SOLE MEANS NAVIGATION AND INTEGRITY THROUGH HYBRID LORAN-C AND NAVSTAR GPS

Frank van Graas
Avionics Engineering Center
Ohio University

BIOGRAPHY

Ir. Frank van Graas received the B.S. degree in 1983 and the "Ingenieurs" degree in 1985, both in electrical engineering with specialization Avionics from Delft University of Technology, Delft, the Netherlands. Currently he is a research associate for the Avionics Engineering Center and Ph.D. student at Ohio University. During the past three years he has been involved with the NASA Ames differential GPS program, and system development and flight testing of GPS and LORAN-C.

ABSTRACT

A minimum of four GPS range measurements or two LORAN-C Time Differences (TDs) is normally required for a position solution for enroute navigation, area navigation, and non-precision approaches.

This paper describes a new technique that hybridizes GPS and LORAN-C used in the pseudorange mode to process efficiently all available navigation information. Emphasis is placed on combined GPS and LORAN-C timing, both for the ground/space facilities and the user.

The hybrid system has the potential to solve the GPS and LORAN-C integrity problems; more range measurements are available than required for the navigation solution.

1.0 INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is expected to become operational around 1991. At that time, given the currently planned 21 satellite constellation, GPS will only qualify for a supplemental type certification. GPS does not fulfill the integrity requirements for a sole means navigation system. Several schemes have been proposed to solve the GPS integrity problem, including additional GPS satellites, geostationary satellites with ground based monitoring stations, and differential GPS. These approaches require either major government investments or significantly increased user costs (additional uplink equipment).

Another way to achieve integrity is by combining navigation systems. For the continental United States, the Long Range Navigation system, LORAN-C, combined with GPS has the potential to meet both the availability and the integrity requirements for a sole means navigation system. In addition, it is expected that the requirements for non-precision approaches will be fulfilled.

This paper is mainly concerned with the interoperability of LORAN-C and GPS. It should be emphasized that other navigation aids such as Omega, DME, IMU/INS, and altimeter could be integrated as well. The resulting navigation system should be based on a generic design that allows for effective and transparent processing of all navigation data simplifying certification and training procedures.

2.0 WHAT CONSTITUTES A SOLE MEANS NAVIGATION SYSTEM ?

Air navigation in controlled airspace requires the presence of a sole means navigation system. Although many descriptions and even a definition* exist for a sole means navigation system, not all requirements that constitute such a system are specified. Consequently, the question raised in the title of this section cannot be fully answered.

Looking at currently accepted sole means navigation systems such as VOR/DME, and considering five major performance characteristics: accuracy, availability, reliability, coverage, and integrity, both the known requirements and deficiencies of the definition for a sole means navigation system can be derived as follows: (Formal definitions for some of the requirements can be found in references [1,2]).

Accuracy: Both current accuracy requirements and future goals exist. Table 1 summarizes these accuracies for specific phases of flight in the continental United States (CONUS).

Coverage: Navigation signals must be adequate to determine position accurately within the coverage area.

Availability: This is the percentage of time that the navigation system can be used at a certain location. Availability should be close to 100 percent (VOR); the exact percentage is not specified. Generally, the requirement states that a system outage should not overload the air traffic controller. Whether an availability of 99.9% (526 minutes of outage during a year) or 99.9999% (32 seconds of outage during a year) would satisfy this requirement is not known. Also, a VOR outage only affects a relatively small area; a failing GPS satellite affects a large service area.

Reliability: This is the probability that a system will be operational continuously over a specified period of time at a certain location. A low reliability indicates that the system is likely to experience an outage over the specified period of time. Systems with long outage periods should therefore be very reliable. Solid-state VOR or DME stations have a specified Mean Time Between Failure (MTBF) of 10,000 hours [4]. For area navigation, two signals are needed at the same time. Redundant VOR/DME results then in a reliability of 95% over a period of approximately 120 days.

Integrity: This is a fairly recent requirement for navigation systems. An adequate definition of integrity used for the Institute of Navigation workshop on GPS integrity is given by [5]:

> Guaranteeing to the user (with probability p) that he will be promptly (within time T) notified when GPS system induced errors are greater than a prespecified level.

Other definitions of integrity exist, they all have the same three ingredients: a warning time T, an error limit, and a probability p. The integrity working group of RTCA Special Committee 159 has developed goals for warning times and error limits, these goals are summarized in Table 2 for navigation in CONUS [5]. A figure for probability has not been specified.

