"Loran-C Augmentation for GPS and GPS/WAAS"

Final Report – NGST2004-R-413

FAA Cooperative Agreement 99-G-038
July 26, 1999 through July 29, 2004

Prepared for:
Federal Aviation Administration
Aviation Research Grants Program
William J. Hughes Technical Center
Atlantic City International Airport
Atlantic City, NJ 08405

Prepared by:

Robert W. Lilley, Ph. D., Co-Principal Investigator
John G. Kirk, Ph. D., Co-Principal Investigator

Northrop Grumman Simulation Technologies Corp.
130 Robin Hill Road
Goleta, CA 93117

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Robert W. Lilley, Ph. D., Co-Principal Investigator
John G. Kirk, Ph. D., Co-Principal Investigator
Northrop-Grumman Simulation Technologies Corp.
Goleta, California

Foreword

This document reports the activities carried out in support of FAA Cooperative Agreement 99-G-038. Reference is made to earlier work which set the scene for the Cooperative Agreement. If the reader is reading the paper version of this report, the full text of reference materials will not be available. The compact-disk version of the document contains hyperlinks **to the report index** and reference materials for easy access.

The CD version is configured for auto-run, and it should display this introductory page when inserted in the reader's CD player. If the user's computer is not configured for auto-play, select the page D:\start.htm to access this page and then the index. (D:\ represents the drive letter assigned to the CD player.)

The hyperlink below is typical of the format of hyperlinks throughout the report. "Clicking" on these links with the left mouse button offers easy access to reference materials which may then be downloaded and viewed or printed.

References are in Adobe Portable Document Format (.pdf), and the reader will require access to an appropriate Adobe Acrobat reader. This software is available for free download at world-wide web sites such as:

http://www.adobe.com/products/acrobat/readstep2.html

and at sites where the Acrobat logo is displayed:

Robert W. Lilley, Ph. D
John G. Kirk, Ph. D
Santa Barbara, California
April, 2004

Final Report

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Robert W. Lilley, Ph. D., Chief Engineer
Northrop-Grumman Simulation Technologies, Corp.
Goleta, California

I. Introduction

Illgen Simulation Technologies, Inc., (ISTI) participated in Loran-C and other navigational programs for the Federal Aviation Administration (FAA) and other governmental agencies for some fifteen years. The Cooperative Agreement reported here was carried out in support of the evaluation of the Loran-C navigational system as a partner for GPS systems in the National Airspace System (NAS), with recognition that other navigational and precise-timing applications exist.

In December, 2003, ISTI was acquired by Northrop Grumman Corporation and was renamed Northrop Grumman Simulation Technologies Corp. **(NGST)**. There were no personnel changes of significance to this cooperative agreement as a result of the acquisition.

ISTI/NGST cooperated within a large and diverse team assembled by the FAA offering expertise in specific Loran-C-related areas. In 1997, ISTI personnel assisted the FAA in forming what is now the Loran-C Evaluation Program. Working with AND-740 at program inception and prior to initiation of Cooperative Agreement 99-G-038, hypotheses were formulated, and these are still pertinent today:

Program Hypotheses

- **Loran-C meets the requirements to support NAS operations including non-precision or LNAV/VNAV approach procedures.**
    - ***Loss of availability due to p-static no longer expected to be a significant factor***
    - ***Loran-C meets RNP 0.3 requirements – accuracy, availability, integrity, continuity***
- **Advantages of a GPS/Loran-C combination are demonstrated in flight**
    - ***Availability of horizontal nav with integrity through approach if GPS is lost***
    - ***Ability to dispatch in the absence of onboard GPS capability***
- **CONUS and Alaska demonstrations show utility of Loran-C**
    - ***Coverage improvements for enroute navigation through NPA***
    - ***Augmentation of WAAS communication of GPS integrity***
    - ***Loran-C communication of Loran-C integrity, timing, control information***
- **Loran and Loran/GPS hybrids can be certified, and have NAS benefits**
    RTCA, FAA documents, ops concepts

This report is organized chronologically, but there are schedule overlaps due to concurrent tasking. For reference and completeness, the first report section presents some background, including work performed under FAA contract DTFA01-97-Y-01003 prior to the inception of 99-G-038. This work set the scene for the Cooperative Agreement.

All reference materials are included as files on the compact-disk version of this final report. For readers who reference this text on CD, hypertext links will provide easy access to the reference files. The reader will need to have Adobe Acrobat Reader available.

II. Background

A. General Information

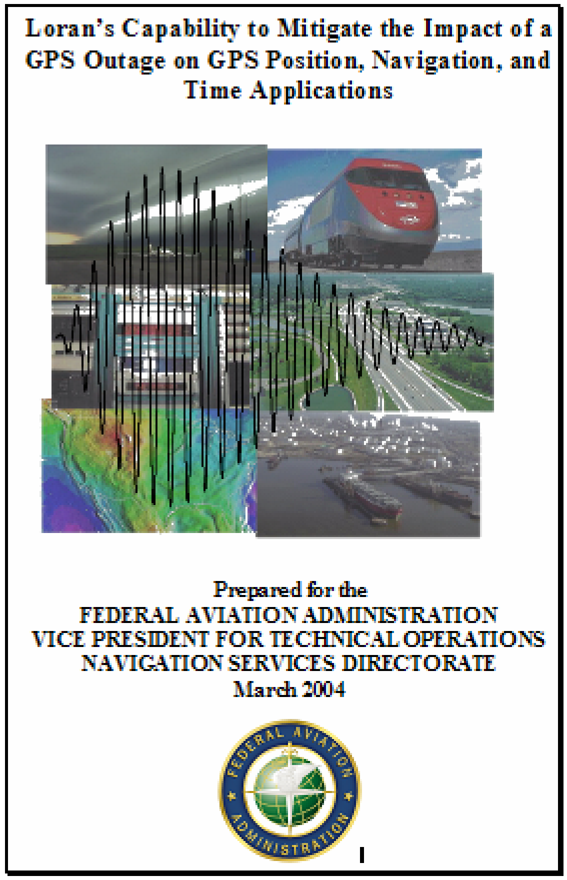
Loran-C has provided radionavigation signals since 1957. Since that time Loran-C has been extensively used for marine navigation. By the late 1980s, Loran-C receivers were in wide use in aviation, particularly in general aviation aircraft, and the system was approved by FAA as a supplemental aid to navigation. In 1990, for aviation applications, four transmitters were added to close the "mid-continent gap." These transmitters, together with the existing coastal chains, provided complete coverage of the continental United States.

