

GPS WORLD

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Designing and Implementing Solutions with Global Positioning Technologies



Design

Integration

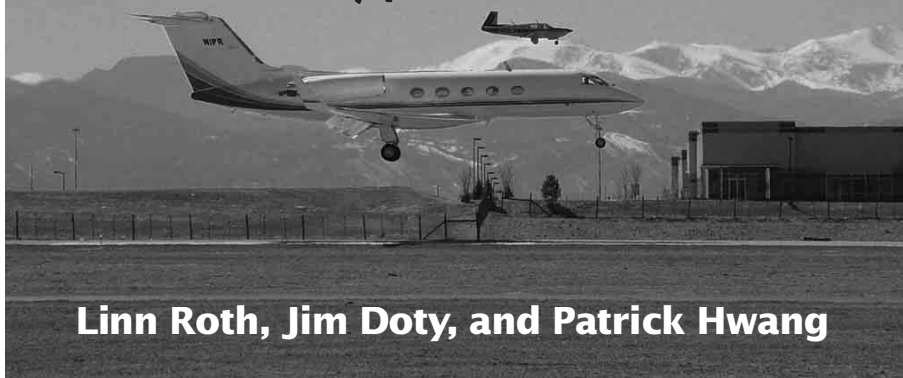
Innovation

News

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Linn Roth,
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Craig Mills

A prototype GPS-Loran integration processor generates GPS-only, Loran-only, and combined GPS-Loran solutions. Developed for Federal Aviation Administration testing in an effort to support and complement GPS in multimodal applications, it also features a fault-detection and exclusion algorithm to incorporate Loran data and identify Loran faults.

The results of U.S. Department of Transportation's Volpe Center study of GPS vulnerabilities heightened interest in the potential ability of independent systems to support and complement GPS in multimodal applications. The timing of its release — September 10, 2001 — added punch to the study's conclusion: GPS is not immune to disruption, both intentional and unintentional.

Loran is the only other multimodal radionavigation system in operation besides GPS that provides both timing and position information. Can the modern Loran system effectively augment and back up GPS in critical aviation, marine, terrestrial, and timing applications? During the past several years, new-technology Loran receivers and antennas demonstrated substantially enhanced performance, and the U.S. Coast Guard began to modernize the U.S. Loran infrastructure, instituting changes that will improve the system's accuracy, availability, integrity, and continuity.

Concurrently, the Federal Aviation Administration (FAA) implemented an active Loran assessment program. The department seeks to determine Loran's ability to meet nonprecision approach standards using new required navigation performance (RNP) guidelines of 0.3 nautical miles (NM) as well as more-stringent requirements for availability, integrity, and continuity. FAA's plans to transition to an area navigation (RNAV) system based on GPS has accelerated evaluation of a modern Loran system because Loran also provides RNAV capabilities.

Under the leadership of Mitchell Narins, FAA program manager, a team of academic, government, and industry personnel has been tapped to carry out this task. Rockwell Collins and Locus, Inc. participated in the effort and have worked together to build an integrated GPS-Loran prototype system for FAA flight tests.

The two companies have made substantial progress in the development of an integrated GPS-Loran system for the FAA Loran evaluation program. Initial flight tests using a modern, all-in-view Loran receiver and H-field (magnetic) antenna have provided accuracies well within the desired goal of RNP 0.3 NM. The companies fabricated a prototype GPS-Loran integration processor that can generate GPS-only, Loran-only, and combined GPS-Loran solutions, including GPS-calibrated additional secondary factor (ASF) corrections. The team developed a fault-detection and exclusion algorithm adapted to incorporate Loran data and identify Loran faults. The companies are currently working to refine the algorithms and evaluate their effectiveness for enhancing navigation integrity and continuity.

This article provides an overview of that prototype development program and example data from preliminary tests. A later report will provide FAA flight test results from the prototype.

