Availability Performance Comparisons of Combined Loran-C/GPS and Standalone GPS Approach Navigation Systems

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Abstract - Operational air navigation systems not only must provide adequate position estimates, but they also must be available to the user when needed, and able to warn the user in a timely manner when the system becomes unusable. This paper addresses the availability of a combination Loran-C and GPS radio-navigation system during nonprecision approach (NPA). Also, GPS by itself cannot meet the sole means integrity requirements for NPA. Simulation models were developed to quantify statistically the availability of the Loran-C/GPS system, and to compare it with GPS alone. The results presented in this paper show that the combination Loran-C/GPS navigation system enhances the availability of either standalone system by at least a factor of ten. Loran also enhances the integrity of GPS. In addition, Loran-C can use the same approach geometry and cockpit display instruments now allowed for GPS.

INTRODUCTION

The Federal Radionavigation Plan [1] states that "the availability of a navigation system is the percentage of time that the services of the system are usable by the navigator," and that "signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. It (signal availability) is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities."

Integrity is the probability that a system will not fail in a way that provides erroneous guidance information to the pilot or autopilot. Integrity means the capability to detect and isolate faults in the navigation system, and to alert the user in a timely manner. Recent analysis indicates that GPS by itself cannot meet the sole means integrity requirements for NPA [2], [3]. Supplemental navigation systems require only a fault detection capability to ensure integrity, whereas sole means systems require fault detection and isolation (FDI). Loran-C integrity is provided by blinking the signals of the master transmitter. This process is on the verge of being automated to meet FAA approach integrity requirements. GPS integrity can be provided by requiring that satellites in addition to those required for a navigation solution be tracked. The need to track more satellites simultaneously reduces GPS availability.

The results presented in this paper show that the combination Loran-C/GPS navigation system significantly enhances the availability of either standalone system. Loran also enhances the integrity of GPS. In addition, Loran-C can use the same approach geometry and cockpit display instruments now allowed for GPS. The two systems thus are very compatible, yet also are complementary with respect to integrity and redundancy.

Another benefit to combining Loran-C and GPS is that the relative cost to the FAA of incorporating them into the National Airspace System is rather low. Loran-C is an operational, reliable system maintained by the US Coast Guard. Loran has served maritime interests effectively for over four decades, and with the advent of new technology is increasingly playing a major role in general aviation navigation. Several Loran receiver models have been certified for the en route and terminal area flight phases, and about 150,000 receivers are now in active use among the GA community.

BACKGROUND

The Global Positioning System was developed by DOD for military purposes, but it - and does - support civilian navigation uses. GPS has
just achieved Initial Operational Capability\(^1\), and is rapidly being developed for use in the NAS. Although the ultimate non-DOD role in the maintenance of the GPS system has yet to be determined, GPS still is a bargain for the FAA and aviation user. Finally, as a result of IOC for GPS and the recent construction of four Loran transmitters (the "mid-continent" expansion), both systems essentially cover the entire land area of the CONUS ("lower 48" states) on a 24-hour basis. These developments have the highly desirable consequence of opening up to general aviation aircraft instrument approach capability at thousands of smaller airports where the installation of other approach aids is not economically feasible.

The availability of transmitted Loran-C signals for NPA is about 99.75% \(^2\). Results from the analysis show that the availability of 24-satellite GPS with a baro-altimeter and Receiver Autonomous Integrity Monitoring (RAIM) is about 99.0%. Without baro aiding, GPS-RAIM availability is about 97.7%. These results assume that the navigation system is "available" if reliable navigation signals are present at the start of a nonprecision approach.\(^2\) The results presented in this paper show that the combination Loran-C/GPS navigation system has an availability which exceeds 99.99%, and can achieve at least 99.997% under special yet realistic conditions. This is at least 100 times better than standalone GPS with RAIM.

**Objective.** Determine the availability in the CONUS of a hypothetical combination Loran-C/GPS receiver.

\(^1\) Initial Operational Capability (IOC) means that a full constellation of 24 GPS satellite vehicles (SVs), some of which may be the Block I test satellites, is operable. Full Operational Capability, expected in the spring of 1994, means that the GPS constellation consists entirely of operational Block II SVs.

\(^2\) Because of system integrity, loss of navigation once an NPA has been initiated will be announced to the pilot, who then will execute a missed approach according to published procedures.

**Availability Considerations.** The Federal Radionavigation Plan defines availability as applied to NPAs as follows:

*Availability is the probability that suitable navigation with guaranteed integrity will be available for the start of a nonprecision approach.*

This definition applies to the availability of the signal in space. It assumes that the onboard navigational equipment is properly installed and functioning, and that system integrity is assured.