During this period also, the FAA Early Implementation Program (EIP) provided for study and experimentation leading to Loran-C supported non-precision (lateral guidance only) instrument approach procedures. The FAA issued Technical Standard Order (TSO) C60b as guidance for receiver certification, and published several approach procedures. For a variety of reasons, the widespread public use of these procedures did not occur.

Since that time, Loran-C has continued in wide use for VFR and IFR enroute and terminal-area navigation. The emergence of the NAVSTAR/Global Positioning System (GPS) technology and its selection by the FAA as the centerpiece of the future NAS navigation structure caused a reduction of interest in making the Loran-C improvements in ground and airborne systems which would correct concerns raised by the EIP. Nevertheless, advances continued, encouraged by non-US countries' interest in the system as a potential backup or alternative to GPS and by the US communications industry, which is dependent on the availability of precise timing signals with extremely high reliability. Such applications make use of GPS and Loran in combination, taking advantage of the fact that the two systems are independent with respect to nearly every failure mode and that both are referenced to highly accurate atomic standards.

Recently, there is increased interest in navigation systems which can act in partnership, adjunct, or backup roles for a transition period during which satellite navigation systems are expected to accept more and more responsibility for NAS support. The work reported here was carried out to re-evaluate specific aspects of Loran-C performance, with emphasis on establishing whether recent technical advances, especially in the antenna and receiver architecture areas, permit the system to provide improved enroute, terminal, and missed-approach guidance services, plus cost-effective non-precision instrument approaches for the National Airspace System (NAS).

After this program was awarded, results form the FAA’s overall Loran-C evaluation program were formally reported to the U.S. Department of Transportation (DOT) in a document delivered on March 31, 2004. Task 2 results were of particular interest to some members of the navigation community, in that the susceptibility of low-frequency systems to precipitation static noise were long remembered from earlier days. This report was expected to result in decisions on the future of Loran-C as a part of the Nation’s infrastructure for positioning, navigation, and timing applications.


Loran’s Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications

Prepared for the
FEDERAL AVIATION ADMINISTRATION
VICE PRESIDENT FOR TECHNICAL OPERATIONS
NAVIGATION SERVICES DIRECTORATE
March 2004

B. Contract DTFA01-97-Y-01003, *August, 1998 through April, 1999*

This work was not a part of cooperative agreement 99-G-038. However, it is summarized here to provide context and background for the motivation, requirements, and task definition which resulted in the cooperative agreement.

The two principal parameters studied during ISTI work under contract **DTFA01-97-Y-01003** were Loran-C availability in weather and obtainable absolute accuracy using all-in-view, "pseudoranging" techniques in the receiver. In both cases, encouraging results were obtained.

A third factor, communications via the Loran-C signal, was also included briefly because of its potential for enhancing the value of Loran-C as an adjunct to GPS. The present-day Loran-C communications channel is called "Eurofix" when it is used with specific modulation and content defined by researchers at the Technical University of Delft, the Netherlands.

Results from the **accuracy and coverage** modeling activities during the contract were significant, in that they predicted that all-in-view processing of Loran-C signals would result in predicted accuracy of 0.2 nmi or less over the entire CONUS and a large portion of Alaska, using the existing Loran-C system transmitter locations. *This modeled result gave increased confidence that a physical receiver capable of all-in-view (GPS-like) processing could provide the necessary accuracy and availability of accuracy for a nationwide navigation service. This receiver later became the subject of Cooperative-Agreement 99-G-038, Task 4 (see below).*

Results from the **availability** portion of the work (the e-field vs. h-field antenna performance tests) generated much interest. ISTI teamed with Megapulse, Inc., LOCUS, Inc. and Ohio University in definitive tests comparing electric- and magnetic-field antenna tests on an aircraft experiencing electrostatic charging simulating flight in precipitation. *Clear performance benefits for the h-field antenna were noted, showing that the system remains available during flights in precipitation-static conditions. This result removed one of the most difficult and persistent criticisms of Loran-C as a NAS "player." Validation and verification of this work on another airframe type became the subject of Cooperative-Agreement 99-G-038, Task 1 (see below).*

Details of results are included in the final report described in the link below:

> [01] Lilley, R., Cohen, R., Poppe, D.; "Loran-C in Support of the National Airspace System: Modeled and Experimental Results", Report IST99-R-217, April, 1999.

The material was also presented to FAA representatives from AND, AIR, AFS, ACT, the Coast Guard and others at a formal briefing:

> [02] Lilley, R., "Loran-C as a Supplemental Navigation and Landing System in the NAS: Work in Progress", Briefing, January 7, 1999.

Considerable press attention was given to the antenna tests and to the developing FAA program. See the report described in the link below for the fact sheet of source information which was picked up by various trade publications and feature writers.

> [03] Illgen Simulation Technologies, Inc., Fact Sheet, "Loran-C P-Static Eliminated Using Loop Antennas", December 1, 1998.

The cooperative agreement 99-G-038, with Tasks 1 and 2 active, was awarded on July 26, 1999 as a response to this foundational work. The antenna test results were carried forward with ISTI's presentation of a conference paper on the work at the 1999 London meeting of the International Loran Association (ILA):

> [04] Lilley, R., "Comparative Performance of E-field and H-field Loran-C Antennas in P-Static Conditions", International Loran Association, 29th Annual Convention and Technical Symposium, London, UK, November, 1999.

By invitation, the paper was also presented in briefing form at RTCA and at the FAA Technical Center in early 2000:

> [05] "Comparative Performance of E-field and H-field Loran-C Antennas in P-Static Conditions", Briefing, Presented at RTCA, Inc. (Washington, DC), January, 2000 and at FAA W. J. Hughes Technical Center, January 2000.

At that same ILA-1999 conference, an overview was given of the FAA's developing Loran-C program as a work-in-progress briefing, on behalf of the FAA Program Manager:

> [06] "Loran-C Augmentation for GPS and GPS/WAAS: Work in Progress, November 1999", Briefing, International Loran Association, 28th Annual Convention and Technical Symposium, London, UK, November, 1999.

III. Cooperative Agreement 99-G-038, Tasks 1-6

The FAA Cooperative Agreement 99-G-038 was awarded on July 26, 1999, initially consisting of Tasks 1 and 2.