Building the Prototype

Using a certified multimode receiver (MMR) with a GPS sensor as a prototyping platform, Rockwell Collins incorporated a Loran receiver board with special interface card into the MMR and integrated the GPS and Loran sensors. Locus produced a small version of an existing all-in-view Loran receiver card and generated receiver interface electronics for the MMR. The all-in-view receiver typically tracks 20-30 stations in North America and uses a subset of those stations to generate the navigation solution. Locus also developed a combined GPS-Loran antenna suitable for operation with the GPS sensor for use in flight trials. **Figure 1** shows a block diagram of the prototype integrated system within the MMR. More details about the various efforts are provided later in this article.

Each company applied its area of expertise to the task of developing an integrated GPS-Loran prototype for this program. Rockwell Collins specializes in aviation electronics design, production, and support with significant GPS and integrated navigation sensor expertise, and Locus, a wireless technology company, supplies

INTEGRATION Challenge

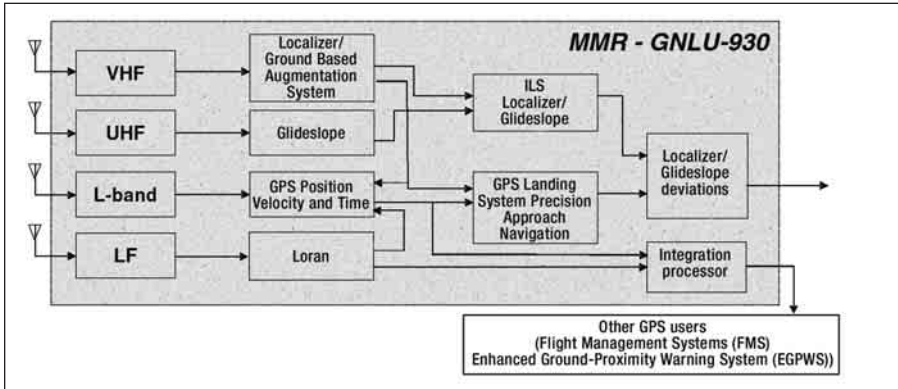


FIGURE 1 Block diagram of the integrated GPS-Loran system within the MMR. The Loran receiver is mounted in a space reserved for the microwave landing system card.

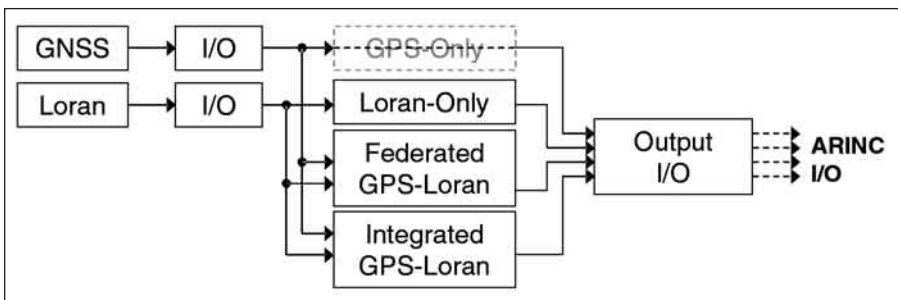


FIGURE 2 Block diagram of GPS-Loran integration processor functions and data formats.

the navigation and timing industries with Loran receiver and antenna expertise.

First Steps

We started the integration process by defining the hardware, software, and mechanical interface requirements to operate the Loran receiver inside the MMR and used these requirements to design a board to interface the receiver card to the MMR.

To adapt the all-in-view receiver for operation within the MMR, we had to use pre-existing MMR voltages and available surplus power levels. Although an MMR has several supply voltage levels, we were limited to using only two supplies for powering the embedded Loran receiver system. Neither of these MMR voltages was matched to the requirements of the Loran receiver, and both supplies were necessary to provide the total wattage needed to power the Loran receiver. Using MMR power level specifications from Rockwell, Locus designed highly efficient, on-board synchronized switching power supplies that provided the analog and digital power for the embedded Loran system. These power supply designs are approximately 90% efficient, which limits any unwanted heat rise within the MMR. In addition, they do not overextend the available power output of the MMR's voltage supplies, and they do not introduce noise within the MMR. We suc-

cessfully integrated Locus power supplies as well as the Loran system itself into the MMR system, with no redesign required.