3.0 AVIONICS EQUIPMENT INTEGRATION OPTIONS

The avionics implementation of combined LORAN-C and GPS can be divided into two approaches:

1) Two Separate Systems. This approach requires a third system that combines the two receivers in one of the following ways:
   a) A (processor) system that obtains navigation data from the GPS and the LORAN-C receivers, executes the integrity checking algorithms, and provides the "best" navigation solution to the pilot (this solution may be based on data from both systems).
   b) An interface that converts the data from one system in such a way that it can be used as an extra input to the other system (e.g. LORAN-C as a pseudolite input to the GPS receiver). This approach might require minor modifications to the data receiving system.

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* The 1984 Federal Radionavigation Plan [1] gives the following definition for a Sole Means Air Navigation System: An approved navigation system that can be used for specific phases of air navigation in controlled airspace without the need for any other navigation system.

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Phases of Flight	Current System (1),(2) Accuracy Requirements AC 90-45A [3] 95% conf. for cross track and along track	Future System (1) Accuracy Requirements FRP-84 [1] 2 drms
Enroute Domestic	1.5 nmi	1000 m
Terminal	1.1 nmi	500 m
Non-Precision Approach	0.3 nmi	100 m

(1) System accuracy requirements do not include Flight Technical Errors.

(2) Does not include radiated signal accuracy. It is not clear from AC 90-45A how to account for these errors.

Table 1. Current and future navigation system accuracy requirements for specific phases of flight in the continental United States.

Phases of Flight	Radial Alarm Limit	Time to Alarm
Enroute Domestic	1000 m	30 s
Terminal	500 m	10 s
Non-Precision Approach	100 m	6 s

Table 2. Goals for integrity criteria as developed by the integrity working group of RTCA Special Committee 159.

2) Hybrid GPS and LORAN-C. Several grades of hybridization can be implemented. Since this system is currently non-existent, it is necessary to identify the most effective method of hybridization.

Figure 1 illustrates the separated and hybridized GPS/LORAN-C functional block diagrams. The main features of the hybrid system are the shared clock and receiver/processor assembly. The shared clock enables both systems to obtain timing information from each other, maximizing the use of all available navigation information. This will be illustrated in more detail in section 6.

Before the introduction of the navigation solution for combined GPS/LORAN-C it is necessary to take a close look at the timing of both systems. GPS maintains all timing relations between the space segment and the ground segment. However, for navigation users LORAN-C timing is established for each chain only. Current developments in LORAN-C include proposed system timing changes. This will result in a major improvement of navigational accuracies. Section 5 presents LORAN-C timing options and their effects on the navigation accuracy. LORAN-C pseudoranging is emphasized, since this allows for LORAN-C signal processing in a manner very similar to GPS, and will take advantage of the LORAN-C clock information.

4.0 GPS TIMING AND COVERAGE

The timing of the GPS system is very well defined [6]. The Master Control Station at Falcon AFS maintains GPS system time. Each satellite operates on its own reference time (space vehicle time) which is closely monitored by the GPS Ground Control Segment. Information about space vehicle clock phase offset with respect to GPS time can be calculated continuously from the navigation data transmitted by the satellites with a typical accuracy of 15 nanoseconds [7].

Currently, GPS system time is monitored to within 100 nanoseconds with respect to Universal Time, Coordinated (UTC). Offset between GPS time and UTC is also transmitted by the satellites and can be determined continuously by the user with a resolution of 1 nanosecond [6]. With the installation of three hydrogen masers at the Master Control Station, the capability exists to determine time offset between UTC and GPS time to within 30 nanoseconds [8].

The 21 satellite constellation will provide full coverage for CONUS. However, there are several hours out of each day that only four satellites are visible. During these periods, there is no ability to detect so-called "soft" GPS errors, such as might result from satellite clock degradation. Periods of limited visibility are also vulnerable to single satellite outages, causing the GPS system to be unavailable. The availability of the 21 satellite constellation is estimated to be about 75% [9].

5.0 LORAN-C TIMING AND PSEUDORANGE COVERAGE

In order to consider the effect of LORAN-C system timing on navigation and timing accuracies, four timing options with respect to LORAN-C and GPS/LORAN-C interoperability are described below. Table 3 summarizes the anticipated error budgets for pseudorange measurements to LORAN transmitters for the four timing options. Although not specifically mentioned in the following sections, pseudorange measurements are considered to be made with respect to a known time reference (UTC or GPS) at the user. In general, the knowledge of UTC or GPS time at the user is not only a function of geometry, but also depends on the magnitude of common bias errors in the pseudoranges (e.g. unmodeled propagation delays). These errors hardly affect the position solution, but will appear as an additional bias in the estimate of the system time reference (UTC/GPS). Note also that receiver hardware delays from the antenna phase center to the measurement point in the receiver are considered to be calibrated and known.