A. Task 1: Loran-C Accuracy and Availability Model Using Validation Data

System accuracy is one of the essential evaluation parameters for a safety-critical navigation system. The method developed in this task remains in the "toolbox" as a risk-mitigation method should additional accuracy improvements be needed later, to provide more headroom for receiver-autonomous integrity computations.

This task was awarded July 26, 1999 with a period of performance through July 24, 2000. The statement of work (SOW) required a data collection plan which was submitted along with the monthly progress report in September, 1999:

> [07] "Data Collection Plan," Cooperative Agreement 99-G-038, Task 1, August 26, 1999.

The SOW also required a task report:

> [08] Roland, W., Stoeckly, R., van Gool, P., "Measurement of Variations in Loran-Baseline Propagation Velocity and Emission Delay", IST2000-R-239, June, 2000.

The accuracy of the Loran-C position determination is limited because the effective propagation velocity of a Loran-C signal varies in time and space, depending as it does on atmospheric conditions and the conductivity of the Earth's surface. The time differences for each transmitting station pair within a chain are monitored at or near both stations of the pair. This information can be used to determine the current effective propagation velocity along each baseline (or similar parameter characterizing propagation along the baseline) and the actual emission delay of each secondary, and this information would be communicated to users. To the extent that the effective propagation velocity along baselines is correlated with that along the paths to the user receiver, the receiver could use this information to improve position determination.

Results from this task were not as conclusive as we would have liked, but they do show some improvement in accuracy (and thus availability of accuracy) for the system, using the on-baseline documentation of Loran-C propagation velocity. An FAA program decision led to this work not being continued because the relatively small amount of additional accuracy was not considered critical at present for aviation applications, including support for LNAV/VNAV approach procedures.

B. Task 2: Validation of Predicted E-Field and H-field Antenna Performance

Task 2 was awarded July 26, 1999 and continued throughout the 99-G-038 period of performance as test and safety plans were prepared, reviewed and updated; equipment was procured and tested; instrumentation was designed and fabricated; and the resulting complement was installed aboard FAA's Aero Commander aircraft N50 at the agency's William J. Hughes Technical Center in Atlantic City, NJ. This task is a direct outgrowth of the antenna-test work performed under the contract DTFA01-97-Y-01003. Cooperative Agreement 99-GT-038 Task 2's in-flight and independent calibration tests validate those ground-based antenna performance results obtained earlier. Since evaluation of Loran-C availability is a critical-path element in the FAA's overall program, the demonstration of the system's availability during flights in precipitation is essential.

Electric-field (e-field) and Magnetic-field (h-field) antennas were mounted on FAA Technical Center aircraft N50, together with instrumentation to measure aircraft position, air data, airframe electrical potential and charge/discharge rate. Both Megapulse, Inc. and LOCUS, Inc. supported this effort, providing antennas and preamplifiers under purchase orders. The FAA Technical Center procured LOCUS and II-Morrow Apollo receivers for the work. A purchase order was issued by ISTI to TCO, Inc. of Nogales, AZ and Ft. Myers, FL to obtain high-voltage systems fabrication and testing expertise.

To document the performance of the aviation-grade electric-field antenna, which was adapted to the LOCUS receiver for the flight tests, a test was performed to compare its operation with the standard-issue LOCUS antenna. A supplemental report was prepared and submitted to capture these results:

[09] Stoeckly, R., "Performance Comparison of Two Loran-C Electric-Field Antennas", Report IST2000-R-234, February 2000.

Legacy (Apollo) receiver and antenna equipment, and a high-voltage field-mill instrument were procured and delivered to the FAA Technical Center. Documentation of the necessary aircraft changes and test procedures was provided in a draft test-plan document which was posted on the ISTI web site and was then updated as the various equipment and procedure items were finalized. A safety plan was drafted by ISTI at the request of the FAA Technical Center and was submitted to the Test Director for further use.

[10] Lilley, R.,"Loran-C E-Field and H-Field Antenna Evaluation Test Plan", Draft document dated September, 2000.

TCO Inc. designed and built an "active discharger" system for the Technical Center aircraft, providing a complete high-voltage power supply for aircraft installation, plus plans for modifications necessary to the aircraft tail-cone for the "stinger" required for controlled artificial airframe charging in flight.

At various times during the program, Illgen/NGST personnel presented status reports at FAA-scheduled program reviews. Typical of such reports, material for Task 2 appears in:

[11] Lilley, R., "P-Static Effects Testing", Presentation ISTI2002-P-284, Loran Project Team Meeting, Washington, DC, July 30-31, 2002.

In November, 2003, NGST/ISTI and WJHTC team members co-authored a paper which presented preliminary Task 2 results and preparations to the larger Loran-C community and the public:

[12] Erikson, R., Lilley, R., "FAA Tests An H-Field Antenna To Increase Loran-C Availability During P-Static Events", Federal Aviation Administration W.J. Hughes Technical Center and Illgen Simulation Technologies Inc.; Briefing presented at International Loran Association 33rd Convention and Technical Symposium, Boulder Colorado, November 6, 2003. [PowerPoint presentation]

[13] Erikson, R., Lilley, R., "FAA Tests An H-Field Antenna To Increase Loran-C Availability During P-Static Events", Federal Aviation Administration W.J. Hughes Technical Center and Illgen Simulation Technologies Inc.; Paper presented at International Loran Association 33rd Convention and Technical Symposium, Boulder Colorado, November 6, 2003. [Word document]

FAA Technical Center electrostatic and flight tests were supported throughout the period by TCO, Inc. and ISTI personnel, culminating in on-site p-static evaluations in Atlantic City in March, 2004. These tests are being analyzed and reported by the FAATC team directly, and are anticipated be the subject of a paper/presentation co-authored with ISTI personnel, likely to be a part of the International Loran Association's 2004 annual meeting.

A complete set of **photographs** was made to document the ground-calibration tests on site at FAATC. These photos are included in the CD version of this report.

Results were also quoted in a trade newsletter:

[14] "Our Position", LOCUS, Inc. Trade Newsletter, Madison, WI, April 2004

and were also provided by the test team for inclusion in the March 31, 2004 FAA report to the U.S. Department of Transportation on the suitability of Loran-C for use as a backup system in NAS operations and other applications.

Another outcome of these efforts is the interest expressed by representatives of the FAA Technical Center in maintaining the capability to perform high-voltage tests and aircraft calibration for effects of p-static and other applications.

