Evaluation of Loran Performance as a DGPS Backup System in the HEA Domain

Using a Target Level of Safety Criterion

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1. Overview

A series of U.S. Coast Guard-sponsored efforts spanning the period 1997 – 2002 (see the References) analyzed the navigation performance of Differential GPS (DGPS) in the maritime domain. The analysis techniques developed under these efforts were organized as part of a decision aid software tool known as NAAT (Navigation Aid Analysis Tool). Among other applications, this tool was used to analyze specified DGPS backup systems in terms of the Target Level of Safety (TLS).

In this paper, we briefly touch on the background of this work, trace the origin and meaning of the TLS criterion, describe some of the more critical sub-models contained in NAAT, look at the relationship of the TLS and conventional definitions of availability, but focus most attention on the performance of Loran-C as a backup to DGPS in the harbor entrance and approach (HEA) domain. Our general conclusion is that, of the backup systems considered, Loran was the only navigation system that consistently satisfied the TLS criterion for a variety of vessel types and harbor entrance/approach conditions.

2. Background

In keeping with its charter to operate, maintain, and control the Maritime Differential GPS System, the U.S. Coast Guard Navigation Center (USCG NAVCEN) sponsored the studies mentioned above to better serve the maritime user of DGPS. Specifically, NAVCEN set out to determine:

- A more quantitative definition of "Target Level of Safety" and how it can be used as a performance criterion for navigation systems supporting vessel transit scenarios in the harbor entrance and approach (HEA), and inland waterway domains
- The conditions under which DGPS satisfies a specified Target Level of Safety
- The DGPS backup systems for maritime navigation that satisfy the Target Level of Safety

The conditions referred to in the second bullet include placement and reliability of DGPS beacon stations. Placement means that for a given waterway or system of neighboring waterways, how much beacon station coverage redundancy is needed to ensure that larger vessels meet the TLS criterion. For example, a network of 3 – 4 beacon stations may provide dual station coverage for several waterways in a given area. The reliability of DGPS as an entire system directly affects the TLS and depends on the reliability of GPS, the beacon station transmitting the differential correction, and the receiver. USCG NAVCEN has control only of the second of these two reliability components. Thus, for example, NAVCEN could ensure that each station had uninterruptible power supplies as a means of improving beacon station reliability and decreasing the incident rate.

The economic need for operations in low/no visibility conditions is also an important factor, since that increases the criticality of DGPS, but also increases the incident probability relative to operations under normal conditions satisfying the TLS. The size of the vessels (mainly their beam) identified for principal navigation support is also critical, since the incident rate depends strongly on the "free-half-channel" and, if a cross-current is present, there is a high sensitivity of the incident rate to vessel length.

The relative navigational risk of a given harbor channel is an important factor for determining the protection to be afforded by DGPS. For example, if the goal is to ensure that a narrow channel with several turns must satisfy the TLS, this places severe constraints on the level of service performance provided by DGPS in this area as well the performance of the selected DGPS backup systems. These backups include onboard systems, such as marine radar and inertial navigation systems (INS)/inertial measurement units (IMU) as well as external systems. External aids include electronic systems, e.g., Loran-C, and visual structures that include conventional short-range aids.

3. The Target Level of Safety (TLS) Criterion

The comprehensive *Port Needs Study* (Ref. 15) was consulted to determine the incident[1] rate/ship-hour in ports and harbors used by larger vessels in CONUS (>10,000 gross tons). Based on the data reported in this document, a total Incident Rate of 3×10^{-4} incidents/ship-hour was derived.

Based on the categories used to classify incidents, those incidents resulting from navigational errors amounted to approximately 30% of the total. Thus, the incident rate due to navigation errors is specified as 9×10^{-5} incidents/ship-hour.

From this historically based incident rate, the Target Level of Safety (TLS) criterion was developed using a risk allocation approach. Using this approach, the risk components of incidents resulting from navigational error were allocated using a standard risk tree model.

Figure 1 illustrates the allocation technique for navigation risk. Risk allocation is really the assignment of probabilities of an incident as a result of specified categories of system failure. The risk of an incident is partitioned among three event categories:

1. The incident occurs even though the "system" (any critical component of DGPS) is functioning properly.
2. The incident occurs as a result of DGPS system failure even though the failure was detected in advance.
3. The incident occurs as a result of a DGPS system failure that was not detected in advance.

The figure indicates that the risk allocation (probabilities) is equal among each of these categories. This is equivalent to the assumption that incident are twice as likely to arise from system faults as from "rare" fault-free conditions.

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[1] Here, "incident" refers primarily to groundings or allisions. Collisions with other vessels are relatively rare and not considered here.