In the early stages of development, Rockwell Collins built a "breadboard" GPS-Loran system consisting of an unmodified MMR, a stand-alone Loran receiver with H-field antenna, and a GPS-Loran integration processor (GLIP) box to perform a variety of integration functions and compute navigation solutions. To minimize development risk and time, Rockwell Collins used a proven processor card design repacked to fit into the MMR. **Figure 2** shows a block diagram of GLIP functions.

The GLIP card takes in raw GPS and Loran data and generates multiple position solutions and integrity limits to facilitate test evaluation of alternative techniques. All position estimates and raw Loran data are provided by means of ARINC 429 and RS232 output formats for data log-

ging. The GPS-only solution passes through the standard GPS solution, and the Loran-only solution computes the Loran position from time-of-arrival (TOA) measurements. The federated GPS-Loran solution processes GPS and Loran data but maintains independence between the two systems to improve integrity. Finally, the GLIP produces an integrated GPS-Loran position estimate that calibrates Loran ASF corrections using GPS and produces a more accurate position.

ASF terms correct for Loran propagation velocity changes over the ground that result from variations in Earth's conductivity over the signal path. These ASF corrections are analogous to ionospheric and tropospheric corrections for GPS except that ASFs typically vary quite slowly.

Once the breadboard GPS-Loran system was functional, we performed dynamic tests using a mobile navigation lab van. **Table 1** shows typical results. These data come from one test representative of the 38 data collection runs made on 10 different days. We also used these tests to verify that the GLIP Loran-only and the Loran receiver solutions were similar. Table 1 shows SatMate and GLIP Loran solutions — generated with and without ASF corrections — relative to GPS.

Results from the two devices are virtually identical. Most important, the data demonstrate that when GPS is used to derive ASF corrections for Loran (that is, the GPS-aided solution), then the average Loran positions are within approximately 2 meters of GPS positions. However, these tests also confirmed that Loran position noise is not reduced by the GPS-derived ASF corrections. The navigation algorithms currently in development feature a more tightly coupled solution to reduce position noise when GPS is available.

The Loran Sensor

The Loran sensor is an all-in-view receiver capable of tracking as many as 40 Loran signals simultaneously and operating with an H-field antenna. As part of the FAA assessment program, Ohio University's

TABLE 1 Van test solution errors relative to GPS in meters.

	Average North Position Offset	Average East Position Offset	North Position Noise	East Position Noise
SatMate receiver solution (No ASF corrections)	-164.3	-195.6	20.9	26.6
GLIP Loran-only solution (No ASF corrections)	-164.0	-196.4	20.9	26.8
GPS-aided solution	-2.0	-1.4	18.8	24.3

Avionics Engineering Center flight-tested a stand-alone Loran receiver to determine how well it could perform without GPS support and learn how ASF corrections might improve Loran accuracy.

Even as the U.S. Loran infrastructure is undergoing a complete modernization that will improve overall system accuracy, these empirical trials demonstrated what will be possible with modern Loran user equipment. Because overall system accuracy includes all error sources, improvements in the transmission infrastructure such as chain timing synchronization will improve the ability of a receiver to determine position.

In 2002, Ohio University conducted approximately 40 instrument landing system (ILS)-guided approaches at various

Midwest airports and along the eastern seaboard. For these tests, two airplanes were outfitted with a Loran receiver and a 12-channel GPS/WAAS receiver for reference. An H-field antenna was housed in an automatic direction finder (ADF) radome mounted under the fuselage. Data were recorded simultaneously from each receiver at a rate of once per second.