C. Task 3: Preparation of Program Plan and Work Breakdown Structure

This task provided up-to-date program planning information and a Gantt-type chart, showing the critical-path work necessary to answer the program hypotheses and the interdependencies among those tasks. Although the overall program plan had been developed earlier, this task was necessary as a point of entry into the actual aviation-receiver test bed effort. The task was awarded September 23, 1999 with a contracted end date of March 25, 2000.

On October 26, 1999, a letter-type program plan description with Microsoft Project charts was delivered by telefax to the FAA COTR. A bound report containing the same information as the more informal deliverable above, was prepared and submitted in December, 1999.

[15] "Program Plan: Loran-C Augmentation for GPS and GPS/WAAS", IST99-R-230, December, 1999

D. Task 4: Loran-C Augmentation for GPS and GPS/WAAS

Task 4 was issued on April 13, 2000, with a period of performance through December 31, 2000.

The goal of Task 4 is to show that the Loran-C component of a hybrid system can meet the requirements for horizontal navigation and approach procedures during loss of the GPS signal. The steerable H-field antenna and the all-in-view user position algorithm developed and tested in Task 4 are necessary elements of this proof.

1. Steerable H-field Antenna

ISTI hosted the Locus, Inc. effort to develop an h-field (i.e. magnetic) antenna steering system and then integrate the control system with the antenna itself . The goal of the h-field work was to produce a combination loop-antenna sensor plus processor which results in omni-azimuthal coverage with minimal phase error as a function of azimuth.

> [16] "Loran-C Augmentation for GPS and GPS/WAAS, Volume 2: SatMate Receiver Adaptation for H-Field Antenna",LOCUS, Inc. under subcontract to Illgen Simulation Technologies, Inc., IST2000-R-241, 25 September, 2000.

The effort was successful, and the antenna-receiver combination has been used by various program team members as the work has proceeded.

2. All-in-View Receiver Positioning Algorithms

ISTI's Loran-C all-in-view positioning algorithm development began with a first-principles review of existing models and error sources. Among many other effects considered and dropped from further consideration as not useful, brief analyses were made of possible accuracy improvement from an enhanced Loran-C station set giving world-wide coverage and of the effects of skywaves on positioning accuracy and their possible use for altitude estimation.

ISTI developed and validated all-in-view Loran-C position algorithms analogous to those used for the Global Positioning System (GPS). These algorithms are suitable for use in a weighted combined GPS/Loran-C positioning model.

The main algorithms developed in this effort are listed as follows:

- Interchain Phase Ambiguity and Closed-Form Triad Solution – these algorithms enable a reliable cold start of the system.
- *A Priori* ASF/ED Model and *A Priori* ASF/ED Error Model – these algorithms establish a framework for correcting ASF/ED effects, and propagating the formal ASF/ED errors and error correlations into the horizontal protection level (HPL) of the navigation solution.
- ASF/ED Prediction – this enables statistical prediction of ASF/ED effects along user-to-transmitter paths, based on calibrated ASF/ED effects along arbitrary given paths.

- TOA Error Model – this enables the proper weighting of the TOA measurements in the navigation solution and the proper propagation of formal measurement errors into the HPL of the navigation solution.
- On-the-fly ASF Calibration – this enables the use of the all-in-view geometry to improve the *a priori* ASF/ED model simultaneously with the navigation estimation. If, in addition, an external position and/or time update is available, this algorithm enables direct calibration of ASF/ED effects based on the external updates.
- Receiver Autonomous Integrity Monitoring (RAIM) – these algorithms enable the verification and validation of the measurements, error models, functional model, and measurement geometry used in the navigation. These algorithms provide safety of navigation to the required probabilities of missed detection and false detection.

[17] "Loran-C Augmentation for GPS and GPS/WAAS, Volume 1: All-In-View Navigation Algorithm Development", Illgen Simulation Technologies, Inc., IST2000-R-242, 4 October, 2000.

As work progressed further, an update to report R-242 was delivered. This material originally appeared as Appendix K in report IST2000-R-247 [21].

[18] "Appendix K: IST2000-R-242 Errata and Revisions", Illgen Simulation Technologies, Inc, 30 March, 2001.

Task 4 work was reported to the Loran-C community and the public at the 29th Annual Convention and Technical Symposium of the International Loran Association in Washington, D.C.:

[19] Cruz, J., "Covariance Analysis for On-the-fly ASF Calibration During Multichain Navigation", Illgen Simulation Technologies, Inc., Paper presented at ILA-29, Washington, DC, November, 2000.

[20] Cruz, J., Stoeckly, R., "Accuracy and Integrity Potential of Multichain Navigation", Illgen Simulation Technologies, Inc. Briefing presented at ILA-29, Washington, DC, November, 2000.

E. Task 5: Software to Implement All-In-View Receiver Capability with RAIM and FDE

Task 5 was awarded in February, 2001 and was renewed with expanded requirements twice during the program. In stages, models and algorithms plus a software package later named LUPS – Loran-C User Position Software – were created, documented and tested. LUPS was operated both in post-flight data-reduction mode and in a real-time implementation.

As the series of reports cited below will attest, the this work was successful in demonstrating the capability of Loran-C to meet instrument-approach accuracy and spatial availability requirements under specified conditions. Throughout the work, technical support was provided to the Loran Integrity Performance Panel and the Loran Accuracy Performance Panel, as these bodies prepared analyses for the FAA's March 31, 2004 evaluation report to U.S. DOT. Complete files for these reports are included in the compact-disk version of this document.

Two versions of LUPS were built, Version 1 as the first a developmental, post-flight version to prove algorithms, and to evaluate and demonstrate the all-in-view positioning concept. Version 2 was implemented in the C programming language specifically with a view toward real-time airborne operation, and it included expanded RAIM and FDE routines, plus improved ASF capabilities. Version

2 was subsequently carried over into Task 6 of the program, reported below, and modified for specialized use.

[21] "Loran-C User Position Software (LUPS) Engineering Notes, LUPS Version 1.0", Illgen Simulation Technologies, Report IST2001-R-247, 26 March 2001.

[22] "A Modern Flight-Capable Loran-C Receiver: Requirements for RAIM-Capable All-In-View Loran-C Software for use with DDC or SatMate Loran-C Sensors", Illgen Simulation Technologies, Report IST2001-R-254, 28 September 2001.