The risk category “Detected Failures” is further subdivided into two mutually exclusive event classes:

- Integrity Design Risk
    - Risk attributable to design of the system integrity function. This may occur if the warning is not given far enough in advance to avoid an incident
- Backup Design Risk
    - Risk attributable to the backup system performance following DGPS failure.

This work focuses on incidents arising from navigation errors under non-faulted conditions, i.e., all components of the “system” being used at any given time, whether that system is DGPS or backup, are functioning as intended. In these situations, errors arise from misinterpretation of data or factors external to the system, such as the signal propagation channel.

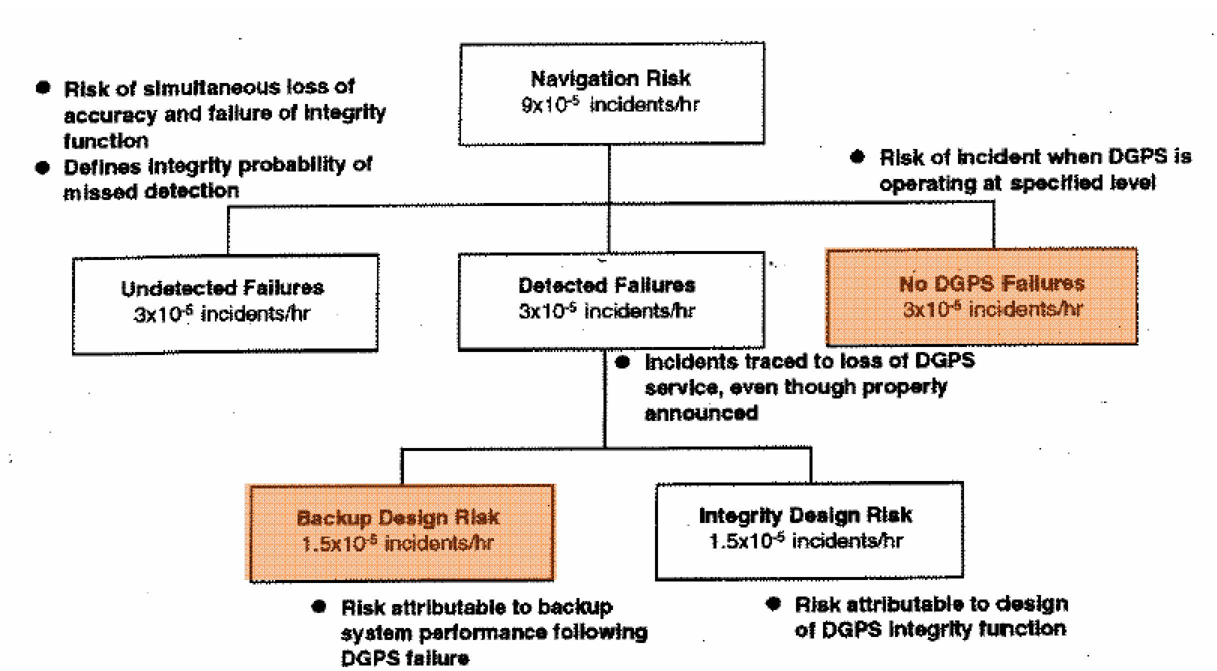

Figure 1 Navigation Risk Allocation

This assumption is motivated by the fact that the incidents compiled in the database occurred prior to the advent of DGPS and thus had nothing to do with the integrity of the system. In fact, most of the navigation systems in use during the period covered by the incident database were visual or short range aids.

Hence, we consider only incident risks associated with errors resulting from the following mutually exclusive events:

- “No-fault” DGPS operations (3×10^{-5} inc./hr)
- Backup system operation in the event of a detected DGPS failure (1.5×10^{-5} inc./hr)

Since these events are mutually exclusive, we can add their probabilities to obtain 4.5×10^{-5} /ship-hour. This means that for $10^5/4.5$ hours that all ships are in transit in the HEA domain (counting all ships and U.S. ports), the probability is exceedingly high (e.g., 0.99999, depending on the exact distribution) that an incident will have occurred. This probability of an incident/ship-hour is generally referred to as the TLS in subsequent analysis.

The TLS as a Threshold

As noted above, incidents that were classified as being navigation-related occurred during that period of maritime history when visual and other short-range aids were the dominant form of marine navigation. A question often asked by users of performance evaluation tools that employ the TLS as a criterion is: Should the TLS have the same numerical value for modern electronic aids as that reflective of the historical incidents incurred while short-range aids were the primary means of marine navigation?