5.1 Current LORAN-C Timing.

LORAN-C Master station transmissions are synchronized to UTC within ± 2.5 microseconds. Whenever a Master drifts too far away from UTC, two methods can be used to adjust the offset: a frequency adjustment or a microphase stepper adjustment. Intentional time-steps and frequency adjustments are always announced in advance [10]. Frequency adjustments are on the same order as the drift rates of the LORAN Cesium frequency references, typically 50 - 300 nanoseconds per day.

Secondary stations are held to within ± 50 nanoseconds of the Controlling Standard Time Difference (CSTD), a reference TD established for each Master-Secondary pair, measured by a System Area Monitor (SAM). The SAM initiates Local Phase Adjustments (LPAs) at the Secondary station to maintain the CSTD. This results in an extremely stable TD for users close to the line-of-position (LOP) the SAM is located on.

The main disadvantage of the current LORAN-C timing procedure is that the time of transmission of the Secondary station varies when propagation delays to the monitor (SAM) vary. This results in an uneven error distribution with relatively large errors in areas not close to the line-of-position defined by the CSTD [11,12]. Also, propagation delay models cannot be applied easily; besides the signal path delay from the Secondary transmitter to user, the variations caused by the SAM would need to be predicted as well.

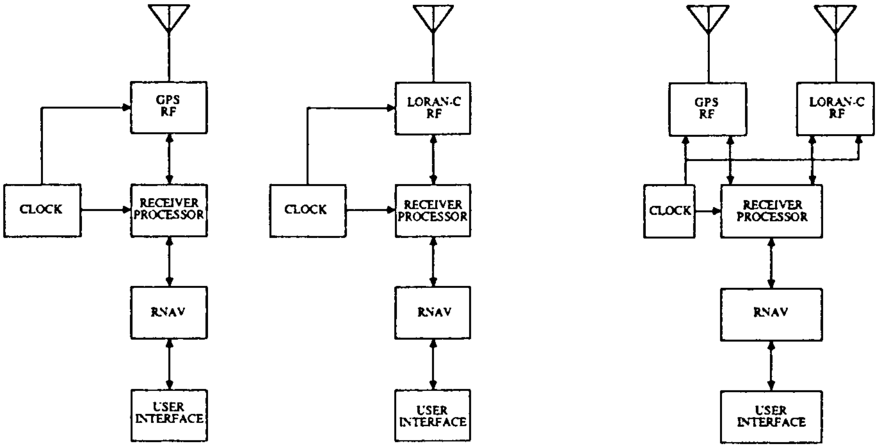
5.2 Master Station Time of Transmission Control.

Controlling the LORAN-C Master stations to an accuracy of better than 100 nanoseconds with respect to UTC will reduce the uncertainty of the LORAN-C clock phase offset relative to GPS. Including propagation uncertainties, pseudorange measurements to Master stations could be within 200 nanoseconds. Ranging to Secondaries would introduce approximately another 100 nanoseconds due to chain timing and temporal propagation effects. Users of LORAN-C only will see no net change. In fact, LORAN-C users can benefit from the increased coverage and accuracy offered by cross-chaining, approximately a factor of 2 in position accuracy with respect to current LORAN-C, mainly caused by improved geometry.

5.3 Time of Transmission Control for all LORAN-C Stations.

This option proposes a radical change in the timing control of the LORAN-C system. Each transmitter will be synchronized with respect to UTC. This approach is similar to the French direct ranging LORAN-C chain where GPS is used to monitor the timing control [12]. Time of transmission control will result in improved navigation accuracies for areas not close to line-of-positions maintained by SAMs. The main disadvantage of this option is the upward compatibility of existing LORAN-C receivers. The very high TD repeatability around the SAM will be lost, and tables for ASF corrections would have to be replaced by propagation delay models. Single chain LORAN-C users would not necessarily see an improvement in navigation accuracy when compared with Master time of transmission control. Chain timing errors and temporal propagation effects would be replaced by timing uncertainties with respect to UTC. Cross-chaining users on the other hand would benefit tremendously; all transmitters are equal, opening up a larger coverage area with good geometry. This would also increase the LORAN system availability: a failing Master station does not result in an unusable chain.

For the combined GPS/LORAN-C system, this option would be very effective: all LORAN transmitters could provide ranging with accuracies typically better than 200 nanoseconds.



(a) (b)

Figure 1. Separated (a) and hybridized (b) GPS/LORAN-C functional block diagrams.