[23] Cruz, J., Stoeckly, R., Lilley, R., Kirk, J., Chavin, S., "Loran-C User Position Software (LUPS) Navigation Performance with Flight Test Data in the New Jersey Area", Illgen Simulation Technologies, Inc., Paper presented at ILA-30, Paris, October, 2001.

[24] Cruz, J., Stoeckly, R., Lilley, R., Kirk, J., Chavin, S., "Loran-C User Position Software (LUPS) Navigation Performance with Flight Test Data in the New Jersey Area", Illgen Simulation Technologies, Inc., Briefing presented at ILA-30, Paris, October, 2001.

[25] Sroeckly, R., Cruz, J., "Task 5 Completion Status", Briefing presented at the Loran-C Project Team Meeting, Illgen Simulation Technologies Inc. Briefing IST2002-P-285.

[26] "Algorithm Description Document for the Loran-C User Position Software (LUPS) Version 2", Illgen Simulation Technologies, Inc., Report IST 2002-R-302, 27 September 2002.

[27] "Implementation of All-in-View Loran-C Navigation Software with Integrity and FDE Capabilities: Final Report", Illgen Simulation Technologies, Inc., Report IST2002-R-303, September 2002.

[28] Stoeckly, R., "Timing Biases of Transmitted Loran-C Signals", Illgen Simulation Technologies, Inc., Technical Memorandum, August 15, 2002.

[29] Cruz, J., Stoeckly, R., "Loran-C User Position Software (LUPS) Navigation Performance with the August 2001
Cross-Country/Alaska Flight Test Data", Illgen Simulation Technologies, Inc., Report IST2002-R-321, 7 October 2002.

[30] Cruz, J., Stoeckly, R., "Loran-C User Position Software (LUPS)Navigation Performance with the August 2001 Cross-Country/Alaska Flight Test Data", Illgen Simulation Technologies, Inc., Presentation ISTI2002-R-332, Briefing presented at ILA31, October 2002, Washington, DC.

[31] Stoeckly, R., "Loran-C User Position Software (LUPS) Version 2.1: User's Guide", Illgen Simulation Technologies, Inc., Report IST2002-R-341, 4 December 2002.

Task 6: Generation of Local ASF Corrections to Support Loran-C Non-Precision Approach (NPA) Accuracy Analysis Requirements; Implement LUPS for real-time operation.

Other members of the FAA Loran-C evaluation program team, the Ohio University Avionics Engineering Center and the Loran-C Integrity Performance Panel (LORIPP), had a need for local airfield-specific Loran-C additional secondary factor (ASF) corrections to support NPA accuracy analysis requirements. The ASF corrections are applied to receiver-measured times-of-arrival (TOA) data to produce a locally calibrated Loran-C position which can be examined to see if the accuracy requirements for NPA are satisfied at a specific locale. To date, this need had been met through the "good-offices" of the SatMate 1020 Loran-C receiver manufacturer, Locus, Inc. From a Loran-C program perspective, it was desired that this capability be institutionalized and made accessible in a standard form for all program participants. Under program direction, software previously written by Illgen [26], [30], [31] was adapted, with modifications, to generate local-area ASF corrections.

In close cooperation with Ohio University, Illgen performed the following tasks:

> **1. The Loran-C User Position Software (LUPS) was modified** to accept a SatMate 1020 ASCII output file generated at a fixed location over a minimum two-hour static data collection period. The file, among other data elements, contains Loran-C signal TOA data collected at the receiver's known geographic location as a function of time for a specific set of transmitters-in-view.
>
> **2. The additional propagation delay** due to errors in modeling the emission delay and ground conductivities was determined using this SatMate 1020 data file, and the nominal propagation path between the known receiver position and each Loran-C transmitter with a valid TOA in the data file (information currently generated within LUPS), using the true location of the static receiver. A space-delimited output file with ASF corrections for each valid transmitter was produced. Each correction includes mean and standard deviation, plus a measure of the correlation with corrections generated for other transmitters in view. Tests were then performed to establish the utility of the correction for the local area in the vicinity of the user position.
>
> **3.** A second modification implemented in LUPS allows the corrections generated in Task 6.2, above, to be included in the processing of each respective TOA data point to produce a **locally corrected aircraft position**. A space-delimited, ASCII output file was produced. This file, when compared with a corresponding truth file of aircraft position (e.g., often derived from WAAS-corrected GPS), permits the user to determine the accuracy of the locally corrected Loran-C position information versus the truth reference.

It was subsequently determined that real-time outputs were not required at this time, so this portion of Task 6 was de-emphasized even though progress was made in speed-up and optimization of the LUPS code during the above activities. The code runs at nearly real-time speed (on the 1-GHz Intel processors used during development).

The task activities were reported in:

> [32] Cruz, J., "Loran-C User Position Software (LUPS) Engineering Notes, Version 2.2ex", Report IST2003-R-370, Illgen Simulation Technologies, 20 May 2003.

IV. Summary

Cooperative Agreement 99-G-038 was successful from a number of viewpoints. Illgen Simulation Technologies, Inc., which became Northrop Grumman Simulation Technologies Corp. in December, 2003, provided analysis, algorithm development, computer software tools, engineering, and technical support services over the full range of requirements for the FAA Loran-C evaluation program. The visibility thus gained facilitated our contacts with industry, academic, and governmental representatives as we participated in the educational aspects of Loran-C evaluation. We applied our expertise in electrical engineering and computer science to appropriate aspects of the work, and contributed directly to what must certainly be considered the principal program outcome – the FAA report to the U.S. Department of Transportation on the suitability of Loran-C as a GPS backup system in the NAS and for other purposes.

V. References

[01] Lilley, R., Cohen, R., Poppe, .D.; "Loran-C in Support of the National Airspace System: Modeled and Experimental Results", Illgen Simulation Technologies, Inc., Goleta, CA, Report IST99-R-217, April, 1999.

[02] Lilley, R., "Loran-C as a Supplemental Navigation and Landing System in the NAS: Work in Progress", Briefing, January 7, 1999.

[03] Illgen Simulation Technologies, Inc., Fact Sheet, "Loran-C P-Static Eliminated Using Loop Antennas", December 1, 1998.

[04] Lilley, R., "Comparative Performance of E-field and H-field Loran-C Antennas in P-Static Conditions", International Loran Association, 29th Annual Convention and Technical Symposium, London, UK, November, 1999.

