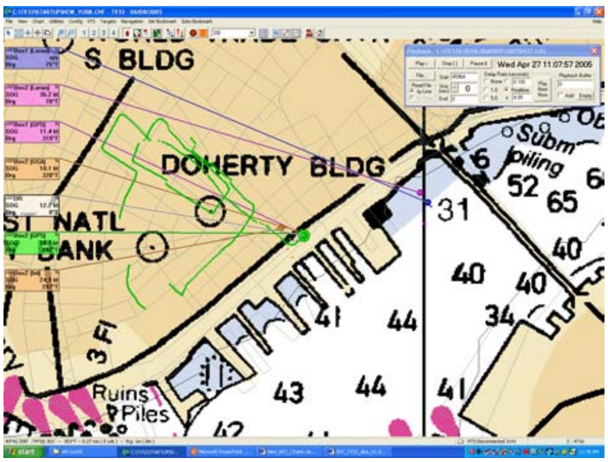


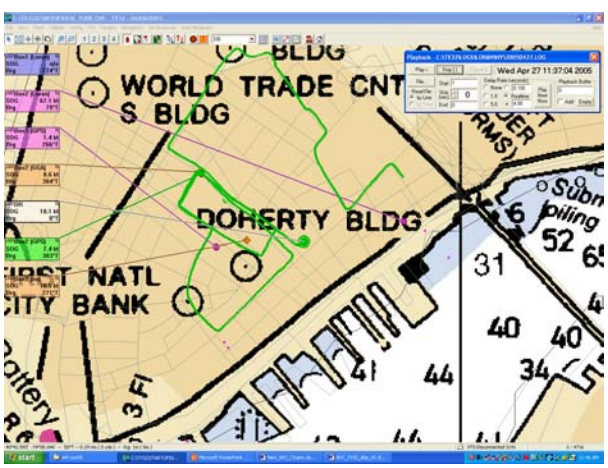
Figure 5. Onset of blockage and multipath effects near Wall Street

Dead reckoning (DR) performance for the system examined deteriorates in two ways. One, more common, is due to the drift error in the heading gyro output. This error grows steadily in time, unless the GPS signal has a good fix often enough to keep the gyro error contained. In areas like Wall St., where GPS can be unreliable for extended periods of time, there is no check on this error. Alternate options exist for measuring heading, but this issue is not a major focus of the work done to date.

The second problem may be more specific to the SBR-LS 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 (Figure 6).



(a)



(b)

Figure 6. DR unit operating for an extended track without navigable GPS. Part (a) shows the track executed with GPS antenna attached; part (b) shows DR operation on the same track repeated with GPS antenna disconnected.

This figure shows the Wall St. area of Manhattan with two DR tracks superimposed. The van traveled the same circuitous, repetitive route two times. The first time (Figure 6a) shows the result with the GPS antenna connected to the DR unit (the normal configuration) for the full track. Each track lasted about the same time, 25 minutes. The GPS and Loran outputs have been suppressed in Figure 6 by TV32, to highlight DR performance.

Figure 6b shows DR performance when the GPS antenna has been disconnected from the DR unit. The result is better than the Figure 6a result, reflecting the de-stabilizing effect of continuing to receive “bad” GPS signals. The gyro drift is evident, but not to the extent that fairly reliable location information is denied. In fact, it is very evident which street the van is on at all times.

Figure 7 shows the track made along the East River on the Manhattan side, heading north on the FDR Parkway. At the time the figure was made, the van had just cleared the “semi-open” tunnel that goes under the UN Building. Safely away from Wall St., the track shows normal performance from all units until the southern entrance to this tunnel is reached (right at the feature labeled “TALL STACK” on the map). GPS begins to go bad at this point, but Loran remains basically nominal, until nearly half way into the tunnel (a 270 – 300 meter lateral offset remains steady). Loran lock then is lost, and it will be regained along with GPS lock on clearing the tunnel. Through this entire segment, DR has been performing exactly as expected, because less time was spent without navigable GPS in this situation than driving around Wall St. in the prior example.