Figures 3 and 4 show example results from a May 2002 test series in Madison, Wisconsin. These tests demonstrated that an all-in-view Loran receiver could provide accuracies that meet FAA requirements. Using the Dane County Regional Airport as a base, the plane flew various routes around the area and conducted 10 fly-over, ILS-guided approaches at the main runway. In this test, ASF corrections were derived one week before the flight at a location approximately eight miles from the Madison airport, and after the flight, the ASF corrections were applied to the Loran data. The receiver tracked 24–28 stations during these tests and used 18 of those stations to generate the navigation solution. Figure 3 shows data from the entire flight. At this scale it is difficult to differentiate between GPS/WAAS and Loran. The arrow indicates where the ASF corrections were generated, and the circle indicates the runway area where data are shown in an expanded scale in Figure 4.

Figure 5 shows representative data taken in July 2002 from a similar test series around the Athens, Ohio, airport. In this case, the ASF corrections



Housed in a certified ADF radome, the H-field antenna was mounted under the fuselage of a Piper Saratoga.

were generated three days prior to the flight, and 10 ILS-guided approaches were performed. The receiver tracked 27–29 stations during these tests and used 16 of those stations to generate the navigation solution. The cross-track errors between ASF-corrected Loran and GPS/WAAS were also approximately 10 meters.

Integration Process

As described earlier, the GLIP card generates GPS and Loran stand-alone navigation solutions as well as combined GPS-Loran position estimates using various levels of integration. Figure 6 shows a block diagram of the combined GPS-Loran solutions.

The federated solution maintains independence of the GPS and Loran measurements and does not use GPS to generate ASF correction factors for the Loran data. An extension of the GPS receiver autonomous integrity-monitoring-fault-detection and exclusion (RAIM-FDE) algorithm detects and excludes errors or mis-

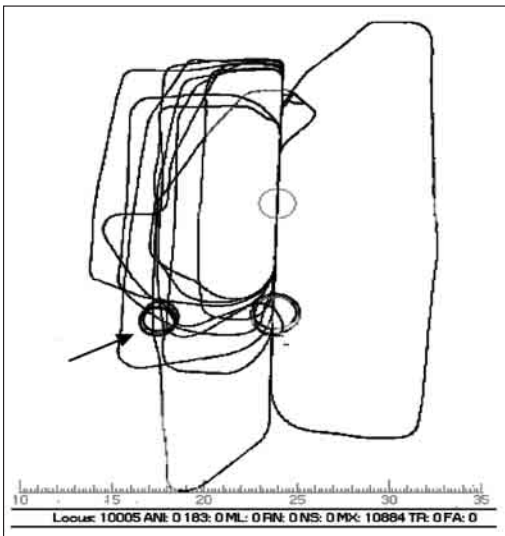


FIGURE 3 GPS and Loran data illustrating the routes of the May 2002 flight tests around Madison, Wisconsin. Scale is kilometers.

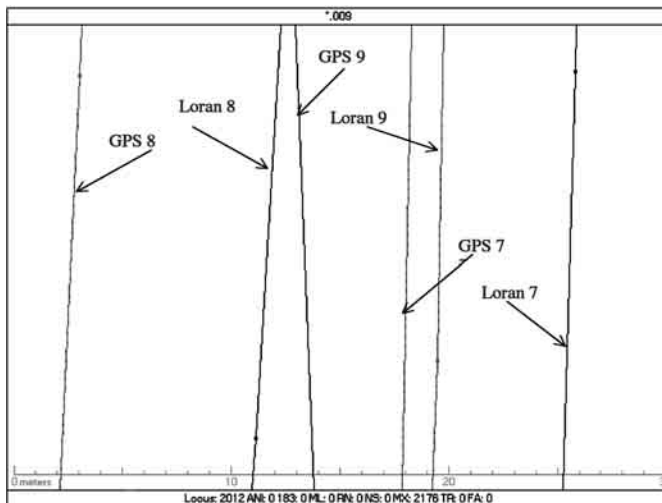


FIGURE 4 Three representative examples of GPS/WAAS and ASF-corrected Loran data from the runway area. The cross-track error between the systems is approximately 10 meters. Scale is meters.

