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

Using a Target Level of Safety Criterion

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Overview

- In a series of USCG efforts from 1997 – 2002 the maritime performance of DGPS and specified backup systems was analyzed in terms of the Target Level of Safety (TLS).

- Of the backup systems considered, Loran was the only one that consistently satisfied the TLS criterion for a variety of harbor entrance and approach conditions.
Background

• **USCG sponsored these studies with the goal of determining**
  – The conditions under which DGPS satisfies the Target Level of Safety
    • placement and reliability of DGPS beacon stations
    • degree of visibility
    • vessel type
    • relative navigational risk of harbor channel
  – The type of DGPS backup systems needed for maritime navigation
    • onboard (marine radar, INS)
    • external
      - electronic, e.g., Loran-C
      - visual, e.g., short-range aids
The Target Level of Safety (TLS) Criterion

• The comprehensive *Port Needs Study* was consulted to determine the incident* rate/ship-hour in ports and harbors used by larger vessels in CONUS (>10,000 gross tons)
  - Total Incident Rate = $3 \times 10^{-4}$ incidents/ship-hour

• Based on the categories used to classify incidents, those resulting from navigational errors were approximately 30% of the total
  - Incident Rate due to navigation errors
    $= 9 \times 10^{-5}$ incidents/ship-hour

* An incident is defined as a grounding or allision
The Target Level of Safety (TLS) Criterion – Risk Allocation

- The risk of incidents resulting from navigational error were allocated using a standard risk tree approach.
- The risk allocation for incidents arising from errors resulting from the following mutually exclusive events:
  - “no-fault” DGPS operations ($3 \times 10^{-5}$ inc./hr) or
  - backup system operation in the event of a detected DGPS failure ($1.5 \times 10^{-5}$ inc./hr)
- The resulting figure of $4.5 \times 10^{-5}$ as the probability of an incident/ship-hour is generally referred to as the TLS in subsequent analysis.
Risk Allocation

- Risk of simultaneous loss of accuracy and failure of integrity function
- Defines integrity probability of missed detection

Navigation Risk
9x10^{-5} incidents/hr

- Risk of incident when DGPS is operating at specified level

Undetected Failures
3x10^{-5} incidents/hr

- Incidents traced to loss of DGPS service, even though properly announced

Detected Failures
3x10^{-5} incidents/hr

- Risk attributable to backup system performance following DGPS failure

No DGPS Failures
9x10^{-9} incidents/hr

- Risk attributable to design of DGPS integrity function

Backup Design Risk
1.5x10^{-5} incidents/hr

Integrity Design Risk
1.5x10^{-5} incidents/hr
TLS as a Threshold

• Incidents comprising the navigational component of the TLS
  - resulted primarily from short-range aids

• With the advent of electronic aids in the maritime domain
  - more difficult operations (low visibility, ice) could be executed

• As a result, most pilots we interviewed recommended
  - the TLS threshold used to evaluate DGPS performance and backup systems should stay the same, i.e.,

  riskier operations compensate for increased accuracy and situational awareness
A system performance evaluation tool, known as the Navigation Aid Analysis Tool (NAAT), was developed as a decision aid for USCG NAVCEN to determine:

- The number and reliability of DGPS beacons required to satisfy the TLS under specified conditions
- The performance (reliability, availability) of requisite backup navigation systems in the event that DGPS was unable to satisfy the TLS under certain conditions
Application of NAAT to the Comparison of Backup Navigation Systems

• A variety of vessel types was considered, but most emphasis was given to the larger vessels
  - Incidents involving these vessels had more serious financial and environmental consequences

• Oceanographic/Environmental conditions included in the model
  - Current
  - Fog (in terms of visibility)
  - Season/hour (for EM noise level in the LF band)
Tampa Bay Channel Plot