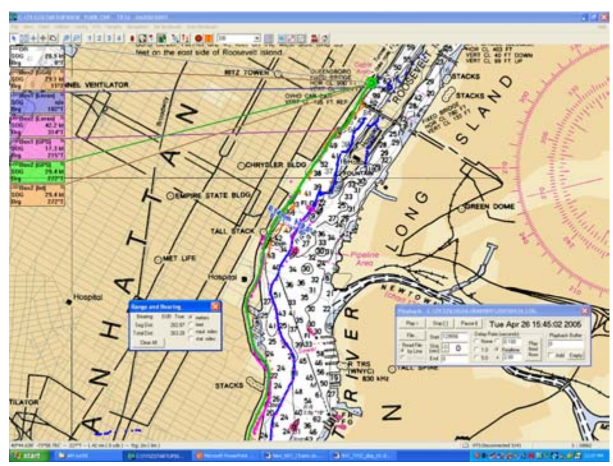


Figure 7. System performance along the East River

Several hours of data was gathered during this test, and most of it has not been examined in detail yet. Three positioning systems were tested to the extreme in Wall Street: GPS, Loran, and DR. It seems that a minimum of two systems are needed at all times, and even three cannot perform well in the immediate Wall Street area (unless the trip is relatively quick). The performance of the DR system selected for the tracking system, the uBlox SBR-LS, is much worse when non-usable GPS signals are fed into it. The unit logic does not appear to reject these bad inputs beyond a certain time. It is unclear whether this is a relatively easy design fix, or whether it is the consequence of difficult constraints.

Loran, especially when using ASF corrections, works very well in most normal areas of Manhattan. It does appear that Loran is of little help in the Wall St. area, unless aided by DR. 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. Finally, Loran's edge on GPS in signal penetration is evident in situations like the open tunnel under the UN Building.

IV. PERFORMANCE ASSESSMENT, NEW MEXICO

Planning and executing the integrated system performance assessment in New York City lent focus to getting a clearer picture of system performance when GPS is denied for lengthy periods – on the order of an hour or more. A rare opportunity to conduct jamming tests occurred just after the NYC tests were run. Although this meant deferring for a while more extensive analysis of the urban canyon data, a trip to White Sands, New Mexico seemed – and proved to be – very worthwhile. Jamming - and countering such jamming - the GPS band is not only a military objective. In the post- 9/11 era, mitigating GPS jamming can be critical to maintaining safety and security in urban and other areas as well.

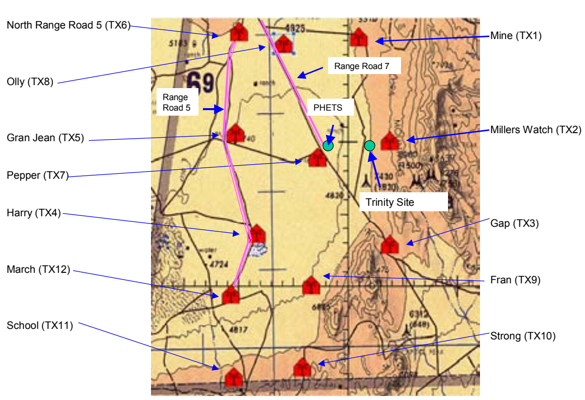


Figure 8. Jamfest III venue at White Sands Missile Range

Figure 8 shows the jamming test venue at White Sands Missile Range, between Socorro and Alamogordo, NM. The GPS jamming exercise, "Jamfest III," was conducted in May 2005 by the USAF 746th Test Squadron, based at Holloman AFB, NM. Figure 8 shows the location of twelve jamming transmitters located to form a jamming gauntlet along Range Road 7, along which participant organizations were escorted.

Jamming was conducted overnight, to minimize disruption as much as possible. Based in part on participator input, many jamming scenarios were run over Jamfest's duration. Many combinations of jammers used, one, six, twelve, and many varieties of jamming signal, signal strength, shape, etc., were run. Volpe Center objectives at Jamfest were to observe Loran and DR performance when jamming denied the use of GPS.

Following three days of testing (May 16 – 18, 2005), many more hours of useful data were gathered for analysis. As with the NYC data, the detailed analysis process has only begun, but some observations appear pertinent at this time.

No Loran-C anomalies to normal operation of any significant kind have yet been detected. For the thousands of Loran fixes observed on plots, fewer than 1% were of "bad" signal quality. This result is not really a surprise, but nevertheless is reassuring. All GPS receivers were rendered fully inoperable under the jamming periods examined to date. Again, this is not a surprise. DR system performance in total GPS denial is similar to New York, but dominated by gyro drift errors. This is in part due to the operation for between two and five hours during the tests. There was a jamming respite of about fifteen minutes following about 90 to 120 minute intervals of continuous jamming. As in NYC, however, the DR signal was not usable when there was no navigable GPS signal for at least twenty minutes.