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Appendix A: Scientific Collaborators – Résumés of key personnel

Robert W. Lilley, Ph. D., Co-Principal Investigator

John G. Kirk, Ph. D., Co-Principal Investigator

Jaime Y. Cruz, Ph. D., Principal Engineer

Robert Stoeckly, Ph. D., Senior Engineer

Dr. Robert W. Lilley		**Engineer, Navigation SME**		
	Ph.D., Ohio University, 1974 MSEE, Ohio University, 1967 BSEE, Ohio University, 1963			
Status:	Full-Time	*Qualification Summary*		
			Education	*Experience*
Clearance:	Secret	*Actual*	Ph.D.	40 years

WORK EXPERIENCE

Present Position

Consultant **2004 -**

Dr. Lilley continues his support of FAA and other programs in the navigation and systems areas.

Previous Positions

Northrop-Grumman Simulation Technologies Corp., Goleta, CA **12/03 – 4/04**
(formerly Illgen Simulation Technologies, Inc.)
Chief Engineer

Dr. Lilley brings his 35+ years of experience to this position, supporting the wide-ranging Northrop-Grumman Simulation Technologies (NGST) technical program. Current technical activity includes the completion of aircraft antenna evaluation in cooperation with the Federal Aviation Administration's Technical Center, plus participation in integrated navigation studies for FAA systems engineering. He directed the recent Illgen/NGST/CECOM study and demonstration of alternative positioning technologies for use in the urban environment.

Illgen Simulation Technologies, Inc. (ISTI), Goleta, CA **10/97 – 12/03**
Vice-President

Dr. Lilley provides considerable management and technical experience in advanced communications, navigation, and position-location systems. He has contributed to navigation/position evaluation, test, operations, system integration and national/international navigation policy. Since joining Illgen, his leadership of the program to demonstrate the benefits of magnetic-field aviation antennas for Loran-C in weather operations has led to reconsideration of the system as a backup or complement to GPS.

With his participation, the Illgen navigation team has carried out navigation receiver software development, maintained the Illgen GPS simulation and analysis capability, and investigated UWB communications technology in various implementation scenarios. He is the Illgen point of contact for FAA's Systems Engineering and Technical Assistance Program-II in which Illgen supports FAA communications, navigation and surveillance operations in Washington, DC.

Dr. Lilley is Director Emeritus of the Avionics Engineering Center, Ohio University, earned his Ph.D. at Ohio University and is an instrument-rated commercial pilot. Dr. Lilley was awarded the FAA's first Excellence in Aviation Award in 1997 in connection with his work as a Principal Investigator in the NASA/FAA Joint University Program in Aviation Systems. He has authored or co-authored well over one hundred technical publications and reports.

Ohio University
Avionics Engineering Center: Professor, Research Engineer and Director 1964 – 1997

As Director, Dr. Lilley held full responsibility for this multi-million dollar 50-person research and engineering activity, with internationally-recognized programs in communications and navigation spectrum protection, GPS navigation and landing, ILS and MLS landing systems, in navigation and communications interference detection and management. He participated in airport navigational and visual-aid surveys in Ohio and at LAX.

As a research engineer, Dr. Lilley participated in FAA and DoD projects involving the Microwave Landing System (MLS), Instrument Landing System (ILS), and the Loran-C navigation system. Dr. Lilley coordinated the ILS Marker Beacon precise location study for the Federal Aviation Administration, and the United States Coast Guard Omega Navigation monitor receiver evaluation program. He served as Project Engineer for the U.S. Army CECOM evaluation of airborne distance-measuring equipment. He served as project engineer for the NASA Ames Research Center's computer-controlled VOR receiver project. His team developed a prototype communications system designed to detect blocked-channel conditions affecting air/ground communications at VHF frequencies, and GMSK data link prototypes for weather broadcast to aircraft.

In the pre-GPS era, he designed and implemented the Avionics Engineering Center's 3-d tracking system for flight documentation of navigation and communications coverage and precision landing system validation, including optical theodolite and RF ranging sensors, and custom data link communications for time-synchronization of airborne and ground data recording.

His group developed the local-area differential GPS positioning and landing-guidance system used by CECOM in early helicopter landing evaluations, and by NASA Ames Research Center in similar tests.

He investigated on site and through analysis the potential negative impacts of construction of the Metro Green Line on the various visual and radio navigation aids at LAX; performed flight studies of VOR vertical polarization error; recommended alternative navigation system sites for the Portsmouth, OH, airport; and co-wrote the implementation plan for RNAV (Loran-C) instrument approach procedures in Ohio.

His team demonstrated alternative and shared uses for VOR spectrum including advanced communications systems now being implemented as data-links for operational data, GPS corrections and other NAS functions.

He was one of the early evaluation pilots to fly GPS-guided instrument approaches to Category-III minima, and was the first to test-fly the military mobile microwave landing system (MMLS).

Dr. Lilley participated in the development of the digital sensor processor for Ohio University's Omega and Loran-C navigation receivers. This work involved the development of the memory-aided phase-locked loop (MAPLL), and the binary rate-multiplier frequency synthesizer. Working with the LF navigation project team, he flight-tested prototype receiver hardware, using the Avionics Center DC-3 Flying Laboratory and light aircraft.

Dr. Lilley interacted with various federal government sponsoring agencies, participated in meetings of RTCA SC-125 (MLS Implementation), SC-176 (Loran-C MOPS), SC-159 (GPS) and presented papers at technical symposia of the Institute of Navigation, International Loran Association and International Omega Association.

Dr. Lilley's experience with electronic circuitry, antenna systems, satellite communications, and digital computer systems at Ohio University's Radar Hill Laboratory and with the University Computer Center provided appropriate background for contribution to the Avionics program.

Dr. Lilley also demonstrated his leadership during the time he was responsible for organizing and implementing the technical and academic computing Center at Ohio University. While in this position as **Director of the Academic Computer center (1968-1973)**, his duties included administration of Center activities, with a staff of twenty and an annual budget in excess of one-half million dollars, programming work in the areas of Center administration, systems, simulation, installation accounting, and specialized sorting routines for University administrative information (budget committee, capital improvements). Under his leadership, the Computer Center was a leader in the early stages of decentralized computing on campus. Upon his move to the Avionics Engineering Center, he established the necessary line drivers, modems and terminal network to permit department-wide computing on-site. This network was changed to an Ethernet-based system in the mid-80's.

Dr. Lilley provided support to the FAA Microwave Landing System (MLS) as Project Engineer. He designed airborne flight data measurement and processing equipment. This included MLS sensors at C-band, a digital telemetry link, ground angle/range tracker, and general-purpose data processor with graphics input/output. This system was used for field and laboratory use in navigational system evaluation.