To answer the question, contractors for the U.S. Coast Guard interviewed river pilots to determine how their level of risk would be expected to change as they acquired and became comfortable with modern electronic aids to navigation. The general response of the pilots, which included those from the Delaware Pilots Association and the Port of Montreal, was that the TLS threshold used to evaluate DGPS performance and backup systems should stay the same. This is because the pilots felt that they would likely attempt riskier operations, such as transits in ice-filled rivers, during night, and in fog conditions, and these would probably compensate for the increased accuracy and situational awareness afforded by modern electronic aids, such as DGPS.

Consequently, in succeeding performance evaluation efforts, the numerical value of the TLS was maintained at 4.5×10^{-5} /ship-hour. In later work, a performance evaluation tool was developed in which the user could specify virtually all the navigation parameters associated with a transit scenario. For this tool, an arbitrary value of the TLS may be specified, although the default value remains 4.5×10^{-5} /ship-hour.

4. A Decision Aid Tool for System Performance Evaluation

As mentioned in the last part of the previous section, a system performance evaluation tool, known as the Navigation Aid Analysis Tool (NAAT), was developed as a decision aid for USCG NAVCEN. This tool was used to assist the USCG in finding the number and reliability of DGPS beacons required to satisfy the TLS under specified conditions. It was also used in gauging the performance (reliability, availability) of requisite DGPS backup navigation systems in the event that DGPS was unable to satisfy the TLS under certain conditions.

For typical applications, the tool requires the specification of a scenario, including

- Vessel type (length, beam)
- Channel description (width as a function of distance along the channel)
- Current speed and direction
- Environmental condition (illumination, visibility)
- Navigation systems to be utilized, including priority (primary, first backup, second backup, etc.)
    - Data on backup navigation systems, including coverage, accuracy, availability, reliability, continuity, etc.
- TLS figure

With these specifications, NAAT calculates the probability of an incident along the transit route (channel) and compares it to the TLS. This incident probability clearly depends upon the parameters of the environmental scenario, including those listed above, as well as the hierarchy of navigation systems employed by the vessel and the system in current use (which may be the primary, secondary, etc. system). A Markov state space model is used to determine the transition probabilities between navigation "states", i.e., the likelihood that any given system transitions from operational to non-operational (or *vice versa*) in a given time step.

Figure 2 shows a typical channel specification input for the tool. The example

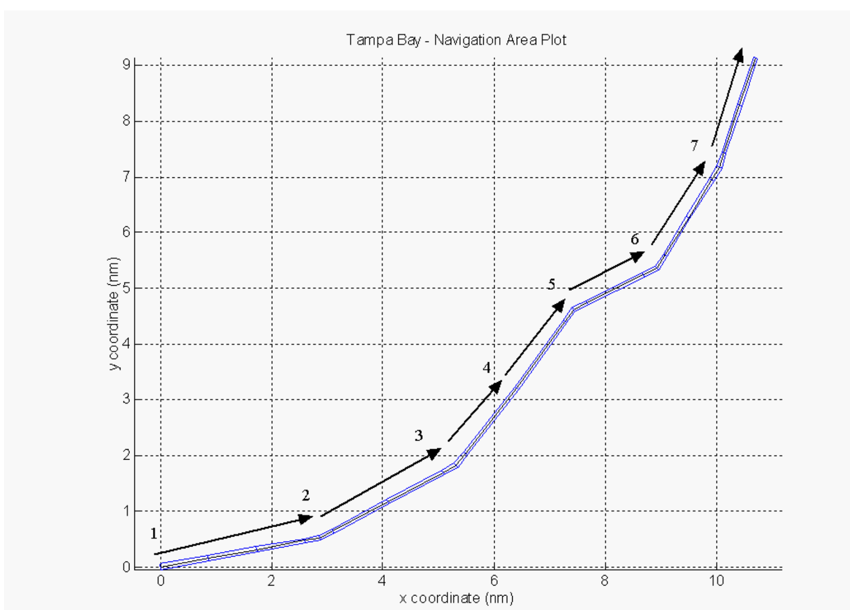

Figure 2 Tampa Bay Navigation Area - A Sample Input Scenario to NAAT

channel is Tampa Bay, a navigationally challenging scenario because of its narrow channel and unforgiving channel boundaries.

The transition probabilities produced by the Markov state space model depend strongly on the reliability parameters (Mean Time Between Failure (MTBF) and Mean

Time to Restore (MTTR)) for each navigation system. These probabilities also depend on the probability law assumed, but NAAT uses the same probability distribution (Poisson) for each selected navigation system employed by the given vessel. Table 1 lists typical reliability parameters for two example backup navigation systems: Loran-C and DGPS.