ERROR SOURCE	LORAN-C TIMING OPTIONS			
	I	II	III	IV
TRANSMITTER - UTC SYNCHRONIZATION ERROR (ns)	± 2500*	100*	100*	60*
SECONDARY-MASTER SYNCHRONIZATION ERRORS (ns)				
CHAIN TIMING	±50	±50	—	—
TEMPORAL PROPAGATION EFFECTS	0 - 50	0 - 50		
PROPAGATION ERRORS (ns) (TRANSMITTER TO USER, AFTER MODELING)	50 - 100	50 - 100	50 - 100	50 - 100
RECEIVER MEASUREMENT (ns) ERROR	25	25	25	25

I = CURRENT LORAN-C TIMING

II = MASTER STATION TIME OF TRANSMISSION CONTROL

III = TIME OF TRANSMISSION CONTROL FOR ALL LORAN-C STATION

IV = DETERMINATION OF LORAN-C TRANSMITTER OFFSETS WITH RESPECT TO GPS TIME

* NOTE THAT THE TRANSMITTER OFFSET WITH RESPECT TO UTC ONLY AFFECTS THE ESTIMATE OF UTC AT THE USER; THE POSITION SOLUTION BASED ON TRANSMITTERS FROM THE SAME CHAIN IS HARDLY AFFECTED. CROSS-CHAINING ON THE OTHER HAND IS AFFECTED SIGNIFICANTLY, UNLESS AN EXTRA TRANSMITTER IS TRACKED TO DETERMINE THE OFFSET BETWEEN DIFFERENT CHAINS.

Table 3. A comparison of error budgets for LORAN-C pseudorange measurements with respect to current and proposed system timing.

5.4 Determination of LORAN-C Transmitter Offset with respect to GPS Time.

All of the timing options discussed above should also be considered in combination with GPS receivers at each transmitter site. Data collected from GPS can be used to determine the transmitter clock offset from GPS time with an accuracy better than 30 nanoseconds. The clock offset with respect to either UTC or GPS time can then be transmitted to the user. This approach establishes, in essence, time of transmission control without affecting existing user equipment. Ranging accuracies to the transmitters will only be limited by the sum of GPS time transfer accuracy, remaining uncertainties after propagation models are applied, and user receiver errors. State-of-the-art LORAN receivers would typically achieve ranging accuracies better than 150 nanoseconds.

The use of the LORAN-C blink codes or additional pulses for the transmission of the clock offset data can be justified by the significant improvement of the timing and navigation capabilities created by this approach.

5.5 LORAN-C Pseudorange Coverage.

Use of LORAN-C in the pseudorange mode improves the geometry for users outside the center of the service area, and facilitates user clock synchronization with LORAN-C system time. If all stations are synchronized to a common time reference, coverage would significantly improve. Every combination of three stations could be used for positioning.

To predict LORAN-C pseudorange coverage for synchronized stations, a computer program was written based on a hyperbolic coverage prediction model developed for the FAA [13]. The current program predicts pseudorange coverage accounting for geometry and signal-to-noise ratio at the receiver. Figures 2 and 3 show predicted coverage for CONUS with the "mid-continent gap" filled. The mid-continent stations are indicated by triangles around the circular-shaped stations. Coverage is declared when the geometry (Horizontal Dilution of Precision HDOP), number of stations, and the signal-to-noise ratio conditions are satisfied. Figure 2 shows predicted pseudorange coverage for 3 or more stations with SNR above -10 dB and HDOP less than 4. Figure 3 shows the predicted coverage for 4 or more stations with SNR above -10 dB and HDOP less than 7.8. This figure illustrates that redundant coverage is available. Current efforts are focused on the determination of the quality of the redundant coverage. That is, given a transmitter failure, do the remaining stations satisfy the coverage requirements. One important note should be made about the atmospheric noise values used for the predicted coverage. These values are based on CCIR Report No. 322 and are rather conservative [13]. Further research is required to determine atmospheric noise values that are in closer agreement with actual measurements.

From Figure 2 and Table 3 it can be concluded that positioning with synchronized LORAN-C stations can result in navigational accuracies on the order of 100 - 200 meters throughout CONUS.

6.0 AIRBORNE NAVIGATION SOLUTION

Several schemes can be implemented to combine the navigation data from LORAN-C and GPS. For example, a humongous Kalman filter could be developed that processes all available GPS pseudorange measurements and LORAN-C time differences. Even though such an approach promises to be optimal, certification procedures are most likely to be hindered by the physically impossible task to ensure the performance of the navigation filter under all input conditions [14]. Another concern is the complexity of modifications caused by the addition or deletion of navigation sensors or upgrades of existing sensors. These modifications should not necessitate a new system design with related certification and training procedures. Instead, the system should recognize the change and take appropriate actions.