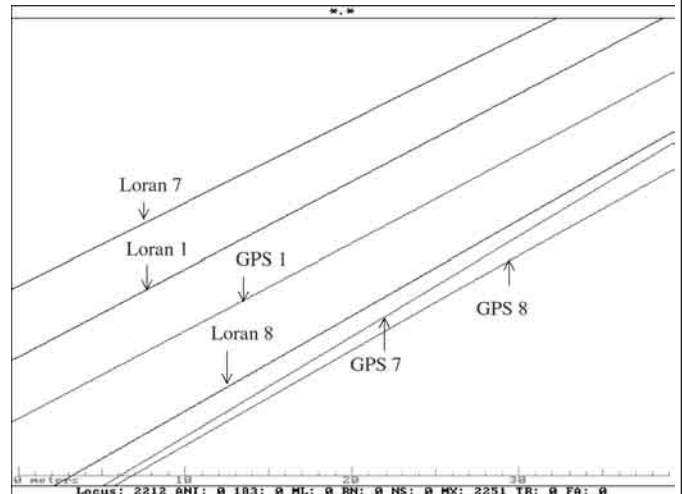


FIGURE 5 Three representative examples of GPS/WAAS and ASF-corrected Loran data from the Athens, Ohio, runway area. Scale is meters.

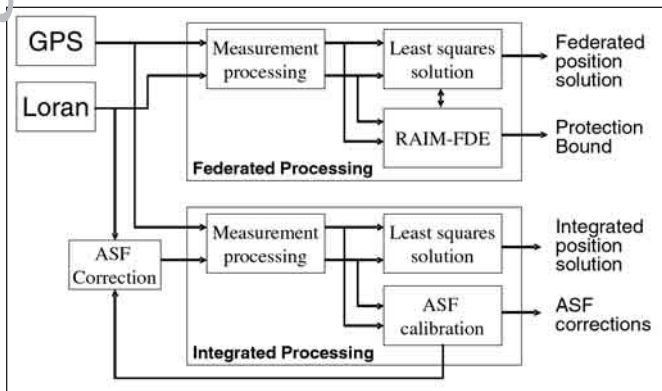


FIGURE 6 A block diagram of the combined GPS/Loran solutions generated by the GLIP.

leading data from both GPS and Loran measurements. The system then combines the separate receivers' fault-protected measurements into a single GPS-Loran position estimate that has greater integrity than is possible using GPS or Loran alone. Continuity of the federated solution is also increased significantly because of the greater number of measurements used and because the measurements are based on two RF signal sources quite dissimilar in frequency band, power, and propagation characteristics.

Clock Offsets. The current Loran system includes independent clock offsets for each chain of stations. The current navigation and RAIM-FDE algorithm implementations use Loran time difference of arrival (TDOA) measurements for computational convenience. This approach eliminates the need to keep track of independent clock offsets. However, a fully synchronized worldwide Loran system of the future most likely will eliminate such offsets. When that capability becomes available, it will be possible to exploit this synchronization for potential performance improvement by directly processing Loran TOA instead of master-to-slave TDOA measurements.

The integrated GPS-Loran system performs a Loran-only navigation solution as well as a self-consistency test to detect and identify large errors that might arise from any station. The Loran TDOA measurements are also compared in the GLIP, with predictions based on the GPS-only position solution. This technique effectively identifies large Loran errors, including those that may result from cycle slips or skywave-tracking errors in the receiver. Rockwell Collins is currently working to extend the RAIM-FDE algorithm to identify and protect against smaller master errors and ensure an accurate integrity-bound estimate in the event of master sta-

tion errors.

Corrections. In the integrated GPS-Loran solution, the GLIP uses GPS to calibrate ASF and generates the ASF corrections for the Loran measurements. In the current implementation, a simple one-state filter per station approach yields an estimate of "true" ASF corrections and a residual common clock error, which

drops out when the ASF correction is applied.