Table 1 Sample DGPS/Loran-C Reliability and Accuracy Parameters

System	Reliability Parameters		Accuracy (m)			
Service and Receivers	MTTR	MTBF	Non-Loran-C (CEP 95%)	Loran-C (CTE 95%)		
	(minutes)	(hours)		5 Stations	4 Stations	3 Stations
DGPS Service	10	1000	10			
GPS Service*	5	900	100			
Radar	30	4000	78.4			
Loran-C Service - St. Mary's	14	587		18.9	26 ***	53.8 ***
Loran-C Service - Tampa Bay	14	587		17.5	23.6 ***	27.1 ***
Receivers**	?	20000				

* Selective Availability On
** DGPS/GPS/Loran-C
*** Worst-case station geometry configuration

Table 1 also lists the accuracy parameters for the primary system (DGPS) and a sample secondary system (Loran-C). From these parameters and an assumed error distribution, one can find the error contributed by the "unfaulted" navigation system. The incident probability calculation depends not only upon the particular navigation system employed during the specified time period, but also on the channel geometry, current, and vessel size (length, beam)

Piloting Error Model

Errors leading to an incident may arise as a result of the navigation system(s) employed as well as the skill of the pilot in maintaining the desired trackline. The tool includes models not only of navigation system error, but also of track-keeping error. The latter model was based on data obtained from the Merchant Marine Academy at King's Point. Precise positions of training vessels were tracked and compared with the desired tracks for a variety of pilot skill types.

In general, the actual ground-track of the vessel is a curve resembling a sinusoid centered approximately on the desired trackline. The data on this "random sinusoid" (see Figure 3) was Fourier-decomposed and the peak of the power spectrum corresponded to a period of 6 minutes. The cross-track amplitudes corresponding to this 6-minute period harmonic component were found to have a standard deviation of 4 – 6 meters. The piloting error distribution was combined with the navigation sensor error distribution model to form the total error model.

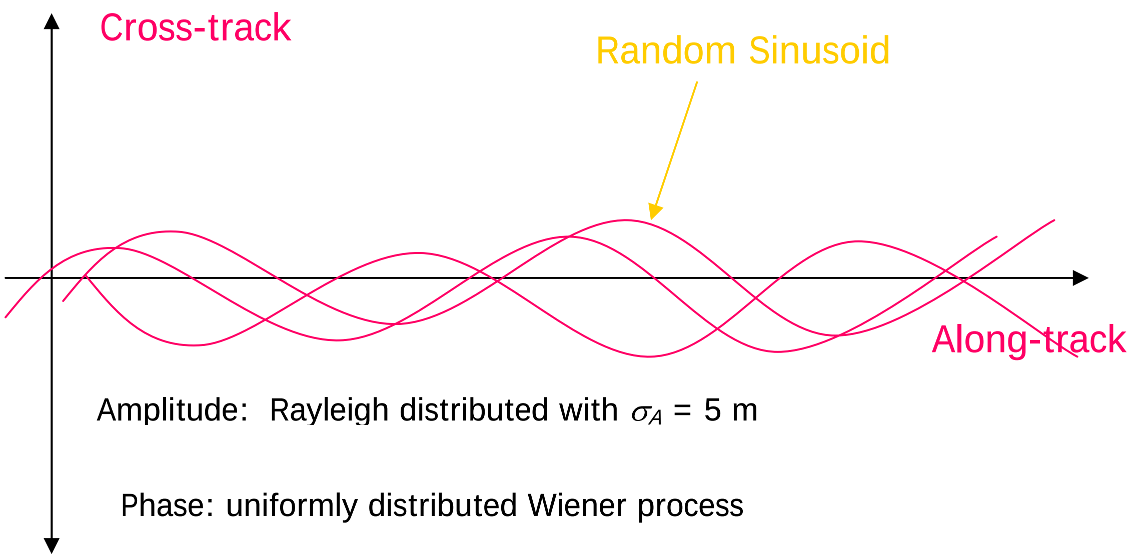

Figure 3 Piloting Error Model

Application of NAAT to the Comparison of Backup Navigation Systems

A major application of NAAT is the comparison of DGPS backup navigation systems. A variety of vessel types was considered, but most emphasis was given to the larger vessels since incidents involving these vessels have the greatest environmental and financial consequences. Various environmental conditions were included in the model, although low visibility was usually specified since precise navigation under such conditions requires modern electronic aids. For radio aids, season and hour must also be specified to quantify the EM noise level.

Backup navigation systems considered

NAAT permits users to select one or more of the following backup navigation systems:

- GPS (no augmentation)
- Loran-C
- INS/IMU
- Marine radar
- Visual aids
- User-input navigation system

If more than one navigation system is selected, then a priority assignment (hierarchy) must also be chosen. This means that if the primary backup system fails, the navigator switches to next system in the priority assignment.