Therefore, the navigation solution should be based on a generic design that emphasizes effective, modular, and transparent rather than optimal processing.

A system design philosophy that satisfies the above requirements could be based on the conversion of all sensor inputs into comparable quantities. Differences in sensor performance can be accounted for by assigning weights to the individual sensor measurements. These weights can for instance be determined by the magnitude and variance of measurement residuals, differences between actual measurements and predicted measurements based on previous data.

Pseudorange measurements are in common to both GPS and LORAN-C. The main advantages of using pseudoranges over time differences are the additional clock phase offset information and the option to use single transmitters instead of pairs. For instance, 4 GPS satellites could be used for navigation in combination with only one LORAN station to achieve integrity.

Noise on the pseudorange measurements can be effectively reduced by range domain filtering techniques [15,16]. This eliminates the possibility of navigation domain filtering divergence and allows for straightforward filter tuning. Although process noise cross-correlation terms are discarded in the range filters it was shown for stand-alone GPS that the overall system performance is essentially that of navigation domain filters [16]. Similar results may be expected for a solution based on both GPS and LORAN-C pseudorange measurements.

6.1 GPS Pseudorange Measurements.

Pseudorange measurements to GPS satellites are made by taking the difference between the measured time of signal arrival and the known time of signal transmission, corrected for known and estimated error sources. Figure 4 illustrates the ranging geometry. The general equation for the measured pseudorange is given by:

$$P_i(t) = |\vec{S}_i(t - \beta_i(t)) - \vec{u}(t)| + c_{GPS}(T_{GPS}(t) - T_{S_i}(t) + d_{GPS_i}(t,r)) \qquad (1)$$

where:

$\vec{S}_i$	position vector satellite i
β_i	line-of-sight travel time for signals from satellite i
$\vec{u}$	user position vector
c_{GPS}	GPS value for the speed of light
T_{GPS}	user clock offset from GPS system time
T_{S_i}	satellite i clock offset from GPS system time
d_{GPS_i}	delay for measurement i caused by GPS error sources

Typical GPS pseudorange accuracies are on the order of 10-40 meters (C/A code), mostly depending on ephemeris uncertainty, ionospheric and tropospheric delays, and intentional signal degradation, if active. GPS position accuracy is specified to be 100 meters 2 drms.

6.2 LORAN-C Pseudorange Measurements.

LORAN-C pseudorange measurement geometry is different from GPS; in the coverage area, LORAN-C ground waves basically travel great-circle distances. A receiver at sea-level will interpret the signals as if they came from transmitters located in the locally level plane at distances equal to great-circle distances to the transmitters, as depicted in Figure 5. The LORAN-C

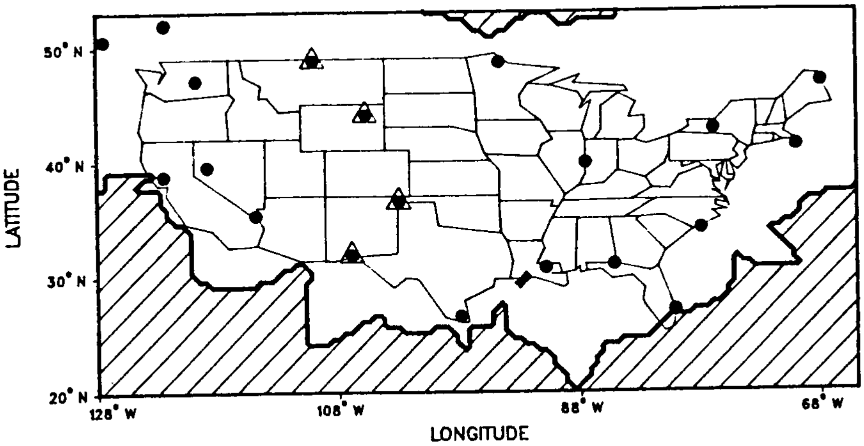


Figure 2. Preliminary LORAN-C predicted pseudorange coverage with the "mid-continent gap" filled. Coverage is computed under the following assumptions:

- All stations are synchronized
- All-in-view solution using 3 or more stations
- SNR greater than -10 dB
- HDOP less than 4
- Receiver bandwidth = 20 kHz
- Atmospheric noise values used are for the summer season, based on CCIR Report No. 322
- Search increment = 0.5°