GPS restored operation smoothly immediately following jammer shut-down. The proportion of "good" GPS data matched nearly perfectly the portion of time there was no jamming. When the van was fully at rest for almost 25 minutes at one point, the standard deviation of Loran-measured latitude was measured to be 2.1 E-05 latitude degrees (about 7.7 meters). There is more analysis to be conducted with this data as with the New York data.

Figures 9 through 18 show Matlab plots of a few of the many variables that are available for analysis. The Figure 9 plot covers almost two hours, from 4h 00m 00s UTC to almost 6h 00m 00s UTC, late May 16, 2005 local time. This plot shows Loran latitude remaining steady throughout the jamming. The pattern over time reflects starting from rest (level portion), moving at steady speed down Range Road 7 for a turnaround near the Trinity site, and returning back up Range Road 7 at a fixed speed. The sequence then repeats. Figure 10 shows the DR latitude output for the same scenario. The gaps in this plot reflect GPS jamming that is sufficient to prevent generation of GPS ranging solutions, which shortly thereafter impacts DR performance.

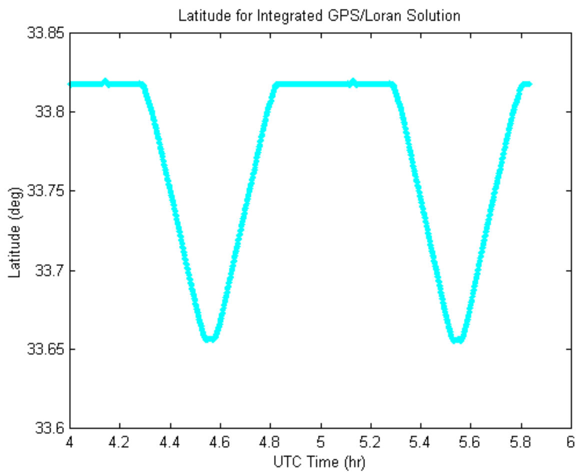


Figure 9. Loran latitude vs. UTC time under jamming. No GPS outputs were plotted here.

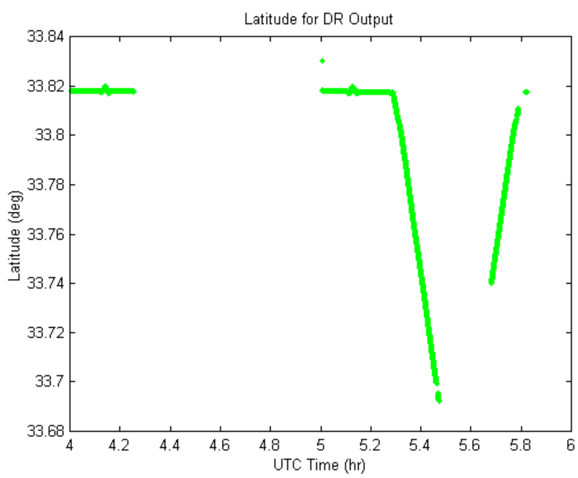


Figure 10. DR latitude vs. UTC time, reflecting periods without GPS aiding.

Figure 11 shows Horizontal Dilution of Precision (HDOP) outputs for the $GPGGA NMEA header (cf., Figure 3), as recorded by three GPS receiver elements, one each from the Locus Satmate receiver, and from the Loradd and uBlox integrated receivers. Note that the two time segments showing intense GPS jamming – about 4.3 to 5.0 hr UTC, and 5.5 to 5.6 hr UTC – correlate very well with the "no-solution" regions in Figures 10 and 12. The vertical scales in Figures 9, 10 and 12 differ, in order to highlight response during jamming onset and recovery.

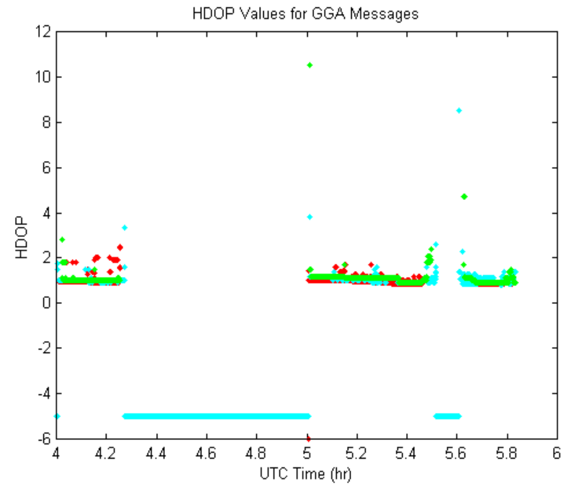


Figure 11. HDOP values for three GPS-only outputs.