Following the development of NAAT, the USCG sponsored an effort (Reference 1) to quantitatively compare the performance of certain DGPS backup navigation systems. The objective of this work was to determine whether vessels with DGPS as their primary means of navigation can safely transit navigationally challenging waterways in the U.S., given that their backup, or secondary source of navigation is one of the following:

- Loran-C
- Inertial Navigation Systems (INS)/Inertial Measurement Units (IMU)
- GPS without selective availability.

In this work it was assumed that these three DGPS backup systems are coupled to the primary DGPS receiver so that the accuracy of the combined primary/secondary system is that of DGPS whenever DGPS signals are available and the receiver is properly functioning. For the first two DGPS backup systems listed above, it was assumed that a GPS receiver, using signals subject to selective availability, serves as a second backup, or tertiary, system. Use of this second backup system presumes, of course, that GPS is not the source of failure for the primary system. Moreover, the assumption is made that a vessel operating in the selected waterways is equipped with marine radar (in a standalone configuration) as a third backup, or quaternary, navigation system for the Loran-C and INS/IMU backup cases and as a tertiary system for the third backup case listed above. Thus, the backup scenario cases were as follows:

1. DGPS – primary ; Loran-C – secondary (first backup) ; GPS (w/SA) – tertiary (second backup) ; marine radar – quaternary (third backup).
2. DGPS – primary ; INS/IMU – secondary (first backup) ; GPS (w/SA) – tertiary (second backup) ; marine radar – quaternary (third backup).
3. DGPS – primary ; GPS (w/o SA) – secondary (first backup) ; marine radar – tertiary (second backup).

As noted above, the transition from primary to secondary (backup) navigation system is assumed to be smooth. This smooth transition is ensured by a continuous calibration of the secondary system by the primary system while both are available. When the primary system fails, the secondary backup continues with nearly the same accuracy as that of the primary system for a certain period of time (depending on the characteristics of the backup system). After a certain period of time, the secondary reverts to its native accuracy performance.

Performance of Loran-C as a DGPS Backup System

For Case (1) above, the highly coupled configuration of the primary DGPS receiver and the secondary Loran-C system means that all station TOAs/TDs (single-chain or multi-chain) are continuously calibrated, i.e., correctly given based on the receiver's position (to within the DGPS position accuracy). The assumption of continuous calibration means that, at the onset of DGPS failure, no biases are present in the processing of Loran-C signals. For marine applications, no such coupled receiver system is known to exist at this time, although the technology is currently available. Thus, it is assumed that, given a favorable economic and political climate, shipboard navigation systems of this type will become available in the near future.

The performance of Loran-C as a DGPS backup system depends critically on its "coherence", i.e. the ability of a fixed, remote receiver to replicate previous TOA readings. If one assumes the clock drift is effectively calibrated while coupled to DGPS, then coherence depends primarily on noise and propagation effects. To determine the Loran-C TOA coherence over various time intervals, several sources of measurement data were explored. By a wide margin, the most precise and applicable data were Cesium-referenced Loran-C TOA measurements made at the U. S. Coast Guard Academy, New London, CT. This data (shown in Figure 4) was processed to determine the Loran-C error growth profiles following loss of DGPS for the coupling assumed in these scenarios.

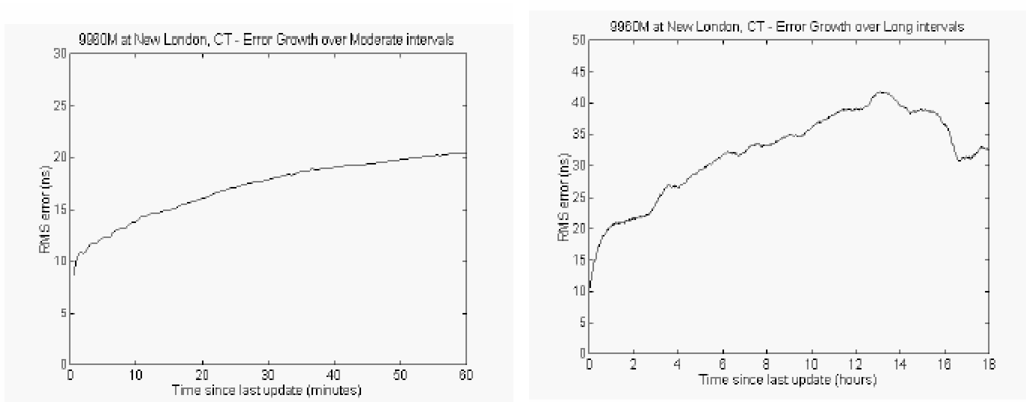

Figure 4 Coherence Profiles for the Seneca, NY Loran-C Signal at New London, CT

The resulting error growth profiles for both TOA and fix position were characterized by an initial excursion followed by an error growth of about 1 meter/10 minute interval (95% CEP). Detailed examination of this data indicates that Loran-C effectively preserves DGPS navigation accuracy for a period of approximately one hour following loss of DGPS data. Since the DGPS mean time-to-restore is nominally 10 minutes, this means that the DGPS/Loran-C user can effectively navigate with DGPS accuracy through nearly all DGPS outages.