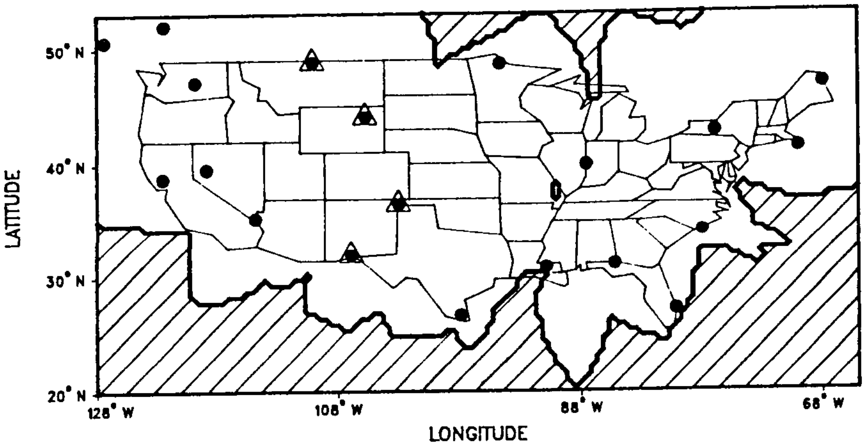
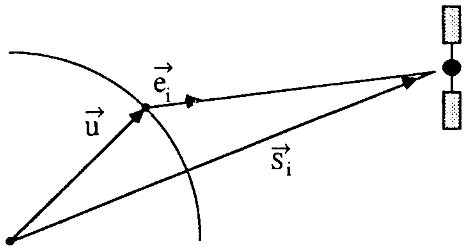


Figure 3. Preliminary LORAN-C predicted pseudorange coverage with the "mid-continent gap" filled. Coverage is computed under the following assumptions:

- All stations are synchronized
- All-in-view solution using 4 or more stations
- SNR greater than -10 dB
- HDOP less than 7.8
- Receiver bandwidth = 20 kHz
- Atmospheric noise values used are for the summer season, based on CCIR Report No. 322
- Search increment = 0.5°

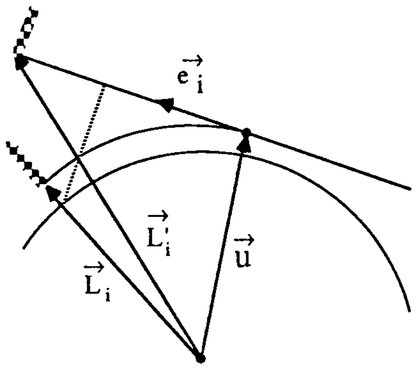


$\vec{S}_i$ position vector satellite i

$\vec{u}$ user position vector

$\vec{e}_i$ line-of-sight vector for satellite i

Figure 4. GPS ranging geometry.



$\vec{L}'_i$ position vector LORAN-C transmitter corrected for earth curvature

$\vec{L}_i$ position vector LORAN-C transmitter

$\vec{u}$ user position vector

$\vec{e}_i$ line-of-sight vector for transmitter i

Figure 5. LORAN-C ranging geometry.

pseudorange equation is given by:

$$P_i(t) = |\vec{L}'_i(t) - \vec{u}(t)| + c\,(T_{LC}(t) - T_{L_i}(t) + d_{LC_i}(t,r)) \qquad (2)$$

where:

$\vec{L}'_i$	position vector LORAN-C transmitter corrected for earth curvature
$\vec{u}$	user position vector
c	speed of light in vacuum
T_{LC}	user clock offset from LORAN-C time
T_{L_i}	transmitter i clock offset from LORAN-C time
d_{LC_i}	delay for measurement i caused by LORAN-C error sources

LORAN-C pseudorange performance is given in Table 3 for different timing options. Stand-alone LORAN-C positioning using pseudoranges yields typical accuracies of 100 - 200 meters for HDOP less than 4.

6.3 Hybrid GPS/LORAN-C Navigation Solution.

From the pseudorange geometries given in Figures 4 and 5, and equations (1) and (2), the user position and clock biases can be obtained by solving the following set of equations:

$$\left(\begin{array}{ccc|cc} e_{11} & e_{12} & e_{13} & 1 & 0 \\ e_{21} & e_{22} & e_{23} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e_{n1} & e_{n2} & e_{n3} & 1 & 0 \\ \hline e_{(n+1)1} & e_{(n+1)2} & e_{(n+1)3} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e_{(n+m)1} & e_{(n+m)2} & e_{(n+m)3} & 0 & 1 \end{array}\right) \left(\begin{array}{c} X \\ Y \\ Z \\ \hline T_{GPS} \\ T_{LC} \end{array}\right) = \left(\begin{array}{c} \vec{e}_1 \cdot \vec{S}_1 - P_1 + T_{S_1} \\ \vdots \\ \vec{e}_n \cdot \vec{S}_n - P_n + T_{S_n} \\ \hline \vec{e}_{n+1} \cdot \vec{L}'_{n+1} - P_{n+1} + T_{L_{n+1}} \\ \vdots \\ \vec{e}_{n+m} \cdot \vec{L}'_{n+m} - P_{n+m} + T_{L_{n+m}} \end{array}\right) \qquad (3)$$