![Tampa Bay Channel Plot](image)
Piloting Error Model

- Track-keeping error was determined from data obtained by the Merchant Marine Academy at King’s Point.
- Data was Fourier-decomposed and a peak period of 6 minutes was identified.
- This random sinusoid of amplitude standard deviation of 4 – 6 meters was combined with the navigation sensor error to form the total error model.
Piloting Error Model

Cross-track

Random Sinusoid

Along-track

Amplitude – Rayleigh distributed with $\sigma_A = 5$ m

Phase: uniformly distributed Wiener process
Application of NAAT to the Comparison of Backup Navigation Systems

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

- Transition from primary to secondary (backup) system
  - Simulated using a Markov state space model
  - Assumes secondary is continuously calibrated by primary while both are available
  - After a certain period of time, secondary reverts to its native accuracy performance
**DGPS/Loran Reliability Parameters**

<table>
<thead>
<tr>
<th>System</th>
<th>Reliability Parameters</th>
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<tbody>
<tr>
<td>Service and Receivers</td>
<td>MTTR</td>
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<tr>
<td></td>
<td>(minutes)</td>
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<tr>
<td>DGPS Service</td>
<td>10</td>
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<td>GPS Service*</td>
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<tr>
<td>Radar</td>
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<tr>
<td>Loran-C Service - St. Mary’s</td>
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</tr>
<tr>
<td>Loran-C Service - Tampa Bay</td>
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</tr>
<tr>
<td>Receivers**</td>
<td>?</td>
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</table>

* For GPS interference emulation, MTTR = transit time for waterway
Accuracy/Availability Models

- **GPS**: 5 – 8 m pseudorange error
  - Availability criterion: HDOP<4 ; 5° mask angle

- **DGPS**: 10 m CEP$_{95\%}$ ; 5.8m CTE$_{95\%}$
  - Availability criterion: when GPS is available and the beacon service is available

- **Loran-C**: Accuracy is a function of location (typically 20 – 50 m CTE$_{95\%}$)
  - Availability criterion: when all Loran stations in the coverage area are available
Accuracy-Preserving Characteristics of Loran-C

Loran Coherence Profiles
Seneca, NY to New London, CT
St. Mary’s River with Loran as DGPS Backup under GPS Interference Conditions
Changing Propagation Conditions

• DGPS is assumed to continuously calibrate Loran while the two systems are available
• What if propagation conditions change following loss of GPS?
• We assume that a future ASF model (embedded in each receiver) continuously monitors the propagation path to each station
  – When the predicted ASFs change by more than a designated threshold, the ASF model will add the change in ASFs to the prior DGPS-calibrated ASF value
Changing Propagation Conditions

- Loss of DGPS Track of Vessel
- Loran Station
- Loss of DGPS
St. Mary’s River with INS/IMU as DGPS Backup under GPS Interference Conditions
Comparison of FRP Requirements and the TLS

- FRP requirement for availability is 0.999 for the inland waterway domain.
- Equivalence of the two is not direct since availability is related to MTTR/MTBF, whereas TLS = TLS(MTTR,MTBF).
- Looking over a range of reasonableness parameters, we found that the TLS is roughly equivalent to an availability of 0.9999.
Conclusions

• In work done for the USCG, Loran was the only DGPS backup system that consistently satisfied the TLS criterion for large vessels transiting the most challenging harbors under low visibility conditions.

• For several of the HEA conditions we considered, DGPS, either stand-alone or with non-Loran backups, was unable to satisfy the TLS.

• If we require the TLS criterion to be satisfied under all HEA conditions, Loran backup to DGPS is absolutely required.
Backup Slides
### Tampa Bay Channel Description

<table>
<thead>
<tr>
<th>Segment ID</th>
<th>Latitude (degrees)</th>
<th>Longitude (degrees)</th>
<th>Width 1 (feet)</th>
<th>Width 2 (feet)</th>
<th>Description</th>
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Time-to-Alarm for Maneuvering

Safe Turn Initiation Region

FHC

Ideal Turn Initiation Point