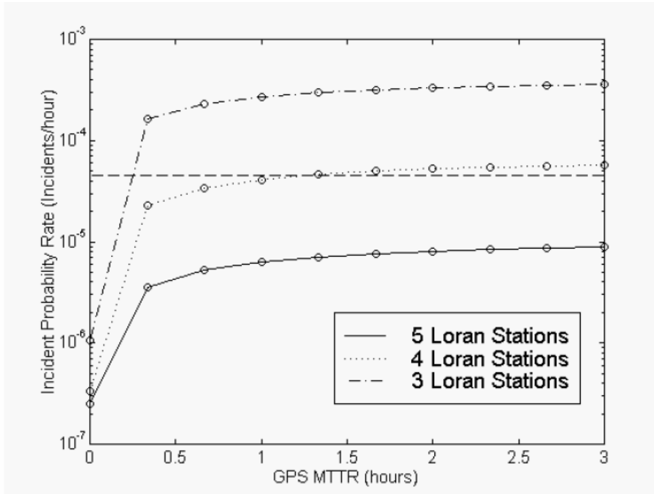

Figure 5 St. Mary's River Scenario with Loran as DGPS Backup under GPS Interference Conditions

In applying the Markov chain methodology to the Loran-C backup system case, station off-air data was compiled from Coast Guard databases and station signal coverage was obtained using the Loran-C Availability Tool (LOCAT) for both the St. Mary's River and Tampa Bay. For the default case (see Table 1), the calculations show that the TLS is satisfied for *all* Loran-C and DGPS station coverage scenarios for both St. Mary's River and Tampa Bay. In fact, the TLS is satisfied even for the sparsest coverage scenario of three Loran-C stations (having a geometric configuration with lowest accuracy) and a single DGPS beacon. It is important to recognize, however, that this strong performance is based partly on Loran-C's limited error growth, thus allowing the coupled system to "coast through" the duration of most DGPS failures.

Sensitivity analyses show that DGPS MTTR values of less than ten minutes (the default value) are required for the most critical scenario - coverage by 3 Loran-C stations in the St. Mary's River. This finding further underscores the importance of Loran-C's accuracy-preserving behavior since the coherence effectively reduces the mean time-to-restore of the DGPS service to essentially zero. Other sensitivity results indicate that the incident probability rate depends critically on the high accuracy of DGPS but is effectively independent of DGPS MTBF and Loran-C accuracy.

Changing Propagation Conditions

Signal coherence can be significantly degraded when phase variations due to changing propagation effects on the station-to-receiver signal path occur *after* the DGPS outage. Because the default DGPS MTTR is only ten minutes, however, such variations are unlikely to occur during the DGPS outage. If they do occur, however, we assume that a future signal propagation model (embedded in each receiver) continuously monitors the propagation path to each station, noting especially the conductivity profile over which the signal travels. This profile is translated into an additional secondary phase factor (ASF) via an ASF model (alternative models are currently under study). Prior to the DGPS outage, the path is effectively calibrated by an ASF computed by accurate knowledge of the user's position via DGPS. When the predicted ASFs change by more than a designated threshold, the ASF model will add the change in predicted ASFs to the prior DGPS-calibrated ASF value. This method will likely benefit from the general finding (based on experience with other LF/VLF systems) that relatively small *changes* in the ASF are nearly always more accurate than the ASF itself. This is illustrated in Figure 6.