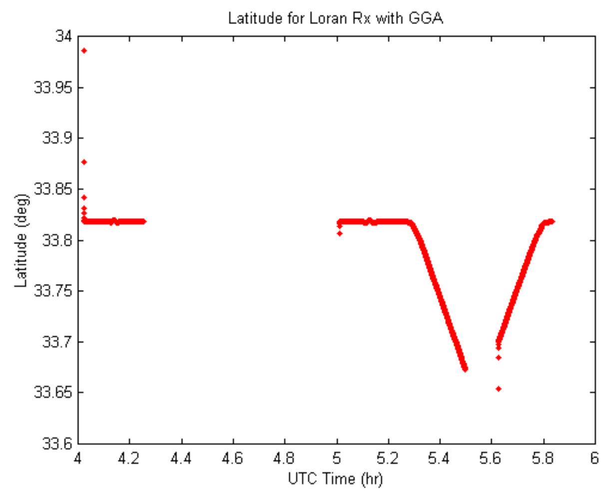


Figure 12. GPS latitude vs. UTC time, from an integrated GPS/Loran-C receiver.

All three GPS HDOP outputs in Figure 11 range between 1.0 and 2.0, until GPS is jammed. When this happens, HDOP deteriorates rapidly to he receiver default value of 100. In the interest of showing adequate HDOP detail throughout the full time interval, HDOP values exceeding 12.0 were set artificially to –5.0. HDOP is a good indicator of jamming onset.

The results just discussed reflect data gathered on the first night of testing. The next night's results will now be reviewed. Given the plot scale constraints, the non-jam, and many of the jamming intervals produce plots that overlay each other nearly perfectly. Thus, some of the following plots are shifted vertically by a fixed amount, again in order to expose as much detail as possible. Also, the time values are modified to reflect the facts that the UTC clock was six hours ahead of local (New Mexico)

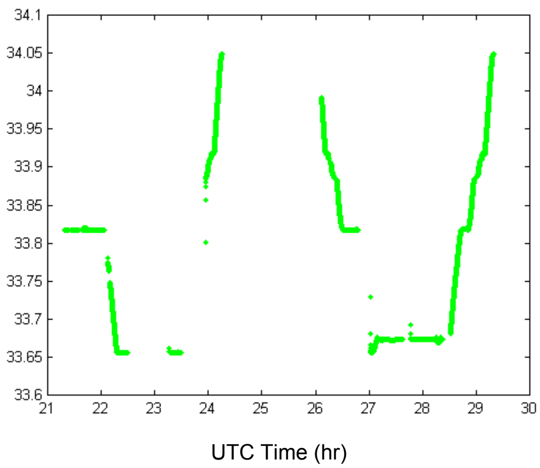


Figure 13. GPS latitude (deg) vs. UTC time (hr), from the Locus Satmate $GPGGA header. Day 2 of testing.

time, and that the tests passed through midnight UTC, and that monotonic (not "modulo 24") time should be plotted. The Figure 13 and related plots therefore rune from 21 to 30 hours. There is clear evidence of jamming in Figure 13, and it should be clear that corresponding longitude plots show similar behavior. Note that there is a test gap centered around 25.0 hr UTC, which corresponds to 1900 local time – dinner break. Day 2 tests lasted almost nine hours, and the jamming scenarios differed in Day 2 from Day 1.

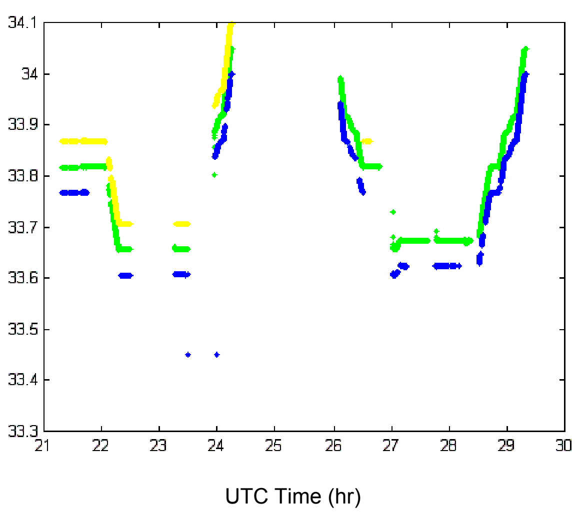


Figure 14. GPS latitude (deg) vs. UTC time (hr), from the $GPGGA header, using all 3 GPS receivers (Satmate, Loradd, uBlox.) Day 2 of testing.