Variations on these equations result when different LORAN-C timing options are considered. As an example, option IV, "Determination of LORAN-C transmitter offset with respect to GPS time," would remove the user clock offset uncertainty with respect to LORAN-C system time from the set of unknowns. In other words, only 4 measurements are needed to solve for user position and clock offset from GPS time.

Generally, a total of at least 8 measurements will be available throughout CONUS, leaving 3 or 4 measurements (depending on accuracy requirements) for integrity checking. Current LORAN-C timing would either require some of the redundant measurements to solve for clock offsets between chains and/or stations, or GPS could be used to (continuously) calibrate LORAN measurements. In the latter case, calibration could start with 5 GPS satellites, or only 4 GPS satellites and either one accurate LORAN measurement, or one additional measurement such as (airport) altitude.

6.4 Hybrid GPS/LORAN-C Integrity.

As indicated in the previous sections, integrity can be obtained through utilization of redundant pseudorange measurements from GPS and LORAN-C. Recently, several papers have been published on the subject of user autonomous integrity checking with redundant measurements [17-20].

Measurement residuals are commonly used to indicate a bad signal. This may be accomplished through maximum likelihood detection schemes, a parallel bank of Kalman filter failure hypothesis testers, or even through direct comparison of the residuals. Further research is needed in this area to determine the most effective method, once the proper requirements for integrity are established.

7.0 EXPERIMENTAL HYBRID SYSTEM DESIGN

Early in-flight comparison of GPS and LORAN-C indicated 2-dimensional differences of up to 300 meters for data collected across southern and central Ohio [21]. Most of the navigation error was found to be inherent to the LORAN-C part of the system. A TI 9900 LORAN receiver and the Experimental Dual Channel GPS receiver were used during these tests [22]

Currently, work is ongoing to replace the hyperbolic LORAN receiver with a RACAL Megapulse Accufix 500 LORAN-C receiver. The resulting system will be configured as depicted in Figure 1b. Both the GPS and the LORAN-C receiver can be fully controlled by an external computer system. The main advantage is that tracking and data smoothing filters can be adjusted. This eliminates large navigation errors during maneuvers due to filter lag which is especially the case for most LORAN-C receivers. All data from the receivers will be collected on magnetic tape and disk for postprocessing on the ground in combination with ground based tracker data. This will create a data base for performance evaluation of navigation and integrity algorithms.

8.0 CONCLUSIONS AND RECOMMENDATIONS

A sole means navigation system does not only call for integrity, but also for coverage, reliability, availability and accuracy. Even though ground monitored GPS will provide integrity, availability is still not sufficient. One satellite outage can affect a large service area for several hours per day. The same holds for differential GPS, a total satellite outage cannot be corrected for. To obtain sufficient coverage, extra measurements are needed. Either in the form of extra GPS satellites (expensive) or through redundant measurements from other systems. LORAN-C is available and will, hybridized with GPS, result in a system that has the potential to satisfy the requirements for a sole means navigation system for use in the continental United States.

Assumptions are made about the qualification sole means, mainly based on current sole means systems such as VOR/DME. In order to allow for system design that will satisfy sole means requirements, it is recommended that a definition of a sole means navigation system be established. This definition must include requirements for availability, reliability, and integrity currently not specified.

In addition to the definition of a sole means navigation system, certification requirements must be established for hybrid navigation systems. This will allow for design and production of a new generation of airborne navigation systems that will reduce overall system costs and simplify training procedures.

The current LORAN-C navigation and timing system could be greatly enhanced by upgrading the synchronization between stations. It is recommended to implement time of transmission control for all LORAN-C stations under the condition that the impact on current users will be minimal. Otherwise, GPS receivers should be installed at each LORAN-C station to determine the station clock offset with respect to GPS. These offsets should be transmitted to the users using blink codes or additional pulses. This would establish, in essence, time of transmission control without affecting current users. Either timing option would significantly increase the LORAN-C coverage area (see Figures 2 and 3) and also result in navigational accuracies on the order of 100 - 200 meters throughout CONUS. In addition, hybrid GPS/LORAN-C would have a minimum of three redundant measurements to insure system availability and integrity.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Federal Radionavigation Plan - 1984. DOD-4650.4 and DOT-TSC-RSPA-84-8, U.S. Department of Defense and U.S. Department of Transportation, Washington, D.C., 1984.