The NPA availability criterion is not met (unavailability criterion) when:

1. The navigation error is larger than required for the NPA; or, when
2. System integrity cannot be assured, even with acceptable navigation accuracy.

When these conditions are quantified, the availability criterion becomes:

\[
\text{Availability} = 1 - \frac{\text{No. unavailable time-space points in 24 hours}}{\text{Total time-space points in 24 hours}}
\]

where a time-space point is a location in three dimensional space consisting of the time line and two position dimensions (Earth surface).

A simulation and analysis capability was established at the Volpe Center to quantify Loran-C/GPS NPA availability under the above criterion. The primary elements in this activity included:

- Assimilating Loran-C and GPS data
- Developing realistic assumptions and scenarios
- Adapting or upgrading existing software, and generating new software as needed
- Conducting simulation and analysis

A point of departure for the work presented here is Reference \([2]\). The methodology and results presented here are therefore consistent with that effort.

GPS and Loran-C/GPS availability was computed by establishing a uniform set of locations throughout the CONUS, using a square grid of size \(1^0 \times 1^0\) (60 by 60 nautical
miles). At the nodes of this grid, Loran availability was determined from a combination of historical outage data for transmitters nominally able to "cover" the node, and from conductivity and geometry algorithms derived at the Volpe Center from those in the Loran-C Airport Screening Model. GPS availability was determined from DOD-supplied historical data on the useful life of a GPS satellite vehicle (SV). These were combined with simulations which used ephemeris and geometrical information (mask angle, dilution of precision, etc.) to develop an availability measure.

A Loran-C receiver can measure the time difference (TD) for all secondary Loran stations "in view" and convert this information into a two dimensional position estimate (intersection of two hyperbolic arcs representing two distinct TD values). The receiver must be able to track the signals from at least a triad of transmitters (one master and two secondaries) in the same chain. Factors influencing receiver ability to track signals are:

- The transmitter is operating
- The transmitted signal meets specifications
- Location-dependent parameters such as conductivity, geometry, range, and signal-to-noise ratio are favorable

The study discussed in this paper dealt primarily with the first condition listed above. If the transmitted Loran signal is defective (second condition), the master station initiates "blink," which warns the user of unreliable signals and thus ensures Loran integrity. Similarly, local adequacy of signal (third condition) is accommodated in the coverage models. In like manner, the effect of local conditions on GPS reception is accommodated in GPS coverage models.

A Loran signal outage is classified by the Coast Guard as a momentary if it lasts less than 60 seconds. Momentaries by their nature are recoverable "glitches," and are not logged by the Coast Guard as unusable time. According to actual data for all five Loran-C chains in the CONUS [2], momentaries occur at a rate of about two to three times per day per triad, or less than one per station per day. Over 90% of all Loran outages are momentaries. Thus, while a momentary Loran outage may cause the pilot to execute a missed approach, the brevity of the momentary makes circling around to attempt another NPA at the same runway a viable option. The pilot in any case must have full navigation (receiver locked and tracking) before second or subsequent instrument approaches can be initiated.

In a similar manner, GPS availability is based on the number of SVs in view which are sending an adequate navigation signal. The nominal GPS constellation has 24 satellites. The analysis used in this study utilized the "Optimized 21 + 3" constellation, which contains the actual target locations for the operational Block II SVs. Further, like all operational navigation systems, GPS must guarantee integrity for all flight phases. GPS integrity will be supplied by algorithms within the receiver, collectively known as Receiver Autonomous Integrity Monitoring (RAIM). At an unspecified later date, the GPS Integrity Channel (GIC) will provide GPS integrity.

Sole means GPS RAIM integrity means that six SVs must be visible to the receiver. Four SVs are needed for the three dimensional navigation solution, and the extra two provide the FDI function for RAIM. Supplemental GPS RAIM integrity requires only five SVs, since only detection, but not isolation, of the failed SV is required. Even with the full 24-satellite constellation, there are periods when only four SVs are visible in the CONUS. GPS then fails RAIM availability. Availability thus is driven not only by the basic navigation requirement, but also by integrity. Another factor is that DOD imposes regular down times for maintenance of each SV, which reduces availability.

GPS availability can be enhanced to a small degree by such methods as reducing the mask angle, using baro aiding, or launching ranging geostationary satellites. However, a practical and effective way to provide GPS RAIM while maintaining adequate NPA availability is to use data from Loran transmitters, in place of extra

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3 In the context of the discussion, the signal of an "in view" transmitter can be acquired and tracked by the receiver.
GPS SVs, acting as GPS pseudolites. This indeed is the major benefit of a combination system, and is why such a system greatly enhances the availability of either of its components.