He participated in a U.S. Air Force Communications System Simulation project at Wright-Patterson AFB to design, implement, and apply a complete system simulator for multi-mode tactical communications studies. He designed and implemented the simulator executive routines on the IBM System/370 and Digital Equipment Corp. DEC-10 computers. He adapted the existing executive routines for the unique needs of image-processing applications.

For the NASA Joint University Program in Air Transportation Systems, Dr. Lilley provided engineering and administrative support and guidance for graduate and undergraduate student interns involved in the program. He participated in designs for Omega and Loran-C navigation receivers, flight evaluations, and report generation. He co-invented the digital Memory-Aided Phase-Locked Loop. He initiated design for the low-cost Loran-C receiver, based upon single-microcomputer use for all signal processing and display functions, including the pilot control/display unit. He aided in integration of coordinate conversion to latitude-longitude output, area-navigation software, and performed flight tests on the unit.

Dr. Lilley served as the project engineer for VOR and DME receiver evaluations carried out for the U.S. Army against Army and RTCA specifications.

For the FAA Remote Maintenance Monitoring project, he performed a study of digital monitoring of navaid ground systems at Chicago O'Hare Airport, involving digital sensors, data communications, and processing/alarm/display functions. The system objective was to provide out-of-tolerance alarm annunciation plus continuous monitoring of critical system elements for incipient failure, for a wide variety of ground installations ranging from surveillance radar through landing systems to runway lighting systems.

Dr. Lilley was the Task Engineer for evaluation and redesign of prototype equipment for the FAA to produce aircraft groundspeed on approach at an ILS localizer-equipped airport. Analog phase-locked-loop designs were produced, together with flight evaluation and reporting. Groundspeed was measured to within ±2 knots. This project was a part of the FAA wind shear protection program.

Also for the FAA, Dr. Lilley was the Project Engineer for literature search and experiment design to determine extent to which Loran-C is affected by aircraft-generated static discharge noise in flight, and to suggest strategies for reduction of such noise. Follow-on work concentrated on demonstration of reduction techniques and broadened the study to include lightning discharge noise.

Dr. John G. Kirk			**Program Manager**
Education:	Ph.D., Astronomy, University of Michigan, 1966 A.M., Astronomy, University of Michigan, 1962 A.B., Astronomy, Amherst College, 1960		
Status:	ISTI Full Time	*Qualification Summary*	
		Education	*Experience*
Clearance:	Secret	Ph.D.	40 years. Commercial Pilot, CFI.

WORK EXPERIENCE

Present Position

Illgen Simulation Technologies, Inc., Goleta, CA **1995 - Present**
Director, Simulation Engineering Division
Dr. Kirk is responsible for all Illgen tasks and activities related to the development of simulations of physical processes. Division activities include: 1) Tasks from the Army's Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI) to model and simulate performance characteristics of large-scale, distributed military training simulations, and 2) Tasks from the FAA to develop an all-in-view positioning algorithm for Loran-C navigation receivers using a measurement model analogous the pseudorange measurement model used in the Global Positioning System (GPS), and using an Illgen-developed end-to-end software simulation of the FAA's Wide Area Augmentation System (WAAS, an augmentation to GPS to provide the accuracy, availability, and integrity enhancements to the basic GPS system required for GPS use in aircraft navigation) to assess candidate WAAS estimation and integrity algorithms and to provide simulated WAAS operational data to test the resulting WAAS software. As part of his experience with PEO STRI, he has developed a combined interest and time management algorithm which promises to be both scalable and significantly less costly in processing and message-handling resources than the currently-used High Level Architecture (HLA) Real-time Infrastructure (RTI). As a result of his experience in helping develop the WAAS simulation, he has extensive experience in creating interfaces which edit formats, units, timing, and fidelity for data exchange between disparate simulation components. He also provides technical analyses and reverse-engineering for algorithms related to satellite orbit determination and management, and for those proposed for determining corrections to broadcast GPS satellite ephemeris and clock state parameters. He wrote an Algorithm Description Document for the GPS satellite message ephemeris and clock state parameters corrections code in the Stanford University Wide Area Differential GPS computer program after reverse-engineering this code.

Previous Positions

Geodynamics Corporation, Goleta, CA **1980-1995**
Senior Systems Engineer
Dr. Kirk provided formal instruction in the use of the TRACE satellite orbit analysis program. He provided operational scenario development and analyses using TRACE. He verified and isolated TRACE problems and devised capability enhancements, identifying the TRACE source code locations where changes were required, and testing and validating the changes.

Dr. Jaime Y. Cruz		**Principal Engineer**	
Education:	Postdoctoral Research, The Ohio State University, Columbus, OH, 1986 Ph.D., Geodetic Science, The Ohio State University, Columbus, OH, 1985 MS, Geodetic Science, The Ohio State University, Columbus, OH, 1982 MS, Geodetic Engineering, The University of the Philippines, 1974 BS, Geodetic Eng., The University of the Philippines, 1973, cum laude		
Status:	ISTI Full -Time	*Qualification Summary*	
		Education	*Experience*
Clearance:	None	*Actual:* Ph.D.	25

WORK EXPERIENCE

Present Position

Illgen Simulation Technologies, Inc., Goleta Operations **10/95 - Present**
Principal Engineer

Developed next-generation Long-Range Navigation (LORAN) algorithms, with improved accuracy and safety of aircraft navigation through the introduction of statistical detection and exclusion of measurement blunders, computation of network reliability metrics, and least squares collocation estimation of signal propagation velocity errors along transmitter-to-receiver paths based on calibrated paths. Developed a satellite ephemeris integrity monitoring algorithm for the Local Area Augmentation System (LAAS) based on least squares position estimation. Developed wrappers for interfacing the army's Next Generation Performance Model (NGPM, a battlefield communication network simulation) with NVTHERM (a night vision sensor) for the collaborative simulation environment being developed by ISTI.