[2] Braff, R., Shively, C.A., Zeltser, M.J., "Radionavigation System Integrity and Reliability," Proceedings of the IEEE, Vol. 71, No. 10, October 1983.

[3] Department of Transportation Federal Aviation Administration Advisory Circular No. AC 90-45A: "Approval of Area Navigation Systems for Use in the U.S. National Airspace System," February 1975.

[4] Blythe, P.D., "Reliability of Navigation Systems," Draft Report, ARINC Research Corporation, Contract No. DTFA01-80-C-10030, March, 1982.

[5] GPS Integrity Workshop held at Interstate Electronics Corporation in conjunction with ION Technical Meeting, Anaheim, CA, 23 January 1987.

[6] Rockwell International Corporation, "ICD-GPS-200," 26 September, 1984.

[7] Bowen, R., Swanson, P.L., Winn, F.B., Rhodus, N.W., and Feess, W.A., "Global Positioning System Operational Control System Accuracies," Navigation: Journal of the Institute of Navigation, Vol. 32, No. 2, Summer 1985.

[8] Green, G.B., "Global Positioning System A Status Report," Proceedings of the Fourth National Technical Meeting of the Institute of Navigation, Anaheim, CA, January 20-23, 1987.

[9] Jorgensen, P.S., "Achieving GPS Integrity and Eliminating Areas of Degraded Performance," Proceedings of the Forty-Third Annual Meeting of the ION, Dayton, Ohio, June 23-25, 1987.

[10] U.S. Naval Observatory, "Daily Time Differences and Relative Phase Values", Washington, D.C.

[11] Campbell, L.W., Doherty, R.H., and Johler, J.R., "LORAN-C System Dynamic Model Temporal Propagation Variation Study," Report No. DOT-CG-D57-79, July 1979.

[12] Vicksell, F.B., and Goddard, R.B., "Implementation and Performance of the TOT Controlled French LORAN Chain," Proceedings of the 15th Annual Technical Symposium of the Wild Goose Association, New Orleans, Louisiana, 21-24 October, 1986.

[13] El-Arini, M.B., "Airport Screening Model for Nonprecision Approaches Using LORAN-C Navigation," Contract No. DTFA01-84-C-00001, MITRE report No. MTR-83W180, May 1984.

[14] Kruczynski, L.R., and Eschenbach, R.F., "New Data on Two Satellite Algorithms Without an Atomic Clock," Proceedings of the Fourth National Technical Meeting of the Institute of Navigation, Anaheim, CA, 20-23 January, 1987.

[15] Paielli, R.A., "Range Filtering for Sequential GPS Receivers," Proceedings of the Fourth National Technical Meeting of the ION, Anaheim, CA, 20-23 January, 1987.

[16] Van Graas, F., "Discrete Filtering Techniques Applied to Sequential GPS Range Measurements," NASA Contract NAS 2-11969, NASA-CR-177472, 1987.

[17] Kerr, T., "Decentralized Filtering and Redundancy Management/Failure Detection for Multisensor Integrated Navigation Systems," Proceedings of the Second National Technical Meeting of the ION, San Diego, CA, January 15-17, 1985.

[18] Brown, R.G., and Hwang, Y.C., "GPS Failure Detection by Autonomous Means Within the Cockpit," Proceedings of the Forty-Second Annual Meeting of the ION, Seattle, Washington, June 24-26, 1986.

[19] Lee, Y.C., "Analysis of Range and Position Comparison Methods as a Means to Provide GPS Integrity in the User Receiver," Proceedings of the Forty-Second Annual Meeting of the ION, Seattle, Washington, June 24-26, 1986.

[20] Parkinson, B.W., Axelrad, P., "Simplified GPS Integrity Checking with Multiple Satellites," Proceedings of the Forty-Third Annual Meeting of the ION, Dayton, Ohio, June 23-25, 1987.

[21] Morrell, F.R., Compiler, "Joint University Program for Air Transportation Research - 1986," Proceedings of a conference held at NASA Langley Research Center, Hampton, Virginia, January 8-9, 1987, NASA CP-2502.

[22] Campbell, S.D., and LaFrey, R.R., "An Experimental GPS Navigation Receiver for General Aviation: Design and Measured Performance," Contract No. DOT-FA79-WAI-091, Report No. FAA-RD-83/26, September 27, 1983.