In this paper, GPS RAIM is based on the parity space FDI method, using a protection radius of 555 meters [3]. The Volpe Center results for availability in the CONUS of GPS with RAIM and baro aiding, but no Loran-C, is 97%. This will not be adequate for sole means approach navigation. Reference [2] shows that, based on Loran transmitter outage data for the Northeast US chain, the worst case Loran NPA availability is 99.75%. Availability for the entire CONUS is 98.5%. Redundant FDI measurements, as provided by combination Loran-C/GPS, can meet sole means integrity requirements for approach [3]. The combination system, as the analysis reported here showed, also can increase availability at least tenfold.

METHOD

Availability of the combined Loran-C/GPS navigation system was determined by examining Loran and GPS signals at each node in the grid defined above. The simulated sampling of the signals was done at 6-minute intervals over a 24-hour period. Thus, one geographical location represents 240 time-space points. Since 851 grid points were used in the CONUS, a total of 204,240 time-space points were used to determine system availability. Time is an availability factor both for Loran-C and GPS, but particularly for GPS. This is primarily because the GPS transmitters move with respect to the Earth's surface, while the Loran transmitters are fixed. There are diurnal effects on Loran-C signals due to atmospheric differences between night and day, but these are of smaller consequence than the temporal effects on GPS.

The GPS SVs are in constant motion overhead, and this produces changing quality in the user's navigation signal for each particular SV. This variation is quantified via the "dilution of precision" measures, e.g., GDOP (geometric DOP). Eventually, a given SV drops below the horizon (or, more accurately, the "mask angle" elevation), and is replaced in time by others. The GPS receiver continually tracks as many of the visible SVs as it has active channels, and the better receivers use the optimum subset for the navigation solution.

At any time-space point, a fixed number of Loran-C transmitters and GPS SVs are "in view". Different fail scenarios were developed by eliminating the signal from one or more transmitters. The failure of transmitters reflects actual performance data for Loran and anticipated performance for GPS. These data were used to develop Loran-C/GPS availability for various fail scenarios.

At each time-space point, up to four simultaneous SV failures were analyzed. The visible satellite whose failure has the greatest effect on GDOP was failed first. The second failure similarly has the greatest impact of all remaining visible SVs on GDOP, as does the third SV failed. This is the most conservative way to fail satellites. The fourth failed SV was randomly chosen from the remaining SVs.

The probability of 0, 1, 2, 3, or 4 SV failures at any one time is determined from historic data supplied by DOD, or by means of a Markov model. The Markov fail probabilities used are very conservative, since the model includes a two or three month unavailability interval, reflecting the time to launch a replacement SV. In actuality, there usually is a very good indication - for example, from clock drift rates - of an impending failure, so that actual down time is much less and often nothing.

The analysis used a barometric altimeter with GPS to supply redundant altitude data for integrity. In addition, two distinct integrity conditions were analyzed:

- Loran-C with GPS RAIM used in all measurements (Condition A)
- Loran-C in "reversion" mode, which uses Loran-C alone for navigation and integrity if GPS RAIM and Loran-C fails, and if

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4 "Worst case" is a Type A aircraft (maximum approach speed: 90 kt) attempting its initial approach.
Loran GDOP is less than 3,000 ft/μsec (Condition B).

Loran scenarios analyzed were:

- All stations in a chain are in view
- All stations in view, regardless of chain, are used

These conditions or scenarios produced four sets of availability results.

When hyperbolic (TD) Loran is used, the failure of a master transmitter in a chain must be treated differently than secondary transmitter failures. If a master fails, all TDs from its chain also are lost, whereas the loss of a secondary eliminates only its TD.

The 60 nmi square grid used to locate test points in the CONUS for the simulation analysis actually is used only when RAIM navigation fails. A coarser, 300-by-300 nmi grid (5° × 5°) covering the CONUS is used until RAIM fails (becomes unavailable) at a point. When this happens, the finer grid, consisting of a 5-by-5 array of points 1° apart, is constructed centered on the no-RAIM point. GPS alone and Loran/GPS (plus baro aiding) availability is computed at each of these points. The finer grid defines more clearly the boundary between regions with and without navigation.

Availability is thus determined at all CONUS points on a grid as defined above, over a 24 hour period, at 6 minute intervals. This results in 204,240 time-space points analyzed for each scenario. In these scenarios, the probability that there is no navigation due to failure of the 4th GPS SV is computed at each time-space point in the CONUS, for a given Loran availability. RAIM availability then is determined for GPS alone, Loran-C and GPS, and Loran-C and GPS with 1 failed "in-view" Loran station. The computed probabilities were combined to derive the total availability measure. The probabilities are the ratios of no-RAIM (no navigation) time-space points to all time-space points in the CONUS, for each fail scenario. This is detailed further below.