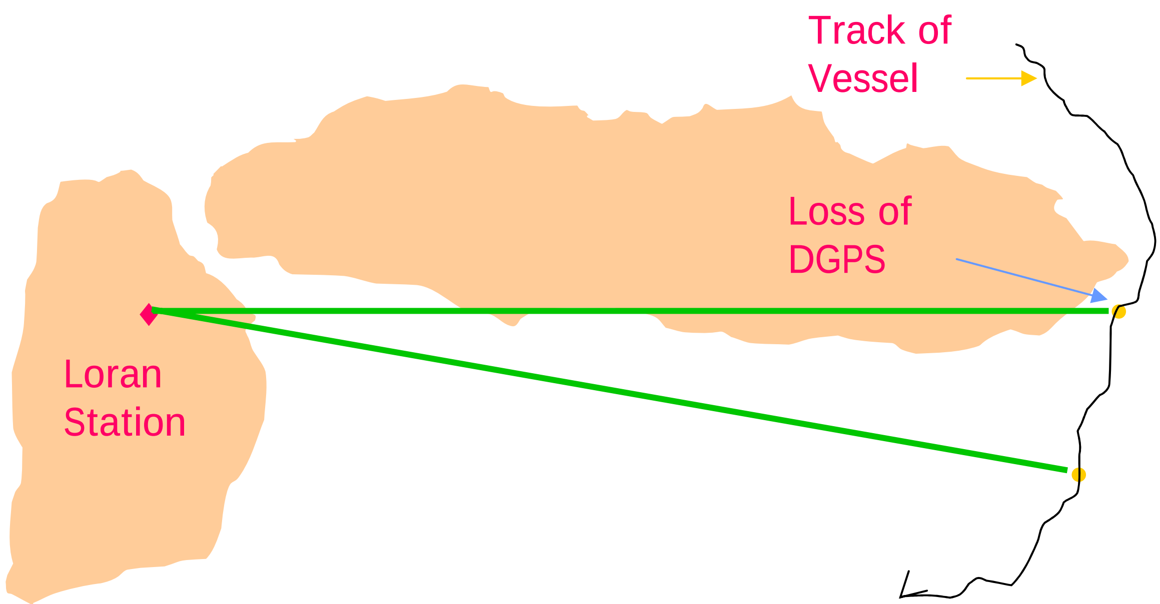

Figure 6 Changing Propagation Conditions following the Loss of DGPS

Performance of INS/IMU as a DGPS Backup System

For this integrated system, it is assumed that filtering acts to calibrate the characteristic INS/IMU errors prior to system update. A brief survey found that several GPS/INS integrated units were then (~ year 2000) commercially available, although no integrated
DGPS/INS systems were found. The survey of commercially available IMU components addressed systems at the low-end (under $20K), medium range ($20K - $50K), and high-end (over $50K) of the economic scale for navigation systems serving vessels executing harbor entrance and approach operations. High-end units include high-quality ring laser gyro systems with very low gyro and acceleration biases. Compact, good quality mechanical systems typify mid-range units with much higher gyro biases and random walk parameters. At that time, complete IMU systems based on low-cost micro-electro-mechanical systems (MEMS) technology were being developed through DARPA-funded and private research. These IMUs were selected to characterize future low-end units with

good accuracy performance. Simulations of representative high-end, mid-range, and low-end units were performed to determine the time dependence of the navigation error following DGPS outage. The simulations showed that the low-end and mid-range IMUs degraded to 100 m accuracy (CEP 95%) in about 4 – 6 minutes following DGPS outage. The simulated high-end systems achieved this same error level in about 12 minutes. Figure 7 compares INS/IMU error growth with that for Loran-C.

To apply the Markov chain methodology to the DGPS/IMU primary/secondary navigation system, a special approach had to be developed because of the rapid error growth of unaided IMUs. Since Markov states are associated with systems defined by roughly “fixed” navigation error statistics (to calculate incident probabilities), intermediate states were established for the unaided IMU following DGPS outage. Thus, the usual notion of “failure” was extended to include discrete transitions into successively larger error states. The end-state is associated with a navigation error just smaller than the fallback system - marine radar. Thus, shortly after the largest error state is reached, it is presumed the navigator would switch to marine radar. Markov chain calculations for the default set of scenarios show that, for the medium and high-end IMUs, the TLS is satisfied only for two-beacon coverage at both St. Mary’s River and Tampa Bay. For the default case, the low-end unit satisfies the TLS for Tampa Bay using two beacons, but not at all for the St. Mary’s River. However, the GPS MTBF itself is an uncertain parameter, based on alternative data sets in earlier analyses. Thus, if the GPS MTBF is increased within the range of its uncertainty interval, the TLS is *marginally* satisfied for the low-end IMU operating as a DGPS backup in the St. Mary’s River with two-beacon coverage.

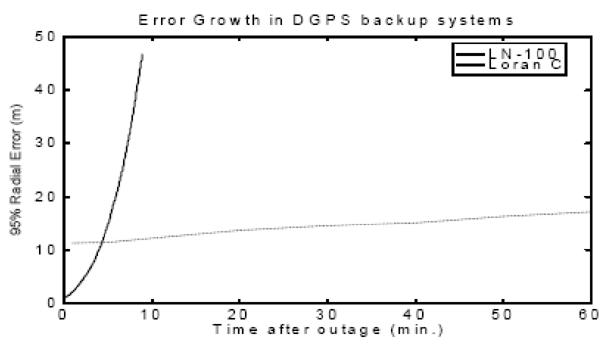

Figure 7 Comparison of IMU (LN-100) and Loran-C Position Error Growth Following DGPS Outage

Comparison of FRP Requirements and the TLS

USCG NAVCEN also sponsored an effort to look at navigation requirements for the Inland Waterway domain. As part of this effort, the TLS criterion was compared to the availability requirement for inland waterways that is contained in the Federal

Radionavigation Plan (FRP). This is important because Federal Radionavigation policy is easier to implement when there are fewer required performance criteria. Although the TLS has a solid basis in terms of maritime incident history, a relationship between these two criteria would establish a firmer basis for the availability criterion. FRP criteria for the inland waterway domain are shown in Table 2.