Two of the three Figure 14 plots were shifted up and down by 0.05 degrees of latitude relative to the green Satmate output, for clarity and comparison. The contrast with Loran performance is emphasized in Figure 15, which overlays an undisturbed Loran-C track on the Figure 14 GPS tracks. In a jamming environment, Loran actually can provide the truth reference for reliable positioning.

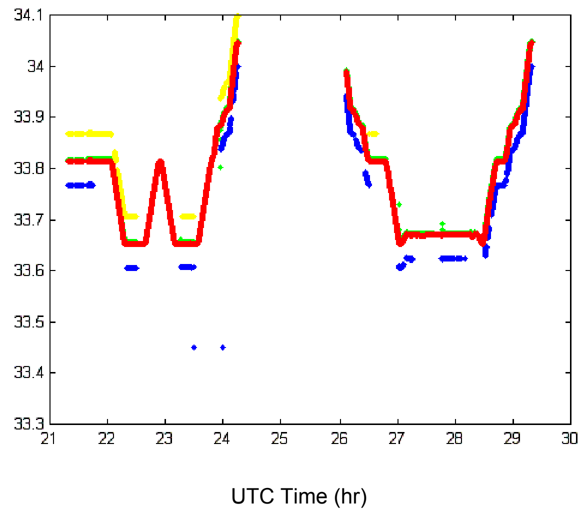


Figure 15. Latitude (deg) vs. UTC time (hr), showing the three $GPGGA tracks from Figure 14, overlaid by the Loradd "basic Loran" track (red).

Figures 16 and 17 show signal-to-noise ratio and ECD tracks measured over a

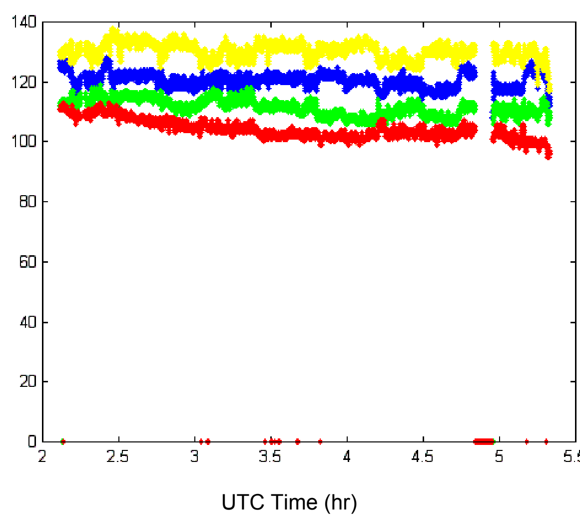


Figure 16. Loran Signal-to-Noise Ratio vs. UTC Time, Day 2. Add 24 to time values here to get time equivalent to Figures 13-15.

portion of the Day 2 test period. For each plot, the South Central U.S. chain, 9610, transmitters are identified as follows:

Master	blue
Secondary W	green
Secondary X	yellow
Secondary Y	red

These data were generated by the Satemate Loran receiver, NMEA header $LCLCD.

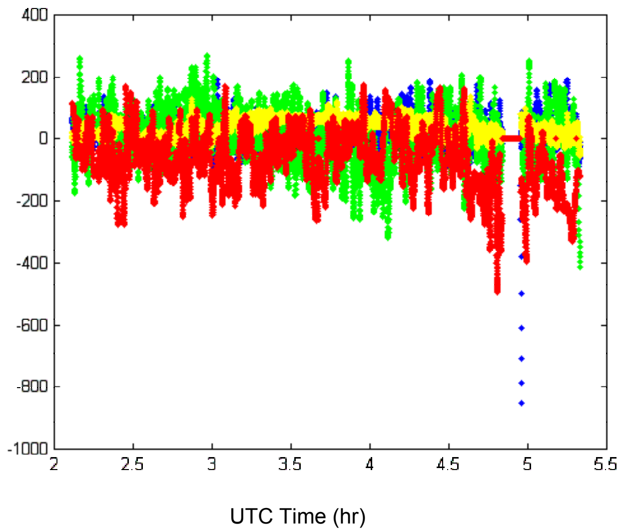


Figure 17. Loran Envelope-to-Cycle Difference (nsec) vs. UTC Time, Day 2. Add 24 to time values here to get time equivalent to Figures 13-15.