Because an integrated solution such as this uses GPS measurements to generate corrections for Loran, the corrected Loran measurements are no longer independent of GPS. However, with a special calibration procedure, we can use Loran to enhance GPS integrity in a manner similar to baro/pressure calibration described in TSO-C129a, the FAA's technical standard order describing airborne supplemental navigation equipment using GPS. The overall integrity/availability performance of this integrated solution depends largely on GPS-inherent characteristics, but the specially calibrated Loran data sustain the integrity performance through brief periods of loss of GPS-only RAIM-FDE. This interdependence is being evaluated for the prototype.

To further enhance integrity monitoring of the integrated solution, step detection on the excessive changes in Loran ASF values and limits on the maximum ASF corrections will be used to identify failures or disruptions in the Loran measurements. Step detectors in the software computing the navigation solutions are used in GPS for protecting against large errors that are primarily jumps from the previous estimated value or nominal condition. Once the integrated navigation system establishes a valid solution for the ASF range-error estimate, it tests all new Loran range measurements against a "predicted" measurement value and monitors the residual difference for the size and stability and for any sudden change in the bias. The GLIP will incorporate a step detector to monitor the ASF estimates for stability and any sudden changes in the ASF bias.

Combined GPS-Loran Antenna

Program participants also designed a combined GPS-Loran antenna that incorporated an H-field Loran antenna. Among

What Is Loran?

Loran-C is a ground-based radionavigation system that operates at 100 kHz and can be used to determine position, velocity, and time in multiple applications. Groups of pulses are transmitted at specified intervals and are phase-coded to enable individual station identification. Transmitters are organized into groups or chains, and each chain emits pulses at certain group rate intervals (GRI). Typical pulse power levels range from 250 kilowatts to 1.6 megawatts, making the signal quite robust. Stations that transmit at two GRIs simultaneously are referred to as *dual-rated*.

Twenty-nine transmitters currently are operating in North America, including several dual-rated stations, and they are under the operational control of the U. S. and Canadian Coast Guards. Substantial Loran systems are now in operation in Europe, Russia, Japan, Korea, China, Kingdom of Saudi Arabia, and North America.

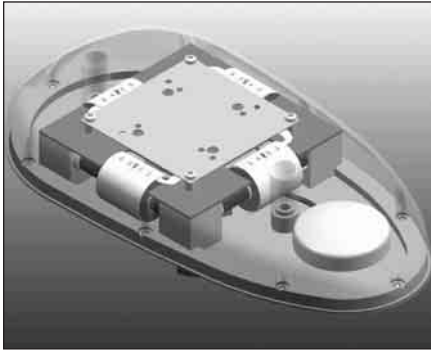
If we consider GPS as a satellite-based, high-frequency, low-signal level system, Loran is a ground-based, low frequency, high signal level system. However, both systems operate on the same basic principles. Loran receivers make time-difference or time-of-arrival measurements on the basis of published pulse transmission timing and apply propagation correction factors in a manner virtually identical to GPS.

Loran transmitters typically use ensemble-averaged Cesium clocks as their time base, and in the future it is likely that Loran systems will be tightly synchronized to GPS UTC. More-rigorous synchronization would facilitate even tighter coupling of the two systems than discussed in this article because Loran systems transmitters could then be treated as GPS "pseudolites."

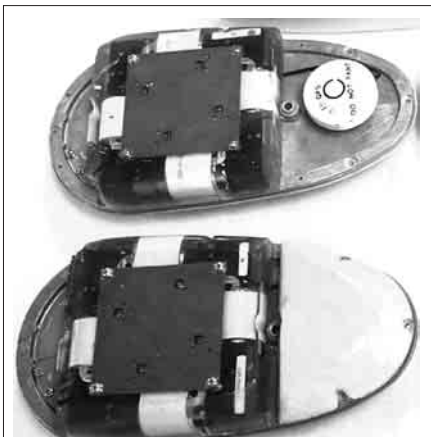
For more information, see <www.navcen.uscg.gov> or <www.loran.org>.

the H-field antenna advantages are reduced size and elimination of a ground. The primary appeal of this technology, however, is its immunity to precipitation static interference (p-static) that commonly builds up on an airframe during snow, thunderstorm, and icing conditions.