Table 2 Maritime User Requirements – Inland Waterway Phase

Navigation Need	**Accuracy (m)** (Predictable and Repeatable)	**Availability**	**Fix Interval** (seconds)
Safety – All Ships and Tows	2 – 5	0.999	1 – 2
Safety – Recreation Boats and Smaller Vessels	5 – 10	0.999	5 – 10
River Engineering and Construction Vessels	0.1* ; 5	0.99	1 - 2

In comparing the FRP and TLS criteria, a difficulty arises in the specification of the availability. The incident rate model contained in NAAT requires both mean failure and restore rates, whereas the FRP specifies only the ratio, i.e., the unavailability. To handle this difficulty, we first re-interpret the availability criterion as a requirement that the total availability be *greater* than 0.999. Then, a range of reasonable availability/reliability parameters, i.e., MTTR and MTBF, for both DGPS and GPS are defined on this space, lying within the FRP constraint space (total unavailability < 0.001). NAAT is then executed for each scenario by holding one set of availability parameters constant and varying the others to determine the set of parameters required for TLS satisfaction. In this way, a sample of the “unavailability space” is tested to determine the size of the population satisfying the TLS, relative to the FRP constraint space.

The results of this work show that a total inland waterway availability of 0.999 using an integrated system is incompatible with the reasonable ranges of the reliability/availability parameters for these systems. In this case, the reason for the incompatibility is that the reasonable range of parameters implies availability figures *higher* than the 0.999 FRP requirement. Thus, if we revise somewhat the FRP availability requirement to stipulate that the availability be *better* than 0.999, the incompatibility disappears, but the two criteria are not congruent, i.e., those cases satisfying the FRP requirement satisfy the TLS, but not *vice versa*.

Further analysis suggests that the TLS criterion is much more closely aligned with the requirement that the total availability be better than 0.9999, i.e., an unavailability less than or equal to 10^{-4}. The analysis indicates that, in only two scenarios, the upper limit of the total unavailability exceeds 10^{-4}. These cases involve the Delaware River scenario, the least challenging of the three waterways considered in this work.

This analysis concludes that the TLS criterion is approximately equivalent to a total unavailability requirement of 10^{-4}, or, equivalently, an availability of 0.9999. Even the two cases noted above would satisfy this requirement, although they would also satisfy a somewhat less stringent requirement.

4. Concluding Remarks on the Performance of Loran-C as a DGPS Backup System

The results summarizing the application of the Markov state methodology to the use of the three DGPS backup systems are given in Table 2. In this table, the interior entries answer the question: Is the TLS satisfied for all/some/none of the backup system scenario(s) listed? These results clearly show that only Loran-C integrated with DGPS was able to satisfy the target level of safety for all scenarios considered. The high performance of the DGPS/Loran-C integrated system is due to the excellent accuracy-preserving characteristics of the processed Loran-C signals as well as the high service reliability resulting from redundant Loran-C station coverage, i.e., availability of more than the minimum three station signals. The results for a DGPS system coupled with INS/IMU were less favorable primarily because the exponential error growth of the INS/IMU following loss of DGPS. This error growth leads to a rather rapid transition to the other backup systems: GPS (if the DGPS failure is due to the service) or, otherwise, marine radar. Moreover, the relatively low accuracy of marine radar yields comparatively high incident rates for a narrow channel in zero visibility.

Table 2 Comparison of DGPS Backup Systems in Terms of Satisfying the TLS

<table>
<tr><th rowspan="3">DGPS Backup System</th><th colspan="4">Waterway</th></tr>
<tr><th colspan="2">St. Mary's River</th><th colspan="2">Tampa Bay</th></tr>
<tr><th>1 DGPS Beacon</th><th>2 DGPS Beacons</th><th>1 DGPS Beacon</th><th>2 DGPS Beacons</th></tr>
<tr><td>Loran-C (3- and 5-Stations)</td><td>All</td><td>All</td><td>All</td><td>All</td></tr>
<tr><td>INS/IMU (Low, Mid, & High End)</td><td>None</td><td>Mid- and High-End Units only*</td><td>None</td><td>All Units</td></tr>
<tr><td>GPS without SA</td><td>No</td><td>No</td><td>No</td><td>Yes</td></tr>
</table>

* The low-end unit *marginally* satisfies the TLS, given the uncertainty range for the GPS MTBF assignment.

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