Technical Lead in Wide Area Augmentation System (WAAS) navigation tasks, including navigation algorithm development, legacy code reverse engineering and porting, software/algorithm verification and validation, and development of the IV&V WAAS Simulator (iWAASs). Authored numerous technical notes on the WAAS system including software engineering notes, algorithm descriptions, user guide for running the iWAASs, development of pseudorange error models based on real data, analysis of equations and results from satellite orbit and clock and ionospheric estimators, and treatment of earth rotation and relativistic corrections in the ranging equations. Suggested corrections to slant ionospheric estimations which resulted in improved performance, and resolved various issues as documented in the technical notes. Principal contributor to studies involving the iWAASs for the purpose of stressing algorithms and quantifying error contributions from the ionosphere, troposphere, satellite orbit and clock errors, Selective Availability (SA), station clock errors, and measurement errors caused by multipath, cycle slips, and receiver noise.

Previous Positions

Geodetic Systems Engineer, Geodynamics Corporation **10/86 - 10/95**
Member of the Professional Staff

Algorithm development and test flight support for a Global Positioning System (GPS)/airborne gravity measuring system. Developed algorithms for crossover adjustment of aerogravity profiles; generation of truth gravity at altitude by combining surface gravity measurements, detailed topographic grids, and upward continuation to altitude using Fast Fourier Transform; least squares calibration of gravimeter cross-coupling parameters; gridding of aerogravity profiles using least squares collocation and locally tailored covariance model; and optimal smoothing of aerogravity profiles.

Tested the smoothing of GPS pseudoranges using carrier phase data and the accuracies in GPS position, velocity, and acceleration achieved by a local differential GPS software. Studied relative positioning accuracies obtainable from different GPS observables, solvability of mean ionospheric effects and carrier phase ambiguities, and dependence of ionospheric effects and pseudorange noise on multipath, satellite elevation angle, baseline length, and daytime or nighttime observations; designed a better-than-50-cm relative positioning algorithm for baselines up to 1000 km long, based on an elevation-dependent model of pseudo range noise, statistical constraints on the ionosphere, and dual-frequency pseudorange and carrier phase data.

Performed a variety of satellite orbit determination analyses in support of the Milstar contract, using the TRACE Trajectory Analysis and Orbit Determination Program on the VAX/VMS environment. Analyses included ephemeris generation, tracking data generation, measurement error modeling, orbit estimation, and calibration of force model parameters such as station keeping thrusts, momentum dumps, solar radiation pressure parameter, and ranging bias. Used weighted least squares in both covariance analysis and simulation approaches, in the multi-satellite/multi-station mode; intimate knowledge of satellite orbit force modeling and parameter estimation.

Verified the Environmental Simulator software (ES) developed by Lockheed for the simulation of real-world ground links and interspacecraft links for Milstar. The effort included verification of coordinate and time-keeping transformations, functional and error modeling, algorithms, methods, and computer coding. Participated in the conversion of the Milstar orbit determination and ephemeris generation software from FORTRAN VAX/VMS to ADA PC/UNIX environment.

Covariance analyzed the positioning of ground targets from NASA's proposed Geodynamics Laser Ranging (GLRS) satellite mission. Used matrix partitioning techniques to make computations tractable; simulated satellite orbits for GLRS using the Simplified General Perturbation theory (SGP4). Compared geodetic heights derived from a global reference frame (DOPPLER transformed to WGS84) with those from spherical harmonic geopotential models (OSU86D, WGS84) and leveling; intimate knowledge of global geodetic systems and their realizations in terms of reference frames, defining parameters, and transformation techniques between frames.

Extensive gravity field modeling and intimate knowledge of gravity field mapping techniques including land/sea/air gravimetry, gradiometry, astronomic techniques, altimetry, and satellite perturbation techniques. Generated high-resolution point mass models covering parts of the U.S. Compared deflections of the vertical obtained from the Global Positioning System (GPS) combined with leveling, with those from astrogeodetic techniques. Filtered and adjusted helicopter gravity data, and compared these with models generated from surface data.

Described gravity field characteristics in terms of stochastic models of the short and long-wavelength components. Developed gravity error models for use in land navigation and accuracy assessment of the rail and small ICBM systems. Extensively applied potential theory while performing a precise upward continuation of surface gravity data onto a 300-m tower at Erie, Colorado, demonstrating a validation of Newton's inverse square law of gravitation and helping to settle the fifth force controversy.

Dr. Robert Stoeckly			**Senior Engineer**
Education:	**Ph.D., Astrophysical Sciences, Princeton University, 1964** **Physics, Massachusetts Institute of Technology, 1960** **Computer Science, University of California at Santa Barbara (continuing), 1991–1992, 1997**		
Status:	Illgen Full -Time	*Qualification Summary*	
		Education	*General Experience*
Clearance:	Secret	Ph.D.	35 years

WORK EXPERIENCE

Present Position

Illgen Simulation Technologies, Inc., Goleta, CA **1997–present**
Senior Engineer
Dr. Stoeckly conducts research in radionavigation and positioning. He is coauthor of a state-of-the-art Loran-C positioning code. He conducts research in low-frequency wave propagation and GPS/Loran-C integration. He helped develop and perform detailed receiver simulations of the FAA Wide Area Augmentation System (WAAS), including ionospheric storms, satellite clock and ephemeris errors, satellite maneuvers, receiver faults, multipath errors, and the uplink and broadcast of WAAS navigation messages. He helped develop the user-positioning tool to test WAAS algorithms and software.

Dr. Stoeckly conducted research on GPS receiver loss of lock due to ionospheric scintillation and on loss of satellite signal due to foliage attenuation and line-of-sight terrain blockage.

Previous Positions

Kaman Sciences Corporation, Santa Barbara, CA **1983–1985, 1992–1996**
Senior Scientist
Dr. Stoeckly developed atmospheric physics models for simulations of nuclear bursts and their effects on the performance of communications systems. He wrote technical documentation for the environment models in these simulations, including the natural environment, weapon radiation output, radiation transport and energy deposition, and fireballs. He also provided technical computer support.

Physical Research, Inc., Santa Barbara, CA **1985–1990**
Senior Research Scientist
Dr. Stoeckly developed a portion of a large code for optical sensor and radar performance and nuclear radiation environments after nuclear bursts. He wrote user manuals for this code and provided technical support to 40 organizations. Dr. Stoeckly managed a VAX computer and trained and supported 40 scientists in using this and the Cray computers at Los Alamos National Laboratory. He administered the company’s wide-area network.

Mission Research Corporation, Santa Barbara, CA **1972–1983**
Scientist
Dr. Stoeckly performed state-of-the-art simulations of nuclear bursts in the atmosphere. He also conducted research on nuclear burst striations, effects of nuclear bursts on communications system performance, atomic collision cross-sections, debris-air coupling, and numerical calculation techniques.