RESULTS

The results were developed for four scenarios, summarized in Table 1. More details are forthcoming in the project final report, now in preparation. The first two scenarios consider a single Loran-C chain, the "best" chain for each location in the grid. The single chain option is consistent with the current FAA requirement specifying a particular triad for each Loran-aided NPA. In the last two scenarios, Loran navigation can use all stations/all chains in view. This is a less conservative option which is technically feasible and furthermore is preferable from a performance point of view, but which has not been sanctioned by the FAA for NPA.

For each of these Loran coverage scenarios, availability is computed either when GPS RAIM only provides integrity (Condition A), or when Loran reversion supplements RAIM integrity (Condition B).

The simulation runs for each case required about 8 hours of processing on a 50 MHz 486 microprocessor. These results assume a Loran-C TD error which produces a 116 meter rms position error. This is equivalent to a TD error of about 250 nanoseconds for a GDOP of 1500 ft/μsec. Extensive field analysis of Loran-C signals at over 20 selected airports throughout the CONUS, conducted by the Volpe Center, indicates that this is a conservative value. If a more realistic value of 62 meters rms is used (not done here), there is a large availability gain.

Case 1 represents the most conservative scenario

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>LORAN COVERAGE</th>
<th>INTEGRITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Single Chain</td>
<td>RAIM only</td>
</tr>
<tr>
<td>Case 2</td>
<td>Single Chain</td>
<td>RAIM or Loran reversion</td>
</tr>
<tr>
<td>Case 3</td>
<td>All Chains in View</td>
<td>RAIM only</td>
</tr>
<tr>
<td>Case 4</td>
<td>All Chains in View</td>
<td>RAIM or Loran reversion</td>
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</tbody>
</table>
examined. The scenarios are progressively less conservative for each case in sequence. Case 2 considers Loran transmitters acting as pseudolites to ensure GPS integrity, and Cases 3 and 4 repeat these conditions, except that the receiver can use all Loran chains (stations) in view.

A major result from the analysis is that combining Loran and GPS typically causes a better than ten-fold reduction in the number of no-RAIM time-space points. For example, in Case 2 when all SVs are functioning, there are only 10 time-space points out of 204,240 in the CONUS which have neither GPS RAIM nor a Loran backup, compared to 547 no-RAIM points with GPS alone. Availability for GPS alone with RAIM (and baro aiding) is 99.0%, and without baro is 94.7%. Loran standalone availability for NPA was determined to be 99.7% [2]. As SV failures are added, the Loran benefit remains strong, but diminishingly so.

In Case 2, the resulting total system availability is almost ten times better\(^5\) than Case 1. When all Loran stations in view are used (Cases 3 and 4), the total system availability numbers remain comparable to the respective results in Cases 1 and 2, except that overall availability improves due to the greater access to Loran transmitters.

Figure 1 shows the availability hierarchy for approaches, starting at the top level with GPS alone, and continuing down with increasingly comprehensive Loran support. The availability numbers shown at each level on the right are equivalent to the probability of initiating a successful nonprecision approach. System integrity will warn the pilot of loss of navigation once an approach is initiated. The basic result is that only 3 out of every 100,000 NPA attempts will have to be aborted because of unreliable navigation, when Loran-C is combined with GPS.

\(^5\) The relative comparison of availability often is best seen from the system unavailability number. If one scenario produces an unavailability number 10% as large as another scenario, the former may be said to have ten times the availability.

**CONCLUSIONS**

The results show that, under realistic assumptions, the combination Loran-C/GPS navigation system can provide up to 100 times improvement in availability over GPS as a standalone system. Furthermore, the combination Loran-C/GPS system has sufficient integrity to be used as a sole means approach navigation system. Based on integrity, GPS alone can only be a supplemental approach navigation aid, so that it must be combined with another system such as Loran-C. In summary:

- Availability of GPS and a barometric altimeter with RAIM is 99.0%, without the baro, availability is 94.7%
- Availability of transmitted Loran-C Signals exceeds 99.7% for approaches
- Availability of Loran-C and GPS with Loran-C augmenting GPS RAIM (Condition B) exceeds 99.997% for approaches
- Loran-C improves GPS RAIM integrity at least tenfold for up to four simultaneous GPS satellite failures
- Loran-C can use the same approach plates and CDI scale as GPS

The results reported here support earlier work [3] in confirming Loran-C/GPS as a feasible and practical approach navigation system.

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Figure 1. Loran-C/GPS Availability Hierarchy

REFERENCES


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