Locus previously developed an H-field antenna that could fit into a certified ADF radome, and that antenna was used for the flight tests described earlier in this article. To reduce development time, we colocated the GPS antenna used for the MMR and the H-field antenna in the same radome (see mechanical drawing).



Mechanical drawing of the GPS and Loran antennas within the ADF radome. The H-field antenna measures approximately 130 × 130 × 50 millimeters.



Prototype combined GPS-Loran antennas. The top view shows the GPS antenna before encapsulation with protective foam.



The Loran receiver and interface boards in the MMR. The interface card is mounted on the MMR door and supports the receiver card. The receiver card measures 100 × 160 millimeters.

After fitting the two devices within the ADF radome, the team set out to determine if collocation of the antennas impeded the performance of either system. Locus performed a series of static and dynamic vehicle tests with identical systems to simultaneously compare GPS and Loran performance with stand-alone and combined antennas. Initially, the presence of the GPS antenna introduced noise into the Loran H-field, but the H-field had no discernible effect on GPS. We incorporated additional shielding into the GPS cable, which resulted in identical Loran performance with either stand-alone or combined H-field antennas.

Upcoming flight tests planned for this summer will produce more comparisons. Meanwhile, Locus has delivered prototype combined GPS-Loran antennas to Rockwell Collins and the FAA Technical Center (FAATC). The Loran antennas are encapsulated in silicon, and the GPS radome is shown with and without the foam encapsulation added for stability.

Note that the combined GPS-Loran antenna prototypes must be remounted on top of test airplanes for GPS reception. The Loran antenna can be positioned either under or on top of the airplane, and a software command inverts polarity for correct operation.

Next Steps

Currently, Locus has completed porting its design to the new hardware platform, and Rockwell Collins is completing the integration software development, finishing the electrical and mechanical integration, and testing the system. The Locus receiver and its interface card have been mounted within the MMR, and the GLIP and Loran receiver are communicating with one another.

Testing thus far has shown no degradation in GPS or Loran performance in the integrated unit when compared to standalone GPS or Loran systems. Implementation and testing of the improved

integration algorithms are currently in progress.

Rockwell Collins is scheduled to have delivered an integrated GPS-Loran system to the FAATC by May 1, and flight tests will be performed this summer and fall. Locus has also delivered to the FAATC two units of a stand-alone version of the Loran receiver and interface board with combined GPS-Loran antennas, and flight testing on those systems will begin immediately. Both companies will continue to support FAA team members involved in the test program by providing technical assistance for unit installation, operation, and data analysis.

Locus will also add real-time ASF correction capabilities to the Loran receiver so that the combined receiver can use stored ASF values. This change, scheduled for September-October 2003, will facilitate performance comparisons between GLIP-generated ASF corrections and stored ASF corrections. 🌐

Manufacturers

The flight tests used a *SatMate 1020* all-in-view Loran receiver from **Locus, Inc.** (Madison, Wisconsin). The company has delivered stand-alone *SatMate 1030* receivers with combined GPS-Loran antennas to the FAATC for flight testing. The prototype also used the *001802* H-field antenna from Locus. A *GNLU-930* MMR from **Rockwell Collins** (Cedar Rapids, Iowa) served as a prototyping platform. The flight tests used an *OEM4* 12-channel GPS/WAAS receiver from **NovAtel, Inc.** (Calgary, Alberta, Canada) for reference.

Linn Roth is president of Locus, Inc., a Madison, Wisconsin, company specializing in all-in-view Loran receivers and spread-spectrum radios for industrial, utility, GPS, and other applications. He is president of the International Loran Association (ILA).

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Patrick Hwang is a principal systems engineer in the Rockwell Collins, Inc. Advanced Technology Center. He received his Ph.D. in electrical engineering from Iowa State University in 1986.