Finally, Figure 18 shows GRI 9610 master time-of-arrival (TOA) from the Loradd receiver, plotted against UTC time in seconds, for the Day 2 test period that corresponds to 26.0 to 29.5 hours in Figures 13 – 15. The features of this plot, if inverted about the horizontal axis, appear to resemble the Figure 15 Loran latitude plot for the same time period. It is expected that TOA would reflect changes in latitude (and longitude).

V. SUMMARY

Tests of an integrated GPS/Loran system aided by DR were recently conducted n New York City and at White Sands Missile Range, NM. Each of these test venues presented extreme conditions for GPS operation, and in many cases, the backup Loran and DR systems as well. The tests showed that conditions can be severe enough to disrupt even the "no-GPS' performance of the DR system, which was produced commercially for auto users. Extended GPS outages can make the DR system unstable.

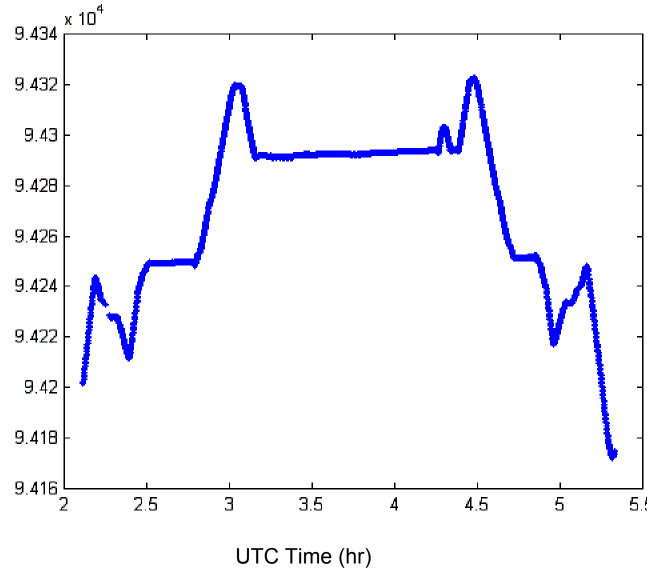


Figure 18. Loran 9610 Master Time-of-Arrival (µs) vs. UTC time (sec). Add 24 to time values here to get time equivalent to Figures 13-15.

Loran-C Performance in the GPS jamming environment remained on lock. There were no discernable performance degradations of meaningful duration in data analyzed to date. Loran-C is no cure-all in the environments these systems were exercised in, as described in this paper. When eLoran design details are fully implemented in a production receiver, however, eLoran should become an even more valuable element in the future radionavigation and timing mix.

Disclaimer. The statements and opinions in this paper are those of the author only, and they do not necessarily reflect policy or opinions of the U.S. Government.

ACKNOWLEDGMENTS

The author wishes to thank Mitch Narins of the FAA for his leadership on this important project, Dr. Ben Peterson of PIG, LLC, for his technical insight, Lee Boyce of Stanford for catching a units problem in one of the plots, Capt. Brett Casey of the 746th TS, and LT Anthony Hawes of the USCG Loran Support Unit for providing via Ben Peterson some very useful Matlab code.

REFERENCES

1. *Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications,* FAA Navigation Services Directorate, March 2004.

2. *Loran-C Users Handbook,* 1992, U.S. Coast Guard COMPDTPUB P16562.6.

3. *Specification of the Transmitted Loran-C Signal,* COMDTINST M16562.4A, 1994.

4. *LORAN-C Operations Manual,* NAVCEN INST M16562.1," and changes dated June 25, 1999.

5. *The Potential Role of Enhanced LORAN-C in the National Time and Frequency Infrastructure,* M. A. Lombardi, T. Celano, and E. D. Powers, presented at the 34th Annual International Loran Association Conference, Santa Barbara, CA, October, 2005.

6. *Evaluation of Radionavigation Systems in an Urban Environment,* B. Peterson, CAS report no. 14-94, USCG Academy Center for Advanced Studies, September, 1994.